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“The History and Design of Propellers”

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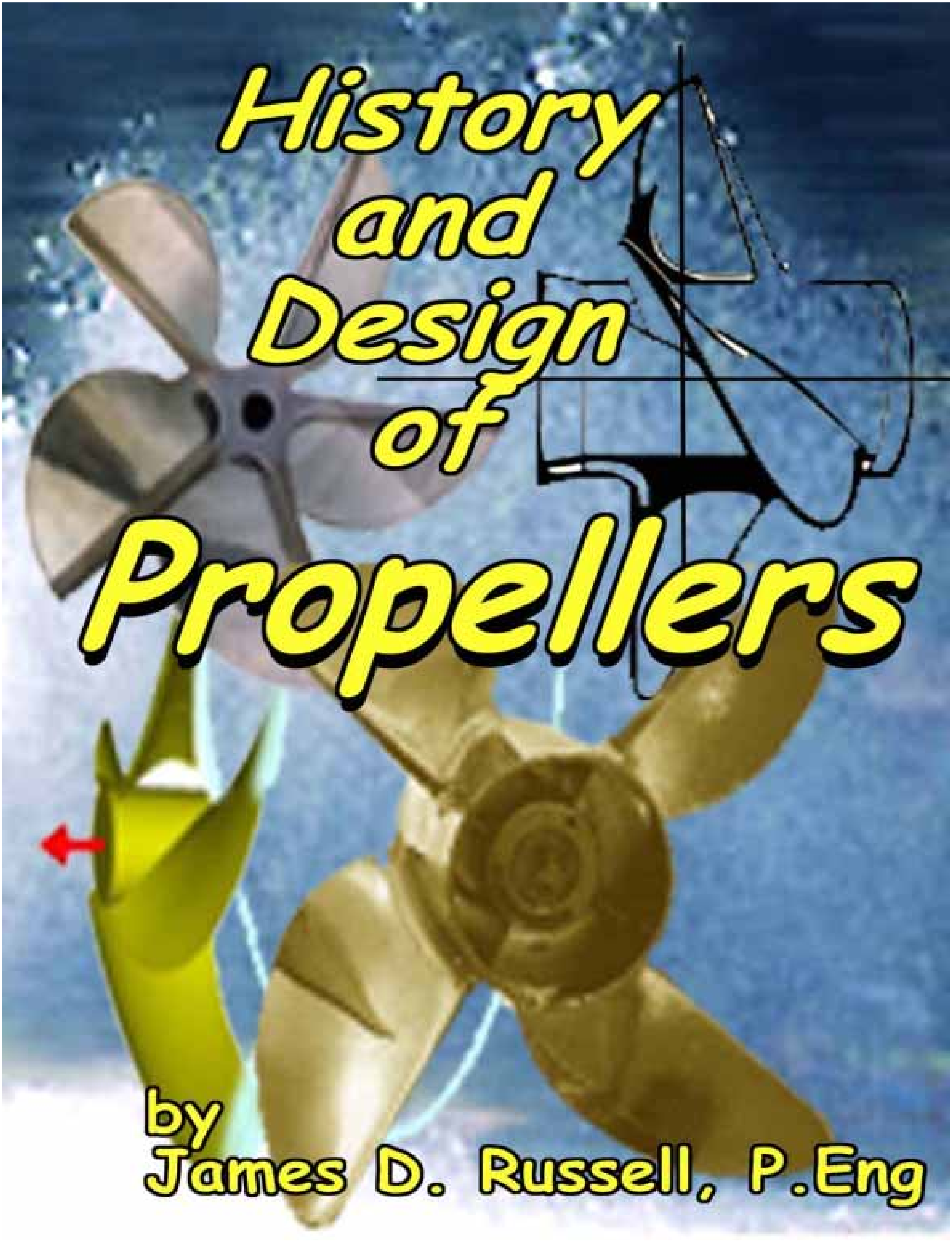

History and Design of Propellers

by
James D. Russell, P.Eng

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Jim Russell is a professional engineer with a mechanical and aeronautics background. Currently living in Canada, he has done extensive aerodynamic research at University of Michigan, MI and University of Toronto, Canada and marine research at the NRC water channel laboratory in Ottawa, Canada. His published papers are highly acclaimed, and are specifically related to the aerodynamics and hydrodynamics of high performance catamarans and tunnel boats. Russell has designed and built many tunnel boats. As a long-time professional race driver, he piloted tunnel boats to Canadian and North American championships. He has written powerboating articles for many worldwide performance magazines and has covered UIM and APBA powerboat races. . He has also appeared on Speed Channel's 'Powerboat Television Show' speaking on tunnel boat design. Russell is the author of the "Secrets of Tunnel Boat Design" book, "History of Tunnel Boat Design" book, and the "History and Design of Propellers". His company has designed and published the well-known powerboat design software, "Tunnel Boat Design Program©", specifically for the design and performance analysis of tunnel boats and powered catamarans.

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1.1 History of the Propeller

The concept of a propulsion device or screw propeller is not new. The experience of ancients with sculling oars, coupled with the later development of rotary engines, intuitively led to the combination of a series of inclined plates secured to a rotary hub. In 945 BC, the Egyptians even used a screw-like device for irrigation purposes.

Archimedes (287-212 BC), the first scientist whose work had a lasting effect on the history of naval architecture and ship propulsion, has been credited with the invention of the screw, which he created to pump out flooded ships. His screw pump, also designed for supplying water to irrigation ditches, was the forerunner of the screw propeller.

Drawings done by Leonardo da Vinci (1452-1519) contain pictures of water screws for pumping (see figure right). However, his famous helicopter rotor more nearly resembles a marine screw. Despite this knowledge, application of screw propulsion to boats and ships did not take place until the advent of steam power.

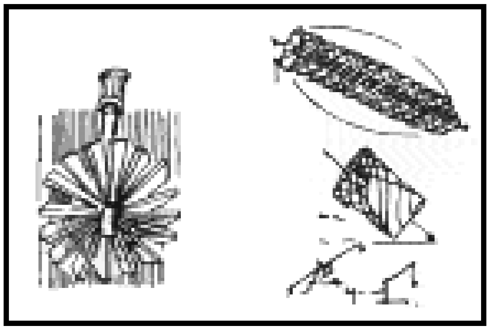


Figure 1 da Vinci's 'water screws'

Due to greater suitability with the slow-turning, early steam engines, the first powered boats used paddle wheels for a form of water propulsion.

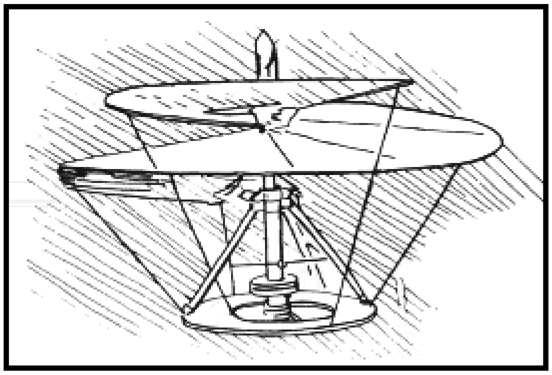


Figure 2 da Vinci’s helicopter rotor (most like a propeller design)

In 1661, Toogood and Hays adopted the Archimedean screw as a ship propeller, although their boat design appears to have involved a type of water jet propulsion.

At the beginning of the 19th century, screw propulsion was considered a strictly second-rate means of moving a ship through the water. However, it was during this century that screw propulsion development really got underway. In 1802, Colonel John Stevens built and experimented with a single screw, and later a twin-screw, steam driven boat. Unfortunately, due to a lack of interest, his ideas were not accepted in America. Josef Ressel, a Czech-born inventor applied in 1826 for an Austrian patent for what he called 'a never-ending screw which can be used to drive ships both on sea and rivers'. Ressel was the first to place the propeller between the helm and the stern so that the propeller worked under the water thus being most efficient. In the autumn of 1829 a steamer called "Civetta" sailed over the Gulf of Trieste. The inventor Josef Ressel was very proud that it was the first passenger steamer. Unfortunately, the steam engine failed after half a sea mile, its passengers screaming and shouting amidst clouds of smoke and steam.

1.1.1 The Invention of the Screw Propeller

The credit for the invention of the practical marine screw propeller is recorded to two men, Francis Petit Smith and John Ericson. In 1836, Smith and Ericson obtained patents for screw propellers, marking the start of modern development. Ericson's patent covered a contra-rotating bladed wheel, as well as twin-screw and single-screw installations. Ericson's propeller design took advantage of many of the unique benefits of the bladed wheel.

With the wheel, it was possible to obtain the increased thrust of a large number of blades in a small diameter without cluttering up the area adjacent to the hub. Yet, both the inner and outer elements supplied propulsion thrust.

The wheel design was inherently strong, without unnecessary material to interfere with its basic action. The outer ring also served to keep lines, ice, and debris away from the blades.

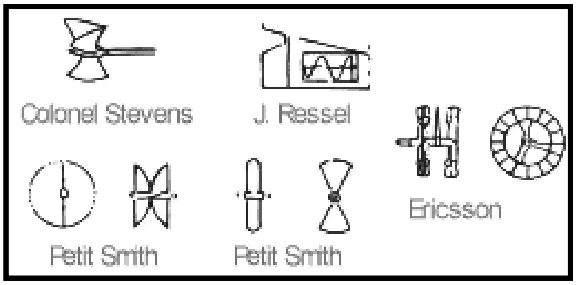


Figure 3 Early propulsion devices

There is no clear-cut evolution of the bladed wheel into the modern screw propeller, although the bladed wheel had most of the elements of a successful propulsive device. It seems to have been used in the original Ericson form and then discontinued in favor of the conventional screw.

1.1.2 Just like today...a mishap Causes Improvement

Most of these Archimedean screw inventors suggested little to improve the configuration of the screw for use as a propulsion device. Their main variations consisted of changing the number of convolutions or altering the diameter along the length of the screw. Francis Petit Smith accidentally discovered the advantages of a shortened Archimedean screw. Originally, his wooden propeller design had two complete turns. Nevertheless, following the collision on the Paddington Canal in which half of his blade was carried away, his boat immediately gained speed.

Smith capitalized on his observation by increasing the number of blades and decreasing the blade width – and came up with a design not unlike modern propellers. In 1839, impressed by the superior performance of Petit Smith's screw, I.K. Brunel changed the design of the Great Britain, an iron ship under construction, to screw propulsion. The Great Britain had 1500 indicated horsepower and achieved a speed of 11 knots. Despite this success, it was many years before screw propellers overwhelmingly displaced paddle wheels for seagoing applications.

1.1.3 The Last Step

Although the Archimedean screw in a wide variety of forms continued to be proposed for ship propulsion, the final transition of this type of propulsion device to what is now recognized as a screw propeller was made by George Rennie's conidial screw. Rennie combined the ideas of increased pitch, multiple threads, and minimum convolutions in what he called a Conidial propeller, which was patented in 1839.

Despite the successes of Smith and Ericson, there were still many problems to be solved in the design, construction, and operation of screw-propelled ships. The early wooden-hulled ships were subjected to heavy vibration, and iron hulls were needed to resist the vibratory forces. With shaft and machinery below the waterline, stuffing boxes had to be developed to prevent leakage without damaging the rotating shaft. Thrust bearings were required to transmit the forward force exerted by the propeller to the hull. Higher speed engines had to be developed in order to realize the inherent efficiency of the screw, and techniques were needed for casting and machining strong, tough metals. As many problems were gradually overcome and as higher speed engines were developed, more and more screw propellers were installed to supplement or replace paddle wheels.

In 1869, C. Sharp, of Philadelphia, Penn., patented a partially submerged propeller for shallow-draft boat propulsion. It employed a large yaw angle to offset the transverse force generated by the propeller, as well as high pitch and cambered or cupped blades. Sir Charles Parsons inadvertently discovered the phenomenon of propeller super-cavitation when his first turbine ship, the Turbinia, initially failed to achieve its predicted speed of 30 knots due to the envelopment of the propeller blades in air cavities.

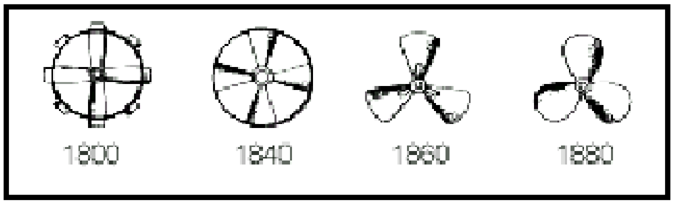


Figure 4 Paddlewheels & Screw propellers

Fitting three propellers to each of three shafts solved this problem. The invention of the marine reduction gear soon rendered multiple propellers per shaft unnecessary.

