CHAPTER 4 - PROPELLER TERMINOLOGY

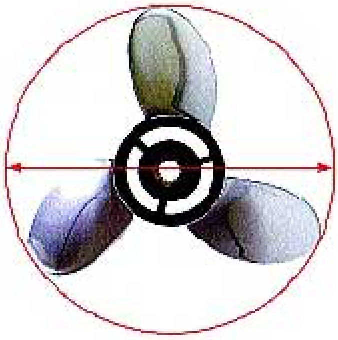


Figure 4-1
Propeller diameter

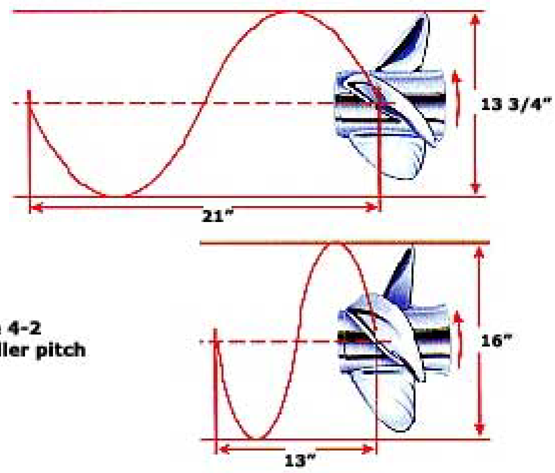
There are a variety of terms used to describe propeller characteristics as well as performance attributes. It is important that you have a good understanding of them, as detailed here.

Diameter

Diameter is the distance across the circle made by the blade tips as the propeller rotates (Figure 4-1).

Diameter is determined primarily by the RPM at which the propeller will be turning and the amount of power that will be delivered to the propeller through the shafts and gears. The degree to which the propeller may operate in a partially surfaced condition, as well as the intended forward velocity, will also play a role in determining the most desirable diameter. Within a given propeller line, the diameter usually increases for propellers used on slower boats and decreases for faster boats. If all other variables remain constant, diameter will increase as power increases; diameter will increase as propeller RPM decreases (slower powerhead or engine speed and/or more gear reduction); and diameter should increase as propeller surfacing increases.

Figure 4-2
Propeller pitch



Pitch

Pitch is the distance that a propeller would move in one revolution if it were moving through a soft solid, like a screw in wood (Figure 4-2).

When a propeller is identified as 13 3/4 x 21, it has a 13 3/4" (35 cm) diameter with 21" (53 cm) of pitch. Theoretically, this propeller would move forward 21" in one revolution.

Pitch is measured on the face of the blade (Figure 4-4). A number of factors can cause the actual pitch of a propeller to vary from the advertised pitch stamped on it. Minor distortion may have occurred during the casting and cooling process. Adjustments or modifications may have been made by propeller repair stations. And finally, undetected damage may have altered the pitch.

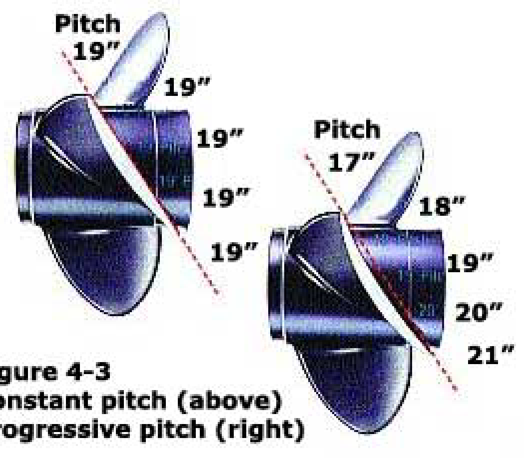


Figure 4-3
Constant pitch (above)
Progressive pitch (right)

There are two common types of pitch: constant (also called "true" or "flat") pitch and progressive pitch (Figure 4-3). Constant pitch means the pitch is the same at all points from the leading edge to the trailing edge. Progressive pitch (also called blade "camber") starts low at the leading edge and progressively increases to the trailing edge. The pitch number assigned (for example, 21") is the average pitch over the entire blade.

Progressive pitch improves performance when forward and rotational speed are high and/or the propeller is operating high enough to break the water surface. It is commonly used on mid- to high-horsepower Mercury propellers.

Pitch is rather like another set of gears. For a given engine that wants to run at a given RPM, the faster the boat can go, the higher the pitch you need. If you select too low a pitch, the engine RPM will run too high (above the top of the recommended limit), putting an undesirable higher stress on many moving parts. You may have a great acceleration but your top speed will probably suffer and your propeller efficiency will definitely suffer. If you select too high a pitch you will force your engine to lug at a low RPM (below the recommended range) which is generally at a higher torque level and can be very damaging to your engine. Top speed may not suffer too much, but acceleration will be seriously reduced.

