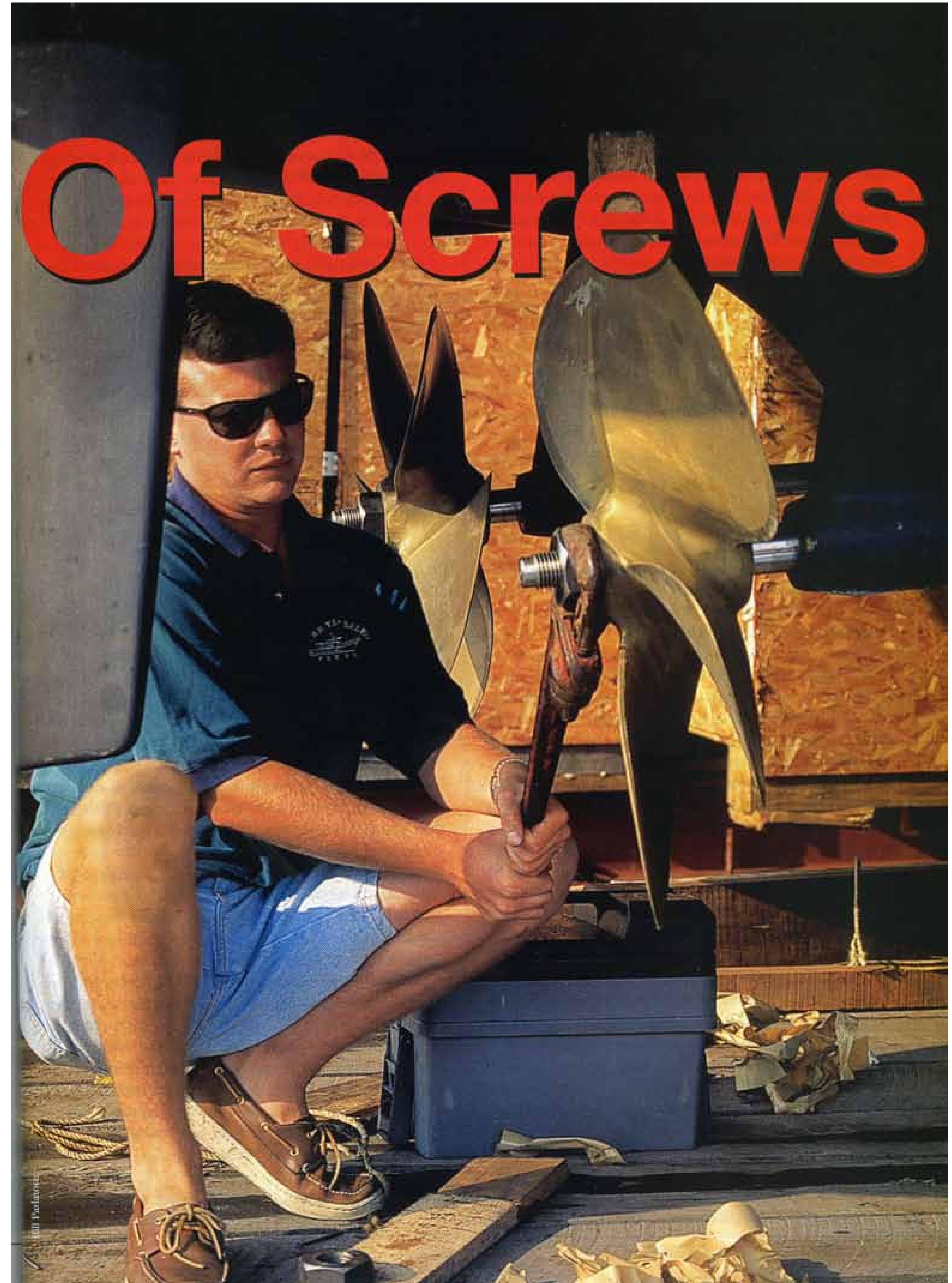
The Nuts & Bolts



Propellers, Part One

By Steve C. D'Antonio

The course propellers take as they spin their way through the history of seafaring–and of mankind in general–is an interesting one, indeed. In 1836, a Swede named John Ericsson and an Englishman named Francis Petit Smith simultaneously filed the first "screw propeller" patents. Ericsson's prop–ahead of its time in that it consisted of two contra-rotating "bladed wheels," a design that has since been used in various forms to propel everything from aircraft to torpedoes–eventually gained wide acceptance in the United States, where it was first used to power the frigate *Princeton* in 1843. Among the propeller and other inventions, Ericsson is also credited with designing the United States' (that is, the Union Navy's) first armored warship, *USS Monitor*.

