Propeller Handbook

The Complete Reference for Choosing, Installing and Understanding Boat Propellers

DAVE GERR

International Marine

International Marine
A Division of The McGraw-Hill Companies

10 9 8 7 6 5 4

The Library of Congress has cataloged the cloth edition as follows:
Gerr, Dave.
Propeller handbook : the complete reference for choosing, installing, and understanding boat propellers / Dave Gerr.
p. cm.
Bibliography: p.
Includes index.
ISI
1. Propellers. 2. Motorboats—Maintenance and repair. I. Title.
VM753.G47 1989
623.8'73—dc19 89-2042
CIP

Paperback ISBN is 0-07-138176-7

Questions regarding the content of this book should be addressed to
International Marine
P.O. Box 220
Camden, ME 04843
www.internationalmarine.com

Questions regarding the ordering of this book should be addressed to
The McGraw-Hill Companies
Customer Service Department
P.O. Box 547
Blacklick, OH 43004
Retail customers: 1-800-262-4729
Bookstores: 1-800-722-4726

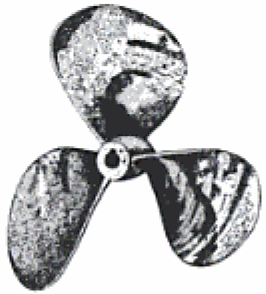
Typeset by Graphic Composition, Athens, GA
Printed by Quebecor Printing Company, Dubuque, IA
Design by Abby Trudeau
Production by Janet Robbins
Edited by Jonathan Eaton and David Oppenheim
Cover photo courtesy W. H. Den Ouden Vetus (U.S.A.) Inc.

Contents

may seem odd, but in practice, at planing speeds, power-to-weight ratio alone and not length is the overriding factor. Length cannot be neglected in your considerations, however. Longer, narrower boats (vessels with low DL ratios) should get higher C values, as we discussed above. Additionally, long, narrow boats with fine entries can be driven at high speeds in rough water, whereas wide, shallow-bodied craft cannot.

We can work through the example of the *Flying Spray*, a 35-foot (10.66 m) twin outboard runabout with weekender cabin forward. She is 30 feet (9.14 m) on the waterline, displaces 10,890 pounds (4,940 kg), and should operate at a V of 25 knots (28.8 MPH). Her displacement-length ratio of 180 is average to a bit light for a planing powerboat of this type. On the other hand, the lower unit housings of her outboards are not very efficient and create turbulence at the propellers, as well as appendage drag. Accordingly, an average C value of 150 is about right (from Table 2-2). From Chart 2-3 or Formula 2-4, we see that *Flying Spray* would require one horsepower per 36 pounds at the propeller. This gives 300 HP (224 kw) **[10,890 lb. ÷ 31 LB/HP = 302 HP]**. Since we want to operate continuously at this speed we have to figure on running at 70 percent of full throttle—outboards are light, high-speed engines. Thus, we need engines rated at a total of 430 HP (320 kw) **[300 HP ÷ 0.7 = 431 HP]**. Twin 215 to 220 HP (160 to 165 kw) outboards should do nicely.

At this point, we can start to answer another of the frequent questions we mentioned at the beginning of Chapter 1: "Why doesn't my boat reach the top speed claimed by the manufacturer?" You can run through the speed prediction methods outlined here to see how fast your boat should actually be capable of going with her real horsepower and at her real weight. Do not be surprised if you discover that, after taking your vessel's true weight into consideration (as opposed to the sales literature weight), her maximum cruising speed works out to less than claimed on the showroom floor. If, however, you discover that your engine has enough power to drive your vessel faster than you have been able to get her to go, then and only then is it time to consider a new propeller. This is particularly so if your engine cannot reach top RPMs, or if it reaches maximum RPMs well below full throttle. We will take a detailed look at propeller selection in Chapters 5 and 6.



Chapter 3

Propeller Anatomy

Parts and Definitions

Before we can begin to examine the propeller selection process in detail, we have to define clearly the propellers we will be choosing: How are they shaped? What are the differences and similarities between them? What types of propellers do we have to choose from, and which types are best suited for which service? We will answer these questions in the next two chapters.

PARTS OF THE PROPELLER

Hub The *hub* or *boss* of a propeller is the solid center disc, bored for the propeller shaft, to which the propeller blades are attached. Since the hub generates no drive, the ideal would be to eliminate it. As a practical matter, though, the hub can seldom be much less than 14 percent of the diameter in order for it to have sufficient strength.

Keyway Most propeller shafts transmit the torque from shaft to propeller through a *key.* The *key* is a long, slender rectangle of metal along the shaft that fits into a slot or *keyway* milled (cut away) into the interior at the hub. Standard keyway, shaft and hub dimensions may be found in Appendix C.

Blades The *propeller blades* are the twisted fins or foils that project out from the hub. It is the action of the blades that drives a boat through the water.

Blade Face and Blade Back The *blade face* is the high-pressure side, or *pressure face,* of the blade. It is the side facing aft, the side that pushes the water when the boat is moving forward. The *blade back* is the low pressure side or *suction face* of the blade, the side facing ahead.

Blade Root and Blade Tip The *blade root* is the point at which the blade attaches to the hub. The *blade tip* is the extreme outermost edge of the blade, as far from the propeller shaft center as possible.

Leading and Trailing Edges The *leading edge* of a blade is the edge of the blade that cleaves the water. The *trailing edge* is the edge from which the water streams away.

ROTATION OR HAND

A critical aspect of propeller shape is its *hand.* A propeller that drives a boat forward when it rotates clockwise, as viewed from astern, is called a *right-handed propeller.* By the same token, a propeller that rotates counterclockwise, as viewed from astern, is *left-handed.* You can tell a right-handed propeller from a left-handed propeller just by looking at it. As you view the propeller from astern, the leading edges of the blades will always be farther away from you than the trailing edges. If the leading edges are to your right,

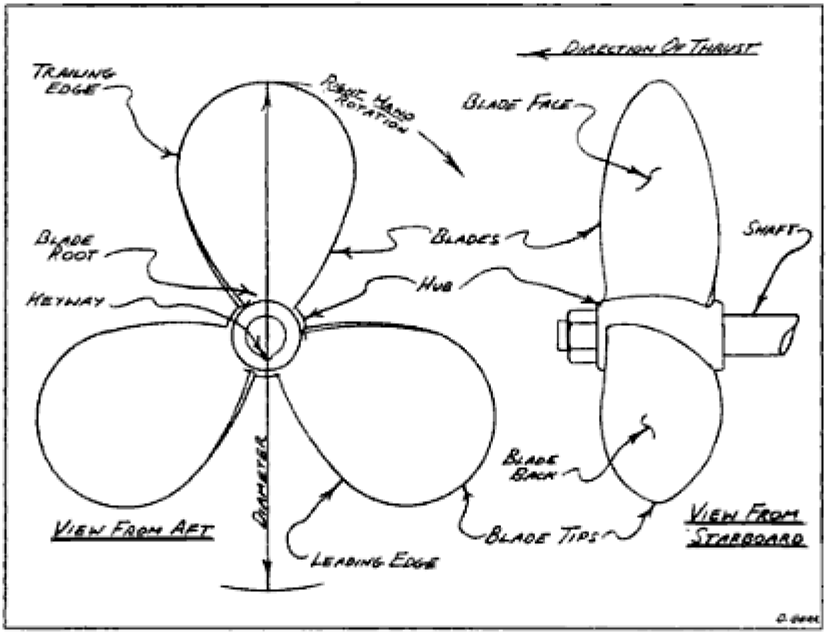


Figure 3-1

Propeller anatomy.

the propeller rotates clockwise and is a right-handed propeller. If the converse is true, it is a left-handed propeller.

