Self-Steering for Sailing Craft

John S. Letcher, Jr.

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by John S Letcher jr

"One of perhaps 20 books published in the last 35 years that is considered a true modern classic for any sailing enthusiast. It is truly a book that should be in any comprehensive personal (or organizational) reference library. This extensive book features over 250 pages of detailed (yet practical) text, illustrations, photos, and diagrams"

"This is easily THE BEST boat engineering book I've ever read. John Letcher applies his considerable engineering knowledge and practical experience to the problem of boat self steering. He uses a systems approach to breakdown all the discrete elements that comprise an effective self steering system. He suggests a methodology of testing to develop each element in a prototype steering system before investing in more permanent materials. The reason for this is the variability in relative steering damping in each boat's design that every self steering system has to be adapted to, which also helps explain why many commercial windvane steering solutions with their "one size fits all" approach tend to work well only to windward in strong winds. He also gives several "cookbook" solutions that provide an effective design guide book, while pointing out the limitations of this approach. This book has a reputation as being the best book on sheet to tiller steering systems ever written and it deserves praise for this, but it is also the best book written for anyone that wants to design a self steering system for their boat or troubleshoot the flaws and improve the effectiveness of an existing windvane system"

Many thanks to Len Hiley for converting John Letcher's book to pdf files and obtaining permission from John Letcher.

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FOREWORD
by Hal Roth

One September afternoon a few years ago, a 25-foot cutter named *Aleutka* glided smoothly under San Francisco's Golden Gate bridge and anchored in nearby Sausalito. The next day my wife and I invited the owners of the trim cutter, John and Pati Letcher, to dinner aboard our yacht *Whisper* where we swapped sailing stories of Alaska. John's stories topped mine. Even now, four years later, I can recall one that dealt with the value of seeking "local knowledge."

"We came to Lynn Canal, a huge fiord that ran north for 120 miles," said John. "There was a south wind blowing to make our passage up the bay a cinch, but I was worried about getting back south and out. So I asked a commercial fisherman.

" 'No problem' said the fisherman. 'She always blows north in Lynn Canal.'

"Marvelous," replied John, who like a good sailor immediately cast off and headed north with the usual south wind. They sailed to the most remote northerly stretches of the great bay. However, when it came time to sail south John began to look for the northerly wind. It didn't come and it took John and Pati three weeks to beat and row their way out. When they neared the entrance they saw their fisherman friend and hailed him.

"Say, where's that north wind you said always blew here?" asked John.

"The fisherman scratched his head and replied: 'North? What do you mean? She's blowing toward the north right now'."

A long time ago I read the accounts in *Yachting* magazine of John Letcher's singlehanded passages in *Island Girl*. His technical inclinations were apparent because he sometimes worked out his position at sea from lunars — simultaneous observations of the moon and another heavenly body which, together with tedious calculations, gave the longitude without recourse to exact time. It was a rigorous and difficult procedure, for which he had derived a simpler solution. Now after his latest Alaska trip I admired the *Aleutka*, the new small yacht that he had built himself. John eschewed an engine, and I recall a vigorous discussion of Japanese rowing oars. The *Aleutka* was as spare and functional as a mathematical equation, but she had everything necessary for the long voyages the Letchers were making. Each detail had been worked out carefully as a separate engineering problem. There was respect for nautical traditions and wisdom, but the strength, function, and position of each item — the chain plates, for example — had been painstakingly calculated before John had made them. In addition, he demonstrated that a simple and cheap yacht can be both practical and rewarding.

John has continued to marry engineering and seafaring, and his new book is a hard look into the world of steering, especially self-steering mechanisms for sailing vessels. The only other book in this field is the Amateur Yacht Research Society effort that was assembled some years ago. Though useful, the AYRS book is a collection of miscellaneous ideas and notions without the engineering and practical analyses that the ocean-crossing sailor needs. The Letcher book, on the contrary, is a carefully organized inquiry into the whole world of steering systems by a competent engineer who is a seaman with tens of thousands of bluewater miles behind him. The writing style is pleasant and readable and the book is filled with technical information. John emphasizes that sheet-to-tiller steering arrangements — once again the simple and cheap — are often excellent and practical. I was pleased to see that John made all the drawings himself instead of using manufacturers' handouts.

During the past 15 years or so, the number of small sailing vessels has increased a dozenfold or more. For many reasons — perhaps because of self-steering gears, dacron sails, better, cheaper designs, more leisure time, longer life, a more general affluence, an urge to simplify one's life, or general travel. Or more likely from some combination of all these things, plus or minus the personality of the captain. In 1972 I was asked to look into the number of small, seagoing yachts and after some investigation came up with the estimate that 1,400 yachts made ocean passages of 1,000 miles or more. This is a remarkable number of small seagoing homes.

As I write I know that somewhere a bold blue and white sloop is heading offshore toward a distant island of shimmering green. If the captain has a copy of this book it will help make his voyage easier and more pleasurable. What more can an author wish?

ACKNOWLEDGEMENTS AND DEDICATION

The author takes pleasure in acknowledging the contribution of many persons to this work. First, there is the great company of modern seafarers who have experimented with self-steering and have shared their findings with me through their writings. I have tried to name the originators of innovations whenever they were known to me, and I apologize in advance for any oversights. Second, there is the Amateur Yacht Research Society, Woodacres, Hythe, Kent, England, whose Publication 13 entitled *Self Steering* and edited by John Morwood has played such an important seminal role in the development and popularization of self-steering all over the world. Third, there are the many manufacturers of self-steering equipment who have provided information on their products; these are listed in the appendix. Finally, I would like to express special appreciation to my personal friends who have contributed in one way or another to my understanding of the subject and to the success of the book: Dr. Peter Lissaman, Frank Rogganbuck, Roland Anderson, Irwin Giroux, Eric Hiscock, Ron Mitchell, Hal Roth, and Dr. Jerome Milgram; and to Warren Roll for his superb photographs.

Phil Bolger, Frank Kibbe, Jr., and Peter Spectre read the manuscript and made valuable suggestions for improvements.

I dedicate this book to my beloved wife Patricia, who inspired me to design and helped me to build *Aleutka*. Three different times she gave me whatever encouragement I needed to leave a secure job and go voyaging with her, and she still comes on deck to steer during sail changes even though the vane gear would do the job well enough.

John Letcher,
Southwest Harbor, Maine

1 STEERING AND SELF-STEERING

Self-Steering is the sailor's term for any way in which a sailing vessel can be made to maintain her course without having someone steering. It is a term peculiar to sailing; ships and aircraft have their autopilots for the same purpose, but they are called *autopilots* or automatic helmsmen, and the vehicle is described as "on autopilot" and not as "steering itself." I think it is because of our tendency to think of sailing vessels as sentient beings that this term has come into common use. And never does my ship seem so alive and conscious as when I stand in the companionway to watch the clever way she threads a path through a jumbled sea left over from a gale, or when I wake up at night for a glance at the compass and find her purposefully driving, exactly on course, for a landfall a thousand miles ahead.

The value of this ability in a cruising boat is simply not to be argued — I feel a little absurd just drawing up a list of its uses. Steering is, at least 90 percent of the time, a mindless task less demanding than the most trivial assembly-line job, done in far less comfortable surroundings. Consider the prospect of a short-handed voyage offshore. Single-handed, you will be engaged in this task for sixteen hours a day, including weekends, and even so the boat is losing a third of her speed potential. With two aboard, the boat can be kept moving all the time, but only by having each person work a twelve-hour day. Even with four aboard, each person will be putting in more than 40 hours a week at this menial occupation. Of course, the scenery is often spectacular, and the adventure makes it all worthwhile. Many voyages, even circumnavigations, have been successfully completed under these conditions; adventure meant a lot to these people.

Self-steering means release from this task. It gives you back the sixteen or twelve or eight hours a day. It means all night in a warm berth on at least some nights; or if watches must be kept, one can sit in a sheltered place or read in the cabin. It means good meals leisurely prepared, and enjoyed by the whole crew together. There is time to shave, time to bathe, time to play chess, time to make love, time to read and write. For days together the ship makes her own way, with only an occasional trimming of sheets, and the voyage is an idyll rather than an endurance contest. Today perhaps eight out of ten yachts undertaking long voyages are equipped with windvane self-steering, and I think it is largely the development of this gear that accounts for the remarkable number of small-boat voyages in recent years.

The advantages of self-steering in coastwise cruising are less painfully obvious. In America the windvane is still the mark of the distance sailor, but in Europe it seems to be well on its way to acceptance as standard cruising equipment. Self-steering makes the owner much less dependent on finding skilled crew members, for it makes single-handing even a large yacht quite easy in moderate weather. It reduces the requirement for a watch to one man, who can be a more effective lookout, can move freely about the deck, and can keep more comfortable than if he were tied to the helm. Just the chance of a few minutes of undivided attention to the chart before entering a strange harbor makes it worthwhile; even for coming to anchor we set it to keep the boat shooting into the wind while we lay forward to lower anchor and sails.

Having reliable self-steering is like having an extra hand on board – one who is an expert helmsman, who doesn't eat, doesn't sleep, doesn't drink, doesn't talk back to the captain, and doesn't mind sitting out in the bad weather.

Ways to achieve freedom from the helm fall into four basic categories: natural course stability, sheet-to-tiller gears, windvane gears, and electrical autopilots. The characteristics, advantages, and disadvantages of each type are briefly discussed here, and then one or more chapters are devoted to each category.

NATURAL COURSE STABILITY

At first thought it is not at all obvious why a sailboat, properly trimmed in a steady breeze, with her rudder fixed at exactly the right angle, should *not* go along happily on the same course. The fact is, some boats on some courses do this, and there are other boats whose sails can be trimmed in some way (with less than optimum propulsive efficiency) so they maintain course with the helm fixed. Except for the loss in speed, this sounds like the best possible self-steering arrangement, because it is the simplest, it costs nothing, and it can't be washed away in a gale. But I doubt if there is any boat that can do this on all courses; and, too, the wind is never altogether steady in force, so I'm sure the helm would need frequent adjustment. Still, it is an interesting and useful first step to see why some boats will sail some courses (and why most won't sail most courses) by themselves.

SHEET-TO-TILLER GEARS

The next simplest approach to self-steering is an assortment of ways to connect the helm to the running rigging so that, if the boat goes off course, the change in pressures on the sails will be transmitted to the rudder and correct the course. These are known collectively (and somewhat too restrictively) as sheet-to-tiller gears. Some arrangements require special sails, but the rest are composed mainly of spare blocks and lines, so they are cheap, durable rigs, and readily repaired on board.

Over the years many voyagers have worked out sheet-to-tiller arrangements on particular points of sail for their particular boats. Aside from twin running sails, none of these arrangements has come into general use. Most people assume that their boats don't have the magical qualities required for self-steering, so they don't even try, or they give up much too easily. In this book I have two chief messages, and the first message is this: *sheet-to-tiller gear can do the steering, simply and reliably, on all points of sail.* I base this assertion on 20,000 miles of offshore voyaging without a windvane, with sheet-to-tiller gears steering practically every mile except in gales — at least 95 percent of the way. Most of the arrangements I have used are detailed in Chapter 3 along with many aspects of a general approach to devising and adjusting sheet-to-tiller gears.

The disadvantages of sheet-to-tiller gears are (1) they require a period of experimentation and adjustment for each particular yacht, and (2) they are totally dependent on the sails, so any change of sail or major change of course generally requires a different arrangement, and of course they fail completely during reefing or sail changes.

WINDVANE GEARS

When the aerodynamic device that monitors the apparent wind direction, senses changes, and controls the steering is a separate windvane (instead of the sails themselves), we have a windvane gear. The windvane, the way in which the steering is controlled, and the linkage by which information is transmitted from the windvane to the steering control all take many different forms. Being a separate device from the sails and rigging, the vane gear requires only very minor readjustment for operating on any point of sail, and it can steer right on through reefing and sail changes, and perhaps through a gale under bare poles. In concept it is a wonderful idea.

The disadvantage of windvane self-steering is the special equipment it requires. To operate over a useful range of conditions, the mechanism must be very sensitive and well adapted to the particular yacht it is used on. To have any chance of surviving offshore, it must be very robust and durable. The resulting devices are usually mechanically complicated, expensive, unsightly, vulnerable to all sorts of damage, and irreparable outside of a machine shop — and often do not work very well after all! So far, the number of windvane gears that have operated satisfactorily through an entire ocean crossing is very small indeed. Which leads me to the second message of this book: *achieving successful windvane self-steering is not nearly as easy as it looks.* But it can be done. The operating principles of many varieties of windvane gears and methods for designing a successful installation are the subjects of Chapters 4 through 9.

ELECTRONIC AUTOPILOTS

Units using an electronically read compass, an amplifier, and an electric motor to actuate the rudder have long been doing a satisfactory job of steering fishing boats and larger powered vessels. In the design of an autopilot for a powerboat, there is little reason to be frugal with electric power, so most of the commercial units are unsuitable for use in a sailing vessel unless she has an unusually ample electrical system. However, there are a number of ways of reducing the power requirement, and several commercial systems designed specifically for sailboats are available.

The electronic autopilot differs essentially from the other approaches to self-steering in that it steers *by the compass* instead of *by the wind.* A gradual wind shift when running could thus lead to an accidental jibe; but a more serious objection is the limited efficiency sailing to windward with the system unable to respond to wind shifts. On the other hand, the list is long of yachts that steered themselves into danger and disaster because of a wind shift while the crew was asleep, too close to land. If steered by compass instead of by the wind, these yachts may have jibed, or gone about or into irons — but not ashore. In a yacht with auxiliary power, the electronic approach has a considerable advantage over all wind-operated methods, since the boat can also be steered under power — which is one of the few jobs more tedious than steering under sail.

The electronic system is normally not so mechanically complicated as a windvane gear, and it can be sheltered below decks. But electricity in place of mechanical complexity is perhaps a poor trade in the marine environment, and few will want to have their self-steering ultimately dependent on the generator and storage batteries.

So each approach has its good and bad points, and certainly there is no easy universal answer to all self-steering needs. Much depends on the individual yacht and the scope of cruising intended, and on the mechanical aptitude of the sailor. A wonderful assortment of methods and ideas have been proposed, tested, and developed by experimenters all over the world. I hope to include as many of these ideas as I know of. But I want to make this book a great deal more than just a cookbook-type compendium of methods. As an engineer I believe that the best route to the successful solution of any problem is through sound understanding of the fundamentals — and so I drag the hopefully willing reader through a lot of basic aerodynamics, hydrodynamics, and mechanics, and hope he comes out with a better understanding of how sailboats sail, as well as how they steer themselves. As a teacher I feel the most I can do for the student is to present the material in a clear and organized way — hence my efforts to arrange ideas and classify methods into consistent categories, where alternatives and relationships stand out clearly. As a practical sailor, I know almost everyone would much rather have just a simple universal answer and forget the fluid mechanics and formulas. But so far the simple, cheap, reliable, universal self-steerer has eluded us, and any kind of successful self-steering takes some thinking.

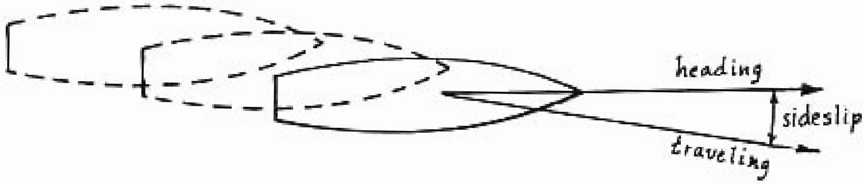
BALANCE OF HELM: FORCES AND MOTIONS OF SAILING

As a preliminary to a thoroughgoing investigation of self-steering in sailboats, it seems useful to be on familiar terms with the forces that act on a boat sailing on various courses, and to see how these forces tend to turn the boat, how they balance each other, and how the rudder acts to counter unbalanced turning tendencies. This discussion, as well as many points throughout the book, will be a whole lot easier to follow if you have a small model boat before you. I strongly recommend that you go out right now and whittle a boat-shaped block of wood with at least a mast and a sail, and preferably with a keel and a movable rudder; or else buy a plastic dime-store model with all the essential parts.

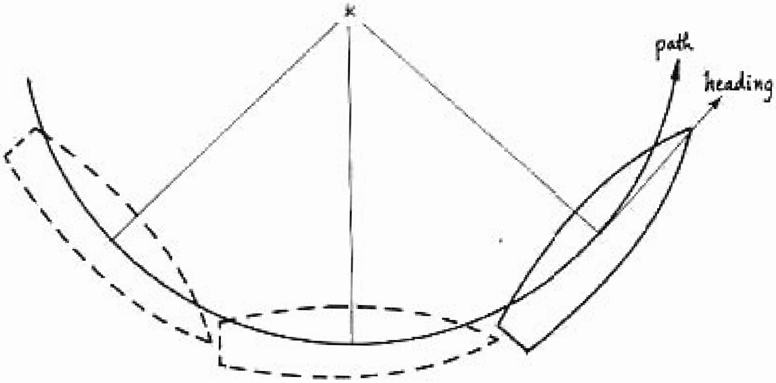
The various motions of a boat that we will be concerned with should be carefully distinguished. All these are small variations on a theme of steady forward motion at a constant angle of heel; they can occur individually or in combination.

1. *Sideslip* is the angle between the direction the boat is *heading* and the direction she is actually *traveling*. Leeway is the sailor's term for steady sideslip (Figure 1-1a).

2. *Yawing* means the boat's heading is changing with time (for example, as would be indicated by the changing reading of a perfectly accurate compass), and *yawl rate* is the rate of change of heading (for example, degrees per second). It is rotation of the boat



1-1 (a). Steady sideslip (leeway) without yaw.



1-1 (b). Steady yaw without sideslip.

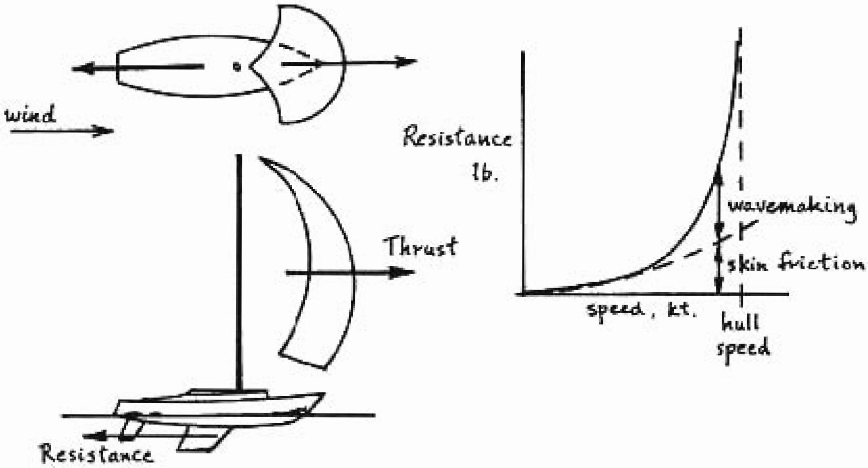
1-1 (c). A motion combining roll, yaw, and sideslip.

about a vertical axis. A boat traveling in a circle at constant speed provides an example of steady yaw rate (Figure 1-1b).

3. *Rolling* means the heel angle is changing with time. It is rotation about a horizontal axis that lies fore-and-aft in the boat.

These three motions can occur singly or simultaneously in any combination (Figure 1-1c).

First let's look at the simplest sailing course, straight downwind, and assume that the boat sails upright under a balanced rig such as a spinnaker alone, or twin running sails (Figure 2-11), or bare poles. The propulsive force here is the total drag of wind on the sail, rigging, and hull, arising from differences in pressure between the weather and lee sides; it is a force acting in the direction of the wind, hence straight ahead for the boat (Figure 1-2). Under its influence the boat can accelerate until the resistance (which is ordinarily a strictly increasing function of the boat's speed) is equal to the thrust from the wind. Then the two forces, thrust and resistance, balance each other, and (according to Newton's first law) the boat can continue at this steady velocity. Resistance arises mainly from skin friction on the streamlined underbody, keel, and rudder at low and moderate speeds. At higher speeds, wave-making resistance, representing energy expended in generating the wave system that accompanies the boat, becomes important. Finally, at an ill-defined "hull speed," wave making becomes an insurmountable barrier to higher speeds, at least for displacement hulls. In this perfectly balanced condition, the rudder remains centered, exerting no

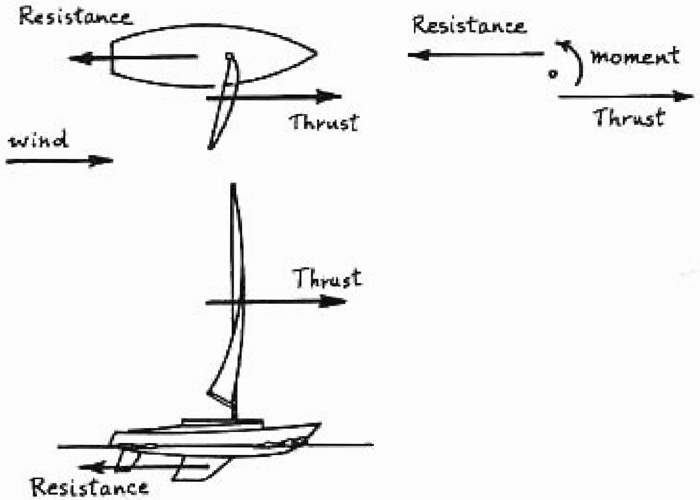


1-2. Equilibrium of thrust and resistance in balanced downwind sailing.

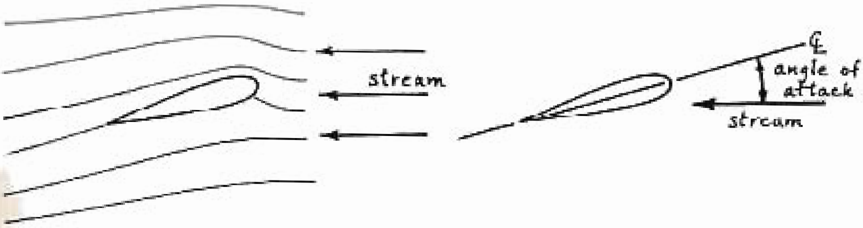
influence on the boat's motion (except for a slight drag due to skin friction).

Next, consider the boat running straight downwind with an unbalanced rig – such as a mainsail only (Figure 1-3). Again the sail produces its thrust through drag in the wind direction; again the hull generates an equal resistance force that balances the thrust, to result in steady motion at a certain speed. But, though these forces are equal and opposite, the boat is not in equilibrium under their action alone, because they don't act in the same vertical plane: the mainsail on the starboard side tends to turn the boat to port, and with the rudder centered she would go off course.

To steer a straight downwind course with this unbalanced sail requires that the rudder be held at an angle of attack so that it produces a steady yawing moment, offsetting the steady yawing moment of the sail. *Moment* is the same thing as *torque:* a combination of forces tending to rotate the object it acts on. The combined forces on the hull and sail tend to rotate the whole boat about the vertical or yaw axis. A *couple* is a closely related concept: a pair of equal and opposite forces that do not act along the same line and con-



1-3. Under mainsail only, thrust and resistance make a yawing moment.

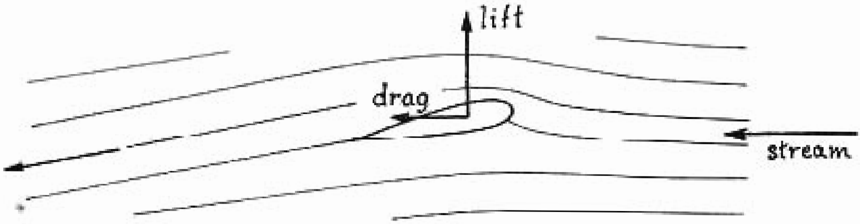


1-4. The rudder deflects part of the stream to the side.

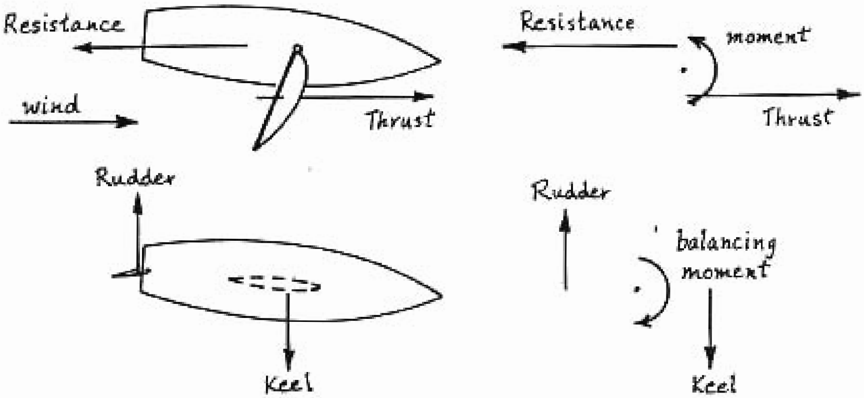
sequently exert a moment; for example, thrust and resistance.

For simplicity, picture a boat with separate keel and rudder. The rudder is a very typical hydrofoil — that is, a thin streamlined blade whose purpose is to generate force perpendicular to the stream of water flowing past it (Figure 1-4). Much more will be said in Chapter 5 about the properties of hydrofoils and airfoils; for the present only a very qualitative picture is required. First, for the generation of fluid-dynamic forces, it is immaterial whether the foil moves through the fluid or the fluid streams past a stationary foil. (Note that *fluid* is a term that includes both liquids *and* gases.) Looking at it from the second viewpoint, the action of the foil is to *deflect* a certain portion of the stream, forcing it to leave the sharp trailing edge smoothly, tangent to the foil's centerline. The fluid has mass; you have to exert a force on it to cause it to change its direction this way; and the (equal and opposite) reaction of this force on the fluid is the force on the foil, lift and drag (Figure 1-5). The cross-stream component of force corresponds to the deflection of the stream and is called *lift*, regardless of its direction — vertical for an airplane in level flight, horizontal for our rudder, or otherwise. The component of force in the direction of the stream is called *drag;* it corresponds to the deceleration of part of the stream by friction, and in part to energy carried away by the stream in the form of turbulence and vortices.

A fin keel is a hydrofoil also, whose purpose is to generate side force when the yacht sideslips. In balanced downwind sailing (Figure 1-2) there is no sideslip, hence no lift on the keel. But if the yacht is running downwind under an unbalanced rig, the hull



1-5. Deflection of part of the stream's momentum produces lift; loss of part of the stream's momentum causes drag.

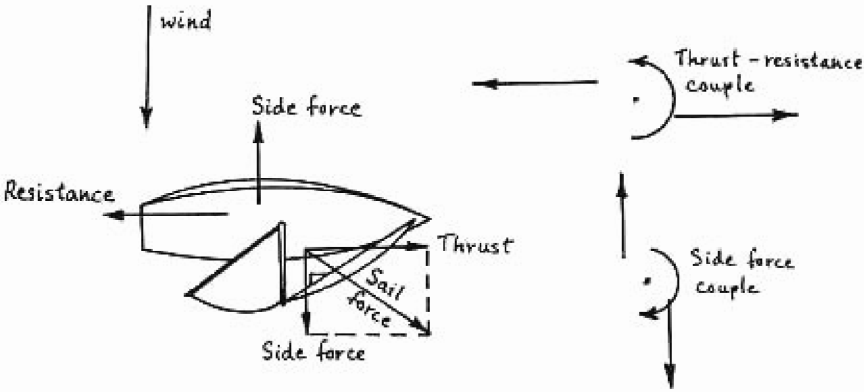


1-6. Yawing moment of keel and rudder balances yawing moment of the unbalanced sail.

must have a small (probably imperceptible) angle of sideslip so the keel can resist and balance the side force of the rudder (Figure 1-6). Thrust and resistance, the forces aligned *along* the direction of travel, are an equal and opposite pair resulting in a moment tending to turn the boat in the example to port. The rudder lift and keel lift are an equal and opposite pair of forces *across* the direction of travel, resulting in a moment or torque tending to turn the boat to starboard. The boat will remain on course, without yawing, only if the rudder-keel moment is exactly equal and opposite to the thrust-resistance moment — that is, only if exactly the right amount of weather helm is supplied by the helmsman or steering device.

The more general sailing situation is exemplified by a typical reaching course (Figure 1-7). Here the sail force is neither directly downwind nor along the direction of travel, but somewhere in between. The component of sail force in the direction of travel is still called *thrust,* since this is the propulsive force, and as before it is balanced by resistance. The component of sail force to the side causes heeling; it has to be balanced by an equal and opposite side force generated on the hull, keel, and rudder, or else the boat would continue to accelerate sideways. And yet a third balance is required to sail a steady course without yawing: the yawing moment from the combined side forces has to be exactly equal and opposite to the yawing moment arising from thrust and resistance.

This complex equilibrium of yawing moments is the heart of the problem of "balance of helm." In fact it is the heart of all steering problems, because any change of course requires that the equilibrium be somewhat upset, temporarily causing an unbalanced excess yawing moment to turn the boat. Clearly, a lot of variable quantities affect this balance. The relative fore-and-aft positions of keel and sails is a major factor frequently discussed. The cut and, more important, the trim of sails can have a significant influence on the effective center of side forces. On the other hand, the variable thrust-



1-7. Balance of forces in steady sailing. Unbalanced yawing moments must be compensated by rudder action.

resistance yawing moment, dependent on angle of heel, and height and trim of sails, is seldom given the recognition it deserves as a major influence on balance of helm.

Once the sails are set and trimmed for best speed on a particular course, most of the variables are determined: choice of sails, trim of sails, angle of heel, amount of thrust, amount of side force, and position of keel (or centerboard). In general, the keel does not turn out to be in exactly the right place to carry all the side force and balance out the yawing moments exactly. So the rudder is called into play to supply the additional steady yawing moment required to hold the boat on course. This moment is called *weather helm* or *lee helm*, according to whether the boat would turn toward her weather or lee side if the rudder moment were discontinued, for example by releasing the tiller.

A slight weather helm is generally accepted as the most desirable balance. This provides a safety factor, as the boat will round to and spill wind in case the helm is let go in any emergency. But with the number of variables entering into balance of helm it is too much to ask that *any* yacht should be "perfectly balanced in all conditions." It's just not possible. In designing and tuning the boat, the aim should be to achieve slight weather helm when sailing to best advantage to windward in moderate winds (at, say, a 10-degree to 15-degree angle of heel in a normal monohull). Then, considering the contribution of the thrust-resistance couple and its strong dependence on the angle of heel, one should not be disappointed to find lee helm in lighter winds, when the angle of heel is small, and considerable weather helm when eased off to a reach and heeling more in stronger winds. This is just normal behavior for a monohull sailboat. You can read a lot of nonsense about heeling making the underbody asymmetrical, about the lee bow wave becoming bigger than the weather one, and about the boat trimming down by the bow so her center of lateral plane moves forward. Tank tests indicate that all these effects are insignificant compared with the simple, transparent, geometrical explanation of the connection of weather helm with heeling: if the driving force on the boat (that is, the sail thrust) is placed well over to the lee side of the hull by heeling, it naturally tends to turn the boat toward the other side (that is, to windward). The more she heels and the harder she is driven, the more she wants to luff.

Sailing to windward, the forces and moments are much like those reaching (Figure 1-7), except that side forces become two to four times as great as thrust and resistance. A sail trimmed close to the wind for beating or close reaching should be looked on as an airfoil, intended to produce a cross-wind force (lift) accompanied by a minimum of drag and heeling moment. It generates this force by deflecting a portion of the incident stream of wind, forcing it to come off the sail tangent to the trailing edge.

TRUE AND APPARENT WIND

Every sailor learns early on to distinguish between the *true wind,* which would be felt by a stationary observer, and the *apparent wind,* felt by an observer on a moving boat. In general the apparent wind is different from the true wind in both strength and direction. Of course, it is only the apparent wind that can act on the sails or windvane to produce driving or course-correcting forces; so, when I show an arrow labeled "wind" in the illustrations, I generally mean to indicate the direction of the *apparent* wind.

In order to simplify the explanation of most of the self-steering actions described in this book, I have chosen to be a little imprecise about apparent wind effects. Only when changes in the apparent wind appear to have a dominant effect on the self-steering action will I mention them explicitly. Otherwise I will assume that the apparent wind has a constant direction in space (for example, true north) while the boat is slightly off her desired course. In fact, it is the *true* wind that should be assumed to be constant, and any change in the boat's course or speed naturally makes a small change in the apparent wind direction. I don't think I'll lead anyone astray by doing this. My quantitative theory of self-steering indicates that the changed apparent wind direction modifies the performance of most self-steering, but only in special circumstances such as multihull breakaway (p. 192) does it have a controlling effect on the stability of the system.

There are two alternative ways to analyze the response of a self-steering system to course errors. Both start by considering the boat on course, balanced out, in equilibrium under all the forces acting.

1. You can consider the wind to keep the same direction while some unnamed force (perhaps a sea) causes the boat to be thrown off course a small amount to one side — say 10 degrees to port. Then see if the steering moment that results tends to return the boat to course or not. It is not generally necessary to consider errors on *both* sides of the original course — 10 degrees off to starboard just reverses all the correcting effects and the conclusion is the same, but it's often worth doing as a check.

2. Starting again with the boat on course, you can assume instead that the true wind suddenly veers (clockwise) or backs (counterclockwise) a small amount — say a veer of 10 degrees — and then remains steady at that new angle. Then see if the steering moment that results tends to turn the boat the same way as the wind turned (stable) or the opposite way (unstable); for, after correcting, the stable boat will take up a new course changed by the same angle that the wind changed, keeping to her assigned apparent wind direction.

These two viewpoints are used interchangeably throughout the book, according to which seems to provide the most transparent explanation.

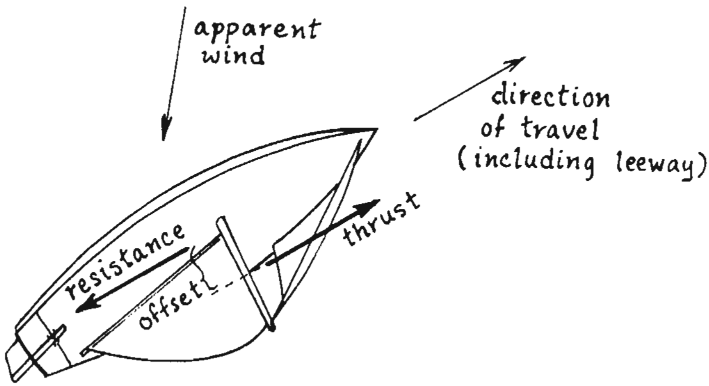
2 NATURAL COURSE STABILITY

This is the chapter that tells why some boats will steer some courses by themselves. The subject serves as a framework for starting to think about the forces that act on a boat, how they interact, and how they change with a change in course. Also, it serves as an introduction to the general idea of stability. There is not a whole lot of help with the problem of designing a boat for natural self-steering. This is because it is so easy to use sheet-to-tiller or windvane gear that the limited possibilities of natural course stability are not worth a sacrifice in any aspect of the design.

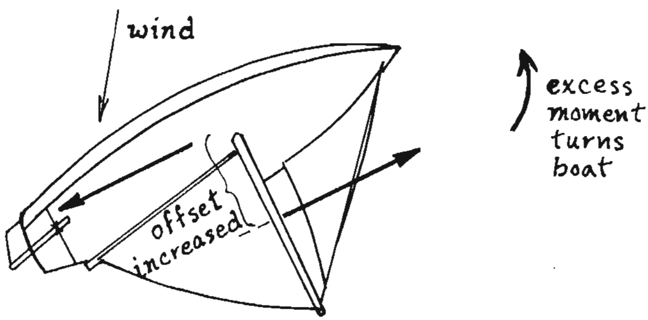
SAILING TO WINDWARD

TO WINDWARD WITH HELM FIXED

Most single-hull craft will steer themselves close-hauled or close-reaching with the helm fixed in steady wind. ("Helm fixed" means the rudder is immobilized, and there are any number of ways of doing this. I would prefer the simple method, capable of continuously fine adjustment, of lashing the helm or wheel with lines, over the discrete adjustment afforded by a tiller comb or pin rail.) This inherent stability is primarily an effect of heeling, and this is a good place to start thinking about the profound effect of heeling on the steering of the boat. When the hull moves ahead through the water, it experiences resistance – a force opposing the motion. If the forward motion is steady, an equal and opposite thrust force must be acting on the sails. Heeling determines the lateral offset between



2-1. Balance of thrust and resistance in steady sailing — close reaching (view looking straight down).



2-2. Bearing away, heel increases, causing boat to luff.

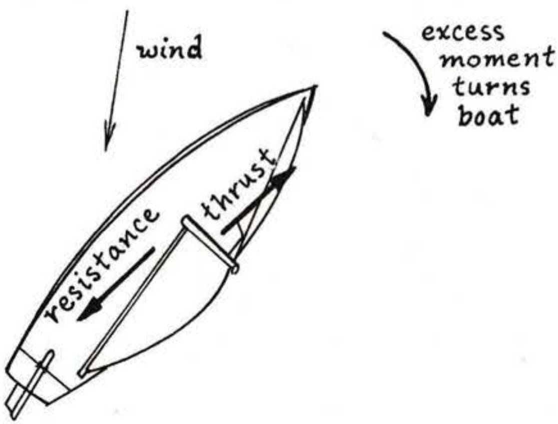
the centers of these resistance and thrust forces, so heeling controls a potentially very large turning moment. These forces and directions are diagrammed in Figure 2-1. Omitted from the picture, for simplicity's sake, are the side forces on hull and sails, which do not change very much with heeling. Now, if the boat bears away a little, for any unspecified reason, she heels over more, making the thrust-resistance couple bigger (Figure 2-2) and so she has to luff. (*Luffing* means turning so the boat heads *closer* into the wind — not necessarily so close that the sails shake, but just in that direction. The opposite of luffing is *bearing away*.) But if she heads *above* the equilibrium course, she heels less, bringing the thrust more nearly over the resistance and reducing the thrust-resistance couple (Figure 2-3), so the less variable side forces provide an excess moment making her bear away again.

A *couple* is simply a pair of equal and opposite forces. If they don't act along the same line, they exert a torque (or moment) on the body they act on.

Now this is obviously a gross simplification of a very complex system. Really the magnitudes of thrust and lateral force vary as the boat yaws; the centers of effort and lateral resistance do shift a little with angle of heel; the boat also changes speed as the thrust varies. All these effects can be estimated quantitively, and the variation of the thrust-resistance couple with heeling dominates all of them in a monohull of normal stiffness (see Letcher, "Balance of Helm and Static Directional Stability of a Yacht", *Journal of the Royal Aeronautical Society*, vol. 69, p. 241-7, 1965).

SENSITIVITY TO WIND STRENGTH

Sailing to windward with the helm lashed only works while the wind is steady, because a change of wind force changes the weather helm required for a steady course, and this clearly can't be provided

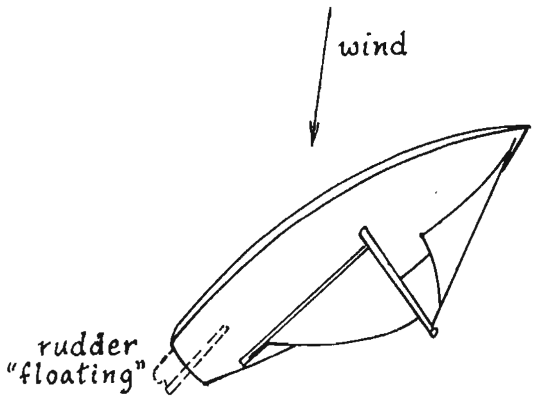


2-3. Luffing up, heel decreases, causing boat to bear away.

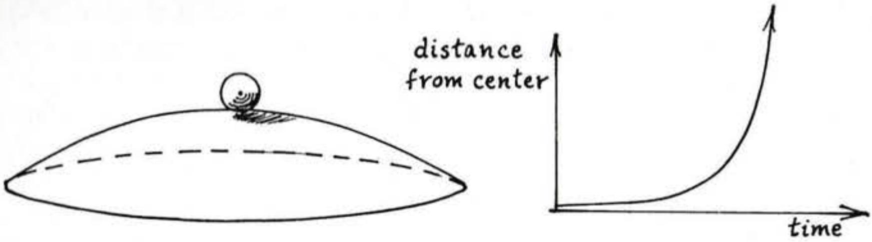
by the lashed helm. If the wind increases the boat will tend to luff and even bring herself about following a sharp puff; if it decreases she will bear away and, with the helm lashed up, she can go right on around and jibe. This is annoying. If you have to go on deck to adjust the helm for every change of a few knots of wind — or if you are trying to sleep in a nice lee berth and wake up every ten minutes to find the boat comfortably hove to on the other tack — then you might as well be steering. But we will shortly see that an adjustment to compensate for an unsteady wind can be automatically provided in a simple way, allowing very good use to be made of this inherent stability while close-reaching.

CLOSE-HAULED WITH HELM FREE

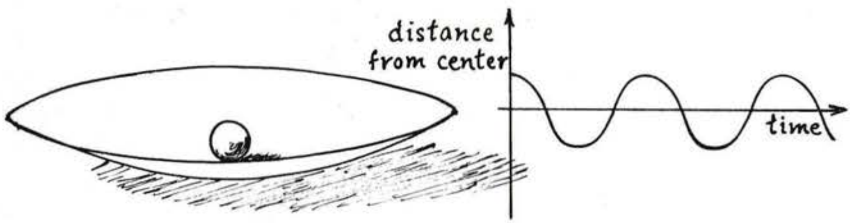
Eric and Susan Hiscock, before they had a windvane gear in *Wanderer III,* close reached many thousands of miles with the helm completely free *(Voyaging Under Sail,* Oxford Univ. Press, 1959, p. 63). The rudder and tiller should be viewed as a lever with the pintles and gudgeons as the fulcrum. This makes it clear that if there's no force applied to the tiller, there can be no lift or pressure difference carried on the rudder blade (unless the rudder is perfectly balanced, page 103). To balance out the weather helm the mainsail had to be reefed according to the headsail used (Figure 2-4), but once the



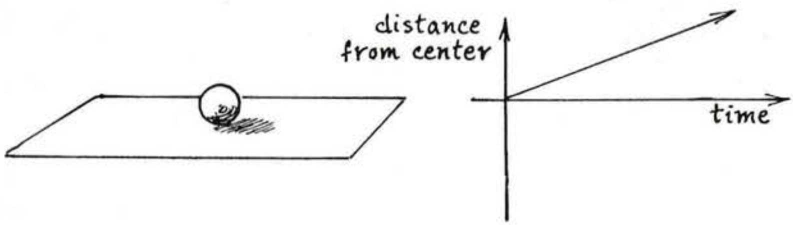
2-4. Wanderer III *sailing to windward, with mainsail reefed and helm completely free.*



2-5. Unstable equilibrium.



2-6. Stable equilibrium.



2-7. Neutral equilibrium.

boat was balanced she continued to steer herself by the wind regardless of variations in the wind force. I can't be sure what was compensating for the varying thrust-resistance couple in this case, but I think I have a likely explanation. I believe *Wanderer's* rudder was built of such heavy wood and metal fittings that its weight provided sufficient increased weather helm as the angle of heel increased.

There is a real opportunity here to use mass imbalance of the rudder to compensate for much of the weather helm that necessarily accompanies heeling.

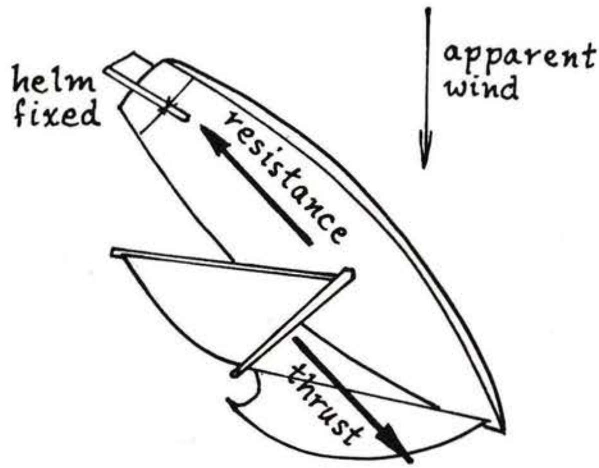
STABILITY CONCEPTS

If we try sailing helm-fixed on other courses it usually doesn't work at all. The boat might go along for a few lengths, but then some small disturbance puts her a few degrees either side of her course, and instead of correcting she swings farther off, faster and faster, until we must intercede to prevent her from jibing or flying into the wind. This is typical behavior for an unstable system, ex-exemplified by a ball resting on a convex surface (Figure 2-5). The ball can rest on the summit for some time, but if it ever gets the slightest bit off center, it accelerates ever faster away from its equilibrium position. Compare this with the prototype of stable behavior, the same ball resting in a concave surface (Figure 2-6). The ball can stay happily in its stable equilibrium position at the bottom, or can oscillate about this position with a certain period. Somewhere between the stable and unstable systems there is a "neutral" system, represented by the ball on a level plane (Figure 2-7).

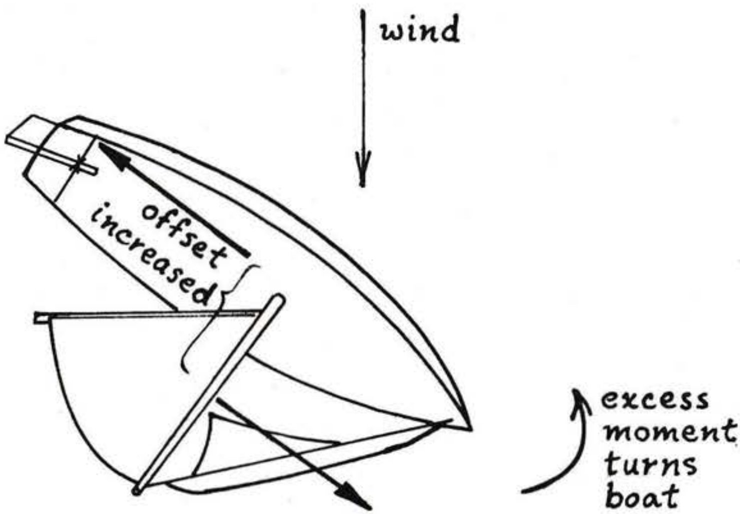
BROAD REACHING

CAUSE OF INSTABILITY

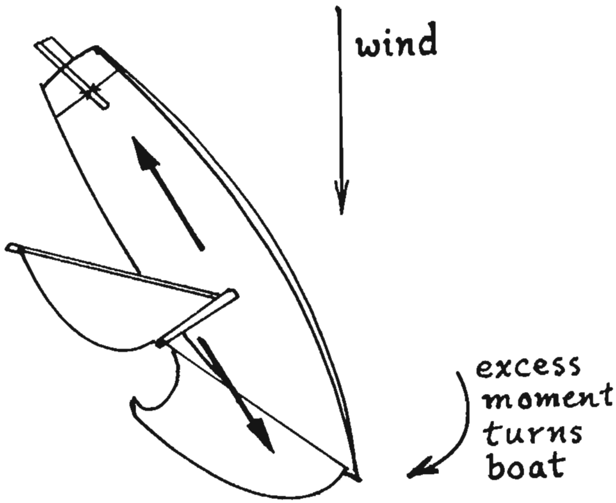
Remarkably enough, the key to the unstable behavior of a yacht broad reaching is the *same* effect of heeling that produced stability while close reaching. Figure 2-8 is a similar view looking straight down on a broad reach. Again the lateral forces are not shown because they don't change much with heeling. Now, if the boat should luff slightly, she would heel over farther (Figure 2-9) increasing the thrust-resistance couple so she tends to luff more. On the other hand if she should bear away a little, she would heel less (Figure 2-10), diminishing the thrust-resistance couple and allowing the other moments from the lateral forces and the fixed rudder to turn her farther and farther off the wind. Again, the picture has been



2-8. Balance of thrust and resistance in steady sailing — broad reaching (view looking straight down).



2-9. Luffing up, heel increases, causing boat to luff more.



2-10. Bearing away, heel decreases, causing boat to turn farther off the wind.

extremely simplified and there are lots of other things changing as the boat changes course; but again, for monohulls of all usual proportions, the variation of the thrust-resistance couple with heeling is the dominant effect.

Since heeling is the main reason for lack of natural course stability when broad-reaching, stiffness of the hull (resistance to heeling) and height of the sail plan are important determinants of the degree of instability. If the boat is very stiff there are some ways, explained below, that the sails can be trimmed to provide enough stabilizing influence to overcome the heeling instability. However, I have never seen a yacht steer herself with the helm fixed on a broad reach, and I've tried it on quite a variety of boats.

RUNNING

CAUSE OF INSTABILITY

To complete this rather pessimistic chapter on natural self-steering qualities, we should take a look at running and understand why, even when the sails are placed well forward, the boat won't follow her sails downwind except perhaps in light weather and smooth water. Suppose we run twin jibs up the headstay, boom them out to port and starboard, and tie the tiller amidships (Figure 2-11). You would think she would have the decency to run downwind, wouldn't you? But she won't. She gets a little off course, and that puts the wind on the quarter so she heels a little (Figure 2-12) and that puts the thrust off to the lee side and makes her turn farther off course. She won't stop turning until the weather sail backs.

Only when the wind is light enough so the boat heels very little will the forward position of the sails provide stability. Even then a sea running will cause her to steer an irregular course, for as she rolls the thrust is swung far off to one side or the other and she must respond to these yawing moments by swinging far off course. The now classic solution for achieving course stability with twin running sails – tying the sheets to the tiller – is a subject for the next chapter.

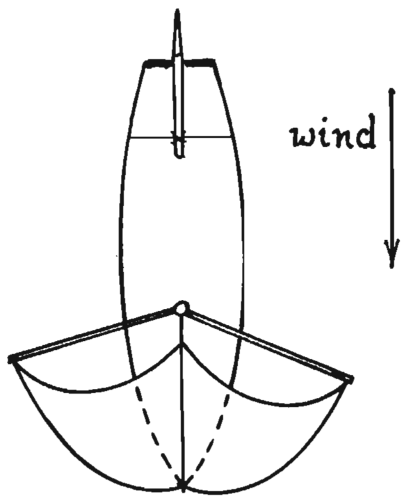
INFLUENCE OF THE HULL

Two aspects of the hull that contribute to self-steering by *any* method will be introduced here – one that is widely recognized and one that is seldom mentioned in connection with boats.

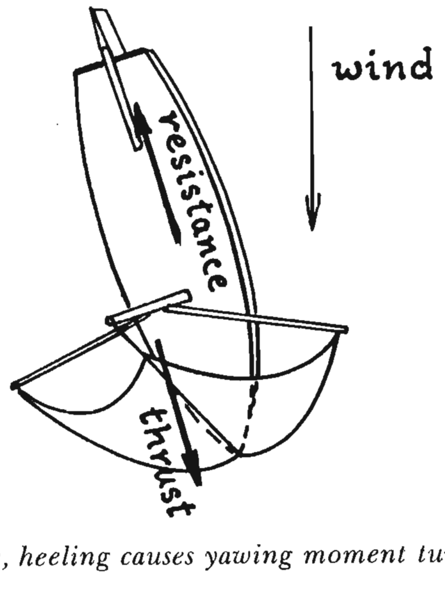
LATERAL PROFILE

The first is the lateral profile of the hull. The belief is widespread that a long keel is a desirable feature for self-steering because as the boat turns (angular velocity about a vertical axis) the keel generates an opposing yawing moment. An aerodynamicist calls this property *yaw due to yaw*, or *adverse yaw*, or *yaw damping*. I think the sailor will be more comfortable calling it *yaw resistance*, and I hereby coin the term to mean any yaw moment that arises because of yawing, proportional to the rate of change of the vessel's heading.

Consider a boat with a long keel turning about a vertical axis and moving ahead at the same time. Let's catch her at the moment she's on course but still turning to port (Figure 2-13). Due to the



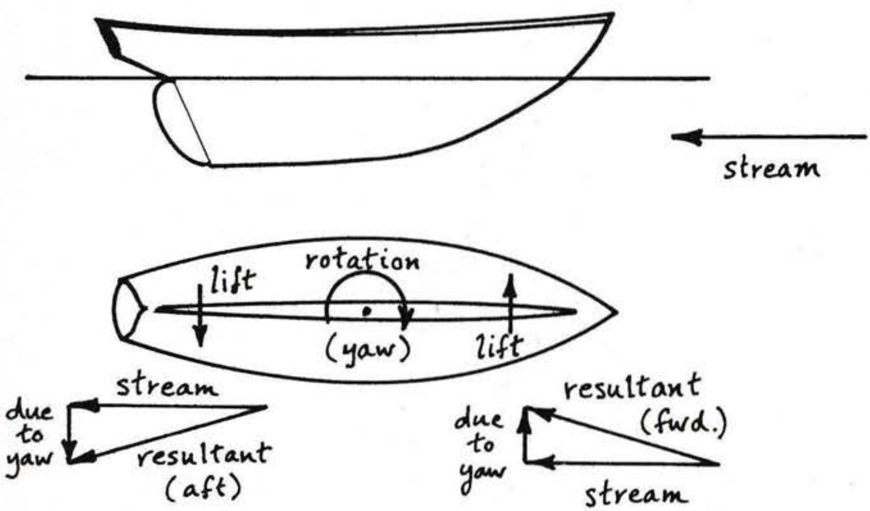
2-11. Running with twin headsails, helm fixed.



2-12. Off course, heeling causes yawing moment turning her farther off course.

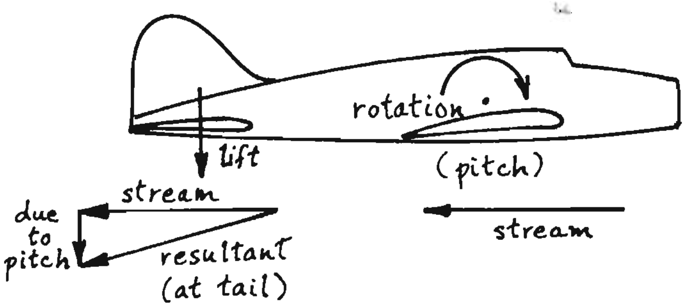
combination of forward velocity of the boat and sideways velocity resulting from rotation, the forward end of the keel sees a flow coming from the port side and the aft end a flow from the starboard side. It is apparent that the lift forces due to these angles of attack will be distributed so as to oppose the rotation — hence adverse yaw results. Note, too, that portions of the hull are effective in producing adverse yaw in proportion to the *square* of their distances from center: the distance enters once in creating the sideways velocity by rotation, and again because the force acts at that distance from the center to produce yawing moments. So a short keel is *very* much less effective than a long one.

But the keel isn't everything. If we had to use a long *wing* (long in the chord direction) to make an airplane have sufficient damping in pitch, we would have been a long time getting off the ground with all that wetted surface. A small surface like the airplane tail, placed a long way from the center of the wing (Figure 2-14), is a much more efficient way to achieve both control and adverse pitch and was universally used until supersonic flight speeds

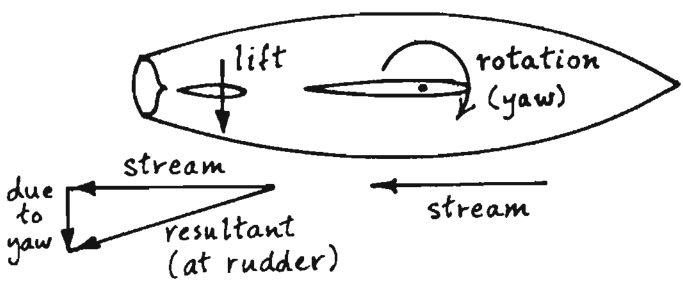


2-13. Apparent angles of attack at ends of keel, due to yaw (view from below).