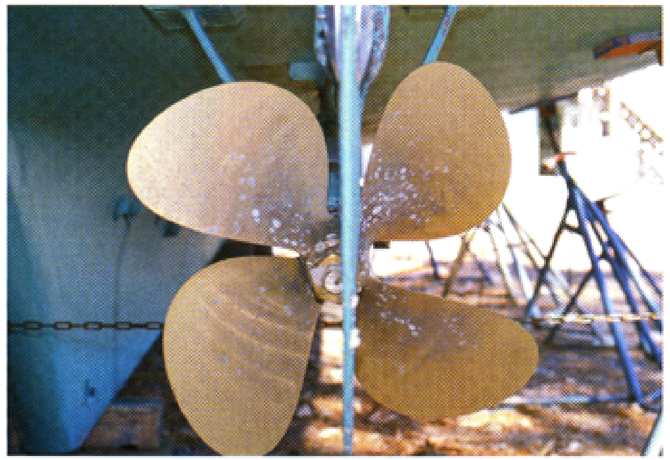
Smith's design originally consisted of a screw-like device, which initially wasn't very efficient. A collision with another vessel during testing, however, damaged the screw, transforming it into a near-conventional propeller. After the collision, his test vessel immediately gained speed, and he knew at that moment that his design had been inadvertently improved.

The concept of the propeller, however, goes much further back than Ericsson and Smith, making its initial appearances in ancient Egypt and Greece, and reappearing in Renaissance-era Italy. The Egyptians used a screw-like device to lift water from the Nile and transport it for irrigation purposes in the 10th century B.C. Some 700 years later, Archimedes developed what would later become known as the "Archimedes screw" for pumping water out of flooded ships. More recently, Leonardo da Vinci drew what are believed to be the first designs for a threaded screw fastener, a "water screw," and a helicopter rotor that bears a distinct resemblance to early marine propellers. (The bulk of da Vinci's notebooks were lost; perhaps one of these contained a marine version of the helicopter rotor.)

Today, the art of propeller design and manufacture has advanced to its zenith in the form of submarine propulsion. Propellers found on the current crop of U.S. fast attack and ballistic missile submarines are classified (the most recent unclassified "official" photos of U.S. submarine propellers date from the 1960s), their design being integral to the stealthiness of these craft. A poorly designed submarine propeller would announce its position with every revolution, negating the primary value of this weapon, which is that the enemy doesn't know where it is.

As far as propellers for trawlers and recreational powerboats are concerned, quiet running, although desirable, isn't a matter of national security. Rather, the concern is for maximum efficiency (depending on the skipper, this may translate to maximum speed or maximum fuel economy and range) and performance with a minimum of vibration and noise. Additionally, the importance of properly selecting and matching a propeller to a given vessel has other far-reaching, and sometimes incipient, effects. A propeller that is inappropriate for the vessel and the drivetrain it is attached to may lead to excessive hull vibration and the associated damage this may cause, as well as increased engine maintenance requirements and a shortened service life.

Marine propellers are a subject upon which volumes have been written. Dave Gerr, noted naval architect and author of *Propeller Handbook*, believes the volume of information written about propellers is a sure sign that we still do not fully understand them, and I concur. Propeller "science" is still described by some as a black art. What follows is the tip of the proverbial iceberg–just enough information on this fascinating, but often overlooked, component to guide you between the rocks and shoals of propeller design, selection, and service. Although it is by no means comprehensive or all-encompassing, I hope you find it enlightening and useful.



A representation of the disc area ratio or DAR is clear to see in this image. If no light were visible between the blades (if they overlapped), the DAR would be something over 100%.

PROP SPEAK & PROPELLER PARTS

The propeller industry is replete with terms–many of which you may have heard but might not fully understand–that describe the various components, characteristics, and performance aspects of the most important part of your vessel's running gear: the prop. Often referred to as a screw or wheel, the propeller has a substantial lexicon that is easily deciphered and demystified.