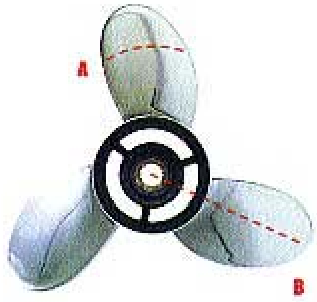


Figure 4-4
A. Propeller pitch line
B. Propeller rake line

Rake

When a propeller blade is examined on a cut extending directly through the center of the hub, as in Figure 4-4, the face side of the cross section of the cut blade relative to a plane that is perpendicular to the propeller axis would represent blade rake (Figures 4-5, 4-6, and 4-7).

If the face of the blade is perpendicular to the propeller hub (Figure 4-5), the propeller has zero degree rake. As the blade slants back toward the aft end of the propeller, blade rake increases (Figure 4-6). With standard propellers, the rake angle varies from -5° to 20°. Basic propellers for outboard engines and stern drives commonly have around 15° of rake. Higher-raked (high-performance) propellers often have progressive rake which may go as high as 300 at the blade tip.

Rake is either flat (straight) as shown in Figures 4-5 and 4-6, or curved (progressive) as shown in Figure 4-7.

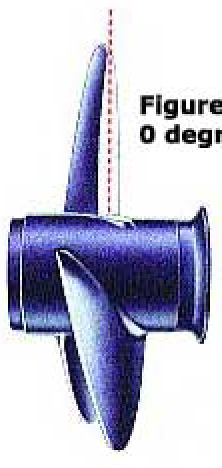


Figure 4-5
0 degree rake

A higher rake angle generally improves the ability of the propeller to operate in a cavitating or ventilating situation, such as when the blades break the water's surface. With such surfacing operation, higher blade rake can better hold the water as it is being thrown off into the air by centrifugal force, and in doing so, creates more thrust than a similar but lower raked propeller. On lighter, faster boats, with a higher engine or drive transom height, higher rake often will increase performance by holding the bow of the boat higher, resulting in higher boat speed due to less hull drag.

However, with some very light, fast boats, higher rake can cause too much bow lift, making hese boats more flighty or less stable, in which case a more moderately raked propeller would be a better choice.

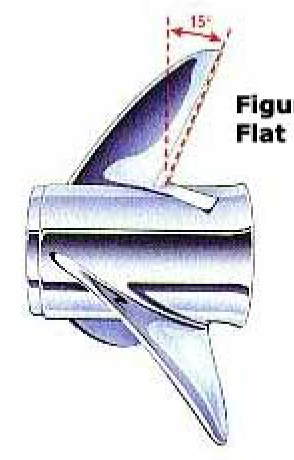


Figure 4-6
Flat rake

Cupping

When the trailing edge of the blade is formed or cast with an edge curl (away from the boat), it is said to have a cup (Figure 4-8). Originally, cupping was done to gain the same benefits as just described for progressive pitch and curved or higher rake. However, cupping benefits are so desirable that nearly all modem recreational, high-performance or racing propellers contain some degree of cup.

Cupping usually will reduce full-throttle engine speed about 150 to 300 RPM below the same pitch propeller with no cup. A propeller repair shop can increase or decrease cup to alter engine RPM to meet specific operating requirements on most propellers.

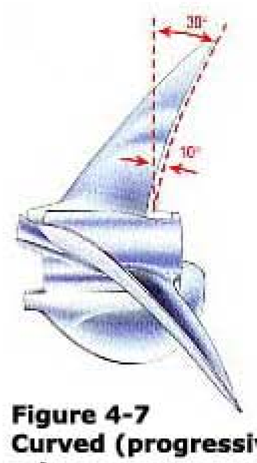


Figure 4-7
Curved (progressive)
rake

For a cup to be most effective, it should be completely concave (on the face or pressure side of the blade) and finish with a sharp trailing edge. Any convex rounding of the trailing edge of the cup, on the pressure side, detracts from its effectiveness.

where the propeller remains fully submerged.

Importance of Cup Location

Using a round-bladed propeller as an example, if the cupped area intersects pitch lines, as in Figure 4-9, it will increase blade pitch. Cupping in this area will reduce RPM by adding pitch. It will also protect somewhat against propeller "blowout" (see Cavitation, below). If the cup is placed so that it interests rake lines, Figure 4-10, it then has the effect of increasing rake (see Rake, above). There is clearly some overlap where cup effects both pitch and rake.