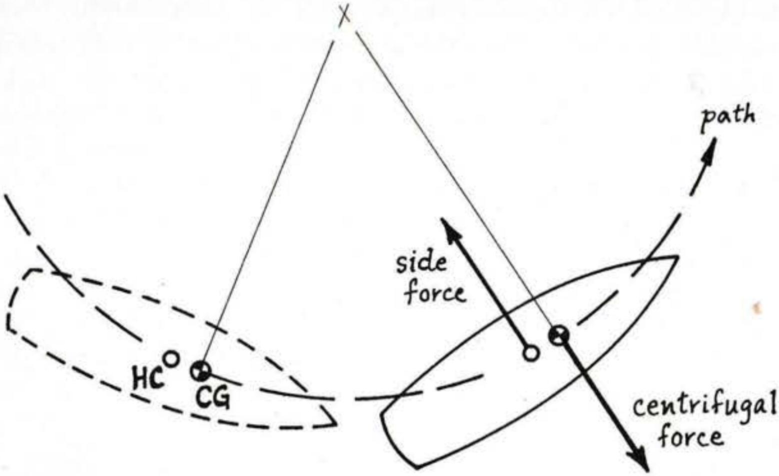
made highly swept, low-aspect-ratio wings necessary. Similarly with the sailboat: from the hydrodynamic standpoint, it is more efficient (equal lift and satisfactory control characteristics with less drag) to divide the keel and rudder, so both can be relatively high-aspect-ratio foils. Certainly it has been amply demonstrated that boats with short keels and separate rudders can be made to steer themselves quite adequately by windvane or sheet-to-tiller gear, so length of keel for self-steering ability need not be a consideration in the choice of the design of a voyaging yacht. But such boats are quicker to turn off course when the helm is simply let go, and have less ability to damp out oscillatory yawing that might be induced by a self-steering gear.



2-14 (a). Apparent angle of attack of airplane tail due to pitch. Resulting lift on elevator opposes pitching.



2-14 (b). Apparent angle of attack of separate rudder due to yaw. Resulting lift on rudder opposes yawing.



2-15 (a). CG located ahead of HC — resulting moment opposes yawing.

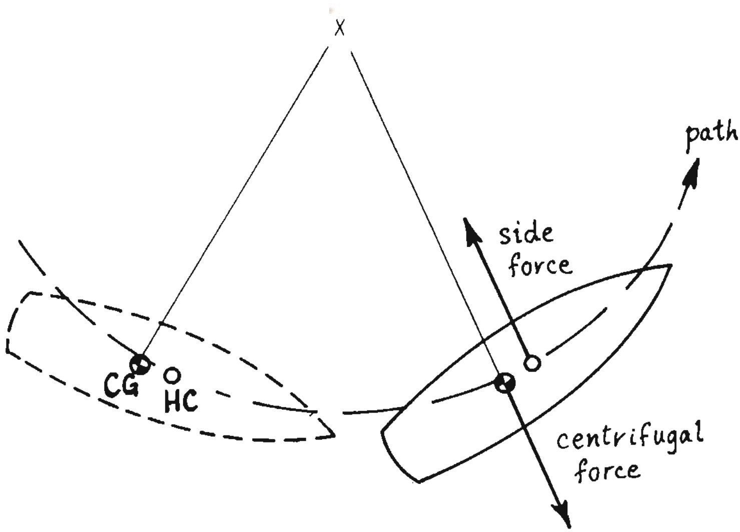
CENTER OF GRAVITY LOCATION

Another feature of the hull that affects damping in yaw just as much as the character of the lateral plane is the longitudinal location of the center of gravity of the whole boat (CG) relative to the hydrodynamic center (HC). I avoid use of the familiar term *center of lateral resistance* because it is used in yacht design with at least three distinct meanings:

1. The geometric center of area of the lateral plane. This point is easy to find but means very little.

2. The center of side pressures acting on the hull. This point depends strongly on the rudder setting and so is not really a property of the hull.

3. The hydrodynamic center. On a symmetrical shape like an unheeled hull with the rudder centered, this is just the center of side pressures at a small angle of yaw. When the shape has camber, like a heeled hull, or one with the rudder turned, the definition is more complicated — it is the center of *additional* side force due to a small *change* in yaw angle — but experiments in the towing tank indicate that HC varies but little over a wide range of yaw and heel



2-15 (b). CG located behind HC — resulting moment diminishes yaw resistance.

angles and speeds. There are theories for calculating the hydrodynamic center but they are far from being proven or accepted. (Figure 5-27 gives several rough ways to estimate HC position.)

The complicated dependence of stability on the relative locations of CG and HC has been explored but it is not yet clear whether it can be exploited to improve the state of yacht design (see J. H. Milgram in *Annual Reviews of Fluid Mechanics,* 1972, vol. 4, p. 397-430; H. C. Curtiss in *2nd A.I.A.A. Symposium on Sailing,* 1970, p. 21-32; and J. Gerritsma in *3rd A.I.A.A. Symposium on Sailing,* 1971, p. 10-29). The principal conclusion is that there is a limited range of positions of CG ahead of HC for which the hull has directional stability of its own. This is a factor that is largely unknown and is difficult to calculate for a particular design, and it can have marked effects on the performance of a self-steering system. The main use I put it to is as one explanation for the varying success of identical vane gears when applied to outwardly similar craft.

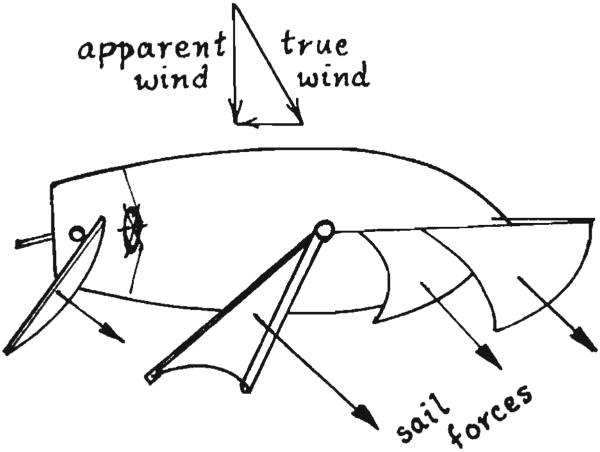
The influence of the center of gravity location can be qualitatively understood by considering a boat traveling on a circular path (Figure 2-15). The centrifugal force is outward, acting effectively through the CG. To counter the centrifugal force, an equal hydrodynamic side force acts toward the center of the circle, resulting from sideslip – this acts effectively through the hydrodynamic center. If HC is abaft CG, the resultant couple tends to straighten the turn out (stabilizing); if HC is forward of the CG, the couple tends to make the turn tighter and tighter (unstabilizing).

INFLUENCE OF SAILS

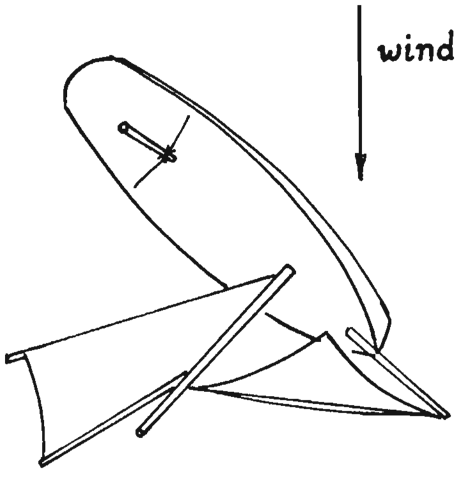
There are two aerodynamic effects of the sails alone that have a bearing on natural course stability, as well as on self-steering by any other method.

STABILIZING TRIM OF SAILS

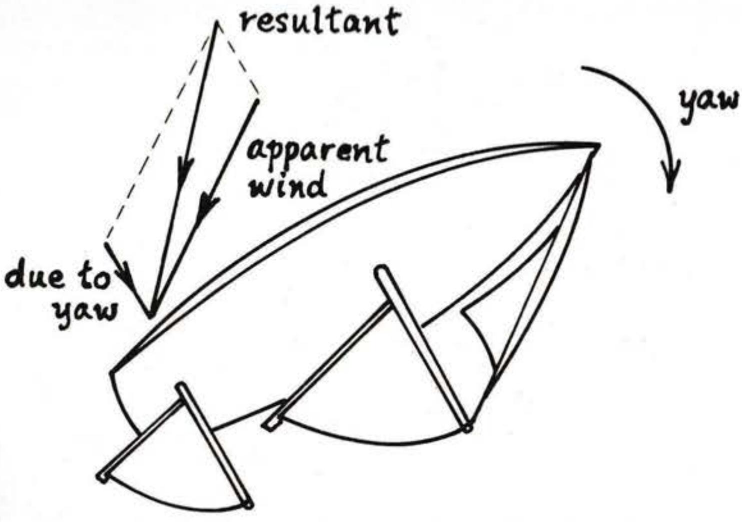
Most multihulls and some very stiff monohulls heel so little in moderate winds that the natural instability can be overcome by trimming the sails to achieve a stabilizing effect. Here is where the ketch and yawl rigs have made their reputation for superior self-steering ability. Slocum fitted a mizzen to *Spray* for this purpose, though he continued to call her a sloop. To realize this advantage, the mizzen apparently must be sheeted somewhat freer than the main and headsails. Ignore heeling for a moment and look at *Spray* with the apparent wind abeam (Figure 2-16a). If she should bear away, the mizzen would fill more while the other sails, trimmed close to their maximum drive, would experience little change in force from this change in angle of attack, so the mizzen would make her luff back onto course. If she should luff above her course, the mizzen would luff, lose its drive, and allow the drive of the forward sails to restore her to course. The method requires the mizzen to be working below its maximum drive, and unless the mizzen is large or placed far aft the effect is rather weak. It can only work under conditions where the boat doesn't heel much at all. It doesn't really require two masts; putting the jib out on a long bowsprit and flattening it more than the main has also achieved self-steering on a broad reach (Figure 2-16b). In sloops and cutters I have sometimes noticed that trimming the headsails flatter than the main adds a little stabiliza-



2-16 (a). Spray *sailing a broad reach, mizzen sheeted freer than other sails.*



2-16 (b). Broad reaching with jib flattened.



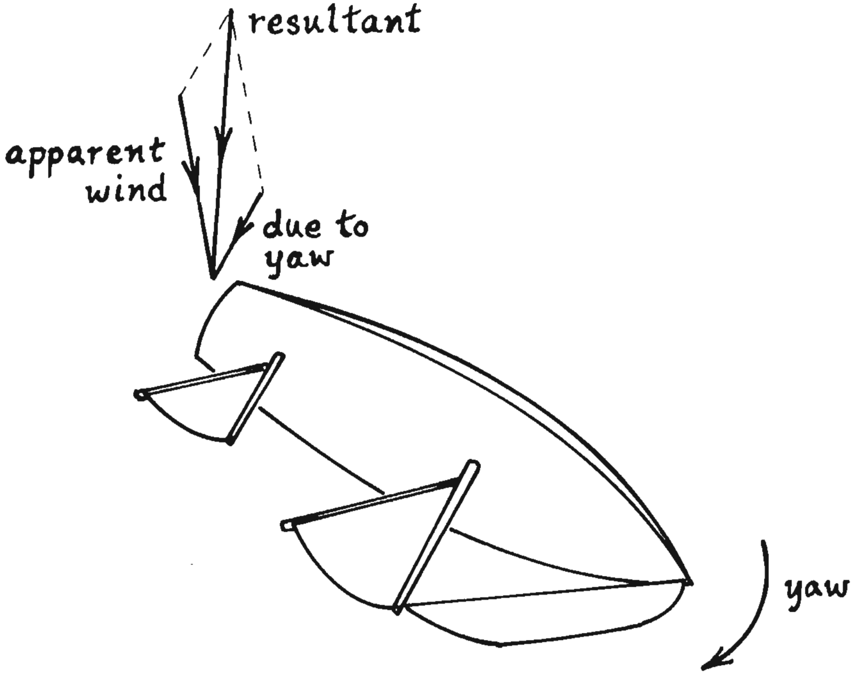
2-17. Yaw resistance of yawl rig – close reaching.

tion and can make the difference between self-steering and not when added to a self-steering system that *almost* works.

SAIL YAW RESISTANCE

A divided rig (or any rig that is well spread out fore-and-aft) has another stabilizing effect similar to adverse yaw. To see how this works, consider a yawl sailing close-hauled (Figure 2-17). Suppose she is on course at the moment but has a rate of yaw away from the wind. A component of apparent wind due to this yaw increases the angle of attack of the mizzen; the increased lift of the mizzen sail makes a moment directly opposing the yaw. Similarly, if she were yawing *toward* the wind, the mizzen lift would be *reduced* by the wind component due to yaw. In either case the "length" of the sail plan causes moments opposing yawing much as the lateral plane does. I will refer to this as *sail yaw resistance*. It combines with the hull yaw resistance.

Figure 2-18 shows that the same effect is present when broad reaching. Here a yaw away from the wind increases the wind velocity at the mizzen, so its drive is augmented and opposes the yaw.



2-18. Yaw resistance of yawl rig — broad reaching.

Any sail plan has these effects to some extent, but they are much more pronounced on sails that are located well away from the hydrodynamic center.

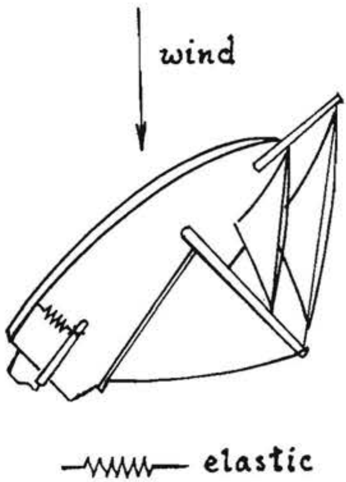
Notice that these two sail effects are different in *kind*. The stabilizing effect exerts a yawing moment whenever the boat is off course, whether she is turning or not. The yaw resistance effects exert yawing moment whenever the boat is turning, whether she is on course or not. They contribute to self-steering in quite different ways.

3 SHEET-TO-TILLER SELF-STEERING

Back in 1962, when ocean crossings in small sailboats were still something of a novelty, I was cruising the Southern California coast and islands in my 20-foot cutter *Island Girl,* sometimes single-handed. Naturally there were times when I wished I could leave the helm, and so I discovered empirically many of the conclusions of the last chapter – that the boat would go along with the helm lashed, or sometimes free, in a steady wind somewhat forward of the beam, but that on anything from a beam reach to a run it was hopeless. At that time I had never heard of a vane gear, and it's probably a good thing, for it's just the sort of idea I would have been delighted with and would have wasted huge amounts of time on, making totally unseaworthy equipment and testing it in the harbor.

During that summer I was reading the classic voyage accounts and gaining confidence in my boat, and at the same time tiring of the limited cruising opportunities of Southern California. So my thoughts turned often to the Pacific Islands and to the pleasure of sailing day and night for weeks on end in the steady winds far from shore. I received further encouragement and much guidance from Eric Hiscock's inspiring text *Voyaging Under Sail.* I could see no reason why *Island Girl* would not be suitable for such offshore voyages, so by early 1963 I was deeply involved in preparations for a summer voyage to Hawaii.

From Hiscock, I learned of twin running sails, and I made a large and a small pair (p. 63) and actually tested them once in Los Angeles harbor, much to the amazement of the Sunday sailors. I expected to have to steer by hand most of the first 800 miles or so, to reach the northeast trades, and then the twins would do the rest. But Hiscock also diagrammed a few peculiar sheet-to-tiller arrangements that had worked for particular boats on some reaching courses, and the idea was with me that maybe sheet-to-tiller self-steering could be generalized. An account of my passage to Hawaii will serve as a convenient framework for showing the arrangement I worked out and the wonderful success I had. As it turned out, I quickly learned to make *Island Girl* steer herself on any course in winds below Force 6, and I averaged less than an hour a day at the helm, including all the experiments.



3-1. Elastic to supply weather helm: too sensitive to wind strength.

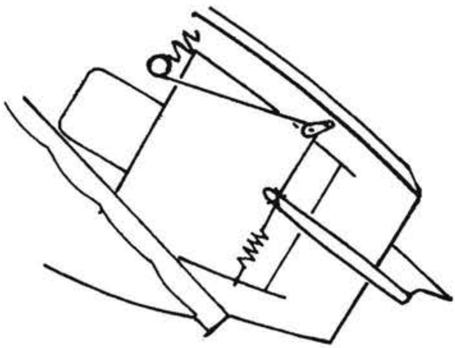
SAILING TO WINDWARD

LASHING HELM WITH ELASTIC

We left Los Angeles harbor in the mid-afternoon of June 6 and close-reached toward the familiar outlines of Santa Catalina Island in the fresh westerly typical of a sunny summer day. On the way across I got out a piece of thin rubber tubing and tried out a method I had dreamed up some time before, but never tested: simply stretching a piece of rubber between the tiller and the weather coaming to provide weather helm (Figure 3-1). This was based on the observation that the weather helm -- the pull on the tiller -- eases if one is pinching (so the rubber would pull the helm up and make the boat bear away) and increases if one bears away without easing the sheets (so the rubber would stretch and let her come back up to her course). No sheets were involved in this arrangement. But she needed a lot of watching, and no matter how carefully I adjusted the rubber she would only go for a few minutes before she started luffing or running too far off -- one or the other. After a particularly sharp puff the boat all but put herself about, and I realized it was in the puffs that she luffed up and in the lulls that she bore away. She was being even *more* sensitive to the strength of the wind with the rubber tubing than with her helm lashed. The whole idea was a failure, because the rubber provided less weather helm in the puffs when the boat needed more. As I steered on by hand over the late-afternoon sea, I mulled over a sobering realization -- that any self-steering system I devised, to be at all successful, was going to have to correct for variations in wind strength as well as deviations from course. Nevertheless, I got a good night's sleep that night, for we were becalmed until late next morning under Catalina's lee.

CONVENIENT ADJUSTMENT FOR LASHING HELM

The second afternoon we had the same fresh westerly, again close reaching, to pass the west end of San Clemente Island. I sat in the cockpit watching how she steered with the helm lashed and trying to figure out why. When the wind freshened, I was pleased to see she did just as well under reduced sail. To simplify adjusting the lashing I led a line through a block on the weather coaming and to the unused sheet winch and a cam cleat, with stiff elastic on the lee side (Figure 3-2). This effectively immobilized the tiller while allowing easy, fine, one-handed adjustment. After dark we had a tiresome beat against moderate wind and much current around the off-lying rocks of San Clemente's west end. Those were the last dangers of the California coast, and a little after midnight we had put them astern. I was feeling tired and not a little seasick, and so I turned in. But the westerly breeze came and went, and I must have been awakened a dozen times by the clash of the blocks shifting over on the travelers as she tacked or jibed herself. Then I would roll out



3-2. Convenient way to lash the helm, with fine adjustment.

and put her back on the southwest course and adjust to the new wind force, and think a little about how to do it better.

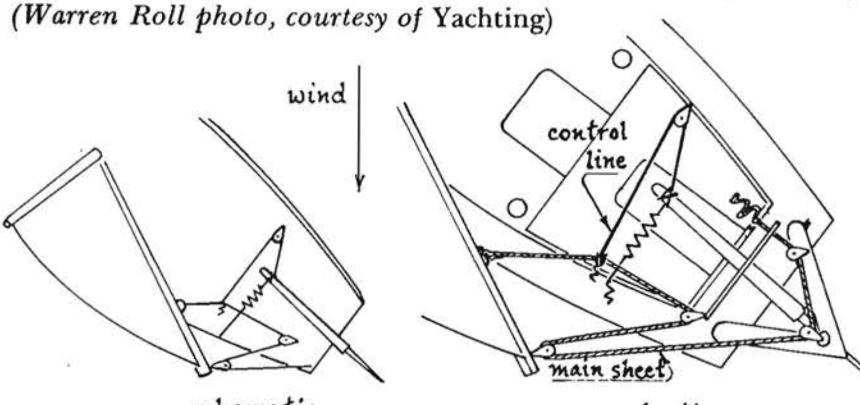
MAIN SHEET SUPPLYING WEATHER HELM

By morning of the next day, seasick though I was, I had come upon the close-reaching arrangement that has served me ever since, steering a variety of craft for me, at least 3,000 miles altogether. It essentially capitalizes on the boat's natural stability close-reaching (p. 18) and uses the mainsheet tension to adjust for change in the wind force. The *control line* from the tiller passes through a block on the weather coaming and then is bent to the middle of one part of the mainsheet tackle, so it pulls a bend in it; this provides weather helm. The pull of the control line has to be partly balanced by elastic to the lee coaming as in Figure 3-3. (When bending a line to the bight of a sheet tackle, it is best to use the bight at the standing end as shown here—otherwise it's possible for the hitch to get jammed in a block.)

OPERATION AND ADJUSTMENT

Now, if the wind is steady, the tiller is held in the same place and the boat goes along by herself. When the wind eases, the elastic can pull more bend in the mainsheet and let the helm go down a little; when it freshens the mainsheet pulls tighter and puts on more weather helm. The trick is to adjust the strength of the elastic and

Island Girl, *the 20-foot cutter in which the author made single-handed passages from California to Hawaii and Alaska and return in 1963-5. She is steering herself with the arrangement of Figure 3-3, with the sheets eased well off and the wind almost abeam. The poles for twin running sails are shackled to a shroud for stowage. (Warren Roll photo, courtesy of* Yachting)



3-3. Basic arrangement for close reaching as set up in Island Girl.

Island Girl *driving to windward. Sailing from Honolulu to Sitka, she punched 400 miles through the northeast trades in five days this way. Except for reefing and setting sails, I kept dry below, reading and sleeping. (Warren Roll photo, courtesy of* Yachting) the amount of bend in the mainsheet so that the amount of weather helm provided is exactly the right amount for the changing wind. This takes some time to work out when you first try it. You just have to set her up in one strength of wind and wait awhile for the wind to change. Say it increases. If the boat still tends to luff, clearly the arrangement needs to be strengthened, with more bend in the sheet, and stiffer elastic. But if she tends to bear away in the puffs, the arrangement is too strong, and both control line and elastic need to be slackened. Somewhere in there is the right setting, where the boat will take care of herself over a wide range of wind speed. The first time it took me about a day to find it, but on the fifth morning, with the wind still almost right ahead, I wrote in the log, "She steered herself all night and I slept right through." I took notes on the successful setting, and when we tacked several times that day I was able to get the adjustment right almost on the first try each time. Since then I have had many chances to try it in half a dozen different boats under all combinations of reduced sail, in winds as strong as I cared to sail into, and it has never failed.

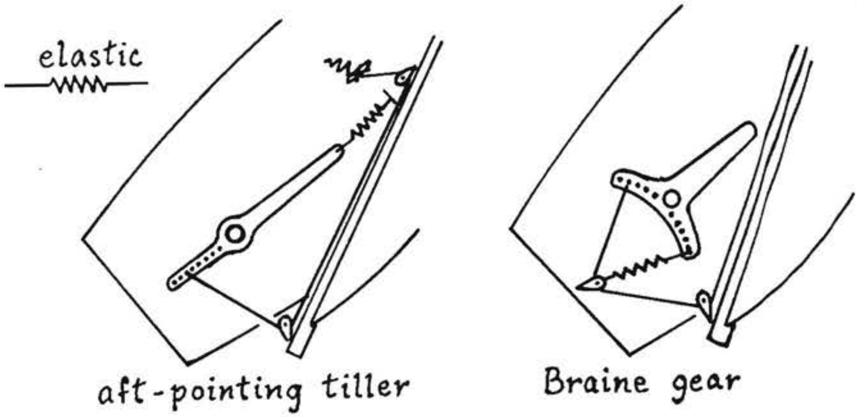
MODEL YACHT ARRANGEMENTS

My independent discovery of this close-reaching arrangement came a little too late for patent rights. At least 50 years before, model yachts had been steering themselves by essentially the same method—weather helm provided by the pull of the mainsheet, and balanced by elastic (Figure 3-4). The aft-pointing tiller and the Braine gear quadrant (which was used full scale in *Sopranino*) were just alternate mechanical ways of coupling the sheet to the tiller. Experimenters had long ago found, as I was now to find in my turn, that this worked well enough with the wind on the bow but not at all with the wind on the quarter.

ELASTIC FOR SHEET-TO-TILLER ARRANGEMENTS

STRENGTH OF ELASTIC

When you are using elastic, there are really two variables — the *stiffness* and the *relaxed length* (or the position where the elastic re-



3-4. Two self-steering arrangements used on models. The main sheet tension supplies weather helm, balanced by elastic.

laxes and stops pulling). Say you are using one piece of 3/8″ rubber tubing between the tiller and a cleat. You can double the pull on the tiller by (1) adding a second identical piece of rubber tubing in parallel, or by (2) casting the single piece off the cleat, pulling it tighter and belaying it again. But the results are not identical, because the variation of force with tiller angle will be quite different in the two cases – in (1) the stiffness has been doubled without changing the relaxed length; in (2) the stiffness is unchanged but the rubber won't stop pulling until the tiller is way over to leeward.

GENERAL RULE FOR ADJUSTMENT

It took me about 5,000 miles of sailing to notice that the proper adjustment of elastic for any sheet-to-tiller gear, for any point of sailing, seemed always to be with the relaxed length where the tiller is centered or slightly to leeward. There is a good reason for this. We want the arrangement to hold course over a wide range of wind speed, hopefully including very light wind, when the sheets will be almost slack and the helm will be very light. So the elastic will have to be almost slack, too, and it better be slack (relaxed position) with the tiller centered or a little alee, whatever is required in the very light wind – certainly not far on either side of center.

TYPES OF ELASTIC MATERIALS

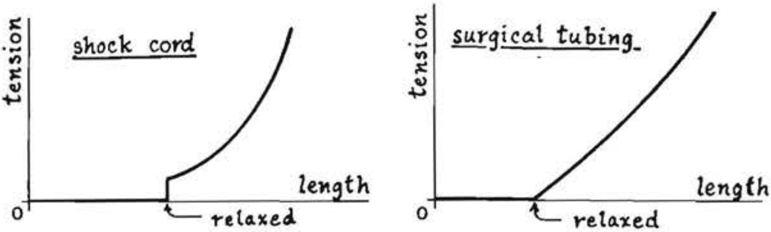
There is a wide choice of elastic materials to use:

1. Shock cord or "bungee" (composed of a large number of parallel rubber strands enclosed in a braided jacket). This is what yachtsmen always think of first, but I have not found it particularly useful. The jacket tends to chafe through or deteriorate quickly, and even while it lasts its constriction gives the cord a peculiar "non-linear" relation between stress and extension (Figure 3-5). This characteristic might be useful for some jobs, but not usually for self-steering.

2. Rubber tubing is my favorite. Of course, the properties of rubber vary widely, but the more stretchy varieties are what I mean. The amber *surgical tubing,* available in several sizes from hospital suppliers, pharmacies, diving and sport-fishing shops (used for fish spears), and hobby shops (used for slingshots and model-airplane power plants) is excellent. It eventually perishes in sunlight, so keep it below when not in use; but I have gone many thousands of miles on a couple of feet of it. For me, 3/8″ O.D. has always been the most useful size. Black rubber tubing seems to resist sunlight better than the amber variety.

3. I usually have on board a piece of an old inner-tube. This is useful for gaskets and big rubber bands, but I had poor success using a strip of it in sheet-to-tiller rigs — it always breaks in a few hours.

4. Metal springs are available in an infinite variety. Spring steel is highly prone to rust, though, so some corrosion-resistant spring alloy should be sought.

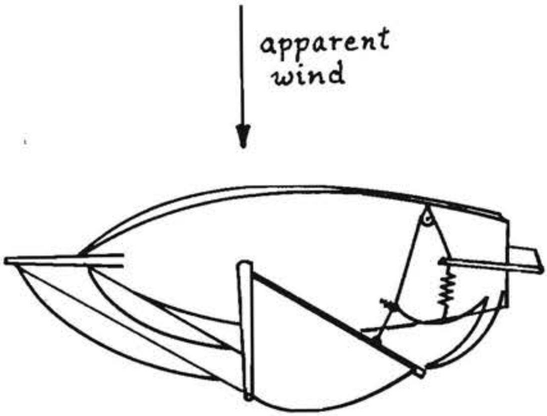


3-5. Stress-strain curves for shock cord and rubber tubing.

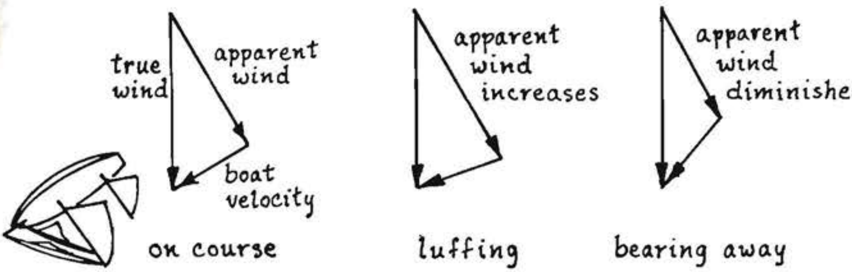
BEAM REACHING

MAIN SHEET CONTROLLING

On the sixth day out we had a fine fresh breeze from the northwest. I found that, with all sails drawing properly, exactly the same arrangement was working with the apparent wind almost abeam, provided the control line was bent to the main sheet with a rolling hitch so that it carried most of the pull of the boom (Figure 3-6). Here it is not so easy to explain the self-steering action, as the boat was at best neutrally stable with her helm lashed on this course. In some way the mainsail was noticing the change if the boat luffed a little, and pulling harder to make her go back on course. If you hold the main sheet and steer deliberately a little below, then a little above, course, you can feel the change. You can also feel the strength of the apparent wind change, increasing as she luffs and diminishing as she bears away (Figure 3-7) – and this change in apparent wind explains the strong variation in mainsheet tension. Of course, the right sort of correction for wind force can be built into this rig also, for stronger wind will provide more weather helm as needed. Again, the right stiffness and length of elastic have to be sought to balance out sensitivity to changes in the wind strength; but once they are found they are easily remembered.



3-6. Beam reaching with main sheet controlling.



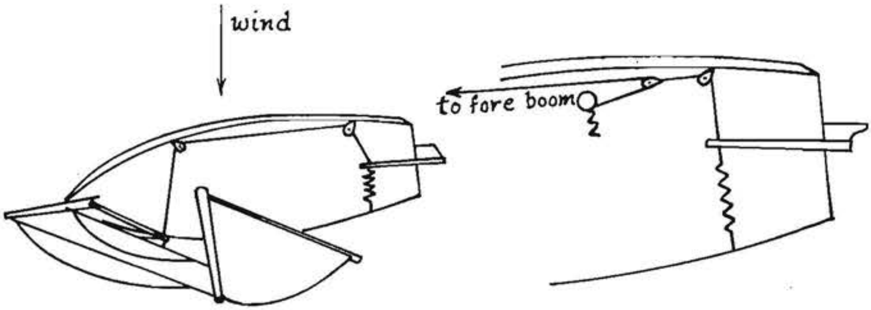
3-7. Strong variation of apparent wind with course changes on a beam reach.

FORESTAYSAIL CONTROLLING

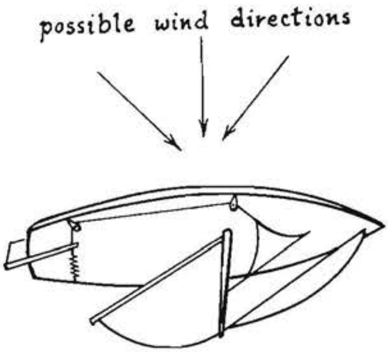
The northwest wind fell light and shifted more to the north on the seventh day, with a long swell from the northwest. I tried the beam-reaching arrangement especially for cutters suggested by Hiscock, using a line led around the weather deck from the foreboom to supply weather helm, and balanced by elastic (Figure 3-8). That worked all right as soon as I used an extra block to double the pull of the tiny forestaysail. But it was almost disastrous. Having no lifelines, I made the forward block fast to the starboard lower shroud about two feet above deck. For most of a day the swell banged us about, with every tug from sail or tiller flexing the wire, and after a day of such punishment the shroud broke – lesson number one on metal fatigue. But there's nothing wrong with the arrangement; the boat stayed on course.

INNER STAYSAIL CONTROLLING

A related arrangement with no foreboom has been applied on a sloop and found to work well on all points from a close reach to a very broad reach (Figure 3-9). Tony Skidmore sailed his 24-foot *Mona Sally* singlehanded from Britain out to British Columbia using this arrangement exclusively. A 30 square foot (3 square meter) storm jib was set flying from the stemhead on a spinnaker pole lift, with the tack 3 feet (1 meter) off the deck. The weather sheet was led through blocks seized to the lower shrouds (I think this is safe enough if some wood or tubing is used to distribute

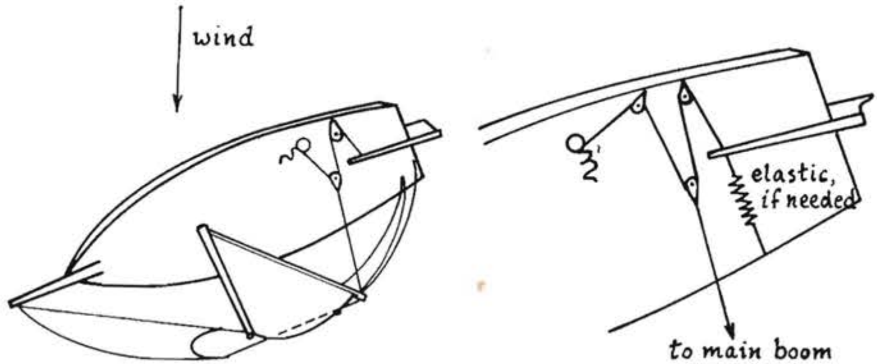


3-8. Beam reaching with forestaysail controlling.



3-9. Tony Skidmore's arrangement for all reaching courses, used in Mona Sally.

the block load over a foot or so of the shroud) and to the lifelines, tied to the tiller and balanced with shock cord. This arrangement worked so well that he scrapped his twins for downwind sailing, preferring the reduced rolling of tacking downwind with main and genoa. Evidently the inner staysail, sheeted to windward, usually sets rather awkwardly, and I'm afraid it would bother me not to have all sails drawing as well as possible. But for many it seems this would be a small price to pay for a universal system serving all points of sail. Frank Kibbe and I tried this out in his 30-foot sloop *Kifaru,* using a 25 square foot (2,3 m^2) and later an 18 square foot



3-10. Broad reaching — main and genoa controlling.

(1,7 m²) sail, and were very pleased with the results, though I felt it slowed her down a little close-hauled.

BROAD REACHING

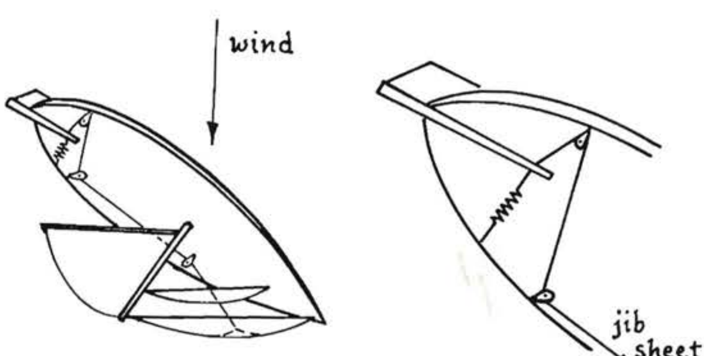
MAIN AND GENOA CONTROLLING

Light headwinds and calms plagued the second week of *Island Girl's* voyage, and not until the twelfth day out, 600 miles from the coast, did I have need for an arrangement that would steer with the wind much abaft the beam. The north wind made up light at first, and we were sailing with our big genoa jib, which I had sheeted through a block at the end of the main boom. Steering by hand, it was easy to notice how the tension in the main sheet, which now carried the pull of both sails, would increase when I sailed above course and drop when I headed too far off. From that observation it was an easy step to self-steering (Figure 3-10). A tackle (fool's purchase) was needed to divide the control-line tension in half. We ran all day with this, in a building wind and sea. At dusk the wind was fresh and we were fairly skipping along, just touching the high spots, it seemed, the whole boat trembling with the strain. She was incredibly stable on her course over this whole range of wind force; she could have been on rails. But I'm sure the only thing that induced me to carry on this spread of sail into the gathering darkness was not knowing how to make her steer herself with any other sails on a broad reach.

JIB SHEET CONTROLLING

There was only that one day of broad reaching on that passage to Hawaii, but on later voyages I learned some wonderfully simple and successful ways to achieve self-steering, reaching with many different sail combinations. Basically, the jib sheet tension, balanced with elastic, is used to provide the weather helm (Figure 3-11). Here's how it works:

With all sails trimmed properly, the jib sheet tension is extremely sensitive to the apparent wind direction. If the boat bears away a little, the jib loses drive by stalling and by moving into the wind shadow of the other sails; also the apparent wind velocity decreases. (By the time the wind is about two points on the quarter, the jib is empty of wind and the sheet falls quite slack.) Then the elastic pulls the helm down to send her back on course. On the other hand, if she luffs a little, the jib finds itself in clearer air, at a more favorable angle of attack, with a stronger apparent wind, and it starts pulling very hard on its sheet. So this hauls the helm up and she has to go back on course. This action is so powerful that in practice the course steered is very precise even in a considerable seaway, and I am certain that any boat with a jib will steer this way.

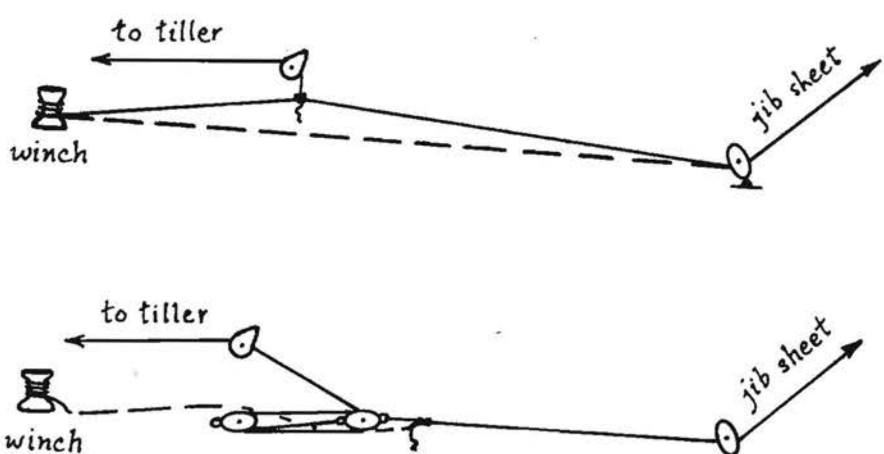


3-11. Basic broad reaching arrangement – jib sheet controlling.

As in most of the other arrangements in this chapter, correct adjustment of the elastic is essential. As usual, the best adjustment is always with relaxed length near the centered position for the tiller, so *stiffness* is the principal adjustment available. I have found broad reaching requires stiffer elastic than the other points of sailing, but obviously the elastic can be *too* stiff, so that the sheet simply can't move the tiller enough. If the elastic is too weak, on the other hand, wild oscillation can result, with the jib alternately empty and full and the boat yawing over a quadrant or more. Somewhere in between is the right stiffness that gives a steady course and also provides minimum sensitivity to the wind strength.

WITH VARIOUS SAILS

Most of my offshore sailing has been singlehanded in *Island Girl* and with my wife in *Aleutka,* the 25-foot cutter we built in 1967. She has exactly the same rig as *Island Girl,* but no bowsprit. In both boats the arrangement of Figure 3-11, using the whole tension of the jib sheet, with our 70-square foot (7 m^2) jib, works beautifully with one, two, or three reefs in the mainsail. By adjusting the elastic, the



3-12. Two ways of using jib sheet tension in larger boats. See also Figure 3-24.

wind could be set anywhere from three points on the quarter to nearly abeam. With the 160-square foot (15 m^2) genoa jib the arrangement was just the same, but a fool's purchase was needed to divide the sheet tension by two.

With bigger sails the sheet tensions can be so strong as to be very inconvenient and dangerous to handle this way. In Frank Shelly's Lapworth-36 *Jo Too,* we used the jib sheet for self-steering by hitching a control line to the sheet midway between the winch and the fairlead or turning block, pulling upward through a snatch block at the top of a lifeline stanchion (Figure 3-12). It seems to me that the adjustment of the length of the control line and the amount of bend pulled into the sheet were very critical, and we had better luck clapping a four-part vang tackle on the sheet and using the fall for the control line.

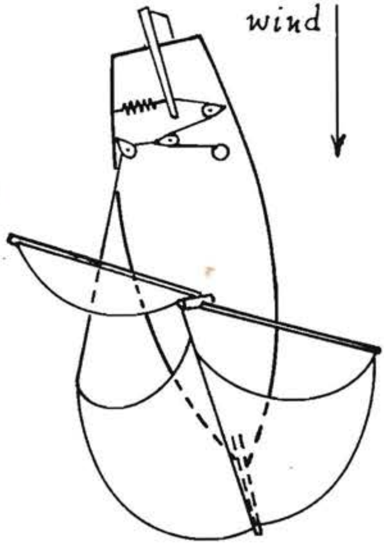
WITH WEATHER TWIN

The addition of one of our twin sails (page 63) boomed out to the weather side boosts our sail area about 40 percent; and this sail scoops wind into the genoa so the useful range of courses is from dead before the wind to about six points on the quarter, again determined by the stiffness adjustment of the elastic (Figure 3-13a). An alternate way of hooking this up, with the weather twin itself controlling, steers just as well and has been used by others (Figure 3-13b). Stanley Bradfield in *D'Vara,* a wishbone ketch, and John Goodwin in *Speedwell of Hong Kong,* a Vertue sloop, reported success with similar arrangements.

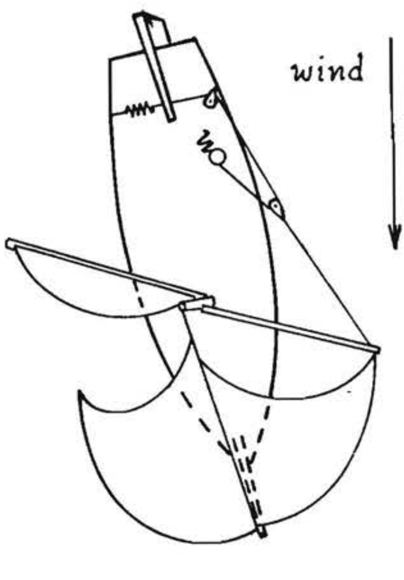
BLOCKS AND TACKLES

MECHANICAL ADVANTAGE

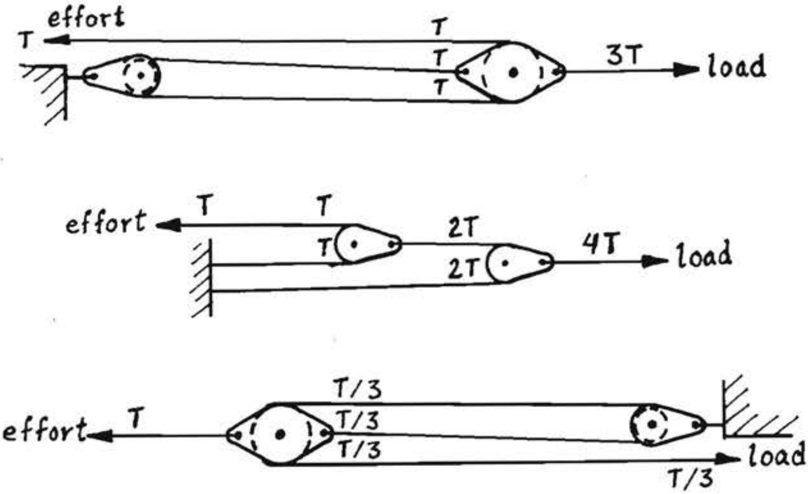
A tackle is a simple machine that can be used to increase or decrease either force or motion, depending on how the blocks are arranged. It is usually easiest to analyze a tackle in terms of force (which is always in the form of tensions in the various parts of line). The key to figuring out the mechanical advantage (ratio of load to effort) in any tackle, no matter how complicated, is to assume that the tension is constant throughout the length of each line making



3-13 (a). Broad reaching with the weather twin.



3-13 (b). Alternative arrangement with weather twin controlling.



3-14. Figuring the mechanical advantage of tackles.

up the tackle. This is a good approximation if the friction in the blocks is small enough. For example, the tackle in Figure 3-14a has a mechanical advantage of 3: the constant tension T in the "effort" line pulls 3 times on the movable block, so it balances a load of 3T. The tackle in Figure 3-14b has a mechanical advantage of 4.

FOOL'S PURCHASE

Any tackle can be reversed to get a fractional mechanical advantage. For example, Figure 3-14 (c) is the tackle in Figure 3-14 (a) used in reverse, for a mechanical advantage of 1/3.

RATIO OF MOTIONS

In any tackle the ratio of *motion* on the effort side to *motion* of the load is the same number as the mechanical advantage (still neglecting friction). If any tackle could be devised for which this weren't true, it could be used to violate the principle of conservation of energy. For example, with a mechanical advantage of 3, the effort end has to move three times as far as the load; whereas with the fool's purchase above, the load moves three times as far as the effort end.

FRICTION AND WEAR

Friction harms the performance of any self-steering system. The usual symptoms are sluggishness in responding to wind shifts or errors in course, and a tendency to oscillate widely about the desired course — as the boat has to wander far off course before the corrective forces become great enough to overcome friction and actually move the rudder.

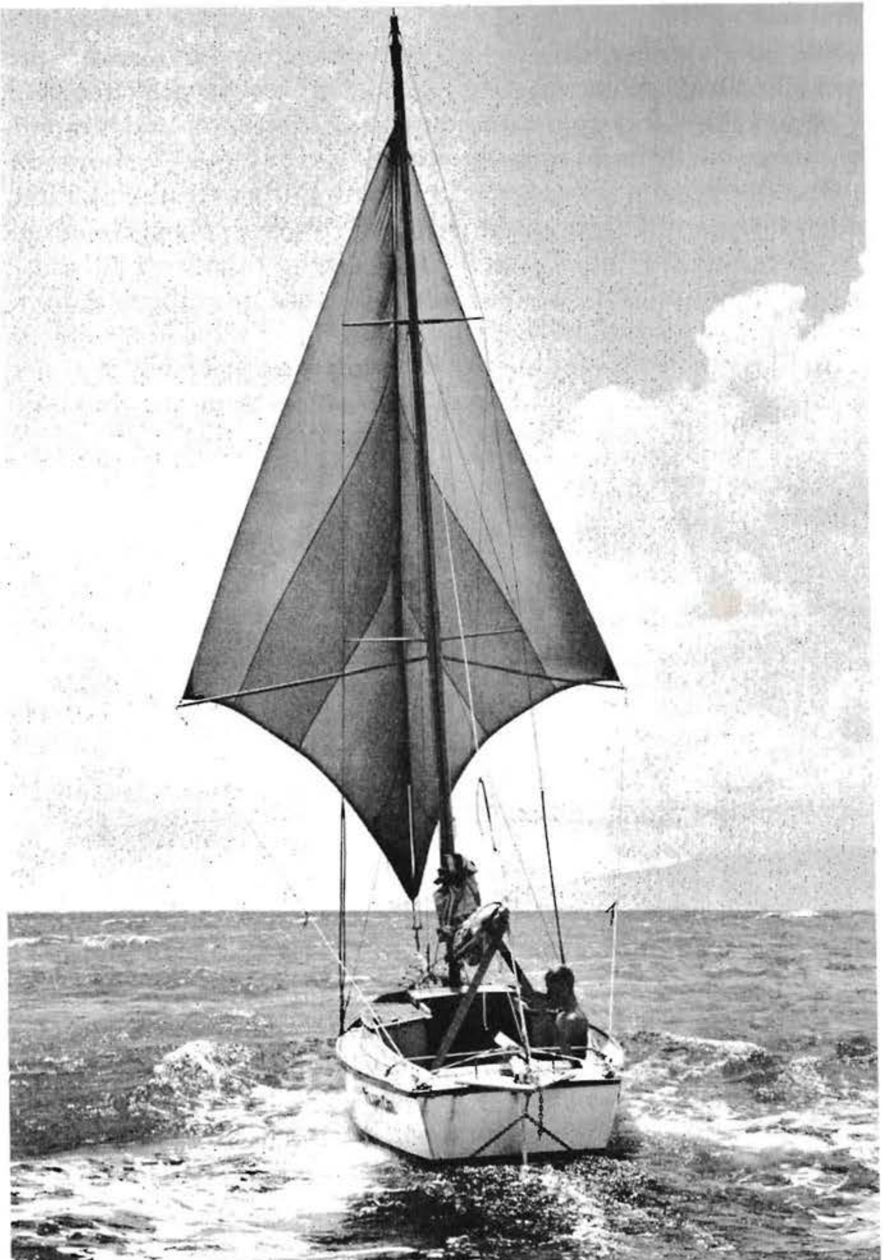
In sheet-to-tiller self-steering, blocks are likely to be the chief site of friction. It is never wise to skimp on the size of blocks — either on the diameter of the sheaves or the clearance for lines to pass through — and this is particularly important for self-steering, since friction can make all the difference between an arrangement working and not working. These blocks often will be under heavy load, and will be almost constantly turning, so wear can be a problem as well. Roller bearings and nylon or Delrin bushings are available in blocks, though I have gotten good success and long life out of the more plebeian Tufnol sheave on a stainless pin.

RUNNING — TWIN SAILS

At dawn of the thirteenth day we found the trade wind, a warm moderate breeze from the northeast, and with the first light I was on deck to set the big twin running sails. Self-steering was immediately successful, and we ran the remaining 1,500 miles to our Hawaiian landfall under twins in 17 days with no attention to the helm, except for an afternoon of strong wind and one memorable rain squall. I had to change to a smaller pair some days when the summer trade came fresh to strong, but sometimes for several days in a row the only work of running the ship was to trim a brace in or out once in a while.

Many variations of twin running sails have been used to achieve successful self-steering downwind in all sorts of yachts. About the only thing shared in common by all these rigs is that two poles are used to boom out two similar sails on opposite sides of the mast.

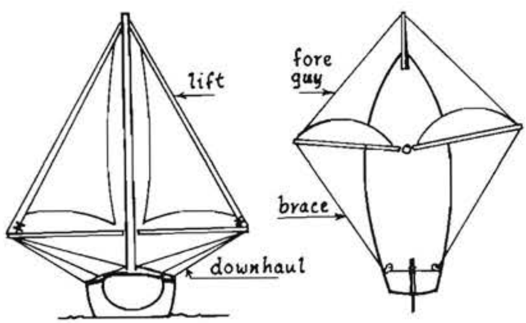
Mile after mile and day after day, twin sails do the steering down the sea lanes of the trade wind. (Warren Roll photo, courtesy of Yachting)



WALLER'S RIG

Capt. Otway Waller, who crossed the Atlantic in *Imogen* in 1930, is credited with inventing the rig. Each of his twin poles required a topping lift, a fore guy, a downhaul, and a brace to hold the pole in place, and the sails were set with jib-furling gear between the pole end and the masthead, with the furling lines running inboard along the poles (Figure 3-15). It must have been an operation to get all this gear set up; I imagine he did it just once.

The "braces" are just the lines leading aft from the pole ends, carrying most of the drive of the sails. Modern sailors would be more likely to call them "sheets" or "after guys," but this is a nice adaptation of square-rigger terminology, braces being the lines controlling the trim of the yards.



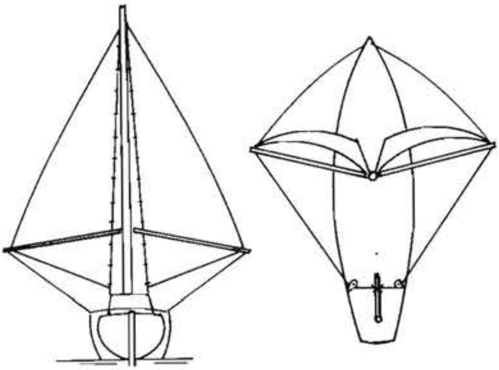
3-15. Imogen'*s twin running sails.*

TYPICAL TWIN RIG

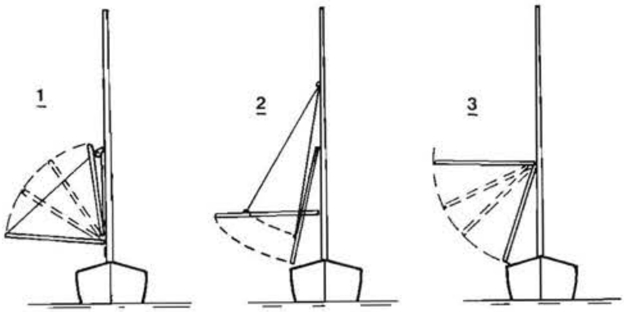
In an adaptation used by many yachts, with no roller-furling feature, the sails are set on two special stays either permanently or temporarily rigged from the mast to the foredeck (Figure 3-16). This rig normally requires downhauls to the pole ends to prevent them from lifting, as the braces leading aft provide little downward pull. What with shipping the poles and extra stays, hanking on sails, and rigging downhauls and braces, it typically requires an hour to shift over from fore-and-aft sail to twins in good conditions, perhaps much more time in bad weather or darkness.

WAYS OF STOWING POLES

Most improvements on the twin running sail idea have been in the direction of convenience, reducing the amount of special rigging, and pole and sail handling required to set the sails. At least three ways of stowing the poles more conveniently than on deck have been used (Figure 3-17): (1) The poles can be pivoted low on the mast and raised by their topping lifts to stow vertically along it (used by the Hiscocks in *Wanderer III*). (2) The poles can be pivoted on a fitting which slides on a track up the forward side of



3-16. Twin set on special stays.



3-17. Stowage for twin poles: (1) topped up along mast, (2) with sliding goosenecks and permanent lift, and (3) on fixed goosenecks up the mast.

the mast. Each pole has a topping lift of fixed length. When the inboard ends of the poles are raised, the outboard ends swing in and down; the poles can be stowed along the mast, or, much better, outside the lifelines (originated by Wright Britton in *Delight*). (3) The poles can be pivoted at a fixed position up the mast and be pulled up to a more-or-less horizontal position by the high-clewed sails as they are raised (originated by T.C. Worth in *Beyond*).

PROTECTING UNIVERSAL JOINTS

The inboard ends of the poles are ordinarily fitted with universal joints, which are potential sites of mechanical breakage. If the pole ever gets into a position *parallel to either axis* of the universal joint, the next movement of the pole can apply tremendous leverage to the joint. This problem can be avoided by having the axis which is fixed to the mast oriented horizontally and at some moderate angle aft. If the pole can never swing into a vertical position (because of the cabin trunk, for instance), then it is safe to have the mast-mounted axis vertical.

POLE END FITTINGS

The outboard ends of the poles can be fitted with simple eye fittings for shackling sails and lines, or with spinnaker pole fittings with remote release. Another possibility which can simplify rigging and sail handling is a sheave or just a smooth fairlead in the pole end, so the brace runs through the end of the pole and on to the clew.

