Propeller Selection
For
Boats and Small Ships

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This course is intended to cover the basic elements of marine propulsion, especially propellers and the selection of standard "segmental section", "off-the-shelf" propellers for boats and small ships. The nominal concentration is on planing and semi-planing boats, but this material is applicable to any sort of boat using commonly available propellers. This course is not about propeller design per se, but about selecting a propeller, essentially from a catalog.

There is a great deal of information available about propellers, and we can by no means cover all of it in this course. However, beyond the material presented here, I can answer specific questions in the forum or discussion sections of the course, or point you to other sources,so if you have any particular problems not covered in this handout, please ask, since that is the purpose of having this course on line instead of just reading an article.

Propeller matching is sometimes regarded as a black art, but like every other magic trick, it's just a matter of standard methods and practice. The ready availability of computers has made prop calculations easier than ever before. The characteristics of the propellers used on most small boats are relatively easy to calculate, either using a spreadsheet program such as Excel or Lotus 123 or with dedicated propeller software. As part of this course, you have been provided with a series of Excel spreadsheets and a dedicated resistance program to help do this, and part of the course will cover using these tools.

The most difficult part of selecting a propeller is predicting resistance, and resistance prediction is also a large subject. However, we will cover the basic aspects of resistance prediction for planing and semi-planing hulls for completeness. Fortunately, in most cases you will be working with an known hull, when you re-power an existing boat, prop up a standard hull, or replace an unsatisfactory propeller. If you are careful about gathering trial data, you can usually get a good resistance data. Getting good trial data and back calculating existing boats will also help you gain experience to deal with new designs.

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Propeller Anatomy

- Efficiency of Propulsion
- How Props Work
- Physical Characteristics
- Hydrodynamic Characteristics
- Hydrodynamic Equations
- Cavitation
- Hull Effects
- Advanced Prop Design

This course first discusses the basic elements of efficiency of propulsion of any type, not only marine propellers but any sort of propulsion other than rockets, since the basic principles apply to any sort of propulsion system that does not carry its own reaction mass.

Then the specifics of how a propeller works, will be discussed, and we will look at the physical characteristics of propellers, the hydrodynamic characteristics of propellers, and the equations or formulas needed to calculate specific aspects of propellers to allow us to predict their efficiency, thrust and so on.

The actual equations won't be derived in this course, due to the limited time, but some explanation will be give about where they come from and how they work. If you are interested in the derivations of the equations, please refer to the references.

Note especially that Saunders, *Hydrodynamics of Ship Design,* available from the Society of Naval Architects and Marine Engineers, or by interlibrary loan, is a very complete, and highly readable book, (actually three volumes) and though it is expensive, and perhaps a bit dated (written in the 50's) it presents a very good discussion and background, without too much mathematics, of virtually every aspect of hydrodynamics as might be applied to ships, yachts and even fish. This text probably represents at least a good beginning point for anyone seriously interested in understanding hydrodynamics of marine vehicles.

We will then discuss cavitation, the effects of the hull on the propeller and the propeller on the hull that have to be taken into account to select propellers, and then comment shortly on advanced propeller design so that you will have a bit of an idea of what sort of advances are potentially available for special problems.

Propeller Selection

- Engine - Prop Matching
- Strategy
- Computer Programs
- Resistance Calculation
- Trial Data
- Shaft Angle/Strut Drag/Clearance
- Vibration
- Nozzles
- Surface Piercing Props/Jets

The basic goal of selecting a propeller is to get the hull, engine and propeller matched to achieve the desired goals in terms of speed, possibly towline pull, thrust and engine loading. This requires some thinking about the overall mission of the boat, and understanding of how the propulsions system should perform overall, not only from an engineering standpoint but from an economic one as well.

There are many techniques for matching propellers, most developed prior to the use of computers, but we will discuss only two, which are related, and in fact, will only use one. The older techniques use various graphs and so forth, but the method implemented in the computer spreadsheets given here is the current standard, and probably the most accurate available, at least for standard type propellers.

We will discuss resistance calculation in enough detail to understand the problem in general and to use the two methods of resistance given that are specific to many small craft.

Most commonly, we will find ourselves working with existing vessels, either to correct problems, or to modify the equipment or service of a boat, such as when it is re-powered. This allows us to get the needed information on resistance by running trials, and then back-calculating resistance.

We will discuss the issue of shaft angle, strut drag, and clearance, and a bit about shaft and system vibration, since these often are part of the issue in problem props.

Finally, we will discuss the application of nozzles in props and quickly cover surface piercing propellers and water jets.

Efficiency

- Propulsion Works by Grabbing And Throwing Mass
- Thrust = m v - but - Energy = 1/2 m v^2
- Lowest Thrust per Pound of Water - Best Efficiency
- Output Velocity Greater than Zero is Wasted
- Efficiency Depends on Frontal Area
- Prop Ideal Efficiency Higher as Pitch Gets Higher - More Mass Flows Through - Thrust Load Goes Down
- Ideal Efficiency Based on Thrust/Speed, Area
- Device Efficiency - No Device Produces Thrust Perfectly
- Best Props Typically Produce 80% of Input Power As Water Flow - Best Jets Maybe 90%

In general, all propulsion works by throwing mass in the opposite direction you want to go, which, by Newton's law produces and equal and opposite reaction of you moving. The thrust you produce is the mass times the speed you throw it away.

(Note that pounds are units of force, not mass - the proper English units of mass are "slugs", which incidentally weigh about 32 pounds. A kilogram is also a mass, not a force. The metric unit of force is the Newton. Weight is the force a mass produces due to gravity, which is why it's confusing.)

All propulsion works this way; even when walking you are grabbing the earth with your feet and pushing it backwards away from you. However, the earth is so massive compared to you, only you seem to move. All propulsion, except rockets (which carry their reaction mass) also takes in mass from the environment, increases its speed to that of the vehicle, then a bit more, and throws it away.

Let's first consider a propeller as just a magic device that grabs and moves water, to see what we can learn without going into detail. To propel boats, we grab water and throw it aft. Thrust is mass times velocity, but the energy required to throw it is one half mass times velocity squared.   The more water we grab, the less thrust we need per pound of water so that we can throw it slower with less energy, producing more efficient propulsion. There are then two ways of grabbing a lot of mass, either by moving through the water fast, or by having a large area "scoop" or whatever, to grab it with.

The ratio of thrust to speed, area and water density is expressed as "thrust load coefficient", C_{tl}, which can be proven to determine the maximum or ideal efficiency η_i of any propulsor:
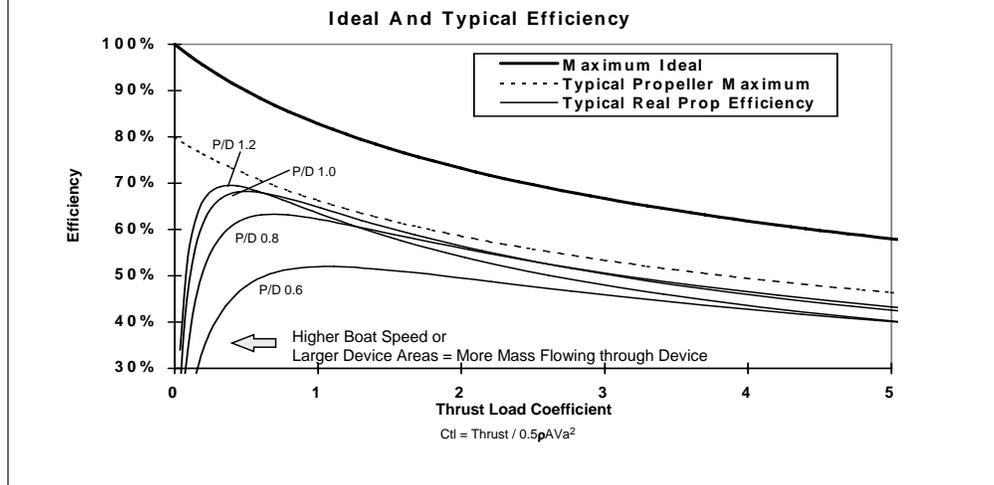
$$\eta_i = 2 / (1 + (C_{tl} + 1)1/2 \text{ with } C_{tl} = \text{Thrust} / 0.5 \, \rho \, A \, V_a^2$$

ρ, "rho", is water density, **A** is area, $\mathbf{V_a}$ is the speed of the device through the water.

Thrust load coefficient is simply the ratio of thrust to the weight of water that passes through the device per second times half the speed it passes through. Since no real device is perfect at accelerating water, real world efficiency is less that the ideal.

Thrust Load Diagram

● Thrust Load Is The Main Limit Of Efficiency

Ideal And Typical Efficiency

- Maximum Ideal
- Typical Propeller Maximum
- Typical Real Prop Efficiency

P/D 1.2
P/D 1.0
P/D 0.8
P/D 0.6

Higher Boat Speed or
Larger Device Areas = More Mass Flowing through Device

Thrust Load Coefficient

$Ctl = Thrust / 0.5\rho AVa^2$

This figure shows ideal efficiency plotted against thrust load factor with the actual efficiency of some typical props. The plot also has a constant line at 80% of ideal efficiency, which is the typical limit for propellers. This is sometimes called "device efficiency" and is the measure of how good a device is at moving water. Incidentally, this figure does not have anything about water in it, and applies equally well to air propellers, but air is much less dense than water, so ρ is small. There is nothing specific about propellers in this plot. It applies equally well to waterjets, oars, paddlewheels or any other forms of fluid propulsion (provided we can identify the area of the device. Some devices may have higher (water jets or some types of sculling hydrofoils - also known as "penguin propulsion" can be a bit higher) or lower (paddlewheels and oars have about 50%) device efficiencies, but we can calculate their approximate efficiency from this plot

This plot shows that thrust load factor is the most important factor for efficiency. The larger the propulsor, (and usually the slower it turns), and the faster it goes through the water, the better the efficiency, though there are other limits on diameter, not only practical limits such as draft, but secondary propeller effects that limit the efficiency of large props. The plot also shows this. If we don't accelerate the water at all, we spend no energy, but get no thrust. This is theoretically very high efficiency, but gets nothing, and since in reality, no device is perfect there is a limit to maximizing the area of the device.