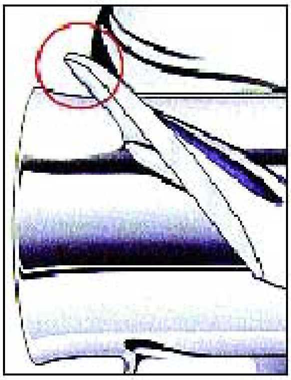


Figure 4-8
Clipping

In some cases, adding a normal cup has reduced engine RPM by an unusually high number, asmuch as 1000 RPM. This "blown out," a situation not uncommon and often undetected until a cupped propeller is tried. A partially blown-out propeller has a mushy, somewhat unresponsive feel, and may produce excessive propeller spray. An accurate slip calculation (see Slip, below) can be beneficial here. Slip will generally jump from its normal 10% to 15% to over 20% for a partially blown-out propeller (on an average - to lightweight boat).

Adjusting the cup on a cleaver-style propeller is moredifficult. Since the trailing edge is very thick and runs straight out on a rake line, any adjustment will have far less effect on altering rake (Figure 4-11).

The added pitch created by the cup can be reduced substantially by filing or grinding away some of the cup. At the same time, rake can be altered slightly. For less rake, decrease the cup in the area close to the tip. For more rake, reduce the cup in the area close to the hub. Obviously, any cup reduction will also result in an RPM increase.

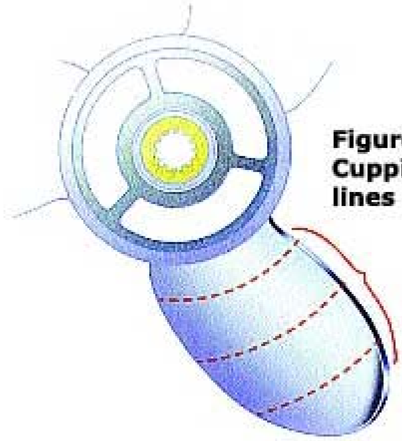


Figure 4-9
Cupping along pitch lines changes pitch

Rotation ("Hand")

There are right-hand rotating (RH) and left-hand rotating (LH) propellers (Figure 4-12). Most outboard and stern drive propellers are right-hand rotation.

To recognize a right-hand propeller, observe the prop from a position shown in Figure 4-12 (resting on either end of the hub is OK) and note that the right-hand propeller blade slants from lower left to upper right. A left-hand propeller will have the opposite slant-from lower right to upper left. The bladeslopes or climbs up in the direction of rotation. A right-hand rotation propeller has the same basic blade slopeas the threads on a common right-hand screw.

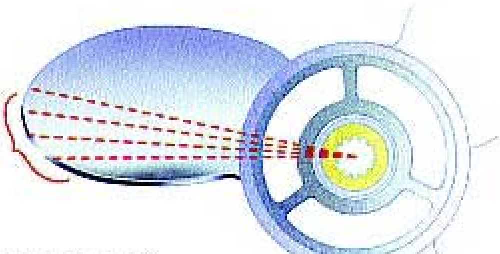
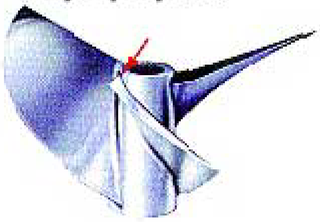


Figure 4-10
Cupping along rake lines changes rake

Another method of recognition is to observe the propeller rotating in forward gear from behind the boat. A right-hand propeller turns clockwise; a left-hand propeller turns counter-clockwise.

Figure 4-11
Cupping on cleaver-style propeller



Number of Blades

A single-blade propellerwould be the most efficient - if the vibration could be tolerated. So, to get an acceptable level of balance with much less vibration, a two-bladed propeller, practically speaking, is the most efficient. As blades are added, efficiency decreases, but so does the vibration level (Figure 4-13). Most propellers are made with three blades as a compromise for vibration, convenient size, efficiency, and cost. The efficiency difference between a two- and a three-bladed propeller is considered less significant than the vibrational difference. Nearly all racing propellers are presently either three- or four-bladed.

In recent years, with the growing frequency of propellers being run at an increased height (surfaced), four- and five- bladed props havebecome more popular. They suppress the higher level of vibration and improve acceleration by putting more blade area into the water. They can also help to make the rake more effective in lifting the bow of the boat for added speed.

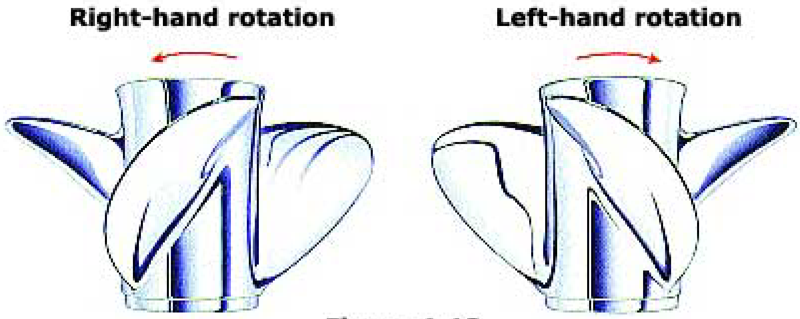


Figure 4-12

Figure 4-13
As blades are added, efficiency and vibration level decrease.