The two terms that are most often associated with propellers are *diameter* and *pitch*. There's no mystery in the first; the diameter is the distance from the tip of one blade to the tip of another blade, measured through the center of the propeller. For a propeller with an odd number of blades (on which a straight line cannot be drawn in this manner because no two blades directly oppose each other), diameter can be calculated by measuring from the center of the hole in the middle of the propeller to any blade tip (the radius) and doubling this figure.

The effects of diameter will be discussed later. However, it's worth planting this seed now: Diameter is the single most important factor governing propeller performance. For vessels in the displacement-speed to roughly 35-knot range, the larger the propeller's diameter is, the more efficiently it will perform. The limitation here is, of course, how much room is available under the boat to swing the wheel. Often, a compromise must be struck, trading diameter for the other (soon to be discussed) variables of pitch, blade area, or shaft speed.

Pitch, on the other hand, is somewhat more mysterious and is a frequently misunderstood characteristic of propeller anatomy. Contrary to popular belief, propeller pitch is related only indirectly to the angle of the individual blades. In actuality, the pitch is the *theoretical* distance a propeller would travel forward in one revolution if, for instance, it were traveling through a highly viscous medium, such as grease or soft wood (in the latter example, think of the threads of a screw spinning their way into wood). Therefore, a propeller whose pitch is 24 inches travels forward, pushing the attached boat along with it, 2 feet with each revolution, in theory. In reality, however, because water is not like grease or wood, the propeller slips, and as a result, it does not push itself and the boat this distance. The difference between the actual distance the propeller travels and the theoretical pitch is called, appropriately, *slip*, which may be as great as 25 to 40 percent of the propeller's travel for a displacement vessel (meaning the vessel advances 60 to 75 percent of the pitch distance with each revolution). Slip is less pronounced for planing and faster vessels.

It's worth repeating at this point in the discussion of pitch that it is not the same as blade angle. If you look at the propeller on your boat, you will notice that the blades have a characteristic twist to them; they usually are not flat. The angle of the blade varies as the blade travels from the *root*, the part closest to the propeller *hub*, or center section, outward. Interestingly, this is referred to as a *constant-pitch* propeller. As strange as that may sound, there is a logical explanation for this apparently incongruous designation.

The outer edges of a propeller's blades travel much faster and a much further linear distance than the inner part of the blade: The tip of a 25-inch propeller travels roughly 79 inches with each revolution, while the part of the blade adjacent to the root travels a mere 19 inches. In order to account for this imbalance, the angle of the blade changes from steep at the root to somewhat shallower at the blade tip, resulting in a constant-pitch propeller.

Propeller pitch and diameter are sometimes discussed as a ratio, called the pitch ratio (more accurately described as pitch/diameter ratio). This is simply the pitch divided by the diameter. A 28-inch diameter propeller whose pitch is also 28 inches has a pitch ratio of 1.0, which is often described as a "square wheel." There's nothing special about a pitch ratio of 1.0; it works for some boats and not for others. For displacement vessels, pitch ratios are usually fairly low, in the region of 0.8 to 1.2.

Photos by Steve D'Antonio

A good example of a positively raked propeller: The blades tilt in the direction of the faces. Raking can be used to increase overall blade area (because the rake creates a cone, the blades are longer) or to influence a vessel's attitude, bow up or down, while under way.

The parts of the propeller include the blades themselves, and, specifically, their leading and trailing edges. The blades are obvious: These are the oval- or petal-shaped appendages that are attached to the center of the propeller–usually there are two, three, four, five, or sometimes six for recreational vessels. (Some submarines use 25-blade propellers!) The leading edge of each blade is the part that leads the advance or rotation, making contact with the water first as the propeller spins. The trailing edge is the edge the water makes contact with last as the propeller rotates. If you were directly behind your boat looking forward at the propeller, the leading edge is always farther away from you than the trailing edge. Leading edges of trawler props tend to be rounded or half-oval shapes, while the trailing edge is often, but not always, straighter.