POSITION OF TWIN SAILS

The twin sails have been tacked down as far forward as the stem or bowsprit, or as far aft as the mast. The disadvantage of placing the tacks too far aft is that the lee pole cannot be braced aft (to sail with the wind on the quarter) without the pole hitting the shrouds. This is a particular problem with the modern single-spreader rig with forward lower shrouds. On the other hand, with the tacks too far forward, it is easy to envisage the weather sail bellying too much as the weather pole is eased forward to bring the wind on the quarter – though in fact this has never been a problem in *Island Girl* or *Aleutka*, where we have normally put the tacks as far forward as they could be, with the sails hanked to the headstays. If the sails are to be set on special stays, or left up while roller furled, they will have to be tacked down fairly far aft to allow tacking with the ordinary headsails.

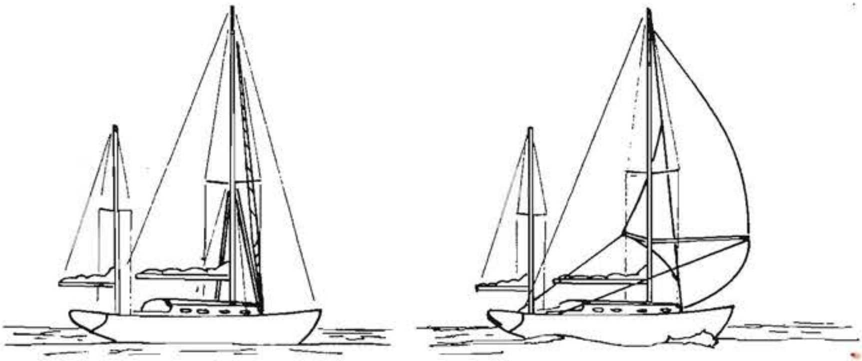
There is a theory that putting a gap between the two sails makes the rig more directionally stable, and that letting the sails swing forward to the magic angle of 23 degrees results in such directional stability that the braces do not need to be led to the tiller. I set *Island Girl's* twin sails this way once (set flying, not on stays), with negative results until the braces were led to the tiller, when she steered herself all right. No doubt easing the braces forward so the sails assume a wedge configuration contributes to stability; but this also sacrifices considerable driving power. I doubt that the stabilizing effects are sufficiently important to warrant either this sacrifice, or giving up any area in the middle to provide a gap.

SIZE OF TWINS – REEFING

The twin sails should have a total area at least as big as the working sail area to be useful in light weather. For a masthead sloop, cutter, or yawl this requires the pole length to be at least the average of the main boom length and the fore-triangle base, and the sails to go all the way to the masthead. These sails will be too big in anything over a moderate breeze, however, so either some form of reefing or a smaller, lower pair will have to be provided for stronger winds. Ordinary jib-furling gear, with the sails rolling up on their own luff wires, has been used successfully for *reefing* running sails in a variety of arrangements. This has met with more success than attempts to roller-reef fore-and-aft headsails, because the running sails are generally under less strain and their shape when reefed is much less crucial.

BRITTON'S ROLLER WINGS

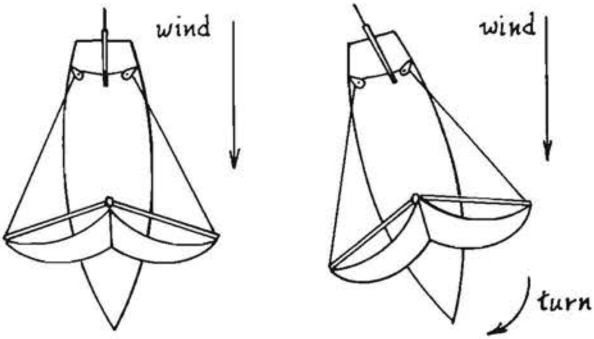
A notable roller-reefing system is that worked out by Wright Britton in *Delight,* the 40-foot yawl in which he and his wife made many voyages in the far north Atlantic. It would seem to be the absolute last word for convenience. The two sails are sewed to a single luff wire, and tacked down to a roller-furling drum in the middle of the



3-18. Delight*'s roller-reefing and roller-furling twins.*

3-19. Trekka *setting a parachute spinnaker above her twins.*

deck about a third of the way from the mainmast to the stem. This is far enough aft that the furled twins can be left up even when working to windward with a genoa. Using the self-stowing poles mentioned earlier, the only running rigging needed is the two braces, which lead through sheaves in the pole ends, and so can be left on when the sails are furled. Setting these sails means only lowering the poles into position, releasing the furling line, and sheeting the sails home (Figure 3-18). In strong winds the sails are partially rolled to reduce the area as much as desired.



3-20. Self-steering with twin running sails.

SPINNAKER ABOVE TWINS

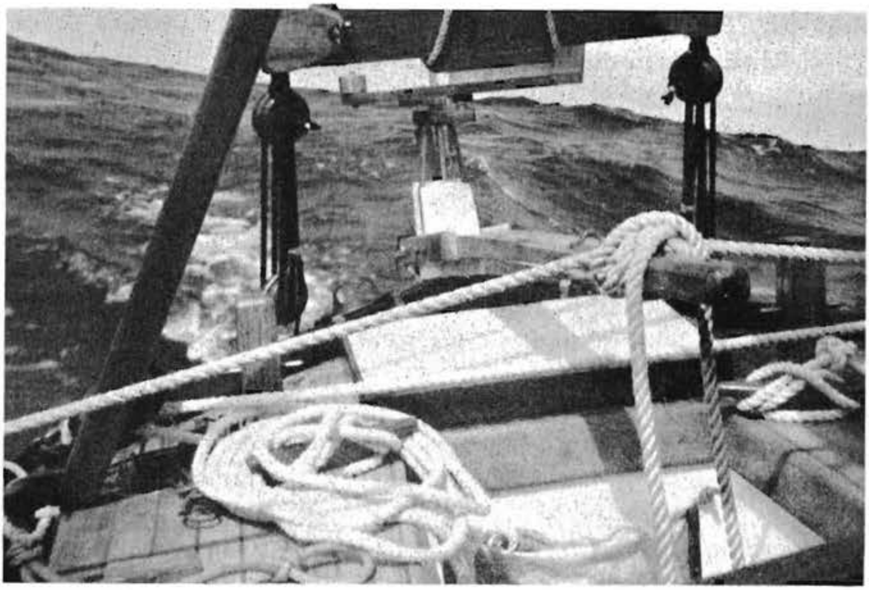
One alternate way to achieve a large sail area for light winds is mentioned by John Guzzwell *(Trekka Round the World,* Adlard Coles, London, 1959). In the 20-foot yawl *Trekka* he sometimes set a parachute spinnaker above the twins, with its head at the masthead and its two sheets led through blocks shackled to the pole ends (Figure 3-19). As in its usual setting, the spinnaker balloons upward and presents a projected area much larger than any flat triangular sails that could be set between the spars. It is also high, where the wind is stronger. In this way Guzzwell made excellent trade-wind passages with a relatively small pair of twins, finding the self-steering worked just the same with or without the spinnaker.

SELF-STEERING ACTION OF TWINS

Twin running sails might have come into use even if they did not provide self-steering, for they are proof against jibing, the ever-present bogey of downwind sailing since the ascendancy of the fore-and-aft rig. The self-steering action is achieved by leading the braces through quarter-blocks and tying them off to the tiller (Figure 3-20) If the yacht goes off course, the weather sail pulls harder than the lee sail, so it pulls the helm to windward and puts her back on course. How accurately the downwind course is maintained varies considerably. Most yachts using twin running sails report a good deal of rolling, and of course this means rapidly varying yawing moments from the thrust-resistance couple, and in general the self-steering system has a busy time keeping up with them. Friction in the heavily loaded quarter-blocks is a frequently mentioned problem. When the wind picks up and self-steering reliability starts to deteriorate, I have often gotten instant improvement by easing both braces out a little — this reduces the thrust a little, and takes out some of the friction.

SENSITIVITY TO WIND STRENGTH

Naturally, if the rig is made highly symmetrical, the boat will steer straight downwind regardless of wind strength, up to the point where she becomes overpowered. Small asymmetries, though, can have a pronounced effect. Using different kinds of rope for the two braces,



Aboard Aleutka, *running down the northwest coast on her 1967 maiden voyage to Hawaii. A metal pin through the tiller is used for tying off braces and other control lines. The pouch in the footwell keeps elastic, blocks, etc., handy for making up sheet-to-tiller gears. The vane gear shown here was a failure, for a variety of reasons.*

or sails of slightly different size, or slightly different locations for the quarter-blocks – even the topological impossibility of tying off the two braces in a completely symmetric way – all can make the course sailed sensitive to the wind strength. Careful attention to symmetry (or perhaps just the right piece of elastic to one coaming) will take care of this.

WIND ON QUARTER

By easing one brace and trimming the other, some deliberate asymmetry can be introduced which will make the yacht run with the wind somewhat on the quarter. The degree to which this can be done with satisfactory self-steering varies a great deal from one yacht to the next – sometimes as little as two points (11¼ degrees per point), seldom more than four points. (These are directions of the apparent wind, and the range of courses relative to the true wind is narrower than this would indicate.)

TWINS FOR ISLAND GIRL *AND* ALEUTKA

When I fitted out *Island Girl* with twin sails in 1963, I never thought of roller-furling, but adopted a relatively simple system worked out by T.C. Worth in *Beyond*. The poles were pivoted on universal joints near the lower spreaders, so they could be stowed by just lashing them to the upper shrouds. With 10-foot poles and a 25-foot hoist, I could get 250 square feet in the big twins, slightly more than her working sail area. I made the big sails of 1.25-ounce spinnaker nylon, with dacron rope and tape sewed in the luffs, and ¼-inch dacron rope in the leeches to help support the poles. The small twins, totalling 150 square feet, were of 4.5-ounce nylon (actually sailbag material) with luff wires and again ¼-inch dacron leech ropes. The sails are cut flat; there is no need to build in shape. I fitted twin headstays so each sail could be set on its own stay, but the hanks were staggered a little so both sails could be bent on one stay if necessary. We have always raised them both at once on the jib halyard, and the only pole rigging is the pair of braces, which are left on the poles and rove through the quarter-blocks all the time at sea.

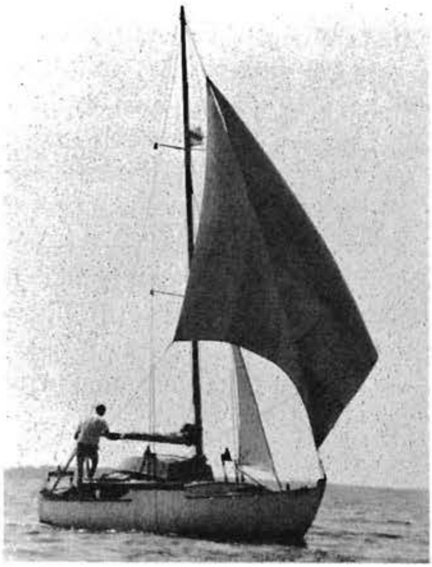
In practice this has been a very convenient and effective rig.

Twin running sails are a wonderfully chafe-free, stable rig for downwind sailing. Here the braces are led to the sheet winches (Figure 3-21) for easy adjustment. A few inches in and out on opposite braces would change course a whole point, and the apparent wind could be brought four points on either side. (*Warren Roll photo, courtesy of* Yachting)

Because it only takes five or ten minutes to change over (with one of us steering to keep her before the wind), it has been useful not only in the steady trades but anytime the wind is astern. Sometimes we have shifted from working sail to twins and back again three or four times a day. No time is lost in these changes, as the twins are hoisted before the main is lowered, and *vice versa*.

Single-handed, changing to twins was more of a scramble. As soon as the jib was down, the boat wouldn't steer herself broad reaching, so I would lower all sail. Then she would lie in the trough and roll badly, and the twins would tend to blow off the deck and bowsprit to leeward. When the sails were all bent on I would lead the halyard aft to the cockpit and steer downwind with the tiller

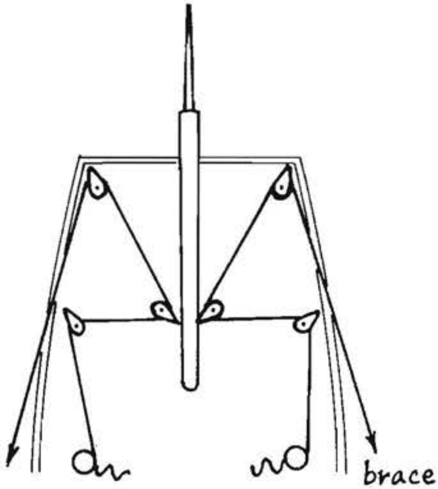
Setting twin sails single-handed can be quite a scramble, as the yacht won't run downwind by herself and the sails tend to blow off the deck and foul themselves. The best system I found was to tie the braces off to the tiller (Figure 3-20 or 3-21) before hoisting the sails, lead the halyard to the cockpit, and hoist them a little at a time while steering downwind. (Warren Roll photo, courtesy of Yachting)



Aleutka *setting* Island Girl's *old twin running sails. She could use a larger pair, but these have given us many days' runs of 120 miles or more. We often leave the forestaysail set under the twins, as it seems to help her keep the wind on the quarter. (Patricia Letcher photo)*

between my knees while raising the sails. Still I doubt if it ever took more than 15 or 20 minutes to change to twins, after the first few times.

These twin sails always steered *Island Girl,* and later *Aleutka,* satisfactorily as long as the wind was not overpowering. I generally think the big twins should come down at about Force 4, but in building winds we have carried the small pair for many hours of hard driving in Force 6. Occasionally in these conditions a bigger-than-normal sea will cause her to broach to, with the lee sail rattling like thunder for a few seconds, but she quickly recovers and runs off again. This rig has been more successful than most in running with the wind on the quarter. Only one or two inches hauled in on one brace and let out on the other is enough to change course by



3-21. Arrangement of braces for self-steering in Island Girl.

a point, and in moderate weather she runs quite nicely with the apparent wind a full four points on the quarter. (It seems to help to leave the forestaysail set under the twins, with a preventer.) The strain on the weather pole and the tendency to broach are increased, though, so in stronger winds it is more comfortable to run off than to brace her around too much.

The only damage I have ever suffered with this rig was in a squall on the twenty-third day of *Island Girl's* passage to Hawaii. I had grown accustomed to the trade-wind pattern of fine weather interspersed with brief squalls of rain and fresher wind, so I paid little mind to the clouds building up to windward during lunch, and left the big twins up. At this time I had rigged up a handy way to lead the braces to the winches for easy adjustment (Figure 3-21). This one squall struck with such ferocity that *Island Girl* caught the first wave and surfed wildly down it, just hanging on the edge of a disastrous broach. I scrambled out and grabbed the tiller to assist the steering gear, and the helm was so heavy for the next few minutes that I had no chance to run forward to the halyard, though I was able to ease the braces out quite far. Still she was hard pressed in the furious wind and finally broached-to, breaking the windward pole across the headstay. Thereafter, I considered the small twins the working rig and saved the big ones for settled light weather. There is something to be said for belaying halyards back within reach of the helm when sailing short-handed, though I must admit I have never gone to the trouble. There's already enough stuff in the cockpit without all the halyards.

With the pole repaired we ran on under twins to a dramatic landfall on the high volcano Haleakala at dusk of the twenty-ninth day. On the last day, though, self-steering failed me, as the trade-wind became strong and I had to steer by hand the entire twenty-four hours under very small sail. So all my projected improvements, left to the last day, went by the board, and we entered the yacht basin at Honolulu after dark on the thirtieth day — unshaven, unshorn, unbathed, and looking about as tired and weatherbeaten as befits the single-handed sailor.

SPECIAL EQUIPMENT FOR SHEET-TO-TILLER SELF-STEERING

Though I have emphasized the possibility of making up sheet-to-tiller gear out of spare parts, naturally if it is used day in and day out some special items of equipment turn out to be handy.

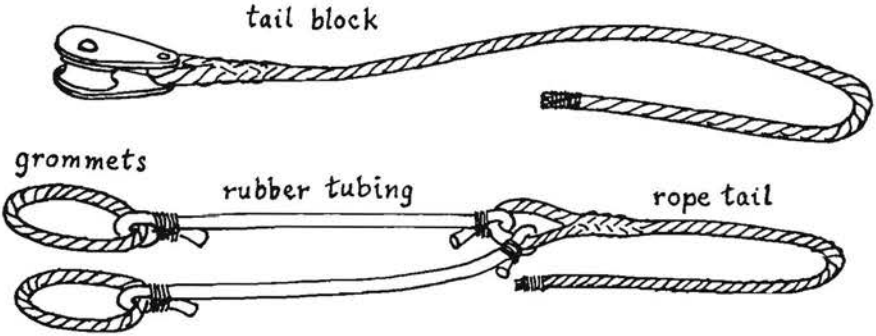
The only permanent hardware I installed in *Island Girl* and *Aleutka* for self-steering was a wood or metal pin athwartships through the tiller about 6 inches (15 centimeters) from the end, to facilitate tying off lines there; and a small jam cleat suitable for 5/16 inch diameter (7.5 millimeters) line outboard of the cockpit coamings each side in way of the tiller.

Good big quarterblocks are required for twins, and they have to be positioned with a clear lead to the tiller; so they are useful for leading sheets and control lines with other arrangements as well. On *Island Girl* these were shackled through the mooring cleats on the quarters. In *Aleutka* we found a neat solution in the oarlock sockets on the rail outboard of the cockpit, whose primary purpose is auxiliary propulsion. The blocks are shackled to a spare pair of ring-type oarlocks, shipped in these sockets.

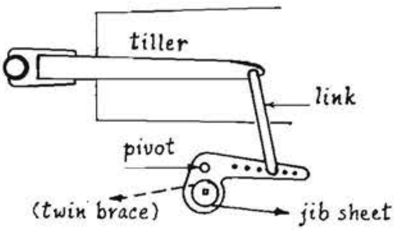
In the category of loose gear, there are two items that we have found very useful (Figure 3-22). We always have handy a couple of *tail blocks,* which are just single-sheave blocks to which are spliced 5-foot (150-centimeter) rope tails. These are used for making up tackles and for temporary leads of control lines. The second is an elastic assembly having two or three parts of rubber tubing, rope grommets to slip over the tiller, and a rope tail to belay to a jam cleat. This overcomes the difficulty of securely belaying stretchy rubber tubing.

There are two ideas in the special equipment line that I have no experience with, so they are put forth only as ideas. Wheel steering would seem to preclude sheet-to-tiller arrangements by definition. Of course the possibility of shipping an emergency tiller should always be provided with wheel steering; but perhaps this would be inconvenient to put in place whenever self-steering is desired. It might well be sufficient to fasten sheets and elastics to appropriate points on the rim or spokes of the wheel. If this provides insufficient rotation of the wheel, a drum could be used at the hub or on the axle of the wheel for a control line to pass around.

The second idea applies to headsails and perhaps twins on boats over about 30 feet (9 meters) when sheet tensions are just too powerful to take directly on control lines or on the tiller. Winches are often provided to assist in handling these sheets, and a novel way of mounting the winches could provide helm forces of the right mag-



3-22. Special gear for sheet-to-tiller steering.



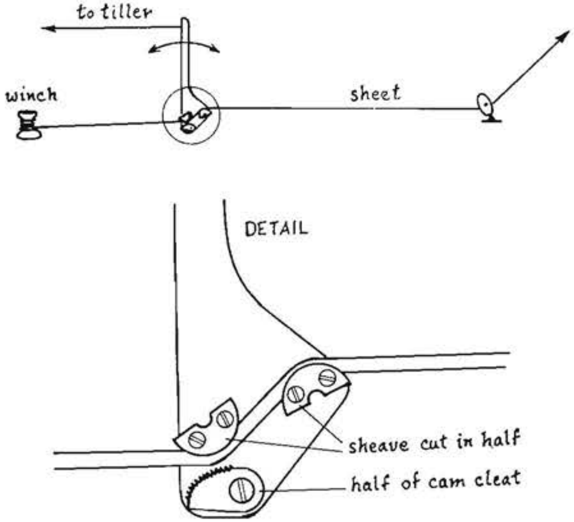
3-23. Special lever winch base for sheet-to-tiller coupling.

nitude with a lot more convenience and less friction than setting up fool's purchases. The idea is to mount each winch on a special movable base rather than directly on the deck or coaming (Figure 3-23). The winch base then is attached to the deck at a pivot or fulcrum, so that it acts as a lever, with a long arm to supply the reduced helm forces. The closer the winch is to the pivot, the greater the reduction. Of course, the winch base has to be built and attached to the deck just as strongly as you would attach a winch, and with as little friction as possible.

A less permanent piece of equipment that can serve a similar purpose is a portable lever designed to be clapped on a sheet, to bend a jog in it. (Figure 3-24). The tension in a control line leading from the top of the lever is then a small fraction of the sheet tension.

THE GENERAL APPROACH

My passage to Hawaii was the beginning of a series of offshore voyages in small yachts now totaling over 25,000 miles. During most of that distance I have not had a windvane gear on board. Instead I relied on sheet-to-tiller self-steering – essentially the arrangements described in this chapter – and these have done the steering about 95 percent of the way, very seldom with any sacrifice of speed or course. I don't attribute this success to any characteristics of the boats. They have all been small, light, single-masted craft with short keels, not particularly well balanced when heeled, and tender enough



3-24. Portable lever for taking off a proportional part of sheet tension.

to heel most of the time. Rather, I have come to the opinion that sheet-to-tiller gear can satisfactorily steer *any* yacht of moderate size in most conditions.

I'm not claiming that all you have to do is hook up the exact arrangement diagrammed and sail away into the sunset. Perhaps some of these will work on your boat just as shown; I think most will work with no more change than increasing or reducing the mechanical advantage of a tackle. Even so, success with a particular boat is going to require a period of experimentation on each point of sailing and with each sail combination. It is likely to require some patience, and perhaps some inventiveness. My attitude has always been, when faced with the necessity of steering, that I may as well pass the time at the helm trying to get her to steer herself, and almost always in a short time my efforts have been rewarded.

The possibility of this does not seem to be generally known. People think of sheet-to-tiller arrangements as singular and specialized, dependent on particular qualities of hull and rig; and so the recurrent theme in voyage accounts in the magazines: "On the fifth night out the vane gear broke, and after all our efforts to fix it failed, we had to set watches and steer the rest of the way" — as if hand steering were the only alternative to vane steering. Considering the reliability record of vane gears, experimentation with sheet-to-tiller gears should really be part of the preparations for any long passage, so that the principles are grasped and some useful arrangements are already worked out before the need arises. All that is required, besides spare line and blocks, is some form of elastic. As in any experimental program, it makes sense to keep detailed notes in a permanent notebook that will be kept on board for future reference.

COMMON FEATURES

Looking back over all the arrangements for self-steering with fore-and-aft sail the following common features stand out:

1. Some part of the running rigging is led around, with or without mechanical advantage, to pull the helm to windward. The choice is based on finding a line whose pull increases when the yacht luffs, and slacks when she bears away. I have always found a sheet to serve, but I imagine a downhaul, an outhaul, a vang, or a guy might someday be called into service.

2. The windward pull is more than the weather helm requires, so the excess is balanced by elastic. Arranging the sheet to pull to *windward,* the elastic to *leeward,* guarantees that increased weather helm will be provided when the wind freshens.

3. The elastic should always be positioned so it becomes slack when the tiller is centered or a little to the lee side. Sensitivity to wind strength is then adjusted out by experimenting with elastics of various *stiffness.*

If it doesn't work, don't give up; figure out *why* it doesn't work. This kind of thinking seems always to lead to some idea for an arrangement that will work better.

4 SO YOU WANT TO TRY A WINDVANE

Windvane self-steering for model sailboats goes back at least fifty years, and Marin-Marie used a windvane gear on his 1936 Atlantic crossing in the motor yacht *Arielle*. But it seems that the first uses in full-sized sailboats came in 1955 when Ian Major made a vane gear for *Buttercup* and sailed her across the Atlantic, and Michael Henderson made a different type for *Mick the Miller* and won the Junior Offshore Group championship racing with it. These successes opened the door for all the developments that have come since.

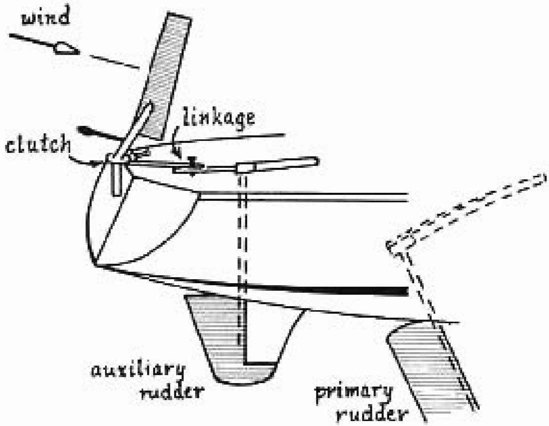
We could look a long way before finding a better example of a vane gear than *Mick's*. Henderson's achievements with this first effort are truly remarkable; twenty years have not made it in any way obsolete. So just in case the reader is not familiar with the basic workings of windvane self-steering, I will use this simple and elegant example as an introduction (Figure 4-1).

The windvane is a piece of thin plywood pivoted so it is free to turn and weathercock into the wind. When the course-setting clutch is engaged, the windvane turns one arm of a simple slotted-bar linkage, and the other arm turns the shaft of an auxiliary rudder. The linkage reverses the rotation. The windvane ordinarily would not have the power to turn even this small rudder, but the rudder is hydrodynamically balanced with part of its area forward of the axis, so only the bearing friction needs to be overcome to turn it.

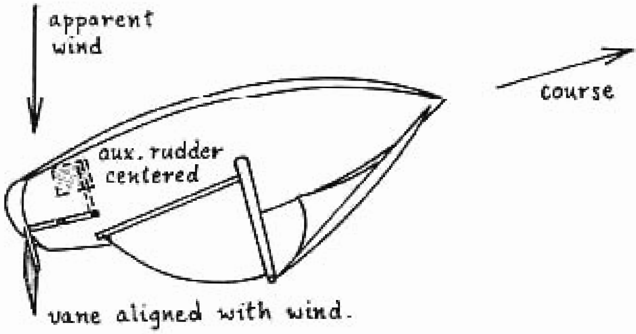
Now with the boat on course and trimmed out, the main rudder can be fixed to supply most of the weather helm. The windvane is allowed to line up with the wind and then the course-setting clutch is engaged (Figure 4-2). (In order to make the vane and auxiliary rudder angles clearer in this diagram, I have drawn them both as if they had simple rectangular shapes.)

Now if the boat should go off course to starboard, the vane would want to stay lined up with the wind. In doing so, it turns the auxiliary rudder the right way to make the boat turn to port (Figure 4-3). Similarly, if she goes off course to port, the auxiliary rudder will turn so as to steer her to starboard. If the turning moments thus provided are strong enough to overcome any inherent instability, self-steering results. The vane gear strives to keep the apparent wind coming from the same direction, so it steers any course "by the wind."

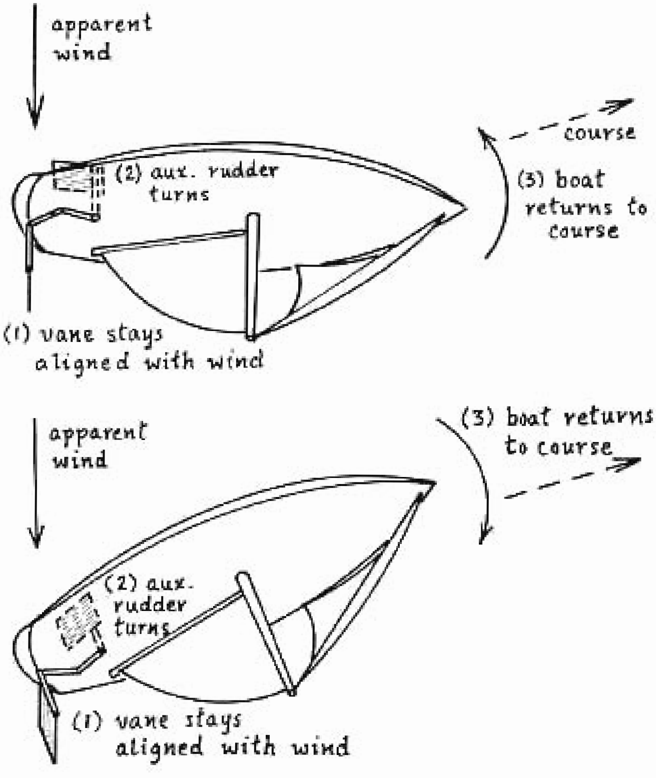
The attractions of this idea are tremendous, even to one who has worked out sheet-to-tiller self-steering for all his needs. Think how nice it would be if the boat would keep on course while the mainsail was being reefed, or while the twins were being bent on. Or maybe the windvane eliminates the need to use twins at all, as it ought to work with the jib wung out, or even with a spinnaker. Being so easy to adjust and independent of the sails, the vane gear could provide instant self-steering on the relatively short boards of coastwise cruising when it often seems not worthwhile to set up



4-1. Mick the Miller's *Vane gear, devised by Michael Henderson in 1955.*



4-2. Vane gear set on course.



4-3. Off course, vane gear correcting.

sheet-to-tiller gear. A major inducement to use a windvane would be certain sail combinations, such as headsails alone for broad reaching in strong winds, for which the helm is light and steering does not seem difficult, but nothing in the sheet-to-tiller line seems to work. Still, I resisted the idea for a long time, recognizing that this special equipment would be subject to mechanical failures not readily repaired on board, and so I trusted in simple things like blocks and elastic and got along fairly well. With two of us on board we could always steer during sail changes and steer watch-and-watch in a pinch.

An encounter that did a lot to change my mind occurred on my last trip down the west coast. My wife Pati and I sailed from Vancouver Island to San Francisco in September 1969 in our 25-foot cutter *Aleutka.* Off Cape Mendocino in northern California we experienced a northerly gale that must live there — it has never failed to be there when I was passing through, and it's reported by practically every boat that passes down that coast in summer or fall. We thought it was Force 6 or 7 and we lay a-hull through two nights, with an exhilarating day between of scudding under a 40-square-foot forestaysail only.

We arrived in San Francisco within a day of two other yachts that had come through the same gale. One was a Tahiti ketch that had also elected to lie a-hull at night, and had been rolled completely over! Perhaps we had been very lucky — you really never can tell when a big one could roll up and do that to you. We didn't think the gale was that bad, or we would have been running before it under bare poles, trying in the dark to keep her before the seas. But steering like this is exhausting, and perhaps eventually, in a longer gale, we would get worn out and would have to lie a-hull anyway.

The other yacht was *We're Here Too,* a 28-foot cutter sailed by Irwin and Grace Giroux, who have made many successful passages in the Pacific in her. Irwin had recently fitted a home-made windvane gear. Although it was still in a somewhat experimental state, they had been able to run before the gale under bare poles, with the windvane doing all the steering. They had stayed below, gotten some sleep, and had not taken any seas aboard. That really sounded nice. I'm not proposing this as the ultimate gale tactic, but it seems clear that a vane gear good enough to operate in gale conditions can take a lot of strain off the crew, and offers a better course than lying a-hull when the crew (perhaps a solo sailor) is exhausted.

So I was finally convinced that we ought to try a vane gear, and perhaps by now you are too. How should we proceed?

REQUIREMENTS FOR SUCCESSFUL WINDVANE SELF-STEERING

POWER

One thing we didn't have trouble with when we were using sheet-to-tiller self-steering was power. The rudder always had enough power to control the course, otherwise we would have put on a bigger one. The sheets always had ample power to pull the tiller — often this power had to be reduced with fool's purchases. But when we try to generate the same steering action out of a windvane with only a tiny fraction of the area of the sails, there is clearly a good chance that it won't be powerful enough.

On close-reaching courses when the boat is stable anyway the requirements are very small. It takes a more powerful system to handle the unstable steering of broad reaching and running. Hard driving in a seaway calls for more power yet — more weather helm, stronger steering action. When does it stop? We all know that eventually, in building winds, sail has to be reduced simply because the human helmsman doesn't have the strength to keep the boat from broaching.

One of the first questions that the designer has to ask, then, is "How powerful a system is desired?" Certainly in moderate weather it ought to be able to steer all courses without a reduction of sail. The worse weather it can handle, of course, the nicer, but also the more rugged, complicated, and sophisticated it must be.

SENSITIVITY

Accurate self-steering requires a device highly sensitive to small changes in the apparent wind direction. Friction is the gremlin that cuts into sensitivity, and it becomes most apparent in light winds.

This is because the frictional torques associated with a rudder shaft log, or with the weights of various components supported on bearings, are fairly constant, while the aerodynamic forces available to overcome them diminish with the square of the wind speed as the wind gets lighter.

Any cruiser spends a substantial amount of time sailing in light winds, and this is when steering is least interesting. Surely the vane gear will be more satisfactory the lighter the wind it will steer in. But this requires a bigger windvane or more delicate and corrosion-prone bearings, or both.

STRENGTH AND DURABILITY

Simple mechanical engineering is the requirement most often wanting in vane gear installations. The auxiliary rudder is *thought* of as auxiliary, and it doesn't appear to be recognized that it is subject to just the same loads as the main rudder and deserves to be built and hung just as strongly. The windvanes and linkages are designed on peaceful evenings ashore without a thought to the damage just one single rogue wave-top can do. Many are the voyage accounts in which metal fatigue, or corrosion, or fouling, or some unanticipated minor accident puts the vane gear permanently out of commission within just a few days of leaving port.

Simply making the working parts heavier and more rugged, or the foils smaller, usually conflicts with the requirements for power and sensitivity. What is called for is good engineering: efficient use of good materials, careful construction, and thoughtful foresight into all manner of off-design loads (accidents). Not that it requires an engineer to do it — some of the best vane gears I have seen were designed on the dock by people with no more formal training in engineering than I have in theology. They just had enough experience working with materials and boats to figure out what was required, and they succeeded.

STEADINESS

A more subtle failing of many vane gears is steadiness on course. First let us admit that the wind is turbulent and constantly varying in both speed and direction; any steering system that uses the wind as its reference direction cannot be expected to hold a perfect compass course. But this observation is no excuse for the yawing and weaving that is so commonly characteristic of vane gears, especially on downwind courses. Even when testing in coastal waters where winds are typically much more shifty than on the open sea, it is easy to watch the telltales and see whether the gear is really keeping the apparent wind at a constant angle, or is oscillating about the desired course. Oscillation is often referred to as "oversteering" because the boat overshoots the direct course with each turn. It can be so bad that the boat wanders far off course and even tacks or jibes herself, and even a powerful, sensitive system can thus fail entirely.

Oversteering may result from nothing but friction or backlash, or it can be a complicated phenomenon involving the rotary inertias of the boat and of the vane gear components, the hydrodynamic properties and weight distribution of the hull, and the type and power of the vane gear. It can sometimes be controlled by deliberately reducing the power of the vane gear, and many gears allow for adjusting the mechanical advantage of the linkage for this purpose; but this is not a very reliable or desirable way to correct the problem. For most types of vane gears certain details of the control, the windvane, and the linkage have a strong effect on damping of oscillations, and a genuine "feedback linkage" can usually eliminate oversteering while retaining ample power and quick response.

OTHER REQUIREMENTS

Is this a complete list of vane gear requirements — power, sensitivity, strength and durability, steadiness? I doubt it. (1) The adjustments necessary for setting it on course should be simple and convenient, and perhaps remoted to the cockpit. (2) For safety's sake it should disconnect instantly and return the helm to ordinary manual control for dodging and maneuvering. (3) Sensitivity to changes in wind strength and changes in location of the crew in the boat ought to be minimized. (4) Most people will ask that the vane gear not be too ugly or obtrusive an addition to the graceful lines and functional gear of a beautiful yacht. (5) And certainly it should make as little drag as possible in both the wind and water flows, so as not to damage the sailing performance of the boat.

It is tempting to put *simplicity* down somewhere in the list, for there is a strong association between simplicity and reliability. "Keep everything simple" is the advice we hear over and over again from the most experienced voyagers, and it is good advice. But simplicity is not *necessary* to the achievement of reliability. We are surrounded with examples of bafflingly complex machines with dozens or hundreds of interrelated parts whose perfect functioning for months or years on end we take for granted – think of a radio, a chronometer, a typewriter. Here a high degree of development and engineering is the price of reliability. Simplicity only makes reliability vastly *easier* to achieve. Every part that is added to a machine is another part than can fail, usually in several ways, and its possible interactions with all other parts have to be considered.

THE THREE COMPONENTS – WINDVANE, CONTROL, LINKAGE

Windvane self-steering has been a fertile field for experimentation, and the problem of satisfying all these requirements has attracted many bright minds. Cruising boats are as different from each other as people are, and the variations in hull, rig, and equipment have demanded different solutions in each particular case. The result is such a dizzying multiplicity of distinct windvane gears that it is really hard to tell where to begin in judging between them and choosing a suitable type.

The place to start is to recognize three functional components that are common to all windvane systems; then to discover that there are really only a handful of distinct forms that each component can take.

1. There has to be some device in the wind that can sense a change in apparent wind direction and generate an "error signal." Originally this took the form of a weathercock, like *Mick the Miller's*. Now other forms have been developed that would not serve as a weathercock at all, but they can all be referred to as the *windvane* (sometimes *vane* for short).

2. There has to be a device that is capable of controlling the

course of the boat. In *Mick's* case this is the balanced auxiliary rudder. Always the steering component includes one or more hydrofoils that generate steering moments from the flow of water past them. Several distinct forms are used; in general terms I will refer to any of them as the *control.*

3. Communication between the windvane and the control requires an intermediate mechanism to process the information from the windvane and deliver the appropriate instructions to the control. It can be anything from a length of galvanized water pipe to a small computer. In *Mick the Miller's* vane gear, the vane clutch and the two slotted bars do this job. My general term for the component of the system that performs this function is the *linkage.*

This represents a fairly complete dissection of any vane gear into three definite sections. Somebody will probably call my attention to an exception, but I can't think of any vane gear in which all three components can't be identified. Further, apart from structural supports and braces, I can't think of any part of any vane gear that doesn't fit logically into one of the three groupings.

The importance of analyzing vane gears into these three components is that practically any type of windvane can be combined with any type of control, and this tends to split one big design problem into two smaller ones. The details of the linkage depend to a considerable extent on the particular choice of windvane and control, but there is substantial freedom of choice in the general type of linkage to go with any control and vane. My teacher, Fritz Zwicky, would construct a morphological box and show that with four different types of vane and seven different types of linkage and five different types of control there are one hundred and forty distinct combinations — such as vertical axis / slotted bar / auxiliary rudder *(Mick's),* or oblique axis / hydraulic / servo tab, etc. — and most of these have never been tried.

LOGICAL SEQUENCE FOR DESIGN — CONTROL FIRST

Recognizing there is a degree of independence between the three components leads us to wonder whether any component is more important or more critical than the others. Certainly all three components eventually have to work — and work together — to achieve the desired result. But it seems logical to me to consider the control foremost. After all, the name of the game is self-*steering*. If the control is inadequate, no amount of enlargement or refinement of the windvane and linkage can improve the system. Being underwater, the control is the hardest part of the gear to get at for installation, modification, or repair; but given an operative control with adequate power any amount of experimentation or jury rigging can be done on the rest of the system. This all points toward designing the control first. It also points toward building and installing the control first. Certainly one should have a design, or some alternative designs, for windvane and linkage in mind before building anything; but before carrying these components into the hardware stage it makes sense to test the control by itself to be sure it has sufficient power and to assess its balance and friction, for these will largely set the requirements for vane and linkage.

In the same vein, it seems logical, whenever time and situation allows, to build first temporary, experimental hardware out of cheap, expendable materials. In this way the design can be verified and improved on at very low cost, before investing time and good materials in a final design and permanent installation. Even on a temporary gear, though, give it a fair shake by using good bearings. A little bit of friction here and there could lead to entirely the wrong conclusion in evaluating the gear's performance. If the design calls for ball bearings, use ordinary steel ones temporarily and grease them up so they won't be rusty by the second day — but do use ball bearings.

IF ANYTHING CAN GO WRONG, IT WILL

The adage that entitles this section, known throughout the engineering world as *Murphy's Law*, is a succinct statement of healthy pessimism. It is an attitude worthy of cultivation by anyone who goes to sea, for it encourages foresight and preparedness, and softens disappointment. It is especially applicable to windvane self-steering;

the biggest lesson we can take from the many ocean passages that have been made with the help of this gear is that any number of things can go wrong, and do. Beside the rest of the equipment on a cruising boat, the vane gear is usually ridiculously delicate and vulnerable to accidents. Whether you build your own vane gear or buy one, you must assure yourself that you are getting a genuine piece of cruising gear, not a toy. Armed with the right attitude, you will be thinking about such accidents as:

1. *Getting in irons*

This is really easy to do, especially when changing sails or reefing. The first big sea throws the whole boat back against her steering gear; the hydrofoils that were so nicely balanced with the flow from the usual direction are suddenly thrown very hard against whatever stops might be present, and if nothing breaks it's a wonder. If things have been thought out right, the thing that breaks can be a shear pin easily replaced from the deck.

2. *A rogue wave top*

This should only happen in a gale, but a gale can happen on any ocean passage, and might overtake the coastwise cruiser. Lying hove-to, or a-hull, or running under short sail, we don't expect to be boarded by a sea; but just in case, we put loose gear below and feel confident that even a considerable wave-top dropping aboard could do no harm to the cabin, masts, rigging, or tiller. But what about the delicate moving parts and lightweight airfoil of the windvane? Here is a case for placing the vane well above deck level and inboard, or for making the vane removable to stow below; also for enclosing as much of the mechanism as possible. Or a shear pin in the windvane axis might allow it to weathercock into a heavy spray without breaking anything.

3. *Snagging or mooring lines, fishnets, kelp; going aground*

The underwater control should allow such obstructions to clear themselves without snagging. If snagging is still remotely possible, a shear pin or kick-up feature could save the day, and should be given careful consideration.

4. *A misplaced step or handhold*

If any part of the gear is located where someone stepping aboard, or climbing aboard out of the water, or reefing the mizzen, can step on or grab it, it has to be *very* strong or it will get bent. This again suggests putting the vane well above deck, and the moving parts under cover.

5. *Accidental jibes*

During an accidental or casual jibe, part of the main sheet might easily catch on some part of a vane gear that is situated too close.

6. *Docks, dinghies, and drunken sailors*

The far-aft, over-hanging position so often chosen for adding a windvane gear makes it particularly susceptible to damage in minor collisions and brushes with docks, such as occur around marinas. Thus an otherwise negligible incident might occasion much grief for the windvane-equipped sailor. Even a towed dinghy running up on an overtaking sea might effectively put it out of action. An inboard location seems much less vulnerable.

MAKE IT OR BUY IT?

I hope by now the reader appreciates my pronouncement in Chapter 1, "Achieving successful windvane self-steering is not nearly as easy as it looks." The key word here is *successful;* we have seen that the requirements for success and the potential hazards are many, and the prospect may well appear discouraging at this point. Probably no installation will completely satisfy all the ideals; everyone has to make his own bargain with the devil.

There are by now quite a number of manufactured windvane gears on the market, some that have compiled convincing records of successful ocean crossings. (A partial list of manufacturers is in the appendix). Each gear is available with mounting hardware to make it applicable to as many different boats as possible, so there is likely to be at least one commercial model more or less suited to your boat. Whether or not it will be a satisfactory installation and worth the price may be a difficult matter to decide. The best approach is to carry any proposed installation through a thorough engineering analysis, considering the size, balance, and friction of the components, the quality of design and construction, and the allowances for accidental loadings. Another approach is to arrange a sailing demonstration in a boat similar to yours. Even this is not infallible, as performance can be strongly affected by various differences between the boats, such as yaw damping, center of gravity location, and balance of helm. I would be skeptical of information received at dockside — remember, it's always painful to admit it if you've wasted a lot of time or money. Often the first response to "How does it work?" is "Oh, fine"; but a little digging by specific questions reveals that it won't steer downwind unless the main is handed, or it can't handle windward sailing in more than 15 knots of wind, etc.

There are vane gears on the market priced from around $200 to about $2,000. The wide range of prices reflects both the degree of complexity of the various systems and the quality of design, materials, and labor that have gone into producing them. The prices may seem high by comparison with other manufactured items of similar character; but in fact this is a rather competitive field, and the high prices only indicate that this is a low-volume market. Most of the manufactured gears could be produced at much lower cost if they were mass-produced, with the development and tooling costs spread out over hundreds or thousands of units. Perhaps we will see this happening if vane gears catch on more generally as accepted cruising equipment.

The cost of installing the unit on a boat can also run anywhere from $200 to $2,000, unless the owner does it himself. This depends on how adaptable the gear is, how well the instructions are worked out, the quality of workmanship in the installation, and the amount of modification necessary to the yacht. This cost must be borne in mind, of course, when selecting a gear.

I tend to feel that anyone with a reasonable amount of mechanical aptitude and knowledge of boats can make a vane gear that is better suited to his own boat and will give results as good as the commercial models; and there is room for a lot of satisfaction in doing it. It is not a project to be left to the last week before a voyage, though.

I tried that with my first windvane gear and the result was a shameful waste of time. My first satisfactory permanent installation took an astonishing 175 hours to design, build, and install — which is more than one-eighth of the time it took to design and build the boat! Hopefully, you can do better with the help of these chapters, but it's not a project to be entered upon lightly.

Now I am faced with a problem. My reader has decided that he wants to build his own vane gear; he has come to my book looking for practical advice. Here am I, armed with a beautiful theory of vane gear performance, phrased in terms of differential equations and the esoteric symbolic language of aerodynamic theory. On what level can we get together? Surely I shouldn't expect one sailor in a hundred to be conversant in differential equations, and the other ninety-nine would probably snap the book shut and put it back on the shelf if they opened it and saw just one. So differential equations are out, and don't worry, you won't see any here. (A paper for a technical journal *is* in preparation by the author.) On the other hand, I think it's reasonable for me to expect that the practical sailor wants to understand how his vane gear works, so he can make rational choices in designing and building it, using, repairing, and improving it. So my job is simply to decide just how much of the theory is likely to be useful, and to translate it into plain English. It is a fact that *none* of the theory is *necessary* — I doubt if Marin-Marie, Henderson, Major, or Hasler had any help from differential equations when they built the original vane gears. But the same can be said of many other fields of engineering where empirical developments preceded theoretical understanding. When a satisfactory theory is eventually developed, it usually indicates a new, logical organization for the body of knowledge that has grown up in the field, it explains paradoxes and resolves conflicting experimental results, it suggests improved design methods to achieve optimum performance, and it often points the way to entirely new developments.

The next four chapters are my attempt to give a correct explanation of the workings of vane gears in plain English for the assistance of the practical sailor. Whatever you can absorb from them will, I believe, improve your chances of making the best choices in fitting out a yacht for self-steering. The calculations suggested are very simple and are illustrated by concrete examples. But even these are not essential, so in the summary (Chapter 9) you can find detailed instructions for the ratios and proportions of five different complete vane gears, if you choose not to work out the proportions for yourself.

PATENTS

I think a word of caution is in order concerning patents. I believe some features of some vane gears are patented in various countries, though I have very little specific information on this subject. Patents serve to protect the interest of the inventor, thus encouraging him to make inventions. While a patent is in effect, the inventor has the sole right to manufacture the device he described in his patent application, and it is a civil offense to use his invention without his license. It is commonly believed that the patent restricts only the right to *sell* the device, and that it's okay to build one for one's own use; but the law doesn't read that way. As a practical matter, though, it seems unlikely that a patent holder would find it worthwhile to bring suit against someone for making just a single copy of his invention.

My own attitude toward patents is a little equivocal. On the one hand I can see that my own experiments and success with vane gears would have been seriously hampered if certain features (for example, differential linkages used with trim tabs, or the horizontal-axis vane), which I imagine were patentable when introduced, had in fact been patented. Undoubtedly the field has grown much faster that it would have in the presence of numerous patents, and the buyer of a manufactured gear benefits from the strong commercial competition resulting from the fact that Col. Hasler, for example, did not obtain a patent on his first servo pendulum. With this book I am releasing at least five ideas that appear patentable on the surface, because I think better use will be made of them in the public domain. But if I came up with a hot new idea that appeared to have good commercial possibilities, I believe I would apply for a patent, and consider the profits and the protection from competition to be just rewards for the years I have spent working on self-steering.

5 CONTROLS

As I explained previously, the *control* is the part of the windvane gear that is able to influence the course of the boat — it is practically always one or more hydrofoils in the water. The principal requirement is that the control be powerful enough to do the job of steering. Desirable features include: low forces or torques required to actuate it, so the vane and linkage don't have to be too big; standards of strength, durability, and protection from accidents should be similar to the primary rudder.

THE PRIMARY RUDDER

The primary rudder — by this I mean the rudder the boat is already equipped with for manual steering — is obviously powerful enough to do the steering. If it can be used as the self-steering control, it has the estimable advantage of adding no additional moving parts or drag underwater.

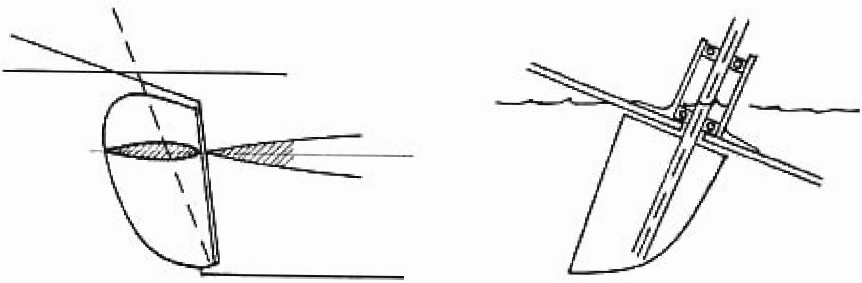
Friction and balance make most primary rudders unsuitable for use as the self-steering control. The helm forces required for weather helm and for active steering on unstable courses are simply too much to ask of a windvane that is much smaller than the sails. A typical rudder that is hung aft of the keel or outboard has no balance area, so that substantial torque about the rudder axis is required to hold it at any angle where it produces a turning effect. Spade rudders are most often partly or completely balanced, but their cantilevered support puts much higher loads on the bearings, encouraging friction, and usually they have a shaft log sealing their entry into the hull, with considerable friction in the packing. None of these problems is an essential one; a rudder can be hung top and bottom with balance area, or a spade rudder can be provided with ball or roller bearings and a water seal (Figure 5-1). These are very promising ideas for self-steering in new designs, but they have not been seen, to my knowledge, in original equipment.

AIRFOILS AND HYDROFOILS

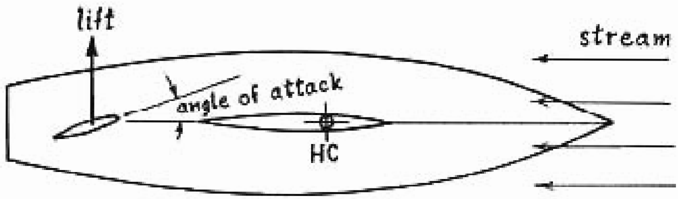
If the primary rudder can't be operated directly by a windvane, the next step is to develop a control that *can* do the steering, either by itself or in connection with the primary rudder. In undertaking this design, a general understanding of the behavior of hydrofoils seems indispensable. At the same time, at no extra cost, we learn about the behavior of airfoils, because, at the speeds used in sailing, the only big difference between the flows of air and water over thin, streamlined shapes is the density of the two fluids. The flows obey the same equations, the streamlines are highly similar, and the design problems are almost identical for airfoils and well-submerged hydrofoils. I am inclined to call them all *airfoils* or *wings.*

APPLICATION OF FOILS

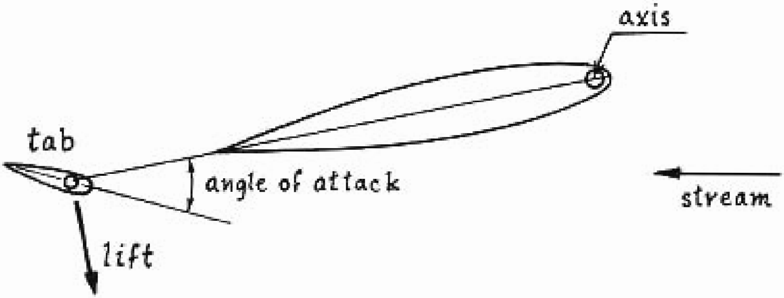
By looking at some of the uses of foils in self-steering, we will see that the main purpose is always to generate a force perpendicular to the stream of fluid. This is the *lift* force of aerodynamics. Lift



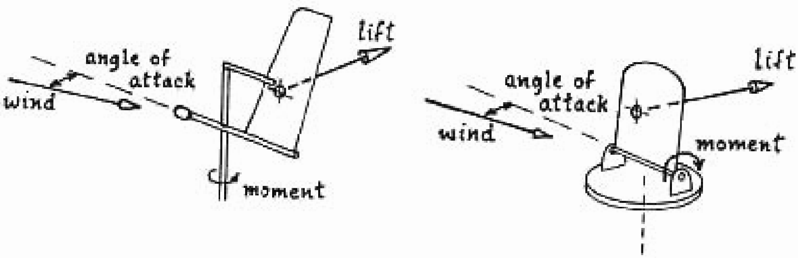
5-1. Balanced, low-friction primary rudders.



5-2. Lift force on rudder turns the boat.

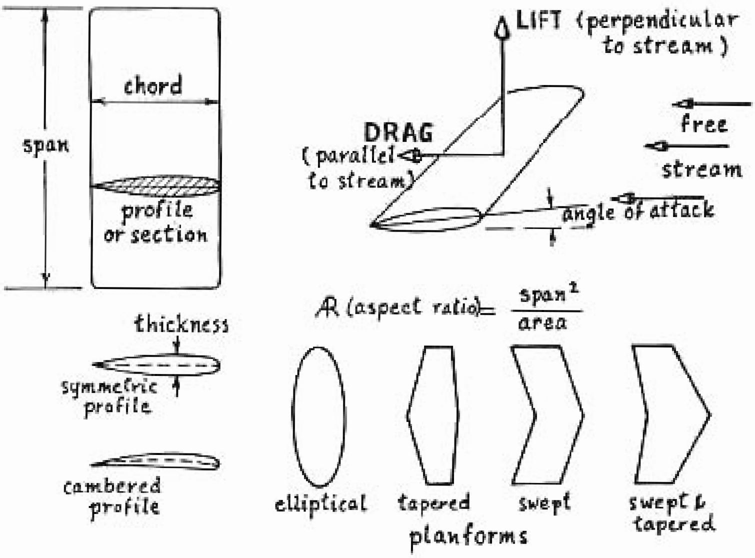


5-3. Lift force on tab turns the rudder.



5-4. Lift force on vane produces output torque.

doesn't have to be directed upwards, as it is for an airplane in level flight, but it is always perpendicular to the stream. In a boat moving through the water, with the rudder at an angle of attack (Figure 5-2), it is the lift force, acting at a distance from the hydrodynamic center, that produces the desired turning moment. If a servo tab



5-5. Airfoil terminology.

is hung on a rudder (Figure 5-3), it is the lift force on the tab, acting at a distance from the rudder axis, that turns the rudder.

If a windvane finds itself at an angle of attack, it is the lift force that makes a moment in the vane shaft to turn the rest of the mechanism (Figure 5-4). The effectiveness of each of these components depends largely on how much lift is produced.