Blade Thickness

Like a tree limb growing from a tree trunk, a blade is thickest at the point where it meets the hub (blade root). As theblade moves out from the hub to the tip, it becomes thinner (Figure 4-14). The basic reason for this is that, as with any cantilever beam, the load that any blade or beam section must support is the load on the blade or beam between that section and the tip of the blade. Thus, at the tip there is zero load requiring zero thickness. However, to be practical, a given minimum edge thickness is chosen for a given propeller material and type of use.

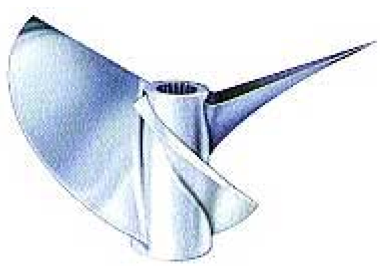


Figure 4-14
Blade thickness

Since there is only so much power available, blades should be as thin as practical (considering the strength of their material) because it takes more power to push a thick blade through the water than a thin blade.

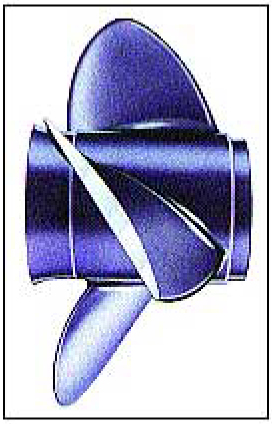


Figure 4-15
Common propeller blade

But what about the thickness variation from the leading to trailing edge? When viewing a common blade cutaway at a given radius from the center of a constant pitch-propeller (Figure 4-15), an approximate flat surface will be observed on the positive (pressure) side and a circular arc surface on the negative (suction) side, with the thickest point in the center. Edges usually are .06" to .08" (1.5 mm to 2.0 mm) thick for aluminum propellers, thinner for stainless steel.

For propellers intended to run partially surfaced, as in racing applications, the "cleaver" blade shape (see Figure 4-14) is popular. Its blade section is usually a wedge. Blades with a thick trailing edge such as this should only be run surfaced. When they are run deep, where surface air can't ventilate the low-pressure cavitation pockets formed behind the thick trailing edge, they are less efficient.

Blade Contour

Contour is the shape of the blades as viewed from directly over the blade face or back. The contour is generally completely rounded, commonly called "round-eared" or shaped with a straight trailing edge, commonly called a "cleaver."

Skew

A blade that is swept back versus a blade that is radially symmetrical in contour is said to have skew (Figure 4-16). Considerable skew (sweep back) is helpful in allowing a propeller to more easily shed weeds. Higher skew on a surfacing application reduce the pounding vibration of a propeller blade re-entering the water.

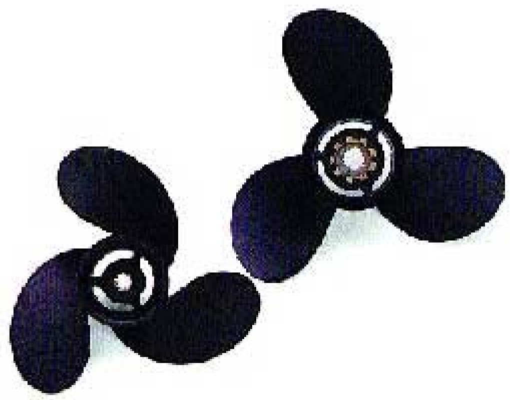


Figure 4-16
Propeller with considerably skewed blades (left)
Propeller with very little skew to the blades (right)

Ventilation

Ventilation occurs when air from the water's surface or exhaust gases from the exhaust outlet are drawn into the propeller blades (Figure 4-17).

The normal water load is reduced and the propeller over-revs, losing much of its thrust; however, as the propeller momentarily over-revs, this brings on massive cavitation (see Cavitation, following), which can further "unload" the propeller and stop all forward thrust. It continues until the propeller is slowed down enough to allow the bubbles to surface, and the original cause of cavitation is eliminated. This action most often occurs in turns, particularly when trying to plane in a sharp turn or with an excessively trimmed-out engine or drive unit.

Figure 4-17
Ventilation: air being sucked into propeller

Outboard engines and stern drive units are designed with a large "antiventilation" plate cast integrally into the gear housing (also commonly called the "gearcase") directly above the propeller (Figure 4-18). This plate is frequently, but incorrectly, referred to as a "cavitation" or "anticavitation" plate. The purpose of this plate is to eliminate or reduce the possibility of air being drawn from the surface into the negative pressure side of the propeller blades.