1.1.4 The End of the Paddle Wheel

Screw propellers installed in the 1860 era lacked refinement, but their performance exceeded all other devices conceived up to that time.

The paddle wheel was gradually rendered obsolete in seagoing ships, as the screw propeller became practically the only type of propulsive device installed in seagoing ships. During the twentieth century, the art and science of marine propeller technology has steadily advanced in the direction of greater efficiency, more reliable design and performance prediction, improved materials, and cavitation resistance.

1.2 How Propellers Work

Let us have a look at how present day propellers work.

1.2.1 Force and Reaction

To understand this concept, let us say we stop a propeller at a point where one blade is projecting directly out of the page (see Figure 5). Let’s say we have a right-hand rotation propeller, whose projecting blade is rotating from the top of the page to bottom and so the propeller is moving from left to right. As the blade rotates (downward), it forces (pushes) water down and back.

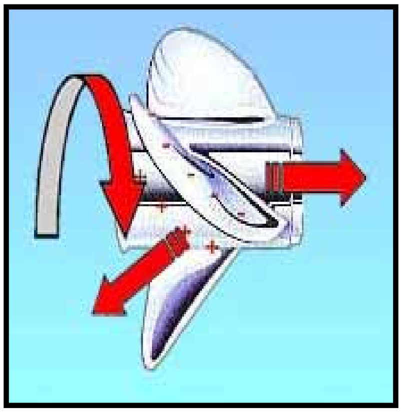


Figure 5 Propeller forces & reactions

At the same time, (because every force has a reaction) water will move rush in behind the blade to fill the space left by the downward moving blade.

This results in a pressure differential ΔP between the two sides of the blade: a positive force or pressure (or pushing effect) on the underside and a negative force or pressure (or pulling effect) on the topside. This is also just how an aircraft wing works. This action occurs on all the propeller blades around the full circle as propeller shaft rotates the propeller. So, the propeller can be thought of as both pushing and being pulled through the water.

1.2.2 __Thrust & Momentum__

The pressure differential (ΔP) causes water to be drawn into the propeller from the front (due to the low pressure zone), and accelerated out the back (due to the higher pressure zone).

This is just as a household fan "pulls" air in from behind it and "blows" it out the front toward you. A boat propeller pulls water in from its front (the end that faces the boat). As the propeller turns, water accelerates through a cylindrical zone around the propeller diameter, creating a stream of higher-velocity water behind the propeller. This exiting water jet will be smaller than the actual diameter of the propeller.

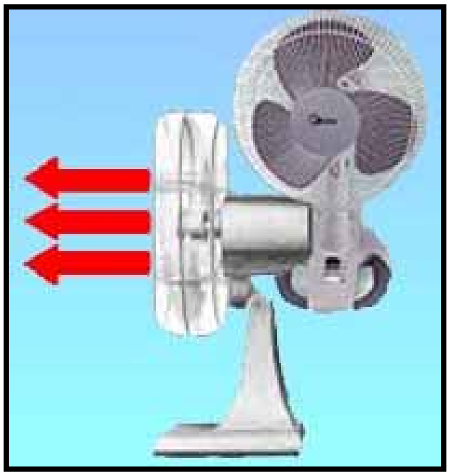


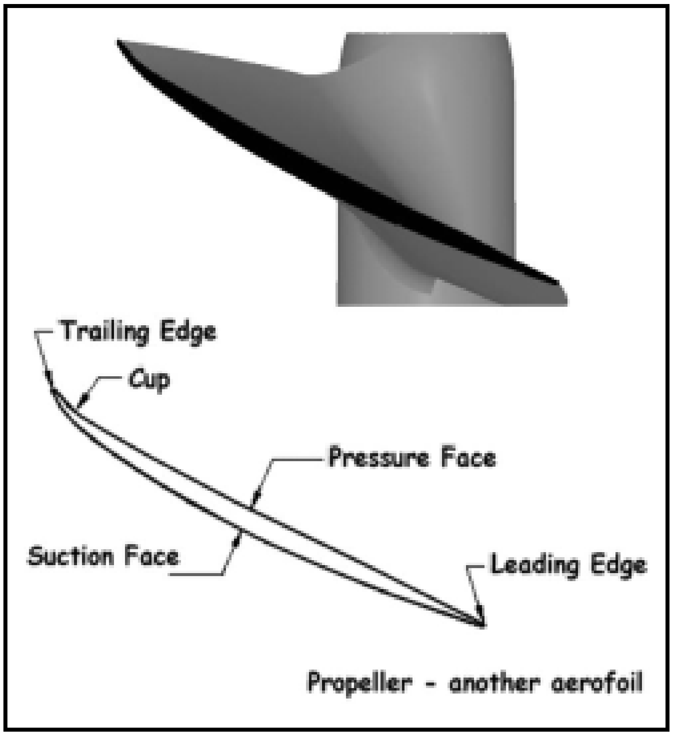
Figure 6 Pressure differences cause propeller 'forces'

This water jet action of pulling water in and pushing it out at a higher velocity adds momentum to the water. This change in momentum or acceleration of the water results in a force that we call thrust.

1.2.3 __The "Aerofoil"__

In the adjacent picture, (see, Figure 7 on page 14) a propeller blade has been cut in half along the blade section (halfway between the centerline of the hub and the tip of the blade). Notice the difference in shape between the top and the bottom of the section. The bottom side has a more pronounced curvature to its shape.

It is this curvature that creates the low-pressure center over the backside of the blade, therefore inducing lift, much like the wing on an airplane. Of course, with a propeller, this "lift" is translated into a horizontal movement component.



A propeller moves though the water in a similar manner as a screw moves forward through a piece of wood. This comparison should be used for illustration purposes alone, since the two mediums in question (water and wood) exhibit extremely different physical characteristics. The amount of forward motion depends mainly on the propeller pitch, which is defined as how far the propeller (or screw for that matter) moves in a complete revolution about its center of rotation.

Figure 7 Propeller aerofoil: Thrust & momentum

1.3 Propeller parts

A. *Blade Tip* - The maximum reach of the blade from the center of the propeller hub. It separates the leading edge from the trailing edge.

B. *Leading Edge* - Part of the blade nearest the boat, first cuts through the water; extends from hub to tip.

C. *Trailing Edge* - That part of the blade farthest from the boat. The edge from which the water leaves the blade. It extends from the tip to the hub (near the diffuser ring on through-hub exhaust propellers).

D. *Cup* - A small curve or lip on the trailing edge of the blade, permitting the propeller to hold water better and normally adding about a ½" of pitch.

E. *Blade Face* - That side of the blade facing away from the boat, known as the positive pressure side of the blade.

F. *Blade Back* - The side of the blade facing the boat, known as the negative pressure (or suction) side of the blade.

G. *Blade Root* - The point in which the blade attaches to the hub.

H. *Inner Hub* - This contains the shock-absorbing hub (described below). The forward end of the inner hub is the metal surface that generally transmits the propeller thrust through the forward thrust hub to the propeller shaft and in turn, eventually to the boat.

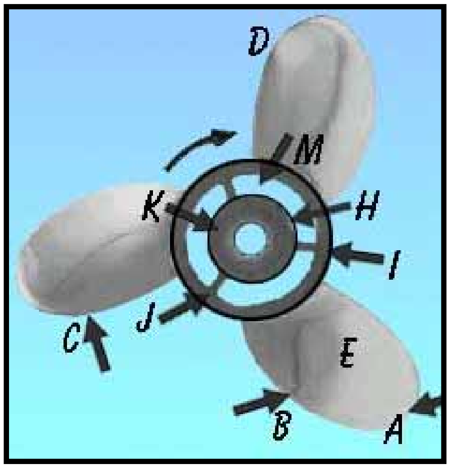


Figure 8 Propeller Parts

I. *Outer Hub* - For through-hub exhaust propellers. The exterior surface is in contact with the water. The blades are attached to the exterior surface. Its inner surface is in contact with the exhaust passage and with the ribs that attach the outer hub to the inner hub.

J. *Ribs* - For through-hub exhaust propellers. The connections between the inner and outer hub. There are usually three ribs, occasionally two, four, or five. The ribs are usually either parallel to the propeller shaft ("straight"), or parallel to the blades ("helical").

K. *Shock-Absorbing Rubber Hub* - Rubber molded to an inner splined hub to protect the propeller drive system from impact damage and to flex when shifting the engine, to relieve the normal shift shock that occurs between the gear and clutch mechanism.

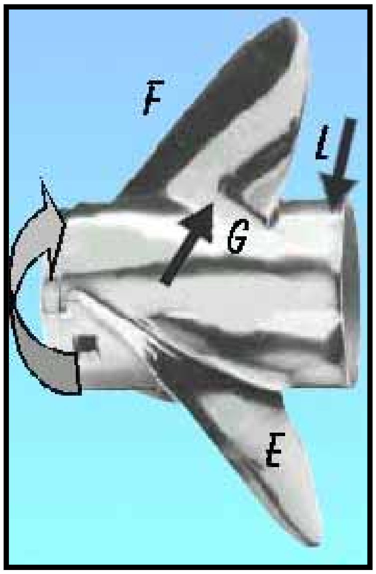


Figure 9 Propeller parts

L. *Diffuser Ring* - Aids in reducing exhaust backpressure and in preventing exhaust gas from feeding back into propeller blades.

Exhaust Passage - For through-hub exhaust propellers. The hollow area between the inner hub and the outer hub through which engine exhaust gases are discharged into the water. In some stern drive installations using a through-transom exhaust system; this passage carries air.

1.3.1 *Types of Hubs*

The hub is at the center of the propeller. The propeller is called a through-hub exhaust propeller when the exhaust gases are discharged into the water through the hub.
If the exhaust gases are not discharged into the water through a passage in the hub, but rather over the hub, the propeller is called an over-the-hub exhaust propeller.

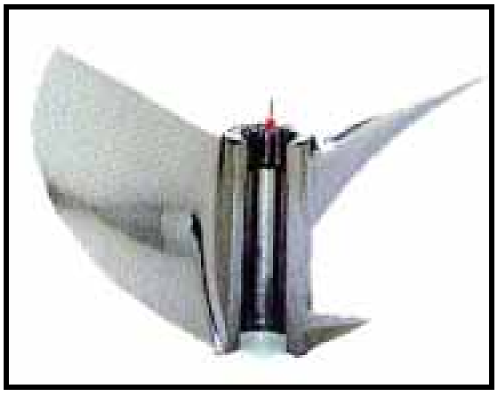


Figure 10 Solid Hub Prop

This design allows the engine to rev-up more quickly as the propeller bites into water and exhaust. Top speed may improve due to the reduction in drag associated with the outer hub, but acceleration may suffer.

Figure 11 Rubber Hub Prop

There are different types of hubs - rubber hub (round or square) (see Figure 11) and a solid hub (see Figure 10) which are generally used on racing engines. Racing engines don’t usually have gear changes, so the “shock” caused by shifting of the clutch/gear mechanisms.

1.4 Modern Day Propellers

So where does this all leave us today? Let's look at propellers as they are designed and used today. To make it as organized as possible, we'll look at the major contributing features to propeller performance and selection.

1.4.1 *Propeller Pitch*

Changing the pitch of your propeller can be the key to fine-tuning boat performance. Pitch is the theoretical distance the prop would travel through water during one complete revolution. It is similar to the distance a screw would travel in one revolution while penetrating a piece of wood. However, a 19-inch-pitch prop never actually travels 19 inches in one revolution. This is because slippage occurs in the water.

There are several “pitch” dimensions referred to commonly. *Constant Pitch* (also called “true” or “flat” pitch) means that the pitch is the same at all points from the leading edge to the trailing edge of the propeller. *Progressive pitch* (also called “blade camber”) starts low at the leading edge and gradually increases to the trailing edge. (*Regressive pitch* decreases along the radial line from leading edge to trailing edge).