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How Props Work

- A Prop is A Wing – Look At A Section Of A Blade:
- Flow Into Blade:
  Vector Sum V_a + RPM $* 2\pi r$
  (r is the local radius to the section)
- Wing Generates:
  Lift (Perpendicular To Flow)
  And Drag (Parallel To Flow)
- Lift, Drag Components
  Resolved Along Shaft
- Force Along Shaft: Thrust
- Moment Across Shaft: Torque
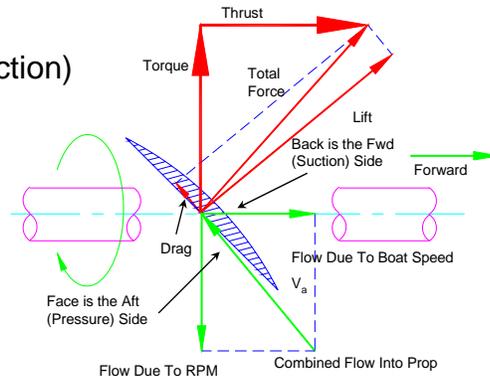
A propeller is several blades sticking out of a shaft, which rotates and moves forward with the boat. The combination of forward speed and rotation adds up at each section of a blade so that the blade is traveling diagonally across the shaft. Each blade is a wing that produces lift at right angles to the direction of water flowing into the blade and a much smaller drag backwards as shown above. These forces can be resolved as shown to those acting along and across the shaft. Thrust is the total force along the shaft from each section of each blade. The torque that's required to spin the shaft equals the total forces across the shaft from each section, times the radius from the sections to the shaft centerline.

Clearly, the angle of flow at each section is important to the relationship between torque and thrust. However, this angle varies from the hub to the tip, so it is easier to characterize the angles by the ratio of speed divided by rotational speed times diameter. This is called the advance ratio, J. J goes up as the boat moves faster relative to the RPM and goes down as shaft RPM goes up relative to boat speed.

The actual angle of the blade relative to the shaft is also very important, but this also varies, and so we have a different way of characterizing this angle as well, called pitch.

Slip is another sort of advance ratio, but it compares pitch and RPM to speed, instead of diameter and RPM to speed. Since most propeller data is based on pitch to diameter ratio, we could use either form of advance ratio, but standard practice happens to based on diametric advance ratio.

Propeller Characteristics

- Diameter D - Radius R = 1/2 Diameter
- Pitch - Stock Props Are Constant Pitch
- Blade Section
  - Segmental - Cheaper, Better For Cavitation
  - Airfoil Section
- Area - DAR, EAR, Projected Area
- Skew - Noise Control, Weedless, Cavitation
- Rake - Improve Shaft Inclination, Clearance
- Cup - Reduces Cavitation, Adds ~1" of Pitch

The important parameters that characterize a propeller are thus diameter, (and/or radius, half or the diameter), pitch, the type of blade section, the area of the blades, which can be expressed in various ways, the skew angle of the blades, the rake angle of the blades, and in the case of stock segmental props, the leading or trailing edge cup.

In this case, we are mainly dealing with constant pitch propellers with segmental sections, which are a slice of a circle. The face (the aft side, which produces pressure) is flat and the back (the forward side which produces suction) is a circular arc. This shape is reasonably efficient, backs down well, resists cavitation reasonably well, and is inexpensive to design and make. Other propellers can have airfoil or wing like sections, cambered (curved) wedges, or other shapes for special purposes. The "Troost" or Wageningen B series of propellers is commonly used for large ships and has partly airfoil sections, which slightly increase efficiency a bit, but are more susceptible to cavitation. (Note that some methods of propeller matching, using "Bp-δ" charts, are based on this series. The airfoil section slightly changes the lift and drag produced at a given angle to flow. As a result, these propellers act as if they had a little bit less pitch than the equivalent segmental propeller, so using "Bp-δ" charts with segmental propellers will tend to "overpitch" the propeller, and the engine may not make required RPM.)

One way to improve the cavitation performance of segmental propellers is to bend down the last inch or so of the trailing edge a few millimeters to form a slight radius of about 25-50 millimeter. This increases the effective pitch a small amount, and does so in the region of the pro not commonly subject to caviattion (cavitation is gnerally a problem toward the leading edge) and it also creates a pressure change at the trailing edge which tends to suck the cavitation bubble off the back and thus delay cavitation even a little bit more.

Many segmental propellers also have a little wedge ground out of the leading and trailing edge. A rounded edge will tend to produce vortices that alternatively form from the face and back. This alternation produces noise; "singing". By cutting the edge at a hard angle one way or the other, the vortices don't switch and this "anti-singing" edge eliminates the noise.

Pitch, Developed, Expanded & Projected Area

- Pitch: Blade Face Defined by a Helix Pitch is Distance Helix Advances in One Rotation (Tip Travel = $2\pi R$)
  - This Means: Angle Along Blade Face Increases As Sections Get Close to Hub
  - Section Angle Φ At Radius r From Shaft Tan Φ = Pitch / $2\pi r$
- Propellers Designed As Flat Surface: Expanded Area, A_E
- Propeller Wrapped Around Shaft: Developed Area, A_D
- Propeller View Down Shaft: Projected Area, A_P

Back

Expanded Area

Face

Developed Area

Pitch

Projected Area
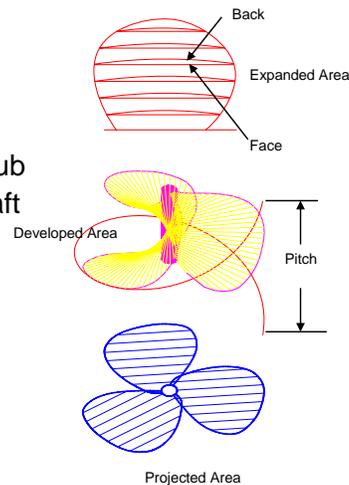
A standard propeller face is part of a helical surface, like the noses of treads on a spiral staircase. A helical surface is formed by a line that advances at a constant speed while it also rotates. Each line is spaced forward (or up in the figure above) uniformly. Each line also is uniformly rotated compared to the next one. This means that the distance along the shaft angle between an inner end of one line and the next inner one is the same, as is the distance between an outer end and the next outer one. However, the distance around the shaft (not the angle, but the distance), is small at the inner end and large at the outer end. Thus the angle between one end decreases as you go out from the shaft centerline, or increases as you go in. There is no single angle that characterizes the surface, but both ends travel the same distance forward, so we can characterize all angles by this distance, which is the pitch. The actual angle at any radius can then be easily calculated from the pitch and the radius. We can also look at the propeller "non-dimensionally", which allows us to scale the data from two similarly shaped propellers of different sizes by specifying the pitch to diameter ratio, P/D.

Since the angle of the water flow into the section is the sum of the speed of the prop through the water (which is constant with radius) and the speed of the blade around the shaft times the radius, (which increases away from the shaft centerline), the angle that the flow assumes into the sections varies in the same way and each section sees the desired "angle of attack" of flow into the section. Some ship propellers are designed taking into account the specific flow pattern at the stern, and have a pitch that changes from one radius to another, but this is rare in boats because such props are expensive to design and build. (This is "variable pitch". Propellers that can change pitch mechanically are called "controllable pitch".)

We can also characterize the area of the propeller is various ways:

The propeller blade is initially designed as a flat surface. The sections are drawn rotated into the paper. This view is the "expanded view", and the area is the expanded area, A_E. Wrapping the flat blades around the shaft results in a slight change of area to the "developed area" A_D. This is the actual area of the face in three dimensions. We can also look at the propeller end on and see its projected area, A_P.

Standard Propeller Drawing
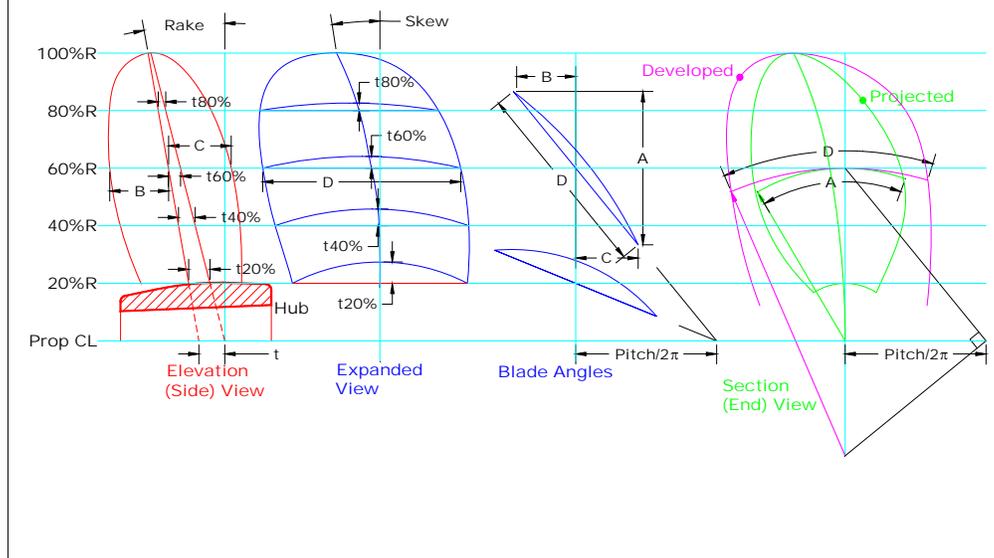
This is the standard layout for a propeller drawing. The drawing starts with the expanded view, which shows the sections and skew, or sweep back angle, of the blades. Skew make the propeller enter a given flow area less suddenly as it spins than if all of the sections were aligned. This reduces noise and change the loading along the blade. Skew can also be used to make "weedless" propellers. Typical stock propellers are skewed from zero to about fifteen degrees. Faster running propellers tend to need skew more than slow ones. More than about 15 degrees of skew or so greatly increases the bending load on the propeller, so highly skewed propellers are only used on submarines or cruise ships or other vessels where low noise is very important.