LIFT CHARACTERISTICS

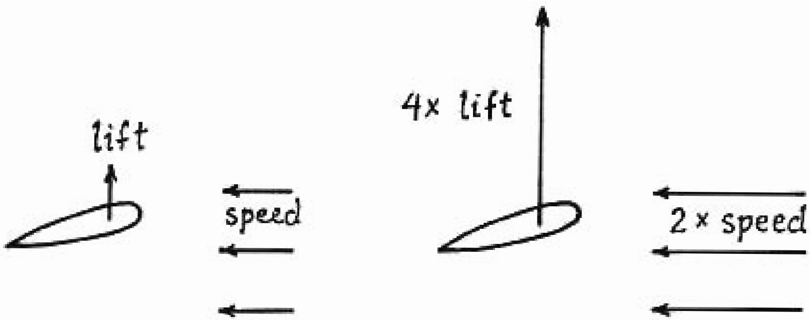
Lift depends on the density and speed of the stream, and on the shape, size, and orientation of the airfoil. Throughout this section, I want to consider only *symmetrical,* or *uncambered* and untwisted airfoils, because camber and twist are seldom of any value for keels, centerboards, rudders, tabs, or windvanes — all have to work equally well with the flow from either side. So our wings are built up from a flat *planform* plus a thickness distribution or *profile.* Let us imagine a series of experiments to determine the influence of speed, density, angle of attack, platform, and profile on the production of lift. Some of the descriptive terms are illustrated in Figure 5-5.

Speed

We set up a wing in a uniform flow of air at a fixed angle of attack and a given speed. If the speed is then doubled, the lift is always found to be almost exactly quadrupled. In other words the lift is *directly proportional to the square of the speed* (Figure 5-6).

Density

We set up a wing at a fixed angle of attack and make a flow of air pass it at a certain speed. If we then change to a flow of water at the same speed, the lift is increased about 830 times — which is just the



5-6. Lift is proportional to the square of the speed.

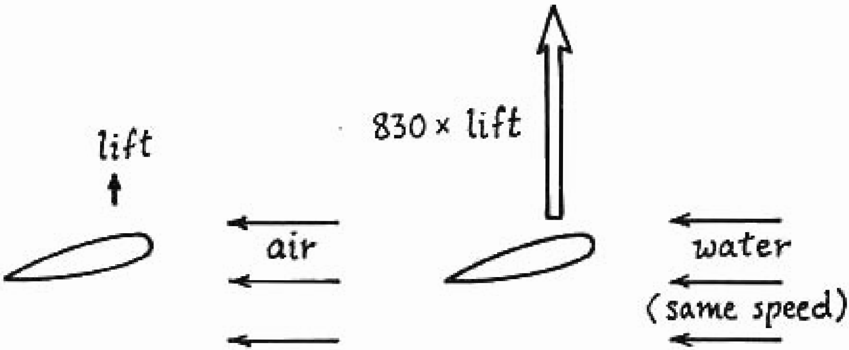
Table 1. Air

Speed, kt.	lb/ft²	kg/m²
5	.086	.42
10	.34	1.68
15	.77	3.77
20	1.72	6.7
25	2.15	10.5
30	3.08	15.1
35	4.2	20.5
40	5.5	26.8

dynamic pressure in lb/ft² = .0034 x (wind in kt.)²
dynamic pressure in kg/m² = .0168 x (wind in kt.)²

ratio between densities of water and sea-level air. For any fluid of low viscosity, we would find the lift *directly proportional to the density* (Figure 5-7).

The combination ½ × density × (speed)^2 is called *dynamic pressure.* It is the rise in pressure required to bring a particle of fluid from its free-stream speed to a stop, so it is a logical measure of the force-producing potential of a moving stream. Values of dynamic pressure for sea-level air and seawater are given in Table 1 and Table 2.

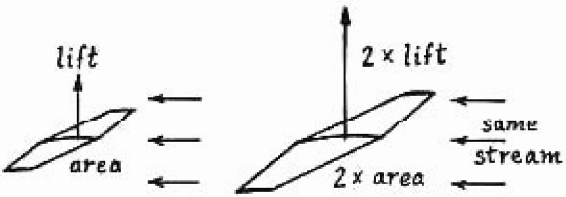


5-7. Lift is proportional to the density of the fluid.

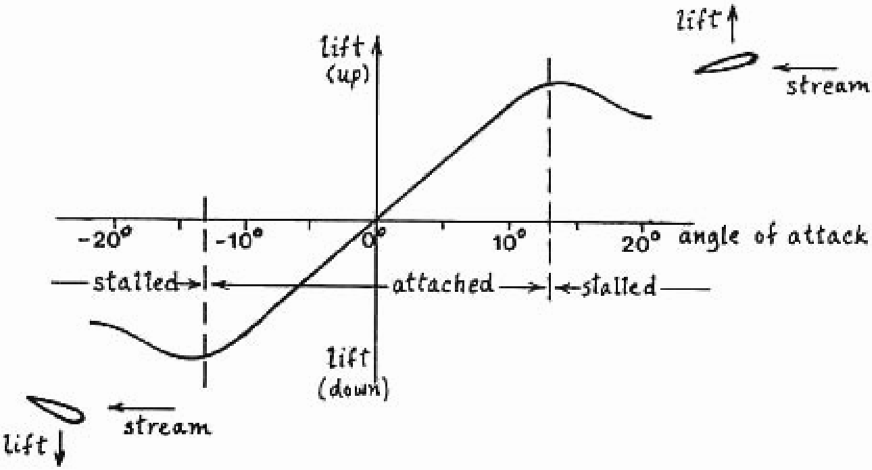
Table 2. Water

Speed, kt.	lb/ft^2	kg/m^2
1	2.85	14.0
2	11.4	56.
3	25.6	126.
4	45.5	223.
5	71.	350.
6	102.	500.
7	139.	680.
8	182.	890.

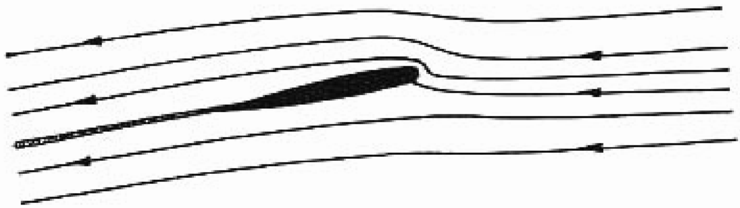
dynamic pressure in lb/ft^2 = 2.85 x (speed in kt.)^2
dynamic pressure in kg/m^2 = 14.0 x (speed in kt.)^2



5-8. Lift is proportional to the wing area.



5-9. Typical variation of lift with angle of attack (thick, symmetrical airfoil section).



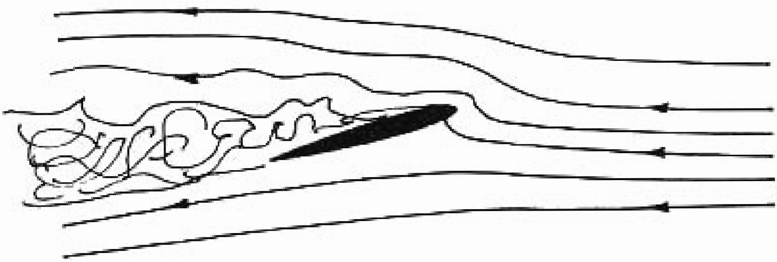
5-10. Streamlines in attached flow.

Area of wing
If wings having geometrically similar planforms but different sizes are tested in the same dynamic pressure, the lift is found to be *directly proportional to wing area* (Figure 5-8).

Now we have found that lift is proportional to dynamic pressure times wing area.

The constant of proportionality is called the *lift coefficient,* and it depends only on the geometric shape and orientation of the wing (and to a small extent on the fluid's viscosity which we will ignore in talking about air and water flows at the speeds and scales involved with boats).

Angle of attack
If the plane of the wing is accurately aligned with the stream (zero angle of attack), no lift results in any case. If the speed is held constant and the angle of attack is varied, the results are likely to be much like the graph in Figure 5-9. Over a wide range of angles the lift of an airfoil is almost *directly proportional to angle of attack.* If we could make the streamlines visible, the picture would look like Figure 5-10, a smooth "attached" flow with a barely perceptible deadwater wake behind the trailing edge (and very low drag). At higher angles of attack, stall takes place — the variation of pressure over the suction side becomes so severe that the flow can't follow all the way to the trailing edge. Instead, it breaks away, leaving a broad, eddying wake downstream with a sharp increase in drag and a decrease in lift (Figure 5-11).

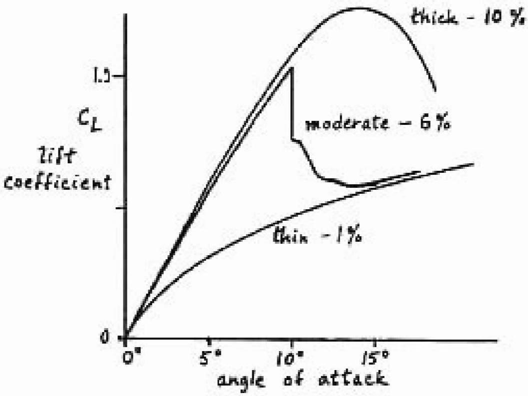


5-11. Streamlines in separated (stalled) flow.

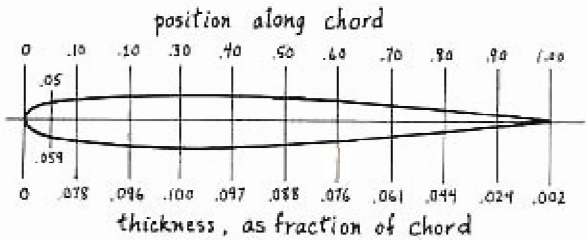
Profile

A very *sharp trailing edge* is necessary to keep the drag low, and wings with blunt trailing edges are found to generate a little less lift. On the other hand, a well-rounded leading edge is required to reach high angles of attack (and high lift coefficients) without stalling. In other respects, the profile has little effect on lift in the range of angles of attack below stalling.

The characteristics of stall depend on the profile, particularly on the leading edge (Figure 5-12). A very thin, flat plate stalls almost from the start, and so develops much less lift and more drag



5-12. Typical variations of lift with angle of attack (various thicknesses).

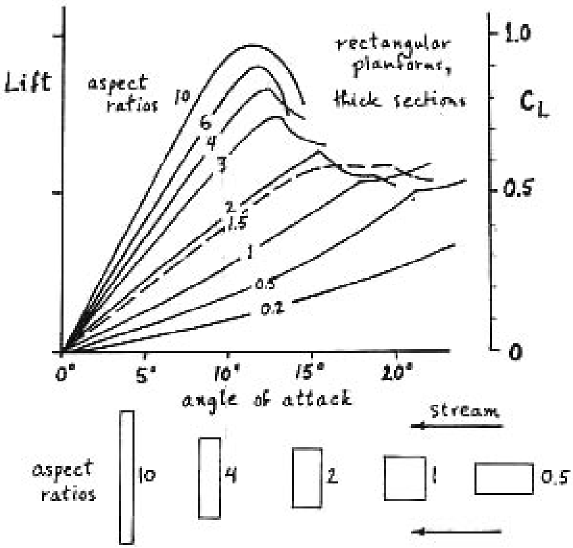


5-13. Offsets for NACA 0010 airfoil section.

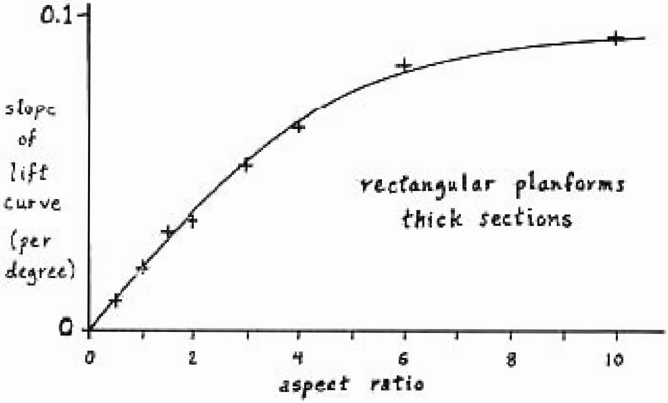
than the thick profile at most angles of attack. A moderately thick section stalls later, but often quite sharply, so its lift curve drops suddenly. It takes a good, fat section to develop the highest lift coefficients and to stall "gently." A good general-purpose symmetrical profile is NACA 0010, with the offsets given in Figure 5-13. The "10" in NACA 0010 just means thickness is 10 percent of chord, and the "00" means there is no camber. Other thicknesses can be made by scaling all the offsets up or down by the same factor. "NACA" denotes a standard family of profiles devised by the U.S. National Advisory Committee for Aeronautics.

Planform

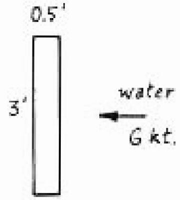
A final set of "experiments" will investigate the influence of planform on lift characteristics. Suppose several rectangular wings of the same area and different aspect ratios are tested over a range of angles of attack. (The aspect ratio of a rectangular wing is the span divided by the chord). This has been done and the results look like Figure 5-14. For planforms other than rectangular, the results look



5-14. Typical dependence of lift curve on aspect ratio.



5-15. Rate of change of lift coefficient with angle of attack — dependence on aspect ratio.



5-16. Example for lift calculation.

much the same, when aspect ratio is defined as span squared divided by area. The principal message of this graph is that high aspect ratio gives a steeper curve of lift versus angle of attack — less angle of attack is required to produce a given lift (Figure 5-15). Stalling is postponed to somewhat higher angles of attack for the lowest aspect ratios, but the lift at stall nevertheless diminishes with decreasing aspect ratio.

A scale of lift coefficient, C_L, is added to the right hand side of Figure 5-14 to assist the more ambitious in making estimates of actual forces: Lift = C_L × dynamic pressure × wing area. *Example:* estimate the lift on a symmetrical rectangular foil with a span of 3 feet (91 centimeters) and a chord of 0.5 feet (15 centimeters) moving at 6 knots through water at a 3 degree angle of attack (Figure 5-16).

$$\text{Area} = 3\ \text{ft} \times 0.5\ \text{ft} = 1.5\ \text{ft}^2 \quad (0{,}14\ \text{m}^2)$$

$$\text{Aspect ratio} = \frac{\text{span}^2}{\text{area}} = \frac{3\ \text{ft} \times 3\ \text{ft}}{1.5\ \text{ft}^2} = 6$$

From the graph, $C_L = 0.33$

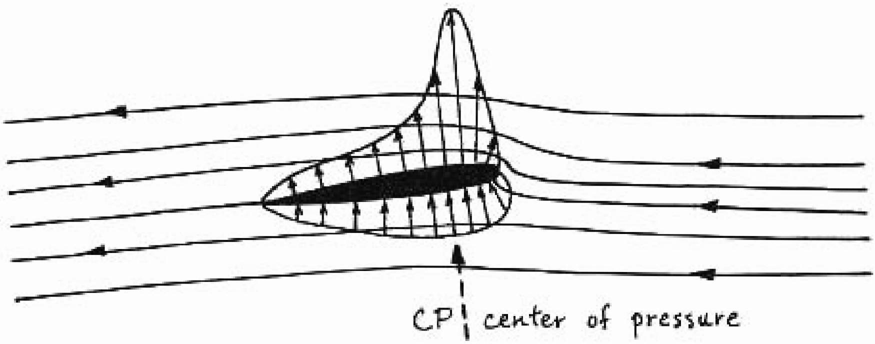
From the table,

dynamic pressure = $102.\ \text{lb/ft}^2 \quad (500\ \text{kg/m}^2)$

$$\text{Lift} = C_L \times \text{dynamic pressure} \times \text{area}$$
$$= 0.33 \times 102\ \text{lb/ft}^2 \times 1.5\ \text{ft}^2 = 51.\ \text{lb} \quad (23.\ \text{kg})$$

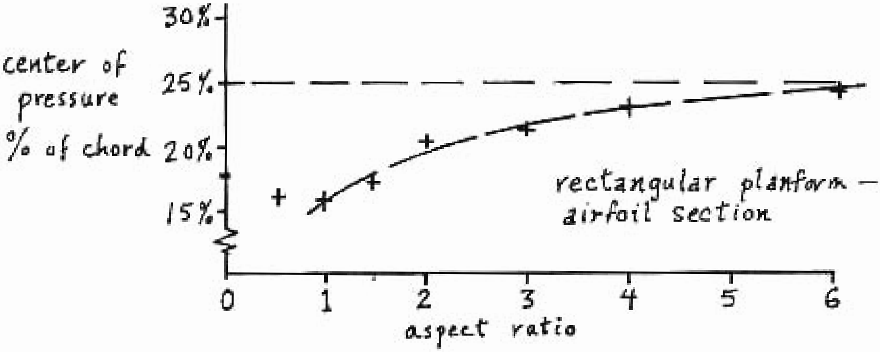
CENTER OF PRESSURE

The lift developed by an airfoil is the resultant of a distribution of pressures over the airfoil surface. The difference in pressure between the two sides is called the *lift distribution*. Lift is not at all uniformly distributed. For symmetrical airfoils below stall, the lift is heavily concentrated toward the leading edge, as shown in Figure 5-17, with the center of pressure, CP, not more than a *quarter* of the chord from the leading edge. The quarter-chord point is a good estimate for rectangular wings of high aspect ratio — say 6 or above — and the one-sixth-chord point agrees with data for aspect ratios between



5-17. Pressure difference concentrated toward leading edge of symmetrical airfoil.

½ and 2 (Figure 5-18). CP moves aft with stalling, to a 35 to 45 percent chord position. (On a wing that is very thin and sharp-edged, with stall occurring from very low angles of attack, CP is likely to be at 35 to 40 percent chord for any aspect ratio.)



5-18. Center of pressure moves forward with decreasing aspect ratio.

As we shall see shortly, locating the center of pressure is crucial in the matter of aerodynamic balance of controls, so a way of estimating the center of pressure for non-rectangular planforms is needed. But the interference between a wing and other nearby bodies in the flow — as, for example, between the keel and the hull, or between a servo tab and the rudder — has important effects on the lift distribution. There are all kinds of aerodynamic theories for these problems, but they tend to be quite complicated, and their accuracy has never been such as to render wind tunnels obsolete. This is a good reason for testing a prototype control of expendable materials before finalizing the design. For initial design purposes, you ought to be able to eyeball the center of pressure location fairly closely by the following:

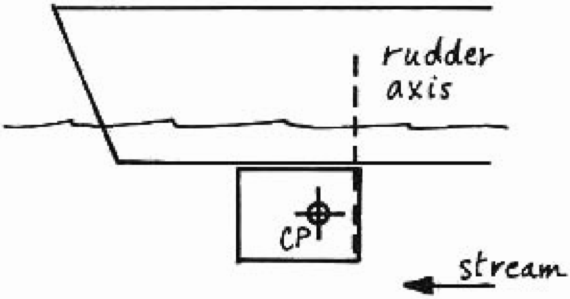
1. Cut the planform out of stiff paper or cardboard and balance it on a knife edge to locate the center of gravity (center of area).
2. Calculate the average chord by dividing the area by the span.
3. The estimated CP will be ahead of the center of area about

¼ of the average chord for the high-aspect-ratio airfoils; about 1/3 of the average chord for the low-aspect-ratio airfoils; and about 1/6 of the average chord for thin, sharp-edged airfoils.

Don't bet your boots on it, but in comparison with experiments on thirty wings of different aspect ratios, sweep, taper, etc., this simple method in every case came within seven percent of the average chord in finding the chordwise position of CP, and for most it was within three percent.

AERODYNAMIC BALANCE

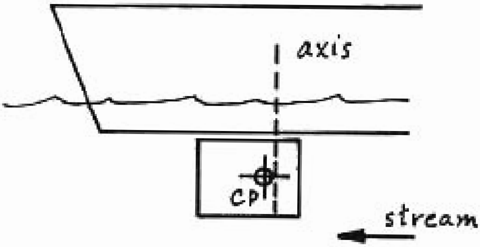
To be used as a control, an airfoil has to be movable. Though there are other ways for things to move, the simplest way mechanically is rotation about a fixed axis, and this movement is almost universally chosen for rudders and such. *Balance* of a control refers to a relationship between the center of pressure and the axis of rotation of the movable foil. Consider the following alternative arrangements of a simple rectangular spade rudder:



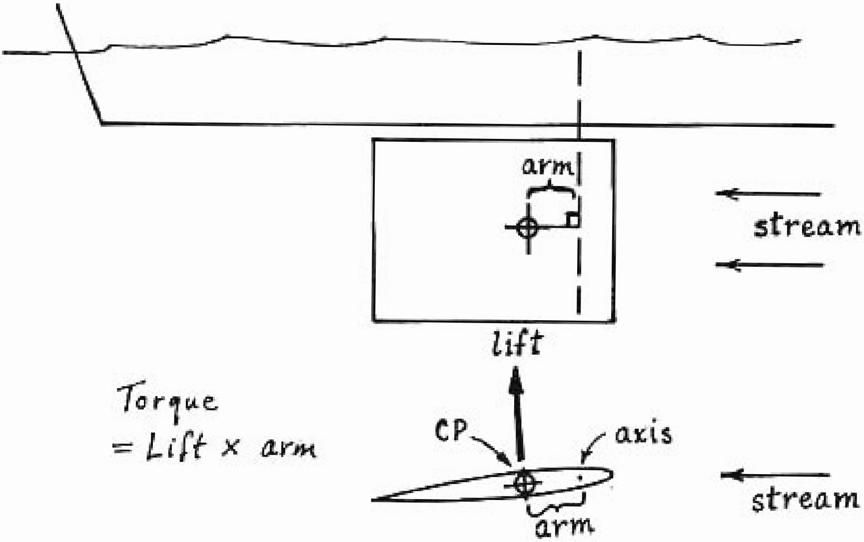
5-19. Unbalanced control surface — axis along leading edge.

Unbalanced

The axis coincides with the leading edge (Figure 5-19). The rudder is stable (in the sense of the ball being stable in Figure 2-6) in that, if it is disturbed from its equilibrium position, the resulting moment tends to turn it back in line with the stream. A torque on the rudder shaft is required to hold it at an angle of attack; the helmsman has to work at it. This torque is called *hinge moment.*



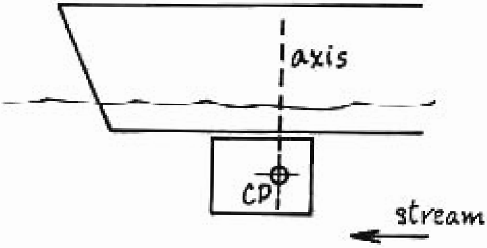
5-20. Partial balance — axis forward of center of pressure.



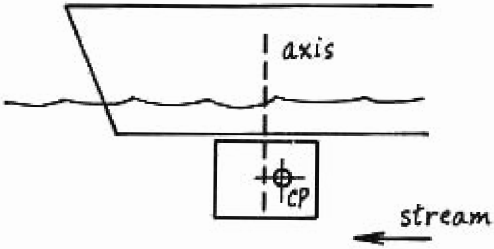
5-21. Torque to turn the rudder depends on the degree of balance.

Partially balanced

In Figure 5-20 the axis has been moved back closer to the CP. The rudder is still stable. But now the torque required to hold it at an angle of attack is less. The hinge moment, in fact, is equal to the lift times the perpendicular distance from the CP to the axis (Figure 5-21). The closer the axis passes to the center of pressure the less helm force is required to do the job of steering.



5-22. Complete balance — axis passing through center of pressure.



5-23. Overbalance — center of pressure ahead of axis.

Completely balanced

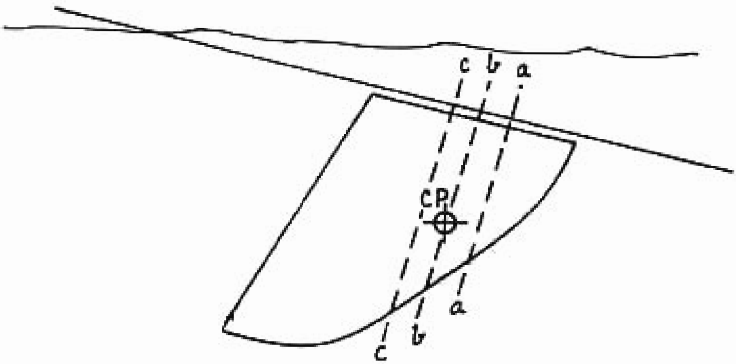
In Figure 5-22 the axis passes right through the center of pressure. No torque at all is required to hold the rudder at any angle of attack up to stall. (As the rudder stalls, the CP moves aft, so the perfect balance becomes partial balance.) Now the rudder is neutrally stable — if it is turned somewhat and let go, it has no tendency to turn either way. To the helmsman the rudder would feel unpleasantly dead, but very little effort would be required to steer.

Overbalanced

If the axis is placed behind the CP (Figure 5-23), the rudder becomes unstable. When it is turned to a small angle of attack, the resulting moment tends to turn it to higher angles of attack, increasing the moment. The helmsman would have a constant fight on his hands, and could not let go for an instant.

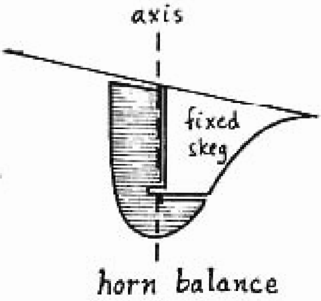
All these rudders have the same area, aspect ratio, profile, and planform. They all produce the same lift at any given angle of attack. But the helmsman sure wouldn't say they were the same rudder. Though it has nothing to do with the power or effectiveness of the control in steering the boat, balance profoundly affects the torque required to actuate the control. Balance is important in self-steering because it allows a powerful control to be operated by a relatively puny windvane.

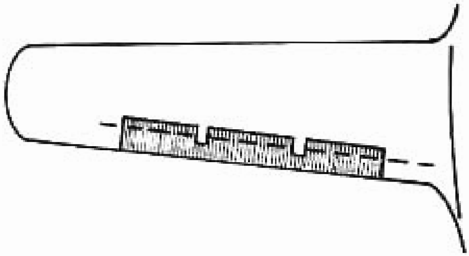
For any other planform, balance has the same meaning — the relation between the CP and the axis of rotation. Complete balance is attained when the axis passes through the CP; and the perpendicular distance from the CP to the axis is the measure of the degree of balance. For example, the spade rudder in Figure 5-24 would be partially balanced on axis a-a, completely balanced on axis b-b, and overbalanced on axis c-c.



5-24. Balance of irregular-shaped rudder: axis a-a, partial balance; axis b-b, complete balance; axis c-c, overbalance.

A spade rudder is what an aerodynamicist would call an "all-moving control surface." Controls that are mechanically better supported can also be balanced by putting some of the movable area ahead of the axis. *Mick the Miller's* auxiliary rudder was "horn balanced" like many airplane rudders. Ailerons are often given some area forward of the hinges for at least partial balance (Figure 5-25). Another approach used in aircraft and allowing good streamlining is



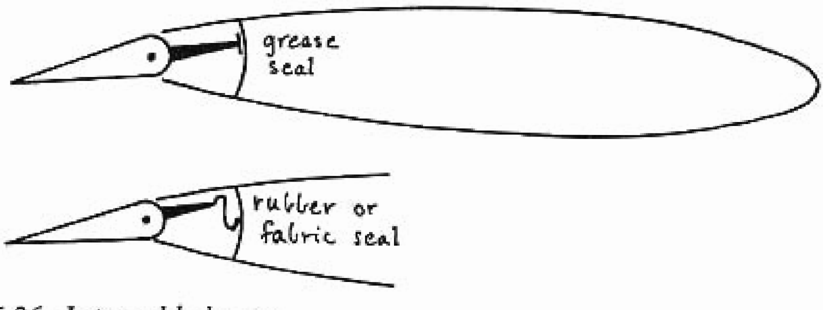


5-25. Aerodynamic balancing devices.

the "internal balance," where high-pressure and low-pressure air is admitted to two chambers inside the wing where it can act on a forward extension of the flap (Figure 5-26); but without more elaborate gearing, this method will not allow the flap to turn very far.

DRAG

You will recall that drag is the component of force acting in the direction of the stream. Drag does not have much direct bearing on the operation of the self-steering gear, but it does have harmful effects on the performance of the yacht. Drag added below water by a control is likely to be more significant than the windage added by the windvane and its supporting structure, but both are damaging, especially to windward sailing ability. If the self-steering gear is to have the minimum impact on performance, drag must be reduced wherever possible.



5-26. Internal balances.

A well-shaped airfoil below stall adds drag about in proportion to its wetted surface. For an example, consider *Mick the Miller* with about 115 ft^2 (10.7 m^2) of wetted surface. Her auxiliary rudder with 1.4 ft^2 (.13 m^2) area on a 1 ft^2 (.09 m^2) skeg adds 4.8 ft^2 (.44 m^2) or 4.2 percent to her wetted surface, and this means a 4 to 5 percent increase in resistance through the water, causing a 2 to 2½ percent reduction in speed at low and moderate speeds. This was probably not noticeable, and evidently she made up for it in other ways, for she won a lot of races.

On the other hand, a stalled airfoil or an unfaired strut can have many times the drag of a fair airfoil. If *Mick's* auxiliary rudder were turned far enough to stall completely, its drag would be more than twice the frictional resistance of the rest of the boat. A control that has to be partly stalled to provide enough steering action is very harmful; a larger control with twice the area might have much less drag. Adding the drag of a round cylindrical strut just 3 feet (90 centimeters) long and 1 inch (2.54 centimeters) in diameter would about double *Mick's* total frictional resistance at any speed; whereas with an airfoil fairing like NACA 0030, the inch-thick strut would have only 2 to 3 percent as much drag.

This is about the minimum amount of aerodynamics necessary for understanding and designing windvane self-steering gear. It has taken a lot of effort to confine myself to this minimum treatment. Aerodynamics is a broad and fascinating field, and I urge the interested reader to look deeper into it, for there is much theory and data that can contribute to a better understanding of all aspects of sailing.

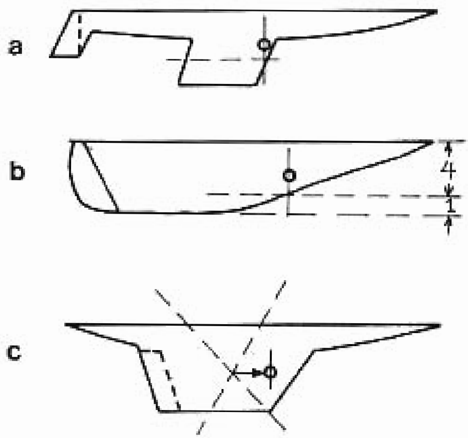
THE BALANCED AUXILIARY RUDDER

A second rudder, usually smaller than the primary rudder and more or less balanced, has been used for self-steering on many sailing yachts, beginning with *Mick the Miller*. This is called an auxiliary rudder. We will investigate the required size for adequate control power, and suggest a variety of ways in which the auxiliary rudder can be arranged. A balanced auxiliary rudder, capable of being operated directly by a windvane, is likely to involve considerably less mechanical complexity than a servo tab or pendulum. Another advantage is that it provides an alternative steering system in case of damage to the primary rudder.

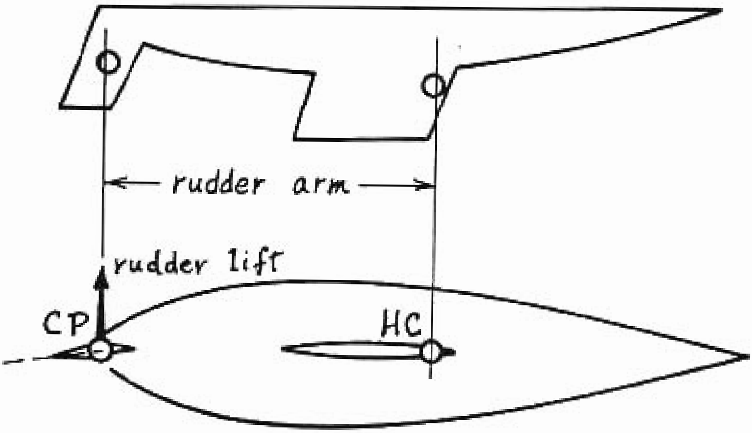
RUDDER VOLUME

The size required for adequate control can best be estimated by comparing the auxiliary rudder with the primary rudder.

First, how can we compare two rudders? If they were side by side, we could rightly expect that their turning effects would be in proportion to their areas. But if they have different longitudinal positions, as they usually will, their respective arms about some turning axis will have to be considered also. The point that these arms should be measured from is the hydrodynamic center (HC) discussed on p. 30. I mentioned there that no way is yet known for accurately calculating the HC, as is required for calculating balance of helm of the boat; but for present purposes we are interested in the distances from HC to the rudders, and a moderate error in finding HC will have little effect on the result. Therefore, a rough approximation will do (Figure 5-27). If there is a distinct fin keel



5-27. Estimating the hydrodynamic center: (a) leading edge of fin, (b) 4/5 draft point on deep keel, (c) 10 percent ahead of C.L.P.



5-28. Rudder arm — distance from hydrodynamic center to rudder center of pressure.

or centerboard, use the leading edge of that. If the keel is relatively long with a sloping leading edge, use the point where it reaches four-fifths of the maximum draft; or find the center of area of the lateral plane (by balancing a cardboard cut-out) and move 10 percent of the waterline length forward of that point. None of these "quick and dirty" methods will locate HC close enough for designing balance of helm, but any will be good enough to estimate the rudder effectiveness.

In producing the constant turning moment of weather helm, or the variable turning moments required for steering, the rudder produces lift centered at its center of pressure; the *rudder arm* is the distance of the rudder CP from the HC (Figure 5-28). The product of rudder area times rudder arm is our basic measure of rudder effectiveness. Since this is an area times a length and comes out cubic feet or cubic meters, we give it the name *rudder volume*. It is obviously not the physical volume of any part of the boat; but for most boats it is around 40 to 60 percent of the volume displaced by the hull. *Example:* 4 ft^2 (.37 m^2) rudder placed 12 ft (3.66 m) from the hydrodynamic center: rudder volume = 4 ft^2 × 12 ft = 48 ft^3 (1.35 m^3).

SIZE OF AUXILIARY RUDDER

The size of the primary rudder is set by the large steering forces required for going about and sudden maneuvers, tasks that the auxiliary rudder will not be asked to do. Probably half the capacity of the primary rudder is sufficient for most ordinary steering, and thus the proper-sized auxiliary rudder would have a volume (auxiliary rudder area times auxiliary rudder arm from HC) about *half* the rudder volume, if it is expected to do all the steering. But if the primary rudder can be fixed (by lashing the helm or other means) so that it supplies most of the weather helm, leaving the self-steering to make only small corrections, a considerably smaller auxiliary rudder can do the job and the performance of the system will be improved in several ways:

1. Fixing the primary rudder effectively lengthens the lateral plane, providing higher adverse yaw (p. 26).

2. The bearings throughout the self-steering gear will be under lighter loads, hence freer of friction.

3. By keeping the control away from stall, its ability to respond with large turning moments in either direction is assured.

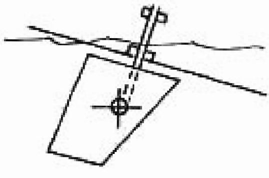
There is a practical lower limit on the size of the auxiliary rudder, though, even when the primary rudder will be fixed to supply all the weather helm. The trouble is that the amount of weather helm required varies with the strength of the wind. If the wind freshens somewhat, more weather helm is needed; the self-steering control has to supply it, and it can only do this by running off course (the boat tends to luff in this case). Or if the wind lightens, less weather helm is needed, and the boat will have to run farther off the wind, so the self-steering control is counteracting some of the weather helm of the primary rudder. The smaller the auxiliary rudder, the more sensitive is the system to wind strength, and the smaller the variations in wind strength that can be tolerated without stalling the control and requiring a resetting of the primary rudder. For the fluctuations in wind normally encountered at sea, where the windspeed in gusts is commonly twice the speed in lulls, it appears the minimum practical auxiliary rudder volume is a *quarter* of the normal primary rudder volume. A *third* to a *half* of the primary rudder volume would be a more conservative choice resulting in less sensitivity to wind strength. *Example:* If the primary rudder has 48 ft^3 (1.35 m^3) volume, and this is judged to be about right for the boat, the auxiliary rudder should have at least 1/4 × 48 = 12 ft^3 (.34 m^3). Suppose 1/3 × 48 = 16 ft^3 (.45 m^3) is chosen. This could be a 1 ft^2 (930 cm^2) rudder 16 ft (4.9 m) from the boat's hydrodynamic center, or a 1.6 ft^2 (1500 cm^2) rudder 10 ft (3.05 m) from HC, etc.

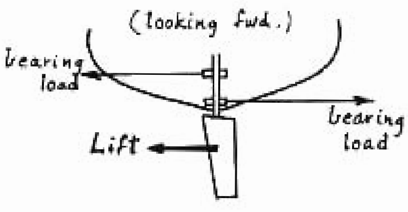
AUXILIARY RUDDER ARRANGEMENTS

The purpose in arranging the auxiliary rudder is to achieve a control that has better balance and/or lower friction than the primary rudder. A vertical axis windvane of moderate size can only drive a relatively small and well-balanced auxiliary rudder; but if a dual-axis vane can be used, only partial balance is required. Friction must be minimized in either case. Remember, for the sake of simplicity we are foregoing the power-multiplying servo devices; we must therefore resolve to go some lengths to make the auxiliary rudder *very* easy to work. The choice between the following arrangements is usually dictated by the type of stern and primary rudder:

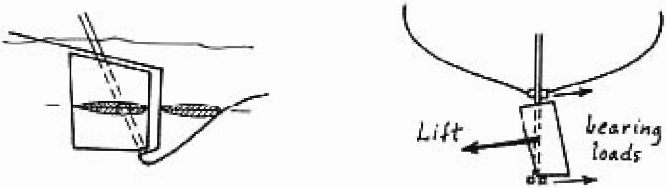
1. Spade rudder (Figure 5-29)

The big problem with a spade rudder is making it watertight without too much friction. Also the placement of the bearings is very disadvantageous from the standpoint of friction — lateral loads in the bearings might be several times the lift force if they are fairly close together. The shaft has to be very strong, something like one inch in diameter for each 20 feet of overall length of the boat, if bronze propeller shafting is used.





5-29. Spade rudder has heavy bending moments and bearing loads.



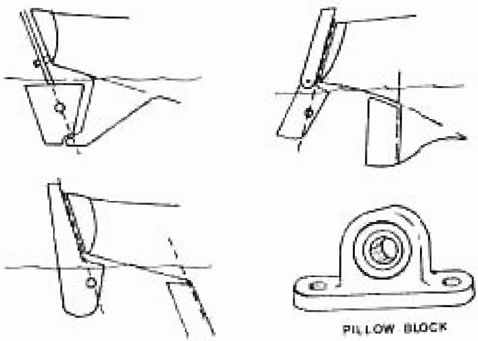
5-30. Lower bearing loads and better support with a skeg.

2. *Skeg rudder*

This can be horn balanced (Figure 5-25) or can be fully protected by a fixed skeg (Figure 5-30). In the latter case both the skeg and the rudder should have good streamlined shapes for low drag. The skeg has to be quite rigid if it is to be effective in supporting the lateral loads – if it bends under the load, the bearings go out of alignment.

3. *Outboard rudder* (Figure 5-31)

Here the bearings can be placed well apart, ball bearings (sealed ones) might be used, since they are above water most of the time, and there is ample space for a strong rudder stock to turn – so this has a good chance of working. Cast aluminum pillow blocks, bolted through the transom, make good gudgeons for this installation, and provide galvanic protection for ball bearings.



5-31. Outboard rudder arrangements.

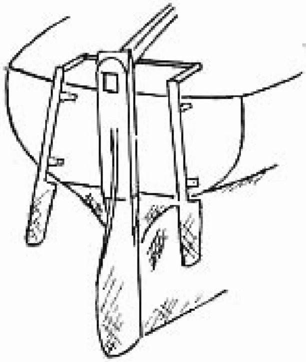
4. Twin outboard rudders
If the primary rudder is already hung outboard, it might be possible to divide the auxiliary rudder area in half and put one on either side of the primary rudder (Figure 5-32). These rudders would have to be placed at some distance from the centerline, to reduce interference with the primary rudder.

Any auxiliary rudder should have its own short tiller to keep it under control — centered when not in use, or immobilized if it has been damaged. Stops of some kind must be provided to prevent injury when going astern in irons, and these can best be arranged with a tiller. Snagging of mooring lines, fishing lines, lobster pot warps, kelp, etc. is a potential hazard with most of these designs. A generous slope on the leading edge and one or more tiny skegs just ahead of the rudder are fairly reliable preventive measures against snagging (Figure 5-33).

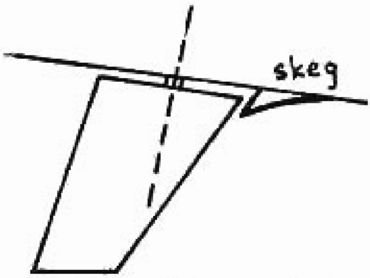
THE SERVO TAB

The tab offers a way to harness some of the power of the water flowing past and put this power to work turning either the primary or auxiliary rudder. ("Servo" is a generic term covering all types of devices that control or multiply mechanical power.) The tab-operated rudder is inevitably more complex than a rudder alone, but in return we get more steering power output, less vane power required, and less care required in the balance and bearings of the rudder. Sometimes, as in the case of a double-ended yacht with an outboard rudder, a tab is the only reasonable way to arrange a control for windvane operation.

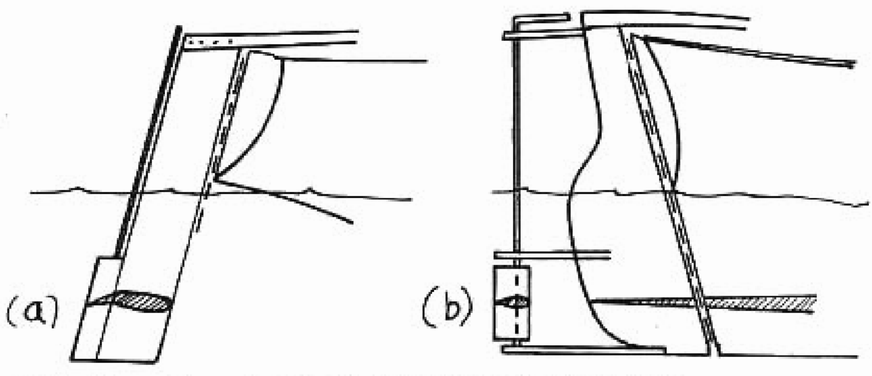
OPERATION
The tab is a flap or a separate small foil hinged on the primary or auxiliary rudder (Figure 5-34). It acts something like a little rudder that can steer the primary rudder, just as the primary rudder can steer the much bigger boat. When the tab is lined up with the rudder, it exerts no turning effect. When it is turned to an angle of attack in the flow coming off the rudder, though, it develops lift —



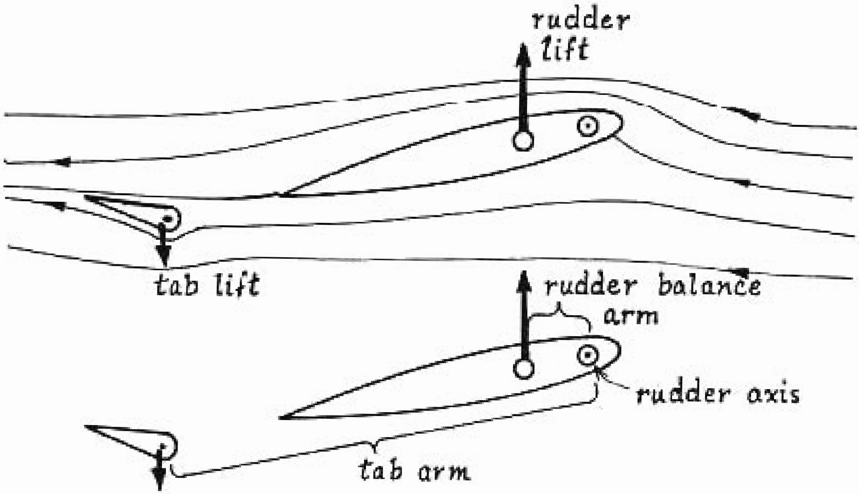
5-32. Twin outboard rudders.



5-33. Skeg to prevent picking up lines on spade rudder.



5-34. Two types of servo tab: (a) flap, (b) separate foil.



5-35. Equilibrium of tab and rudder moments about rudder axis.

force perpendicular to the flow direction. This lift, acting at a distance from the rudder axis, turns the rudder until an equilibrium is established (Figure 5-35). The moments about the rudder axis will be equal when

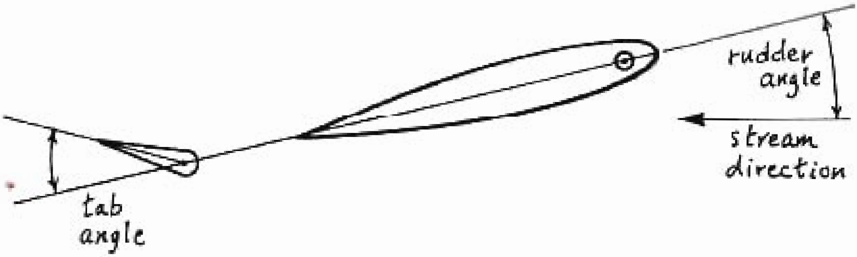
$$\text{tab lift} \times \text{tab arm} = \text{rudder lift} \times \text{rudder balance arm}$$

$$\text{or, rudder lift} = \text{tab lift} \times \frac{\text{tab arm}}{\text{rudder balance arm}}$$

Note the following points:

1. The rudder turns the *opposite* way from the tab.
2. The tab lift acts in the *opposite* direction from the rudder lift, so the effectiveness of the combination is *less* than that of the rudder by itself. In fact the rudder's turning effectiveness is reduced by the

$$\text{factor} \left\{ 1 - \frac{\text{rudder balance arm}}{\text{tab arm}} \right\}$$



5-36. Tab angle is measured from the plane of the rudder.

3. The multiplication of tab lift can be increased by moving the tab aft (to increase tab arm), *or* by improving the balance of the rudder (reducing rudder balance arm).
4. The tab operates in a flow that is strongly influenced by the rudder. The angle of attack of the tab, as far as its production of lift is concerned, is the angle relative to the plane of the rudder, rather than the free-stream direction. This will be called the *tab angle* (Figure 5-36).

TAB VOLUME

How big does the tab need to be to control a given rudder? How "big" is a tab, anyway? Its ability to produce torque about the rudder axis is proportional to both its area and its perpendicular distance from the rudder axis; this suggests measuring the size of the tab by *tab volume* = tab area × tab arm. This is closely analogous to the concept of rudder volume.

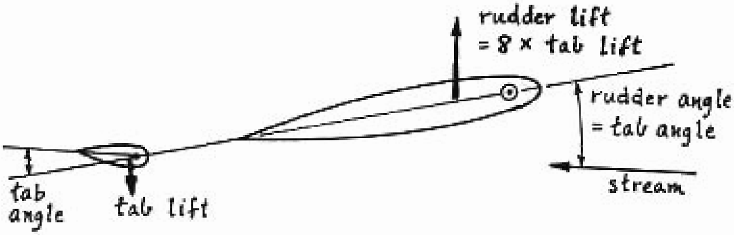
RELATION TO RUDDER SELF-VOLUME

As long as neither rudder nor tab is stalled, a close proportionality exists between tab angle and rudder angle: as the tab angle increases, the rudder angle increases in proportion. Eventually, one or the other will stall. If the tab is too small, it stalls before the rudder does, and so it fails to command full performance by the rudder and could be made larger. If the rudder is first to stall, then the tab is bigger than it needs to be, because further lift from the tab doesn't do a bit of good when the rudder has already stalled. The happy medium is when they both stall together. This will be the case if (approximately)

tab volume = rudder area × rudder balance arm.

The product on the right, rudder area x balance arm, also is a volume, and I hope you will not object to my naming it the *rudder self-volume*. The trouble is that there are two axes involved with the rudder. The rudder turns on its own axis; this rotation determines how much lift it makes, and the balance arm (rudder CP to rudder axis) determines how hard it is to turn. But the lift is utilized in turning the boat, and for this the rudder arm (rudder CP to the boat axis, through the hydrodynamic center) is the relevant length. Rudder *self-volume* is a measure of the size of the rudder, from the viewpoint of the *effort required to turn it* (aside from friction), just as rudder *volume* is the measure of its size from the viewpoint of its *effectiveness in turning the boat*.

Tab volume roughly equal to the rudder self-volume is required if the tab is to provide maximum control. For ordinary steering, as noted before (p. 109), about half of the full rudder power is usually sufficient, so a tab volume of 60 to 65 percent of the rudder self-volume (which allows for the reduced effectiveness of the rudder due to the opposing lift of the tab) might suffice for self-steering, though it would be limited in its ability to cope with strong weather helm conditions. I think it is worthwhile to shoot for 100 percent of rudder self-volume for any tab.



5-37. Example of tab with volume equal to rudder self-volume.

Estimating the rudder self-volume calls for a pretty close guess at the rudder's center of pressure, and this is hard to figure with any confidence. So once you have built an experimental tab, a check is in order to see if the desired relationship between the tab volume and rudder self-volume was realized. The main question is whether large tab angles (tab almost stalled) produce large rudder angles (rudder almost stalled). Try steering with the tab for awhile; see if it has enough power. If the tab and rudder have somewhat similar aspect ratios, then

$$\frac{\text{rudder angle}}{\text{tab angle}} = \frac{\text{tab volume}}{\text{rudder self-volume}}$$

so the efficiency of the tab can be judged by observing the tab and rudder angles.

Examples

A tab is needed to control a rudder that has 4 ft^2 (0,37 m^2) area, with its center of pressure estimated at 4 in. (10,3 cm) behind its axis.

This rudder has a self-volume of 4 $ft^2 \times .33$ ft = 1.33 ft^3 (0,038 m^3). A full-power tab should then have tab volume of 1.33 ft^3 (0,038 m^3). For example, a tab with .5 ft^2 (470 cm^2) area located 2.66 ft. (81 cm) from the rudder axis would do. The tab lift in this case is only .33 ft/2.66 ft = ⅛ of the rudder lift, so only 12½ percent of the rudder effectiveness is lost. The rudder angle will be approximately equal to the tab angle in steady conditions (Figure 5-37).

Suppose a smaller tab, .33 ft^2 (320 cm^2), were used only 2.0 ft (61 cm) from the rudder axis. This would give a tab volume of .33 $ft^2 \times$ 2.0 ft. = .66 ft^3 (0,019 m^3), which is 50 percent of the rudder self-volume. Now the tab lift is .33 ft/2.0 ft = 1/6 of the rudder lift, so 17 percent of the rudder effectiveness is lost. The rudder angle will be about .67 ft^3/1.33 ft^3 = ½ of the tab angle. When the tab starts to stall at 12° angle of attack, the rudder will only be at about 6° (Figure 5-38).

5-38. Example of tab with volume only half the rudder self-volume.

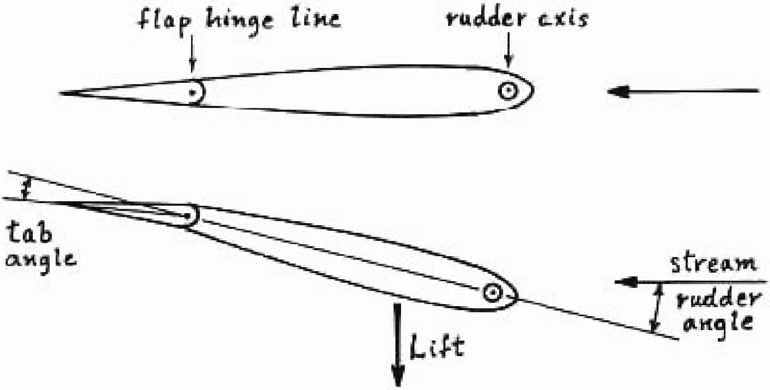
THE PLAIN FLAP AS A SERVO TAB

So far all the pictures I have drawn show the servo tab as a separate small airfoil. In aerodynamics, a "plain flap" is formed by putting a hinge in an otherwise streamlined airfoil, and this plain flap can be used as a servo tab (Figure 5-39). This is the way airplane flaps and tabs are almost always made, because the drag is much lower than with a separate airfoil. The relation of tab volume to rudder self-volume is just the same as before, but in this case the rudder self-volume should be figured *including* the tab (at zero tab angle) in the rudder area and center of pressure.

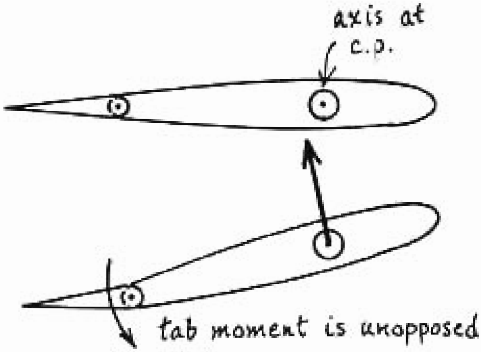
TAB OVERPOWER

Notice that the better balanced the rudder, the less tab volume and tab angle are required to turn the rudder to any given rudder angle. When the rudder is completely balanced, even a very small tab can completely overpower it. With the slightest tab deflection, the rudder starts to turn; but because the rudder is balanced there's no reaction and it keeps going until it stalls (Figure 5-40). A small tab deflection the other way will send the rudder hard over to the other side. Such a powerful control can easily cause oversteering unless the linkage is carefully designed with rudder feedback, as will be detailed in Chapter 7.

This is just a warning of potential trouble, not an argument against balancing the rudder. A *nearly* balanced rudder can be operated by a very small tab, making a powerful, sensitive control that contributes markedly to adverse yaw of the hull. The small size of the tab makes it lighter loaded and less susceptible to damage and in every respect easier to build than the tab for an unbalanced rudder.



5-39. Plain flap used as a servo tab.



5-40. Balanced rudder is overpowered by tab.

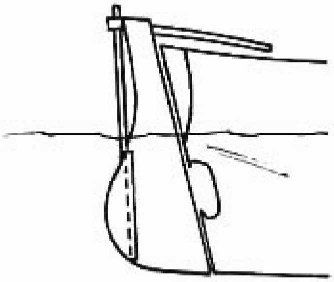
TAB BALANCE

The tab turns on its own axis, and it can be partly or completely balanced by locating its center of pressure near or on this axis. The reason for doing this is to reduce further the torque required to operate the control. However, the tab is generally so small that its balance is not at all critical. As we shall see later, some amount of imbalance can be useful as a means of reducing the sensitivity of the system to varying wind strength. An unbalanced tab has the further advantage of lining up automatically with the rudder and not affecting the steering if it is disconnected and simply allowed to "float."

Tab self-volume is defined similarly to rudder self-volume — just the tab area times the tab balance arm.

SERVO TAB ARRANGEMENTS

A servo tab can be used on the primary rudder or on an auxiliary rudder. In either case, the basic problems are (1) adequately supporting the tab with low enough bearing friction to keep it easy to turn; and (2) transmitting movement to the tab from above the water. The solutions will depend mostly on the type of stern and primary rudder on the boat.



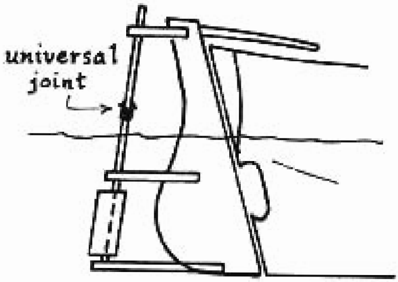
5-41(a). Tab made by hinging part of the primary rudder.