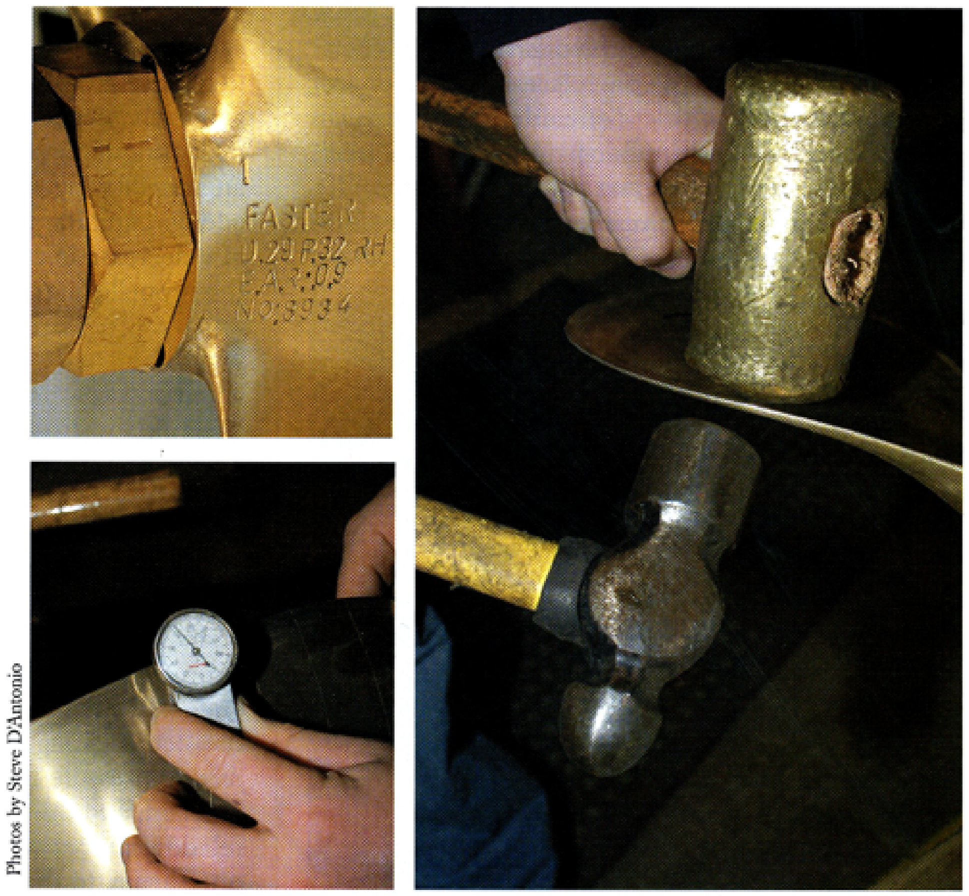
Cup is the slight curl or concave characteristic of each propeller blade's face (a definition of face follows in a moment) at the trailing edge. Cup allows the propeller to get a better bite on the water, increasing lift and thrust, a little bit like the flap on an aircraft wing. This is evidenced by the fact that adding cup to a propeller's blades will usually result in a decrease in engine rpm, effectively increasing the propeller's pitch. In order to avoid this virtual pitch change, a reduction of pitch somewhere in the region of 1 inch, or about 5 percent, is called for when cup is added. Cup also decreases the likelihood of cavitation, a detrimental effect that will also be discussed in the second part of this article, in the upcoming issue.

The blade *back* is the side of each blade that's visible when viewing the propeller from the bow looking aft. This is also referred to as the negative face, because while under way, the pressure on this side of the propeller is negative, or lower than ambient. The other side of the blade, visible from the stern looking forward, is referred to as the blade *face*, or pressure face. Here, pressure is higher than ambient, and this is where thrust is generated. The relationship between blade face and back is similar, once again, to that of an aircraft wing–the blade face being analogous to the underside of the wing, while the blade back could be thought of as the top. Lift is generated in a propeller's blades in much the same way it is in an aircraft wing. The low pressure on the back (remember, the back is on the forward side of the blade) of the blade pulls or sucks the propeller forward, while the high pressure generated on the face of the blade provides a pushing action or thrust. Remember, the back faces forward and the face faces aft.

Propeller *rake* is an expression of the position of a propeller's blades in relation to the hub. Looking at the propeller from the port or starboard side of your boat, the blades of a raked propeller will lean either forward or aft. Forward-raked, or negative-raked, propellers are rare, except on high-performance and racing vessels. Aft, or positive, rake, however, is occasionally used in trawlers to increase a propeller's effective diameter (because the blades lean aft, they can be longer without coming any closer to the hull) and blade area. In some cases, positive rake can also cause the bow to lift, which may be desirable.