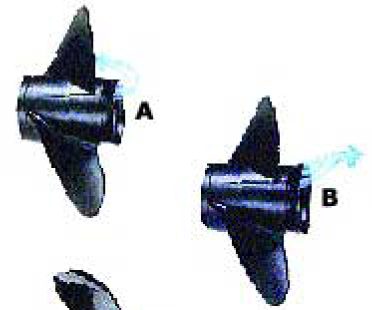
Figure 4-18
Antiventilation plate

For improved engine and boat performance, most Mercury propellers feature a hub design with a flared trailing edge or "diffuser ring." This assists exhaust gas flow and provides a high-pressure barrier that helps prevent exhaust gases from feeding back into the negative pressure side of the blades (Figure 4-19), which is another form of ventilation.

Cavitation

We all know that water boils at 212°F (100°C) at normal sea-level atmospheric pressure. But water also boils at room temperature if the atmospheric pressure is low enough.

Figure 4-19
A. Propeller without flared trailing edge showing exhaust feeding back into blades.
B. Propeller with flared trailing edge showing exhaust being pushed out, away from blades.



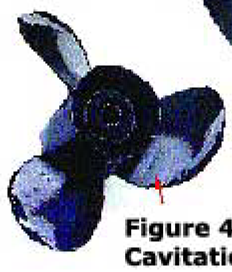


Figure 4-20
Cavitation Burn

As a shape passes through water at an increasing speed, the pressure that holds the water to the sides and back of the shape is lowered. Depending upon the water temperature, when the pressure reaches a sufficiently low level, boiling (i.e., the formation of water vapor) will begin. This occurs most often on a propeller near the leading edge of the blade. When speed is reduced and the pressure goes up, boiling will subside. As the water vapor bubbles move downstream into a high- pressure region that won't sustain boiling, they collapse (condense back to liquid). The collapsing action, or implosion, of the bubbles releases energy that chips away at the blades, causing a "cavitation burn" or erosion of the metal (Figure 4-20).

The initial cause of the low pressure may be nicks in the leading edge, too much cup, sharp leading edge comers, improper polishing, or, sometimes, poor blade design. Massive cavitation by itself is rare, and it usually is caused by a propeller that is severely bent or has had its blade tips broken off resulting in a propeller that is far too small in diameter for the engine. (See Ventilation, above, for another common cause.)

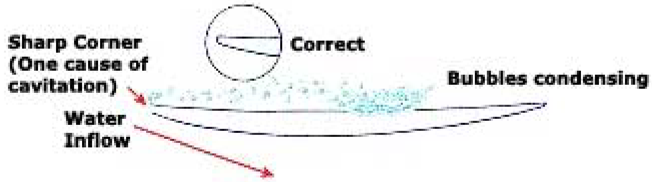


Figure 4-21
A sharp or damaged leading edge can cause cavitation.

The cross section of a propeller blade in Figure 4-21 shows an example of one cause of cavitation. In this instance, a sharp leading edge produces cavitation and resulting cavitation burn as the bubbles condense further back on the blade face. Such cavitation burn can usually be corrected by repairing or rounding off the leading edge directly in front of the burn. Cavitation and cavitation burns can also form on the side of your gearcase. This will almost always be the result of a sharp edge directly ahead of the burn. Rounding off the sharp edge will usually eliminate the problem.

Angle of Attack

To further understand how propellers work, it is important to appreciate the concept of "angle of attack." (This concept is also important in understanding propeller slip, detailed below.) To do so, it is helpful to compare how a propeller blade works to how an airplane wing functions. The wing of an airplane and its ability to carry the weight of the plane by providing lift is very similar to the spiraling travel of a propeller blade, which provides thrust.

If a wing with symmetrical airfoil (Figures 4-22 and 4-23) is moved through the air so that air moves symmetrically above and below the wing, there is equal pressure above and below resulting in no "lift." The wing is said to be operating at zero degree (0°) angle of attack.

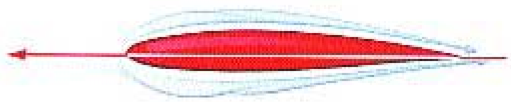


Figure 4-22
Wing with no angle attack

Figure 4-23
No angle of attack, results in no lift (will not fly)

With an angle of attack (Figures 4-24 and 4-25), there is a pressure change ordifference above and below the wing which creates lift: negative (lower) pressure on the top and positive (higher) pressure below.

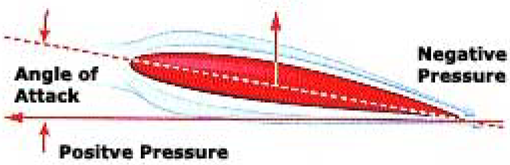


Figure 4-24
Wing with angle of attack

Figure 4-25
Angle of attack creates a pressure difference, resulting in lift

Although it is clear that the airplane wing and the propeller blade move through air and water respectively, marine engineers prefer to talk about the situation in terms of the water moving into the blade. Allowed that freedom, consider Figures 4-26 and 4-27, which show the same angle of attack phenomenon, only in this case, for the propeller blade.