Since the surface moves the pitch distance forward when the propeller turns through a full circle (2π radians), the pitch angles are laid out by measuring the pitch divided by 2π along the center line and drawing a line from this point to each radius. Each section is laid out along the line, and the distances along (B and C) and across (A) the shaft are determined by projection. The elevation view shows the side view, including the blade thickness and the rake angle. Rake takes advantage of the fact that the flow into the propeller is slightly inwards. It also increases the clearance between the blade an the hull. Raked propellers are not common on small craft and tend to be more expensive to make. The blade thickness reduces away from the shaft center, so the nominal thickness is the thickness projected as if the blade went all the way to the centerline. The aft or trailing edge of the propeller is distance B aft of the face of the section, and the forward or leading edge is distance C forward.

The projected view is laid out by wrapping the distance along the shaft (A) in an arc around the shaft centerline. The radius of curvature of a helix is based on the radius at the section, and the pitch and is laid out by the intersection of the section line and a right angle back to the centerline as shown. The developed view is approximated by laying out distance D around this center. (A helicoidal surface is warped, and like any other double curved surface can't actually be exactly laid out flat without some distortion, but this approximation is accurate enough for most propellers. It is less accurate for very wide blades and very high pitch to diameter ratios.)

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More Propeller Parameters

- Z - Number of Blades
- Disk Area, $A_0 = \pi D^2/4 = \pi R^2$
- Expanded Area Ratio, $EAR = A_E / A_0$
  - $EAR \sim 0.34 * DAR * (2.75 (DAR / Z)$
- Developed Area Ratio, $DAR = A_D / A_0$
- Projected Area Ratio, $PAR = A_P / A_0$
- Blade Thickness Ratio = $t_{(at\ CL)} / D$ (see elevation view)
- Blade Width Ratio = Maximum Blade Width / D
- Mean Width Ratio = Average Blade Width / D

The number of blades is another parameter, and because N is revolution rate, Z is used for this. More blades produce a smoother thrust, increase thrust and reduce cavitation, but tend to reduce efficiency.

As discussed above, the various areas characterize the propeller as well. All of these areas can be non-dimensionalized for using at the desired scale by dividing by the propeller disk area. Typical ranges of DAR or EAR are from about 30% to 80% for most propellers, with some two blade props at 30% and some five blade props over 80%. (Manufacturers generally give DAR.) Note that EAR and DAR are two different things, and there is an approximate conversion formula. though they are generally very close to each other numerically. If you actually look at the conversion for typical stock propellers, the difference is only a few percent. Increasing DAR or EAR reduces efficiency a bit, but reduces cavitation a lot, so high powered props generally have high DAR/EAR. These props also have more metal and hence are more expensive. Very high DAR/EAR can be appropriate for some heavily loaded props, but they can get very expensive because the blades overlap and are difficult to cast and machine.

The maximum width ratio also characterizes the blade shape, as does the mean (or average) width ratio. Obviously the mean width ratio, times the length of the blade, is the blade area, and that times the number of blades is the expanded area. In terms of appearance, low EAR / DAR blades look like a rabbits ear's, but high EAR/DAR props look like Mickey Mouse's ears.

Likewise, the thickness can be non-dimensionalized for using at the desired scale by dividing by the propeller diameter.

Propeller quality - tolerance on uniformity of pitch and other dimensions is a final characteristic. Props generally are manufactured to either ISO 484 or an informal but widely used US standard. ISO props come in grade 3, 2, 1 and S with 3 being the worst and S being the best. The informal US standard is approximately equivalent to ISO 2, and generally provides satisfactory performance for boats up to about 25 knots or so.

Prop Hydrodynamic Equations I

- Thrust Coefficient:
  - K_t = Thrust / $\rho\, D^4\, n^2$
- Torque Coefficient:
  - K_q = Torque / $\rho\, D^5\, n^2$
- Advance Ratio:
  - $J = V_a$ / n D
- Cavitation Numbers
  - $\sigma_{0.7r} = P_t$ / $(^1/_2\, \rho\, (V_a^2 + (0.7\, \pi\, n\, D)^2)$
  - τ_{crit} = Thrust / $(^1/_2\, A_p (V_a^2 + (0.7\, \pi\, n\, D)^2)$
- Propeller Efficiency (Measured in Open Water)
  - $\eta_o = (J/2\pi)\ (K_t\ /\ K_q)$

Symbols (English Units)

|	
ρ	Water Density, 1.9905 Ft-Lbs/s
D	Propeller Diameter, Ft
n	Propeller Rev/Sec
V_a	Prop Speed of Advance, Ft/s
P_t	Vapor Pressure At Prop, Lbs/Ft² (2373 + 64 * Hub Submergence, Ft)
A_p	Projected Prop Area, Ft²
$\sigma_{0.7r}$	Cavitation Number @ 70% r
τ_{crit}	Critical Thrust Coefficient

It is possible to calculate the flow over the propeller surface directly with very sophisticated computer programs, but most boat propellers are basically similar, so you can use test data instead.

You can test a propeller in a water tunnel at different combinations of water and shaft speeds, measuring torque, thrust and efficiency as a function of advance ratio, J. The "thrust coefficient" (Kt) is the ratio of thrust to shaft speed, diameter and water density. "Torque coefficient" (Kq) is a similar ratio for torque. Both these factors vary with advance ratio and depend on the prop characteristics, but the tests allow us to plot them or fit them to statistical calculations. Once we know the thrust or torque coefficient for a given J, we can then calculate the thrust produced by the prop or the torque required to spin it at a certain speed. (Torque or thrust is just the coefficient times the factors in the denominator.)

Cavitation number is based on the ratio of the water pressure at the propeller hub to the characteristic pressure produced by the speed of water. Various speeds are used, but in this case, we will use the speed at the section 70% of the radius away from the shaft centerline, since this is often considered to represent the "average" conditions on the propeller. Remember that this speed is the sum of the forward speed and the speed due to the revolution of the prop. We can develop another cavitation related measure based on the thrust the propeller is producing divided by the projected area times the characteristic pressure due to speed. Since thrust divide by area is a pressure this will help us to determine limits of thrust based on cavitation.

Efficiency is the ratio of thrust and speed to torque, so it is determined by Kt, Kq and J. Efficiency, Kt, and Kq are usually plotted against J for a range of pitches for one style propeller.   Note again that theses ratios are non-dimensional. These ratios are used instead of actual RPM, speed, thrust and torque so that they are easily scaled to whatever size and speed prop is required.

J-Kt-Kq Diagram

Segmental Propeller, 4 Blade, 0.75 EAR
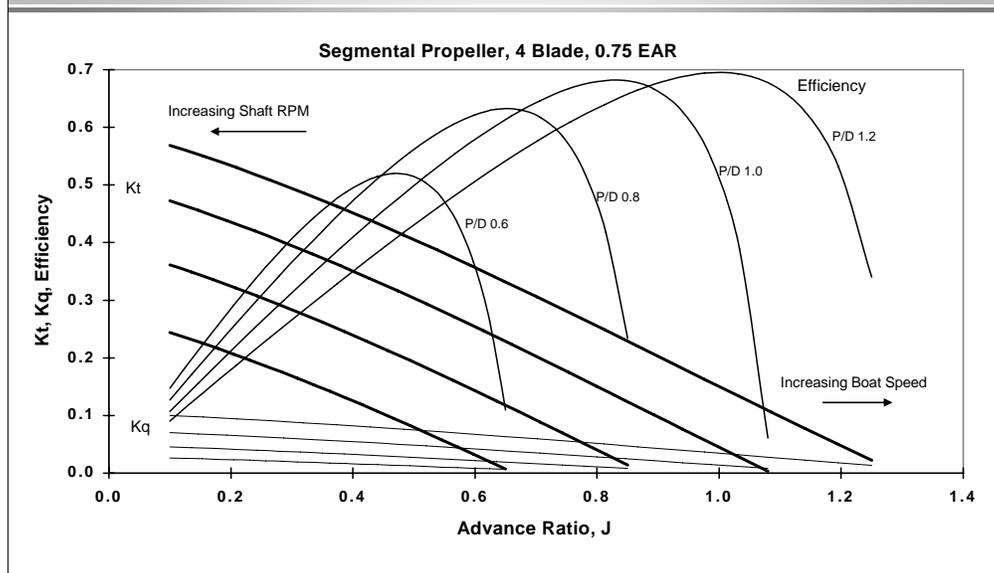
Two systematic series of propeller tests, the Gawn-Burrill and Newton-Rader systematic series, were run in the Fifties to determine the characteristics of typical boat propellers. This data is widely used to determine propeller coefficients without actually running tests. These tests define propellers by the number of blades (Z), pitch divided by diameter (P/D), and the expanded area ratio (EAR). These propellers all have segmental sections and small skew. This is a standard plot using data from a statistical fit to these series, and these plots were used to match props prior to computer methods.

Look at this plot in detail. First, note that both the torque (Kt) and thrust (Kq) coefficient decrease as the advance ratio (J) increases. This is why failure to make speed is a problem. If you selected a prop expecting a certain speed, and got less, the advance ratio is lower and the torque coefficient is higher, so the shaft needs more torque to spin at the rated speed.