The *rotation* of a propeller is just what it sounds like, the direction the propeller turns when you move the gearshift lever forward. In order to determine rotation, the propeller must be viewed from aft, looking forward at the blade face. From this position, as mentioned earlier, the leading edge is always further away from the observer. If the leading edge is to your right, the propeller is said to have right-hand rotation (rotation is typically expressed as "handedness" rather than clockwise or counterclockwise). Most single-screw vessels utilize right-hand propellers.

Twin-screw vessels, on the other hand (sorry, I couldn't resist), utilize counter-rotating propellers, which means they turn in opposite directions. Counter-rotating, twin-screw installations should always be arranged so the tops of the props turn outboard, or away from each other. That is, the starboard prop is right-handed, and the port prop is left-handed. If they are reversed, excessive centerline turbulence will be created, and consequently, the boat's handling characteristics will be detrimentally affected. If both props and engine/gear combinations were right- or left-handed, the boat would suffer from considerable leeway, crabbing its way through the water and making course-keeping a challenge, indeed.



Photos by Steve D'Antonio

Top left: The markings on the hub reveal a great deal about a propeller. In this photo, you're looking at blade number one, with a 29-inch diameter, a 32-inch pitch, right-hand rotation, and an expanded area ratio of 0.90. The last number is the propeller's serial number. Above left: The cup on a propeller is measured using a dial indicator. Above right: Propeller adjustment and the inducement of cup are still very much hands-on affairs. Judicious use of brass and bronze hammers hammers wielded by the right hands yields the desired results.

When naval architects and boatbuilders choose propellers that will be appropriate for a particular hull form, vessel displacement, power-plant horsepower, and gear ratio, one of the criteria they take into consideration is a propeller's *blade area ratio,* or *BAR.* BAR is a measure or comparison of a propeller's *projected* blade area compared to a solid disc of the same diameter. In order to visualize this, imagine the propeller's shape is a silhouette or shadow being cast on the ground (with the propeller hovering above the ground horizontally). The shadow is the blade area, from which the BAR is derived. Thus, a typical three-blade propeller may have a BAR of 50 percent, while a four-blader may be 80 percent and a five-bladed propeller may actually be as much as 120 percent of a solid disc (the blades on these props often overlap).

If, however, the actual surface area of the propeller must be determined, then another formula, called the expanded area, must be calculated. Because the blades of a prop are curved, their surface area is greater than their shadow as described earlier. If you were to carefully trace each blade onto paper and cut it out, you would be left with the actual surface real estate of the propeller's blades. The ratio of this area, compared to the same circle created by the propeller's diameter, is referred to as the *expanded area ratio,* or EAR. Of course, naval architects use mathematical calculations–and now computer programs–rather than tracing paper and shadows to make these determinations.

Now that you know and understand all of these terms, you should, at the very least, be able to read the designation on your vessel's propeller; most props have this information stamped somewhere on the hub. A propeller marked 32RH x 30 - 2 would be 32 inches in diameter, with right-hand rotation, a 30-inch pitch, and a 2-inch bore or shaft. Some props may even provide the BAR or EAR as well, using these acronyms and their corresponding numerical values.

PROP IT RIGHT

Choosing the right prop for your vessel is as important as choosing the right power plant. Regardless of how much power your engine produces, failing to transfer that power to the surrounding water via the thrust created by your propeller means your engine's oomph is simply being wasted.

Making the selection is, initially, a job for the naval architect who designs your boat. However, there's no guarantee that this was done correctly while your boat was on the drawing board. Additionally, as is often the case, the design may have evolved or changed as the model line progressed; different engines are installed and changes are made in displacement. The builder may also decide, for reasons of his own, that the specified wheel is incorrect. Additionally, if your vessel has been repowered at some stage in its life, then the propeller calculations would have to start anew, which presents yet another opportunity for them to have gone astray.