Figure 4-26
No angle of attack

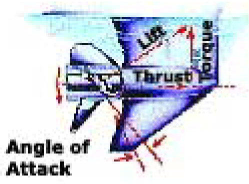


Figure 4-27
Angle of attack

Figure 4-26 shows blades operating at zero angle of attack. This creates no positive or negative pressures on the blade; therefore, there can be no lift or thrust. Blades operating with some angle of attack (Figure 4-27) create a negative (lower or pulling) pressure on one side and a positive (higher or pushing) pressure on the other side. The pressure difference causes lift at approximately right angles to the blade surface. Lift can be divided into a thrust component in the direction of travel and a torque component in the opposite direction of propeller rotation.

Slip

Slip is the most misunderstood of all propeller terms, probably because it sounds like something undesirable. Slip is not a measure of propeller efficiency (see Efficiency, below). Rather, slip is the difference between actual and theoretical travel resulting from a necessary propeller blade angle of attack (see Angle of Attack, above). For example, in Figure 4-28, a 10" propeller actually advances only 8-1/2" in one revolution. Eight and one-half inches is 85% of 10", leaving a slip of 15%. If the blade had no angle of attack, there would be no slip; but, of course, there would be no positive and negative pressure created on the blades and, therefore, there would be no thrust.

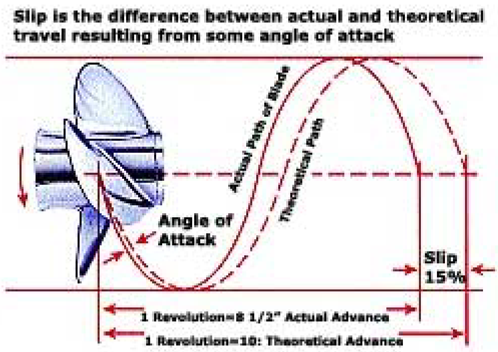


Figure 4-28

To create thrust there must be some angle of attack or slip. The objective of propeller design is to achieve the right amount of slip or angle of attack, which is around 40, give or take a degree (Figure 4-30). This is accomplished by matching the right amount of blade diameter and blade area to the existing engine horsepower and propeller shaft RPM. Too much diameter and/or blade area will lower slip but will also lower propeller efficiency, resulting in reduced performance. Figure 4-29 illustrates this point.