The plot also shows that the efficiency of a propeller increases steadily as advance ratio increases until efficiency reaches a peak and then falls off radically. The increase of efficiency is due to the increased speed of the propeller through the water compared to the speed of outflow from the prop - reduced thrust load producing a higher ideal efficiency. For the same reason, higher pitch propellers have a higher peak efficiency, occurring at a higher advance ratio. The fall off occurs because the angle of the flow at each section is no longer enough to produce efficient lift.

However, for a given advance ratio, the efficiency of a lower pitch prop is better. This is because the blades of a lower pitch prop are twisted more perpendicular to the shaft so that the lift is pointed more along, and less across, the shaft, giving more thrust for less torque.

Finally, note that the range of best efficiency is fairly narrow. If you operate a prop at the wrong advance ratio, you will waste a lot of power. You can easily be forced to use an inefficient propeller by a limited prop diameter or a low gear ratio. If you are re-powering a boat, make sure that you can fit in a good prop before you take the job.

Prop Hydrodynamic Equations II

- Thrust Coefficient (Fit To Test Data)
  - $K_t = \Sigma\, C_{Ti}\, J^{si}\, P/D^{ti}\, EAR^{ui}\, Z^{vi}$
- Torque Coefficient (Fit To Test Data)
  - $K_Q = \Sigma\, C_{Qi}\, J^{si}\, P/D^{ti}\, EAR^{ui}\, Z^{vi}$
- Blount - Fox Thrust Criteria:
  - $K_t / J^2 = R_T / (\rho\, D^2\, v_a^2)$ - This is a method to find RPM if you know resistance, speed and diameter - the equation eliminates RPM. You calculate curves of efficiency, etc. by K_t / J^2 and can then optimize them and pick the point where you get the right K_t / J^2, then calculate required RPM from J. Similar equations can be developed to find any other factor.
- Square of Velocity at 70% r
  - $v_{0.7r} = (J^2 + 4.84 / J^2)\, v^2$

The obvious question is where to get the thrust and torque coefficients if we can't do propeller tests.

There are several sets of data based on statistical analyses of many tests. Each of these sets has been fit to a very messy pair of equations by extensive computer analysis. The equations say that the coefficient is the sum of up to 47 terms. Each term is an arbitrary constant times advance ratio, J, to an arbitrary power, times pitch to diameter ratio, P/D, to another arbitrary power, times EAR to a third arbitrary power, times Z to a fourth arbitrary power. There is a different equation for Kt and Kq, and different tables of constants and powers for different types of propellers. Though these equations are very messy, they don't have to be algebraically manipulated in any way. You only have to plug in your J, P/D, EAR and Z, multiply and add. This would be quite tedious by hand, but it's a snap on a computer, even with a spreadsheet. Incidentally, the equations are a statistical fit to data and don't necessarily make sense on their own, or outside the range of data that was used to develop them. It is interesting to enter nonsense such as one or zero bladed propellers or negative pitch ratios and see what comes out, but this is a reminder that the equations are not valid outside of the data that was used to generate them.

Another equation that is frequently useful, though not used in this course, is the Blount-Fox thrust criteria. This is produced by dividing thrust coefficient by J squared and substituting and simplifying. The result is a coefficient that can also be produced by dividing thrust by density, diameter and speed. The merits of this coefficient is that RPM doesn't enter the equation, so that you can determine some propeller factors before you know RPM, then solve for RPM. Blount and Fox produced charts of this factor for typical small craft propellers, to reduce the effort of hand calculations and it remains a useful technique for early design, and solving some specific problems. However, the speed of computer methods allows you to "beat the problem to death" by just guessing at RPMs repeatedly using the standard equations.

Another factor, the square of velocity at 70% radius (which is used in the cavitation equations) can also be determined in terms of J alone (the resulting number is the same). This appears in some methods, and though not used in this course is included for completeness.

Cavitation

- Boiling Water - Not Air Entrainment
- High Tip Speed And Loading (Too Much Suction)
- Causes Thrust & Torque Breakdown, Damage
  - Bubbles Collapse Against Blade, Rudder, Hull,
- To Prevent Cavitation:
  - Increase Area - More Blades, Bigger Blades (High DAR)
  - Cupping, Blunt Trailing Edge Sucks Bubble Off Blade
  - Cupped Leading Edge Forms A Shock Free Entry
  - Special Sections, Usually With Maximum Thickness Well Aft
- Supercavitating Props - Form A Stable Bubble

A common problem that comes up is cavitation. When the propeller tries to create too much lift for its area, the vacuum on the back (forward) side of the blade is so intense that the water boils. The resulting pockets of steam cause loss of the suction that provides lift, and therefore loss of efficiency, though the prop still produces thrust. Worse, the pockets of steam collapse back into liquid when they reach areas of higher pressure, and the water rushing in to fill the void they leave creates an implosive impact that can damage the propeller or underwater components downstream. You can often hear cavitation by listening to the hull plating near the propeller. It sounds like the boat is running in gravel. Cavitation produces a pitting on the propeller as well, generally on the forward side or face near the leading edge. Sometimes a small portion of the prop at a constant radius will show cavitation damage. This may be due to something in front of the prop changing the flow into it. Look forward for things like scoops or poorly faired struts, and fair them in.
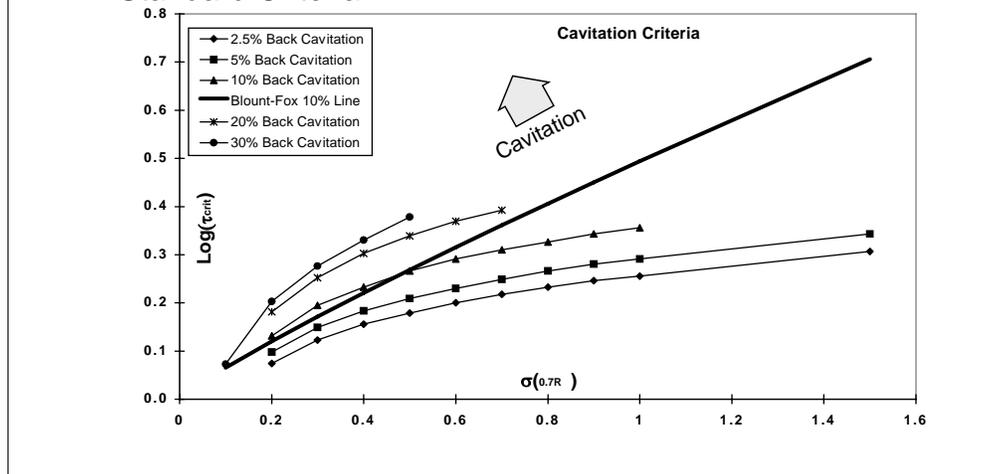
The normal standard for cavitation is when no more than ten percent of the back of the blade is covered in vapor bubbles. This limit is represented as another standard equation, developed by Blount and Fox.

To avoid cavitation, first reduce the RPM of the prop. This requires higher pitch and perhaps a different gear ratio. Reduced RPM may also require a propeller too large to fit under the boat. In this case, increase the loaded area of the propeller by increasing blade area ratio or the number of blades. Finally, cupping acts like increased pitch, but also acts to suck the cavitation bubble off the back of the blade. You may be able to cup a propeller instead of ordering a new one if you are close in pitch or marginal in cavitation. There is limited data on cupping but MacPherson has some data that suggests that a cupped prop can be assumed to absorb torque and produce thrust like it was cupped but to cavitate as if the cup was not present. The spreadsheet includes this estimate of cup effects - run the case with cup to get thrust and torque and without to determine the level of cavitation.

Cavitation is not the same as "ventilation", which is ingestion of air. Ventilation causes reduced efficiency, but not damage. Props also continue to produce thrust when ventilating and surface piercing props are intentionally designed to ventilate. High speed service may require fully cavitating or ventilating props. Special methods have to be used for these conditions.

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Standard Cavitation Diagram

- Plot $\sigma_{0.7r}$ Versus Log(τ_{crit}) and Compare Against Standard Criteria

The standard criteria for small ship and boat (especially planing boat) cavitation was also developed by Blount and Fox based on the GAWN and Newton Rader data.

The light lines show various percentages (in terms of area covered by bubbles) of back cavitation. The two axes are the cavitation number at 70% radius and the log of the critical thrust factor. The dark line is a linear fit to roughly ten percent back cavitation, which is the level at which cavitation is considered to begin to be important. This line is when:

$$\tau_c = 0.494 \, \sigma_{0.7R}^{0.88}$$

Once τ_c exceeds this factor, the propeller will be seriously cavitating, and you may have to take steps to fix the problem. In general, these steps will be to increase the DAR/EAR or to decrease the speed of the blades, which might require increasing the pitch.

There are several other cavitation related factors, notably the thrust and torque for fully cavitating conditions. These are coded on the spreadsheets, but are not really worth discussing. Note that this is a standard simple method for evaluating cavitation. More sophisticated methods, including model tests and direct simulation with very sophisticated computer programs are available when appropriate, but these methods are beyond the scope of this course and should be referred to specialists in propeller design.

It is also worth noting that there are tables/formulas for performance of cavitating standard propellers, but again, the goal is to avoid cavitating conditions.