Many factors must be taken into account during the propeller-selection process. The most critical items, however, include engine horsepower, vessel displacement and hull form, gear reduction ratio (more on this in a moment), propeller pitch, and the aforementioned and all-too-important diameter and blade area. All of these items, with the exception of the propeller information characteristics themselves, can be plugged into longhand arithmetical calculations or a computer program. Most propeller manufacturers and many prop shops (as well as some websites, such as boatdiesel.com) are capable of crunching these numbers for you. Today, it's strictly a computerized process; feeding *accurate* information in will usually produce a wheel that's correct or nearly correct for your vessel.

The issue of gear reduction is one that is often misunderstood or overlooked. Simply put, the reduction gear reduces the speed at which your propeller shaft and propeller turn. Why do this? Because if your shaft and prop turned at the same speed as your engine, the prop's maximum diameter would be severely limited, particularly with today's high-speed diesels. Engine cruising speeds in the range of 2500 to 3000 rpm–which is considerably faster than a *larger* propeller can be efficiently turned–are not uncommon. To an extent, the slower the shaft turns at a given engine rpm, the more power is available to the propeller. More power means you can swing a larger wheel, which is invariably better and more efficient than swinging a smaller prop. For displacement vessels and those traveling under 35 knots, bigger, and slower, turning is better when it comes to propeller diameter.

The disadvantages to using a smaller propeller at cruising speed may not be as noticeable. At lower speeds and during maneuvering, however, you will find it more difficult to stop, back, and kick the stern to port or starboard using propeller thrust deflected off the rudder. You may also find your progress slowed when powering into oncoming seas.

The typical gear reduction ratio for a displacement trawler may be 2:1, 3:1, or greater. For example, with a 3:1 reduction gear, for every three revolutions the engine makes, the shaft and prop turn only once, allowing the engine to develop maximum horsepower (because it reaches higher revolutions per minute, where more power is generated), while the prop delivers maximum thrust, within the limitations of the hull shape and propeller tip clearance (more on the latter in a moment).

I've mentioned on a few occasions thus far the importance of efficiently delivering the engine's power to the prop, which creates thrust. There is a limitation, however, to just how much energy can be transmitted from the propeller's blades to the water. One of the factors that governs this limitation is called *blade loading.* As the term implies, blade loading is a measure of how much pressure or weight the blades are bearing, measured in pounds per square inch, while creating the necessary lift for forward motion to occur.

Charts, graphs, and computer programs help propeller engineers and naval architects determine blade loading, which is worked out simply as a ratio of thrust to blade surface area. Typically, properly loaded blades experience somewhere between 5 and 15 pounds of load per square inch. While these numbers may be of little meaning or value to the reader, the concept remains important for one primary reason: money. Overloaded blades operate with considerable inefficiency, which translates to low fuel economy at best. At worst, improperly loaded blades (overloading is the issue; underloading is not detrimental) suffer from cavitation, which leads to metal erosion, noise, and vibration. The solution

Courtesy of Thomas Marine Propeller

A freshly measured and tuned prop. The radial lines on the face of each blade are scribed during the measurement or scanning process. Using a combination of abrasives, each blade is finished so its face is smooth and even, ensuring maximum hydrodynamic efficiency.

to this problem is obvious: Reduce the load on the blades. This is relatively easy to accomplish in most cases, and the details of the fix are discussed later.

The number of blades your propeller is equipped with determines how much of the engine's horsepower it can transform into motion. Interestingly, the most efficient propeller would have one blade. If that's the case, then how did we get to five-bladed trawler and 25-bladed submarine props? The explanation is simple. A one-bladed propeller owes its efficiency to its lack of drag. Lift and drag, once again much like an aircraft wing, are interrelated. The more lift created by increasing the number and size of blades, the more drag is induced. The drag is, however, a necessary evil. Not only would a one-bladed propeller be terribly vibration prone, but also, it's unlikely that it could possess enough surface area to produce the necessary thrust while keeping blade loading at an acceptable level.

Thus, more blades mean more thrust (provided the necessary horsepower is present) and less vibration. There is yet another advantage to using additional blades. Suppose the propeller calculation computer says you need a three-blade propeller that's 30 inches in diameter to drive your newly repowered trawler. This presents a problem, however, because the aperture–the area where the propeller lives–will accommodate only a 28-inch diameter wheel when enough clearance is left between the blade tips and the hull. The solution is to either increase the size of the three-blader's blades (this is often a special-order prop and thus expensive) or trade in the three-blade prop for a four- or five-bladed model. Voilà! You've successfully reduced the blade loading to an acceptable level by adding surface area in the form of an additional blade (or two). In the process, you may also have reduced the amount of noise and vibration generated by the propeller.