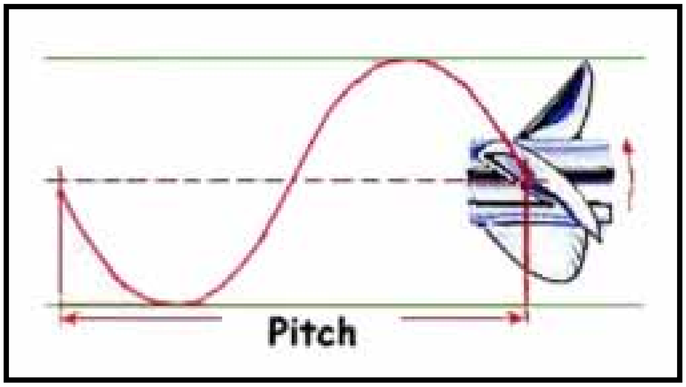


Figure 12 Propeller Pitch Measurement

Pitch reference will be the average pitch over the entire blade surface. Progressive pitch improves performance when forward and rotational speed are high and/or the propeller is operating high enough to break the water surface. *Variable pitch* is different at selected radii. *Controllable pitch* propellers have their blade angle mechanically varied. The Land-and-Sea “*Torque-Shift*” propeller, for example, shifts pitch automatically from the low pitch necessary for strong acceleration to the high pitch for best top end speed, with pitches available from 13” to 32”.

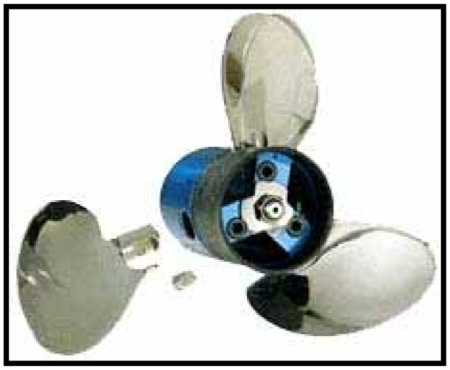


Figure 13 Land & Sea ‘Torque-shift” automatic pitch shifting propeller

Pitch is the primary measurement of prop performance. Other design features of the propeller such as cup, rake, diameter and number of blades can modify what pitch delivers. The best way to use pitch to your advantage is to apply the rule of thumb – "one inch of pitch equals 170-200 rpm". Move up an inch of pitch and you will reduce rpm. Move down an inch and you will increase it.

1.4.2 <u>Propeller Diameter</u>

The diameter of a prop is the width of the by the rotating blades, or twice the radius, which is the distance from the center of the prop to the outermost blade tip. Prop diameter is limited by clearance between the prop shaft and the cavitation plate on outboards and stern drives. For inboards, the limiting factor is clearance between the prop shaft and the hull. By convention, props are identified by diameter and way: 12 X 19. This means the prop has a 12-inch diameter 19-inch pitch. Typically, this information is stamped on the hub.

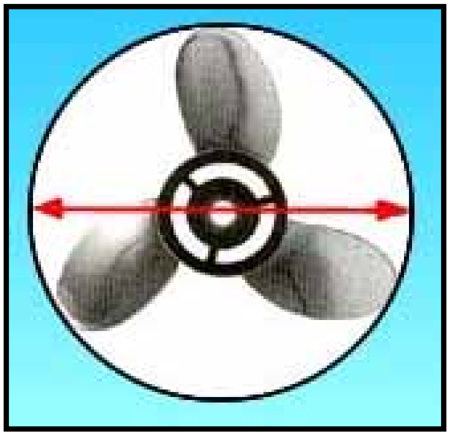


Figure 14 Propeller Diameter measure

So, when tweaking your prop, which is better to experiment with, diameter or pitch? The answer is usually - pitch. While it is possible to alter rpm and performance by changing diameter, experts with pitch. This is because diameter is limited by fixed components - the anti-ventilation plate and the hull-that optimize the flow of water to the prop through a crucial spatial relationship.

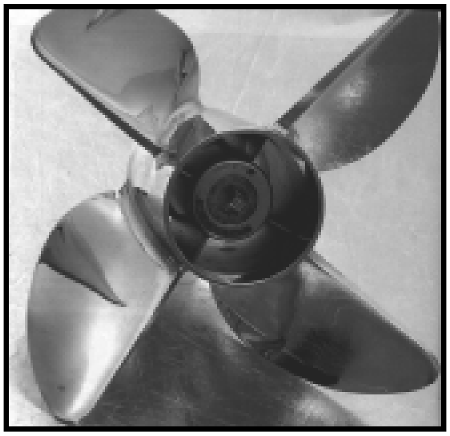


Figure 15 Modern 4-blade propeller

Another important reason to start with pitch is that manufacturers make many more options for pitch than for diameter. So, the best advice is to do what experts do and start with pitch.

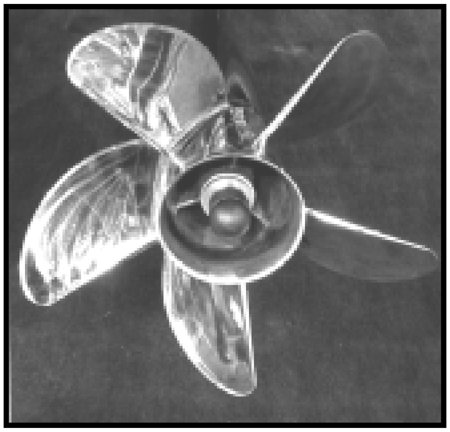


Figure 16 Modern 5-blade propeller

1.4.3 Propeller Rake

If we were to make a cut through the propeller, extending directly through the center of the hub, the face side of the cross section of the cut blade relative to a plane perpendicular to the propeller axis would represent blade rake (see Figure 18). When the face of the blade is perpendicular to the propeller hub, the propeller has zero degree rake. When the blade slants back toward the aft-end of the propeller, blade rake increases. A prop with "*Positive rake*" has a blade that slants towards the aft end of the hub. One with "*Negative rake*" has a blade that slants towards the forward end of the hub.

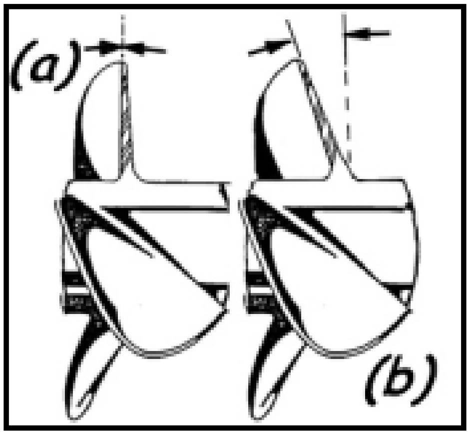


Figure 17 Propeller Rake
(a) 'zero rake'; (b) 'positive rake'

With standard propellers, the rake angle varies from -5° to 20°. Propellers for standard outboard engines and stern drives commonly have approximately 15° of rake. Higher-raked (high-performance) propellers have progressive rake which may go as high as 300° at the blade tip.

Higher rake angle generally improves the ability of the propeller to operate in a cavitating or ventilating situation, such as surfacing propeller applications. With such surfacing operation, higher blade rake will 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 lower raked propeller. On lighter, faster boats, with a higher engine or drive transom height, higher rake can increase performance by generating bow lift.

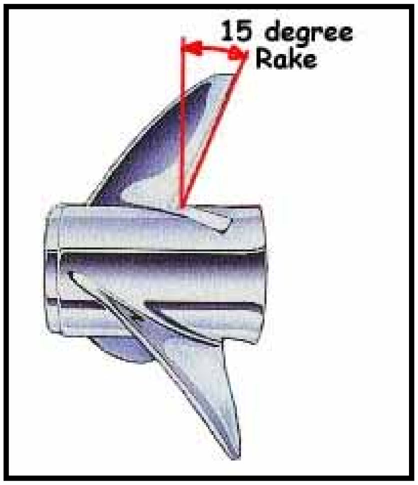


Figure 18 Flat Rake

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

1.4.4 Blade Section Types

The shape of the propeller blade is actually an aerofoil. Different blade section "shapes" or types produce varying performance. These aerofoil sections resemble traditional airplane wing sections – with a rounded leading edge and maximum thickness at about 1/3 length of blade aft of the leading edge.

Some of these aerofoil types include:

- *NACA type* symmetrical section – used when performance is equal going forward or reverse.
- *Troost type* is a common commercially used hydrodynamic profile.
- *Ogival type* is used when pressure-cavitation conditions are high, since this section withstands more pressure before cavitation reaches 3-4% (although it is less efficient than other designs.
- *Hybrid design* is employed by combining the Troost and Ogival sections, maximizing the benefits of both sections.
- *Super-cavitating section* - high speed application Sharp Leading Edge, maximum thickness near Trailing Edge.

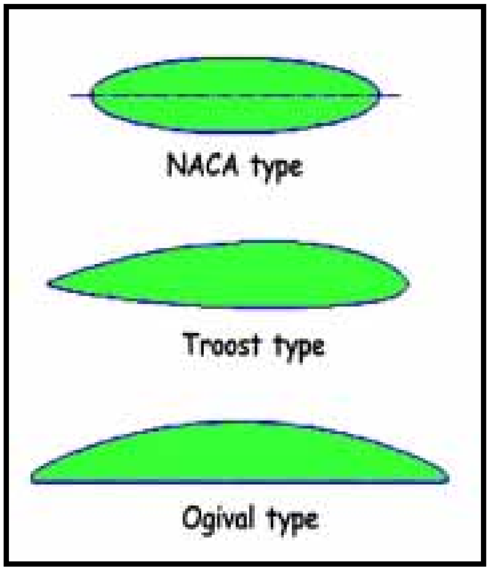


Figure 19 Propeller aerofoil section types

1.4.5 Blade Thickness

A propeller blade is thickest at the point where it meets the hub (root). It becomes thinner further away from the hub. There is a simple engineering reason for this design shape of the blade - as with a cantilever beam, the load that the 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.

Since there is only a certain amount of power available from each engine, the propeller blades are designed as thin as possible, considering the strength of their material. Clearly, since it takes more power to push a thick blade (additional hydrodynamic drag) through the water than a thin blade, thinner is better.

When viewing a propeller blade section at any radius from the center of a constant pitch-propeller, a 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. This is just like the aerofoils discussed earlier. Edges usually are .06" to .08" thick for aluminum propellers - even thinner for stainless steel.

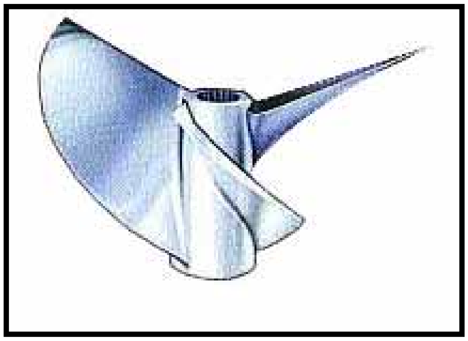


Figure 20 Blade Thickness

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

1.4.6 Blade Skew

A propeller blade has “skew” when the blade center-line is curvilinear sweeping back from the direction of rotation. The contour of the blade is not radially symmetrical about blade center axis. A blade that is swept back versus a blade that is radially symmetrical in contour is said to have skew. Considerable skew (sweep back) is helpful in allowing a propeller to more easily shed weeds. Higher skew on a surfacing applications reduces vibration of the propeller blade re-entering the water.

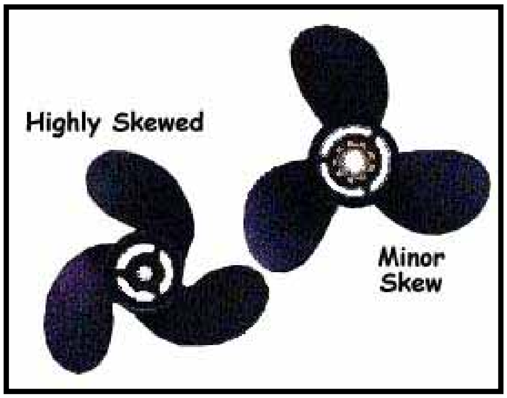


Figure 21 Blade Skew

1.5 Advanced Propping

There is a wide range of propellers from which to choose: three-blade, four-blade, cupped, double-cupped, vented, blue printed, stainless steel, aluminum and many others. These options give you not only the ability to improve overall performance, but also to tweak the particular kind of performance you want to improve.

1.5.1 Prop Slip

Slip is the difference between actual and theoretical travel resulting from the necessity of the propeller blade angle of attack. If the blade had no angle of attack, there would be no slip; but, of course, there would also be no positive and negative pressure created on the blades and, therefore there would also be no thrust. As an example, a propeller with 15" pitch may move forward a distance of 12” for one full revolution. The prop has only moved 12/15 = 80% of its theoretical maximum. *Slip* is then calculated as 20%.

To create thrust there must be some angle of attack or slip. The objective of propeller design is to achieve just the right amount of slip or angle of attack. This can be accomplished by matching the right amount of blade diameter and blade area to the engine horsepower and propeller shaft RPM. Too much diameter and/or blade area will cause less slip but will also lower propeller efficiency, resulting in reduced performance.