Propeller hand can never be changed. If you obtain a propeller of the wrong hand for your installation, you simply have to replace it with one that has the correct hand. You cannot change the hand by turning the propeller backwards.

Right-handed propellers are almost, but not quite, universal on single-screw vessels. In twin-screw installations, propellers and engines of opposite hand are used port and starboard. A single right-handed propeller will tend to push the stern of a vessel to star-

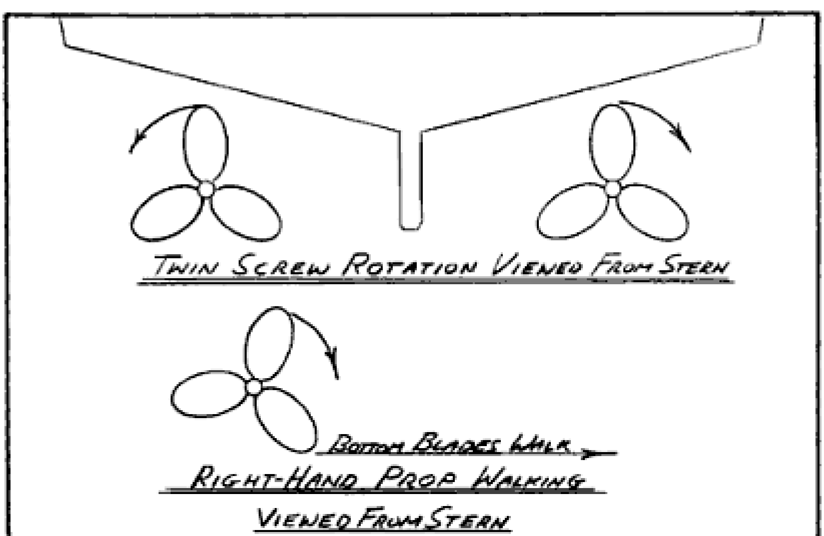


Figure 3-2

Propellers "walk" in the direction of rotation.

board when going forward (to port going astern). The reason—in simple terms—is that the water at the bottom of the propeller is a bit denser and freer to flow (there's no hull above it) than at the top of the propeller. This makes the lower blades a bit more effective, so the propeller and the stern "walk" sideways in the direction of rotation.

On a twin-screw craft the propellers should be out-turning. The starboard or right propeller should be right-handed, and the port or left propeller should be left-handed. This gives the best propeller efficiency. Twin-screw vessels with propellers of the same hand can experience serious handling problems.

THE THREE BASIC CHARACTERISTICS

Diameter, revolutions per minute and *pitch* are the three most significant factors affecting propeller performance and efficiency. Although many other variables need to be considered, the vast majority of calculations for selecting a suitable propeller revolve around these three characteristics.

Diameter

The most obvious characteristic of any propeller is its *diameter (D)*. This is simply the distance across the circle swept by the extreme tips of the propeller blades.

Effects of Diameter Diameter is the single most critical factor in determining the amount of power that a propeller absorbs and transmits. It is thus the most important single factor in determining the amount of thrust delivered.

For the vast majority of installations, the larger the diameter the greater the efficiency. The only exception is for high-speed vessels—over 35 knots or so—in which the extra wetted surface of large-diameter shafts, bearings, and so on causes excessive drag. A small increase in diameter dramatically increases thrust and *torque* load (see section on torque in Chapter 1) on the engine and shaft. For this reason, the larger the diameter, the slower the shaft RPM must be. In theory, a propeller with a diameter as large as one-third of the beam of the vessel and turning at only a dozen or so RPMs is most efficient. Practical limits on draft, hull shape, RPMs and reduction gear losses restrict diameter to far less than this.

Revolutions per Minute

Revolutions per minute (RPM or *N)* is the number of full turns or rotations that a propeller makes in a single minute. Since the propeller rotates at the same speed as the propeller shaft, this is often called *shaft RPM* or *tail-shaft RPM*.

Shaft RPM is frequently very different from engine RPM, the speed at which the engine crankshaft turns at a given throttle setting. On the vast majority of installations, a *reduction gear* is fitted between the crankshaft and the tail or propeller shaft. The purpose of the reduction gear is to reduce RPMs at the propeller so that a larger-diameter, more efficient propeller may be used with an economical, compact, high-speed engine.

Some common reduction ratios are 2:1, 2.4:1 and 3:1; however, a vast number of reduction gears are available with a wide selection of ratios. In practice, it is frequently most economical to match the propeller to the standard reduction gears supplied by the engine manufacturer for their various engine models. When this is not possible, you can find a number of companies that specialize in producing marine reduction and reverse gear for a variety of special installations. In many cases, the gears may also serve to solve engine placement problems. Vee drives, offset drives and angled drives can combine a reduction gear with radical changes in shaft direction.

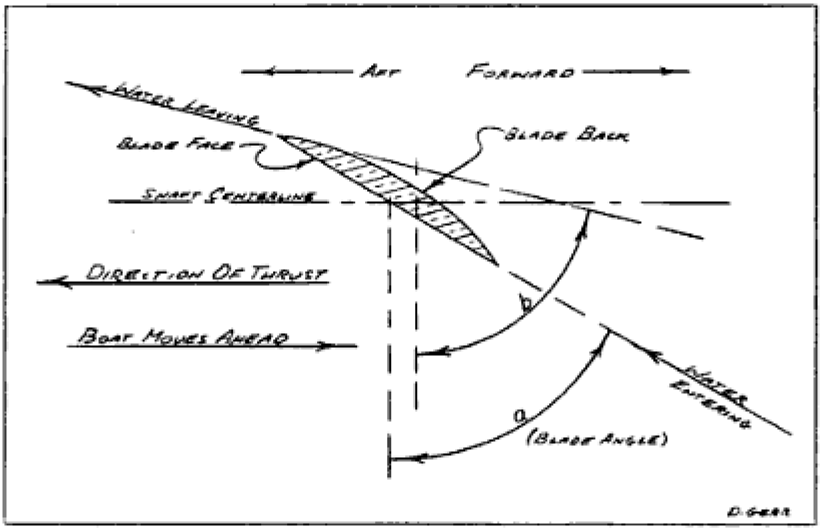


Figure 3-6A

Virtual pitch angle.

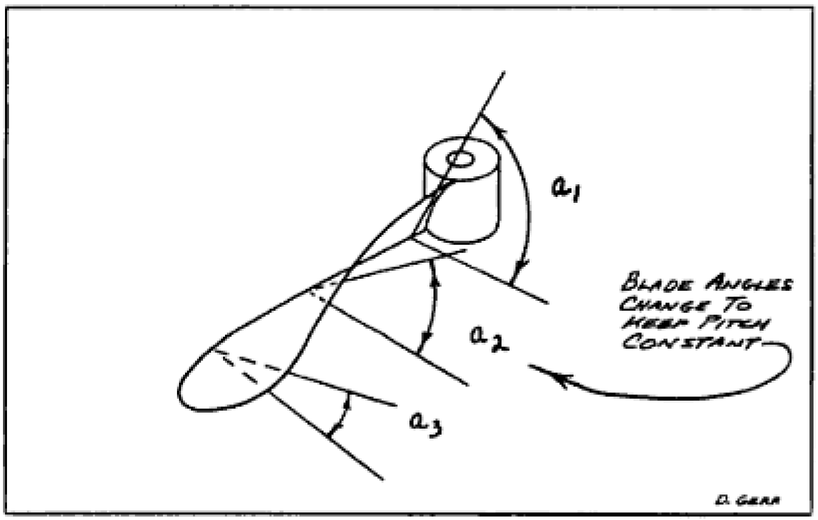


Figure 3-6B

The blade angle a changes continuously from root to tip in order to keep the pitch constant.

trollable-pitch propeller allows the operator to change the pitch of the propeller blades at will while underway. Usually, a hydraulic mechanism or a direct mechanical linkage permits rotation of the blades around the individual blade axes, independent of shaft revolutions.