1. A slice off the primary rudder (Figure 5-41a)

This is a simple and effective way to make a plain flap — the only cost is for gudgeons (standard rudder fittings can usually be used) and a piece of shafting. Usually about 20 to 25 percent of the rudder area is required for a tab volume about equal to the rudder self-volume. This arrangement can be made very strong, but because the tab is relatively large, bearing friction and balance are likely to demand a powerful windvane.

2. Separate tab hung on rudder (Figure 5-41b)

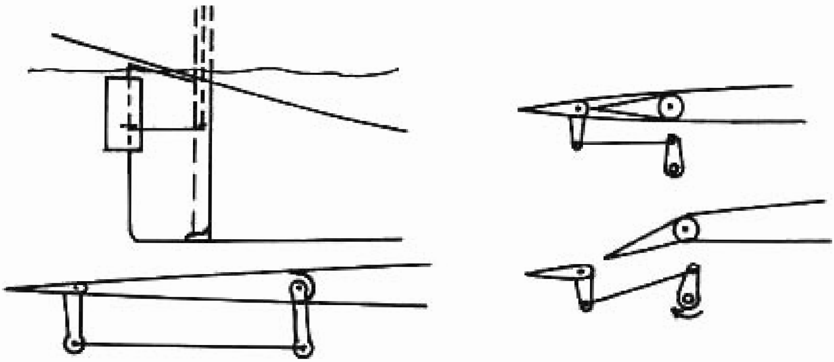
The tab can be smaller and is easy to balance as it is moved back from the rudder trailing edge. The struts and shaft have to be made extremely strong, and careful attention should be given to streamlining them, or the drag added by all the underwater paraphernalia is likely to be noticeable. A universal joint in the shaft is advisable so the bearings won't bind when the struts bend under load.



5-41(b). Tab supported by struts.

3. Tab with an inboard rudder

Here, a flap or separate tab is possible, but transmitting motion to it becomes complicated (Figure 5-42). This has been done using a small shaft turning inside a hollow rudder shaft, but obviously the machining becomes very expensive. A cheaper solution would be to lead the tab shaft out through its own through-hull fitting.



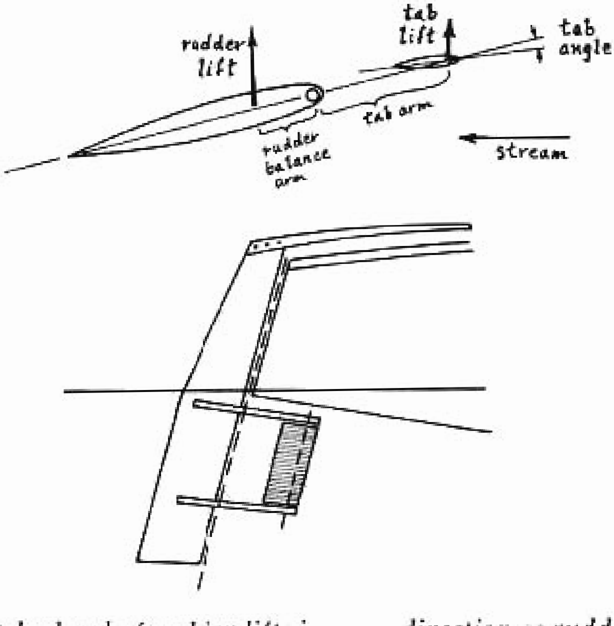
5-42. Inboard rudder with two possible ways of transmitting tab motion.

4. Tab ahead of rudder

There's no law that says a tab has to go *behind* the rudder. If there is room to hang it forward, there are some big advantages. In this position the tab lifts the same direction as the rudder and so it *adds* to the rudder lift instead of reducing it (Figure 5-43). Ahead of the rudder, the tab operates in the free stream and its angle of attack should be measured from the free stream direction, not the rudder plane. This requires some differences in the linkage. Under the counter, the tab is better protected from some occupational hazards but is more exposed to others.

5. Twin tabs

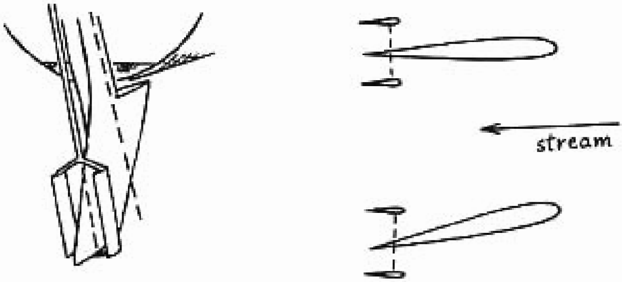
Instead of a single tab on the centerline of the rudder, a pair of smaller tabs that turn together can be used (Figure 5-44). With this arrangement nothing projects beyond the rudder, and attachment to the rudder can be relatively simple and strong.



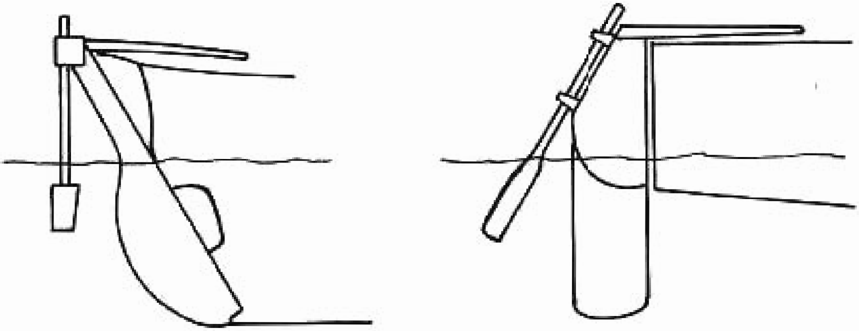
5-43. Tab ahead of rudder lifts in same direction as rudder.

6. Tab cantilevered from the rudder head (Figure 5-45)
The simplest tab arrangement has no bearings underwater — in fact, there is only one part underwater and that is the tab. Naturally, the structural requirements on the cantilever shaft are severe. Also, the placement of the bearings indicates they have to carry very high side loads; but as they are well out of water, ball or roller bearings can be used, so friction can be kept very low.

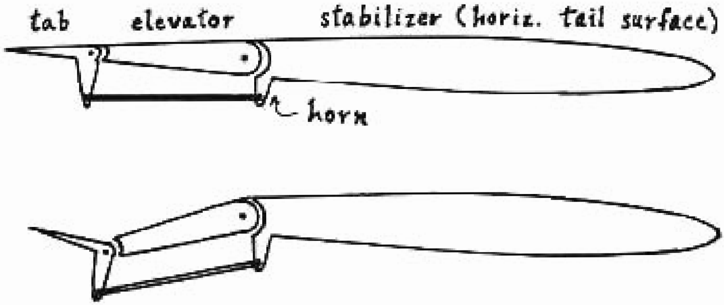
USING TAB TO BALANCE RUDDER
Before closing the subject of servo tabs, I want to point out a way of using them that does not appear to have been exploited for self-steering. Consider the use of a "balancing tab" in aircraft (Figure



5-44. Twin tabs turning on one shaft.



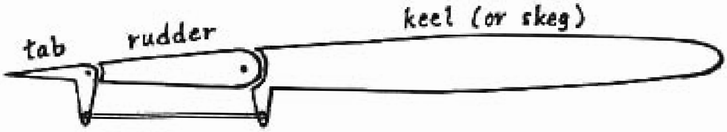
5-45. Cantilevered servo tab arrangements.



5-46. Action of "balancing tab" on airplane elevator.

5-46). The tab is not connected to anything except to a rigid horn on the stabilizer. The elevator is connected to the control stick in the usual fashion. When the elevator is turned the tab automatically turns the opposite way so the tab lift assists in turning the elevator. On the stick, it can feel like the elevator is perfectly balanced. The analog of this is Figure 5-47. By arranging some simple mechanical linkage to the tab so that it always turns the opposite way from the rudder, partial or complete rudder balance can be provided. Complete balance over the widest range of rudder angles requires a tab volume approximately equal to the rudder self-volume and a linkage making tab angle equal to rudder angle. With the primary rudder effectively balanced, the steering could be done by a dual-axis vane operating the primary rudder directly. The result is that the tab works by itself down in the water; the windvane connects directly to the tiller. By eliminating any need for the windvane movement to be transmitted down a separate shaft to the tab, it seems we can make a major reduction in the mechanical complexity of servo tab systems.

Before adding this to an existing rudder, remember that the tab lifts in the opposite direction from the rudder (Figure 5-35), and so it counteracts a substantial amount (typically 10 percent to 25 percent) of the rudder's turning moment. You would end up with a rudder that feels nearly balanced but is noticeably less effective in putting the boat about, for example. To apply this idea practically,



5-47. Tab automatically balances rudder.

you first may have to add 25 percent or so to the area of the primary rudder.

THE SERVO PENDULUM

In 1964, Col. H. G. Hasler, whose name is intimately connected with the whole history of self-steering in full-size sailboats, developed a new and powerful type of control, quite distinct from the auxiliary rudders and trim tabs that had been used up to that time. The "pendulum" control operating the primary rudder has since been applied successfully in many different yachts. Though it is a considerably more complex and sophisticated mechanism than the other controls we have discussed, its ample power, portability, and suitability for use with inboard rudders and/or wheel steering have made it one of the most popular controls. It is the basis of several of the manufactured vane gears.

OPERATION

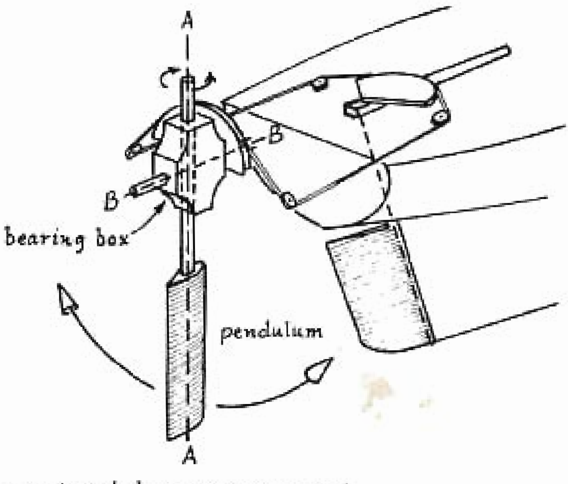
Suppose that, in a moving boat, you held an oar over the stern, projecting vertically down into the water. If the blade is aligned with the flow past the boat there is no force on it but a slight drag. Such an oar could in itself be used as an auxiliary rudder. But it is easy to see that if you turned it a little so it was developing lift to one side, it would also develop a powerful moment tending to lift the blade up toward the surface on that side.

The oar is the "pendulum" of the servo pendulum control. The powerful moments that result from small rotations about the long axis of the blade are transmitted to the primary rudder, usually through quadrants and running lines, so they can exert a strong steering effect. "Servo" just implies a device that controls or multiplies power. The working of the servo pendulum is really not all that different from the servo tab, which also develops a large moment to turn the rudder when *it* is turned to a small angle. It's just that the tab is directly connected to the rudder blade, while the pendulum is connected to the rudder in a very roundabout way that multiplies its leverage.

Mechanically, the arrangement is something like that in Figure 5-48. The pendulum can rotate about its long axis A-A — this is the input signal. It can also rotate about the fore-and-aft axis B-B — the moment it develops about this axis is its output, transmitted by quadrants and cables to the tiller.

SIZE OF PENDULUM

The area of the pendulum hydrofoil required to operate a rudder clearly depends on the length of the pendulum arm (axis B-B to pendulum center of pressure), on the rudder size, and also on the *mechanical advantage* of the quadrant-cable system or other linkage coupling the pendulum to the rudder (the ratio of angle of rotation about B-B to angle of rotation of the rudder, also the ratio of the

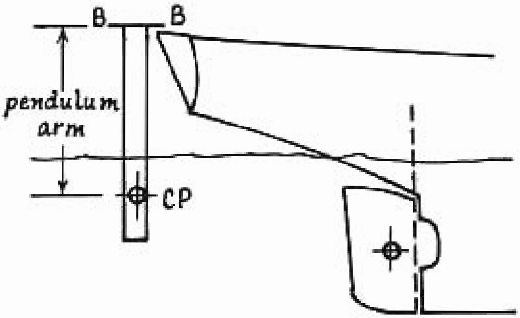


5-48. Basic servo pendulum arrangement.

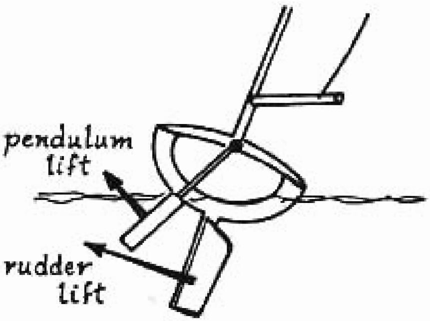
radii of the rudder and pendulum quadrants). It is clear that the rudder self-volume (p. 116) is what counts, and that this will be related to the *pendulum volume* defined as:

pendulum area × pendulum arm (Figure 5-49).

First consider how to choose the mechanical advantage of the quadrants. The higher the mechanical advantage, the smaller the pendulum can be. But there is a limitation set by the allowable rotation about axis B-B. Note that when the rudder turns to put on weather helm, the pendulum has to rotate up toward the water surface, always on the windward side (Figure 5-50). This rotation



5-49. Effectiveness is proportional to pendulum arm.



5-50. Pendulum rotates toward the surface, losing effectiveness.

is added to the angle of heel. Here it begins to emerge from the water; its lift is greatly reduced just by being close to the surface; and worse, it can *ventilate* or suck a bubble of air down along its upper (suction) side, so its lift falls drastically. The greater the mechanical advantage of the quadrants, the lower the rudder angle at which all this begins, so the more limited the system will be in supplying weather helm. A mechanical advantage of 1 is about the upper limit for full rudder control in typical keelboats. For a boat that has particularly good balance, a mechanical advantage of 2 could be tried. For a multihull that heels little and has an easy helm, mechanical advantage up to 4 might well be satisfactory.

Once the mechanical advantage has been decided by such considerations, the minimum-sized pendulum is specified by:

pendulum volume = rudder self-volume/mechanical advantage.

This is the pendulum that has the power — neglecting friction in bearings, cable, quadrants, and rudder stuffing box — to drive the rudder up to stall without stalling itself. Perhaps 30 to 50 percent should be added to the pendulum volume to allow for friction in the average installation. It is clear that a long, narrow (high aspect ratio) pendulum is more powerful than a short one of similar area, and that raising the axis B-B higher above water is an easy way to gain pendulum volume.

Example: Suppose the rudder has an area of 6 ft^2 (0,56 m^2) and is unbalanced, with a balance arm of 0.6 ft (18 cm). This gives a self-volume of 3.6 ft^3 (0,102 m^3). Suppose the boat is relatively stiff and well-balanced so a mechanical advantage of 1.5 will be tried — this could be with a 12 in. (30 cm) radius quadrant on the pendulum axis B-B and an 18 in. (46 cm) radius for the rudder quadrant. Then the minimum pendulum volume required is 3.6 ft^3/1.5 = 2.4 ft^3 (0,068 m^3). Adding 40 percent for friction would give 3.4 ft^3 (0,096 m^3) for the pendulum volume. For instance, the pendulum could be 5 ft (153 cm) long with 2 ft (61 cm) below water, with a constant chord of 5 in. (13 cm):

Area = 2 ft × .42 ft = .84 ft^2
Volume = .84 ft^2 × 4.0 ft (arm) = 3.4 ft^3.

Or a 6-foot-long (183 cm) pendulum pivoted at the same height would only need a 3-inch (76 mm) chord:

Area = 3 ft × .25 ft = .75 ft^2
Volume = .75 ft^2 × 4.5 ft (arm) = 3.4 ft^3.

PENDULUM OVERPOWER

If the rudder is nearly balanced, the required pendulum volume is very small, and too big a pendulum will overpower the rudder and lead to over-strong, erratic steering. The adverse effects can be controlled by rudder feedback, however, and as always the nearly balanced primary rudder simplifies all aspects of providing an adequate, easily operated control.

PENDULUM BALANCE

For all the same reasons as given under "tab balance" (p. 119), precise location of the pendulum center of pressure near or on the long axis of rotation A-A is not necessary. The same advantages mentioned there hold for a moderately unbalanced pendulum — reduced sensitivity to wind strength, and non-interference with steering when the control is allowed to float.

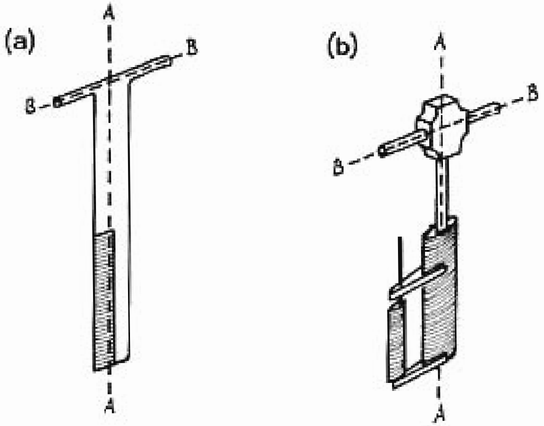
In considering the size of vane needed to operate the pendulum, we will need the concept of "pendulum self-volume," which is just the pendulum blade area times the distance of the pendulum center of pressure from the axis A-A.

MECHANICAL ARRANGEMENTS

Most pendulum gears are hung on a bracket or boomkin overhanging the stern. This puts them in a rather vulnerable position for all sorts of accidents, and out of reach for repairs and adjustments. Any part of the equipment that can be brought inboard or under cover would be an improvement. As the mechanisms become more and more intricate, a prodigious engineering effort is required to achieve long-term mechanical reliability.

1. All-moving pendulum

This is the type illustrated in Figure 5-48, where the pendulum is



5-51. (a) Pendulum with flap, (b) pendulum with tab.

one piece and rotates in two bearings in the bearing box. Because of high bearing loads, ball or roller bearings are required on the long cantilevered axis A-A.

2. Flapped pendulum

The bearing box can be simplified if the pendulum takes the form of a skeg, fixed to the axis B-B, with a movable flap that turns on the axis A-A (Figure 5-51a). The bearings for the flap are much lighter loaded; but they are also under water, and so much harder to keep lubricated and safe from corrosion. A flap that is 50 percent of the pendulum chord seems practical. If this is used, the pendulum volume (based on the area including the flap) should be increased 33 percent over the volume for an all-moving pendulum, because turning the flap produces only 75 percent as much lift as turning the whole foil.

3. Pendulum with tab

Although it should not be necessary if good bearings are used in the bearing box, it is possible to reduce the torque required to actuate the pendulum to almost nothing by driving the pendulum with a tab (Figure 5-51b).

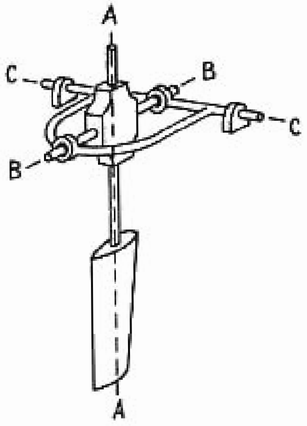
4. Kick-up protection

The long, narrow pendulum blades that are required for efficiency are prone to snagging any line that you sail over; also they are rather precariously cantilevered and subject to tremendous bending loads in normal use as well as in heavy seas, in irons, etc. An answer to the first hazard is to allow for the pendulum to kick up like a dinghy rudder and ride over the obstruction. This can be done by supportings the bearings for the axis B-B on a frame that can pivot about the transverse axis C-C (Figure 5-52). Gravity or shock cord holds the unit in its normal position, but it can kick up over an obstruction, or kick up in case of a temporary overload in the drag direction. Care has to be taken that the rest of the mechanism disconnects in a harmless way if a kick-up occurs under any possible operating condition.

As far as general overloads are concerned, the simplest approach is to make sure that the pendulum blade is the weak link — that it will break before any other part of the mechanism — and carry some spares, with provision for easy replacement.

CONCLUSIONS

The basic types of control that have been used are few, but within each type many variations are possible. I would tend always to look



5-52. Kick-up pendulum control.

for the mechanically simplest arrangement that can be fitted in with the existing steering gear and stern configuration, because this will require the least work. First, investigate the possibility of using the primary rudder by itself. Second, consider how an auxiliary rudder could be fitted. Third, look into using a servo tab on the primary or auxiliary rudder. If none of these proves to be a possible solution, finally consider the servo pendulum.

Guidelines have been given for designing the size of various control components, but I emphasize again that these are based on a series of approximations. The only way to be sure the proposed control has adequate steering power and low enough actuating torques is to build it and go out sailing and steer with it. This can all be done before very much thought is given to the windvane and linkage.

6 WINDVANES

The windvane is fundamentally an angle-of-attack detector, required to produce a signal in the form of force or torque when it finds itself at anything but zero angle of attack in the apparent wind. Its effectiveness will be judged by how much torque or rotation it makes with a given change of angle of attack. Other desirable properties are:

1. low friction, for sensitivity in light winds
2. light weight, for quick response to wind shifts
3. low drag, to avoid impairing windward performance
4. a readily adjustable clutch to allow the vane to be set at any desired apparent wind angle.

VANE VOLUME

Almost all vanes are simple airfoils, with the major classification into types being made according to whether one or two axes of rotation are involved in the vane orientation relative to the boat. In any case the vane produces lift proportional to its small angle of attack, also proportional to the apparent wind's dynamic pressure and to the vane area, with some adjustment for aspect ratio (p. 98) and profile. The torque developed in the vane output shaft is equal to the lift times the vane balance arm — the perpendicular distance from the vane center of pressure to the output axis (Figure 6-1).

So, to compare the torque-producing ability of two windvanes at the same angle of attack in the same wind, the geometrical factors that are left — besides aspect ratio — are just vane area times vane balance arm. Since this product is another volume, call it the *vane volume*. As for the aspect ratio, just remember it has an effect. Most vanes have aspect ratios between 2 and 4, and within this range aspect ratio doesn't make a whole lot of difference. If you are forced to consider using much smaller aspect ratios, make allowance for the lower slope of the lift versus the angle of attack curve.

PROFILES

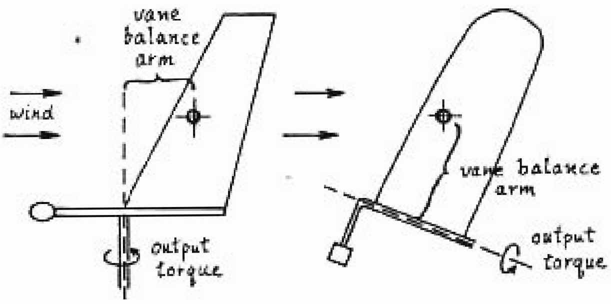
Since vanes are just airfoils, designed to produce lift at an angle of attack, a simple streamlined airfoil will do the job with the minimum amount of drag. But planforms are usually restricted by the presence of lifelines, backstays, sheets, mizzen boom, etc., so that in some cases it is worth accepting a drag penalty for higher sensitivity, or for ease of construction.

1. Thin flat-plate vanes

These are popular because they are so easy to make out of plywood. They stall at a very low angle of attack and so they develop considerably less lift — maybe half as much as a streamlined foil at the same angle of attack. But this is partially compensated for by the center of pressure being back at about 40 percent chord.

2. Wedge sections (Figure 6-2a)

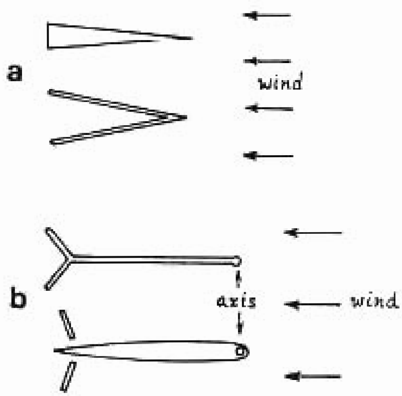
These are frequently seen in weathercock service, though I have not been able to find any aerodynamic data showing any superiority in lift coefficient, and drag coefficients are much higher than for streamlined airfoils. Evidently the center of pressure is farther aft.



6-1. Lift centered at a distance from the axis makes output torque.

3. Flaps

In the 1970 A.Y.R.S. *Self-Steering*, Dr. S. L. Seaton reported finding great increases in vane effectiveness when trailing edge flair, or a pair of fixed split flaps, was added to flat plate and airfoil vanes (Figure 6-2b). At the cost of higher drag, these profiles offer substantial increases in vane power. But note that Dr. Seaton compares them with a flat plate of aspect ratio 1.2 pivoted somewhat *behind* the leading edge, which is a very unfair comparison. I don't think a great advantage will be found if the leading edges are moved back from the axis a reasonable distance.



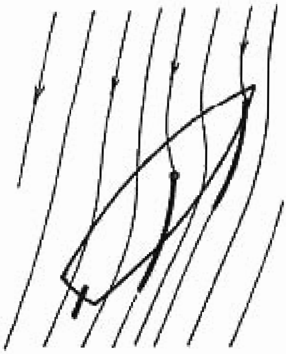
6-2. (a) Wedge section, (b) symmetrical split flaps.

VANE LOCATION

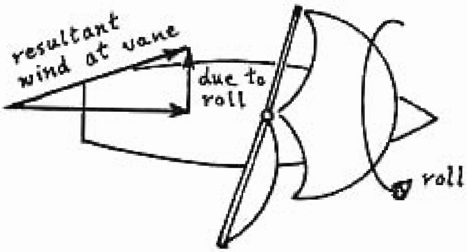
Depending on the circumstances of the installation there is more or less freedom in locating the vane. Aside from the mechanical necessity of connecting it through a linkage to the control, there are at least three things to consider:

1. Clear air

The vane can't function on any point of sail where its wind is blocked by the hull or sails. A low vane close to the stern might turn out to be in the dead air behind the hull or deck house or someone sitting in the cockpit when hard on the wind.



6-3. *Interference of sails with vane angle of attack.*



6-4. *A high vane is adversely affected by rolling.*

Even where the vane has clear air, interference from sails is likely to reduce its sensitivity considerably when close-hauled. The sails, in producing their lift, deflect the flow of air past them so the air leaves the sails tangent to the trailing edges. This modifies the wind at the vane, and means the wind that the vane sees has a tendency to remain parallel to the sails when the yacht wanders off course (Figure 6-3). If the vane doesn't see a change in its wind, naturally it won't signal a change in course. Fortunately this is the course where the yacht's natural stability is greatest (p. 19), so vane sensitivity is needed least.

It is possible for a vane on the lee quarter to be right *in* the strong trailing vortex that streams off the main or mizzen boom;

here it would be strongly interfered with and might behave very strangely and erratically indeed.

All these forms of interference diminish rapidly as sheets are eased on a reach.

2. Height

Freedom from interference and the apparent wind strength both improve with height above deck. This has led to the suggestion of putting the vane at a mast-head, assuming a practical linkage could be arranged, which doesn't appear impossible. But there is one very adverse effect of height which dictates against such high placement; this is the shifts in the apparent wind due to rolling.

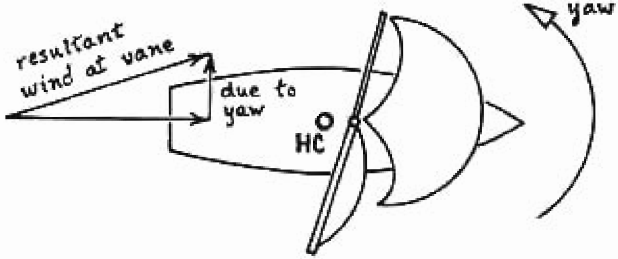
Suppose the yacht is running right downwind and rolling; let us catch her at the instant the mast is vertical during a roll to starboard (Figure 6-4). The apparent wind at the vane includes a component due to the rolling — directly proportional to the height of the vane — and at this instant this makes the vane think the wind is on the starboard quarter; so it orders a turn to port. A roll to port would similarly cause a turn to starboard. This is exactly what we *don't* want. Here is almost our only opportunity, short of gyroscopes, to have a system that could *anticipate* steering requirements by sensing the roll and acting before the thrust-resistance couple actually puts the boat off course. But it works the wrong way, and so it makes the rolling and yawing worse instead of better. This adverse behavior is present whenever the apparent wind is abaft the beam, and is at its worst when running right before the wind.

So put the vane no higher than necessary to get it in clear air and above heavy sprays. (How high does spray go? Good question. I'll leave that to your imagination.)

3. Fore-and-aft location

A somewhat similar line of reasoning reveals an adverse effect of placing the vane too far aft. Suppose the same yacht is running the same way, and catch her at a moment when she is on course and upright but yawing to port (Figure 6-5). The vane sees an apparent wind that includes a component due to the rate of yaw (proportional to the distance between vane and hydrodynamic center); at the moment, this makes it appear that the wind is on the starboard quarter, so the vane signals a turn to port. Again, this is exactly the wrong direction, and it contains the seeds of instability.

This particular instability is one that yaw resistance can overcome, and which can also be counteracted by a feedback linkage; but make the job no harder than it needs to be; put the vane no farther aft than necessary.



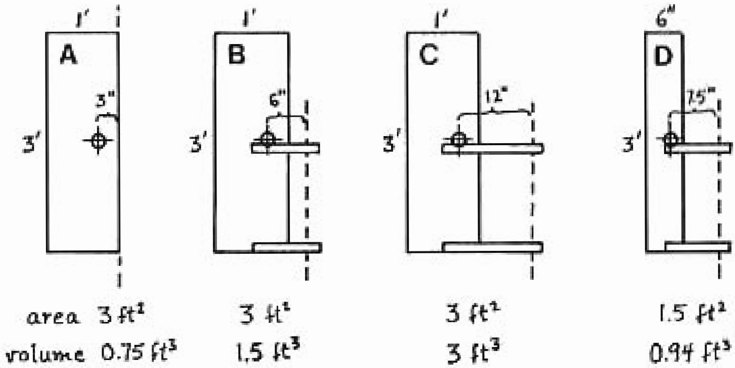
6-5. A vane placed far aft is adversely affected by yawing.

MASS BALANCE

Most windvanes have a counterweight arranged so the weights exactly balance out relative to the vane's output shaft; that is, the center of gravity of the vane-plus-counterweight falls right on the axis. This eliminates any tendency for the vane to be turned by gravity when the yacht heels; also it largely eliminates movements of the vane due to accelerations of rolling and pitching. Though there are some possible advantages of moderate mass imbalance in the control and linkage, it appears that good mass balance of the *vane* is highly desirable to retain sensitivity in light winds.

SINGLE AXIS VANES

The simplest vane has only a single axis of rotation relative to the boat, used for both course-setting and output torque. This was used in the original installations in *Arielle, Buttercup,* and *Mick the Miller* (Figure 4-1). It has often been called the "vertical-axis wind-



6-6. Moving the vane leading edge away from the axis is always advantageous.

vane," though there is no need for the axis to be vertical. The newer dual-axis vanes have some advantages, as we shall see, but the single axis has some of its own and it has certainly not been put out of business by the competition. Its mechanical simplicity makes it easier and cheaper to construct. A major advantage is that it naturally weathercocks and can be completely ignored when disconnected and not in use. The natural weathercocking also makes the single-axis vane less susceptible to spray or water damage in heavy weather, especially if it is provided with a shear pin or other overload protection. While it takes more area than a dual-axis vane to provide the same power, still it doesn't take a very big single-axis vane to operate a well-balanced auxiliary rudder or an efficient tab or pendulum control.

PLANFORMS

As explained previously, vanes can be compared in their ability to produce torque from a given wind strength and angle of attack by the quantity: vane volume = vane area X vane balance arm.

Area is essential, but distance from the axis means just as much. Since the center of pressure is only 25 percent of chord from the leading edge (less for low aspect ratios), it becomes apparent that the secret is to keep the leading edge of the airfoil back from the axis (Figure 6-6). Suppose a foil with a 1-ft chord (30,5 cm) by

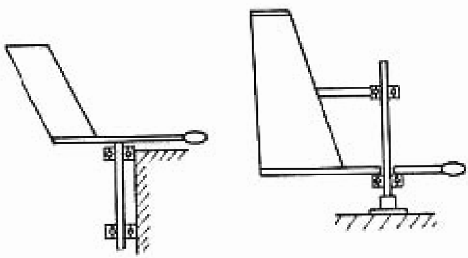
3-ft span (91,5 cm) is pivoted at its leading edge (A): the volume is only 3 ft^2 × 0.25 ft = 0.75 ft^3 (0,021 m^3). If the same foil were moved 3 in. (76 mm) back from the axis (B), its volume would be doubled: 3 ft^2 × 0.5 ft = 1.5 ft^3 (0,043m^3). Moving it 6 in. (152 mm) farther back would double the volume again (C): 3 ft^3 × 1 ft = 3 ft^3 (0,085 m^3). If swinging room for the vane is the problem, note that a foil with 6-inch (152 mm) chord by 3-ft. (91,5 cm) span (D) will swing in the same space as the original 1′ x 3′ vane (A), and has 50 percent less area and 25 percent more volume. It *never* pays to have the vane axis along the leading edge; even when swinging room is extremely limited it is always better to use a smaller area spaced away from the axis.

MECHANICAL ARRANGEMENTS

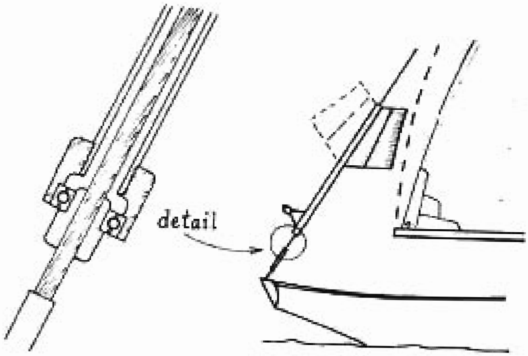
1. Cantilevered

All the single-axis vane arrangements I have seen support the vane on a single shaft which is cantilevered from the boat (Figure 6-7). This shaft is subject to bending, and evidently has to be very strong—Hal and Margaret Roth in *Whisper* used a one-inch stainless steel shaft, and this was broken off in a Gulf of Alaska gale, leaving them to steer most of the last 600 miles of their return crossing of the Pacific by hand. (Roth, *Two on a Big Ocean*, Macmillan, New York, 1972).

As usual with cantilevered shafts, a wide spacing of the bearings is desirable to reduce friction. One of the bearings has to be a thrust bearing to carry the weight of the vane and counterbalance.



6-7. Cantilevered single-axis vanes.



6-8. Single-axis vane pivoted on backstay.

The rudder stock or the tab shaft often offers an attractive base for cantilevering a vane, but the temptation should be resisted. As will be explained in more detail in Chapter 7, this leads to a strong tendency toward oscillation.

2. *Pivoted on backstay*

It seems that the standing backstay on a sloop or cutter is one of the main interferences with swinging room for a vane. In some cases the problem could be neatly solved by pivoting the vane on the backstay itself (Figure 6-8). The taut stay provides excellent structural support and protection for the vane (compared with cantilevering) and the spacing of bearings is advantageous. I envisage the vane attached to a tube of sufficient inside diameter to pass the swaged fitting on the end of the wire. A ball bearing (also big enough to pass the swaged fitting) could be used as a thrust bearing at the bottom where it is accessible for lubrication; a plastic bearing might be sufficient at the top.

The main interference with this scheme is the possibility of the main boom lifting in a jibe and hitting the vane. In many boats the boom can foul the backstay itself, a very dangerous situation; and most designs would not provide enough clearance for an adequate vane without relocating the backstay or shortening the boom. The flexing of the backstay wire at the upper bearing might pose a metal fatigue hazard, depending on the size and weight of the vane, wire size, etc. This danger can be positively avoided in any case by making up the backstay in two lengths, connected by a rigging toggle just above the position of the upper bearing.

RAKE OF VANE AXIS

Note that the single axis does *not* have to be vertical, and that a forward rake of the axis, as provided by the backstay, has an advantage in response to heeling. When the yacht heels in a freshened breeze, the angle of attack of the forward-raked vane changes as if the wind had drawn ahead, and so the vane signals the control to bear away. This is the correct signal to provide more weather helm as required by the freshened breeze. (The geometrical situation is hard to picture; playing with a model helps here.) Whether the increased weather helm is the right amount to keep her exactly on course is a complicated question. At least this effect is working in the right direction, counteracting the ever-present tendency to luff when the breeze freshens. An aft-raking vane axis would work in the opposite (adverse) sense, promoting the natural luffing tendency and increasing the sensitivity of the system to changes in wind strength.

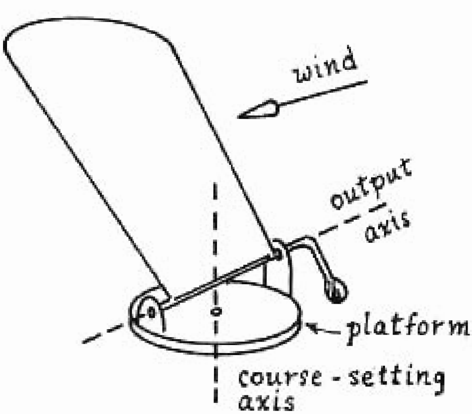
DISADVANTAGE OF SINGLE-AXIS VANES

The big limitation on single-axis vanes is that they are very restricted in the amount of output shaft *rotation* they can produce. For producing torque they are fine — vane volume is what counts, and there is no inherent advantage in either the vertical or horizontal axis in achieving vane volume. But the trouble is that the torque rapidly diminishes as the vane rotates about its single axis in response to a wind shift or course change. Suppose there is a wind shift of 10 degrees. This angle of attack on the vane produces a handsome torque and turns the control. But by the time the vane output shaft has been turned only five degrees, before the boat has had time to turn at all, the vane angle of attack is down to five degrees and so the vane torque is reduced by half. The most the vane shaft could possibly turn is 10 degrees, and this would leave the vane at a zero-degree angle of attack, producing no torque at all. Another way to look at the problem: the vane turning in response to a windshift temporarily upsets the course setting, making the device think it's not as far off course as it is.

It's quite possible to live with this weakness. A control typically requires only 10 to 15 degrees of rotation to develop its maximum steering effect. The vane rotation can be multiplied if necessary in the linkage, though the torque is then proportionally reduced. Single axis vanes are still in service all over the world, and will continue to be used by those willing to accept their limitations in return for their simplicity and other advantages.

DUAL AXIS VANES

For the 1964 singlehanded transatlantic race for the Observer Trophy, Eric Tabarly equipped *Pen Duick II* with a vane gear having many new features. Outstanding among these was a new design for the windvane, in which separate axes were provided for course setting and output (Figure 6-9). Although Tabarly's elaborate vane gear broke down early in the race and he steered most of the way to his impressive victory by hand, the potential advantages of his "horizontal axis" windvane were widely recognized and appreciated.



6-9. Pen Duick II*'s dual-axis windvane.*

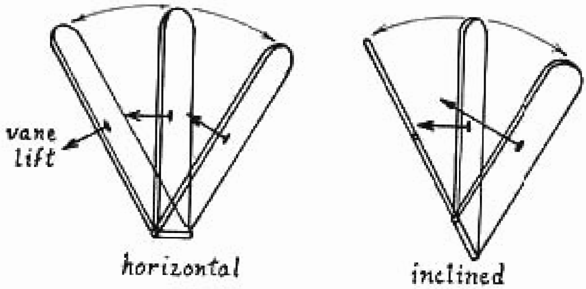
OPERATION

The action of the device is not hard to understand. The course is set by rotating the platform about the course-setting axis until the output axis is aligned with the wind. At this point the torque about the output axis is zero. Now if the wind changes direction or the boat goes off course, the vane finds itself at an angle of attack, and torque is produced about the output shaft. The power of the device lies in the fact that the horizontal-axis vane can produce a *rotation* of 20 degrees to 30 degrees in either direction in the output shaft without significant change in its angle of attack, and can still produce substantial torque even when it has rotated 60 degrees or more. This is a manifold improvement in power compared with the single-axis vane, which can only rotate through an angle equal to the course error, thereby losing all its lift. Using a linkage with mechanical advantage to increase its torque, a much smaller dual-axis vane can produce the same steering action.

ADVANTAGES AND DISADVANTAGES

Other potential advantages of the dual-action vane can be noted. The independent course-setting axis lends itself to remote course setting using lines or other connection to the cockpit or deckhouse. The bearings in the output axis are advantageously placed to reduce friction. The smaller area of the vane reduces the likelihood of weather damage, and the small size reduces inertia and so promotes quick response. Its smaller size and different space requirements may make it easier to fit around existing pulpits, backstays, etc.

The big disadvantage of the dual axis vane, compared with the single-axis type, is the degree of mechanical complexity. Providing two axes of rotation is no problem at all; but transmitting the rotation of the upper (output) axis down to the linkage in a way that is sufficiently free of friction and independent of the course setting — there's the challenge. Though natural weathercocking is possible when the vane is disconnected, it adds substantially to the device's complexity and detracts from light-air performance. Probably stowing the vane foil itself is a better idea. The supports, platform, and vane can all be made very strong using ball or roller bearings, but still it seems the device can't be made as safe from damage while operating in heavy weather as a single-axis vane.



6-10. Effect of output axis inclination (view looking along the wind direction).

ORIENTATION OF AXES

There is some freedom for choosing the inclinations of the two axes. First, the course-setting axis can be raked forward, with the same benefit observed with the single-axis vane, automatic increase of weather helm with heeling (p. 142). Second, the output axis does not have to be perpendicular to the course-setting axis — in fact, in *Pen Duick II's* gear it was tilted about 10 degrees from horizontal. The inclination of the output axis from horizontal has important effects on both the power of the windvane and the stabilization of the system against oscillation.

In general, inclination of the axis *reduces* the possible output axis rotation and *increases* resistance to yawing, and even a 10 degree inclination has a marked effect. To picture how the power is reduced, compare the actions of the horizontal- and inclined-axis vanes shown in Figure 6-10. The viewing direction is along the horizontal streamlines of the wind, so the angle of attack of the vane (initially 10 degrees) will show up clearly. The horizontal-axis vane hardly changes its angle of attack at all in rotating 30 degrees as shown, so it still puts out plenty of torque. But the vane with its axis inclined just 20 degrees comes to zero angle of attack in 30 degrees of rotation, so its output torque falls to zero; it turns out to be about a third as powerful as the horizontal-axis vane, if the two have the same volume. The stabilization of the system results from the weathercocking tendency of the inclined-axis vane, an effect to be analyzed in the next chapter. Actually there is a continuous transition from the characteristics of a horizontal-axis vane to those of a vertical-axis vane as the inclination varies from zero to 90 degrees.

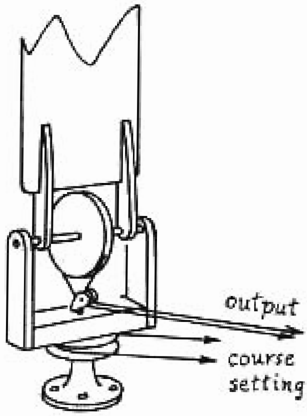
Notice that it is the angle of the output axis *from horizontal* that counts, and that an inclination introduced by heeling has just the same effect as one built into the gear. This means that a horizontal-axis vane sailing on a beam reach at 20 degrees angle of heel actually behaves like a 20 degree-inclined-axis vane, with far less power than when it was truly horizontal.

MECHANICAL ARRANGEMENTS

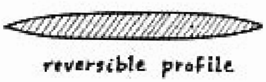
The choices center around the means of transmitting rotation and torque from the output axis to the linkage.

1. Running lines

These provide one of the simplest connections to either the primary rudder (Figure 4-4) or another control. A drum on the output axis



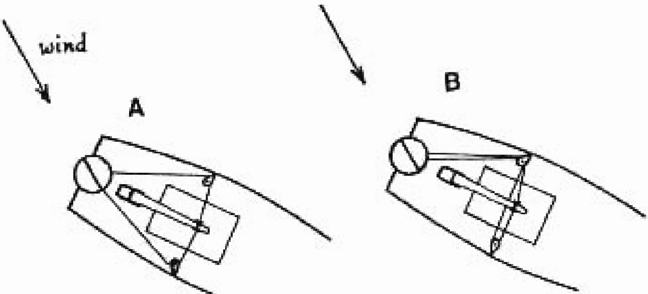
6-11. Horizontal-axis vane with drum for running lines.



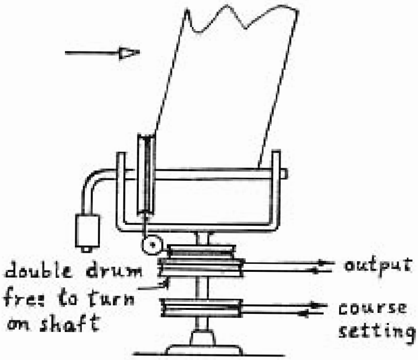
6-12. A sharp trailing edge with flow from either direction.

converts output torque to tension in a rope or wire (Figure 6-11). This is a very flexible arrangement, for the running lines can then be led to a control in any location, through blocks and fairleads. Friction adds up in such a series of blocks, so make the lead as simple as possible. The big disadvantage here is that the output lines interfere with course setting by limiting the course setting axis to less than 180 degrees of rotation. To cover all courses the vane has to be reversible, so either edge can be used as the leading edge; the airfoil section has to be abandoned, and a profile with two sharp edges and thickness 8 to 10 percent of chord is indicated (Figure 6-12). When the vane is switched around to exchange the leading and trailing edges, the lead of the running line has to be reversed as well. This is much easier if the lines run parallel (as in Figure 6-13b) rather than to opposite sides of the cockpit (as in Figure 6-13a), although this requires an extra block with a 180-degree turn, which means considerable added friction. An arrangement that very simply avoids all these problems has been suggested by Jock Burroughs. It uses an intermediate double drum (which ought to have ball bearings); Figure 6-14 is self-explanatory.

In reality, drums with the line just wound around a few times are very prone to slip. They should really be more like quadrants, with the line following around far enough to permit whatever degree of rotation is required, then the line should attach to the drum. For most small yachts, a small braided dacron line will have sufficient strength and freedom from stretch to serve, but a small-diameter



6-13. Alternate leads for running lines to tiller.



6-14. Jock Burrough's running line transmission.

flexible wire rope would be superior in these respects and probably would have less friction through blocks.

2. *Gears*

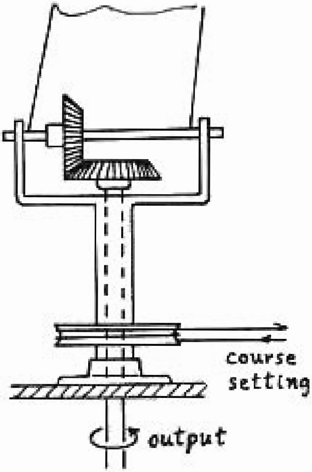
The torque of the vane can be transmitted down a shaft inside the course-setting shaft. This requires a change of direction, which is most efficiently accomplished by bevel gears (Figure 6-15). Tough, corrosion-free molded-nylon gears are available in suitable sizes. For experimental purposes, try cannibalizing the lower unit of an outboard motor.

3. *Push-rod*

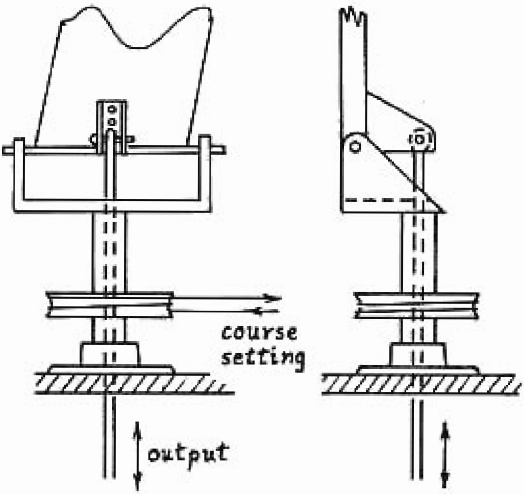
A little simpler than gears is a vertical push-rod in the center of a hollow shaft (Figure 6-16). It is hard to see a simple way to convert this up-and-down output to a useful steering signal without a lot of friction.

4. *Weathercocking*

While the vane is disconnected, weathercocking is possible if all these are provided: (1) low friction in the course-setting axis; (2) vane center of pressure offset behind the course-setting axis; (3) stops (in some form) to limit output axis rotation to 60 degrees or so; and (4) an oversize counterweight so the vane tends to prefer

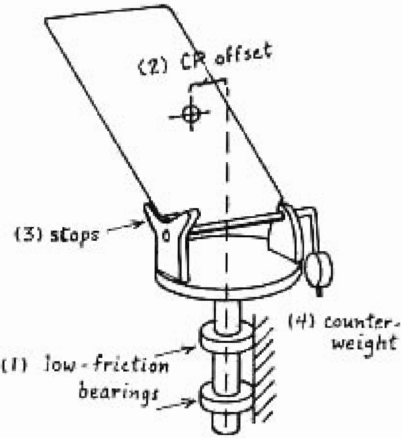


6-15. *Bevel gears transmitting output axis rotation.*

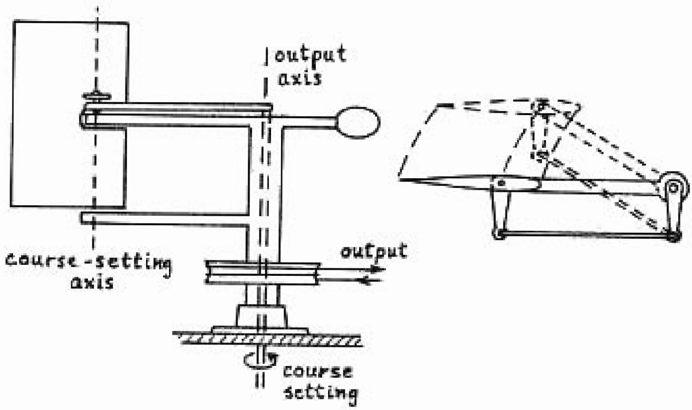


6-16. *Push-rod transmission of output axis motion.*

the vertical center position (Figure 6-17). Then if both axes are disconnected, the vane will stream with the wind and can be ignored. The only harmful effect is that the oversize counterweight reduces the sensitivity of the vane in light winds by resisting rotation about the output axis.



6-17. Provisions for allowing a horizontal-axis vane to weathercock when disconnected.



6-18. Derek Fawcett's new dual-axis windvane.

5. Parallel-motion mechanism

In the 1970 A.Y.R.S. *Self-Steering,* Derek Fawcett proposed an interesting new variation of a dual-axis vane. In its simplest form, the vane looks much like a single-axis vane, except that it is pivoted about a second axis parallel to the first (Figure 6-18). This second axis is used for course setting, using a parallel-motion mechanism that allows the vane to undergo large output rotations without reducing its angle of attack.

In this device, the output torque is readily available, appearing in the main support shaft; the trick is to transmit the course setting up through the output shaft to the vane. This is easily done with a crank and push-rod, since the loads in the course-setting linkage are very light. So Fawcett has effectively turned the dual-axis vane inside out, and the rearrangement makes a lot of sense: the heavier output torques appear in structural members, and the more delicate inner mechanism has only to transmit information. It has all the power of the horizontal-axis vanes, and it further appears that it could be easily made to weathercock when not in use. It seems this clever development has a lot of promise.

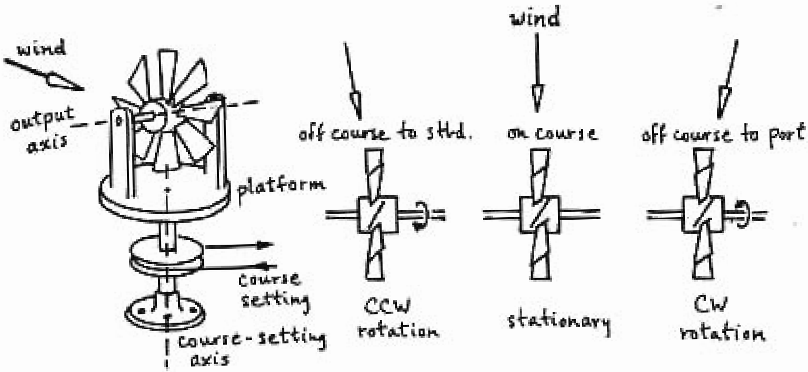
OTHER VANES

There are many things that are sensitive to small changes in the flow direction, and most of them could be used as the basis of a "windvane" for self-steering. Undoubtedly there will be entirely new ideas appearing. For the moment we will consider only one.

THE WINDMILL AS WINDVANE (Figure 6-19)

A windmill disk, composed of a balanced rotor with two or more inclined airfoil blades, is normally used to extract energy from the wind. It can be used as a wind-direction sensor, and, though it has a course-setting axis and an output axis, its operation is sufficiently different from the other two-axis vanes to put it in a class by itself. This idea was advanced by John Morwood in the first edition of the AYRS *Self-Steering*, but evidently it has not seen much use.

The neutral position of the windmill is with the plane of its



6-19. Windmill used as a wind-direction sensor.

disk parallel to the wind, when it has no tendency to rotate. If the wind comes on one side, the mill exerts a torque in one direction and can revolve in that direction indefinitely without a reduction in torque — in fact the torque increases with rotor speed, up to a point. To develop steering torques, the mill has to operate through a large mechanical advantage, but this is quite possible because of its unlimited freedom in rotation.

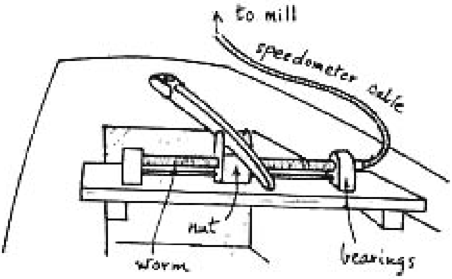
Transmission of the mill output to the control is a problem, as it is with most two-axis vanes. A running line might be led from a small drum on the rotor axis, but it appears that reduction gearing should be used first. An interesting possibility for driving the primary rudder with a windmill vane would be a lead screw (worm) driven by a flexible cable (similar to speedometer cable) connecting to the mill's rotor shaft (Figure 6-20). This affords tremendous mechanical advantage, and quite low friction is possible.

Some tentative suggestions for the design of the rotor and blades may be offered. For smooth starting at any angle, the number of blades has to be large, at least six or eight. For a given diameter, a propeller with wide blades, high "solidity" (total blade area/disk area, Figure 6-21a) will be more effective. Looking at the disk almost edge-on (from the wind direction) makes it seem that a very low blade pitch — something like five degrees — would be best (Figure 6-21b). It looks as if the main reason the rotor starts turning is the difference in *drag* between the top blades and the bottom blades, and lift has little to do with it until the rotor starts spinning. A reversible airfoil section (both edges sharp, Figure 6-12) is indicated for the blades.

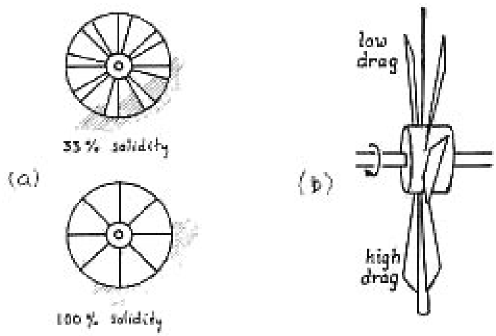
PRACTICAL CONSTRUCTION

MATERIALS FOR VANES

The requirements for the airfoil are mainly lightness and strength. Lightness promotes quick response and reduces the bearing loads. For most vanes an airfoil profile — at least a rounded leading edge and a sharp trailing edge — is desirable.



6-20. Worm drive for tiller, operated by a windmill.



6-21. Windmill design features.