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Wake Fraction And Thrust Deduction
Hull Affects Prop - Prop Affects Hull

- Wake Fraction - $1-W_t$: Slower Flow Into Prop Due To Hull
  - 6^0 Shaft: Semi-Planing & Planing 100% - 96%,
  - 12^0 Shaft: Semi-Planing & Planing 97% - 95%,
  - Slow Displacement - Twin Screws: 90%, Single: 80%
  - Outboards, Outdrives: 97%
- Thrust Deduction - $1-t$: Lost Prop Thrust: Hull, Rudder
  - 6^0 Shaft: Semi-Planing & Planing 98%-99%,
  - 12^0 Shaft: Semi-Planing & Planing 98% - 99%,
  - Slow Displacement - Twin Screws: 92%, Single: 85%
  - Outboards, Outdrives: 100%
  - Both Depend On How Much Hull In Front Of Prop, Rudder

Most propellers operate behind the hull of a boat, but standard thrust and torque tests are run with the propellers operating in clear water in a tunnel. (The mechanism supporting and turning the propeller is behind it.) You have to correct for the effect of the hull on the propeller. The hull slows down the water entering the prop. The percentage the boat slows down the water is called "wake fraction". Typical planing and semi-planing boats have a wake fraction less than 5%, so a boat may be going 20 knots, but the propeller seems to go a bit over 19 knots. The water near the boat is being dragged along at about one knot. Strictly speaking, there two wake fractions, one for thrust and one for torque, but these two factors are generally quite close, so you can usually assume they are the same.

The suction of the propeller also adds drag to the boat hull so it doesn't really produce as much useful thrust as it would in a water tunnel test. This is called "thrust deduction", and is also about 5% for planing boats. Both factors depend on shaft angle.

Some hulls also make the flow into the propeller rotate. This makes the propeller acts as if it was spinning slower or faster and is called "relative rotational efficiency". There are even devices that do this intentionally to improve efficiency, especially for large ships, but in most boat hulls, this factor is unity.

There is no one simple method of estimating wake fraction and thrust deduction for all hulls but there are estimating techniques and typical data available for most boat types. These factors are best found from trials data. Even if you are not exact, the trial data will tend to cancel out the effects.

For a first cut, you can use 10%-20% for wake fraction and thrust deduction for most displacement type hulls like trawler yachts or sailboats with the propeller in a cutout in the keel, 10% for sailboats with fin keels and a prop on a strut and 0%-5% for most planing boats. Multiply the speed by one minus the wake fraction. This is the "velocity of approach", Va, the speed the prop actually sees. It is also worth checking to see how much difference it makes, by checking a range of values.

Hull Efficiency, Relative Rotational Efficiency, Quasi-Propulsive Efficiency

- Hull Efficiency: $\eta_h = \eta_r (1-t) / (1-W_t)$
  - Boat Uses Power Based On Boat Speed, V
    Non-Propelled Resistance, R_T(With Appendages, Air)
  - Prop Produces Power Based On $V_a=(1-w)V$
    Prop Produces Thrust Based On $T = R_T / (1-t)$
- Relative Rotational Efficiency: η_r
  - Due to Swirl Into Prop
  - Typically Small: 101% - 97%,
- Quasi Propulsive Efficiency: $\eta_D = \eta_o \eta_r (1-t) / (1-W_t)$
  - η_D =EHP / Delivered HP = $(R_T V / T V_a) * \eta_o \eta_r$
  - May or May Not Include Gearset, Shaft Losses (~3%)

Since "hull efficiency" and other terms are frequently used, it's important to understand them. The effect of the propeller in slowing down flow into the propeller acts to reduce the power the propeller puts out because power is force times speed. However, if the propeller has to produce extra thrust (because of thrust deduction) to push the boat through the water, this is a loss. Finally if the flow around the hull acts in some way to change the propeller efficiency there are more potential losses or gains. In one way, these factors might be considered an accounting issue, since all of these factors come from the effort to predict power requirements from model tests run in specific standardized ways.

Unfortunately, there is no source for small scale water. You have to use regular water, and its viscosity (stickiness) is proportionately larger than it would be at full scale. Thus effects due to viscosity are larger at small scale, and they have to be corrected for by subtracting out calculated small scale viscous effects (mainly skin friction) and then adding back calculated large scale effects. The result of this is that the force to move a full size vessel that weighs say 100,000 pounds is less than 1000 times that of a model that weighs 100 pounds. Traditionally, initial resistance model tests are run unpowered, and also often without appendages like struts and shafts. Sometimes actual measurements of flow velocities in the propeller area are made during these tests to help determine wake fraction. If a series of self-propelled tests is run, the model is also pulled to make up the additional drag caused by small scale and the scale speed of the propeller is noted. The various thrust deductions, wake fractions and so on are then determined from the various scaling adjustments to this process, and these interaction factors essentially get the books to balance out.

Thus we have a "hull efficiency" that expresses the effect of wake fraction and thrust deduction on the efficiency of propulsion, and then a quasi-propulsive efficiency that takes into account everything except bearing and gear losses (sometimes – sometimes they are included – make sure you know what is meant - the difference is about 3%). For most boats, this is about 55% of less, so ultimately, you have to buy about twice the engine as the hull alone requires with perfect propulsion.

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Advanced Prop Design

- Use Of Advanced Sections
  - Cavitation Resistance Is Most Common Goal
  - High Lift Sections Adapted From Modern Wings
- Wake Adapted
  - Adjust Radial Pitch to Match Inflow
    - Improved Cavitation Characteristics, Efficiency
    - Common Strategy for Outboard Engines
  - Circumferential Variations Cause Problems
- Relative Rotational Efficiency Devices
  - Reaction Fins - Proven on 41 UT
  - Grimm Wheels

Though this course is not about advanced prop design, it is worth knowing what can be done by experts with sophisticated computer programs and possibly model tests.

The most common problem is to get an effective propeller on a boat that is too fast, or too heavily loaded for the feasible propeller diameter, so that cavitation is a problem. This problem can be attacked through refinements of the section. "Barn roof" sections are designed to have a suction distribution that comes up to the maximum possible value that can be sustained without cavitation and then remains at this value until the pressure is dropped suddenly near the trailing edge. (The term "barn roof" refers to this pressure distribution, not the section shape itself. They were originally developed for short take off aircraft which have to delay stalling, a problem somewhat similar to cavitation.) These sections generally have a carefully rounded nose, their maximum thickness well aft and a reverse turn in the back surface. Though these sections are highly resistant to cavitation, they are not as efficient as some other sections. There are also other tricks with skew, variable rake and other things (including holes through the blade) that can help as well. These propellers can look very peculiar.

Wake adapted propellers use the fact that the flow into a propeller is generally not uniform, due to the effect of the hull. Unfortunately, a propeller blade has to rotate all the way around the shaft, so it can't specifically adapted to a certain area, but none the less, there is some possible advantage to changing the pitch close to the hub compared to the tips based on the field of flow. This type of adaptation works best in the flow around a big bossing on a single screw, so wake adapted propellers are very common on large ships, but there may occasionally be advantages for wake adaption, particularly on large hubs behind big objects, such as outboards or I/O legs.

A final strategy is to take advantage of the rotational flow due to the prop and extract the energy remaining in the swirl. The Volvo Penta DuoProp is just such a device. Small fins that cause the flow into the prop to swirl in the opposite direction also can work sometimes, and a device called a Grimm wheel is an extra unpowered propeller that is spun by the swirl left in by the powered one.

Engine - Prop Matching

- Thrust Must Equal Drag
- Engine Torque Equals Shaft Torque
- Engine Speeds/Slows to Match Torque
- Boat Speeds/Slows to Match Thrust
- Power Reduced If Prop Can't Make Turns
- J Increase, Torque Increases, Engine Slows Further
- Major Problems - Wasted Power, Damaged Engines - Particularly With Turbochargers

The engine and gear produce torque that spins the shaft. The propeller spins and produces thrust, which overcomes drag to produce speed.   Available engine torque depends on the engine, fuel flow, gear ratio, and engine RPM. Required propeller torque depends on RPM, propeller design, and boat speed. Drag depends on hull characteristics and speed.

If the engine provides more torque than the propeller absorbs, the shaft speed will try to increase. This will produce more thrust and the boat will speed up. An equilibrium will be achieved between torque, thrust, drag and speed at a higher speed unless the governor on the engine prevents increased RPM. If the RPM can't increase, the boat can't reach the full speed potential of the engine and is "underwheeled". You may not want to accept this condition because it doesn't produce the deseired speed, but it is not harmful.

Conversely, if the engine is unable to provide enough torque to turn the propeller, the shaft slows down, and thrust and speed drop, again to equilibrium. However, this "overwheeled" condition won't allow the engine to achieve full RPM and power, so the engine may smoke and lug and eventually suffer damage. This is especially a problem with turbocharged engines because they depend on aiir flow to cool the heads, and in the long run can be damaged by lugging.

Note also that we need to know the engine characteristics as well. The amount of either power or torque available varies with RPM. The data for a specific engine is generally available from the manufacturer. However, read the rating conditions carefully for an engine as well. The full power or RPM may not be available for more than a short time, for example.

Matching a propeller, gear and engine means that the equilibrium between the available engine torque and the required propeller torque will not overload the engine and that the thrust required to make speed is available throughout the range of operation

Strategy

- Full Load Vs Part Load
- Range/Efficiency Vs Top Speed
- Getting Onto Plane/Top Speed
- Mixed Service
  - Towing, Trawling, Special Cases
- Speed Vs Towing Power
  - Economic Analysis
  - Probabilistic Voyage Simulation May Be Required For Fishing or Towing

A boat is not generally just required to make top speed on trials day. The owner will generally want a long-lived, fuel efficient match to some specific mission profile (even if he doesn't know it). It is important to fully understand the required mission for a boat before deciding how to prop it. Often range or fuel efficiency may be better with some prop other than the one that gives the highest top speed. A common case for recreational boats is a good "hole shot" prop, for skiboats. A prop that works best at top end may require everything an engine has to accelerate because it is overloading the engine at lower speeds. The boat thus will accelerate slowly and not be as useful for waterskiing. A prop that is sized differently will have more low speed thrust by letting the engine run up more but won't have as high a top speed.

Boats that tow fishing gear or other vessels require some additional thought, because there is generally a conflict between towing performance and top speed. A fishing vessel may need to get to and from the ground quickly, but then tow well. Rescue vessels have to get on site very quickly, and often execute a long difficult tow. Sailing yachts need to balance good speed and possibly range under power with the possible need to power into a heavy blow and to maneuver smartly in confined spaces. This also has to be balanced against the loss of speed under sail. Dinner cruise vessels usually don't need lots of speed, but do need plenty of thrust to dock in a bad blow.