Controllable-pitch propellers offer significant advantages in economy of operation for vessels that operate under varying conditions of load, such as tugs, trawlers and motorsailers. This is because the operator can adjust pitch to suit the thrust required for, say, running free or towing. Obviously, however, controllable-pitch propellers are considerably more expensive and complicated than ordinary solid propellers. We will deal with them at greater length in Chapter 8.

Virtual Pitch The final consideration in pitch is called *virtual* or *hydrodynamic pitch*. In reality, a propeller does not operate like a wood screw, although the analogy is useful. Water enters the propeller blades at an angle (angle *a* in Figure 3-6) relative to a plane at ratios of around 1.4 can result in efficiencies as high as 0.74. At pitch ratios higher than 1.5, efficiency generally starts to fall off. Lower pitch ratios are usually suited to lower-speed craft, and higher pitch ratios are best for high-speed craft.

A propeller that has a pitch ratio of 1.0—say, an 18-inch (457.2 mm) diameter and 18-inch (457.2 mm) pitch—is said to be a *square wheel*. In the past, some designers have given this proportion a sort of mystic importance. In practice, though, there is nothing special about a square wheel, although a pitch ratio of 1.0 is in a reasonably efficient operating regime.

Effects of Pitch Pitch converts the torque of the propeller shaft to thrust by deflecting or accelerating water astern. The formula describing this is Newton's Second Law: force (or thrust) equals mass times acceleration, or F = MA. In this light, a propeller drives a vessel forward exactly as a jet engine or rocket motor propels a plane or missile. The force or thrust is directly proportional to the mass or weight of water moved astern times the acceleration of that mass.

Since the mass being accelerated is water, thrust can be calculated as follows:

Formula 3-3 Theoretical Thrust Formula

Formula 3-3

Thrust = Force, F

$F = MA$ or

$F = W/g\,(V_o - V_i)$

Where:

W = weight in pounds of the column of water accelerated astern by the propeller

g = the acceleration of gravity, 32.2 ft./sec.^{2}

V_o = velocity of water before entering propeller in feet per second

V_i = velocity of water after leaving propeller in feet per second

M = mass in slugs

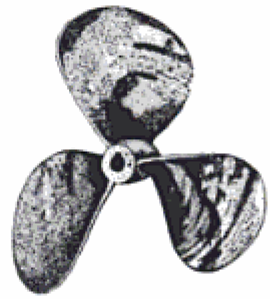
A = acceleration in feet per second squared

In a similar fashion, the speed of the vessel is proportional to the momentum of the water according to the law of conservation of momentum, or $M_1V_1 = M_2V_2$. In other words, the mass of water accelerated astern times its velocity will equal the mass of the vessel accelerated forward times its velocity. This relationship is very much complicated by the resistance of the water surrounding the hull, which is constantly working to slow it.

Even on a large diameter propeller, wide round "blades" like baseball bats, without pitch or angle of attack, would not accelerate any water astern and so would do nothing but generate tremendous churning. Such a propeller would not drive a boat forward at all. Conversely, ordinary blades with too much pitch would attempt to force more water astern more quickly than the engine could accommodate. This would simply place such a load on the engine that it would slow and never reach its maximum RPM or rated output power. This is both inefficient and potentially damaging to the engine.

The fundamental task in selecting a propeller is to choose a pitch and diameter that will generate the maximum thrust possible at normal operating speeds without overloading the engine. Increasing pitch increases thrust, but increasing pitch too much reduces the efficiency of the engine and propeller combination by slowing the engine. On the other hand, while too little pitch will not overload or slow the engine, it will not accelerate as much water astern and thus will not generate maximum possible thrust or speed.

Chapter 4
Blade Characteristics
Blade Shape, Cavitation, Special Propellers, and Rules of Thumb



In the preceding chapter, we described the parts of a propeller, defined its overall dimensions, and saw how blades are twisted to create the pitch that generates thrust. Nevertheless, it's important to bear in mind that two propellers of identical diameter and pitch could be quite different. For instance, one propeller could have very wide blades, and the other narrow or skinny blades. It's intuitively obvious that the wider-bladed propeller would absorb more thrust and horsepower, but we need to be able to define blade area, shape and width exactly to specify the correct propeller for a specific application. (Blade area is particularly important in determining if a propeller will cavitate or not.)

Likewise, the blades themselves may have different sectional shapes—differing thicknesses and contours—or, of course, two propellers of the same diameter could have a differing number of blades. Again, we need to be able to understand and describe all these variables exactly in choosing a propeller. Furthermore, there are specialized propellers, such as controllable-pitch propellers and ducted propellers, that are particularly suited to specific applications.

CHARACTERISTICS OF BLADES

Number of Blades

Let's consider the question: How many blades? Surprisingly, the ideal is one. A single blade does not have other blades disturbing the water flow ahead of it. Unfortunately, trying to get a single-bladed propeller to balance is like trying to clap with one hand. Having two blades is the logical answer. Both sailboats trying to reduce drag and very high-speed powerboats frequently use two-bladed propellers. The problem with two-bladed propellers for most vessels is that such propellers require very large diameters to get the blade area required for effective thrust. As a result, three-bladed propellers have generally proven to be the best compromise between balance, blade area and efficiency.

Effects of Multiple Blades

Four- or five-bladed propellers—and propellers with even more blades—are useful for two reasons. First, their extra blades create more total blade area with the same or less diameter. Accordingly, an installation that needed a 20-inch (508 mm) three-bladed propeller but only had room for an 18-incher (457.2 mm) could obtain sufficient thrust from, say, a properly sized four-bladed propeller. The four-blader, however, would seldom be as efficient as the three-blader because the closer blades create additional turbulence, literally scrambling up each other's water flow.

Another reason to use more than three blades is to reduce vibration. If a propeller is in the habit of producing annoying, rhythmic thumping and humming, a propeller with more blades will often go a long way toward curing the problem. Every time the blades of the propeller pass under the hull or by the strut, they cause a change in pressure that causes a push (or a suction). If the push is strong enough it generates a bang. Lots of rapid bangs equals vibration.

The blades of a three-bladed propeller turning at 1,000 RPMs pass under the stern 3,000 times every minute, or 50 times a second—a vibration of 50 cycles per second (cps), or 50 Hz (hertz). Switching to a four-bladed propeller—still at 1,000 RPMs—would change this to 4,000 times a minute, or 66 cps. The more rapid the cycles, the smoother the feel—and the less likely the hull is to resonate (amplify the sound like the body of a guitar) with the vibration.

For reducing vibration, there is a further advantage to substituting a propeller with more blades and consequently smaller diameter. If, for example, a 30-inch (762 mm) diameter three-bladed propeller were replaced with a 28-inch (711 mm) four-bladed propeller, the tip clearance (the distance between the hull and the propeller blades) would increase by 1 inch (25 mm). If the original tip clearance had been 4.5 inches (114 mm), this would amount to a 22 percent increase. Increasing tip clearance will greatly reduce the force of the pushes that cause vibration. When dealing with an installation that has been producing severe vibration, such an approach can be very effective in solving the problem.