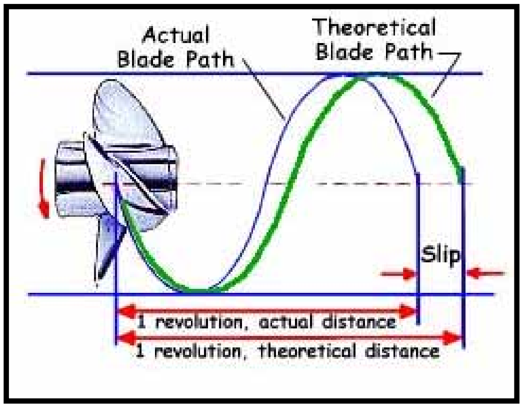


Figure 22 Propeller Slip

Propeller testing using “*Slip*” can follow these guidelines:
No Slip – a propeller cannot have slip unless it is under load. When the propeller is coasting, for example, there is zero slip.
Too much slip – propeller diameter is too small for the load to be carried or too small for the power of the engine. There can be excessive slip when there is too much cavitation or ventilation.
Too little Slip – propeller diameter is too large for the engine power, thus wasting power on overcoming slip (friction) rather than moving forward.
Acceptable Slip – best sizing of propeller for shaft power available.

1.5.2 Types of Propellers

We can differentiate types of propellers by material (see section 1.7 Materials and Blade modifications, page 29) and design configuration. Here are some of the propeller design configurations used in their specific applications:

Conventional Round-eared – This type is seen on most general-application boat setups. It has a rounded contour, slight amount of sweep-back (skew) and may be of a variety of shapes based on the type and application of the propeller. Always designed to be fully submerged, but will still work when slightly surfaced if under very light loads. Available in wide variety of diameters, pitches and rakes for many applications.

Figure 23 Conventional Round-ear Propeller

Large diameter designs give good mid-range performance, good fuel economy, good tope-end performance and superior "holding" in turns. Large blade designs offer high-thrust for large work-boats or applications requiring good holding at planing speeds or at slower speeds in high seas conditions.

Weedless – This is a somewhat general term, as there are clearly varying degrees of "weedlessness" in propeller design types. The blade type that is most weedless is a rounded blade with a high degree of skew (leading edge is swept back to a high degree, leaving no "weed-snagging" leading edge projections).

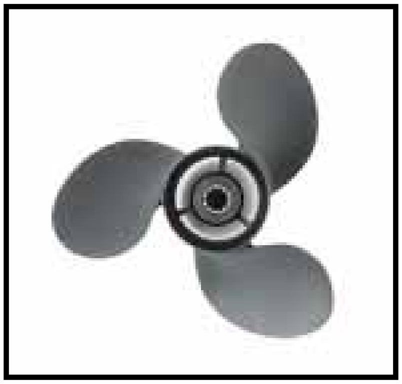


Figure 24 Weedless Prop

High-Performance round ear – made of stainless steel, usually exhibit thinner blades. General application designs still maintain leading edge thickness for impact resistance. Larger diameter/high-rake designs used for large boat and high-power engine applications, perform well in higher "X-dimension" installations (raised engine height); provide increased tope-end performance, better acceleration.

Figure 25 High-performance Round-Ear Prop

Cleaver – Originally this name was applied to props that have blades with trailing edge cut on a straight line (on a rake-line). Blade cross-section was often a “wedge-shape”, where the leading edge is very thin and sharp, while the trailing edge is the thickest point on a pitch line. Best suited for elevated engine installations and surfacing applications. Mostly used for high-performance hull that do not require bow-lift from the propeller.

Figure 26 Sport Cleaver Prop

Cleavers are run at very high RPM, used in surfacing applications. Typically they have a curved or parabolic rake design, and are specifically designed to operate in ventilating applications. If this type of prop were used on hulls that are not capable of high speed or with submerged prop application, it would likely degrade performance.

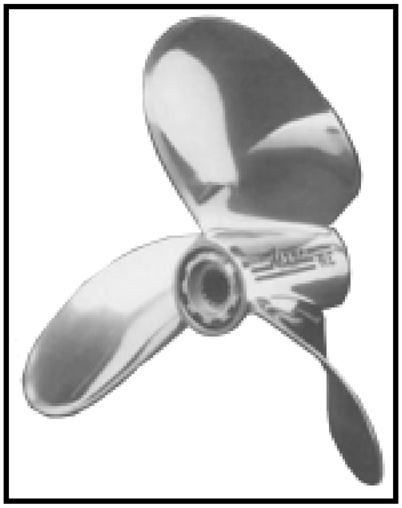


Figure 27 Chopper style prop

Chopper – Used for high-performance applications; and usually have a very high progressive rake that can develop considerable bow-lift and permits higher engine/drive mounting, reducing drag and increasing speed. These are usually “over-hub” exhaust design props. Exhaust gases pass over the blades rather than through the propeller hub, allowing engine RPM to “wind-up” more quickly during initial planing phase of acceleration. The Chopper propeller design is very resistant to breaking loose when on plane. The usual extreme blade sweep-back (skew) also provides a propeller that tends to cut weeds. Thinner blade edges allow for good surfacing operation.

Racing Cleaver – Used for high-performance and racing applications. These are traditionally of higher pitch ranges than more standard cleaver designs, required due to the combination of high-horsepower engines on very light hulls. These props usually have a flat rake of 15° to 20°. These props are most always very highly customized, often "labbed" (see paragraph 1.7.3 on page 30) to optimize every part of the design for the specific racing application and setup conditions.

Figure 28 Racing Cleaver Prop

1.5.3 Three, Four & Five-Blade Props

Three-blade propellers are the most commonly found props on the water because they offer the best potential for all-around efficiency, overall performance and affordable pricing. This is the reason boat companies install three blade propellers as standard equipment.

Prior to development of the surface-piercing propellers, most racing and sports boat propellers were three bladed. With the significant increase in pressure on the props blades caused by running at the surface, four, five and six-blade propeller technology took off. With the improvement of propellers, it has been found that with an increase in the number of blades the pressure is substantially reduced.

On a three bladed prop, each blade carries 33% of the load, whereas on a five bladed prop each blade only carries 20% of the load, a very substantial reduction. So the reduced load on each blade, allows the propeller designer to make the blades lighter and thinner, which is more efficient, while still being strong enough to carry the required load. Multiple blade props were developed for boaters looking for maximum low end and mid-range without sacrificing top end.

Four-blade props have become increasingly common in recent years. With more blade area in the water, these props run at slightly lower rpm, and deliver slightly slower top speed, all things being equal. Nevertheless, they make up for it by improving handling in rough conditions, increasing hole-shot and reducing blowout in turns.

In certain applications, four blade props actually can improve top end performance, but these are limited. Such applications include stepped hulls, tunnel hulls and boats equipped with jacking plates or high trim angles that raise the tips of the blades near the surface or partially out of the water while running.

Four-blade props work well on stepped hulls and tunnel hulls because the flow of water to the prop is disturbed (filled with air bubbles) as it comes off the complicated shapes of the running surface. Disturbed water is less dense than solid water because it has filled with air.

Figure 29 5-blade propeller

This condition is used to advantage by four-blades in two ways: First, the aerated water allows the blades to spin easier, enabling the engine to run at greater rpm and power. Secondly, although the water is aerated, the four-blade grips more than a three-blade because it has more blade area.

Disturbed or aerated water also comes into play on boats with jack plates and high trim angles. When a prop is raised close to the water surface, the tips draw in air as they spin, making the water less dense. In these conditions, the greater blade area of the four-blade prop enables the prop to maintain its bite.

Figure 30 6-blade propeller

Hering Performance Propellers even makes a “mulit-diameter”, 6-blade prop that has two (2) diameters. The concept reportedly uses larger blades effectively at top-end speeds, and the smaller diameter blades are effective while slowing down or cornering. The prop reports less slip and 2% higher top-end mph.

1.6 Cupping

When the trailing edge of the blade is formed with an edge curl (away from the boat), it is said to have a cup. Originally, cupping was done to gain the same benefits as a propeller would exhibit with a 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 pitched propeller with no cup. A professional propeller repair shop can increase or decrease cup to alter engine RPM to meet specific operating requirements on most propellers.

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. Cupping is usually of little value on propellers used in heavy-duty or applications where the propeller remains fully submerged.

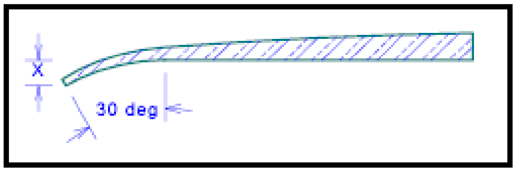


Figure 31 Propeller Cup

All stainless steel and most aluminum props today are cupped - a curved or concave lip is added to either the leading edge or the tip. Some props add a curved lip to both locations and create a double-cupped design.

Adding cup to the prop's trailing edge (the part of the blade farthest from the boat) tends to increase pitch. Adding cup along the tip of the blade tends to add rake. (Recall that rake is the angle that the blades tilt toward or away from the hub.

Cupping tends to increase the prop's grip on the water and decrease ventilation (also called blowout, a condition caused by excessive aeration). The effect of cupping is similar to adding a fourth blade, but less pronounced. It will reduce blowout in turns and allow the boat to run with higher trim angles and transom mountings.

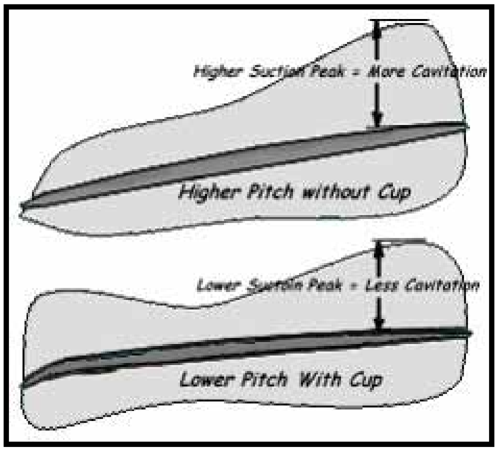


Figure 32 Lift Distribution curves for propellers with cup and without cup

1.6.1 What Is Propeller Cup?

Propeller cup is the deformation of a propeller's trailing edge toward the pressure face. Providing a measure of camber to the blade, it changes the pressure distribution along the blade's chord length, adding lift toward the trailing edge. This change in lift distribution is useful in controlling cavitation. Typically, there is a peak in the lift distribution on the leading half of the blade (see Figure 32, above).

Cavitation occurs in this region when the local lift is greater than the vapor pressure of the water, causing it to vaporize or boil. (This vaporization creates the vapor cavity that gives cavitation its name.) Cavitation can be controlled if the peak lift can be reduced below the vapor pressure, while still generating the necessary total lift.

By adding lift away from the peak via cupping, the entire lift can be reduced by a reduction in pitch. The more a pitch reduction is required to lower the peak lift, the more cup is needed to compensate for the lost thrust. (see Figure 32, above, page 28)

1.6.2 <u>Location of Cup</u>

If the cupped area of a propeller blade intersects *pitch lines* (see Figure 33, page 28, below), it will increase 'effective blade pitch'. Cupping in this area will reduce RPM by adding pitch. It can also protect somewhat against propeller "blowout". If the cup is placed so that it interests *rake lines*, (see
, page 29) it then has the effect of increasing rake. Cupping can affect both pitch and rake.

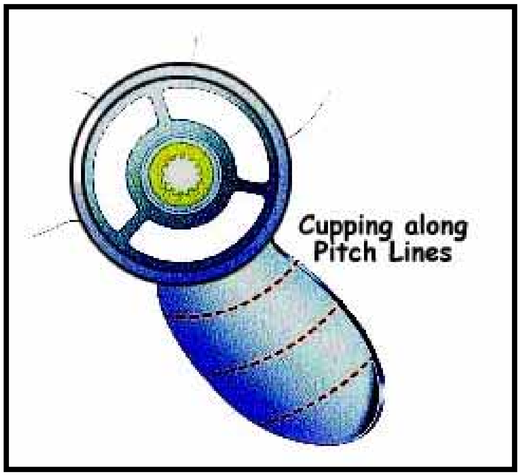


Figure 33 Cupping along Pitch Lines changes the 'effective pitch'.

Adjusting the cup on a cleaver-style propeller is more difficult than it is on a round-bladed propeller. Since the trailing edge of the "clever" is very thick and runs straight out on a rake line, adjustments have less effect on altering rake.

The added pitch "created" by cupping can be reduced substantially by filing or grinding away some of the cup.