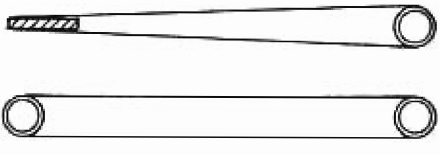
The thin, flat plywood vane is obviously an easy approach, but its aerodynamic properties are found wanting. The relatively flexible thin blade has a tendency to flutter. Alternative methods of construction that offer an airfoil profile and greater stiffness and strength with little more weight than plywood are:

1. Foam plastic core with fiberglass facings

The core material is easily shaped with a sanding block. One layer of 10-ounce cloth makes a fairly strong vane and two layers seems indestructible. Epoxy resin is required on styrofoam; polyester or epoxy resins can be used on polyurethane foam. Using a 3-lb/ft³ foam 1½ in. (36 mm) thick and one-layer facings, the finished weight will be about .80 lb/ft² (0,4 g/cm²), which compares with 0.2-inch (5-mm) plywood.

2. Tubular frame with fabric surface

High-tensile aluminum tubing and flat stock make a frame over which a sock of light fabric is pulled or laced (Figure 6-22). A finished weight of .80 lb/ft² (0,4 g/cm²) can be attained in a 3-ft² vane using ⅝″ O.D. x 1/16″ tubing and 2-ounce nylon. This scheme has a great advantage when it comes to stowing the windvane if this becomes necessary — just slip the sock off and leave the frame.



6-22. Fabric-covered tubular frames.

BEARINGS

The general purpose of bearings is to reduce friction and/or wear in supporting rotating shafts. Friction is the more usual problem in the lightly loaded windvane applications. Friction coefficients afford a numerical comparison of the effectiveness of various bearing surfaces: the lower the coefficient, the less friction under load.

For sources of bearings, look under "Bearings" in the Yellow Pages telephone directory for any large city.

1. Bronze

Certain bronze alloys containing lead are widely used for bushings because they have relatively low friction with steel, and high heat conductivity. They might be used for primary or auxiliary rudder gudgeons, but they require lubrication, so underwater use is doubtful. Oil-impregnated porous bronze bushings might be considered for reducing wear in some locations. Friction coefficients with steel are about .10 (oily).

2. Plastics

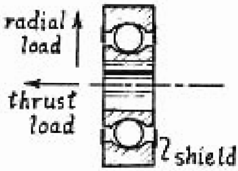
In lightly loaded applications where wear is not a problem, plastic bushings can reduce friction well below that of metal-to-metal contact. These require a good polished surface on the metal shaft. A tight fit is not desirable, as most plastics swell a little after absorbing water or oil. Fabric-reinforced phenolics (Tufnol, Micarta, Formica, Bakelite) are tough and machinable, but the coefficient of friction with steel is .12 to .20. Nylon, Delrin and other reinforced plastics are smoother, with friction coefficients around .08 to .12. Some of these are available filled with graphite or molybdenum disulfide as lubricants. Teflon is the slipperiest material yet, with friction coefficients against steel of only .05 to .08 (unlubricated); but it is relatively soft, so bearing deformation and wear can be considerable if there is much load involved.

Some vane gears have been successful using only plastic bearings. *Mick the Miller* is an example (Figure 4-1) where the polished Tufnol bushings were sufficient in both the vane and the auxiliary rudder.

3. Ball and roller bearings

The quest for low friction almost always leads to ball bearings. I can think of few machines that are both robust and sensitive that do not depend on ball or roller bearings for these qualities. These bearings are available in an endless variety of types, sizes, and shapes. Unfortunately, most are in high-alloy steels that are very prone to rusting and corrosion; but with careful attention to sealing and greasing, these can be made to serve. A fairly good variety is now available in stainless steel, especially in the smaller sizes. Because of the requirement that the balls and races be hardened, 400 series (martensitic: attracted by a magnet) stainless steels are used, which are much more inclined to corrode in sea water than the 300 series (austenitic: non-magnetic) stainless that yachtsmen are accustomed to. Underwater, they need protection with zincs and plenty of grease, but on and above the deck the stainless bearings stand up with very little attention.

For almost all self-steering purposes, the ordinary garden-variety radial ball bearing (Figure 6-23) is all that is required. It is capable of supporting moderate thrust loads as well as its intended radial loads. At cost of a little extra friction, seals or shield rings can enclose the balls, retaining grease and keeping out water and dirt.



6-23. Radial ball bearing can support radial and thrust loads.

The friction of a properly installed ball bearing can be many times smaller (10 to 100 times smaller at least) than that of the best metal or plastic bushing. Careful alignment of the bearing is required to achieve the best results, and this might require some good machining. If the bearing seems to have more friction after installation than before, alignment is probably the trouble. This can be avoided by using so-called "self-aligning" bearings, but I don't believe they're available in stainless.

New ball bearings often have disappointingly high friction. Sometimes this can be improved by washing out the heavy grease they come with and replacing it with a lighter grease. More often, they need a running-in period in which the bearing is rotated at high speed with some radial or thrust load until it has loosened up. New bearings might well require such treatment before they could be used on the windvane axis.

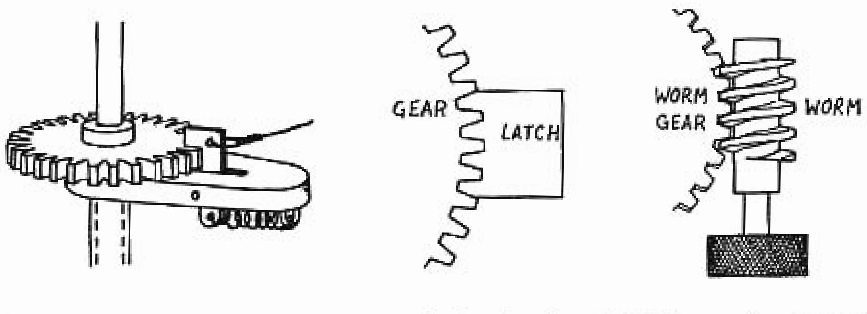
At least one ball bearing (to carry the weight of the vane and counterbalance) is almost always necessary to achieve good sensitivity in light winds. You may as well use two on the vane axis. Other places where they are likely to be needed: the course-setting axis of a vane that is expected to weathercock (Figure 6-17); hanging an auxiliary rudder (Figure 5-31); axis A-A of a servo pendulum (Figure 5-48); the rotor axis of a mill windvane (Figure 6-19); and perhaps on the axes of some moving parts of the linkage. Ball and roller bearings are also useful in making low-friction blocks for sheet-to-tiller and running line gears.

CLUTCHES AND BRAKES

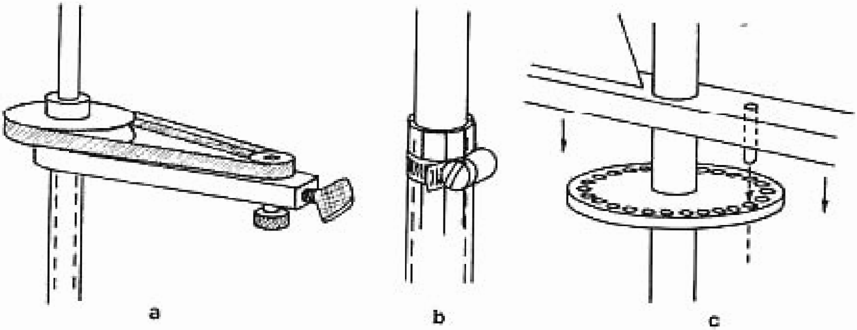
A variety of clutch and brake mechanisms are available for the purpose of setting the course axis on dual-axis vanes, and for engaging the single-axis vane with the linkage at the proper angle for the desired course. Some ideas are given here:

1. Toothed wheel and latch (Figure 6-24)

This must be the most popular clutch. A gear or sprocket makes a good wheel. A problem is the number of teeth. Even if there are 36 teeth, the course can only be adjusted to the nearest 10 degrees,



6-24. Clutches employing a toothed wheel and latch, and a worm gear.



6-25. Course-setting clutches.

not close enough for most people. If there are too many teeth, they are too small and liable to break.

A large diameter wheel helps. A latch can be made with matching teeth so four or more teeth are engaged. An attractive solution is to use a worm gear for the wheel, with the worm as the engaging latch. Then rotation of the worm allows a continuous fine adjustment.

2. *V-Belt brake* (Figure 6-25a)

This idea uses standard, widely available hardware components to make a sturdy, fine-adjustment clutch.

3. *Slotted tube and hose clamp* (Figure 6-25b)

Fine adjustment is a little troublesome, but you get a lot of clutch for your money. I've seen one like this that steered 5,000 miles before it even needed a new hose clamp.

4. *Perforated wheel* (Figure 6-25c)

This is the same idea as the toothed wheel and latch, but much easier to make in the home shop.

7 OVERSTEERING

We all know how a beginning sailor, unable to appreciate the turning power of the rudder and the importance of timing, tends to oversteer. His tiller movements are much too large, and poorly timed, so that whenever the boat gets back on course she is still turning and she overshoots. At first he can only steer a weaving course. With a little practice he learns that only a little helm is required, and that the proper amount depends not only on how far off course the boat is, but also on how fast she is turning. But then if you put him in a bigger boat or one with wheel steering, he oversteers again and there is another learning period before he "gets the feel of the helm" and can keep a good steady course. A vane gear can do just the same thing, applying too much helm with incorrect timing. The trouble is, it never learns. The timing and information processing it does are built in, and the only way to teach it anything is to take it back to the machine shop, and then it's not at all clear what to do to it.

The symptoms of oversteering are often all too evident — a weaving course, usually with a period of ten to twenty boat lengths, unrelated to wind shifts. You can watch the compass, or the wake can usually be seen for this distance, with the foreshortened view making weaving obvious; but there the fault can always be put on supposed wind shifts. Watch the telltales, and remember the device is supposed to keep the apparent wind coming from the set direction. The telltales show up a wind shift instantly, and the response of the boat in bringing the apparent wind back in line can be observed — sluggish or quick, overshooting or not, oscillating or not. The oscillations typically have a period of 10 seconds to a minute, and can swing over just a few degrees or over a wide arc. Unless the arc is pretty big the extra distance sailed is really quite small (p. 228), but there is no denying the oscillation is annoying. If you are trying to get somewhere in a hurry you just won't tolerate a beginner at the helm who is now 20 degrees above the course, now 20 degrees below. The course changes introduce a distracting rhythm of sound and heeling that constantly contrasts with the ideal of steady progress.

CAUSES OF OVERSTEERING

There are a number of ways that oversteering can arise:

1. Friction

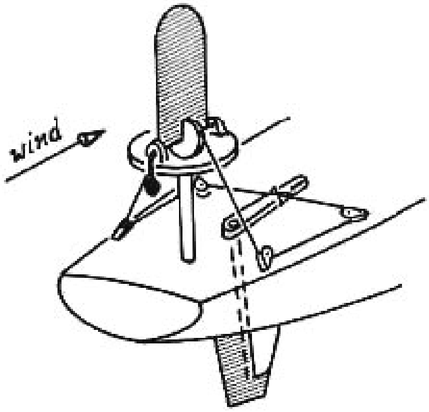
It is easy to see how static friction in any part of a self-steering rig can cause oscillation. The boat has to get far off course before the correcting force is sufficient to overcome the friction and move the control. If this is causing the trouble, it is usually easy to discern in the jerky movements of the vane. The cure is obvious — better bearings.

2. Backlash

In a mechanism that transmits motion through a series of parts, with a little looseness in the fit of each part to the next, all the little misfits add up so there is considerable slop from one end of the mechanism to the other. The input end can move quite a lot before the output end knows anything has happened, as the motion is taken up in "backlash." If the vane can turn more than two or three degrees without moving the control, it's clear that a perceptible oscillation could result. The cure for this is obvious, too — careful machining and a minimum number of parts in the chain of command. Ball bearings often find uses for reducing backlash as well as friction.

3. Inertia

The rotary inertias of parts of the mechanism — most likely the windvane and its counterweight — naturally reduce the ability of the system to respond to wind shifts and course changes. If the windvane has high inertia and the yacht has low inertia and the steering



7-1. An unstable combination: horizontal-axis vane/balanced rudder.

system is very powerful, it is possible for the vane's oscillations to get in phase with the boat's yawing in such a way as to make the boat go into oscillation. The cure is to reduce the weight and swinging radius of the windvane, use a heavier counterweight closer to the axis, and modify the linkage or the control to *reduce* the power of the self-steering. The objective is to make the period of oscillation of the windvane itself very short compared with the period of oscillation of the controlled yacht.

4. Overpower

There is no limit to the power that can be achieved by balancing the control, and this should be recognized as a potential problem. For example, a balanced rudder can be overdriven by a tab or pendulum (pages 118 and 129) so that its steering efforts are much too drastic. As another example, consider a balanced auxiliary rudder operated by a horizontal-axis vane, set for running downwind (Figure 7-1). If the boat goes off course by the smallest amount, the vane tends to turn; but it meets no resistance from the balanced rudder, so the vane keeps going until it's blown flat and the control is hard over and stalled. This over-reaction should bring her back on course in short order, but she's sure to over-shoot, so the vane flips to the other side and slams the rudder hard over the other way.

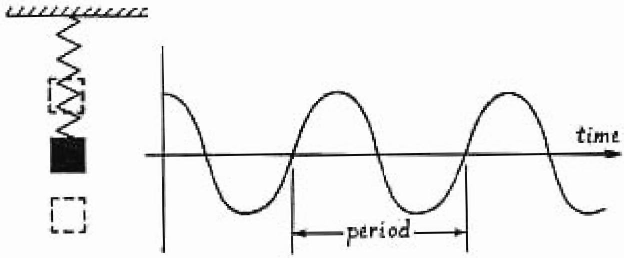
A rapid oscillation seems likely, but at best this would be a nervous helmsman to live with, who only knows two commands, "hard over port!" and "hard over starboard!" This problem would be readily brought under control by a little inclination of the vane output axis, which provides a simple form of rudder feedback.

5. Simple harmonic oscillations

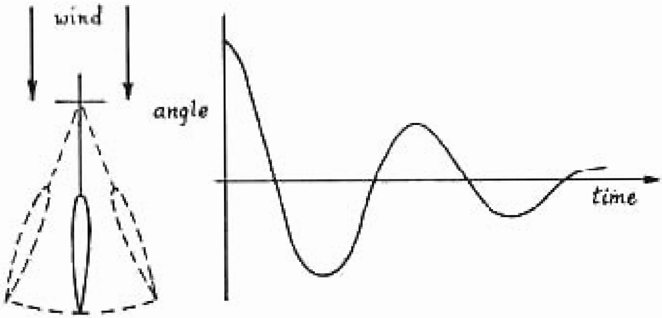
Actually the very idea of an autopilot that commands turning moments in proportion to the angle off course contains the formula for oscillation. To see why this is so, consider a couple of very simple mechanical systems that are capable of oscillation.

The prototype of this is the motion of a mass attached to a spring (Figure 7-2). The mass has an equilibrium position at the relaxed length of the spring. If it's moved from this position the spring applies a force proportional to the displacement. If it's moved upward and let go, this force causes the mass to accelerate down toward its equilibrium position. But when it arrives there, it has considerable momentum, so it overshoots. Then as it moves on down, the spring applies force upward, bringing it back to center; but again it overshoots. The natural motion of this system is a simple oscillation which continues indefinitely unless there is friction present. The period of the oscillation depends on both the stiffness of the spring and on the size of the mass. The amplitude can be small or large, depending only on how you start it off.

Take another example, more closely related to our topic. Suppose a vertical-axis windvane on perfect bearings is disconnected and



7-2. Simple harmonic oscillation of a mass-spring system.

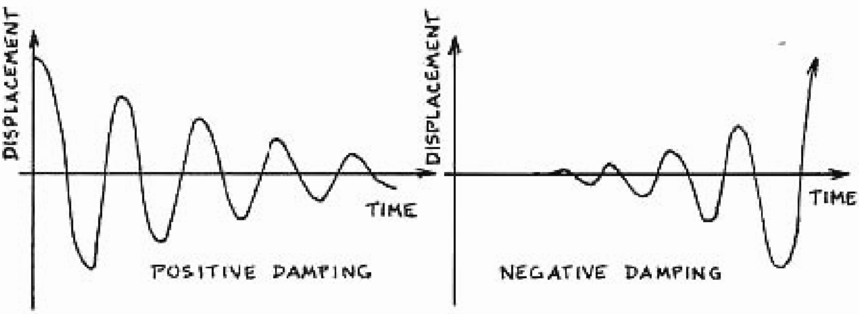


7-3. Damped oscillation of windvane.

allowed to "float" in an airstream (Figure 7-3). It has an equilibrium position — lined up with the wind. If it's moved from equilibrium, the aerodynamic pressures exert a moment on it, proportional to its angle of attack up to stalling angles. If it's turned out of line and let go, the aerodynamic moment imparts angular acceleration back toward the neutral position. But when it gets back there, the vane and counterweight have acquired a rotation, and because they have rotary inertia they overshoot. We have the same essential requisites for oscillation — inertia combined with a restoring force which is proportional to the amount the system is away from its equilibrium position — and so the vane oscillates. In air the damping is considerable, and so it settles down in just a few cycles. This is the "oscillation of the windvane" mentioned on p. 161.

Now on to sailboats. Here the inertia is rotary inertia of the whole boat (around a vertical axis through the center of gravity) which tends to carry her past the proper course. The restoring moment is the steering action of a simple windvane gear, a steering moment proportional to the amount the windvane senses the boat to be off course. If damping is absent, the natural motion is a continuing oscillation, with a period that depends on the rotary inertia of the boat and on the power of the self-steering (how much restoring moment it makes for each degree off course). This is the "oscillation of the yacht" mentioned on p. 161.

Damping of any of these oscillations is possible by adding other forces or moments to the system. The key to damping is providing a force proportional to the velocity of the mass, or to the *rate of rotation* of the vane, or the boat. Adverse yaw (p. 26) is such a

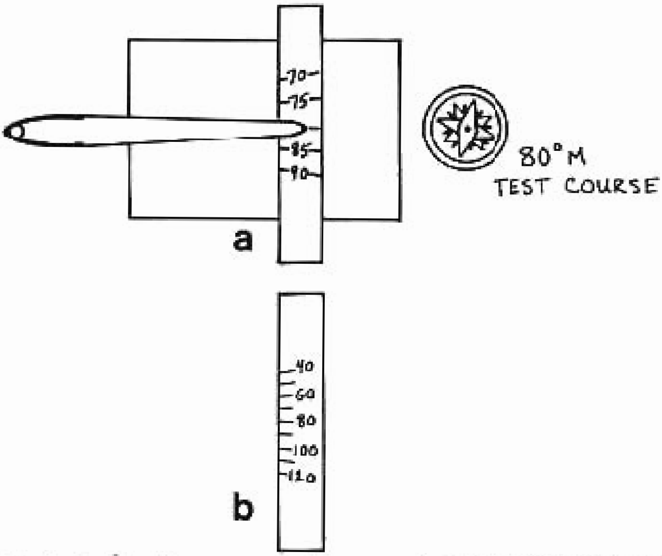


7·4. Effect of positive and negative damping on motions of oscillatory systems.

moment that acts on any boat, to a greater or lesser extent. But the motion of the boat really is yawing combined with forward motion and sideslipping, and under these circumstances the center of gravity position can introduce a moment opposite to adverse yaw (p. 30). The fact is that some boats behave as if they have fairly high yaw resistance, some have very little, and some seem to have negative yaw resistance.

The effect of positive damping in an oscillatory system is to reduce the amplitude of oscillations with the passage of time. The effect of negative damping is startling — the oscillations, starting from any disturbance at all, grow with time and eventually become very large (Figure 7·4). This is called "dynamic instability."

So we conclude: a yacht with the simplest kind of vane gear — one which generates restoring moments simply proportional to the error in the course — has a natural tendency toward oscillation. Whether the oscillations damp down or grow with time depends not only on the profile of the boat, the length of keel, but also in a complicated way on the relationship between the center of gravity and the hydrodynamic center. This relationship is not well understood, and in any case would be expensive to modify! Fortunately, with most types of vane gear, it is easy to provide additional damping in the design of the vane gear, if it is needed. It is also easy, if you're not careful, to design *negative* damping into the linkage and make a stable boat dynamically unstable!



7-5. (a) Set-up for testing yaw resistance of a boat with tiller steering; (b) a finer scale can be used to slow the oscillations (scale in degrees).

SAILING TEST FOR YAW RESISTANCE

First, there is a simple test to assess the effective yaw damping of the boat by herself. It takes almost no equipment, but you need two people to carry it off — one reads the compass and the other steers. A third person as lookout is advisable, so the first two can concentrate on what they're doing.

Find a reaching course that is comfortable to steer. I don't think it has to be in any extreme conditions; moderate wind and sail are sufficient. Now clamp a board across the cockpit close under the tiller and mark on the board a scale of degrees, with the chosen magnetic course as center and the numbers increasing clockwise as on the compass card (Figure 7-5).

Starting with the boat, say, 10 degrees off course, steer by the following procedure. The compass man continually reads the course off the compass, aloud. The tiller man pays attention to neither wind nor sails, nor to the force on the tiller; but concentrates on keeping the tiller at all times on the same number that the compass man is reading out. The effect of this is to apply to the boat a restoring moment always proportional to the error in course — you are simulating the action of that simplest vane gear. Keep this up for several minutes if necessary to see how she behaves, and then start her off course again.

If the boat oscillates too rapidly in this test for the helmsman to follow the compass readings, or for the compass to keep up with the heading changes, a slight modification is required to get meaningful results. (Time lags in the compass and in steering will cause the boat to act *less* stable than she really is, resulting in an underestimate of her natural yaw resistance.) Paste paper over the first scale of degrees you used and mark on this paper a new scale with the degree marks substantially closer together — try one-quarter of the original spacing to double the period of oscillation. Tape a piece of stiff wire rigidly to the tiller to act as a pointer on this new, finer scale. In this way, increase the period for a full cycle of the oscillation to at least 20 seconds.

After several such trials, you should be able to put her behavior into one of these categories:

1. Strong damping

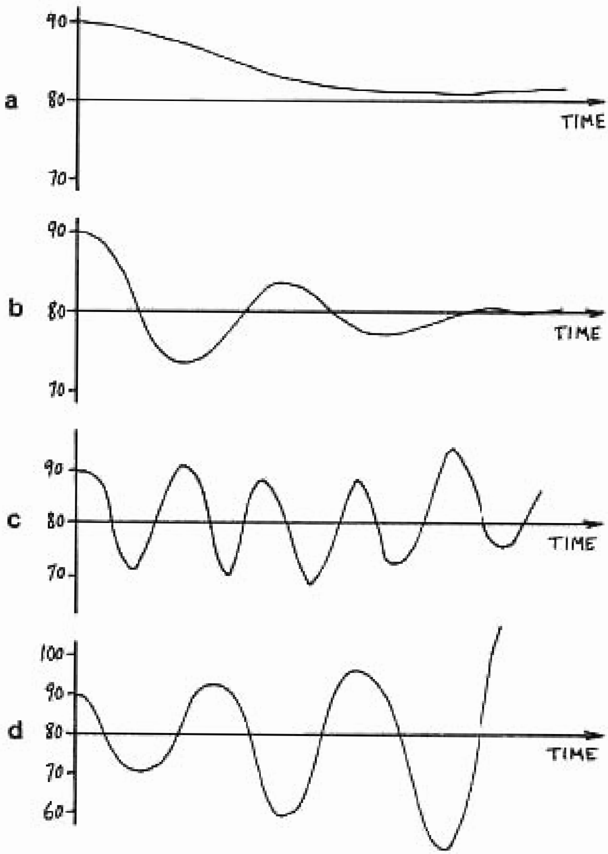
Each time she is put off course she finds her way back to a fairly steady course without overshooting (Figure 7-6a). This boat can tolerate almost any type of vane gear without oscillating. If she is slow coming back on course — more than three or four lengths — it may well be desirable to build deliberately negative damping into the vane gear to improve the response time.

2. Positive damping

She overshoots, but after a couple of cycles settles down to a steady course (Figure 7-6b). Adding an auxiliary rudder or a pendulum to this boat would add enough adverse yaw to give satisfactory performance; no damping would be needed in the linkage design. However, direct use of the primary rudder with a dual-axis vane is unlikely to succeed unless the system is designed to supply additional damping. A tab on the primary rudder will be successful only if the linkage is carefully worked out to give as much damping as possible.

3. Neutral damping

She wanders around near the proper course but doesn't settle down (Figure 7-6c). This boat definitely needs some help from the mechanism. It is doubtful whether any system that uses the primary rudder, except with a pendulum, can provide enough damping.



7-6. Typical responses to test, indicating varying degrees of yaw resistence.

You should count on lashing the helm to contribute adverse yaw and adding an auxiliary rudder for the self-steering.

4. Negative damping

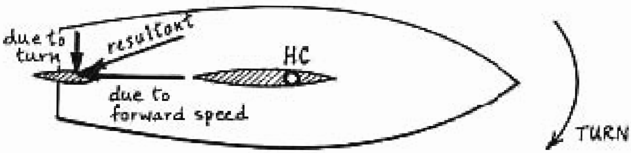
Each cycle of the oscillation is bigger than the one before, so after some cycles you have to give up, to avoid tacking or jibing (Figure 7-6d;) or she settles into an oscillation over an arc much bigger than the original error. The choice of types of vane gear for this boat is fairly restricted – only with a pendulum or large balanced auxiliary rudder, and a linkage and vane, with strong stabilizing measures built in, can the boat's natural waywardness be corrected.

PREVENTION AND CURE

So how can the linkage be made to perform these miraculous functions – make unstable boats stable and *vice-versa,* control damping and response time of the complete sailboat-vane gear system? There has been a lot of confusion on this point. Many articles have referred vaguely to "feedback" and "differential linkages"; others have diagrammed changes that improved the steadiness of particular combinations of vane, control, and yacht. The damping function of a differential linkage with a single-axis vane and a servo tab control has been explained in an essentially correct way by a few writers, but the extension to other combinations of vane and control types has not become clear. In the first journal article on the subject of vane gears, Buchan and Flewitt *(Royal Institution of Naval Architects Quarterly Transactions,* vol. 110, pp. 347-361, 1968) conclude theoretically that rudder feedback and differentials have no effect whatever on damping oscillations, and pin the whole blame on rotary inertia of the windvane.

RESISTING OSCILLATIONS

In fact, the details of the control, the windvane, and the linkage *all* have profound effects on the damping of oscillations. Describing the effect as "feedback" is not specific enough. Nor does it necessarily involve a differential mechanism in the linkage. To avoid confusion with earlier uses of these terms, I prefer to call the effect *synthetic damping* – yaw damping that is "manufactured" in the steering



7-7. Resultant angle of attack of rudder due to combination of forward speed and yawing (See also Figure 2-14b).

gear rather than a natural property of the boat. The way in which synthetic damping arises and the controlling aspects of the design are different for each combination of vane and control types. After examining some particular combinations, we will be in a position to propound a few general principles.

1. Primary or auxiliary rudder

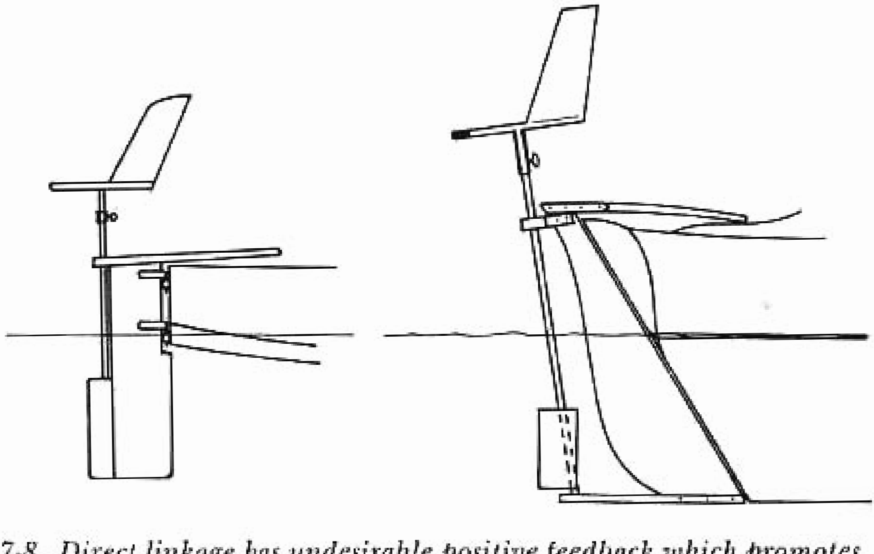
Using an auxiliary rudder allows the primary rudder to be fixed so it provides as much yaw damping as it can; then the auxiliary rudder can add some more. With these controls the explanation of the damping is simple. As the boat turns (to starboard, for example), pivoting about the hydrodynamic center, this rotation causes a component of flow at the rudder coming from the port side (Figure 7-7). This flow combined with the forward velocity puts the rudder at an angle of attack. The resulting turning moment that the rudder now exerts on the boat depends on what the rudder is connected to. If it is fixed, or very stiffly held by the windvane and linkage, it obviously develops a powerful lift to starboard, opposing the boat's rotation. At the other extreme, if the linkage leaves the rudder very free to turn (and the rudder is not completely balanced), it just lines up with the stream and makes no opposing lift at all.

The maximum yawing resistance is obtained when the rudder is completely balanced, with no tendency to line up with the stream. In this case the vane and linkage have no bearing on yaw damping; there is nothing they can do to improve on the damping qualities of the balanced rudder.

With a rudder that is *not* completely balanced, the tendency of the rudder to weathercock with the flow past it can be partially opposed by proper design of the linkage and vane. The force that resists the rudder is the weathercocking tendency of the *windvane;* this must be either a vertical- or inclined-axis vane, and the damping is improved by increasing the vane volume and by increasing the mechanical advantage of the vane over the rudder – both of these help the vane to hold the rudder at the angle the vane wants, against the turning action of the water flow.

2. *Servo tab with single-axis vane*

Because the tab is mechanically hung on the rudder, and because it operates in water streaming off practically parallel to the rudder (tab angle is measured relative to the plane of the rudder), the tab, rudder, and vane angles are interrelated in unexpected ways. The key to adding positive damping is to arrange the linkage so that, *with the vane held fixed, turning the rudder causes the tab to turn so as to oppose the rudder's turning.* Since information about the rudder angle is communicated to the vane and linkage that control the rudder, it is appropriate to call this technique "rudder feedback."



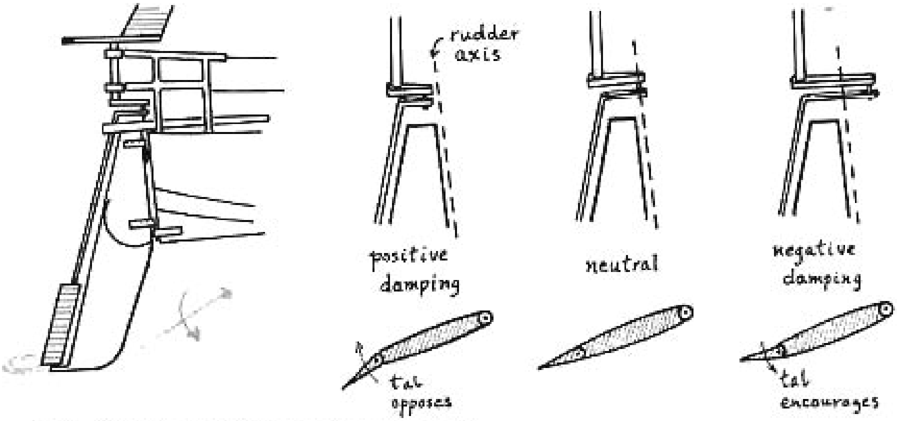
7-8. Direct linkage has undesirable positive feedback which promotes oscillation.

The mechanical arrangements for achieving this action range from obvious connections by gears, running lines, etc., from the rudder head to the tab or windvane, to some means so simple as to be almost invisible. The invisible kind can be very deceptive, sneaking negative damping into the system where you don't expect it. This can be found in many of the vane gears described in boating magazine articles and offered commercially.

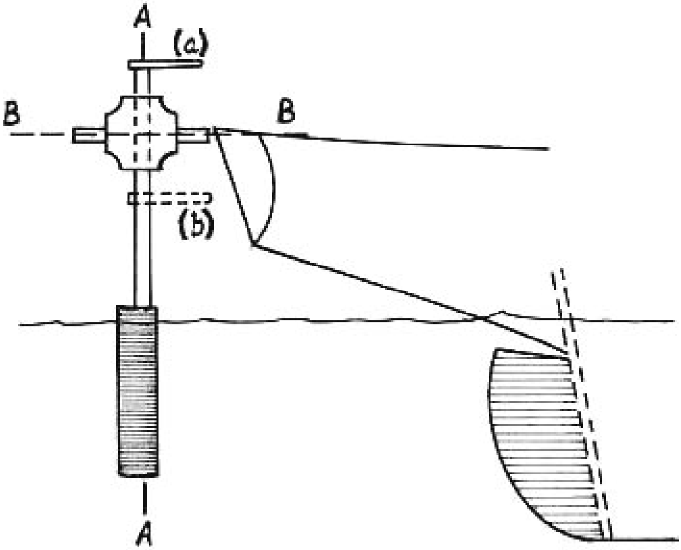
The simplest way of hooking the vane to the tab is to put them both on the same vertical shaft, "direct linkage" (Figure 7-8). This is one of the invisible feedback systems with *negative* damping. In this case, if the vane is held fixed and the rudder is turned, we find the tab taking up an angle equal to the rudder angle, urging the rudder to turn further. Only on a boat with strong adverse yaw can it work; on most it oversteers badly. After using this system in *Joshua* (with an especially long, deep keel), Bernard Moitessier wrote: "*Joshua* yaws about 15° maximum under self-steering vane, the average being about 10 degrees [either side of course]." I got a similar report from Frank Rogganbuck, who used this system with an auxiliary rudder on his Pacific voyages in *Sea Love,* with a relatively long fin keel and attached rudder which was kept fixed: "She keeps going 10° to 15° either side of course; wind, sail trim, and sea conditions all make very little difference."

If the vane is supported on the boat instead of on the rudder, positive or negative damping is available, though hardly more visible (Figure 7-9). It all depends, most remarkably, on whether the pin that links the vane shaft and tab shaft is behind, on, or ahead of the axis the rudder turns on.

Incidentally, where Buchan and Flewitt went wrong in their journal paper was in neglecting forces on the rudder due to the yawing of the boat. The real hero is the first discusser of their paper, Mr. Bernard Hayman, editor of *Yachting World,* a non-mathematician who stood up to all their differential equations and stability diagrams, and told them they were wrong. His spirited insistence that rudder-to-tab feedback is at the core of windvane stability problems inspired me to look closer into the theory, and when rudder incidence was properly included, all the possibilities of synthetic damping emerged!



7-9. Feedback linkages for servo tab.



7-10. Rudder feedback to pendulum controlled by pendulum tiller location. (a) Tiller above axis B-B gives positive feedback to enhance yaw resistance. (b) Tiller below *axis B-B gives negative feedback to control overpowering of balanced rudder.*

3. Servo pendulum

The strong contribution of a pendulum to yaw damping can be similarly understood by considering the component of flow at the pendulum due to yaw. Let the boat again be yawing to starboard. As a result of the turning, the pendulum sees a component of flow from the port side. The pendulum itself generates lift to starboard, resisting the yaw; and by following the action through in Figure 5-48, you can see that the pendulum forces the rudder blade to port, which also opposes the yaw. This combined action makes the pendulum potentially the most effective control for damping yaw; however, care has to be taken in the linkage design to ensure that this advantage is realized. The key to adding strong, positive damping is to arrange the linkage so that *with the vane fixed, turning the rudder causes the pendulum to turn (on axis A-A) the same way as the rudder.* For example, the linkage shown in Figure 7-10 has this desirable property because the short pendulum tiller is located *above* the axis B-B. Positive damping is still present if the pendulum doesn't turn on axis A-A during this test, but it is possible for the pendulum to cause strong *negative* damping, consequently unstable oscillations, if the linkage is arranged so as to turn the pendulum the *wrong* way when the rudder turns.

CONTROLLING OVERPOWER

An excessively powerful vane gear oversteers by simply applying much more steering action than is warranted by the errors in the course. This is likely to happen whenever a *balanced* rudder is operated by either a servo tab, a servo pendulum, or a horizontal-axis vane. In each case, the balanced rudder offers no resistance or reaction to the powerful device that drives it, so it shows no moderation in its response. But rudder balance is *desirable* from the standpoint of getting maximum yaw damping and power with a minimum-sized servo or vane. Can we have these advantages without risking excessive power? The answer is another facet of rudder feedback. Sending back information about the rudder angle to the tab, pendulum, or windvane tells these devices when to stop pushing, and provides positive, smooth control over the power of a balanced rudder. Here's how it works in several cases:

1. Balanced primary or auxiliary rudder with dual-axis vane

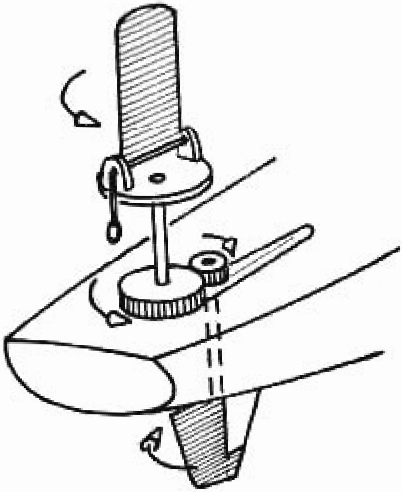
If the vane output axis is horizontal, rudder rotation must be fed back to the *course-setting axis* of the vane. Stable operation results if the feedback is connected so that *when the rudder turns, the vane turns the opposite way.* Figure 7-11 is an example of one way to do this. Suppose this boat is running dead before the wind, and a sudden shift brings the wind five degrees on the starboard quarter. The vane swings to port, applying starboard helm; but as the rudder turns 15 degrees (assuming a 3:1 ratio in the gears) the vane rotates five degrees on its course-setting axis, and at that point it's lined up with the new wind, zero angle of attack, and it stops pushing. As the boat turns to port, the vane smoothly reduces the rudder angle, keeping it always exactly three times the course error. When the boat has turned five degrees, she is on her new course and both vane and rudder are centered again.

(As an opposite example, consider a horizontal-axis vane mounted on the rudder as in Figure 7-12: when the rudder turns, the vane turns the *same* way. This is an invisible feedback linkage working in the wrong direction, with very strong destabilizing effects.)

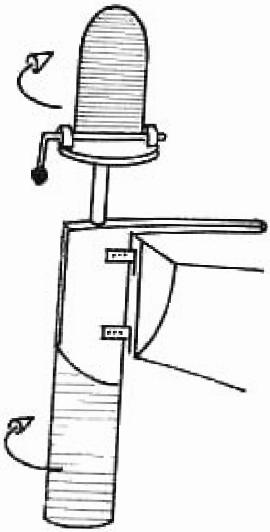
Now I want to show that inclining the output axis of the dual-axis vane has *exactly* the same effect as the feedback linkage just described. The big difference between a horizontal-axis and an inclined-axis vane is that, with the inclined axis, rotation about the output axis reduces the vane angle of attack (demonstrated in Figure 6-10). Add this to an output linkage that keeps the rudder angle proportional to the output axis rotation and we have rudder feedback: rotation of the rudder reduces the vane angle of attack. If we assume the vane-to-rudder gearing ratio in the *output* linkage is 3:1 (45 degrees vane rotation to produce the 15 degrees rudder rotation) then just five degrees of inclination would be equivalent to the feedback linkage of Figure 7-11 with a 3:1 gear ratio, and the whole system would behave just the same.

2. Servo tab on balanced primary or auxiliary rudder

Rudder feedback to the tab must be arranged so that *when the rudder turns, the tab turns to oppose it.* Again, the simplest way to arrange this action is likely to use a short tab tiller that ends some-



7-11. Stabilization of vane overpower by rudder feedback (output linkage as in Figure 7-1 not shown here). Arrows indicate sense of rotation.



7-12. An "invisible" case of positive (destabilizing) rudder feedback.

what behind the rudder hinge line (Figure 7-9). When the tab is turned to command a course change, the balanced rudder will keep turning until the tab is lined up with it again — the tab angle reduced to zero. At that point there is no further force turning the rudder. Through feedback the rudder "tracks" the tab, attempting to keep zero tab angle at all times. In this way a very small tab keeps smooth, perfect control over all the power of the balanced rudder.

3. Servo pendulum operating balanced rudder

In a very similar way, overpower can be governed by a linkage that reduces the pendulum angle (about axis A-A) as the rudder swings over. There are very simple mechanical ways to arrange this, such as using a short pendulum tiller *below* the axis B-B in Figure 7-10.

Thus each type of control can be made to resist oversteering and contribute to dynamic stability. The most effective yaw damping, and also the highest power, is obtained when the control rudder is fully balanced. Whether the rudder is balanced or not, the "rudder feedback" function of the linkage plays an important role, governing the power when the rudder is balanced and the damping when it is not. In most vane gears this detail of the linkage is the key to prevention and cure of oversteering.

8 THE LINKAGE

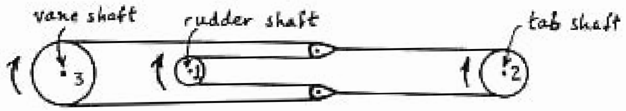
As defined previously, the "linkage" is whatever connects the windvane with the control to transmit the error signal. The error signal is most often a torque developed by the windvane; the simplest case of *direct linkage* just applies this torque to the control. Most often, the linkage at least has mechanical advantage to multiply the torque (and reduce the rotation) between vane and control. Frequently the linkage can be made to combine other information with the windvane's error signal, to improve the steering performance of the system.

The kinds of machinery that can be used for interconnecting the vane and control are unlimited. Gear trains, levers, chains, running lines, bell cranks, and dozens of combinations of these elements have been used. The choice seems to depend entirely on the requirements of the individual installation. The ideals to be kept in mind are freedom from friction, backlash, and wear, and general mechanical durability.

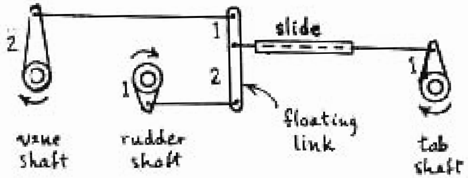
DIFFERENTIAL LINKAGES

There are a number of places where two inputs have to be mechanically combined into a single output. A device that accomplishes this is called a *differential mechanism*. For example, in connecting up a single-axis vane to a servo-tab control with rudder feedback, the function of the linkage can be diagrammed as in Figure 8-1. This could be done using running lines (Figure 8-2), or using a floating link mechanism (Figure 8-3), or it could be accomplished

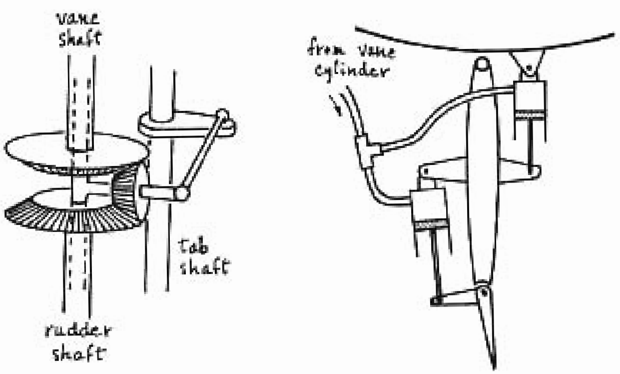
8-1. Block diagram of feedback linkage for servo tab. The vane course-setting axis turns with the rudder.



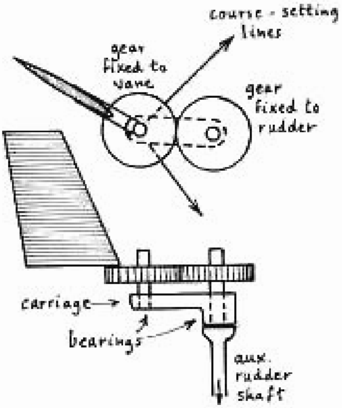
8-2. Running-line differential linkage: tab angle = ¾ x vane angle minus ¼ x rudder angle.



8-3. Floating-link differential: tab angle = 1/3 x vane angle minus 1/3 x rudder angle.



8-4. Gear and hydraulic differentials.



8-5. "Moving-carriage" vane.

with gears or hydraulics (Figure 8-4). In each case the output has the form: tab angle = G × vane angle + F × rudder angle, where G and F are determined by the dimensions of the various mechanical parts. F is the rudder feedback ratio that influences the damping so strongly, and G is the vane-to-tab gearing ratio, which has a strong effect on the power of the system.

Another place where differential linkages are important is in remote course-setting arrangements. The "moving-carriage" gear is an example of this: rudder angle = programmed wind direction − vane angle (Figure 8-5).

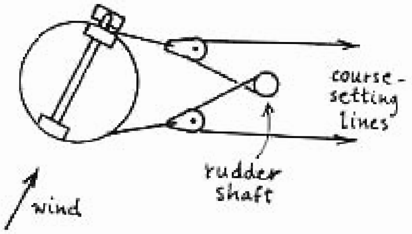
Similarly, any remote course setting with a horizontal-axis vane employing rudder feedback requires some kind of a differential mechanism, e.g., vane angle = programmed wind direction − 1/10 × rudder angle (Figure 8-6).

LINKAGE RATIOS

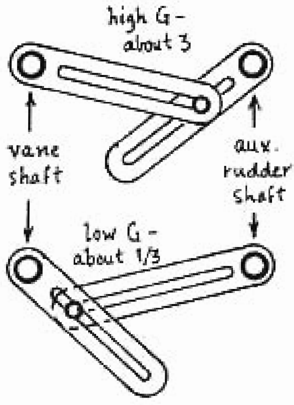
GEARING RATIO

In the simplest vane gears, like *Mick the Miller's,* the linkage might serve only to reverse the rotation of the vane before the signal is passed to the tab. But we have seen that *Mick's* linkage was a little more than this — the pin connecting the two slotted bars was adjustable, allowing different settings of the mechanical advantage or "gearing ratio" between the vane and rudder defined by: rudder angle = G × vane angle (Figure 8-7). In many other vane gears, a similar adjustment in the vane-to-control gearing is provided as part of the linkage. (In calling this the "gearing ratio," I don't mean to imply that the linkage necessarily employs gears — only that the linkage provides an approximately direct proportion between control angle and vane angle, with G being the constant of proportionality.)

What is the significance of this ratio in the system performance? Does it need to be adjustable?

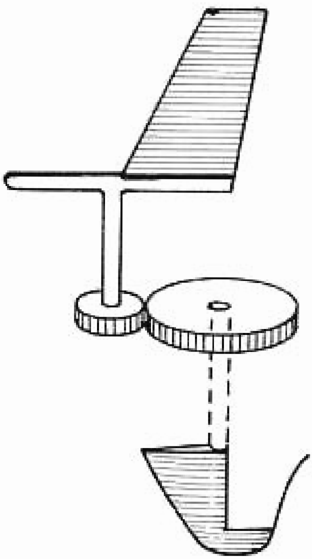


8-6. Remote course-setting with rudder feedback.



8-7. Slotted-bar linkage with adjustable ratio.

Gearing the vane rotation down provides more torque to overcome friction and hydrodynamic moments on the control. Helped by gearing, a small vane can apply the same amount of torque as a big one. But there is a penalty. Any linkage that multiplies torque by a mechanical advantage also *divides* the rotation by the same number. For example, the geared linkage in Figure 8-8 multiplies the vane torque by three, but the rotation of the rudder is only one-third that of the vane. (It's the same for any kind of simple machine forming the linkage; conservation of energy requires it.) Compared with a simple 1:1 (G = 1) reversing linkage, the vane would have to turn three times as far — the boat three times as far off course — to produce the same turning effect from the control. This means two things: (1) in strong winds, reaching and running, the geared-down vane will be less able to cope with any inherent instability of the boat and will have to be relieved sooner; and (2) in any conditions it will tend to change course more with varying wind strength, since the boat has to run three times as far off course to make up a given increase in weather helm angle.



8-8. Geared linkage with fixed ratio, G = 1/3.

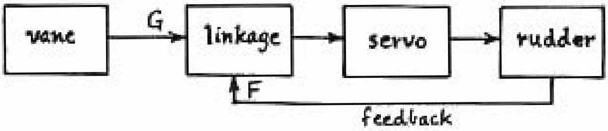
Single-axis vane

The same trade-off applies to any control used with a single-axis vane. Increased mechanical advantage (lower G) allows a smaller vane, but makes a less powerful system, and one more sensitive to changes in wind strength. This is an area where it is hard to give quantitative recommendations. I'm all for a small vane, but then I'm all for having a system that can handle pretty hard driving, too. I think if the control has been sized according to the recommendations of chapter 5, a gearing ratio G between 1 and ½ (control rotation/vane rotation) can be expected to give satisfactory results with a single-axis vane.

Dual-axis vane

Because of the much larger vane rotation available, considerably lower gearing ratios can be used with the dual-axis vanes. Obviously 1:1 gearing would be wasteful, because only a small part of the potential vane rotation would turn the control to its stalling angle. Considering that the horizontal-axis vane can rotate 45 degrees without much loss of torque, while the control stalls by about 15 degrees angle of attack, gearing ratios around 1/3 appear to utilize the full potential of both vane and control. In fact, I got satisfactory results in moderate weather with G = 1/20 (one degree of helm for 20 degrees vane rotation), driving a partially balanced primary rudder, while G = 1/40 definitely did not give enough tiller motion; but this was with a running line linkage allowing easy weather helm adjustments. Again, performance in varying wind strength sets a limit on mechanical advantage; the lower the gearing ratio, the narrower the range of wind speeds over which the system will hold a course without adjustment of the vane-to-control linkage.

The gearing ratio seems somewhat open to experimentation, and I would recommend that it be made variable in the experimental stages. But once a satisfactory value is established, there is no need to make it variable in the final design. That only complicates the linkage and makes mechanical reliability more difficult. The requirement on G is set mainly by performance in heavy weather, and there is no harm done if G is higher than otherwise necessary in lighter winds.



8-9. Block diagram of feedback linkage for servo control.

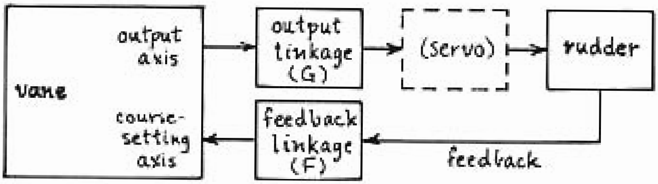
The natural frequency of oscillation of the yacht with a vane gear – whether this oscillation is damped or not – depends directly on G. Thinking of the system as a simple harmonic oscillator composed of the rotary inertia of the boat and the restoring moment provided by the vane gear (p. 163), it is clear that the strength of the restoring moment is proportional to G. This leads to the frequency of oscillation being proportional to the square root of G. If oscillations are too rapid for comfort, or their frequency gets too near the windvane's natural frequency (p. 163), and they cannot be sufficiently damped, they can at least be slowed down by reducing G. Sometimes this slowing down makes a marginal amount of damping noticeably more effective; this is the reason adjustable G was often used in the early windvanes. But now that rudder feedback is clearly understood, this relatively weak damping effect need not be relied on, and it is easiest to build a linkage with G fixed.

Feedback ratio

The action of rudder feedback was described in the last chapter in qualitative terms – how it works, and which way the feedback has to be to get a positive synthetic damping effect. With a single-axis vane operating a servo control, the feedback works like Figure 8-9 with a differential linkage whose characteristic is: tab or pendulum angle = G × vane angle + F × rudder angle. With a dual-axis vane the diagram is quite different (Figure 8-10), and the linkage performs two distinct functions:

$$\text{control angle} = G \times \text{vane output angle},$$
$$\text{vane course-setting angle} = F \times \text{rudder angle}.$$

In either case the sign and magnitude of F, the *feedback ratio*, determines the sign and magnitude of synthetic damping.



8-10 Block diagram of feedback linkage for dual-axis vane.

The amount of feedback required depends, as we have seen, on the inherent yaw damping characteristics of the boat. The effect of too little, or negative, synthetic damping is a tendency toward oscillation and oversteering. Too much synthetic damping, though, makes the boat slow to respond to windshifts, and noticeably reduces the power of the gear, since the rudder is in effect fighting itself through the feedback loop. The right amount of feedback definitely damps the oscillations while retaining adequate power and a quick and lively response to changing wind direction. This is definitely an area for experimentation on the individual boat. I strongly recommend that the feedback ratio be made adjustable in the experimental stages, allowing both positive and negative values. Because the requirement for feedback might depend on the speed or point of sailing, it could be worthwhile to provide adjustable F in the final design. This would surely make more sense than providing adjustable G.

EXPERIMENTS IN BESS

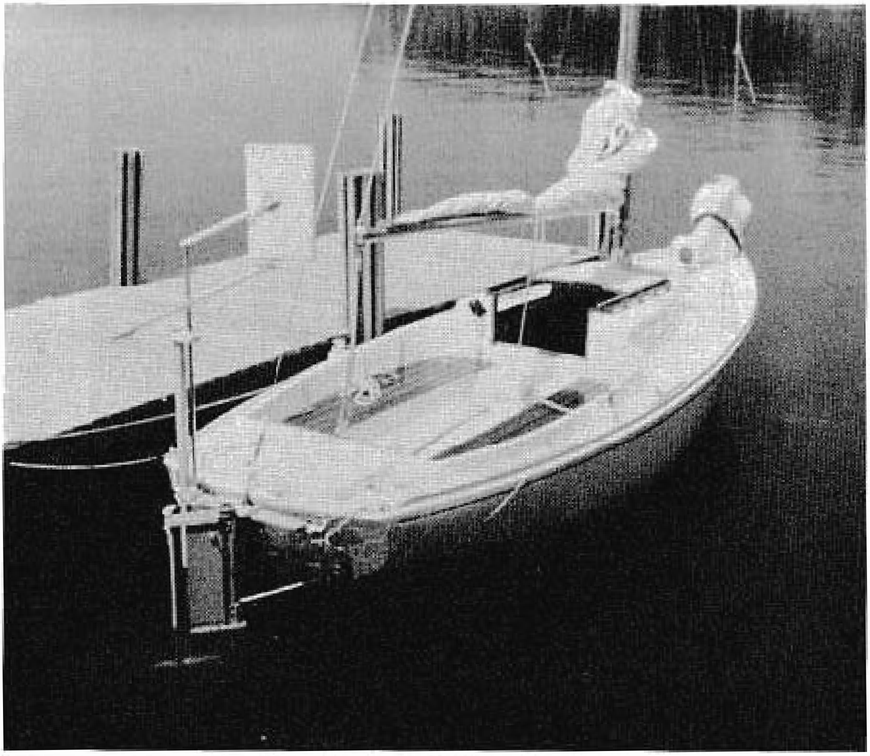
After coming to these conclusions theoretically, I thought some direct experimental tests were in order. The idea was to build a vane gear in which everything possible would be adjustable, then make sailing trials with systematic variations of all the variables, observing the performance of the system.