Blade Area—Projected and Developed (Ap and Ad)

Blade area is the surface area of the individual propeller blades. The blade area has a direct effect on a propeller's tendency to cavitate and on the power it absorbs, but because of the complex shape of propeller blades, it is not easy to measure directly. The most common two measurements are *projected blade area*, Ap, and *developed blade area*, Ad (also called *expanded blade area*). Projected blade area is the area of the blades as viewed from directly astern. Another way to visualize this is as the area of the silhouette or shadow cast by the blades with a light shining from directly ahead.

Since the blades are twisted, the projected blade area is always less than the true blade area (the expanded or developed area). To find the developed blade area, a designer systematically expands (straightens out) the curved and twisted area on a drawing and measures this expanded area. This is the same as carefully fitting a piece of paper flush against the surface of the blade, cutting it to match the blade outline, laying it out flat on

CHART 4-1 DEVELOPED AREA TO PROJECTED AREA CONVERSION

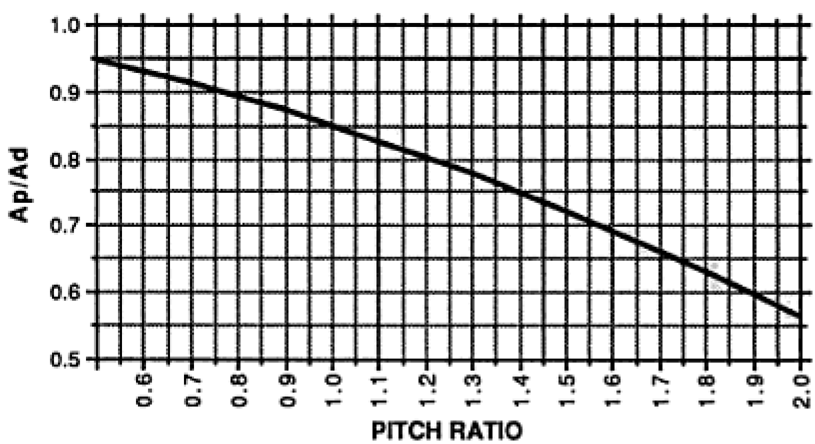


Chart 4-1. *This chart, based on Formula 4-1, plots the developed-area to projected-area ratio against the pitch ratio. If, for example, you know the projected area (Ap) and the pitch ratio, you can find the developed area (Ad) by dividing Ap by the factor shown in the chart.*

the table and measuring the area. (See Appendix B.) Developed blade area is the area most frequently used in making propeller calculations, since it represents the true total area actually absorbing thrust.

Developed Area to Projected Area Conversion Chart 4-1 gives the approximate ratio of the developed area to the projected area as plotted against the pitch ratio. If you know the developed area of a propeller with, say, a pitch ratio of 1.2, then Chart 4-1 gives the Ap/Ad ratio as 0.8. Accordingly, if the developed area (Ad) were 1,000 square inches (6452 cm^2), the projected area (Ap) would be 800 square inches (5162 cm^2). If the projected area is known, you can find the developed area by dividing by the Ap/Ad factor from Chart 4-1. For instance, if the Ap (projected area) of a propeller with a pitch ratio of 0.9 is 500 square inches (3227 cm^2), then the Ad (developed area) would be 573 square inches (3696 cm^2). (The factor from the chart is 0.87, and **500 sq. in. ÷ 0.87 = 573 sq. in.**)

Chart 4-1 is based on the following formula:

Formula 4-1 Developed Area to Projected Area Formula

$$Ap/Ad = 1.0125 - (0.1 \times PR) - (0.0625 \times PR^2)$$

Formula 4-1

Where:

Ap/Ad = Approximate ratio of projected area to developed area

PR = Pitch ratio of propeller

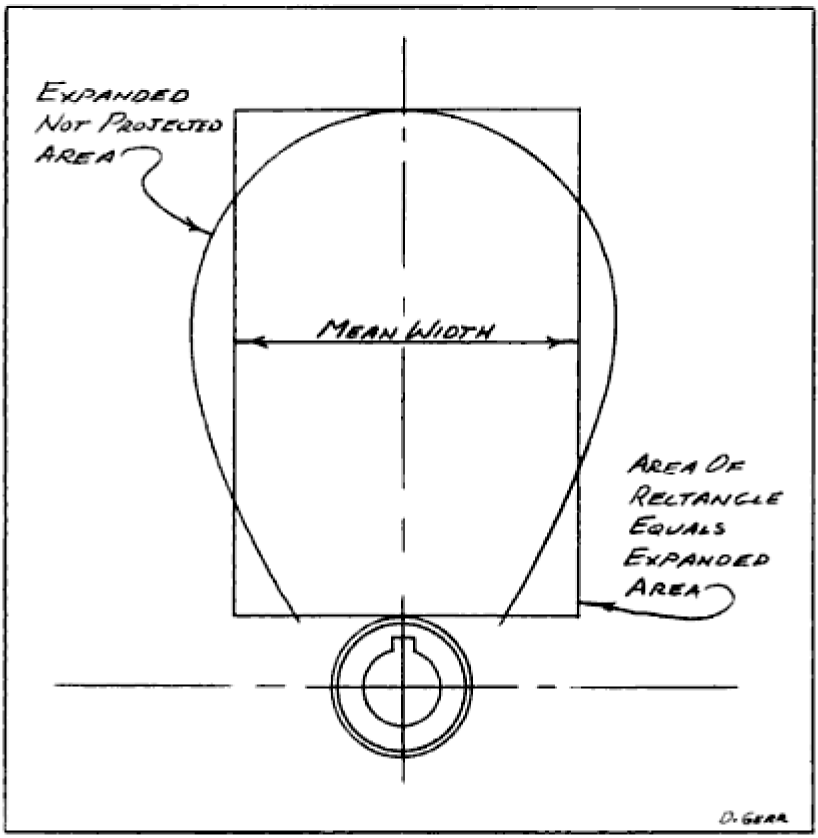


Figure 4-1

Determining the mean width of a propeller blade.

determined shape that can dramatically affect performance. The two most common shapes for cross-sections through a propeller blade are *ogival* and *airfoil*. An *ogival* or *flat-faced* blade is made with its face dead flat—as expanded—and its back symmetrically rounded. The leading and trailing edges of the blade are usually as sharp as possible, consistent with strength. The back or suction surface is rounded in a perfect circular segment, an ellipse, or a sine curve, with the maximum height or blade thickness exactly at the midpoint of blade width.

Airfoil blade sections resemble traditional airplane wing sections. The leading edge is rounded—not sharp—and the maximum blade thickness, or *chord*, usually occurs about a third of the blade width aft of the leading edge. The blade face is generally flat, though some airfoil blades have a small amount of convexity to their faces.