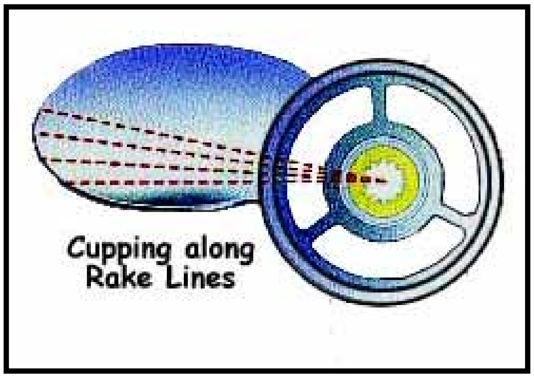


Figure 34 Cupping along Rake lines changes 'Effective Rake' of propeller

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*. Cup reduction will also result in an RPM increase.

1.7 Materials and Blade modifications

1.7.1 Propeller Materials

The three most common prop materials are composite plastic, aluminum and stainless steel. Each offers differences in price and performance. (Bronze props, another option, are now typically are found on slower speed yachts.) Prop materials in many ways determine their suitability when matched to engines of varying horsepower. Plastic props are limited to use on engines of 50 hp or less. Aluminum props are suited use on engines of up to 150 hp. Stainless props are pricey and worth it because they make the best use of any amount of horsepower.

Most boaters familiar with composite plastic props use them as spares rather than everyday equipment. Although economically priced, their efficiency is limited by blade flex and negligible ability to accept cupping. Both of these drawbacks are due to the relative weakness of the thin plastic blades compared with a prop made of aluminum or steel. Most plastic props cannot be repaired, although some offer replacement blades. Aluminum props are slightly more expensive than composite, but deliver more efficient performance through reduced blade flex and the ability to accept minimal cupping, Also, aluminum blades can sometimes be repaired after being damaged.

The most versatile and expensive props are stainless steel. Steel is extremely durable, with more than five times the strength of aluminum. This strength enables the blades to be as thin as possible to reduce resistance while spinning in the water. Despite being thin, the blades are strong enough to accept significant cupping and virtually eliminate flex. Other benefits include the ability to accept repair and the toughness to withstand punishment, such as hitting submerged objects.

1.7.2 Vented Blades

An increasingly popular trend on high-performance boats these days are vented props with holes drilled in the outer hub. These props work by reducing grip instead of tightening it. Vented props are not new, but they were not popular until recently because they go against the grain of traditional thinking and have limited applications.

Traditionally, props vent exhaust through the center of the hub to ensure undisturbed water is delivered to the blades. Vented props, however, allow a limited amount of exhaust to pass into the blade area through holes drilled in the outer hub. This aerates the water and reduces its resistance to the blades. As the boat accelerates, the vented prop spins easier, allowing engine rpm to rise more rapidly for quicker hole-shots. This means that vented props are hole-shot specialists. Once a boat is on plane, water passes over the vent holes so fast that the holes effectively become sealed and only minimal exhaust slips through. With the blades operating in solid, non-aerated water, there is no negative or positive effect on top-end speed.

Too much aeration through vent holes, however, will cause a prop to lose bite. To keep this from happening, Mercury Marine has a Performance Vent System (PVS) allows regulation of the flow by installing plugs into a series of holes with graded sizes. Each PVS prop comes with a set of plugs, which allows you to find one that delivers the best performance for your rig.

1.7.3 <u>Blueprinted Blades</u>

Another new prop trend is a process called blueprinting or labbing (a name that comes from sending the prop back to the lab). To get a prop labbed, you must take it to a specialized shop or send it to a manufacturer, where everything is checked against the original blueprints-blade distortion, pitch, rake, cup and all other design elements. The prop is then ground, heated, banged and massaged until it meets its design specification as precisely as possible.

Field tests have shown that blueprinting can boost top-end performance by 3-5 mph. While the cost is several hundred dollars, some boaters believe it is the easiest and cheapest way to add speed. On the downside, labbing usually thins blades and therefore reduces prop durability. As a rule, experts recommend you have major work done on your prop only once (either repairs or labbing) because the process weakens the blades and often leads to distortion that cannot be corrected.

1.8 Gear case Design

Often the hydrodynamic drag of the gear case is the primary contributor to overall drag – and the #1 determinant of ultimate speed. Gear cases have changed dramatically through the years as designers and manufacturers realized the tremendous impact of aerodynamics and hydrodynamics on hull performance. Today outboard engine and outdrive design has reached a point where model changes can be dictated by the design of the gear case. Several years ago, few performance boaters would have known whether a Mercury 2.5EFI motor came with a CLE or SportMaster gear case. Today, many high performance enthusiasts will take the time to have the CLE or SportMaster sent out for special improvements.

Figure 35 Gearcases can only take so much

The gear case should provide three (3) functions:

- Provide a water intake for cooling the motor; and
- Provide lift (some boaters call this "leverage") to help carry the boat.
- Provide steering capability with as little imposed drag as possible.

If your gear case design is limiting in any of these functions or features, you will not likely reach your hull's peak design speed capabilities. Let's look at each of them:

1.8.1 Water Intake

The advent of nosecones has greatly increased the interest in water intake location. A nosecone's main goal is to reduce hydrodynamic drag while providing proper, or improved, water intake capabilities. They also can serve the additional purpose in higher speed boats of reducing "blowout".

Blowout occurs when the water impacts the gear case at such a velocity that it separates from the leading edge (front) of the gear case and bypasses the propeller. This causes the propeller to "lose its bite" or cavitate, usually results in over-revving the motor, the boat will lose speed and lift, and sometimes turn out of control. Boats traveling under 80 mph will not usually be affected by this phenomenon. Putting a low-water pickup nosecone on a moderately heavy boat will have little positive impact on performance. These boats cannot run the motor high enough to take advantage of the low water pickups and therefore more often than not, end up reducing speed due to the increased drag of the low water pickup. If you don't need a low-water pickup, but need to reduce hydrodynamic drag of the gear case, a "short" nosecone is usually available that maintains the side water intake, but gives the nosecone a more hydrodynamically efficient profile.

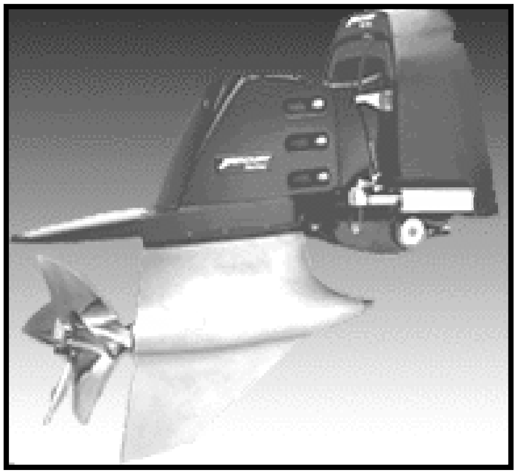


Figure 36 Modern gearcase reduces 'blowout'

1.8.2 Propeller Lift

Each boat has a maximum engine height at which the boat will still be able to accelerate properly – or "get loose". Any higher than that and the propeller will not generate enough lift during acceleration and MPH will be scrubbed off the top end. Heavier boats and boats without a lot of aerodynamic lift typically require lower engine heights than lighter boats or boats that are designed with a lot of aerodynamic lift.

1.8.3 Skeg Design

Performance boaters often overlook the skeg. In general, the less drag-creating 'profile' in the water, the better. On today's high performance boats, torque steer is a major issue. This is often offset by a riveted-on triangular piece or as in the case of Mercury high performance outboard motors, a thickly cast in anti-torque profile at the rear of the skeg. These both help to reduce torque, but unfortunately, they also reduce speed because of the increased drag of the skeg profile. A better alternative is to cut that thickness back and weld in an anti-torque tab. Such tabs maintain the standard skeg thickness but curves to the starboard side of the gear case reducing torque. Gear cases with this modification are much more efficient, and can improve performance by as much as 4-5 mph.

1.8.4 Blowout

Blowout is a phenomenon that is better when somebody else has it – unfortunately, we all experience it. Let's investigate the reasons and results of this sudden change in performance characteristics. Blowout occurs when the ratio of air to water around the propeller gets so high that the propeller is no longer grabbing water, but is trying to propel itself through air (or a relative vacuum). This causes the propeller to lose "bite", and then a chain of events occurs that can range from merely a "loose" steering feeling, to a vicious turn to the right (typically). The speed at which this occurs varies with boat design, gear case design, and propeller design.

1.8.4.1 Causes of Blowout

The 4 main contributors to blowout are as follows:

Gear case inconsistencies:
If the gear case has been damaged (run up on the rocks a few too many times?); or has an improperly installed nosecone; or a damaged skeg; the gear case cannot provide the proper aerodynamic direction (steering) effect. The impact can be the need for the gear case to "crab" or slide sideways through the water, creating an area void of pure water, like a vacuum or air pocket in which the propeller tries to operate. This is bad for the propeller – it needs water to work properly. Cleaning up all nicks and gouges in the gear case so that it is very smooth will help.

Motor is too high:
If the motor is too high, the propeller will not be able to provide lift for the boat, causing the driver to apply excessive trim. This causes the propeller angle of attack to be angled downward (more than it needs to be) thus trying to force itself to go sideways through the water. This is bad for the propeller, and inefficient for the boat performance. Designing the hull with the engine at the optimum height will help overall performance.

Hull Design:
Some designs of boats are more susceptible to "blowout" than others are. Why do we think that is? Well, it's difficult to know whether you have a good one or a bad one, but the well-designed hull will have a dynamically balanced performance through all phases of performance (all operating speeds). The poorly designed or poorly dynamically balanced hull will need much more time and effort in "on the water" set-up. It is, of course, better to design the stability and performance characteristics into your hull ahead of time. This makes the set-up much easier, and the hull performance more predictable in all operating conditions.

Velocity:
When you go faster than a stock gear case is designed to perform, the

water separates from the leading edge (front) of the blunt bullet and sort of "bounces" around the propeller. In engineering terms, we have a disturbed flow, and when this occurs near the propeller, it really impacts the propeller's performance. Smaller gear cases with smaller, aerodynamic bullets will always improve this situation, delaying "blowout" tendencies to a higher velocity. Adding a nosecone will also increase the velocity that a standard gear case can operate effectively.

The cause of blowout is typically a combination of all of these. Gear case modifications and propeller changes can reduce your chance of blowout. So can a properly designed and dynamically balanced hull. However, when you go fast, blowout becomes part of the business, so you will experience it eventually.

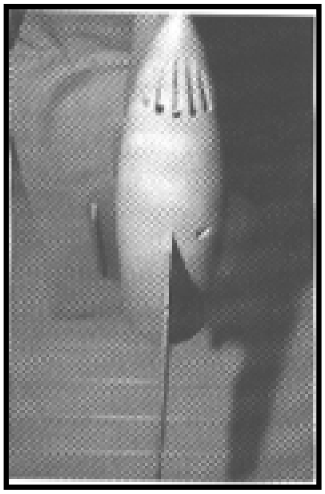


Figure 37 Nose cone & skeg modification to stock XR unit

Typically, a blowout is immediately preceded by a "loose" steering feeling, an increase in RPM with no speed increase, a loss of lift, and a resulting drop of the nose of the boat. Hold on.

1.8.5 __Lower Unit Designs__

Race boats today are reaching speeds of 150 mph or more. Many of today's high-performance recreational outboard hot boats are reaching speeds that just a decade ago would have qualified them as pure race hulls. When powered by a stock Mercury 2.5 280hp or 300hp Drag outboard motor, it is possible for a light, fast tunnel or v-bottom to top out at well over 100 mph. Many of these single-engine rockets have the capability to top 120 or better.

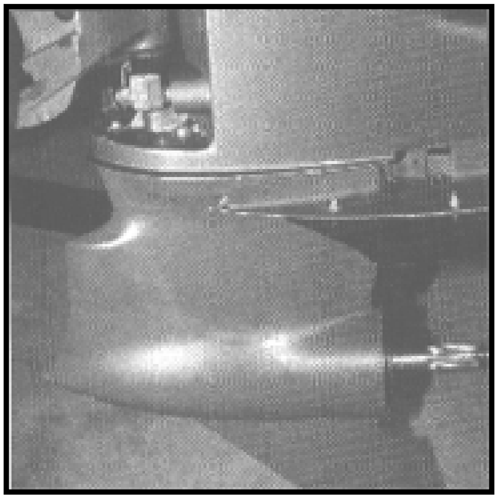


Figure 38 Slimmer profile of XR Drag gear case

At those speeds, propeller and gear case design become critical to performance and more importantly, to safety. On ultra-fast hulls, it used to be an old racer's trick to swap the standard size V-6 gear cases for the smaller-diameter, more streamlined unit that's installed as standard equipment on lower horsepower models.