For this purpose, Bob Carson loaned me *Bess* for a couple of weeks in 1970. She is a Sailmaster-22 keel-centerboard sloop, designed by Sparkman and Stephens, and built of fiberglass by Sailmasters, Inc. of New York. Since she has an inboard rudder, I built a complete vertical axis/servo tab/auxiliary rudder vane gear which mounted on her transom with suction cups, with the auxiliary

Adjustable vane gear made for the experiments in Bess. *The linkage is diagrammed in Figure 8-11.*

rudder volume equal to her primary rudder volume, about 25 ft^3 (0,71 m^3). The following were independently adjustable:

Vane volume: 0.8 to 2.5 ft^3 (0,023 to 0,071 m^3)
Rudder self-volume: 0 to 0.7 ft^3 (0 to 0,020 m^3)
Tab self-volume: 0 to 0.02 ft^3 (0 to 0,0006 m^3)
Vane-to-tab ratio: G = 1, ½, ¼
Rudder-to-tab ratio: F = −1 to 1



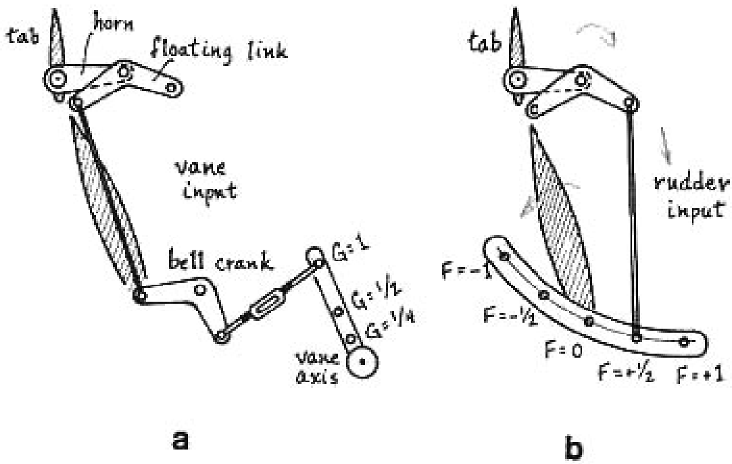
Bess with her adjustable vane gear. Her vital statistics are as follows:

Bess

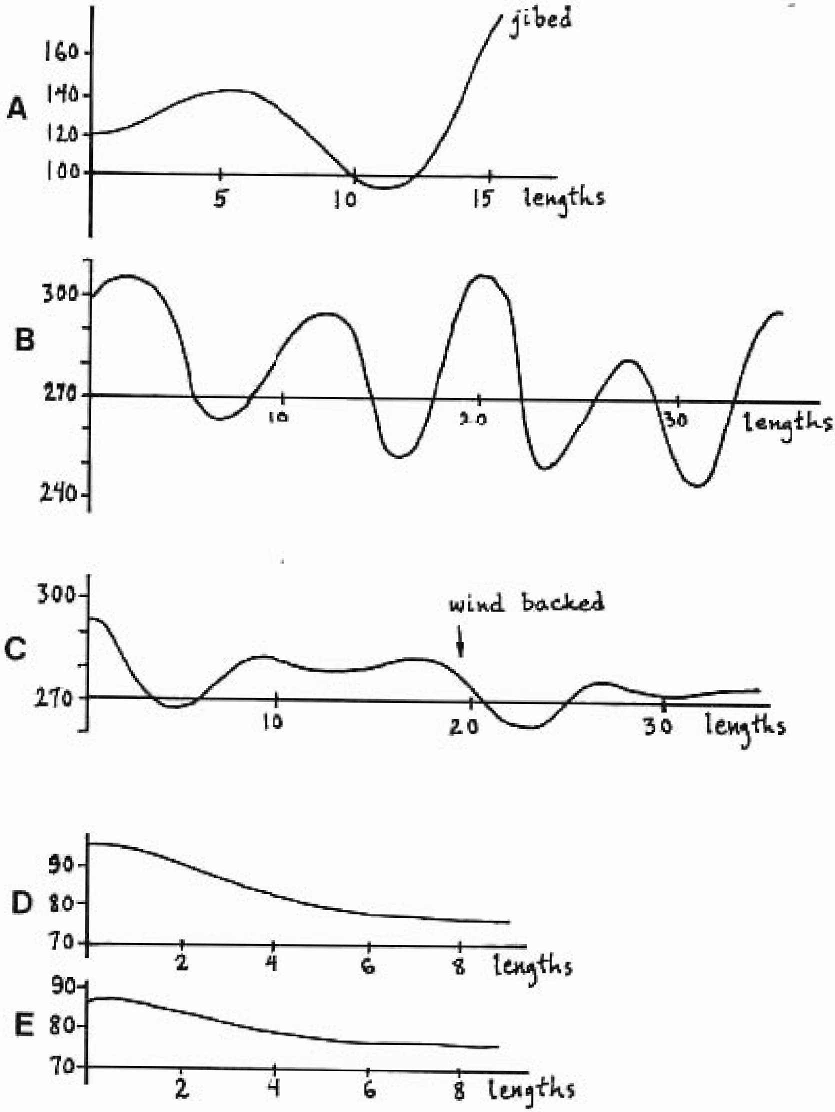
LOA 22′	(6,7 m)
LWL 16′6″	(5,0 m)
Beam 7′	(2,1 m)
Draft 2′4″	(71 cm)
to 5′	(152 cm)
Sail 228 ft^2	(21 m^2)
Displ't. 3650 lb	(1650 kg)

Tab volume was fixed at 0.25 ft^3 (0,0071 m^3). The linkage used bell cranks and a floating link (Figure 8-11) to combine vane and rudder inputs to the tab: tab angle = G × vane angle + F × rudder angle. Ball and roller bearings were used on the vane axis, and friction and backlash were kept to a minimum throughout.

The experiments were most gratifying in terms of verifying the theory. In general, G had slight effect on performance, though the period of oscillation was observed to be shorter with higher G; and with no rudder feedback (F = 0), a lower value of G would usually reduce the amplitude of oscillations. But the effect of F was profound. Figure 8-12 shows actual records of the compass reading versus distance sailed with various settings. Evidently *Bess* has little effective yaw resistance of her own; but by simply switching one connecting rod from one hole to another in the linkage the *system* could be made to have any degree of negative or positive damping. It seemed to me, for this particular boat, the pattern with F = −½ was the most desirable one, and this was true for all settings of rudder self-volume and vane volume, and all wind speeds – except I found that with F = −1 she would run perfectly steady with the



8-11. Details of adjustable linkage for Bess *experiments – (a) linkage from vane to tab, (b) linkage from rudder to tab.*



8-12. Actual records of Bess' steering performance with different feedback ratios: (a) F = +½, dynamically unstable; (b) F = 0, no damping; (c) F = −½, positive damping; (d,e) F = −1, critically damped. (G = ½ in each case.)

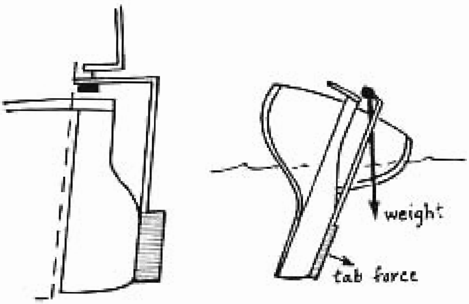
genoa jib wing-and-wing (no pole), while with $F = -\frac{1}{2}$ she oscillated just enough to collapse it occasionally.

LINKAGE REFINEMENTS

There are many possibilities of improving various aspects of vane gear performance by adding further information to that received and processed by the linkage. Whether or not the additional complexity is justified is not always clear; but here are some ideas, anyway.

MASS IMBALANCE TO REDUCE HEEL SENSITIVITY

The yawing moment that results from heeling (because of changes in the thrust-resistance couple, mainly) is always a disturbing factor that a vane gear has to combat. In freshening winds the boat always tends to luff, so she has to run above course at least a little to make up the extra weather helm. Also, in small boats the crew position changes the heel angle significantly, and the resulting yawing moment makes the course vary annoyingly when the crew changes position. I pointed out previously (p. 22) that a heavy rudder puts on increasing weather helm with heeling. The same effect can be achieved with a lot less weight by mass imbalance of a servo tab or pendulum (Figure 8-13). What is required is that the center of



8-13. Excess weight forward of the tab axis applied added weather helm with heeling.

gravity of the tab and its shaft, etc., be *forward* of the tab axis — then its weight tends to apply weather helm as the vessel heels.

HYDRODYNAMIC UNBALANCE TO REDUCE WIND STRENGTH SENSITIVITY

A perfectly balanced control can be used with a single-axis vane, and requires the smallest possible windvane because only bearing friction opposes the vane's rotation. But it isn't necessarily desirable. One advantage of moderate unbalance is reduced sensitivity to wind strength.

If a servo tab, pendulum, or auxiliary rudder is perfectly balanced, it requires no vane angle of attack to provide weather helm, so the vane is always at practically zero angle of attack. Now, if the wind increases, the system can supply additional weather helm only by a change of course. Contrast this with the case of an unbalanced control which requires the vane to be at an angle of attack in trim condition. An increase in wind increases the dynamic pressure on the windvane; and as the speed of the boat does not increase in proportion, the windvane forces the control to a higher angle of attack, hence applying more weather helm. Proportioning things to get the *right* amount of additional helm might be complicated; but at least this effect is working in the right direction.

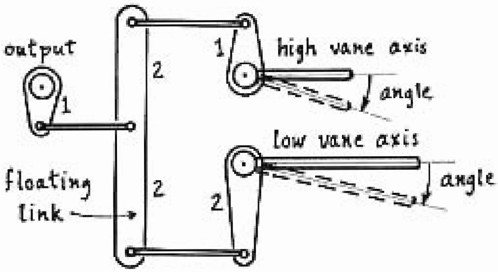
GYROSCOPIC INPUT

Tabarly's 1964 vane gear (p. 143), which introduced the dual-axis windvane, included another new feature — a wind-driven gyroscope connected into the system so as to exert steering influences. Tabarly's gyroscope appears to have been an attempt to provide synthetic damping. The torque exerted by the gyro is proportional to the rate of rotation about the yaw axis, and if it can command steering moments in proportion and of the correct sign, synthetic damping would result. Of course this can now be achieved much more simply by rudder feedback.

Another idea is that in brief moments when the boat is surfing and the apparent wind becomes relatively light, unable to exert much force on the vane, a gyroscope might take over as a gyro compass, temporarily providing a reference direction to steer by until the wind comes back. I don't know if this idea has ever been successfully applied, but it *is* a possible way of extending the range of conditions in which a steering gear will work. Whether or not a yacht will spend a sufficient amount of time surfing to justify the complication is hard to say.

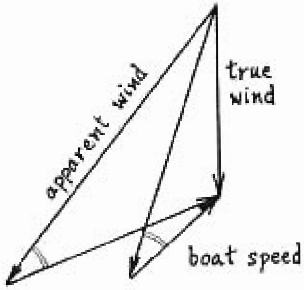
DIFFERENTIAL VANES TO ANTICIPATE YAWING

While discussing the placement of a windvane (p. 137), I noted that a high vane is affected by rolling, in an adverse sense for running before the wind. This effect could be turned to advantage by using two single-axis vanes, one high and one low, and combining their two outputs in the right way with a differential mechanism (Figure 8-14).

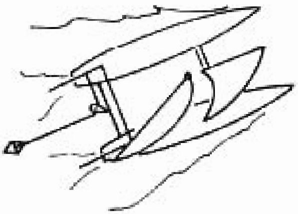


8-14. Example of linkage combining wind angles from two vanes.

To set a course, both vanes are allowed to weathercock and then are locked to their axes with separate clutches. As long as the boat doesn't roll, the two vanes indicate the same wind direction and the output movement is simply proportional to the error in the course. Any difference in the angle between the two vanes, caused by rolling, also provides a movement of the output, with the correct sign to command a turn to the side toward which the roll is taking place. The differential has to reverse the upper vane angle and combine the two like: output angle = low vane angle — ½ × high vane angle. This refinement has the potential of dramatically improving system performance in difficult, rough conditions, and might be worthwhile for racing.



8-15. Apparent wind diagrams for "breakaway."



8-16. As the craft accelerates, the drogue pulls the helm down.

ANEMOMETER OR SPEEDOMETER INPUT

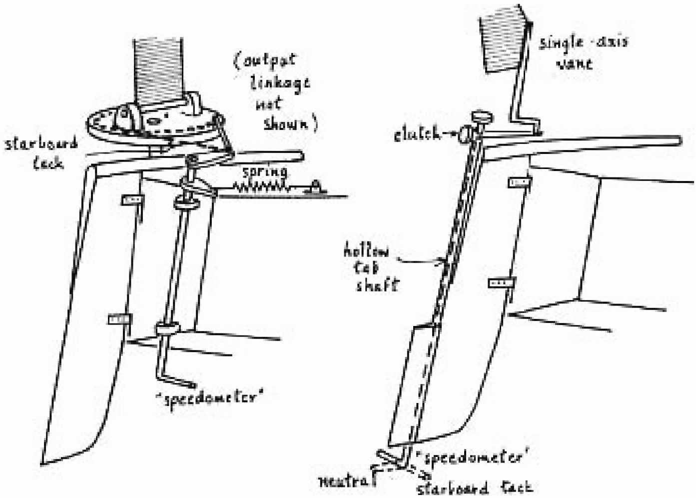
A major problem in self-steering for fast trimarans and catamarans is the phenomenon called *multihull breakaway*. Because of its stiffness, a multihull does not have the strong natural course stability (p. 19) of a monohull while close reaching, so it is largely dependent on its vane gear for course stability. But because of its high speed capabilities reaching, there can be a wide range of true course angles having almost the same apparent wind angles. This renders the vane relatively insensitive to course changes. The "breakaway" referred to occurs while close reaching at relatively low speed, when the boat falls off the wind and accelerates enough to keep the apparent wind angle the same (Figure 8-15).

Breakaway is accompanied by a major increase in boat speed and a lesser increase in apparent wind speed. Fixes have been proposed using either of these to provide additional input to the steering system. Increased apparent wind or increased speed should apply a luffing moment through the control. This can be done by brute force, such as towing a drag which is led to the lee side of the tiller (Figure 8-16); or it can be done more elegantly using the power gain capabilities of a dual-axis vane or a servo control, by introducing wind speed or boat speed information to the linkage. This requires an anemometer or a speedometer of sorts. It doesn't have to be fancy, as shown in Figure 8-17 by two of the many possible arrangements. Because the boat speed shows a bigger relative increase than the apparent wind speed, it seems to be the best input signal to use for the breakaway problem.

Anemometer input could be used for extending the operating range of a vane gear broad reaching in strong winds. A puff has to be answered with weather helm, to make her hold her course or drive off somewhat before it. Some device that is sensitive to wind strength, coupled into the linkage, could achieve this.

SPRINGS

In sheet-to-tiller self-steering, sensitivity to wind strength is always balanced out by adjusting elastic to the right stiffness and tension.

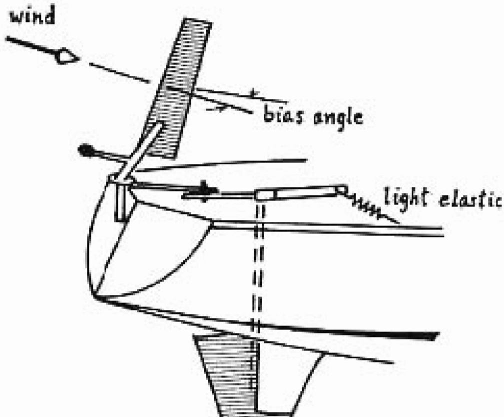


8-17. Two servo systems to counteract breakaway.

It is surprising, when you come to think of it, that springs do not play a similar role in most vane gears. In fact they *can* be used, in any number of ways, to control the response of the boat to changing wind speed.

There are several facets to the question of wind strength sensitivity. First, an increase in wind almost always calls for more weather helm, and no matter how powerful the vane gear, it has to change course some to supply more weather helm. Second, even if you could maintain constant apparent wind direction, this would not be a constant true course, because the boat speed increases proportionately less than the apparent wind speed. The object in most conditions is that the boat should keep a constant true course, though this isn't always the case — running off in puffs is desirable when broad reaching, and feathering up with the puffs is essential to best performance close-hauled. A further complication is that the true wind usually shifts direction in the puffs, in a fairly consistent pattern, as explained by Alan Watts in *Wind and Sailing Boats* (Quadrangle Books, 1965).

To meet all these varied circumstances, it may be desirable to provide an adjustable input sensitive to wind strength. The windvane itself is highly sensitive to wind strength, as the force on it (as



8-18. Biasing elastic to reduce sensitivity to wind strength.

long as its angle of attack is different from zero) is proportional to the dynamic pressure. All you have to do is provide something for the vane to work against – an unbalanced control (p. 190), or a spring – so that it takes up an angle of attack in the trim condition. A spring would be an easily adjustable solution. It could be connected to almost any point on the vane or linkage. To show how simple this could be, Figure 8-18 shows *Mick the Miller* set up with a biasing spring. When the wind freshens, the vane tends to straighten out, applying more weather helm to hold her on course or make her bear away. Elastic to the *weather* side could be used for close-hauled sailing if needed to make her lift up into the puffs.

Of course this reduces the power of the system somewhat, as the vane has to work against the elastic, as well as friction and unbalanced hydrodynamic moments, to move the control.

9 THE COMPLETE VANE GEAR

We have gone about as far as we can go talking about the control, windvane, and linkage separately — the time has come to make them work together. Let's start back at the beginning, with a bare boat, and apply all this knowledge to the problem of fitting her out with successful windvane steering. In its most logical development, this process will take five steps.

1. Take her out sailing

The one characteristic of the boat that bears most heavily on self-steering — yaw resistance — is something that can't be divined by looking at the boat, or by calculations based on the design, or by model testing, at least not at present. It can be judged qualitatively by just a short period of steering if you know what behavior to look for; but an almost *quantitative* determination can be made by the test outlined on page 165. If possible, this test should be repeated on several points of sailing and in different winds. The longer the period of getting to know the boat, the more useful data you can gather. Yaw resistance observations are the most important, but other more qualitative impressions can be helpful. Judge the adequacy of the rudder, because it is the basis of comparison in choosing the control volume. Judge whether her helm is relatively easy or hard, and assess the degree of balance of the rudder.

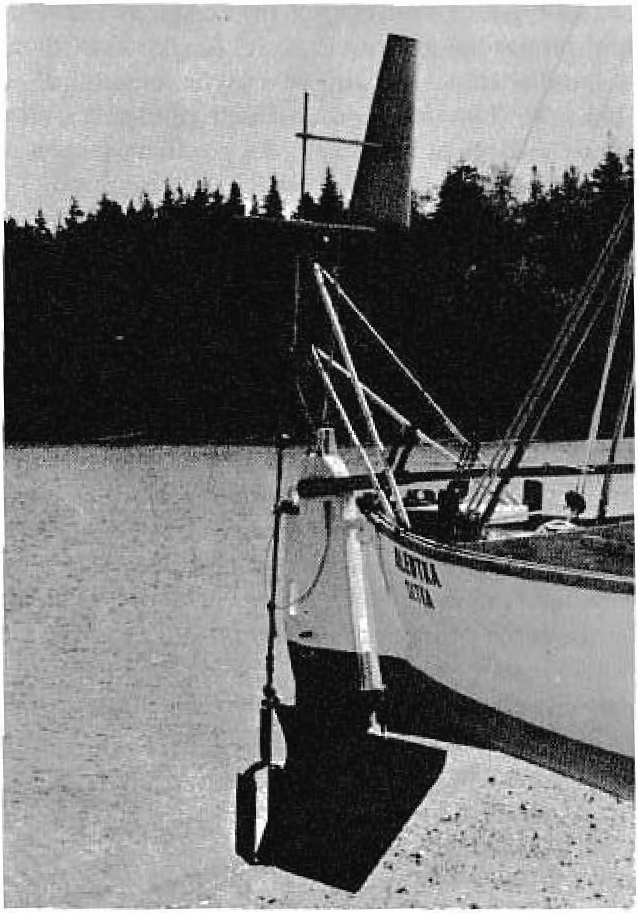
2. Design the control

The choice of the control depends to a great extent on the yaw resistance findings, as analyzed on pages 166-8. The self-steering control may have to add more or less synthetic damping. For this quality, the various types of controls fall into order as follows: (1) The servo pendulum has the greatest capacity for synthetic damping, and could be a suitable choice for any boat if the mechanical complexity is acceptable. (2) The balanced auxiliary rudder is a close second; it can be made as large as necessary. An auxiliary rudder with a tab has similar effectiveness, if rudder feedback is employed. (3) Using the primary rudder either directly or with a tab can give sufficiently stable operation on any boat that shows definite positive damping in the sailing test. Either control requires some rudder feedback, more feedback the closer the boat is to neutral yaw resistance. These controls can approach, but not equal, the yaw resistance observed in the test. (4) A tab on the primary or auxiliary rudder with direct linkage to a vertical-axis vane makes a feedback system ($F = +1$) that detracts from the boat's natural yaw resistance; it should be chosen only if the boat tests out with strong yaw damping.

Logical sizes for all these control have been suggested in Chapter 5, based on rudder volume and self-volume. Once the type of control is chosen, the design is a matter of fitting it in on plans of the boat so it doesn't interfere with anything, so it can be amply supported, and it will be big enough. By all means think about how a permanent installation will be built, but don't spend much money on it yet. Use steel bearings, steel bolts, plywood, and electrical conduit until the design is verified.

3. *Take her out sailing again*

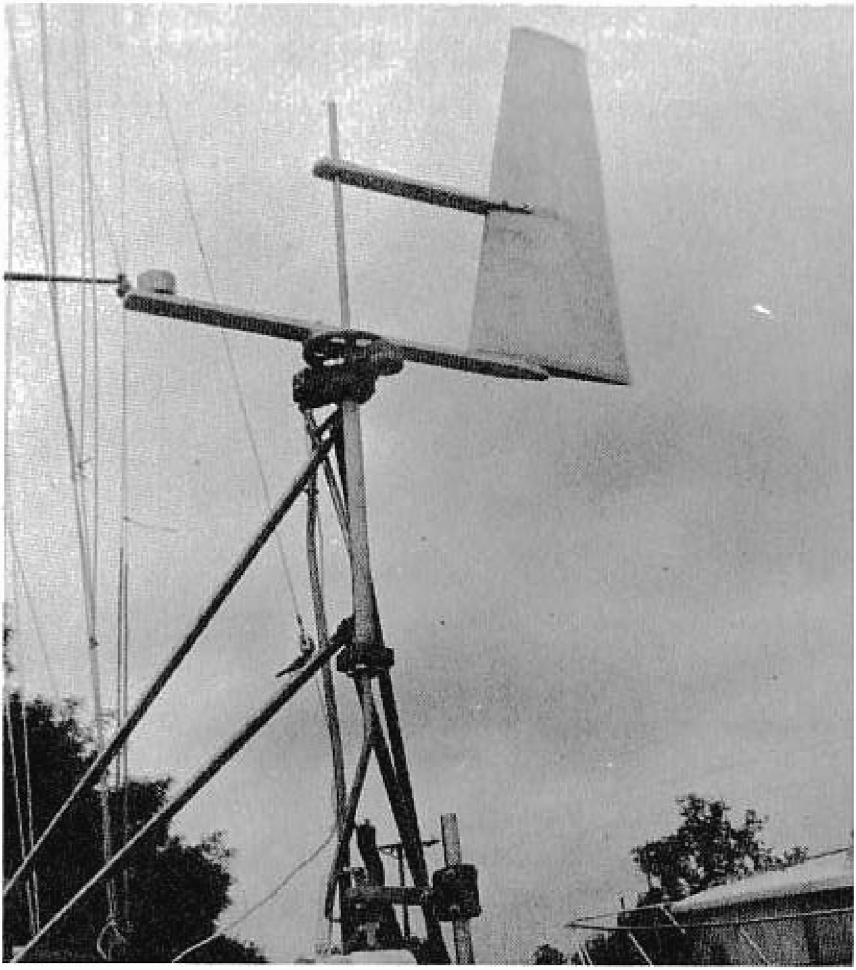
Another sailing test is desirable once the control is installed. This is mainly to assess control power, balance, and friction. The best way to tell about this is to steer with the control. Lash the primary rudder and use the auxiliary rudder for steering under a variety of conditions. If you've put on a tab or pendulum, put your hand on the tab or pendulum tiller and steer from there. (With a tab, add a reversing linkage so the movements have the same sign as with tiller steering — otherwise steering in reverse is pretty confusing.) If the control has insufficient power, you won't be able to steer in a breeze. If it has friction or is completely unbalanced, you can feel the torque necessary to turn it, and have time to think about whether a small vane would make that much torque. If it is overbalanced



Aleutka's complete installation.

(p. 103), that too will show up in the control's instability, suggesting a reduction of balance area. Chances are good that some unanticipated problems will show up, and you'll be ahead of the game if you've just used disposable materials so far.

Another thing to check if you're adding an auxiliary rudder is the yaw resistance with the control centered and locked. Go through a new series of yaw damping tests. Positive damping better show up



Aleutka's *single-axis vane and clutch.*

now; if not, stable steering is still unlikely unless the auxiliary rudder is made bigger or moved farther aft.

When the control works smoothly and easily, provides sufficient steering power for the conditions you want the gear to handle, and provides positive yaw damping — then you can be confident of success. All this can be worked out and refined at a very low cost in

Aleutka's *feedback linkage.*

materials, and without having to explain to every curious onlooker why your vane gear isn't working yet.

4. Temporary vane and linkage

Logical linkage ratios for each combination of vane and control were suggested in the last chapter. Vane size requirements will be explored in a few pages, but it's all very much open to experimentation. I recommend making the linkage ratios adjustable, by any kind of Rube Goldberg contrivance, and trying several vanes to find the

The vane gear steering Aleutka *to windward in a fresh breeze (Patricia Letcher photo)* smallest you can get away with. Go off on a cruise, or make several day sails to test all points of sailing in a variety of winds. Try to settle on values of linkage ratios that work for all conditions, so as to simplify the final linkage.

5. Permanent hardware

With the successful temporary design in hand, go to work on making it permanent. You'll want to duplicate the control with materials that will steer through a gale, or sail across oceans, and cause less trouble than the primary rudder installation. Now is the time to spend three dollars a pound for Everdur stock, or forty hours of time molding a fiberglass rudder; to hunt up stainless steel bearings and pay out ten dollars per joint for heliarc welding of stainless tubing. If you know you have a design that works, and is near the optimum for your boat, it's not at all painful to spend lots of time and money making gear that will last.

VANE SIZE REQUIREMENTS

In Chapter 5, logical requirements were found for the minimum size for each type of control — auxiliary rudder volume in relation to primary rudder volume, tab or pendulum volume in relation to rudder self-volume. In Chapter 8, logical values were found for the gearing ratios between various vanes and controls. In Chapter 6, windvane effectiveness was described in terms of vane volume, but at that point the requirements on vane volume could not be specified.

It's not hard to tell when the vane is too small. If the control is strong enough, and has low enough friction — you can judge this easily by manual steering with the control — yet the vane doesn't turn it when the boat goes off course, then the vane isn't big enough to do its job. This is most likely to show up when running, when air dynamic pressure is lowest relative to water dynamic pressure, and especially in strong winds when the boat's instability is strong.

There are three ways to improve on this. (1) A bigger vane (more volume) is the simple answer. (2) Increasing the mechanical advantage would be one way, though we have seen this has its limitations. (3) Improving the control balance is the most promising answer. The more nearly balanced is the rudder, the tab, or the pendulum, the less work the vane is required to do. When perfect balance is reached, nothing is left for the vane to do but overcome friction.

A vane bigger than necessary does not give itself away by any defect in performance. If the vane steers all right running, it will have excess power on other courses, but there's no harm in this. But an unnecessarily large vane means more drag, more materials, bigger structural problems, and more exposure to damage than necessary. So it is worthwhile to seek the minimum size.

Because friction and balance are so critical in determining vane size, and because they are both fairly hard to predict with any confidence, experimentation is the only sound approach. Start out with a vane bigger than necessary and cut it down until you start to notice impaired performance running in stronger winds. If friction is very low, though, a good guideline for all types of vanes and controls is: vane volume = 100 × G × control self-volume. This can be used as a first guess at the vane size, subject to experimental verification.

For example, in *Bess* with the tab volume set equal to the auxiliary rudder self-volume and the tab (.22 ft^2, or 0,020 m^2) moved ¾ inch (19 mm) back from its balance position, I had a tab self-volume of .22 ft^2 × .063 ft = .014 ft^3 (,0004 m^3). Using my minimum vane volume of 0.8 ft^3 (,023 m^3) and my highest gearing ratio G = 1, I had

$$\left(\frac{\text{vane volume}}{\text{G} \times \text{control self-volume}} = \frac{0.8\ \text{ft}^3}{1 \times .014\ \text{ft}^3} = 57\right)$$

and the gear noticeably lacked power running in moderate winds. By *either* increasing the vane to 1.5 ft^3 (0,043 m^3)

$$\left(\frac{\text{vane volume}}{\text{G} \times \text{control self-volume}} = \frac{1.5\ \text{ft}^3}{1 \times .014\ \text{ft}^3} = 107\right)$$

or switching the gearing ratio to ½

$$\left(\frac{\text{vane volume}}{\text{G} \times \text{control self-volume}} = \frac{0.8 \text{ ft}^3}{\frac{1}{2} \times .014 \text{ ft}^3} = 114\right)$$

or moving the tab ahead ⅜″ (9,5 mm)

$$\left(\frac{\text{vane volume}}{\text{G} \times \text{control self-volume}} = \frac{0.8 \text{ ft}^3}{1 \times .007 \text{ ft}^3} = 114\right)$$

I found I could restore the gear to full power. Though I tried values of this ratio up to 2,500

$$\left(\frac{\text{vane volume}}{\text{G} \times \text{control self-volume}} = \frac{2.5 \text{ ft}^3}{\frac{1}{4} \times .004 \text{ ft}^3} = 2{,}500\right)$$

there was no further improvement in performance once the ratio was over about 100.

Another example: I made an experimental horizontal-axis vane to steer *Aleutka* with her 4 ft^2 (0,37 m^2) primary rudder, which is partially balanced, with a balance arm of about 4 in. (10 cm), so the control self-volume is 1.33 ft^3 (0,037 m^3). The vane area was 3 ft^2 (0,28 m^2), with a vane arm of 1.8 ft (55 cm), so the vane volume was 5.4 ft^3 (0,15 m^3). With a gearing ratio of 1/10.

$$\left(\frac{\text{vane volume}}{\text{G} \times \text{control self-volume}} = \frac{5.4 \text{ ft}^3}{1/10 \times 1.33 \text{ ft}^3} = 41\right)$$

the gear had insufficient power for reaching in even Force 3. When the gear ratio was changed to 1/20,

$$\left(\frac{\text{vane volume}}{\text{G} \times \text{control self-volume}} = \frac{5.4 \text{ ft}^3}{1/20 \times 1.33 \text{ ft}^3} = 82\right)$$

satisfactory performance was obtained in all moderate winds.

THE VANE GEAR COOKBOOK

As I noted at the end of Chapter 4, the crux of putting together this book has come in the vane gear chapters. The problem is that even the simplest vane gear — combined into the dynamic system of a sailboat — is a complex mechanism, and there are many technical subtleties in understanding its performance. How am I to explain enough of these to the practical non-technical sailor to equip him to build a satisfactory vane gear, without scaring him away with a bunch of formulas and technical terminology? In this endeavor my greatest encouragement comes from my lay acquaintances who managed to work out their vane gears with absolutely no help from differential equations or aerodynamic theories. There are many who have succeeded by just guessing at proportions, experimenting, and understanding the operation in a purely qualitative way. Can I assist in this process and give some useful directions to the sailor who really doesn't care about the exact relationship of lift-curve-slope to aspect ratio, for example?

The only answer to this is "cookbook engineering." In my student days at Cal Tech, this was a disdainful term for the process of looking up in the right book, finding some step-by-step instructions, and following them blindly to a solution without even trying to understand the theory behind it. It's like looking up the recipe for a cake. The book tells you exactly the proportions and quantities of ingredients, the methods and order of combining them, the size of the pan, the temperature of the oven, everything you need — and if you follow the directions exactly, nine times out of ten you get a beautiful cake without ever having to think about the sodium bicarbonate reacting with the calcium acid phosphate, or the crucial, subtle balances between expanding steam and coagulating proteins.

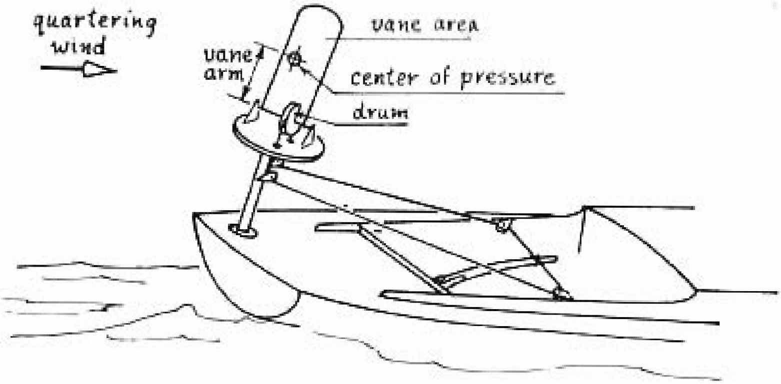
At Cal Tech we had good reason for being scornful, because there are serious limitations to cookbooks. One is that if you just follow recipes, you never discover anything new. Worse, if the solution comes out obviously wrong — if your cake comes out half an inch high, or hard as a rock — you have no idea what went wrong, or where to look for the error, which of the underlying assumptions you overlooked, or which of the directions you misunderstood. We were there to learn the underlying theories. I must say, though, that my respect for engineering handbooks has increased immeasurably since I went to work. So often there just isn't time to understand the theory; the answer is needed by seven o'clock tomorrow morning even if there's a 20 percent chance it's completely wrong. There are too many other pressing problems to permit the luxury of really getting to the bottom of any one of them. The cookbook gives a workable answer a remarkable percentage of the time.

So without further apology, I will offer my recipes for five different vane gears. The proportions and recommendations are based on successful gears, systematic experiments, and theory — most of which are explained in the last four chapters — and some assumptions about the proportions of the boat. They will prove satisfactory for, I would guess, at least four out of five yachts of the "normal" range of types. If you follow the directions (and if your boat is one of the lucky four), you will not have to get involved in the more technical parts of Chapters 5 through 8. The choice between the different types is mainly on the basis of compatibility with the existing steering gear and stern configuration; except where noted, there is no fundamental advantage of one type over another.

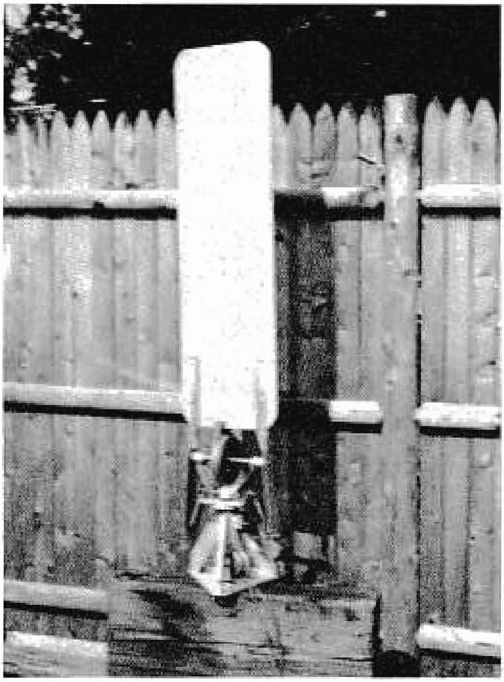
GEAR NUMBER 1 — HORIZONTAL-AXIS VANE/ RUNNING LINES/PRIMARY RUDDER (Figure 9-1).

Make the vane three times as tall as it is wide, with area equal to the area of the rudder. Use ball bearings on the two ends of the vane axle, and a counterweight that exactly balances the weight of the vane. The bearings are supported on a platform or framework that is able to rotate about a vertical axis and then be locked in position for course setting. Rotation of 180 degrees, preferably 320 degrees, or even better, 360 degrees, about the course-setting axis is required. Operation of the vane is explained on p. 144.

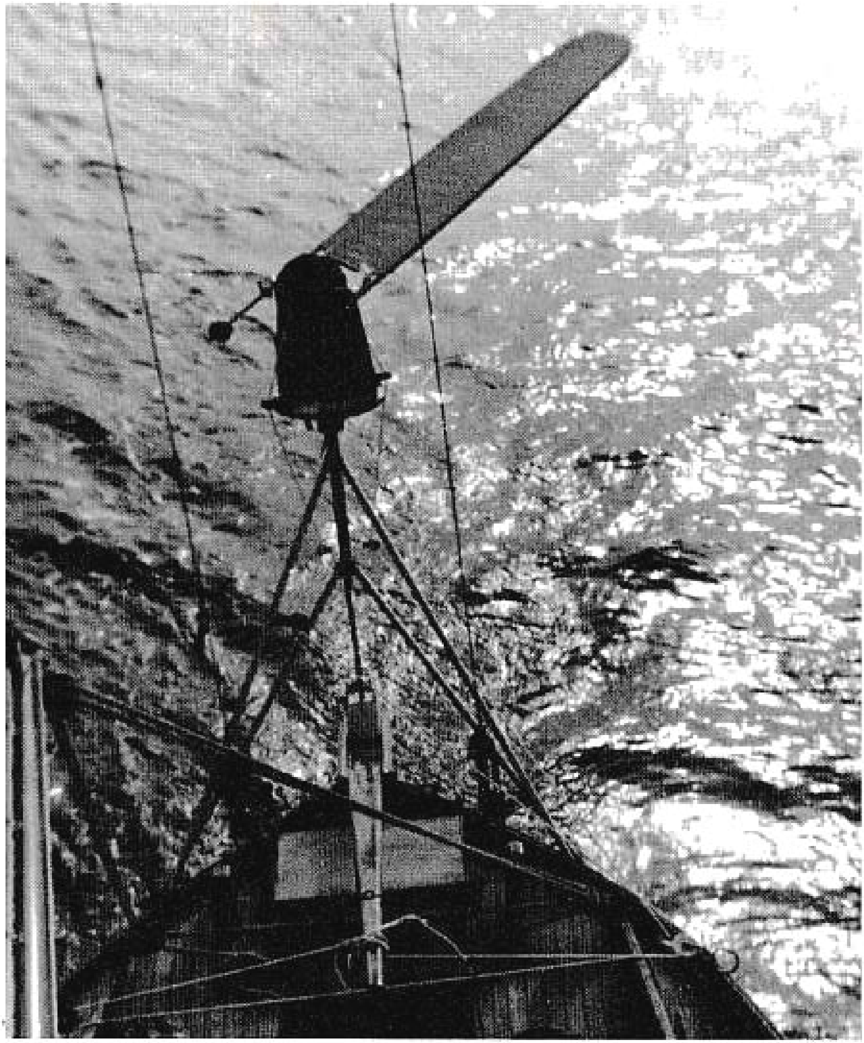
A drum or quadrant on the vane transmits the movements of the vane to the running line. The running line can be dacron rope, but 1/16″ diameter flexible cable with rope tails is better. To allow adjustments to the course setting without upsetting the running line adjustment, each part of the running line must lead from the drum to a sheave located somewhere *on* the course-setting axis, then on to



9-1. Windvane gear number 1: Dual-axis vane/running line linkage/primary rudder.



A sturdy horizontal-axis vane with running-line linkage made by Ratcliffe Marine Design.



A horizontal-axis/running line gear operating Aleutka's *partially balanced primary rudder.*

the tiller. The running line should be routed through the minimum number of blocks, which should be especially low-friction types — generous diameter, preferably with ball or roller bearings. The diameter of the drum is one-tenth of the perpendicular distance from the rudder shaft to the point where the running lines tie off on the tiller. (More generally, 90 degrees rotation of the vane on its axle should move the rudder about five degrees). Loosen the rudder shaft packing and otherwise reduce rudder friction as much as possible.

Operation

(1) With the boat on any desired course, turn the course-setting axis so the vane axle is lined up with the wind, then pull on the running lines to center the vane, so it stands up vertically. (2) Now tie off the tiller (weather side), providing whatever weather helm the boat needs, with one end of the running line. It is important to pick the *right* end of the running line, but this depends on which edge of the vane is being used for the leading edge. (If you've picked the wrong end of the running line, this quickly becomes obvious by the boat's complete disinclination to steer herself.) (3) Then pull the other end of the running line snug, but not so tight as to cause a lot of block and bearing friction, to the lee side of the tiller. Now you should find her steering herself, but maybe a little off the desired course. (4) A little adjustment of the course-setting axis will fix this.

Trouble-shooting

(1) If it doesn't work at all, reverse the ends of the running line. (2) If it lacks power, can't provide the weather helm in strong winds, try a smaller drum, and, if that doesn't work, a bigger vane will be needed. (3) To improve sensitivity in light winds, reduce friction in the bearings, blocks, and stuffing tube. (4) If it oversteers and zig-zags, see p. 174 for an improvement.

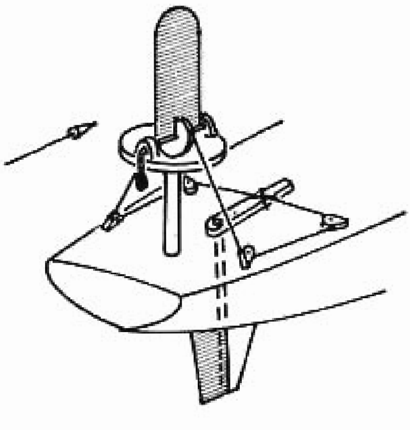
GEAR NUMBER 2. DUAL-AXIS VANE/AUXILIARY RUDDER (Figure 9-2).

The auxiliary rudder can have about one-third the area of the primary rudder. If it is perfectly balanced, or nearly so, the vane axle must be inclined about 10 degrees from horizontal. Make the auxiliary rudder blade between two and three times as deep as it is wide. It can be hung on a skeg if desired.

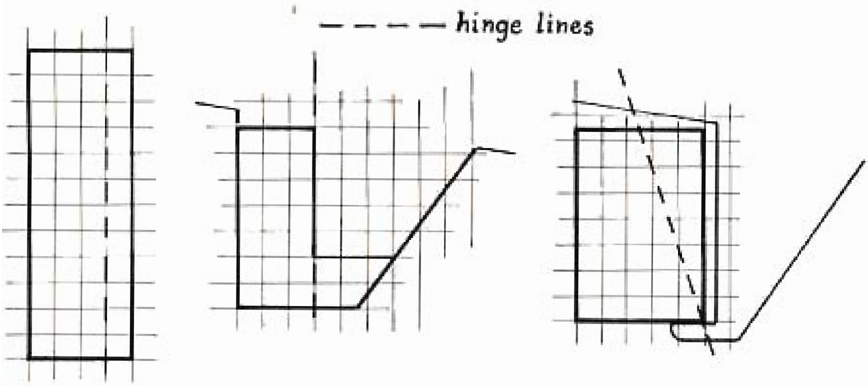
The windvane design and requirements follow the preceding design closely, except the vane area need only be as large as the auxiliary rudder. Any type of linkage between the vane and the rudder that provides low friction and adequate strength can be used, but the ratio of rudder angle to vane angle should be 1/3 (for example, if the vane is turned 30 degrees on its axle, the auxiliary rudder should turn 10 degrees).

Operation

(1) The yacht is put on the desired course and the course-setting axis is turned to line the vane axle up with the wind. (2) Next the auxiliary rudder, previously disconnected, is hooked up to the vane output so self-steering results. (3) Then the helm is lashed so that the primary rudder provides all of the weather helm, plus a stabilizing effect. (4) Probably a small change in the course-setting axis is now required to adjust precisely to the desired course.



9-2. Windvane gear number 2: Dual-axis vane/auxiliary rudder (output linkage is diagrammatic only; this would not permit other course settings).



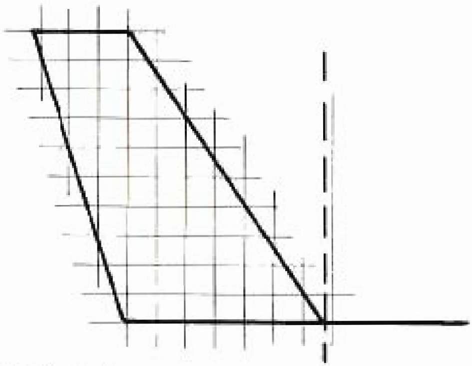
9-3. Three patterns for balanced rudder designs.

Trouble-shooting

(1) If the system lacks power to cope with strong winds and hard driving, probably the auxiliary rudder is not big enough. (2) If the system lacks light-wind sensitivity, look for friction as usual, especially in the auxiliary rudder gudgeons. (3) If she oversteers or zigzags, the linkage or vane can be modified to correct this (p. 174).

GEAR NUMBER 3. SINGLE-AXIS VANE/AUXILIARY RUDDER. This one is like *Mick the Miller* (Figure 4-1). Make an auxiliary rudder with one-third the area of the primary rudder. It must be almost perfectly balanced (p. 103), and this is a hard thing to design with any confidence. I suggest scaling up one of the three designs of Figure 9-3, which turned out well balanced in model experiments I made, but even then be prepared to revise the shape of the auxiliary rudder blade if it takes more than light finger pressure to steer with the auxiliary rudder in any conditions. Also, the bearings have to be good to satisfy this steering test.

If your auxiliary rudder is well balanced, and if you have done a good job fighting friction, the vane can be very small. An experimental approach is advised, starting with a vane area about the same as the auxiliary rudder area, with the vane proportioned as in Figure 9-4, and working down if desired. This is the size used by *Mick the Miller*, with all plastic bearings, so I expect it could be consider-



9-4. Pattern for single-axis vane.

ably smaller with ball bearings. Accuracy of steering downwind in light conditions is the first aspect of performance to suffer if you should make the vane too small.

Operation

With the auxiliary rudder's tiller centered and the vane clutch disengaged (so the vane weathercocks), put the boat on the desired course. Then engage the vane clutch and lash the helm. Lashing the helm supplies whatever weather helm is needed, leaving the auxiliary rudder to make just small corrections; also it improves yaw resistance by lengthening the effective lateral plane. Fine course adjustments can be made either with the vane clutch or with the helm lashing.

Trouble-shooting

(1) If the gear lacks power in all conditions, probably the auxiliary rudder isn't well enough balanced. (2) Lack of light-wind sensitivity, or a tendency to oscillate in light winds only, indicates friction. (3) If oscillation occurs under most conditions, try reducing the gear ratio (so the rudder turns *less* for a given rotation of the vane); but this will probably weaken the system too much before it cures the oscillation. A bigger, well-balanced auxiliary rudder can fix it.

GEAR NUMBER 4. SINGLE-AXIS VANE/DIRECT LINKAGE/ SERVO TAB (Figure 7-8).

Direct linkage of the vane to the tab makes the simplest and cheapest servo system, one that has served satisfactorily for a number of great long-distance voyages. This gear's simplicity is a great recommendation, but it has a disadvantage that should be clearly recognized from the start. *It has an inherent tendency to oversteer and oscillate, so it can only be applied successfully in boats that have a high degree of yaw resistance.* A sailing test for evaluating yaw resistance is suggested on p. 165. I would advise this gear only for boats that show strong yaw resistance in such a test; even then considerable oscillation might have to be accepted.

If an auxiliary rudder is used, give it half the area of the primary rudder, and read "auxiliary rudder" in place of "rudder" in the following three paragraphs.

The tab may be hung right on the trailing edge of the rudder, in which case the area of the tab should be about one-sixth of the rudder area. If the tab is hung farther aft, its area can be less: for example, if the distance of the tab from the rudder axis is one and one-half times the rudder chord, a tab having one-tenth of the rudder area will do as well. Balancing the tab (by putting some of its area forward of its hinge line) is beneficial up to a point, though a perfectly balanced tab will have more tendency to change course with changes of wind strength (p. 190).

The beautiful simplicity of this gear is that the vane and tab turn together on the same shaft, requiring only two bearings. The tab shaft has to support the windvane, as well as pressures on the tab, so it ought to be plenty strong — say 1-inch (25 mm) O.D. pipe or solid shafting in boats up to 30 feet (9 meters overall, and bigger in proportion to the length for bigger boats. I have seen several seagoing versions of this gear that used plain metal-to-metal bearings, but in each case it seemed that much better light-wind performance could have been gotten by using a ball bearing for the upper bearing, to carry the weight of the whole rig.

A clutch and a windvane complete the gear. The vane area required depends on friction and tab balance, so it's open to experimentation. Using a vane proportioned about like that in Figure

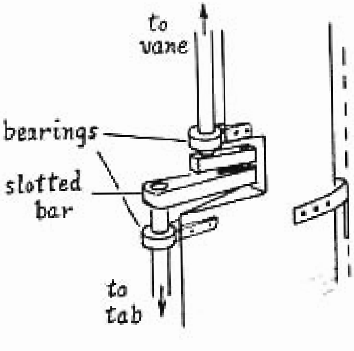
9-4, a vane area that is ten times the tab area should be sufficient in the worst case of a completely unbalanced tab. This is a pretty big vane, but the requirement can be greatly reduced. If you have the tab fairly well balanced, start with a vane (with these proportions) with four times the tab area and then try cutting it down.

Operation

This is simplicity itself. Disengage the clutch and put the boat on course, allowing the vane to weathercock. Engage the clutch. If using the tab on an auxiliary rudder, lash the helm to supply the necessary weather helm. If using the tab on the primary rudder, a fine adjustment of the clutch will now be needed to get her on the desired course with the right amount of weather helm.

Trouble-shooting

(1) If the oversteering is too much to tolerate, try reducing the tab area. This weakens the power of the system, but a compromise might be found. (2) Another way to reduce the oversteering tendency, that might allow the boat's limited yaw resistance to overcome it, is to introduce a reduction in the linkage between vane and tab (Figure 9-5). But this is quite limited in the amount of yaw damping it can provide, and it immediately requires separate shafts and bearings for the tab and vane. So you may as well go to the next recipe and hang the vane on the boat instead of on the rudder, with



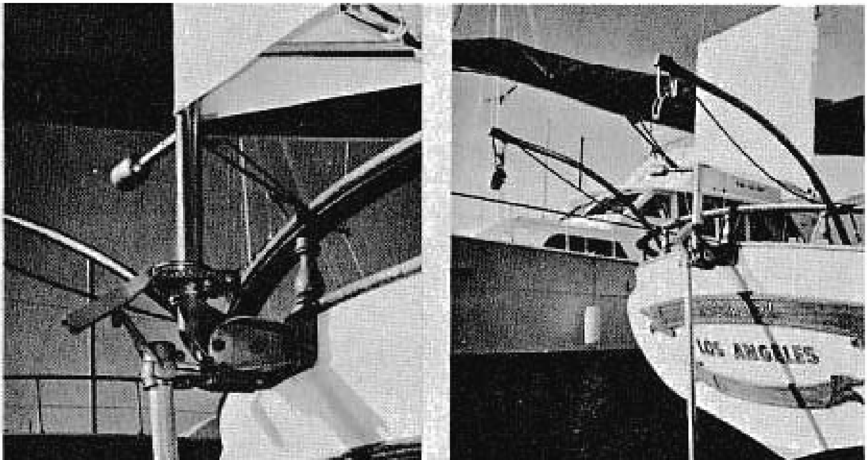
9-5. Reduction linkage between vane and tab.

opportunity for positive yaw damping. (3) If the system is sluggish, especially off the wind in light conditions, a bigger vane will help, but better bearings are the real answer. (4) If the system lacks power for providing weather helm and steering in moderate winds, a bigger vane will help, but better tab balance can help a lot more.

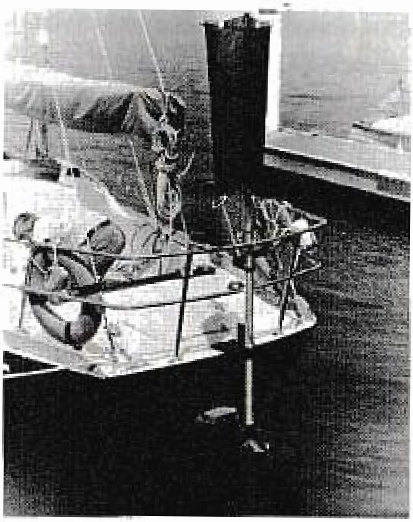
GEAR NUMBER 5. VERTICAL-AXIS VANE/FEEDBACK LINKAGE/SERVO TAB

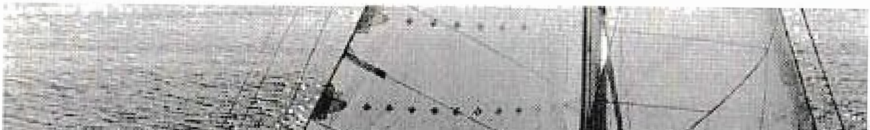
The positive way to overcome the oversteering problem with this combination of vane and control was explained in some detail on page 170. The important change to make from the direct linkage just described is to hang the vane bearings on the boat, the stern pulpit, or the backstay, rather than on the rudder, and then pay particular attention to the way the vane rotation is transmitted to the tab.

This can be done with a servo tab on either the primary or an auxiliary rudder. The auxiliary rudder, the tab, and the vane should be proportioned just as in the preceding article, and again a nearly

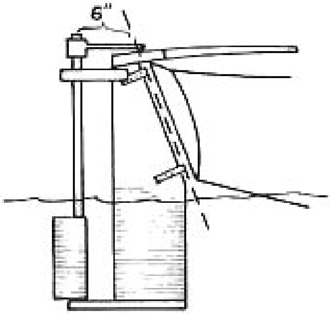


A vertical-axis vane with feedback linkage and a servo tab manufactured by Roland Saye.





Hal and Margaret Roth's Spencer-35 Whisper *with her new Riebandt auxiliary rudder/servo tab gear and a wedge-section vertical-axis vane. She was fitted with a Hasler servo pendulum vane gear for her voyage from San Francisco via many islands to Japan and back.*



9-6. Tab shaft and tab tiller positions.

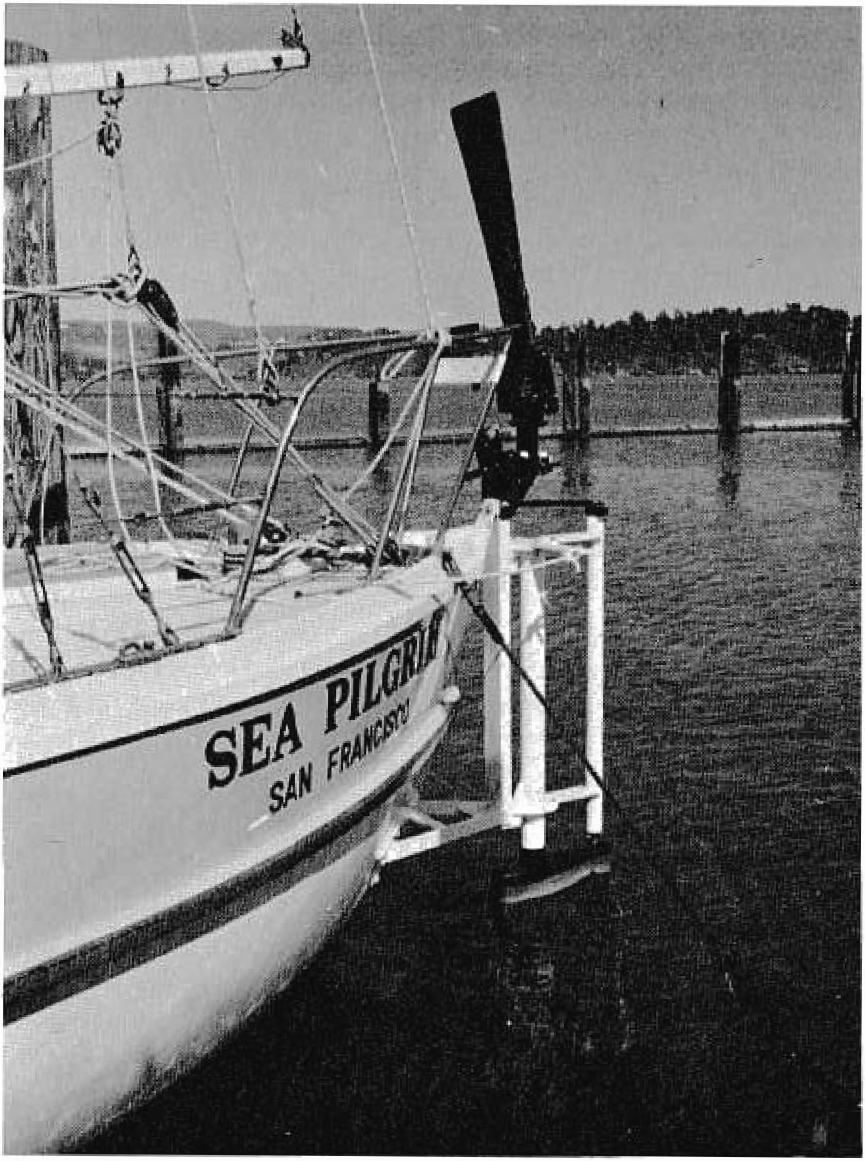
9-7. Tab tiller with holes for several crosslink settings.

balanced tab will be found to require the least amount of vane area.