Effects of Blade Section Shape Since propeller blades generate thrust by producing lift—very much like airplane wings—you might expect that most propeller sections would have an airfoil shape. Interestingly, this is generally not the case. The suction surface of an airfoil blade actually generates too much lift, creating local areas—just

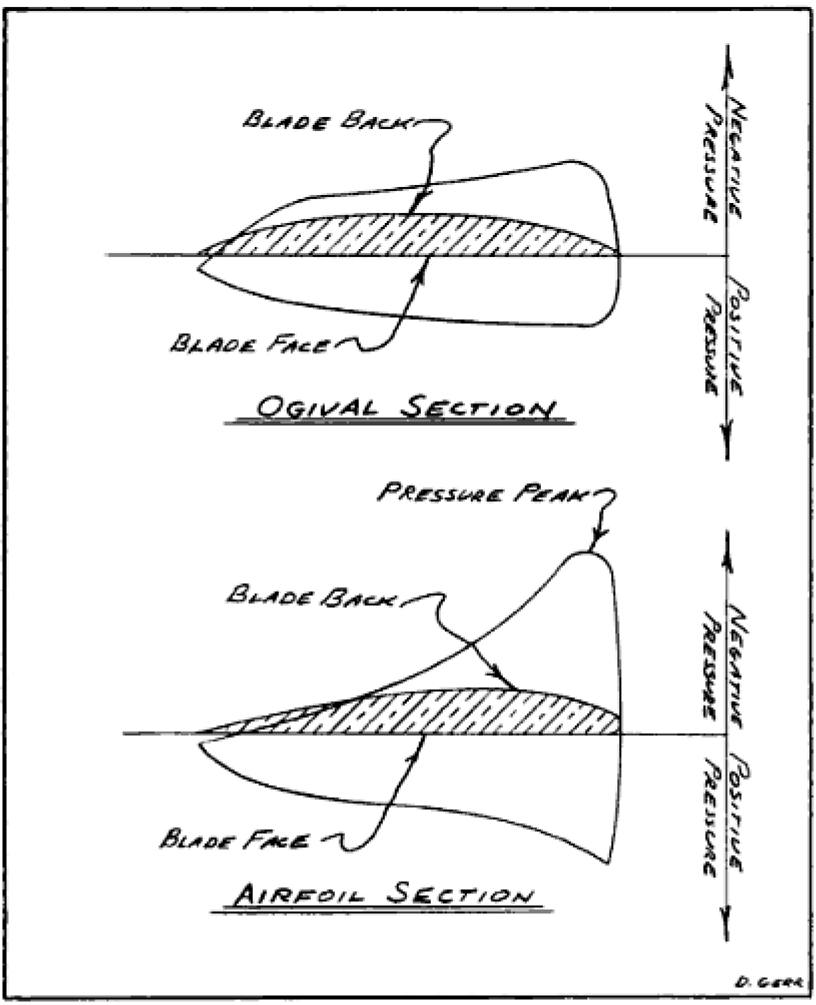


Figure 4-6

Pressures on ogival and airfoil section blades.

behind the leading edge—of very large negative pressure (suction). This leads to early cavitation (see later sections in this chapter). To avoid this, most propellers use the ogival shape.

In many modern propellers, a small amount of airfoil section is worked into the blades at the root. This is because the actual speed through the water of the inner parts of the blade is substantially slower than for the sections at the tip. Thus, the inner parts of the blade can safely be made to generate a bit of additional lift without creating excessive negative pressure and cavitation.

Following such blades out from the root, the airfoil section gradually disappears until—at 55 to 70 percent of the blade length out from the hub—the blades return to completely ogival section. Although such blades can increase performance, the gains are usually small—in the region of a 3- or 4-percent increase in efficiency. Since entirely ogival blades are easier and less expensive to produce, manufacturers continue to offer them, and they are more than satisfactory for most installations.

Blade-Thickness Fraction (BTF) or Axial-Thickness Ratio

Blade thickness is usually defined in terms of *blade-thickness fraction* or *axial-thickness ratio,* which is the maximum thickness of the blade divided by its diameter. Since a blade gets thinner as it progresses from root to tip, the maximum thickness is taken at an imaginary point on the shaft centerline. The line of the blade face is extended down to intersect with the shaft centerline at point O, and the line of the blade back is extended to point A on the shaft centerline. The distance $\overline{OA}$ or t_0 divided by the diameter equals the *blade-thickness fraction.* Blade-thickness fractions for average propellers usually fall between 0.04 and 0.06 (see Figure 4-11).

Formula 4-8 Blade-Thickness Fraction Formula

Formula 4-8

$$BTF = t_0 \div D$$

Where:

BTF = Blade-thickness fraction

D = Diameter

t_0 = Maximum blade thickness as extended to shaft centerline

Effects of Blade Thickness All other things being equal, a thinner blade is more efficient than a fatter, thicker one. There must, however, be enough thickness to create the desired sectional shape. In addition, blade thickness must be large enough to generate sufficient strength—if blades are too thin, they will break under extreme loading. A rough rule of thumb is that the blade thickness fraction should equal 16 percent of the mean-width ratio (MWR). Accordingly, a standard propeller with a MWR of 0.33 would have a BTF of about 0.053 [**0.33 MWR × 0.16 = 0.053**].

In order to keep highly loaded, high-RPM propeller blades from becoming excessively thick and losing efficiency, high-strength alloys are frequently used—particularly in waters where there is substantial chance of hitting floating debris. Manganese bronze is actually a type of brass commonly used for average propellers, though vulnerable to corrosion. Stainless steel is used for propellers under high load, and Nibral or NAB (an alloy of nickel, bronze and aluminum), and also aluminum bronze, are indicated for applications requiring extreme strength and good corrosion resistance.

Blade Contour

The shape of the blades as viewed from astern is their *contour.* Average propeller blades are narrowest at the root and broadest about 50 to 66 percent of the radius out from the centerline. Such blades generally have maximum widths between 25 and 40 percent of their diameters.

The amount of blade area that can be driven by a given horsepower and diameter is limited, so area is distributed where it will do the most good. Since the tips of the blades are traveling the greatest distance, they can do the most work. Thus, the natural tendency is to try to get all the blade area as far out as possible. Obviously, the propeller cannot have tiny shafts supporting huge plates at the tips, so we compromise on the elliptical shape that is most common. That way the root is strong enough to support the loads on the middle and tip, while the outer part of the blade is not so big that it gets in the way of the water going to the blade behind it or bends excessively.

Very slow-turning propellers customarily have their blade areas distributed farther out, with the maximum blade width occurring at as much as 75 percent of the radius. Propellers with four, five, or more blades frequently have long, narrow blades of low mean-width ratio to reduce total blade area.

Effects of Blade Contour Blade contour is very closely related to blade width. Since most blades are roughly elliptical in contour, squatter, broader contours are associated with wide blades or blades of high mean-width ratio. The comments on the effects of blade width apply here, too.

Skew

When the contour of the blade is not symmetrical but swept back, the blade is said to have *skew* or *skew back*. Moderate-speed propellers usually have little or no skew, while medium- to high-speed propellers will have a small amount of skew back.

Effects of Skew Skew causes radial sections of the blades to enter the water sequentially, instead of all at roughly the same time. This can help reduce vibration, especially at high RPMs, by easing the transition of the blades from the full slipstream to the much slower

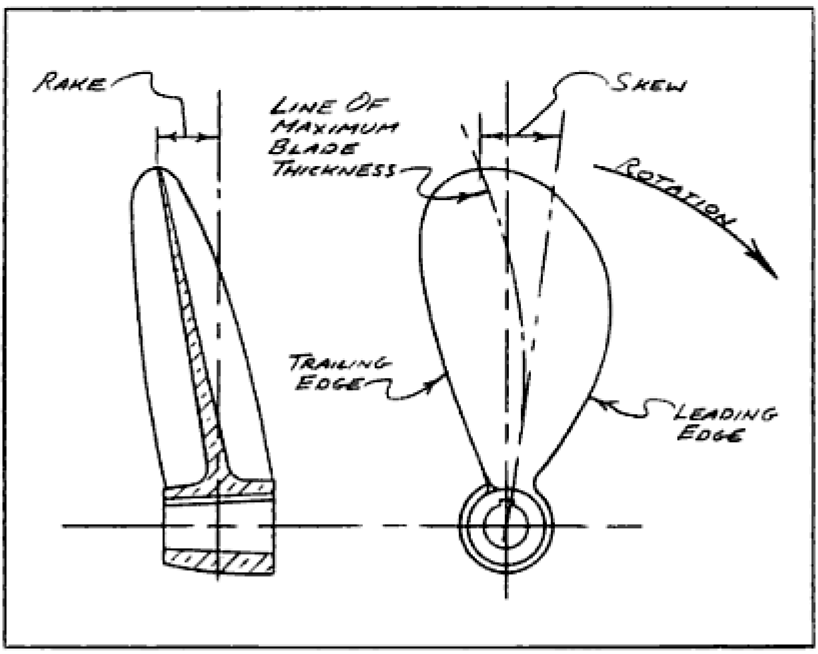


Figure 4-7

Blade with skew and rake.

efficiency at high speeds. In spite of the many advantages cupped blades can offer high-speed craft, they serve no useful function on most vessels operating at under 30 knots.