In the case of commercial vessels, you need to be ready to do at least simple economic studies, such as how much fuel savings is required to pay off a loan to buy a new prop, and spreadsheet programs offer numerous financial calculation tools to do theses studies.

The most sophisticated tool for such studies are probably voyage simulation studies. These are programs that essentially do simple simulations of a voyage, but have randomizers to vary weather, fishing conditions or whatever. They are run hundreds of time to determine the average, best and worse possibilities, and are used to evaluate the economic (or military) effectiveness of just such features as propeller choice. (Or sailing yacht designs in the America's Cup.)

The bottom line is that prop matching requires judgment as well as just calculation.

Propeller Computer Programs

- ● Statistical Fit to Prop Series Model Tests
  - • B-Series - Van Oossanen, (In New PNA)
  - • Commercial - Blount & Hubble, SNAME Props '81
    - • P/D 0.6-2.0, EAR 0.51-1.18, Z =3, 4, and
    - • Cavitation Limits Only
  - • Commercial - Radojcic, SNAME Props '88
    - • P/D 0.6-2.0, EAR 0.51-1.18, Z = 3 Only
    - • Both Cav & Non-Cav Performance Through Full Range
- ● Lifting Line, Lifting Surface, Etc. Methods
  - • Required for Exotic Props or Special Cases
  - • Not Needed For Stock Props

Slide 13 presented the basic equations for the various statistical fits to propeller series. Conventional "Troost" or Wageningen B series merchant ship propellers were fit by van Oossanen, who developed the basic form of the equation in 1975. The Troost data includes 2 - 7 blades, and is thus the only data useful for two blade sailboat propellers, even though the data is strictly speaking not for typical boat propellers. Auxiliary sailboat props should probably be matched to allow full thrust at zero speed to allow good maneuvering characteristics. (There is a spreadsheet with Troost coefficients in the course material as well as the Blount/Hubble one.) This requirement, combined with the relative inaccuracy of such small props, means that as long as the designer leaves a bit in his pocket for extra torque, using this data is probably acceptable. Unfortunately, as discussed before, this data is a bit off for use in most powerboat applications.

In 1981 Blount and Hubble used Newton-Rader and GAWN series data, with other single props that had been tested by the Navy to develop a table of coefficients for typical small craft propellers using the same van Oossanen equation and approach. This series can be considered valid for pitch/diameter ratios of 0.6 top 2.0, EARs of .5 to 1.18 and 3 to 5 blades, so they represent a reasonable range of stock propellers, and this is the series used for the course work.

Radojcic (Propellers'88) has fit a coefficients through the full range of cavitating and non-cavitating data for segmental props, but unfortunately, only for three blade props, which would not generally be chosen for intentional operation in a cavitating environment, so this is of relatively little practical use, especially since props intentionally operated in cavitating condition would also be specially designed, however, the "fastprop" sheet uses this data, which is mainly appropriate for some outboards.

There are very special programs (Computational Fluid Dynamics, CFD programs) that actually calculate the flow over the prop in more or less detail. These are called lifting line or lifting surface methods, and are very useful for special cases, but require extensive special training to use. One such program (as well as consulting services) is available from Oceanic Consulting, in Newfoundland – go to their website.

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Resistance Prediction

- Model Tests Give Best Data
- Most Systems Based on Statistical Fits
  - Mercier, Compton, UBC, Sui Fung, Etc.
- Physical Approximations + Statistical Corr'ns
  - Savitsky, Simple Wave Theories (Holtrop)
- CFD - Dawson Codes, Hybrid Codes
  - Direct Computer Simulation of Flow
  - Not Ready For Prime Time - Good For Optimization
  - Noblesse Work at NSWCCD (SNAME Transactions, 2001)
- Weight Is Single Most Important Problem
  - Run Analyses To Determine Weight Limits For Speed

If you have a completely new vessel, the first part of the problem is to calculate the resistance. This course is not about resistance calculation, but there are a couple of useful methods that we can cover. The best way to get resistance is through careful model tests, but these have to be run in a specific way. Boat resistance is due to three basic effects, the skin friction of the water sliding on the surface, the eddying and so on of water as it bases around a shape, and the generation of surface waves. Each of these factor scales somewhat differently as discussed above. Conventionally, the model resistance is divided into friction resistance, which depend on Reynold's number and residuary resistance, which combines wave and eddying resistance and depends on Froude number. The frictional resistance for a range of Reynold's numbers has been determined by towing thin planks on edge (and many validation studies). We then measure the total resistance of a scale model, subtract the skin friction at model scale, multiply by the ratio of weight, then calculate the skin friction at full scale and add it back.

Most pure calculation methods also follow this same scheme, in that they usually only predict the residuary resistance. Probably the main reason for this is that most methods are at least partly based on some sort of fit to residuary resistance data from model tests. The methods of Mercier, Compton, UBC, Sui Fung, and many others are just fits to a large number of systematically varied craft designs, using various parameters of shape. You have a Mercier spreadsheet, which uses weight to length ratio, beam to weight ratio, entrance angle, and midships to transom cross section ratio, to various combinations and powers to predict the resistance of a 100,00 lb boat, which is then rescaled to the correct size as above. The classic Savitsky and Holtrop methods combine more rigorous physical calculations with some statistical corrections. Holtrop is intended mainly for large displacement craft, and is not given here. Savitsky is the preferred method for planing craft. You have been given two versions of this, a spreadsheet and a free-standing program. The latter works very well and has been widely used for many matches, by many designers. The spreadsheet is offered if you are interested in the specifics of the method.

There are steadily improving programs (again CFD) that actually simulate the flow of fluid around the hull in various ways. Theses are called "Dawson codes" or "RANS codes" and are extremely valuable for optimizing shape. Noblesse used a "simple" (to him, maybe) code that does not accurately predict resistance, but accurately predicts which hull has the minimum resistance, and the relative ratios. This program also optimizes shape to minimize resistance. There are also codes for planing craft that use "Zarnick Entering Wedge Theory" to predict resistance, but is most important for predicting motions in waves. However, these codes must be run by specialists.

More Hydrodynamic Equations

- Effective Horsepower, EHP (Without Propeller Effects)
  - $P_{e \text{ (US Horsepower)}} = \text{Resistance}_{Lbs} * \text{Speed}_{knots} / 326$
  - $P_{e \text{ (Metric)}} = \text{Resistance}_{Newtons} * \text{Speed}_{m/s} / 1{,}000 = KW$
- Shaft Horsepower = $\text{Torque}_{Ft\text{-}Lbs} * RPM / 33{,}000$
  - Delivered = Power at Prop (With Bearing, Gear Losses)
  - Brake = Power at Engine Output
- Froude & Reynold's Number, Etc.
  - $F_{vol} = V / (g\nabla^{1/3})^{1/2}$ (∇ is displacement in cubic ft or m.)
  - $R_e = V * L / \nu$: (ν, kinematic viscosity, $1.2791*10^{-5}$ ft^2/s)
  - ITTC Skin Friction: $C_{f\ ITTC} = 0.075 / (\log_{10} R_e - 2)^2$
  - $R_{total} = R_{bh}$ (bare hull) + R_{app} (appendage)
  - $R_{app} = R_{bh} (1/\eta_a - 1)$; $\eta_a = 1 / (0.005 F_\nabla^2 + 1.05)$

Resistance brings up a few more equations that may be of interest. Note that, like the others, these are already built into the spreadsheets you have been given. (It may be interesting to look for them.)

Effective horsepower is the power absorbed by moving the boat, presumably with a perfect propulsor. Power is just speed times force, and the equations above just handle various unit conversions.

Shaft horsepower is similar, though the speed is not RPM, but the feet per second that a point at a one foot radius travels around the shaft (so there is a 2π built into that 33,000). Delivered power is at the prop taper, hence after the losses for bearings and gears are taken out. Brake is at the engine flywheel before gear losses (remember when looking at engine ratings to also check for conditions of fuel, air, temperature, what devices are attached like alternators, and so on).

Froude's number relates speed to gravitational effects and scales wavemaking in proportion to size. Note that the cube root of volumetric displacement, ∇, is a length unit. Displacement boats usually use length on the waterline instead, but the length of a planing boat is hard to determine, so Volumetric Froude Number is often used for planing craft. Beam Froude Number is sometimes used as well.

Reynold's number scales inertial effects to the viscosity of water, and is the basis for calculating skin friction. The current standard for friction is the "International Towing Tank Conference" line. This produces a frictional coeffiecient, which is added to the residuary coefficient, and possibly a "correlation allowance", basically a fudge factor, so:

$C_{total} = C_{friction} + C_{residuary} + C_{allowance}$ and $R = C_{total} * \rho/2 * \text{Wetted Surface} * V(\text{in ft/s})^2$

Depending on the method, this might be without without appendages, like struts and rudders, and usualy doesn't include air resistance. The additional drag of appendages can be calculated for each item, but Blount and Fox have given an approximate value for typical fast craft as shown above.

Trial Data

- Back Calculation Procedure Is Best Matching Technique
- Many Factors Won't Change
- Measure Horsepower If Possible
  - Strain Gauges On Shaft
  - Fuel Flow (Remember To Correct For Temperature)
  - Ensure Good Engine Conditions, Especially Air
- Check Prop, Right Pitch, Damage - Blunt Edges, Etc.
- Record Boat Weight, Longitudinal Centers
  - Freeboard Readings Along Length + Hydrostatic Tables
- Check Underwater Obstructions
  - Especially Close to Prop - Struts, Intakes, Anodes

However, the main goal of this course is to deal with problems or changes in the propellers on an existing boat. This is also a good first step to gaining experience in resistance calculations. If we know the RPM and the prop characteritics, we can calculate the current resistance, including all of the adjustments already.