In the 1970s and 1980s, this neat swap was made on both OMC and Mercury V-6s by simply using the gear cases from the V-4 (90-140 hp) for the OMC and the inline-6 gear cases (90-150 hp) for the Mercury motors. After making other alterations like swapping drive shafts, propeller shafts and bearing carriers, these cases fit fine. In fact, Mercury racing even offered adapter kits in their catalogues for many years.

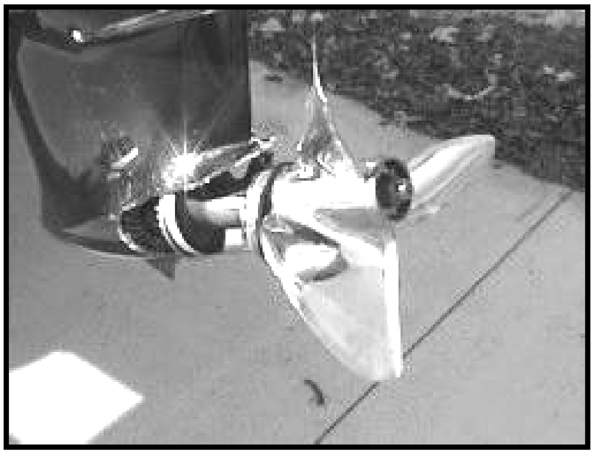


Figure 39 All gearcases are designed to a limit!

Today, not many OMC enthusiasts opt for the smaller gear cases, but for Mercury fans, it is an easier swap than ever before. The gear cases used on the Mercury XR series of 150-hp outboards (XR2, XR4 and XR6) is essentially the same size and diameter as the older 150 inline gear cases, with stronger gears, bearings and shafts to hold up to the rigors of V6 power.

That change works, on most stock 150 hp, 175 hp and 200 hp fishing engines. However, the stock XR gear cases won't hold up for very long when fitted to the housing of a high performance Mercury Racing 2.5 series outboard because the increased torque and horsepower, and the higher speed capability of these engines demands a stronger gear case. Today's drag and river racing experts have learned of this problem, and most experts who run in the modified classes (where non-stock gear cases are permitted) have "trashed" a small gear case at least once under extreme acceleration, top speed or tight turning conditions.

Here are a few of the commonly experienced high-performance gear cases in use:

1.8.5.1 Mercury CLE

This gearcase was first introduced on the Mercury 2.4 Bridgeport and 2.5 Offshore - “Crescent Leading Edge” lower unit. An older-generation Mercury high-performance lower unit with integral nosecone and low water pickups. These were designed for high-speed surfacing applications, and were originally equipped on 2.4 Bridgeport engines. No longer in production, used on 2.0L/2.4L/2.5L applications only. Two versions were built – with holes either below or above the bullet.

Figure 40 CLE with torque tab

1.8.5.2 FleetMaster

Initially designed for use on Mercury Promax 300s. Internal components are built to withstand the saltwater environment. All 3.0 Litre gearcases have a radial discharge stainless steel water pump. These units are the "workhorse" gearcase, best suited for Offshore center console vee-bottom type boats.

Figure 41 Fleetmaster gearcase

1.8.5.3 Speedmaster

Lower units used on
Mercury 2.0 SST120/S2000 and 2.5L S3000 and Champ race outboards were available in 14:15 and 15:17 gear ratios, designed exclusively for racing applications. Later models had thicker skeg and can be used on V6 motors.

SSM#4 (15:17 ratio) was called the "marathon" gearcase, apparently designed for the Parker Enduro and extreme duty assignments. It is now used in F1 racing and is quite durable. This case has a bigger bullet diameter and length than the SSM#6.

The SSM#6 (14:15 ratio) was the "sprint" gearcase. It is now used in SST 120 racing and has a smaller bullet diameter than the #4. Originally, not very durable, now using forged gears, are somewhat better in lifespan.

The SSM#8 was the T4 (3.4L and 3.9L race engines in mid-80's) gear case. This is a much larger gear case than even the #4. Very heavy duty design, it was apparently used on the "wizard" engine (Mercurys. two 2L F1 engines mounted on a single center).

Figure 42 SpeedMaster #6 Gearcase

1.8.5.4 SportMaster

(1.64:1 up to 2.00:1 ratios) is the current-generation Mercury high-performance lower unit. The design has a crescent-nose bullet nosecone and low water pickups and more robust gear/shaft/bearing materials, intended for high-speed surfacing applications. This design replaced the CLE gearcase and has a longer bullet than the CLE.

Figure 43 Sportmaster Gearcase

1.8.5.5 TorqueMaster

(1.78 to 1.87 ratios) – A heavy-duty Mercury lower unit designed without a nosecone, intended for boats with heavier loads. Designed to run at elevated transom heights, later models have low-water pickups. These units are usually stock on Optimax. It is marketed as the replacement for the old V-6 gear cases. The TM has lower and fewer water inlet holes, and a smaller diameter bullet than other shiftable lower units (4.25" vs. 4.75" diameter)

Figure 44TorqueMaster Gearcase

1.8.6 More Speed

Bullet diameter is the secret to what makes the XR gear cases faster, safer and easier to handle than the larger V-6 counterpart. The stock V-6 housing measures 4¾", inches across at the rear of the bullet, while the XR is a full half-inch smaller at 4¼". That means much less diameter dragging through the water. In fact our AR® software for powerboat design (**TBDP©**) predicts that this reduction in diameter alone will have the effect of 10 lbs less drag at a speed of 100 mph – which is the same as 2.7 hp less required to go that same speed. The relationship between bullet length and diameter is called the aspect ratio. The longer the bullet is when compared to its diameter, the lower the aspect ratio. As aspect ratio increases, the gear case becomes less susceptible to crabbing, inefficiency, poor handling, propeller ventilation and blowout. Extending the stock V6 gear case bullet with a nose cone will increase the aspect ratio (we will discuss this modification later), but the bullet size is still quite large. Reducing the bullet size and adding a nose cone is what makes an XR gear case so efficient.

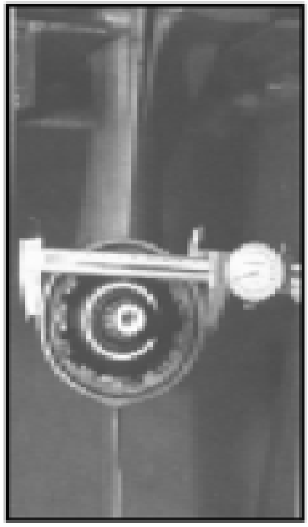


Figure 45 Smaller diameter 'bullet' measures 3 ¼" for XR gearcases.

Just installing the smaller XR case without the nose cone would be enough for most boats running in the 75 to 85 mph range. If low-water pickups were not needed to provide adequate water supply to the power head, the gear case could be run as is (if horsepower was not more than 175 to 200hp). The design limit speed of this gear case in stock form is about 90 mph; for the larger V-6 outboards, it is in the low 80's. This theory applies when all factors are ideal, meaning that the boat is running clean, and very little wetted surface, without the use of much positive trim.

However, most boats require some positive trim to run cleanly, and as trim is applied, the design limit speeds are lowered dramatically. On set-ups where all the wrong parameters apply (e.g.: too much positive trim, engine positioned too high on the transom, weight balance too far forward and the wrong propeller application) blowout can occur at speeds far below the gear case's stock design limit.

Adding a well-designed nose cone and torque tab to a stock V-6 gear cases can raise its design limit speed up to the 115 mph range if the set-up is balanced and using the correct propeller. While there are rigs currently running at 115 mph and faster with these gear cases, it is not the safest or most efficient set-up for these ultra-high speeds. Adding a nose cone and torque tab to the smaller XR case raises its design limit speed to well over 120 mph.

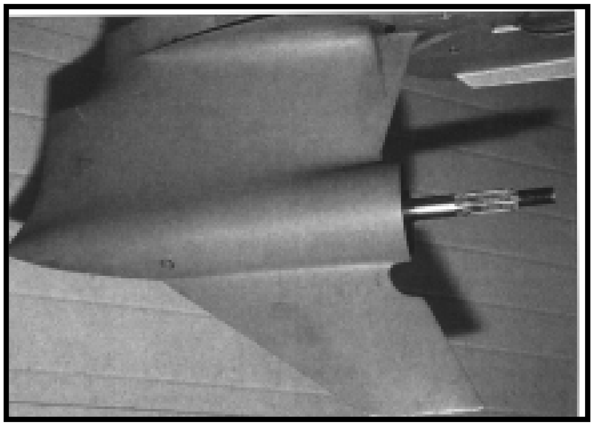


Figure 46 Fastest finish for gear cases is buffed primer paint

Using a stock XR case is not always the answer for most hot-boats since internal parts won't hold up to the strain of all that torque and horsepower. Well, if the stock unit is never shifted and the lube oil is changed every other outing, and it has not run at extremely high transom heights, it will probably last a few seasons. However, you really do not want all that trouble for what you get. There are alternatives, though. Suppliers such as Steckbauer Speedmaster Service in Oshkosh, Wisconsin has developed an alternative to the fragile stock XR unit for ultra-high-performance enthusiasts and racers. Most of his customers are Formula One race teams who need frequent rebuilds on their racing Speedmaster gear cases. This tough "XR Drag" gear case has been available since 1997 with excellent success.

For a heavier, slower hull or you tend to run loaded rather than empty, the XR Drag gear case is probably not needed. The smaller bullet diameter will not carry a heavier load as well as the stock V6 gear case will, nor will it make a 70-mph boat faster. If you are planning to go as fast as 100 mph, then it can give you easier handling, safer driving and a few more mph. The real advantage at speeds of 110 mph and higher is the safety factor the XR Drag case offers; the improvement in handling and reduced chance of blowout are perhaps the best reason to consider this unit for your ultra high-speed outboard.

1.8.7 Nosecones

The process of engineering a well-designed nose cone focuses on the prime concern of eliminating blowout and improving propeller efficiency. "Blowout" is encountered when the water separates from the gear case, to the point where that distance is equal to or greater than the radius of the propeller blade. When this occurs, the blades no longer have any good solid water in which to establish bite. The propeller totally breaks loose and cannot recover until such time as the boat is slowed down to allow water to re-enter the propeller "slip stream" or the void created by the ventilation occurrence. Very often, when this occurs, the bow of the boat drops and immediately hooks to the left reacting to propeller torque. Very few boats run into actual total blowout, but rather more often encounter propeller burn, a phenomenon that occurs prior to blowout.

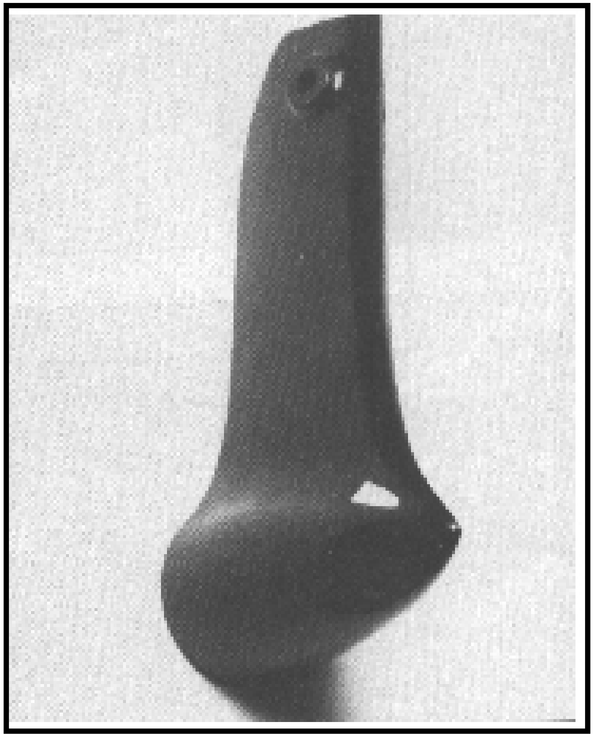


Figure 47 After-market nosecone

Many high performance boaters may be experience propeller burn and not even be aware of it. The addition of a nose cone can eliminate propeller burn, blowout, and allow you to pick up considerable speed if the horsepower is available. However, many design considerations should be taken into account in order to install the proper nose cone.

To eliminate propeller blowout at the highest possible speed, we need to be concerned with something called aspect ratio (Length/Diameter).