CAVITATION

Cavitation is bubbles of partial vacuum caused by excessive propeller speed or loading. To avoid this condition, the negative pressure on the blade back (the suction face) must remain less than the local (ambient) pressure of the water at the propeller. For most installations the ambient pressure is equal to the pressure of the atmosphere at sea level, about 14.7 pounds per square inch (101326 N/m^2), plus the pressure generated by the head of water above the propeller and minus the vapor pressure of the water. On average vessels this comes to around 13.9 PSI. Thus, if the lift or suction on any portion of the blade back exceeds 14 PSI, cavitation is very likely to occur.

High-RPM airfoil sections that produce negative pressure peaks, large amounts of *slip* (see next chapter), excessive pitch, and high tip speeds all tend to create or increase cavitation. Thus, cavitation is seldom a problem on low-speed vessels with slow RPMs. Keeping RPMs down, using ogival section blades (particularly at the tips), decreasing pitch slightly at the blade tips, and keeping pitch ratios as low as possible all help eliminate or reduce cavitation.

Effects of Cavitation

Contrary to what most people think, cavitating propellers can still generate plenty of thrust. The problem is that the vacuum bubbles implode against the propeller, causing vibration and pitting. The vacuum bubbles form and implode irregularly, causing uneven pressure both along the blades and between them. This creates vibration identical to having unbalanced or unequally pitched blades. What's more, the force of the imploding bubbles is so great that it actually sucks metal right off the surface of the propeller. The resultant pitting leads to uneven wear, bad balance and even more vibration.

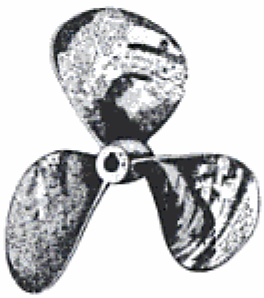
Supercavitating and Fully Cavitating Propellers

Vessels operating at high speeds (over 35 knots) and at high shaft RPMs are frequently forced into operating regimes in which cavitation is difficult to avoid. One solution is to use *supercavitating* or *fully cavitating* propellers, specifically designed to operate during cavitation. Even though supercavitating propellers are not generally quite as efficient as standard noncavitating propellers, practical limitations on propeller diameter and RPM frequently make supercavitating propellers attractive options.

In order to avoid the pitting and vibration caused by cavitation, the blades on supercavitating propellers are shaped so the bubbles will not implode against them. Although there are a number of approaches to this, you can frequently recognize this sort of propeller by its scimitar-like blade shape.

VENTILATION

Ventilation is often confused with cavitation, though actually it is quite different. Whereas cavitation comprises actual regions of partial vacuum, ventilation is caused by the propeller's sucking air down from the water's surface. This is not usually as severe a problem as cavitation, but it can lead to vibration and loss of thrust. Some propellers, such as surface propellers, are specifically designed to work with air entrained in the wake, but for most propellers ventilation should be avoided. The best way to correct ventilation is to get the propeller deeper under the surface, which sometimes can be accomplished simply by reducing diameter. Using a propeller with blades raked aft is also helpful in reducing ventilation, since the force of water streaming out along the raked blades reduces the tendency of air to be pulled into the propeller disc.



Chapter 5
Crouch's Propeller Method
The Empirical Method for Calculating Propellers Using Slip

For many years engineers have used the analogy of a wood screw in soft pine to explain propeller operation. This analogy is so intuitive and has persisted for so long that many propeller terms, including the terms *screw propeller* and *pitch*, are based on this assumption. In fact, in its best form, this analogy is still used by some designers, as embodied by the tables and formulas developed and refined largely by George Crouch.

Because it is so intuitive and because it is the "traditional" method of propeller calculation, we will examine the Crouch or slip method first. I recommend, however, that the Bp-δ method (pronounced "bee pee delta"), which we'll cover in the next chapter, be used for final calculations when precision is needed. Most modern propeller experts use the Crouch method only for rough estimates, relying on the Bp-δ or other more mathematically exact methods for installations demanding efficiency. The slip method is perfectly adequate, however, when peak efficiency is not important, as for example in auxiliary sailboats.

A propeller must meet two completely different requirements: it must match the boat's hull, and it must match its engine. In Chapters 1 and 2 we discussed the selection of a suitable engine and what speed we can expect the vessel to obtain with that engine. Now that we have learned how a propeller's shape is defined, the question remains how to determine the correct propeller for a specific vessel.

DETERMINING SLIP AND PITCH

Matching Pitch to Speed

A hull requires a certain amount of thrust to push it forward, and we need to pick a propeller that will generate as much thrust as possible at the intended operating speed. Let us take, for example, *Svelte Samantha*, a single-screw cabin cruiser intended to cruise at 18 knots (a SL ratio of 3.3), at 75 percent of full engine RPMs—she will have a typical light, high-speed engine. With this information, we can start to calculate the proper propeller pitch. Our aim is to have the propeller advance the same distance the boat will at speed. *Svelte Samantha*'s characteristics are as follows:

Svelte Samantha

34 ft.	10.36 m	LOA (length overall)
30 ft.	9.14 m	WL (waterline length)
11 ft.	3.35 m	BOA (beam overall)
10 ft.	3.05 m	BWL (waterline beam)
1.34 ft.	0.40 m	Hd (hull draft)
12,700 lb	5760 kg	Displacement
18 kt	18 kt	Desired cruising speed

Using Formula 2-4, we determine that *Svelte Samantha* requires 182 SHP (136 kw) at the propeller to achieve 18 knots (using a C of 150, for an average cruiser). Accordingly, *Svelte Samantha*'s engine should be rated 240 BHP (197 kw) **[182 Hp ÷ 0.75 = 242 HP]**, and the engine chosen delivers this at 3,000 RPM, with a 2.4-to-1 reduction gear. This means that *Samantha*'s propeller will turn at 1,250 RPMs with the throttle wide open **[3,000 RPM ÷ 2.4 = 1,250 RPM]**.

Determining Which RPM to Use in Finding Pitch

Here, we face an important compromise. We found in Chapters 1 and 2 that cruising speed should be at 70 to 85 percent of top rated engine RPM (as is the case with *Svelte Samantha*). Since our propeller will be of fixed pitch, however, if it is pitched for ideal operation at 75-percent RPM, it will be way off at full RPM. A good average is to base pitch on operation at 90 percent of maximum RPM, which will yield about 90 percent of the maximum SHP. For *Svelte Samantha*, this works out to a shaft speed of 1,125 RPM at around 216 SHP (161 kw). Our cruising speed will be a bit below this, but we will still be able to open the throttle up to get top revolutions when needed. We must now base our pitch calculation on speed at 90 percent of full throttle. Two hundred and sixteen SHP yields 58.8 pounds per horsepower (35.7 kg per kw). Formula 2-4 gives a V of 19.5 knots.