This can be approached by back calculation of trial results. Just determine the characteristics of the propeller and the gear ratio, then measure speed and RPM. With this data, use the spreadsheets to determine thrust, and torque. Then you can decide what to do about whatever the problem was by trying on other props on the computer. All of the factoir4s such as wake fraction, thrust deduction and so on will be very much the same, so you don't really have to deal with them.

It's great if you can also measure horsepower, if only for your own experience, and this is normally done by fitting a torque strain gauge to the shaft. You can also approximate it sometimes by measuring fuel flow in a Diesel engine. Get as good conditions as possible for the engine. It is worth noting that air supply to an engine room is often a problem on yachts, so running trials with hatches or doors open may be wise. However, if you can't measure horsepower, it's not a terible problem, because you will predict it by the prop calcs as well.

Make sure the prop is clean, undamaged, and actually the pitch and diameter you think it is. It is well to check the boat weight and center of gravity, if possible. If you have hydrostatics tables, this can be determined by measuring draft or freeboards, and you should always record these anyway to spot weight changes after your trials.

Finally, if possible, check any underwater obstruction, particularly those close to, or in line with, the prop.

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Back Calculation Results

- Back Calculation Works!
  - Actual Trials Data From Instrumented Shafts Vs Calculations

Actual Back Calculation Results

◆ Measured SHP
— Calculated SHP

Shaft Horsepower

Speed, Knots
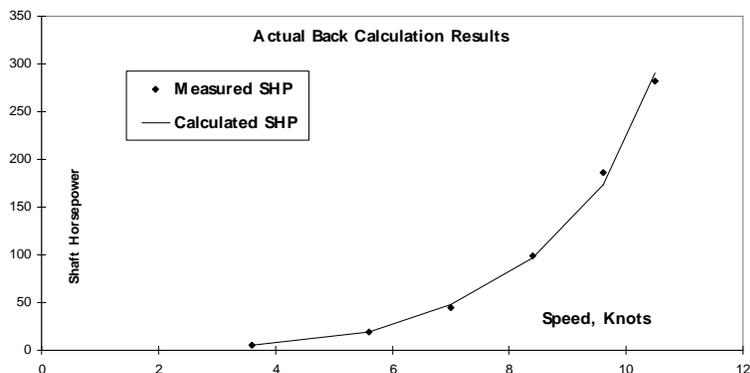
Here is the results of an actual trial (spots) with a torque meter on the shaft, and the calculations (the line). This is probably dead right as close as the meter and other instruments can read.

Good trial data is very important to doing good matches. Measure speed and RPM carefully, measure shaft torque if you can. Make sure the engine is running well. Yachts frequently don't have good air flow to the engine, which sharply reduces power.

There are a number of instruments on the market to help with trials. I have a GPS that connects to my lap top for running trials - It came with a automobile mapping program for a very reasonable price, so not only can I do good trials, but I can get directions to find the boatyard.

Recently sources for much smaller, shorter (which can therefore fit in a boat) and less expensive shaft torque measuring devices have become available. There are also devices that automatically measure and relate shaft RPM and speed to slip and so non and record them on portable computers.

Shaft Angle/strut Drag/clearance

- Cross Flow From Angled Shaft
  - Descending Blade Speed Adds to Cross Flow
  - Ascending Blade Subtracts From Cross Flow
  - Blade Angle Of Attack Varies As Blade Goes Around
  - Neither Blade Operates at Optimum One May Be At Negative Angle of Attack
  - Thrust Variations, Vibration
- High Speed Drag From Struts and Shaft
  - Struts, Etc. Get Bigger With High Angles
- Tunnels Work For Moderate High Speeds

Most boat shafts angle down, in order to get a bigger prop. This has some deleterious effects. Imagine for a moment the effect of angling the flow, looking back at slide 6. The blades on the two different sides will be at different angles and speeds due to the amount of flow across the shaft produced by the slanted flow.

In addition, the larger prop requires longer struts, and a longer exposed shaft, hence more appendage drag.

As a result, shaft angles should be kept as low as possible, and preferably no more than twelve degrees.

If you still need more diameter, even at moderately high speeds, a partial tunnel can be cut up into the hull. Some pushing vessels have tunnels so high that the top half is actually above the outside water level. Nonetheless, they work quite well. Tunnels enclosing as much as 40% of the hull have successfully been used on military patrol craft, so they may be applicable for higher speed regimes as well if carefully designed.

Vibration

- Torsional - Shaft Twist - Speed Varies Through Rotation
- Whirling - Shaft Weight Whips It Out Of Straight Line - Like A Jump Rope
- Longitudinal - Shaft Oscillates Back And Forth
- Blade Rate Induces Pulses Of Vibration
- Structure May React With Blade Rate
- Machinery May React With Blade Rate
- Check Frequencies Of Structure, Equipment
    - Corrosion and Vibration Frequently Work Together
- Torsional Analysis Requires Lots Of Engine Data
    - Usually Must Be Done By Engine Manufacturer

Vibration is another issue with props. Shafts can vibrate by twisting (the propeller rotates, but changes speed slightly relative to the engine), by whirling like a jump rope, and longitudinally, getting longer and shorter. None of these motions are large enough to easily see, but they produce noise and tremendous stress in the shaft, gears and engine. They are avoided by making sure that the shaft is rigid enough not to have a natural frequency near that of the propeller blade rate (the frequency induced by the blades passing near the hull - the number of blades times the RPM).

Everything has a natural frequency, and if a natural coincides with the frequency of a disturbance, the response is magnified. The ABYC standards for designing shafts eliminate whipping, and longitudinals are rare in the short shafts of small craft. Engine and gear manufactures may require a torsional vibration analysis, but in general, it's best for the engine manufacturer to provide it, because they have the internal engine data needed to perform it. You will have to provide torsional characteristics of the shafting, coupling and propeller, generally the torsional stiffness and the polar moment of inertia (weight times gyradius squared "WR^2") of these components. This is only difficult for the propeller, especially because part of the WR^2 is the water that vibrates with the propeller in torsion. The prop manufacturer generally will give WR^2 for the prop in the catalog, it can be estimated or you can determine it by a torsional pendulum experiment - this is done by hanging the prop off two wires so the shaft bore is vertical and twisting it so it spins back and forth on the shaft axis. The rate at which it oscillates shows the WR^2, but unfortunately only in air, and the effect of entrained water (or "added mass") must be added to this. A spreadsheet for estimating both wet and dry WR^2 is included in the course material.

Structure near the prop may also be excited by it, if the frequencies coincide. This can be found on trials. If something vibrates, temporarily add weight (like a sandbag) to change the frequency (weight reduces frequency). If the vibration goes away, then stiffen the vibrating panle (which raises the frequency, but it doesn't matter as long as they don't match). There are a variety of instruments for doing vibration surveys that can be very useful. The simplest is a sort of variable tuning fork that vibrates only at a set frequency.

It is common to see vibration and corrosion acting together to cause damage, especially of struts. It's always worth checking a problem case. It is also worth noting that Cardan shafts produce a torsional disturbance at four times shaft rate, so watch matches on this frequency, such as four blade props on Cardan shafts

The views expressed are those of the author and do not reflect official policy of the U.S. Coast Guard

Nozzles

- Generally Accelerating Nozzles - Contracting Flow
- Moves More Water
- Nozzle Itself Produces Lift From Contracting Flow
- Increase Greatest At High Thrust Loading, Low Speed
  - Good For Tugs, Trawlers, Etc.
- Much of the Force Appears in The Shroud
- Minor Improvement Due to Tip Loss Reduction
- Can Improve Economics For Towing Greatly
- Nozzle is Draggy - Special Sections Improve Performance
- Rotating Nozzles Generally Losers

Nozzles, often called "Kort Nozzles" increase thrust and efficiency at low speed, especially for highly loaded props. They work by increasing the flow into the prop, by reducing flow losses at the propeller tips, and because the nozzle itself produces lift in the forward direction due to the flow into the prop and are effectively a way of fitting a hydrodynamically larger prop. Kort nozzles are the most common of the class of converging nozzles, but specially designed props and nozzles have been developed that are more efficient at somewhat higher speed.

This is a very good system for low speed vessels needing lots of thrust, but at high speeds, the nozzle drag is a problem. Special nozzles with low drag sections have been developed for higher speed service (NautiCan is one such nozzle, out of British Columbia, Canada – see Gruzling's paper on modern nozzles in the 2003 SNAME *Transactions*.)).

Some propellers have been proposed that are fixed to the prop, and spin with it. Unfortunately, the frictional drag of this spinning ring usually adds a lot more torque than it saves through nozzle effects.

Very rarely, diverging nozzles are seen, usually in high speed applications. They degrade efficiency, but they can suppress cavitation and noise. They often include stators to recover rotational energy as well. The only "common" application of these nozzles is torpedos, where getting the rotation out (to keep the torpedo from spinning) is also important.

Surface Piercing Props

- Arneson Type - Transom Add-On
- Tunnel Type - Built In To Hull
- Device Efficiency Reduced
- Larger Loaded Area Gets Back Some Efficiency
- Eliminates Appendage Losses
- Definitely a High Speed Solution
- Matching Problems - Use High Gear Ratios
- Requires Very Special Props
- Requires Special Matching Techniques

Surface piercing props are a good option for high speeds. They eliminate most of the drag of struts and shafts, and generally provide for reduced draft.

They come in two types, sticking out of the transom, and built into tunnels. The latter is for operations that can't tolerate the exposed equipment aft, like sportfishers.

Since they are partly exposed to air, they don't form a cavitation bubble on the back, but an air bubble instead (ventilation). Since the air bubble won't condense like the steam filled cavitation bubble, surfacing props don't get damage.