Arrange the tab shaft to come up a little above the rudder head, to a position six inches (15 centimeters) behind the hinge line that the rudder turns on (Figure 9-6). Provide a six-inch tab tiller on the pattern of Figure 9-7. (This and the crosslink below are standard marine hardware.) A pin through one of the holes into the rudder head will serve to immobilize the tab when the gear is not in use.

The vane axis will be one foot (30 centimeters) or more off the centerline, and will come down to a position athwart the top of the tab shaft. It doesn't have to be vertical, and a *forward* rake is beneficial (p. 142), but for the drawing I'll show it vertical. The upper and lower vane bearings are best supported on a welded tubular framework and a short spar respectively, completely independent of the rudder (Figure 9-8).

On the bottom of the vane shaft, at the level of the tab tiller, there is another six-inch arm with several holes in it. This can be part of the clutch mechanism, or can be a separate part as shown. The coupling is effected by a crosslink between the two arms. Ball-and-socket ends are good for eliminating the effects of misalignment



The Polaris gear uses a horizontal-axis vane, feedback linkage, and a servo tab operating a balanced auxiliary rudder — a very powerful combination. Photo courtesy of James F. Ogg & Associates.

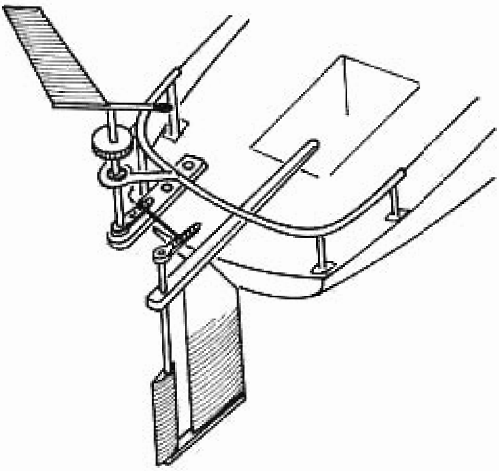
between the two tillers (Figure 9-9a). If the rudder, tab and vane axes are *all* parallel, a much simpler crosslink works just as well (Figure 9-9b). Having several holes in each arm gives considerable freedom in choosing the characteristics of the linkage.

Operation

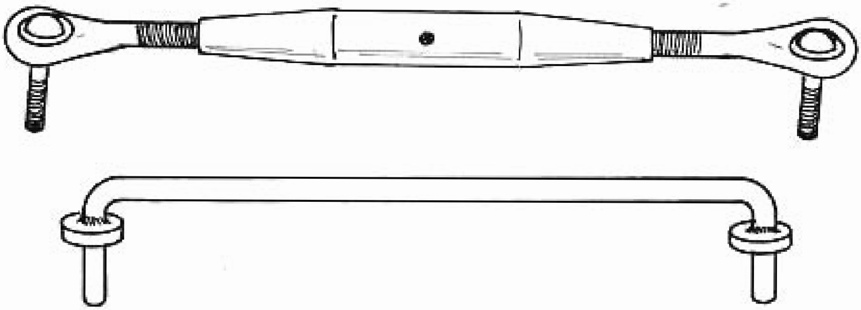
This is just as in gear number 4, except now we have some linkage variables (Figure 9-10). The position of the crosslink on the vane arm controls the power, and the position on the tab tiller controls the damping of oscillations through rudder feedback. (This action is explained on p. 170.) The best settings in different conditions should be sought experimentally.

Trouble-shooting

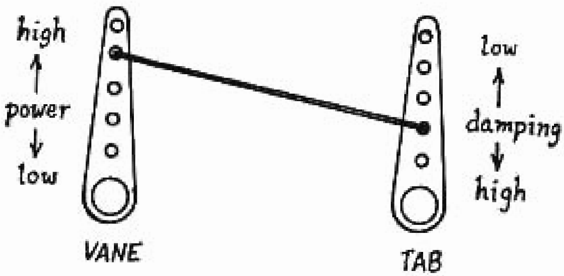
(1) If the system lacks power, determine first whether the tab is big enough — remove the crosslink and steer with the tab tiller to see whether the steering action is strong enough. If not, make it bigger and farther back from the rudder, or both. (2) While steering with the tab, assess its balance by feeling the pressure on the tab tiller



9-8. Windvane gear number 5: Single-axis vane/feedback linkage/servo tab. Vane shaft support independent of rudder.



9-9. Ball-joint and simple crosslinks.



9-10. Linkage settings controlling power and feedback.

required to hold the tab at an angle of attack. If it's badly balanced, a bigger vane will help, but the obvious answer is to improve the tab balance, putting more area forward of the tab axis. (3) If performance suffers in light winds, look for friction. Using three ball bearings, this system can hold a good course in one to two knots of apparent wind.

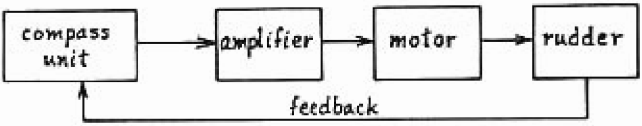
10 ELECTRONIC AUTOPILOTS

The fourth approach to self-steering, through electronics, seems like a different subject from the rest of this book. Suddenly we jump from the familiar world of sheets and sails and mechanical devices that anyone can puzzle out, to an almost magical world of circuit boards crowded with inscrutable components, of electrical impulses intricately interwoven to accomplish nearly any purpose. But electronics is rapidly finding new applications and new acceptance in the marine sphere, and in fact autopilots predate almost all other electronic devices used in boats. The operation of autopilots is perfectly understandable in the same terms that we have used for the mechanical/hydrodynamic self-steering devices. In fact, many of the ideas developed there show the way to making autopilots that are better suited to sailboats than are most of the present commercial ones.

OPERATION

The autopilot consists of three main components: a *compass-reading unit*, which generates electrical signals when the compass detects an error in the course; (2) an *amplifier* to make the electrical signals large enough to operate the control; and (3) a *motor-driven control* (almost always the primary rudder) capable of turning the boat. They are connected as in Figure 10-1.

Compass-reading units work on various principles. The simplest is just a suspended bar magnet equipped with electrical contacts to act as a switch (Figure 10-2). Other principles used for compass



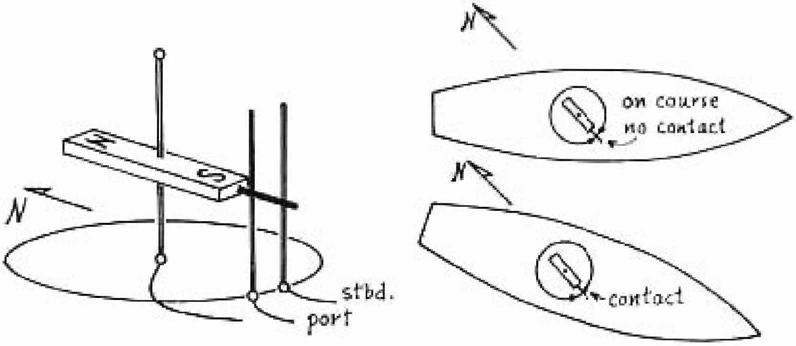
10-1. Block diagram of electronic autopilot.

reading are: *optical,* where the compass card interrupts or reflects a beam of light between a light source and photocell; *capacitive,* where the proximity of a point on the compass card is sensed by a change in a tuned circuit; or *magnetic,* where a special circuit element called a *saturable reactor* responds directly to a change in the magnetic field. Some units use a gyrocompass rather than a magnetic compass as the reference direction, and some recent units have an alternate input from a windvane.

In any case the compass unit produces only small signal currents. These can be amplified by relays, vacuum tubes, or transistors to supply the heavy current requirements of the motor. The motor can be a reversible type, or it can have an electrically actuated clutch and reversing gear. The motor is geared down to have whatever steering power is required to actuate the rudder.

FEEDBACK

All the autopilots I've seen have a provision for rudder feedback — a Bowden cable or speedometer cable mechanically sending back information about the rudder position to the compass unit. This does not have anything to do with synthetic damping, rather it is needed to control overpower. The motor is practically a rudder *positioning* device as opposed to the mechanical/hydrodynamic systems that primarily apply limited *torque* or *force* to the steering control. The autopilot can be compared very closely with the horizontal-axis vane operating a balanced rudder (Figure 7-1). It only knows two commands, helm port and helm starboard. It has all the power it needs to enforce these commands, though it is a little more limited in the speed with which it can execute them. *Without* rudder feedback, the autopilot would drive the helm over as hard as it could first to one side, then to the other, and I think the potential



10-2. Operation of simple compass unit.

for severe oversteering is obvious. As with the dual-axis vane / balanced rudder system, rudder feedback brings this overpower under tight control. *With* rudder feedback the system holds the rudder angle equal to, or at least proportional to, the angle off course, so a much more stable operation results.

REDUCING POWER REQUIREMENTS

Most of the manufactured units (a partial list of manufacturers is given in the Appendix) are entirely capable of steering a sailboat, though they are much more suited to powerboats. The main reason I say this is that the electrical power requirements are so great that few sailboat electrical systems can supply the needed current for more than a few hours. The powerboat has scores of amps available for free whenever it is underway, and so its autopilot can use current lavishly. There is little need for, and little sign of, power economy in its design.

Almost all the power used by the autopilot goes into turning the motor. With transistorized circuitry, the compass-reading unit and the amplifier do not *need* to draw more than a fraction of an amp at 12 volts (although many draw much more than this). But the power required for a motor strong enough to move the rudder is some tens of amps (depending on friction and balance and the weather, as well as on the size of the boat) and this is what takes the batteries down. I recently made an overnight passage in a friend's 40-foot yawl using a well-known autopilot. Although the course was a close reach and I verified that the boat would steer it herself with the helm lashed (except for changes in wind strength) the autopilot motor was running about half the time and we had to run the engine one hour out of every five just to keep the batteries charged. Obviously, this kind of power consumption is inappropriate in a sailboat.

There are ways to achieve reduced power consumption, such as by using a smaller motor and/or a lower *duty cycle* (percentage of time the motor is on). Some of these features are now available in commercial units designed especially for sailboats. But much more could be done to make electronic self-steering really practical.

NON-HUNTING

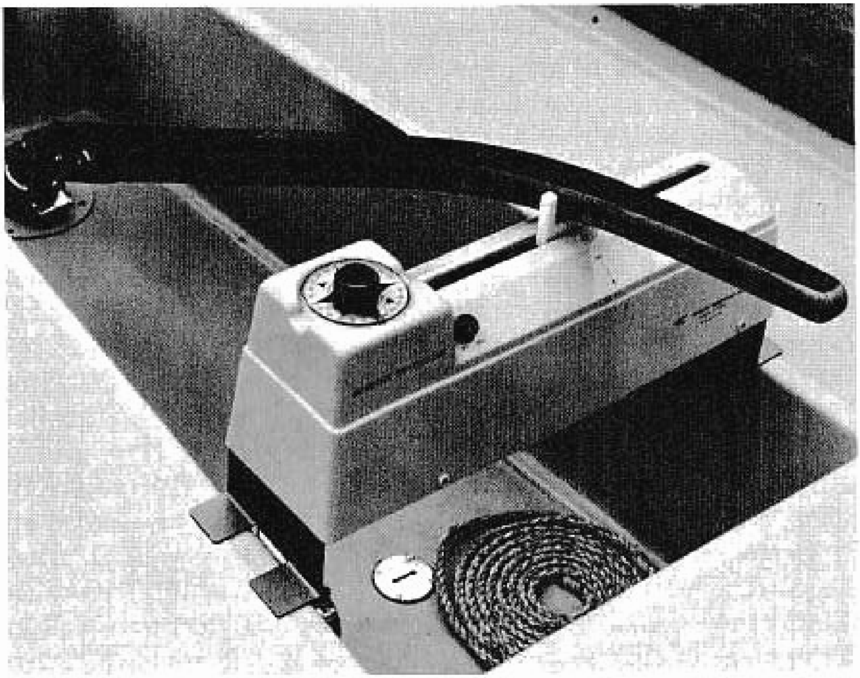
Most autopilots these days are billed as "non-hunting." All this means is that there is a dead zone of courses for which the motor is off, between the contacts where the motor turns on for starboard helm and on for port helm. Clearly this is better than the earlier kind, now, I suppose, extinct, that had the motor on all the time, going one way or the other. Some units have a "sensitivity" control which appears to be just an adjustment of the width of the dead band. A little lower duty cycle is obtained at the cost of somewhat wider angles off course, but the course is still essentially a zig-zag with the motor needed every few seconds, and always over-correcting.

AUTOMATIC ON-PERIOD ADJUSTMENT

It doesn't take a very sophisticated monitoring circuit to notice that the autopilot is oversteering and automatically to make adjustments in its operation to reduce this. If the motor is running at a high duty cycle, it is either because (1) the course is an unstable one or wave action is strong, requiring frequent corrections, or because (2) the corrections being made are too large. The unit can automatically try shifting to smaller corrections by reducing the length of time the motor stays on. If this reduces the duty cycle, it indicates that (2) was the reason for a high duty cycle, and it encourages a further reduction in the size of corrections. In this way the circuit can automatically cut down to the very small, infrequent corrections needed for sailing a stable course. The autopilot manufactured by Safe Flight incorporates this feature.

SYNTHETIC DAMPING

As noted previously, the rudder feedback that is needed to control oversteering does not contribute any yaw damping. This is because the motor that drives the rudder is insensitive to the helm pressures, so there is no way for an unbalanced rudder's sensitivity to yaw rate to be picked up by the controlling circuit. The autopilot leaves damping entirely up to the boat, which may or may not have positive yaw resistance. Aircraft autopilots ordinarily include phase-lead



A compact, self-contained autopilot made for tiller steering. Photo courtesy of Signet Scientific Company.

networks or rate sensitivity in their circuitry, and so are able to anticipate corrections to some extent and provide positive damping of all possible modes of oscillation.

OPERATION THROUGH A SERVO CONTROL

This is where the real power savings can be made. Just as in a windvane gear, the servo tab or pendulum can extract power from the water flowing past to operate the rudder. If the pendulum or tab is well balanced with good bearings, only a very small motor or solenoid, drawing very little current, would be required to turn it. All the same considerations on the size and design of the control given in Chapter 5 apply to this case. For a yacht that is equipped with a servo control for windvane steering, this would seem to be the logical way to add efficient compass steering for use under power, or under sail at times when a wind shift could head the wind-steered yacht into danger. Also for a vessel in which no suitable and safe place for a vane can be found, a compass unit operating a servo control could be the most satisfactory solution for self-steering. At present, the sailor would have to be an electronic technician as well as a mechanical engineer, for there are no commercial units of this type being manufactured.

In fact, it's not a bad idea for *anyone* who expects to go very far with electronic self-steering to be both electronic technician and mechanic. If a vane gear is damaged on a passage, repairs are likely to have to wait until the next machine shop. But specialized *electronic* repairs are totally beyond the skills of most sailors, and of most ports around the world, and the only way to get an autopilot fixed is likely to be shipping it back to the factory. The proven commercial units have been developed to a very high degree of reliability, and, once properly installed, can probably be counted on to operate for thousands of hours without trouble, if you can stand the current drain. But considering the poor reliability record of electrics, and the worse record of electronic equipment, as well as the shortage of electric power aboard seagoing sailing vessels, I personally would be very loath to depend on any of it for my self-steering needs.

11 COURSE-KEEPING AND WATCH-KEEPING

The possibility of self-steering always leads to questions of the wisdom and efficiency of letting the yacht tend herself. As to efficiency, we have considered before the harm done to performance by the windage and drag of self-steering gear, and ways in which this might be minimized. Another aspect of efficiency is related to the fact that a yacht that is steering herself by the wind must be more or less off course almost all the time; we should investigate how much this adds to the elapsed time of a passage.

In regard to safety, we should first realize that self-steering does not imply running without a watch, but rather running without a helmsman. With self-steering the watch can be more effective in trimming sheets, in being aware of changing conditions, and as a lookout. The requirements for an effective watch are reduced to one man in any but the largest vessels. But in most cases, self-steering is installed or worked out in single-handed and short-handed yachts with the expectation of running without a lookout much of the time. This practice is a great breach of nautical tradition. The extent of risk that it involves needs to be carefully assessed, and means of reducing the danger taken whenever possible.

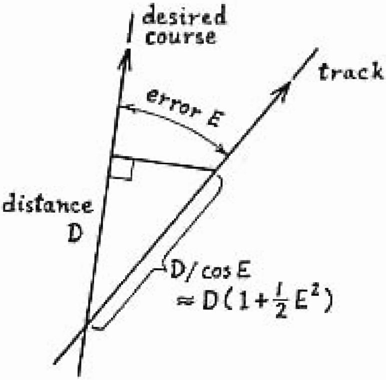
RELATIVE IMPORTANCE OF ACCURATE STEERING

The optimum track for an ocean passage is seldom the great circle (shortest distance) between origin and destination. Prevailing wind patterns and currents often required sailing ships to take roundabout paths two or three times as long as the great circle route. More weatherly modern yachts are less dependent on fair winds, but frequently it makes a much more pleasant, if not faster, cruise to follow the old sailing-ship route than to beat against contrary winds and currents for weeks on end. Except when the winds can be expected to be fair for the remainder of the passage, the navigator is perpetually faced with the question, what is the best direction to go from here? The decision has to be made with consideration of past records of winds and currents, present observations and forecasts, avoidance of calms, storms, and dangers, and the performance characteristics of the yacht. Sometimes the desired course is very narrowly defined, as when the objective is in sight and the wind is expected to be steady; sometimes it is very hard to decide on the desired course, as when a major change in wind direction is expected. Nevertheless, the decision has to be made, and then it is the seaman's job to maximize progress of the yacht along the desired track. When the wind is ahead he chooses the tack which is closest to the desired course. When the desired course can be laid, he sets and trims sails to make the best speed on it.

Self-steering often means sailing a little off the desired course. The wind used as a reference direction is never entirely steady; the yacht, keeping a constant apparent wind direction, changes course with the shifts in wind direction. Also, most self-steering systems have some sensitivity to wind strength, so the course sailed responds to this variable. A gear with a simple toothed-wheel-and-latch clutch has only a limited number of course settings, and you have to choose the tooth nearest to the desired course. Sometimes sheet-to-tiller self-steering cannot be achieved on the desired course, or would require a major sail change, so it appears preferable to run somewhat off course temporarily. Sometimes, too, oversteering cannot be entirely eliminated or wave action is strong, so the course sailed oscillates about the desired course.

EXTRA DISTANCE SAILED

In these circumstances decision-making requires an awareness of the extra distance being sailed. In most cases this is easy to estimate in your head. For all reasonable angles off course (up to 3 points), *the extra distance sailed is proportional to the square of the angle*



11-1. Extra distance sailed due to a steady course error.

off course (Figure 11-1). All you have to remember, then, is that *at one point* (11 ¼°) *off course, the extra distance sailed is two per-cent.* Thus at two points off course, the extra distance is $2^2 \times 2\% = 8\%$, etc. If you reckon courses in degrees, the figure to remember is *at 10 degrees off course, the extra distance is 1 ½%*. Slightly more precise figures are given in the following table:

angle off course	extra distance
½ pt.	·5%
1 pt.	2.1%
1½ pt.	4·7%
2 pt.	8.4%
2½ pt.	13.1%
3 pt.	20.5%
20°	6.6%
5°	·4%
10°	1.6%
15°	3·7%
20°	6.6%
25°	10.5%
30°	15.6%

In the case of oscillation about the desired course, an equally simple rule can be derived, assuming the angle off course to be a sine function of time with maximum error angles ± E (Figure 11-2). For two instants in each cycle, the course error is E; most of the time it is considerably less, and it turns out the extra distance sailed is just *half as much as for a steady course error* of E. That is, the extra distance is proportional to E squared, and is just one percent when E is one point (compass swings one point on either side of course).

If the course sailed combines oscillation with a mean angle of course (Figure 11-3), the extra distances from the two can be added.

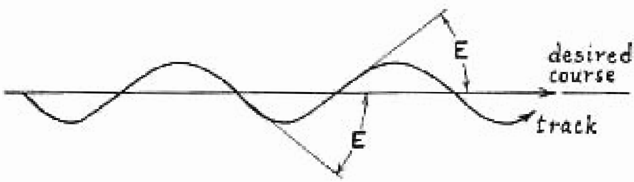
Example

Suppose the desired course is 250°, and the compass swings between 225° and 255°. The mean course is 240°, which is 10° off course, requiring 1.6% extra distance. The swing is 255° − 225° = 30°, so E is 15°, requiring ½ × 3.7% = 1.9% extra distance. Combined, the extra distance sailed is about 3.5%.

In general the extra distance associated with angles off course and oscillations under about one point are negligible except perhaps in racing. Above that level the penalties increase rapidly, and even the leisurely cruising man should be unhappy with the 8.4 percent (2 hours per day) cost of running two points off course.

NAVIGATIONAL ERRORS

Accurate steering is important to the extent that dead reckoning is relied upon for navigation. In most offshore cruising, an independent celestial fix is obtained almost every day, and errors of 10 de-



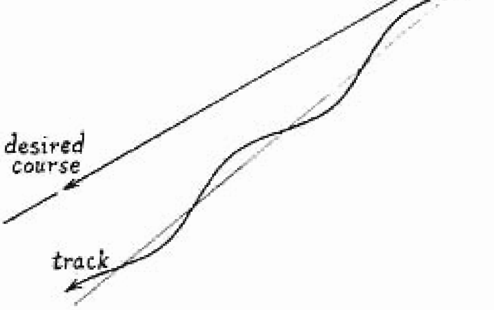
11-2. Oscillation adds half as much distance as a steady error in course.

grees in steering and 10 percent in speed accounting would be quite acceptable even for running fixes over an interval of some hours. When the yacht is in the vicinity of dangers and navigation becomes critical, much more careful dead reckoning will be required, and the steadiness of the self-steering becomes important. It may be necessary to steer by hand rather than try to compute mental averages of the less precise course that results under self-steering.

RUNNING WITHOUT A LOOKOUT

It is obvious that a continuous lookout cannot be kept on a single-handed passage of more than perhaps 36 hours. With a crew of two it is possible but awfully inconvenient. Even with four or five aboard, the two- or three-hour night watch comes to seem a useless exercise as night after night passes and nothing ever happens. Why not just follow the lead of the single-hander and turn in for a good night's sleep every night? Scores of single-handed passages have been completed this way; and many yachts with fuller crews have judged it safe enough to spend at least some nights sailing blind. What risks are assumed, and how can they be reduced?

Only you can decide if the risks are acceptable. Even when you



11-3. Extra distances due to an average error and oscillation are additive.

have consciously evaluated the danger and accepted it as negligible, your imagination can make sleeping difficult. During my single-handed days, I had a grand faith in the supposed lookouts kept by other vessels. In 7,000 miles I never sighted a vessel except on the steamer lanes, and I slept comfortably almost every night — sometimes sitting up for a few hours to cross a lane, but sometimes, I suppose, sailing half a day without ever scanning the horizon. The horrible experience of being run down and dismasted by a steamer, coming at the very end of *Island Girl's* voyage, converted me to radar reflectors and avoidance of the steamer lanes. Then my wife and I sailed another 7,000 miles, sleeping in almost every night, before another awful encounter — a fishing boat this time — pretty well shattered our confidence. We have slept in some nights since then, but seldom have we slept very well unless the other was standing watch. Just to encourage a cautious attitude toward other vessels I will here recount some of the gory details of the two accidents.

ISLAND GIRL'*S CASUALTY*

From Hawaii I sailed *Island Girl* north to Alaska in 1964, arriving in Sitka early in September. I laid her up there for the winter, and early the next summer I returned for two unforgettable months of cruising and climbing in the fiords and islands of southeast Alaska; then in mid-August, alone again, I sailed from Sitka to return to Los Angeles.

The passage was fast, and in pleasure it suffered only from being in the wrong direction — from a remote, wild, exciting region toward a much less thrilling destination, not the way a voyage should be. Fair, fresh winds prevailed, the little black twins drove us over 100 miles almost every day, and the only uncomfortable experience was the northerly gale off northern California. At dusk of the twentieth day we made a good landfall, picking up the lights of the coast near Point Conception. This cape is the dividing line between the chill, foggy Pacific coast weather and the relatively warm, gentle climate of southern California, so I felt we were almost in home waters.

That night I saw the lights of many ships, one or two per hour, passing a little way inshore. We were running under twins, but by midnight the wind had almost died and progress — and maneuverability — had become very poor. One northbound ship appeared for a long while as if it were going to pass a little outside us, but rather close. I assumed they were seeing my lights, and was a little annoyed that they would pass so close. As their lights drew closer, and the muffled whine of turbines and the rush of the bow wave came across the water to me, I turned on my searchlight and aimed it at the ship. This was just to let them know I was annoyed. Imagine my horror when the ship turned and came directly toward me! White over white, red beside green, the group of lights approached with an awful noise, growing by the second, and there was not the slightest chance of getting out of its path. As the pale bow loomed out of the darkness I dived through the companionway and instantly there was a terrible jolt and a rending crash. In a few seconds of shuddering vibration the ship's side rushed past, then we were wallowing in the foamy, hissing wake as their stern light drew rapidly away. They never knew we were there.

It turned out there was no contact between our hulls. I believe that they were a little off their aim, so that their bow wave washed *Island Girl's* hull aside, but her rig rolled into the side of the ship. The mast was broken in three places, the forestay, headstay, and bowsprit were all broken, and the upward pull on the forestay lifted the deck and clamps so the sheer strakes were split on both sides almost back to the chain plates. I got away with my life and felt very lucky. *Island Girl* was towed to Santa Barbara and I refitted her there.

ALEUTKA'S *CASUALTY*

In the late summer of 1969 my wife Pati and I sailed *Aleutka* south from Sitka to California, with many stops on the outer coasts of the Alaskan and Canadian islands. From Vancouver Island, a stormy passage of ten days brought us off San Francisco. We approached through heavy fog on radio bearings and found the lightship, about ten miles outside the Golden Gate, around midnight. We were lacking sleep, so we decided to sail about three miles north, to a position well off all steamer lanes, and heave-to to await daylight and a fair tide.

We got about five hours' sleep. Pati awoke to the sound of an engine approaching. On looking out she saw day was breaking, the fog had lifted, and here was a fishing boat about to cut us in two! Her desperate yell brought me out of my bunk, sleeping bag and all, and when I saw this boat through the portlight I yelled too. Pati was trying to unlash the helm and start the mainsheet, but before she could do either the fishing boat struck us a cruel blow on the lee quarter. *Aleutka* pivoted easily to the shock and the damage was really superficial, thanks to her fiberglass hull and solid construction. But if he had hit us dead center I don't think we'd be alive. We raised Cain, blowing the horn and yelling until the boat was a mile away, but he kept straight on, evidently on autopilot, and we never saw anyone on board. Again, they never knew we were there.

That was a clear abuse of self-steering and it still makes my blood boil to think how they nearly killed us for a few hours' sleep. This is the other side of running without a lookout — you have no moral right (and certainly no legal right) to use your boat in a way that endangers other people. If your boat is small enough to constitute no threat to anyone else, then the risks are all upon yourself.

In retrospect, we were taking a foolish risk ourselves for the sake of a few hours' sleep, by not keeping a watch when so close to the mouth of a busy harbor, and we have benefited by the experience.

RISK OF COLLISION

Probably the only significant risk involved in offshore sailing that can be laid directly to lack of a night lookout is collision with another vessel. A sudden change in weather or failure of some part of the ship's gear are things that might be detected more quickly by a watch on deck; but most people report that they get fantastically sensitive to small changes and sounds, and wake up immediately knowing something is wrong. Collision with flotsam or whales is another very significant hazard of deep-water sailing, but one which is hardly to be reduced by a night lookout. On the other hand, medical risks and the most fascinating hazard of all, that of making navigational or decisional errors under the influence of stress and fatigue, are undoubtedly reduced by getting a good night's sleep.

Other vessels fall into three categories, according to their habits of movement and watch-keeping.

1. *Merchant ships* don't keep much of a lookout, except perhaps on radar. They are usually well lit, but the best thing about them is that their movements are highly predictable. Along most coasts steamer tracks are clearly established, and marked on many charts. On ocean crossings the steamers stick very closely to charted great-circle routes. Of about thirty merchant ships I have encountered out of sight of land, all but three were, as near as my navigation could tell, precisely on routes shown on the Pilot Charts. Two of the others were evidently bound for Vietnam, for they were on the great circle from San Francisco to the Tonkin Gulf. So the rules are to keep off the steamer lanes, cross them as quickly as possible, and keep a lookout for a few hours while crossing. If this is done, you shouldn't lose any sleep over merchant shipping.

For a quantative estimate of the risks from merchant shipping on a particular passage, find out approximately how many ships will cross your projected track during the expected duration of the passage. These statistics are available from port authorities and are compiled in the U.S. Bureau of the Census publication FT975, "Vessel Entrances and Clearances" and in Lloyd's Register of Shipping, Statistical Tables.

First, consider just one of these ships. It will have to pass (on center) within about 50 feet on either side of you to make contact; so there is a section of your track only 100 feet long that is endangered by this ship. If the ship crosses at a random time, the probability that you are in the section is just 100 feet/length of passage. This risk is multiplied by the total number of ships crossing, to give the probability of a collision *if neither party ever looks out.*

Example

On a passage from Hawaii to Alaska (2,500 miles) I expected to take 30 days and I obtained an estimate of five ships per day, on the average, arriving or departing west coast ports for the Orient. This makes 150 ships crossing my track. The probability of collision is

$$\frac{150 \times 100 \text{ ft}}{2500 \text{ mi} \times 6080 \text{ ft/mi}} = \frac{1}{1{,}012}$$

This can be reduced, of course, by several measures on both vessel's parts. But even so it says I could sail blind back and forth continuously across these waters and expect to be run down only once in a thousand voyages — over 80 years of continuous sailing. If daylight hours are assumed safe, and if nine-tenths of the ships are on charted lanes, the probability for a single passage drops to 1/20,000.

2. *Military vessels* are much less predictable in their movements, but seem more likely to have a careful lookout, both visual and on radar. I feel it is safe to assume someone is watching the radar, and will pick up a moderately-sized radar reflector.

3. *Fishing and research vessels and yachts* are the ones to worry about. Their numbers are large, their locations unpredictable; some are practically unlighted and many carry no lookout. Of course, fishing tends to be concentrated in certain ocean areas, but boats are continually going to and from these areas, out of small and large ports all over the world. Along many of the coasts of the world, there is enough coastwise traffic, and fishing and workboat activity to make anything less than a 24-hour lookout quite risky. Near major ports the concentration really goes up.

THE PARTIAL LOOKOUT

The only way I know to be really safe is to have someone scan the horizon carefully about every fifteen minutes, and more often in reduced visibility. This assumes that a small vessel that might be converging at a combined speed of 16 knots would be seen more than four miles away. During periods when the crew is asleep, there is a sleep pattern that allows a little less rigorous regimen to be maintained. Psychological research has shown that sleep tends to be cyclical, an alternating rhythm of deep and shallow unconsciousness, with a period of around one hour. Many voyagers have remarked that they fall into a pattern of waking up about every hour, and that this doesn't interfere at all with getting enough rest in eight hours. I think the sleep cycle adjusts a little so the shallow phase comes just above the surface, and you can get up and take a look around without interrupting the cycle. At times when my wife and I want to be sure of looking out at least once an hour, we make use of an alarm clock. Each time either of us wakes and looks around he or she sets the alarm for one hour later. Normally we pass the whole night without the alarm ever going off, and without ever both being awake at the same time— so someone was looking every half-hour on the average. This is much safer than sailing blind; but that other boat can come a long way in 30 or 40 minutes, so occasionally we have had unpleasant surprises this way. At least look out as often as you wake up. I used to delight in waking up, to shine a flashlight on the telltale compass, listen a moment to the familiar symphony of sounds from spars, rigging, sails, and the water rushing past, and then drift back to sleep. But that was before I had had a collision.

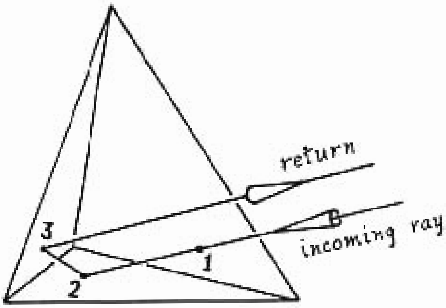
REDUCING RISKS

Heaving to at night is only a little safer than running on. It means you won't collide with another vessel that's hove to, but that's a small percentage of them. It means, too, that you are not overrunning your horizon ahead and your speed is not added to the other boat's in the closing speed, so a partial lookout has a better chance of picking up the danger. But few will consider that the gain in safety is worth the severe loss in average speed.

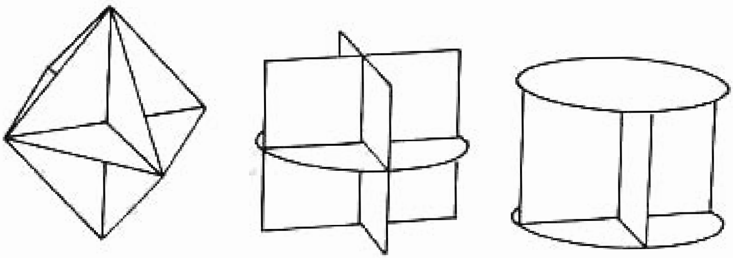
Robert Manry, sailing singlehanded in *Tinkerbelle,* adopted the tactic of sleeping in the daytime in order to stay awake all night. I grudgingly admit there is some merit in this idea. Most fishing boats don't yet have autopilots, so the helmsman is there and he *must* look around the horizon once in a while. Other people on board, too, might be looking ahead often enough to see you and avert a collision in daytime.

RADAR REFLECTOR

There are many times when a radar reflector can contribute materially to safety. Practically every boat on the ocean seems to be equipped with radar these days, and in fog or bad weather and at night, we hope that somebody is checking the radar screen. What they are looking for, besides navigational information, is other boats, which have to be pretty big and built of metal, or equipped with a reflector, to show up. A sailboat simply doesn't make it. Wire rigging and metal masts are ineffective reflectors; and the hull return gets lost in scattered waves from the sea surface, which are screened out



11-4. A single corner, showing a ray reflecting off all three sides.



11-5. Corner reflector shapes show a three-sided corner to most directions.

by a sensitivity threshold in most sets. Makeshift reflectors like a sailbag loosely stuffed with aluminum foil, or a string of aluminum pie plates, hoisted in the rigging, do somewhat better, but still rely on pretty random scattering of the radar waves.

The answer is the corner reflector, which is a beautiful idea. It is based on the geometrical principle that a ray that reflects from three mutually perpendicular planes (a corner) returns exactly parallel to the way it started (Figure 11-4). All the radar waves that enter such a corner are sent back exactly toward the radar antenna, and so they make a much more powerful return signal than would a similar-sized object that just scattered the incident waves in all directions. The same principle is used in highway reflectors, which pick up just a tiny fraction of the light put out by your headlights, but they beam it all straight back at you. The back surface of such reflectors is a honeycomb pattern of right-angle corners.

A corner reflector is just an arrangement of planes that presents such a corner to any direction (Figure 11-5). To reflect 5-cm radar waves, the planes can be sheet metal or mesh, as long as the holes are smaller than about ⅜″ (1 cm). It is obvious that the planes have to be quite flat, and the angles accurately 90 degrees, to make an effective reflector. An error of ¼″ (6 mm) at the edge of one plane can reduce effectiveness by half. The triangular pattern (at the left in Figure 11-5) is the least likely to get bent. The size of the reflector is important, as its effectiveness (radar cross-section) varies as the square of the area of its planes — the fourth power of the linear dimensions. One foot (30 cm) on a side seems to be the minimum useful size. Putting it high is fairly important, too, as this keeps it above the wave tops, and the strength of the return signal is proportional to the square root of the height above the water.

A corner reflector can be collapsible, and sent aloft on a flag halyard. I think it's needed often enough, though, to make a permanent installation worth the windage. In *Aleutka* we have a triangular reflector, one foot (30 cm) on a side, made of ¼″ (6 mm) bronze mesh, permanently in place above the jumper strut at the upper crosstrees — free of chafe, 25 feet above the water, and always ready.

RADAR ALARM

In a letter to the editor of *Yachting* (May, 1972) Mr. James C. Acheson writes that he has found a radar alarm called the Radar Sentry (T.M.), which is manufactured as an automotive accessory for detecting highway speed traps, that works aboard his yacht. The device detects a ship's radar, evidently in any direction, at ranges up to about three-quarters of a mile, and sounds an alarm. This could be a very valuable addition to the yacht's equipment. A device of this type can be found in the catalog of J. C. Whitney & Company of Chicago.

THE OFF-COURSE ALARM

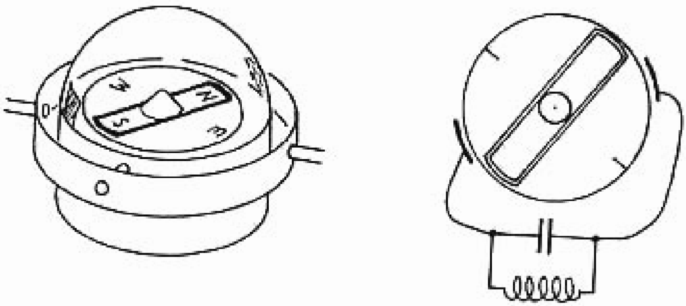
A device that will wake the crew if the yacht goes too far off course while steering herself has obvious value. Whether she is off course because the wind has shifted or changed strength, or because the self-steering has failed, the crew ought to know about it right away.

Is it really needed? At first glance it seems almost essential, if watches are not being kept. I designed one before I took off in *Island Girl,* but it was one of the things that didn't get done. It only took me a few days at sea to learn that I had a built-in off-course alarm. It is wonderful how a person gets attuned to his boat, and wakes up with the smallest change of sound or motion — usually. This has been good enough for most single-handers, but sooner or later most have gotten in trouble by relying on it too much. The extra safety measure of an off-course alarm could have saved a lot of this trouble.

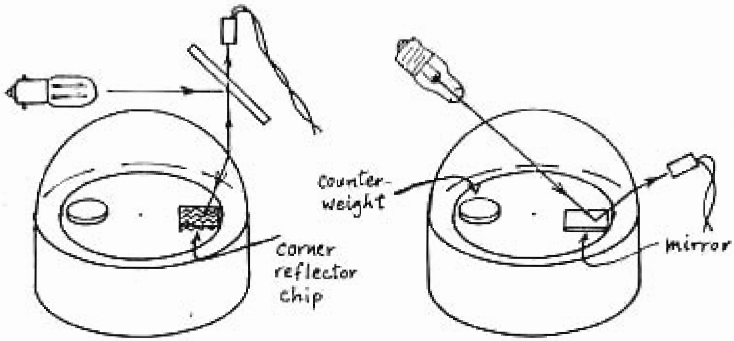
DESIGN AND OPERATION

The alarm has the first two elements of an electronic autopilot — a compass that is electronically read, and an amplifier (Figure 11-6).

11-6. Block diagram of an off-course alarm.



11-7. Compass modified for electronic off-course sensing.



11-8. Compass modified for optical off-course sensing.

Instead of a motor it has a buzzer or other alarm. The compass unit can be somewhat simpler than for an autopilot because it doesn't have to distinguish between being off course to starboard and off course to port; off course on either side should ring the alarm. The battery drain can be very low, because there is no motor to operate.

The compass unit for this purpose can be made from a small liquid-filled, externally gimbaled boat or auto compass. I can think of two good ways for electronic reading, both of which require opening the compass bowl and modifying the card. (1) *Capacitance sensing* can be arranged by adding a wire or a strip of foil across the card from one side to the other (say north to south). Two pick-up electrodes are fixed opposite each other on the outside of the compass bowl (Figure 11-7). Proximity of the wire changes the capacitance between the pickup electrodes, which changes the resonant frequency of a tuned circuit, which is easily sensed electronically. (2) *Optical sensing* can be arranged using a light source and a photocell (Figure 11-8). Locate a reflector on the compass card, say at north, with a compensating weight at south. Maybe the best reflector would be a chip cut from a plastic bicycle reflector based on the corner reflection principle (p. 238), as this will be unaffected by the tilting of the compass card. The light source can be a miniature incandescent lamp, but I expect lower battery drain could be achieved by pulsing a miniature neon or argon lamp. A solid-state photocell is arranged to pick up the light pulses as long as the boat is on or near enough to the set course.

In either case the unit is put on course by turning the whole compass until the pickup is at north. Then, if the boat goes off course, the pickup moves away from the right place on the card and the circuit is actuated. To avoid false alarms and allow for the boat to yaw off course occasionally or to oscillate, it is necessary for the compass unit to allow some deviation — say 10 degrees — from the set course without sounding the alarm. Also a generous time delay should be built in so the alarm goes off only if the boat is sensed to be off course consistently over a period of many minutes.

At this time I cannot present a tested circuit for an off-course alarm based on either of these compass units. The requirements are simple, though, and working out a circuit should be no great challenge to an electronics hobbyist. Though many of the single-handed offshore racers have been equipped with these devices in recent years, I don't think there are any manufactured models available, each one being a custom design.

12 DESIGN FOR SELF-STEERING

In almost every case the application of windvane self-steering in sailing yachts has been at a certain disadvantage: the gear is a piece of equipment added on to a yacht that was originally designed with no thought of self-steering. Inevitably, sacrifices have to be made to work the vane gear in, around, and under the existing steering gear, rigging, lifelines, and other equipment. The manufactured units suffer from this disadvantage to a greater degree than a custom design, for they have to be built to fit not one boat but a large number of different boats to be commercially marketable. Despite the numerous successful applications of windvane self-steering, it seems to me that the idea has very seldom been given a completely fair chance to show what it is worth.

I think any new cruising boat today should be designed with windvane self-steering in mind from the very start. While sheet-to-tiller arrangements can suffice for the great bulk of self-steering needs with a great deal less expense and trouble, most people, and I include myself, will be seduced by the windvane's promise of instantaneous, universal self-steering for all winds, courses, and sail combinations. Whether this means simply providing a really solid mount for a particular proven commercial model and designing the transom, rudder, pulpit, and rigging around it, or developing a completely new self-steering system integrated with the vessel's structure and equipment, the chances of success (in all the senses discussed in Chapter 4) will be greatly improved by the forethought.

There would appear to be a great commercial opportunity for self-steering in the design of stock cruising boats. A substantial fraction of the buyers of such designs today are serious about extensive cruising. One of the foremost equipment purchases in the buyer's mind is naturally a vane gear. He is faced with choosing a boat, and then spending an additional $500 to $1,500 or more on a vane gear, then investing a great deal of effort into putting the two suitably together, wondering all the while — as well he might — whether the combination will indeed work out. If a boat manufacturer could offer a well-engineered self-steering unit, well integrated into the design of his boat, tested and proven, as a standard extra, I believe many buyers would be happy to pay a good price for it. More important, the availability of such an extra would give a considerable competitive edge over other boats a buyer might be considering. He could be much more interested in buying the combination than he was in buying the boat by itself.

Let us collect here, then, various ideas that the designer could apply in providing a new design with really reliable and durable self-steering. They mainly deal with structural aspects of the design and assume that balance, friction, power, and stability can be worked out by proper details.

THE HULL

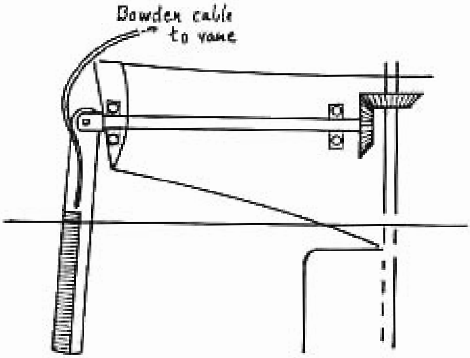
The traditional ideas that self-steering ability is determined mainly by balance of the lines and a long lateral plane date from the time when self-steering meant natural course stability with the helm lashed. The developments in sheet-to-tiller and windvane gears have made this view quite obsolete. Some of the boats today that have been most successful at steering themselves have short fin keels and lines developed much more toward power on reaching and running courses than toward good balance of helm.

YAW RESISTANCE

The most important property of the hull affecting self-steering performance is helm-fixed adverse yaw — the complex hydrodynamic property of a hull producing a net yawing moment as a result of its rotation about the yaw axis combined with forward speed. Negative adverse yaw (the moment *promotes* the rotation) limits the choice of types of vane gear to the systems having positive yaw damping, and might well interfere with sheet-to-tiller self-steering. Positive adverse yaw (the resulting moment *opposes* the rotation) makes stable self-steering possible with simpler types of vane gears. Too much positive adverse yaw, though, makes a boat that is slow turning, slack in stays, and hence unpleasant to sail. I think a small amount of positive adverse yaw is definitely the most desirable condition.

Unfortunately, yaw resistance is not an easy thing to design. While it is related to the length of lateral plane, it also involves several other variables — location of the hydrodynamic center, several stability derivatives, added mass — all of which cannot be calculated with much confidence at present, and might change with heel, sideslip, and speed. Appropriate tank tests can be made to measure adverse yaw of models, and though there are many uncertainties in scaling any model data up to full-size predictions, I think this test might well be worthwhile. It doesn't require a towing tank, just a model ballasted to the correct scale waterline, some still water (at least as deep as the model's waterline length), and no wind. Launch the model by hand on a straight course, then let it go and allow it to drift on under its own momentum. If the model has positive yaw resistance, you will be able to find a rudder setting (close to center, but compensating for small asymmetries of the model) such that the model continues traveling straight. If the model has negative yaw resistance, no matter how well the rudder is centered, or how straight you try to launch it, the model will go into a tightening spiral to one side or the other. Between these is a condition of neutral yaw resistance, where the model travels straight or on a gentle arc to either side, depending on slight misalignments in launching. A similar test, using auxiliary power or a tow for "launching," can be used to evaluate adverse yaw of a full-scale boat, of course.

The known attributes that promote positive adverse yaw are: long lateral plane; keel area moved aft (this requires the rig moved aft to maintain balance of helm); weight moved forward (this is severely limited by the correct trim of the hull); large rudder; and rudder far aft. A longitudinal separation of the center of gravity



12-1. Built-in pendulum control.

ahead of the hydrodynamic center is more important, but at the same time more difficult to accomplish, as the keel becomes shorter and the ballast ratio higher in modern types of hulls. But there is some freedom in design to keep the center of buoyancy forward relative to the centers of sail area and lateral plane area, and I think working in this direction will be found to benefit self-steering qualities through yaw resistance.

BUILT-IN CONTROLS

Considering self-steering from the outset gives an opportunity to design into the hull structure a control that is stronger and better protected than one added later. Several possibilities suggest themselves.

1. Balanced primary rudder

A primary rudder that is nearly balanced, besides being very easy and pleasant to steer with, can be operated by a dual-axis vane, resulting in a self-steering system with the minimum of underwater complexity. If the rudder is a spade type, and especially if its shaft comes into the hull through a packing, careful attention will have to be given to reducing friction. For support and protection, I would much prefer a rudder behind a skeg, and at the same time this makes the bearing requirements much easier to meet.

At the time I changed *Aleutka's* spade rudder from a self-volume of about 4 ft^3 (0,113 m^3) to about 1.33 ft^3 (0,038 m^3), I was worried that this might make a big difference in her performance with sheet-to-tiller self-steering. I found we needed to use somewhat stiffer elastic, but that was the only change we noticed. The new rudder is much more pleasant for heavy going downwind; I would try for even better balance in the future. Partial balance of the primary rudder can also greatly reduce the size of the tab or pendulum required for full rudder control.

2. *Auxiliary rudder*
Much the same considerations apply. Balanced or not, with or without a tab, the auxiliary rudder is best hung from a sturdy skeg that is built into the hull, streamlined and snag-proof (Figure 5-30).

3. *Pendulum*
The bearings for the B-B axis of a pendulum can be built into the hull so that the machinery applying the pendulum force to the rudder shaft is simplified and partly or completely enclosed below decks (Figure 12-1). The rake of the transom is inconsequential; the axis A-A does not have to be vertical, but the axis B-B must be horizontal to maintain the full effectiveness of the pendulum at larger rudder angles.

DECK LAYOUT FOR SHEET LEADS

In the ocean-crossing yacht, in case of trouble with the windvane self-steering (never to be considered unlikely), one further aspect of hull design will assume major importance. If sheet-to-tiller self-steering is to fill the gap, there have to be ways to lead the necessary sheets to the helm. In most cases the mainsheet is accessible enough; it is the jib sheets and twin braces that are likely to cause difficulties that really have to be planned for. If the cockpit coamings are low enough, there is no trouble. In some cases sheaves can be let into openings in the coamings to turn the sheets into the cockpit with little friction. Sometimes lifeline stanchions can be located strategically in way of the tiller, to hang blocks on; but I wouldn't expect the average stanchion to take it without bending. These stanchions can be built with extra braces to the necessary height. For most boats such superficial preparations are all that is necessary. But in some boats I see, especially the raised-center-cockpit types, I just don't see how you would lead the sheets. If the steering system includes an emergency tiller or an alternate steering position, perhaps these will offer an easier place to connect a sheet.

THE RIG

Traditionally, divided rigs—ketches and yawls especially—have been favored by long-distance sailors mainly for their self-steering properties. This attitude stems from genuine advantages in natural course stability — the stabilizing trim and sail yaw resistance discussed in Chapter 2. Modern developments in self-steering have greatly reduced the significance of these properties, and in fact the conflict between a mizzen sail and a convenient location for a windvane has put ketches and yawls at a considerable disadvantage these days. While several ways are available to fit vane gears to existing ketches and yawls, they all seem prone to suffer severe mechanical or aerodynamic interference under some conditions. Let's look at some of the possibilities:

1. Low-aspect-ratio vertical-axis vane under mizzen (Figure 12-2)
The size of the vane is limited, and its lift-curve-slope is reduced by its low aspect ratio. Even though the sheet is moved to a midboom position (likely to require a new boom to take the bending load) it is still too close to the vane for safety in an uncontrolled jibe. Raising, lowering, and reefing the sail must all be very carefully assisted with a mizzen preventer to keep the sail from snagging the vane.

2. Dual-axis vane removable or hinged
The dual-axis vane, being much smaller for equal power, stands a better chance of fitting under a mizzen boom with the necessary clearance. Nevertheless, to be large enough or to get clear air, it may have to stand up too high, so the vane blade has to be removable or temporarily pivoted out of the way while tacking or jibing.

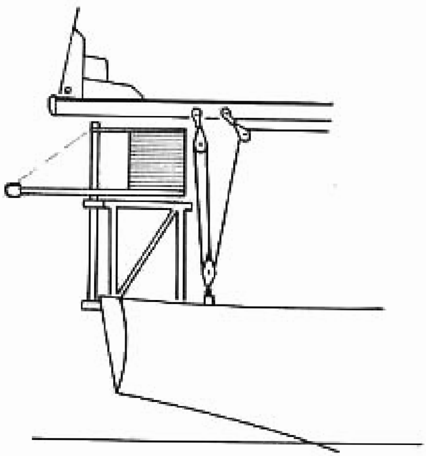
I think a preferable, less risky solution would be to design the sail plan with the mizzen boom unusually high to obtain the required clearance beneath it. This would not interfere with setting a mizzen staysail, or any other use of the mizzen mast.

3. Alternate starboard and port positions for vane

A single-axis vane, readily removable, can have two alternate stations, so it can always be on the opposite side from the mizzen boom. If the positions are abaft of the mizzen mast, a preventer will have to be used religiously and jibing is very inconvenient, as the vane has to be removed before the jibe and can't be set up again until after, and meanwhile she won't steer herself. If there is enough room forward of the mizzen mast that is safe from the main sheet and sail, this will be a much more convenient location. Robin Knox-Johnston gave *Suhaili* two vanes built on outriggers outboard of the mizzen shrouds, but such a solution hardly seems practical for anything *less* than a non-stop around-the-world voyage!

4. Furl the mizzen when the vane is used

This seems a pretty poor solution for anybody – why have a mizzen mast at all if the sail is going to be furled most of the time? But



12-2. Low-aspect-ratio vane for ketch or yawl.

this is what Alec Rose did with *Lively Lady* on her one-stop circumnavigation, and he made good enough use of mizzen staysails to feel the mast was worth its keep.

Compared with any of these options, placing the windvane over the stern of a sloop or cutter looks attractively simple and elegant. A majority of the yachts now making long voyages are single masted, and it is remarkable how many of the most experienced voyagers have settled on the cutter rig as the best, in sizes up to 50 feet (15 m.) L.O.A. and larger.

COMBINED STEERING SYSTEMS

In many aircraft, the autopilot and the power-assisted controls are so integrated that the pilot never actually touches the controls; when he flies "hands-on" he is really just making continuous adjustments to the autopilot settings. The analogous idea for steering sailboats is sometimes proposed: a boat equipped with self-steering to give her synthetic course stability on all courses, and steered by effortlessly adjusting the course setting. Doesn't that appeal? To make a course change you would just dial the new course, instead of disconnecting the self-steering, guiding the yacht by hand onto the new course, and resetting the self-steering. At any time, on an instant's notice, you could leave the steering station and she would take care of herself, holding the same course.

I am skeptical about this proposal, unless the self-steering is based on a magnetic compass or gyrocompass. The wind is just not a steady enough reference direction. This could work all right in open water; but here there is plenty of room and plenty of time to make course adjustments and to reset the self-steering, so it's no advantage. When I will be steering by hand is mainly in narrow waters, in harbors, or close along shores, where I definitely *don't* want the wind interfering with its continuous random shifts, large or small; or in heavy weather offshore, where steering is by the sea more than by the wind, and where I don't want any frail mechanism between me and absolute rudder control.

Remember that these are the great and memorable times for sailing, times that are too good to be left to self-steering anyway. Let manual steering come first in the design, with a safe and comfortable position for the helmsman, and nothing sacrificed for the convenience of self-steering, for nothing has to be. Treat the vane gear as only an added convenience; many of the great voyages were made with no self-steering at all, and many more without a windvane.

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