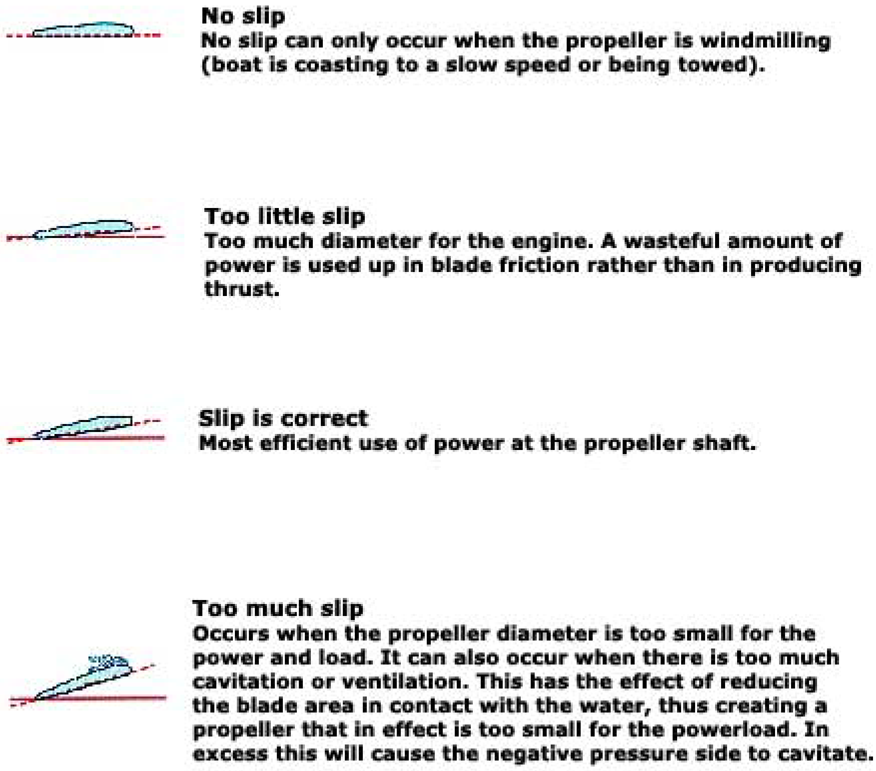


Figure 4-29

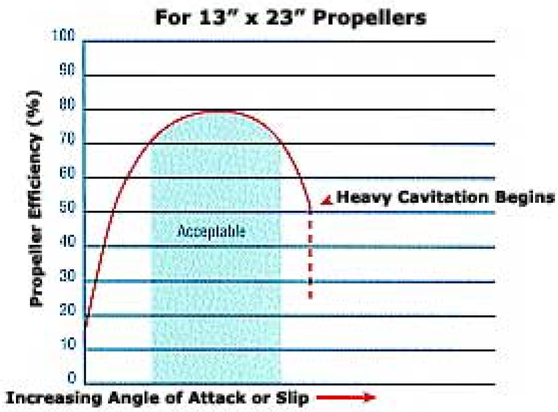


Figure 4-30
Propeller efficiency increases and then decreases as angle of attack is increased

Calculating Rotational Speed, Blade Tip Speed and Slip

The relationship of angleof attack and slip are shown when we consider rotational and forward speeds. Propeller engineers like to study propellers at the 7/10 radius (70% of the distance from the center of the propeller hub to the blade tip), which generally is the section of the propeller blade that is most typical of the whole blade. The 7/10 radius rotational speed (in MPH) can be calculated by the following equation:

$$\text{7/10 Radius Rotational Speed (MPH)} = \frac{\text{Propeller RPM} \times .7\ \text{Radius (in.)}}{168}$$

and can be shown by a vector (arrow) (Figure 4-31).

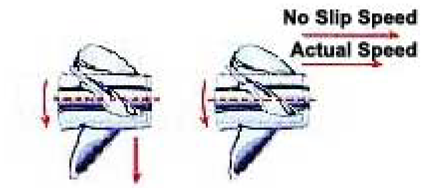


Figure 4-31
Rotational speed

Figure 4-32
Forward speed

Blade tip speed can be calculated using the following equation:

$$\text{Rotational Tip Speed (MPH)} = \frac{\text{Propeller RPM} \times \text{Diameter (in.)}}{336}$$

The forward speed can be shown by an arrow in the direction of travel (Figure 4-32). The length of the arrows again reflects the speed in MPH for both the measured forward speed and the theoretical (no slip) forward speed (see equation below). When the rotational speed and forward speeds are combined in a simple vector diagram, some interesting things appear (Figure 4-33).

Consider the following actual example:

A 16' boat powered by a 135 HP engine with 2:1 gear reduction turning 5400 RPM uses a 14" diameter by 19" pitch, cupped propeller to push the boat 43.5 MPH. What is the slip and angle of attack at the 7/10 radius?

As stated above, the propeller rotational speed equation is:

$$\text{7/10 Radius Rotational Speed (MPH)} = \frac{\text{Propeller RPM} \times .7\ \text{Radius (in.)}}{168}$$

The equation applied to the example boat:

$$\text{7/10 Radius Rotational Speed (MPH)} = \frac{\dfrac{\text{5400 (Engine RPM)}}{\text{2 (Gear Ratio 2:1)}} \times \dfrac{\text{13'' (Prop Diameter)} \times .7}{\text{2 (Convert to Radius)}}}{\text{168 (Constant for Unit Conversion)}}$$

$$= \frac{2700 \times 7 \times .7}{168} = \text{78.8 MPH}$$

Theoretical boat speed equation:

$$\text{Theoretical Boat Speed (MPH)} = \frac{\text{Prop Pitch (in. x Prop RPM}}{1056}$$

The equation applied to the example boat:

$$\text{Theoretical Boat Speed (MPH)} = \frac{19'' + 1'' \text{ (Pitch + Cup)} \times \frac{\text{5400 (Engine RPM)}}{\text{2 (Gear Ratio)}}}{\text{1056 (Constant for Unit Conversion)}} = \text{51.1 MPH}$$

Using some basic trigonometry, the angles and blade velocity come out as shown in Figure 4-33 and slip is calculated as follows:

$$\text{Slip (\%)} = 1 - \frac{\text{Actual Boat Speed (MPH) x 1056}}{\text{Prop RPM x Prop Pitch (in.)}} \times 100$$