As we increase the length of the nose cone, the aspect ratio increases, which provides superior water flow characteristics and gives the water flowing by the unit a greater chance to flow back on the surface of the lower unit before introducing air into the slip stream going by the propeller.

As water flows by the lower unit and begins to separate from the unit at higher speeds, a turbulent flow condition exists which is called a "vortex". In effect, this causes a (relative) vacuum, or at least a much lower pressure, behind the gear case. The addition of this lower pressure increases the drag of the lower unit as it is trying to "spear" the water ahead of it. On top of this increase in drag co-efficient (CdW), the aeration of the water going through the turbulent flow and the water separation causes propeller burning. This phenomenon leads to blowout, and can also reduce top speed before blowout is obtained. You may have noticed pitting on your propeller blades caused by this propeller burn.

Another area to understand is lead angle. A good example of lead angle, or bluntness, is the newer Bravo Drive compared to the Alpha. Both gear cases are equal diameter and equal length; therefore, both have the same aspect ratio. However, the Bravo has a blunter lead angle than the Alpha. The superior design of the Bravo for dependability, horsepower capability, and serviceability required a larger pinion gear above the bullet. This blunter, wide angled portion of the gear case forces water to separate from the case at lower speeds than the Alpha. Consequently, the terminal speed on the Bravo is said to be about 3 MPH lower than the Alpha.

The most important consideration when installing a nose cone can be the problem generated with increased tail lift. The addition to gear case length (improved Aspect Ratio) also adds surface area to the bottom side of the gear case. This increased area translates into increased tail lift. In most cases, this is not desirable. When tail lift goes up the reaction is that the bow goes down. Over trimming to correct the problem just wastes horsepower. The solution in some nosecone designs is a parabolic design that creates a more efficient lift characteristic.

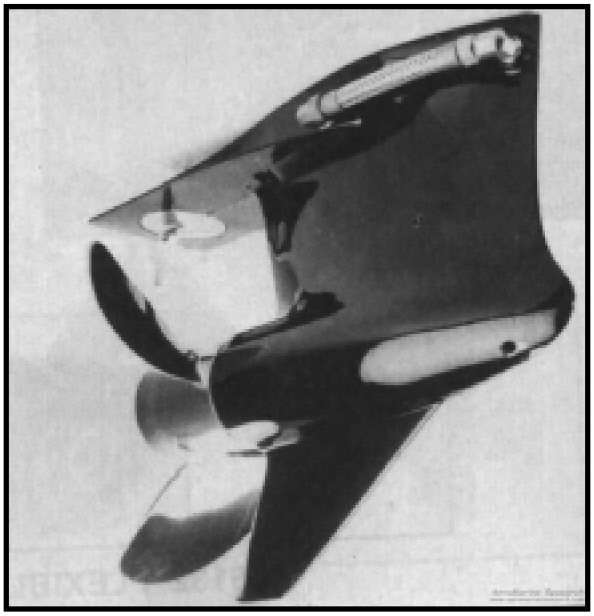


Figure 48 Nosecone installation

As in aircraft wing design, the offset parabola provides a vertical downward force, which counterbalances the increase in tail lift due to the additional surface area. The net result is <u>neutral gear case forces</u> than do not affect boat attitude. It is important that the crescent starts at the nose and gradually blends back to the original leading edge, just below the cavitation plate. Any portion that extends in front of the leading edge, up high towards the cavitation plate, will have an adverse effect on steering. The only exception to this when the drive is run high on the transom (not in the water), such as many outboard applications, particularly those with low water pickup nose cone designs.

To make this even more complex, let's consider that low water pickup - particularly on stern drives. Most experts suggest that we do not use them. In addition to the crescent problem just discussed, the pickup holes can disturb the clean water flow, costing us about 1 MPH loss in top speed. Outboard applications that run high enough to run conventional pickups out of the water are the only applications where low water pickups are a benefit.

Another design aspect to review is that of the “bullet” configuration. Most nosecone designs use either a round pointed bullet or a blade sharp from the front view but rounded from the side view. In race boats that have minimal bow weight, pointed bullets may work. In pleasure boats, the pointed bullet running at a downward angle, while moving forward at high speeds, creates flow problems above and below the bullet. This forces the back of the boat down and can create propeller slip. A round blade profile, looking from the side eliminates these problems and is the best choice for most boats

1.9 Propeller design and motor Exhaust

There are a few different design concepts for exhausting engine gases, and many include the lower unit outdrive and propeller hub as part of the story. Through hub exhaust and over hub exhaust propellers are used on boats where the exhaust passes out through the rear of the "torpedo" on the lower unit, around the propeller shaft. Most all outboards utilize this type of exhaust. Non-through hub exhaust propellers are used for inboards using shaft driven propellers, stern drives using through hull exhaust, and on some outboards that don't route the exhaust through the lower unit torpedo.

1.9.1 Through hub exhaust

Propellers consist of a round barrel to which the blades are attached. The exhaust passes through the barrel and out the back, without making contact with the propeller blades. This provides a good clean water flow to the blades, usually resulting in good acceleration and hole shot.

1.9.2 Over hub exhaust

Propellers have the blades attached directly to the smaller tube that fits over the propeller shaft, eliminating the larger exhaust tube. These types of propellers are often used for attaining maximum top speeds. The hole-shot can often suffer (at least on some boats) due to the extreme exhaust flooding that occurs around the propeller blades during acceleration. On some engines, especially those with lower bottom-end torque, this can be an advantage as it allows the engine to gain RPM before the propeller really starts to "grab".

1.9.3 Combination over/through hub

This actually consists of a propeller with a through hub design and holes drilled through the hub ahead of the blades. This allows some exhaust to escape at lower RPMS, providing a controlled amount of exhaust flooding. This allows the propeller to turn slightly easier during initial acceleration, for a better hole-shot on some engine/boat combinations.

1.10 Surface Drives

Here is a great alternative that is truly an engineering improvement on the normal outdrive design. The Surface Drive was invented by Arneson, and started race testing with female ocean racer Betty Cook KAAMA.

In 1970 Howard Arneson, an inventor well known for the Arneson Pool Sweep™ began developing a marine propulsion unit to take advantage of the surface-piercing propeller.

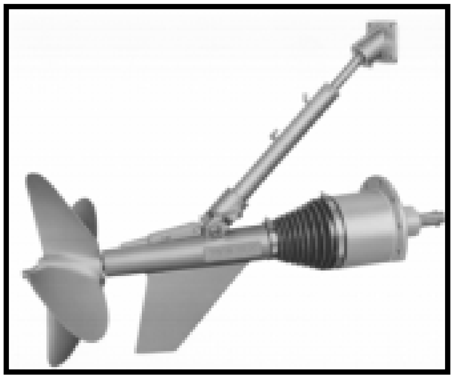
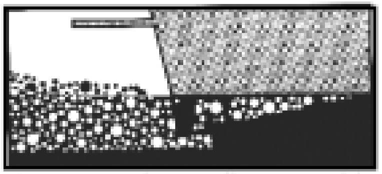


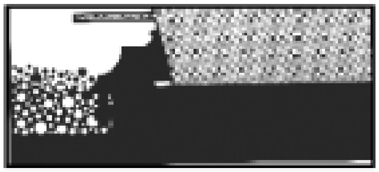
Figure 49 Arneson surface drive

Arneson drew on his long-term experience and involvement in offshore powerboat racing. He used race boats as test vehicles for prototypes of what was to become known as the Arneson surface drive. Arneson won four major offshore races and set the Open Class record with his new drive system, thus establishing a new era in marine propulsion and performance.

The success of Arneson Surface Drives revolutionized the marine propulsion industry. In 1981, after proving his system in rigorous offshore testing, Arneson licensed worldwide marketing of his Drive units. Surface drives are a technically advanced marine propulsion system that utilizes a surface-piercing propeller. It is a revolutionary departure from every other familiar drive system. Surface drives provide higher top speed and increased efficiency through the use of surface-piercing propellers and the elimination of drag caused by conventional underwater shafts, struts, rudders and I/O legs. Combining mechanical simplicity with operational reliability surface drives deliver performance unequalled on pleasure, commercial, military and racing craft.



Conventional propeller or rudder shafts produce drag, turbulence, cavitation and vibration.



The lower part of an I/O unit disturbs water flow to the propeller

With ASD the surface-piercing operates in undisturbed water

Figure 50 Surface drive technology

1.10.1 Here is how it works

A propeller develops maximum thrust in the lower half of its cycle. Surface drives utilize a surface-piercing propeller that operates 50% submerged in the undisturbed water behind the transom at planing speed. It literally pierces the water on the lower segment of the propeller cycle to provide maximum forward thrust, and to deliver optimum engine power. Conventional propulsion systems lose efficiency due to drag caused by underwater shafts, struts, rudders and I/O units. Surface-piercing props eliminate cavitation because they ventilate rather than cavitate beneath the hull. This reduces vibration, noise and eliminates hull and propeller erosion.

The propellers used for most surface drives applications are similar to normal three or four blade round-ear props, but are usually about 15% larger in diameter. Cleaver type props are available for racing and high-performance applications. Diameter, pitch and propeller material will vary with the application for your application.

1.11 Want to get technical?

In a more technical sense, just how do the propellers work? We can first define a Propeller as a propulsion device that converts the power from the engine into a thrust force to propel a boat. The "screw" propeller is the most common form of marine propulsion device.

The motion of the screw is a combination of 1) a rotation with 2) a translation along the axis of rotation (see Figure 51). The propeller itself consists of a number of identical twisted blades (usually 3, 4 or 5) equally spaced around a hub mounted on a driving shaft. The twist (pitch) and inclination of a blade are defined by the angles between a *datum plane* normal to the *axis of rotation* and a number of datum lines fixed relative to the blade. A set of *pitch datum* lines is taken at a series of constant radii from the axis of rotation, and the angle between the datum plane and a pitch datum line is named the *pitch angle*.

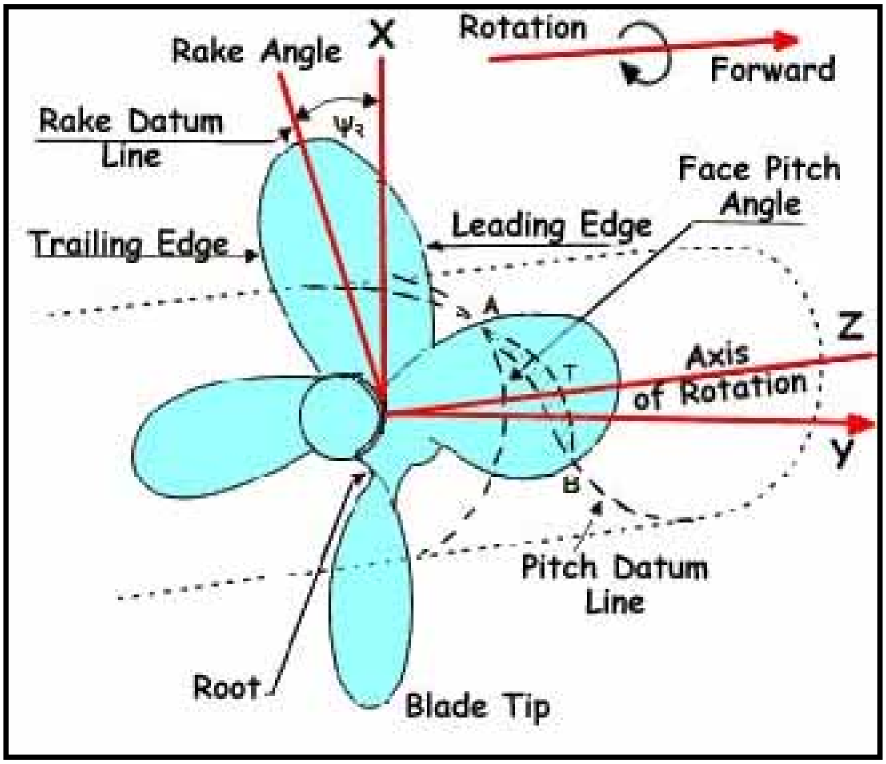


Figure 51 Technical Parts of the Propeller

The operation of a screw can be illustrated by considering an *annular element* of one of the blades. The figure (Figure 52, page 45, above) shows the forces acting on an annular blade element of width *dr* at a radius *r* from the axis of rotation. When a torque *Q* is applied to the screw (by turning the shaft) then the propeller and shaft rotate at a rate of rotation . Due to the reaction of the fluid in which it operates, the blade element experiences a resultant force *dR* which has two components – 1) a tangential torque force *dQ/rB*, where *B* is the number of blades, acting opposite to the direction of rotation; and 2) a thrust force *dT/B* acting ahead, parallel to the axis of rotation.