Figuring Pitch Without Slip

Once we know our speed, all we have to do is find the pitch that will give us the same forward distance traveled per minute as the boat will go at 19.5 knots. Since we know the boat speed in nautical miles per hour (knots) and the propeller pitch in inches and RPM, we have to find some common ground—in this case, feet per minute. To convert knots to feet per minute, multiply by 101.3 (to convert miles per hour to feet per minute, multiply by 88). Thus, *Svelte Samantha* is moving along at a V of 1,975.3 feet per minute **[19.5 knots × 101.3 = 1,975.3 ft./min.]**. Our propeller is turning at 1,125 RPMs. If we divide *Samantha*'s speed of 1.975.3 feet per minute by 1,125 RPMs, we find that our propeller should have a pitch of 1.75 feet (0.53 m) **[1.975.3 ft./min. ÷ 1,125 RPMs = 1.75 ft.]**. Since propeller pitches are usually specified in inches, we multiply 1.75 feet by 12 and find that *Svelte Samantha* requires a propeller with a 21-inch (533 mm) pitch.

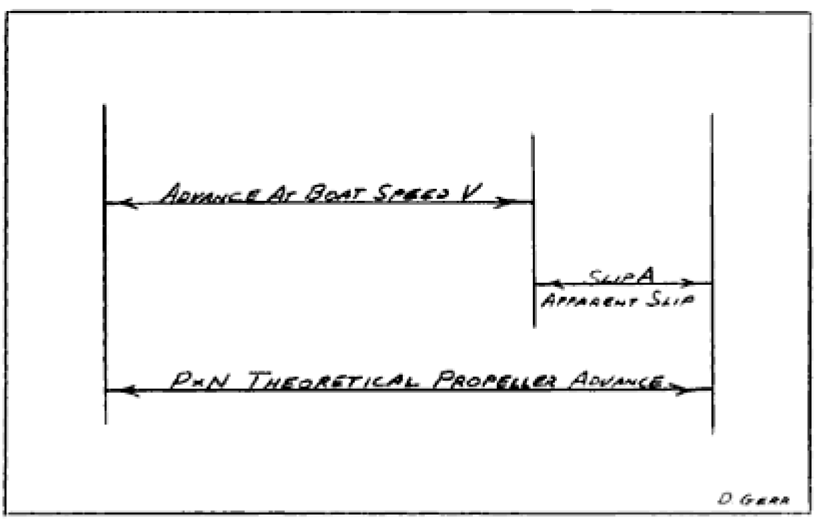


Figure 5-1

Apparent slip.

Slip

In reality, water is not like soft pine. It's a fluid and so a propeller *slips* or slides a bit as it rotates. It's more exact to view slip as the difference between the distance a boat actually travels through the water—in the time of one complete propeller revolution at her speed through the water, V—and the theoretical distance it would travel if it advanced the full pitch of the propeller (see Figure 5–1). This difference is called *apparent slip* (SlipA) and is expressed as a percent of theoretical propeller advance (pitch times RPM).

The only way to find slip exactly is to take a boat out and run her on a measured mile. Carefully timing the runs gives the exact speed and, knowing RPM and pitch, you can use the above relationship with the following formula to find slip:

Formula 5-1 Apparent Slip Formula

$$\text{SlipA} = \frac{(P/12 \times \text{RPM}) - (\text{Kts} \times 101.3)}{(P/12 \times \text{RPM})}$$

Which may be conveniently restated as:

Formula 5-1

$$P = \frac{\text{Kts} \times 1215.6}{\text{RPM} \times (1 - \text{SlipA})}$$

Where:

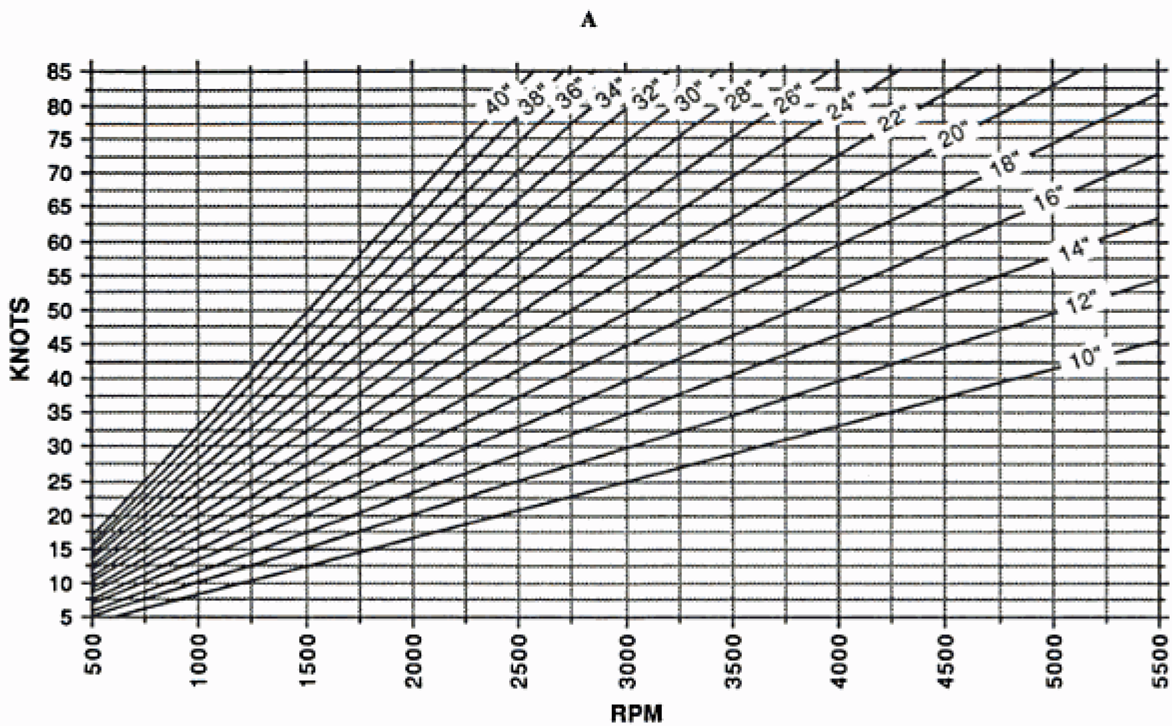
SlipA = Apparent slip

P = Propeller face pitch in inches

Kts = Boat speed through water or V in knots

RPM = Revolutions per minute of the propeller

CHART 5-1 SLIP VS PITCH



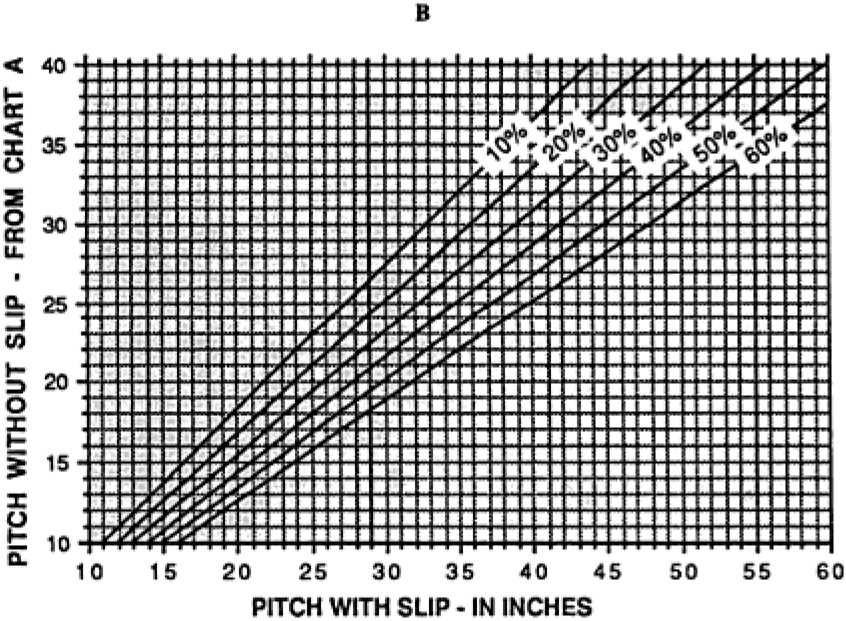


Chart 5-1A and B. *These charts, related to Formula 5-1, may be used in two ways. In the first, apparent slip can be estimated from the results of a timed run over a measured mile. Enter Chart A with the measured speed and RPM, and read off the "pitch without slip." Enter Chart B with this value and your propeller's actual known pitch, and read out the apparent slip as a percent of theoretical propeller advance (pitch times RPM). The second, more common use of the charts is to calculate the needed propeller pitch for a new boat design or a repowering, using the desired speed and RPM and an estimated value for slip. Again, read out a value for "pitch without slip" from Chart A. Then enter Chart B with this value and a slip estimate from Chart 5-2 or Table 5-1.*

It is important to run a course between fixed points as specified on a proper navigation chart. Obviously, using a "measured mile" that was not an exact mile would throw your calculations completely off. Bear in mind that buoys can drag sufficiently to throw off their locations. In addition, the mile should be run at least twice, in opposite directions, and the results averaged to cancel out the effects of wind and current. For really accurate work, run the course both ways three times. Since we are dealing with a new design, a repowering or a new propeller, we have to estimate slip. This is the chief drawback to the slip method of finding pitch. There is no precise way to determine slip short of putting a propeller on a boat and running a measured mile.

Estimating Slip for Finding Pitch

Chart 5-2 plots slip as a function of boat speed in knots. It is based on the formula:

Formula 5-2 Slip vs Boat Speed Formula

$SLIP = 1.4 \div Kts^{0.57}$

Where:

Kts = Boat speed in knots

Formula 5-2

This formula was derived by the author, and checks very well against known slip values from a wide variety of sources. [Note: Appendix D provides a quick math review for those who are unfamiliar with or rusty on decimal exponents.]

CHART 5-2 SLIP VS BOAT SPEED

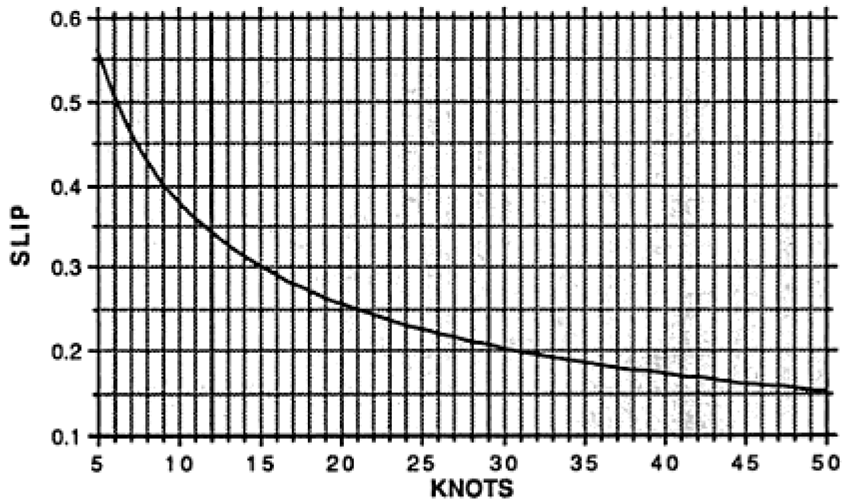


Chart 5-2. *This chart, constructed from Formula 5-2, shows slip as a function of speed. This empirical relationship, derived by the author, checks well against known values.*

The results from Formula 5-2 should be averaged against the information in Table 5-1 to see if the slip value makes sense for the type of vessel being considered.

TABLE 5-1

TABLE 5-1 TYPICAL SLIP VALUES

Type of Boat	Speed in Knots	Percent of Slip
Auxiliary sailboats, barges	under 9	45%
Heavy powerboats, workboats	9–15	26%
Lightweight powerboats, cruisers	15–30	24%
High-speed planing boats	30–45	20%
Planing race boats, vee-bottom	45–90	10%
Stepped hydroplanes, catamarans	over 90	7%

Slip and Efficiency Are Not the Same

People frequently mistake slip (SlipA) for efficiency, abbreviated as e or η (the Greek letter E, pronounced "eta"), and thus try to eliminate it altogether. Actually the two concepts are quite different—although they are very closely related. (See Efficiency vs Slip Chart 5-6.) Slip, in fact, is actually *required* to produce thrust. Though it's a good practice to keep slip fairly low, the slip values given in Table 5-1 are close to optimum. You cannot eliminate slip and would not want to if you could, for then you would have no thrust at all.

Finding Pitch with Slip

Using Chart 5-2 or Formula 5-2, we find a slip for *Svelte Samantha* of 27 percent. Let's check against the Table 5-1, Typical Slip Values. *Svelte Samantha* is a light cabin cruiser. With her accommodations, she is a bit heavier than a lightweight powerboat. The table

- *Why won't your engine reach its top rated RPMs?*
- *Why is your propeller shaft vibrating?*
- *Why doesn't your boat reach the top speed claimed by the manufacturer?*
- *Will more or less propeller pitch improve your boat's performance?*
- *Is a square wheel (pitch equals diameter) best?*
- *Is a folding prop best for your purposes?*
- *Should you choose a two-, three-, or four-bladed propeller?*

All these questions and more are answered in this complete reference—the first of its kind.

Dave Gerr is a naval architect specializing in the design of yachts and commercial craft to 180 feet. He has worked on vessels ranging from 440-foot cruise ships to a 60-foot BOC racer, a 60 mph jet-drive runabout, a 7-knot, 25-foot cruising motor launch, 100-foot aluminum motoryachts, and an assortment of 40- and 50-foot auxiliaries and motorsailers.

Owner of his own design firm, Gerr is a graduate of Westlawn School of Yacht Design and has studied physics at New York University and industrial design at Pratt Institute. He has a particular fascination with the relationship between science and art, function and beauty, and finds in naval architecture a rewarding harmony among these.

Dave Gerr's articles on boat design have appeared in *Cruising World*, *Ocean Navigator*, *SAIL*, *Yachting*, and *WoodenBoat*. He is a contributing editor for *Boatbuilder* and *Offshore* magazines. He is the author of *The Nature of Boats* and *The Elements of Boat Strength*, both published by International Marine.

"We have highly recommended the *Propeller Handbook* to our distributors and repair stations, and have multiple office copies that our sales people refer to."
—Michigan Wheel Corporation

"This book will answer almost every propeller-related question you're likely to come across."
—*Ensign*

"Without doubt the definitive reference for selecting, installing, and understanding boat propellers."
—*Royal Navy Sailing Association Journal*

"This book is for everyone who has ever had to make a decision about a propeller: mechanics, boatbuilders, boat service yard owners, boat owners, as well as naval architects. Dave Gerr and International Marine made a complicated topic understandable and put it into a handbook that is easy to use."
—*WoodenBoat*

International Marine
A Division of The McGraw-Hill Companies
www.internationalmarine.com

ISBN 0-07-138176-7
51995
9 780071 381765