$$= 1 - \frac{43.5 \times 1056}{2700 \times 20} \times 100 = 15\%$$

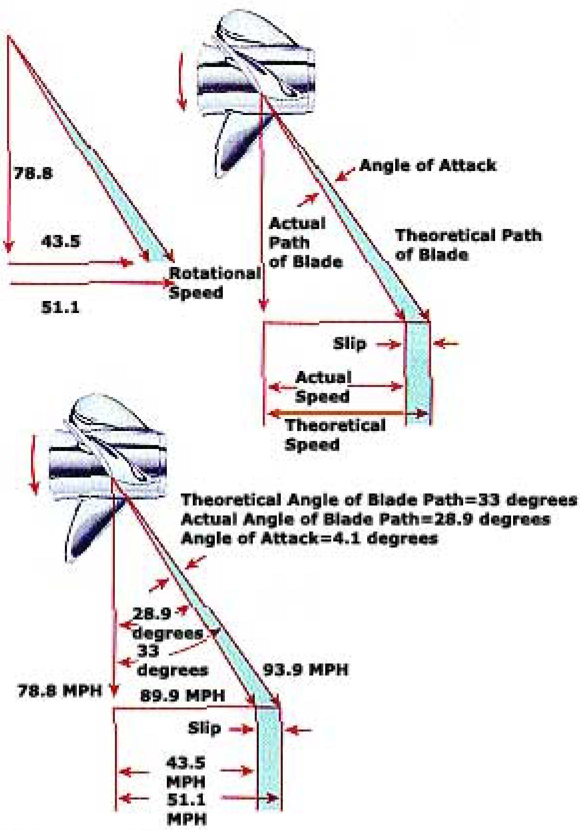


Figure 4-33
Combining rotational speed and forward speed.

Easy-To-Use Propeller Slip Calculator Available

An easy alternative to the above slip calculations is to use the Mercury Propeller Slip Calculator (Figure 4-34). This special slide rule lets you quickly calculate propeller slip. (The other side of the slide rule is designed to calculate the performance of a given boat/engine combination when changing to higher- or lower- horsepower engines.)

To order online click Mercury Parts Express, specify part number **90-86147A1,** OR locate your nearest Mercury Dealer. Suggested retail price is $5.00.

Efficiency

Calculating Efficiency

Although the average boater is not going to be able to calculate propeller efficiency, it is worth explaining to further ensure that propeller efficiency will not be confused with slip, a common misconception.

In simple terms, propeller efficiency is divided by the power going in:

$$\text{Prop Efficiency (\%)} = \frac{\text{Power Out}}{\text{Power In}} \times 100$$

Figure 4-34
Mercury Propeller Slip Calculator

Let's use horsepower (HP) for our units. First, to calculate Horsepower Out, the boat speed (MPH) must be measured (relatively easy). Second, the propeller thrust (lbs.) must be measured (very difficult).

$$\text{HP Out} = \frac{\text{Boat Speed (MPH)} \times \text{Prop Thrust (lbs.)}}{375}$$

To calculate horsepower in, the propeller shaft speed (RPM) must be calculated (easy):

$$\text{Propeller Shaft Speed (RPM)} = \frac{\text{Engine Speed (RPM)}}{\text{Gear Reduction}}$$

Then the propeller shaft torque (ft. lbs.) Must be measured (difficult). Horsepower In, then is calculated:

$$\text{HP In} = \frac{\text{Propeller Shaft Speed (RPM)} \times \text{Propeller Shaft Torque (ft. lbs.)}}{5250}$$

Notice that although all the characteristics of a propeller- diameter, pitch, number of blades, rake, even slip - may affect efficiency indirectly, none appear in the efficiency calculation.

Example

Consider the boat in the previous example - a 16' boat powered by a 135 hp engine (2:1 gear reduction) which runs 43.5 MPH while the engine turns 5400 RPM.

With sophisticated instrumentation, the propeller shaft torque is measured to be 260 ft. lbs. and the propeller thrust at 43.5 MPH is found to be 880 lbs. Now, armed with all of the necessary information, the calculations for horsepower in, horsepower out, and thus propeller efficiency, can be made:

$$\text{Propeller Shaft RPM} = \frac{\text{Engine (RPM)}}{\text{Gear Reduction}} = \frac{5400}{2} = 2700 \text{ RPM}$$

$$\text{HP Out} = \frac{43.5 \times 880}{375} = 102.1 \text{ HP}$$

$$\text{HP In} = \frac{2700 \times 260}{5250} = 133.7 \text{ HP*}$$

***Engine manufacturers are now rating all or some of their models by horsepower available at the propeller shaft, referred to as propeller shaft horsepower. Engines manufactured by Mercury Marine are rated by this method.**

$$\text{Propeller Efficiency} = \frac{102.1}{133.7} \times 100 = 76.4\%$$

Efficiency and Angle of Attack

The graph in Figure 4-30 (above) shows how propeller efficiency increases and then decreases as angle of attack is increased. In the example, in Figure 4-30, efficiency peaks at approximately 80% (3 degree- 4 degree angle of attack) and begins to decline as the angle of attack increases beyond the optimum.

Efficiency and Pitch / Diameter

In a given propeller series, the maximum possible efficiency decreases as pitch decreases. For example, a 23" pitch propeller with 13-1/2" diameter can have a peak efficiency of 80%, but a 13" pitch propeller with a 16" diameter can have a peak efficiency of only 65%.

If all other variables remain unchanged, propeller efficiency increases as the pitch/diameter ratio increases.