Ideally, you–or the yard undertaking the repower–will carry out these calculations before the work begins. Adding blades, in some cases, calls for a different gear reduction ratio. (Because more thrust is generated with additional blades, even at a smaller diameter, it may be necessary to reduce propeller rpm even further.)

The alternative to the addition of blades is an increase in the propeller's rpm. Wait a minute, Steve–you said slower is better and smaller props are bad, right? Well, slower is better, but in some cases, given a certain combination of engine, gear reduction, hull form and aperture, increasing the rpm may be the only viable option. More propeller rpm equates to a smaller prop with the aforementioned caveat of reduced thrust, maneuverability, and ability to punch through head seas. Given the choice, it's almost always better to go first with a larger-diameter prop, then additional blades, then larger blades, and, finally, higher shaft rpm/smaller wheel combination.

All of the above decisions and calculations are mandatory practice for new designs as well as repower projects. Naval architects and boat manufacturers *should* be performing this power plant-reduction/gear-propeller balancing act while the design is still on the drafting table or in the CAD stage. Most do their due diligence, making the necessary effort to choose the best combination. Some naval architects, boatbuilders, and production manufacturers, however, do not. Regrettably, it's a textbook case of *caveat emptor:* Buyer beware.

There is one final option that may be available when sufficient propeller diameter cannot be accommodated: trading pitch for diameter. Although it's not an equal swap, it's a bit like trading in a hardcover book for the same title in paperback; it can be used, provided the propeller repair shop knows its business. The rule of thumb is, for every inch of diameter that must be sacrificed, 2 inches of pitch must be added. This is a less-than-perfect approach, however, because there is a practical limit to how much pitch can be added. At some point, to use the aircraft-wing analogy once again, the propeller's blade pitch, or angle of attack, will

Bill Parlatore

When a boat is able to cruise easily on plane at WOT, it's a sure sign that the proper propeller has been installed.

become so steep that it will fail to generate lift, an occurrence referred to as stalling. In my opinion, trading diameter for pitch is less than ideal, but if it's absolutely necessary, it should be undertaken only as a small, incremental adjustment or for fine tuning engine rpm. There's simply no substitute for blade surface area.

In the final analysis, proper propeller selection comes down to two primary factors. The first is what amount of blade area or loading–derived from the prop's diameter, shape, and number of blades–will provide optimal thrust. The second is what propeller pitch will provide the speed or performance you're looking for. In order to properly load your engine, thus enabling you to gain maximum power and efficiency from its team of horses, these two aspects of a propeller's design must be optimized.

The math involved in this process can become rather involved, but in simple terms, propeller pitch selection is a function of the maximum design speed of your boat (hull speed for displacement vessels, faster for planing hulls). At full throttle, the propeller must advance, factoring in slip, the same distance your boat can cover at its maximum hull design speed. With the wrong pitch, your prop is trying to move forward too much or too little with each revolution.

Wheel diameter selection is, once again, a formula based on several factors. As mentioned earlier, however, in the design stage, it's generally accepted that larger wheels are more efficient and thus are more desirable for vessels operating under about 35 knots. If the engine's power and shaft rpm are known (shaft rpm rather than engine rpm, as altered by the reduction gear), a chart such as the one found in Dave Gerr's *Propeller Handbook* can be used to select wheel diameter. The limitation, however, is the requisite clearance required between the prop's blade tips and the underside of the hull. Ideally, this distance should be no less than 10 percent of the propeller's diameter for displacement vessels (more is always better) and 15 percent for higher-speed semi-displacement or planing hulls. Insufficient blade tip clearance almost always results in excessive generation of noise, often sounding like sand or gravel being blasted against the hull in the area of the propeller. Blade area must also be factored into this calculation, ensuring that the blades do not suffer from overloading, which leads to inefficiency and cavitation.

Doing the necessary homework where propeller selection is concerned will always pay dividends in the form of efficiency and smooth performance.

In Part Two of this two-part series on propellers, we'll take a closer look at some of the specific problems you may encounter with your propeller. A detailed description of computerized propeller repair and service procedures will be included as well.

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