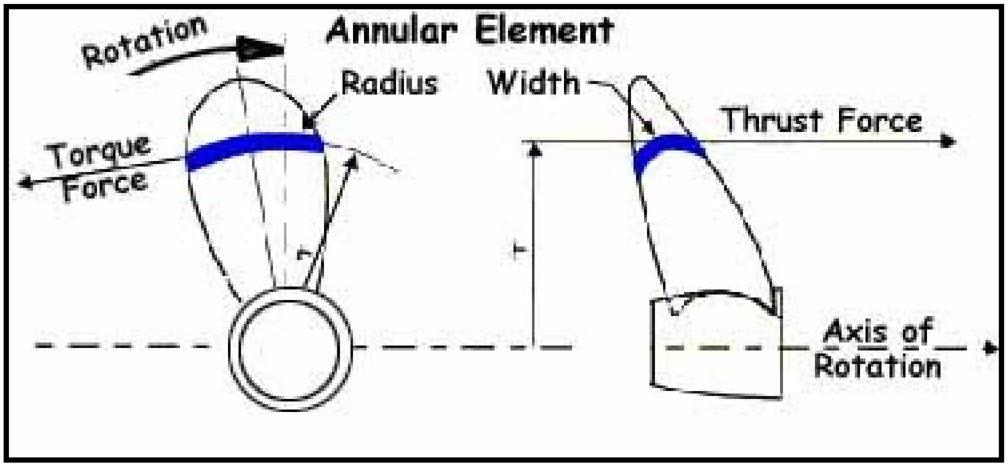


Figure 52 Thrust and Torque Forces on Annular Blade (Sectional) Element

Where:
dT = Thrust
dQ = Torque
dDg = Drag
dL = Lift
dR = Resultant Force

The sum of the moments of the tangential torque forces on all the blade elements is balanced by the torque *Q* applied to the propeller, and the sum of the thrust forces on all the blade elements is equal to the thrust force *T* which propels the screw in a forward direction at a speed of advance.

1.11.1 Cavitation

Propellers supply thrust to a boat by transferring lift from the blades through the hub and up the shaft line. Propeller blade lift is similar to the lift that is found on any aerofoil moving through a fluid – such as an airplane's wing. There are two contributors to thrust – lift from the suction face (negative up) and pressure face (positive up) [see in Figure 53, below].

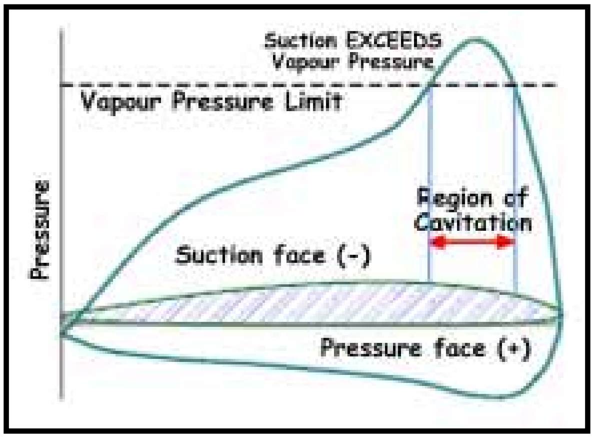


Figure 53 Blade pressures and cavitation region

1.11.1.1 Inception of cavitation

When the magnitude of the suction (negative) pressure exceeds the water's vapor pressure bubbles of water vapor begin to form on the blade surface (The suction triggers the change of state from liquid to vapor). [See the *cavitation region* illustrated in Figure 53, above].

As thrust increases, the magnitude of pressure on both the suction and pressure faces increase. The increasing suction means that the cavitation region will grow and more of the blade surface will cavitate. If the vapor bubble cavity is small, the water flow over the blade is unchanged, and the suction and pressure forces are unaffected. However, once the cavity grows to a size that water actually separates from the blade, water flows will change and suction face lift, total thrust and efficiency are lost.

1.11.1.2 Three modes of cavitation

If cavitation is so low that it does not affect water flow and total thrust, it is *sub-cavitating*. As thrust is lost due to increasing cavitation and flow changes, it is in a *trans-cavitating* mode. The point where cavitation is so extreme that the water flow has fully separated from the suction face is called *super-cavitating* (or fully-cavitating).

The change in water flow and separation from the blade also results in a reduction in the amount of torque that is necessary to keep the propeller rotating. In other words, the vapor cavity makes it easier to spin the propeller. This is what allows the "over-spin" that is seen in propellers that are heavily cavitating.

1.11.1.3 What does cavitation look like?

Figure 54 Cavitation causes bubbles to implode water and remove microscopic particles of metal from the blades

Those bubbles of water vapor that form are really water boiling at very low temperature (such as room temperature). These aren't air bubbles, but rather, are steam bubbles, and they are displaced quickly to the backside of the propeller where they find a higher-pressure zone. There, the bubbles implode water against the propeller blades and can remove a microscopic particle of metal in each implosion. (See Figure 54, below)

Cavitation can be initiated by excess rpm.

Figure 55 erosion caused by cavitation can be seen in the tips of the blades

If the (tangential) speed of the propeller blade tips surpasses certain limits (some research shows that a limit is 150 feet per second in a typical 5-bladed propeller), that the expelled water will carry such strength that it can prevent any other water molecules from occupying the formed vacuum (See Figure 55, below). Thus, cavitation is produced by a tangential velocity that is too high, caused by excess RPM. This erosion can always be seen in the tips of the blades.

Cavitation can also be initiated by a lack of blade area. If the pressure on the blade is too high (some research shows that this limit is approximately 7psi), cavitation is produced by lack of area.

The origin of the bubbles is on the leading edge of the propeller blade, event though the damage shows up on the backside due to the corrosion that goes backwards in its destructive process to the center of the blade. The erosion produced by any type of cavitation is shown with more intensity when the cathodic protection is not adequate. And in some extreme cases the propeller is completely consumed within days or weeks.

1.11.1.4 And how does cavitation affect me?

Despite the issue of propeller material erosion, it is important to point out that cavitation is not necessarily “bad” in all cases – it is often part of the intended design performance. Many propellers operate at such high thrust loading that extensive cavitation is unavoidable. In these cases (eg: outboard propellers for high performance powerboats), the propeller relies predominately on lift from the pressure face, and the propeller’s section shape and other geometry is designed so that it exploits this characteristic.

Propellers on boats operating at high speeds tend to be able to carry more cavitation before thrust loss begins. Propellers operating with high-thrust at low-speed, however, show a more significant loss of thrust and efficiency. It is very important to note, however, that such cases are not limited to traditional conditions such as for tugs or trawlers. Planing boats can also lose thrust to cavitation when trying to accelerate through the hump speed and get up on plane. High cavitation during these dynamic speeds can result in significant thrust breakdown.

1.11.1.5 Performance analysis

The analysis of propeller performance is very well behaved for the sub-cavitating mode. In comparison, very little work has been done over the years for the trans- and super-cavitating modes. One reason for this is that propellers operating with high cavitation are often unstable, and small changes in thrust loading or water flow can result in large changes in RPM. Cupping a propeller further complicates the hydrodynamic analysis process. For these reasons, the prediction of propeller performance when operating in trans-cavitation and super-cavitating modes is not always reliable.

1.12 New drive concepts: One Engine Drives 2 Props

In 2000, Torvec Inc. announced that it was licensing its steering and transmission technologies to give single-engine planes and boats greater maneuverability than twin-engine crafts without the weight and cost of a second engine. (Torvec was founded by the inventors of the Torsen differential, which improves handling in high-performance vehicles including Formula 1, Indy and NASCAR race cars.)

Torvec's technologies can significantly improve the maneuverability of boats, especially when docking or in high seas. From a single engine, Torvec's steer drive can power two propellers at independent speeds and directions, which enables very precise steering. A boat could actually be pivoted 360 degrees in it's own length. Torvec's transmission matches the engine's speed to the torque required by the propeller to accelerate or cruise. This greatly increases fuel economy and reduces pollution. Torvec's transmission eliminates the need for variable pitch propellers, saving tens of thousands of dollars.

This idea just shows us what good engineering can do for the performance industry. The steer drive does not yet have a practical application for high performance tunnel hulls, but the technology is coming.... Watch for it.

1.13 Advanced Propeller Designing

There is much detail and performance optimization of the specific propeller concept and design, through use of modern Computer-Aided Design (CAD) software. Designers can optimize performance characteristics to obtain propeller details for blades, hubs, etc.

From the perspective of thrust and torque performance, the designer will consider the surfaces of the propeller blades. Eventually the designer will also need things like the hub and root fillets, but they only minimally affect performance. (From the design aspect, these details are basically along for the ride so that we can rotate the blades with adequate strength).

Naval architects represent the propeller surfaces using global parameters that define overall size and shape from the stand-point of the 2D blade sections (i.e., how the "wing" shape actually moves through the fluid); and detailed parameters that identify where the 2D blade sections are located in space, and considerations for vibration, clearance, strength and manufacture. Typical Global parameters include Section configuration, Number of blades, Diameter, Nominal Pitch, and Blade area ratio; typical Detailed parameters include Skew, Rake, Thickness distribution, Pitch distribution, and Root fillet radius.

There are engineering tools for analyses that can be performed such as strength analysis with FEA (finite element analysis) and detailed 3D performance analysis with CFD (computational fluid dynamics). Stress distribution analysis can be valuable in helping to determine parts of the propeller that can ultimately fail due to overloading or fatigue.

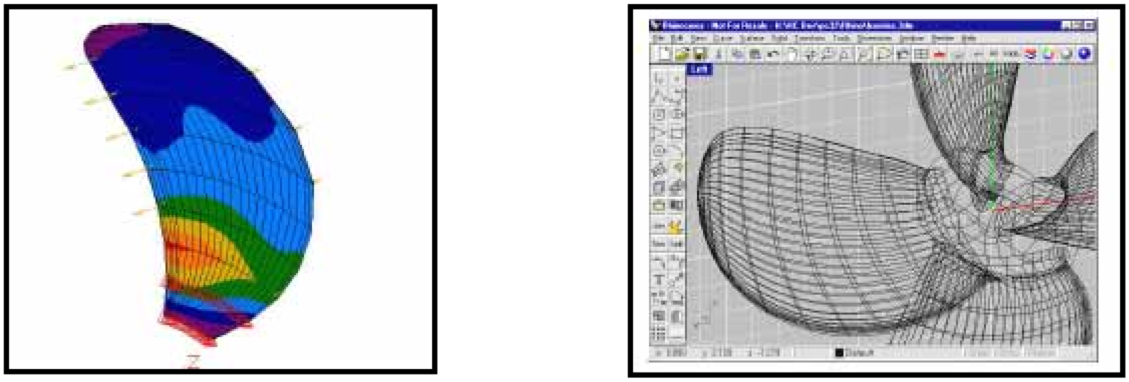


Figure 56 FEA modeling for stress analysis

1.14 Speed Prediction

The speed of your hull can always be calculated using an engineering formula. While some of the variables for the formula may require some experience to apply, the formula works for all hulls, all designs of boats, all power and drive packages, and all speeds.

1.14.1 The speed prediction formula

$$V = \frac{[RPM \ast PP \ast (1- S) \ast GR]}{[1056]}$$

Now, there are other things that can affect the speed prediction - like expert "cupping" of the blades, which increases the effective pitch of the operating propeller.

Where;
V = Velocity (mph)
RPM = revolutions per minute of engine (rev/minute)
PP = Pitch of propeller (inches)
S = Efficiency Slip (percent %)
GR = Drive Gear Ratio (propeller shaft /engine drive)

1.15 PropWorks2© Software

AeroMarine Research® has developed software for Windows 98/98se/NT/2000/XP that will do the speed prediction for your propeller and engine set-up. The PropWorks2© software is extremely user friendly, and makes the calculations, and even the application of "cupping" effects, etc. very user-friendly.

Figure 57 AeroMarine Research® software

The AeroMarine Research® software can be reviewed and ordered at the AR website: http://www.aeromarineresearch.com/prop2.html

Also check out the AeroMarine Research® "Tunnel Boat Design Program" Software. TBDP© software for Windows provides a fast, detailed method for the tunnel boat designer, builder, or driver to generate a total performance and design analysis. The TBDP© makes it easy to predict the effect of any individual or group of design change(s) on the ultimate performance of the hull. The software is a proven, engineering design/analysis program that presents predictive performance results in easy-to-read, comparative-style and graphic format. See TBDP on the web at: http://www.aeromarineresearch.com/tbdp6.html