Unfortunately, the device efficiency of a ventilated prop is lower than one fully immersed (not cavitating), so for a given diameter, surface props are less efficient, but since surface props are often not constrained by shafts and struts, you can use a much larger diameter, reducing the thrust load, and getting a higher ideal efficiency.

However, it's important to note that a large propeller, intended to be operating at high speed while partly immersed will take a lot of torque at low speed when fully immersed, so careful matching is important, and big gear ratios are important to avoid problems of getting the boat up on plane. Note also that the AMI Savitsky program included with this course is actually intended for surface piercing propellers, and has the necessary data to match them built in.

Note also that lifting an outboard somewhat ("jacking" it) on the transom has the effect of making the prop surface piercing, and is done for the same reasons.

Jets

- Jet Pumping Action Is More Efficient
- Jets Have Smaller Loaded Areas - Higher Thrust Loads - Good For High Speeds, Not For Low
- Eliminates Appendage Drag
- Eliminates Underwater Hazard
- Reduced Noise
- Better Matching to Engine
  - Jets Also Cavitate, But At Low Speeds
- Jets Sometimes Increase Hull Efficiency Slightly:
  - $1-t > 100\%$ & $1-W_t < 100\%$
- Jets Heavier - Maybe More Expensive

Water jets scoop water in and pump it out in a nozzle. For the purpose of thrust loading calculations, the area in the thrust load coefficient is the nozzle area, so though a jet has high device efficiency, it has low ideal efficiency at low speed.
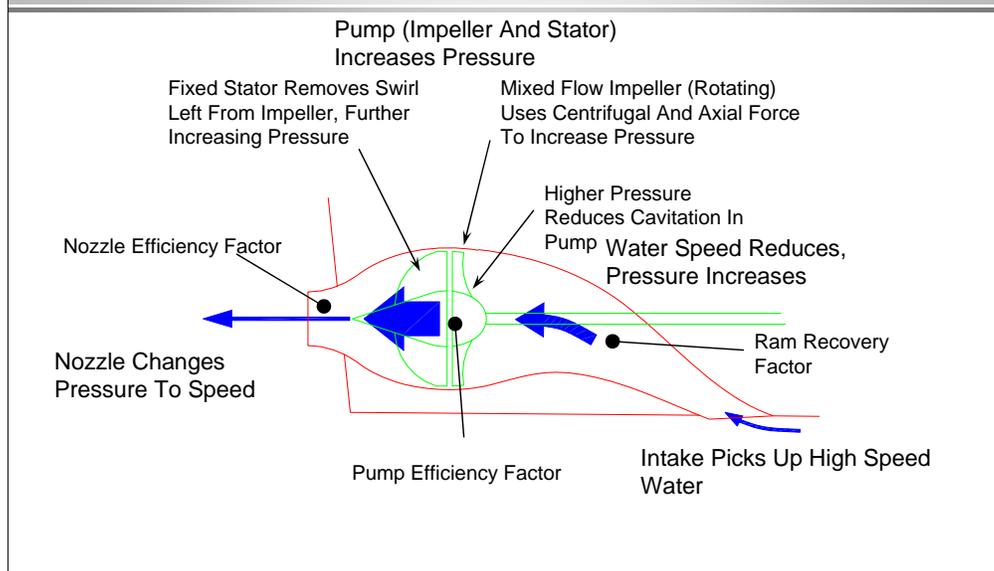
Jets also eliminate appendage drag, and reduce draft, and eliminate hazardous equipment in the water such as spinning props, so jets are good for personnel rescue or other situations that might expose people in the water to props, like jet skis. They can also reduce underwater noise.

Since a jet is basically an enclosed pump, the speed of the boat has little effect on torque. Thus overloading is less likely. This also means that jets don't cavitate at high speeds. They do, however, cavitate at low speeds, when the pump is essentially starved for water.

Jets sometimes can improve the hull efficiency factors. They sometimes have a positive wake fraction and thrust deduction, though they are small either way, and in general, both can be assumed to be unity, as can relative rotative efficiency.

The big problem, beside poor low speed efficiency is that jets are generally heavier and more expensive than either conventional props or surface props.

Jet Action

Pump (Impeller And Stator)
Increases Pressure

Fixed Stator Removes Swirl
Left From Impeller, Further
Increasing Pressure

Mixed Flow Impeller (Rotating)
Uses Centrifugal And Axial Force
To Increase Pressure

Higher Pressure
Reduces Cavitation In
Pump Water Speed Reduces,
Pressure Increases

Nozzle Efficiency Factor

Nozzle Changes
Pressure To Speed

Ram Recovery
Factor

Pump Efficiency Factor

Intake Picks Up High Speed
Water

It worth looking a bit at flow through a jet.

Initially it picks up water that is basically still with respect to the sea floor, or moving fast with respect to the boat.

This flow is then slowed as the inlet expands, and the pressure increases. This slowing process produces a loss, called "ram recovery factor" and not all of the energy of speed is turned into pressure. However the high pressure prevents cavitation.

The rotor then increases the pressure of the flow, and the stator takes out the swirl induced by the rotor increasing pressure even more. Obviously there is some efficiency loss here too.

Finally, the jet nozzle changes the pressure to speed, and the water speed produces thrust. There is a small loss "nozzle efficiency" here too.

Although it is possible to calculate all of these factors, in general, a jet manufacture will provide charts of thrust versus boat speed for a given combination of impeller and RPM, which also absorbs a specific amount of horsepower. The actual efficiency is thus very simple, it is the ratio of the absorbed horsepower divided by effective horsepower (formula on page 23) based on the jet thrust and the boat speed.

If you are interested in jets, please read John Allison's excellent paper in the 1993 *Transactions* of SNAME.

Spreadsheets And Programs

- AMI - Savitsky / Brown Resistance Predictor
  - Full Planing Conditions, Prismatic Hull Forms
  - Also Matches Surface Piercing Props
  - By Paul Kamen ("Call Me Fishmeal"), With Permission
- Mercier Spreadsheet
  - Preplaning Conditions, High Speed Semi-Displacement
  - Statistical Regression On Multiple Model Test Series
- Propcalc Spreadsheet
  - Calculates Kt, Kq, Efficiency, Torque, etc.
  - Has Engine Power Vs RPM Models
  - "What-If" Tool - Use "Goal Seek" or "Solver" To Match

To recap the major programs you have been given:

AMI is a Savitsky program for planing boats, distributed as a "ZIP" file, which includes documentation. Please read this documentation as part of the course. You also have a Savitsky spreadsheet, just to be able to understand the method.

The MERCIER spreadsheet is for semi-planing boats, either those intended for semi-planing speeds of for planing boats not running at top speed. This method is just a statistical fit to a great deal of data on semi-planing boats.

The propcalc spreadsheet does all the calculations necessary to predict thrust, torque requirements, horsepower and so on. Please look at it and try to understand the formulas (many of them are just unit conversions, like revolutions per minute into revolutions per second). It is run from the summary page and has a page each for Kt and Kq that implement the Blount-Hubble formula. It also has a page for putting in and getting out engine data. This has a fit for several types of engines, and space to insert known engine data if it's available. The type of data is selected by inputting a number as shown. Then it will calculate the available horsepower and torque from the input maximum RPM and horsepower. There is also a sheet to put in resistance data.

This spreadsheet can be used in many different ways, but most commonly, you will set up all the prop and engine parameters, and the boat speed, (and possibly the resistance) then use the goal seek function to get the reserve horsepower to zero. You can also use the solver function in various ways to optimize, though you have to be careful about setting up criteria or you will get weird "solutions" like negative pitch. This is then the conditions of balanced torque that the engine will run at for that boat speed and prop characteristics. Note that there is also a cavitation section. If the Blount Fox cavitation criteria is exceeded, the sheet reports the torque and thrust for the fully cavitating condition. The actual thrust and torque will be somewhere between the non-cavitating case shown on the left and the cavitating case. However, this intermediate condition is probably not a stable condition, because the partly cavitating prop will absorb less torque than the non-cavitating case, and speed up, cavitating still more, so the exact torque is not of great interest, and something should be done about it. (This is kind of like spinning your car wheels in the snow.)

Why Buy Boat Propellers From iboats? Ease of Use Prop Selection Tool. Easily find a replacement boat propeller for your outboard, sterndrive or outdrive. iboats.com carries marine propellers designed for Mercury, Yamaha, Evinrude, Johnson, Honda, Suzuki, Tohatsu, Mariner, Force, Nissan, and Chrysler outboard motors. Smaller outboards come with an all-purpose size that meets most requirements. An onboard tachometer to monitor engine RPM is also commonly installed with the larger engine installations. Stainless steel boat props are ideal for large or heavy boats and those running in saltwater. Although more expensive than aluminum, stainless steel is more durable and will last longer. 1 E Marine Training - Prop Matching - February, Propeller Selection For Boats and Small Ships Chris Barry This course is intended to cover the basic elements of marine propulsion, especially propellers and the selection of standard segmental section, off-the-shelf propellers for boats and small ships. The nominal concentration is on planing and semi-planing boats, but this material is applicable to any sort of boat using commonly available propellers. This course is not about propeller design per se, but about selecting a propeller, essentially from a catalog. There is a great deal of informat Ship propeller is used for propulsion in most types of vessels, irrespective of their type and size. The notion of 'pushing' or 'propelling' a ship forward came into being since the advent of ships themselves. After the era of those large sails governing the manoeuvrability and powering the ship, propellers became the most conventional means of driving the ship in the seas. We are familiar with seeing propellers fitted behind the ships, but have we ever contemplated upon the shape, appearance and typical geometry of a propeller? Is there some physics behind the unusual nature of marine propell... boat propeller. Fixed pitch propellers is the simple and safe choice. It can be calculated for to fit most vessels and applications. Constituent material is also a factor. Ship propellers often are custom-built. Manufacturers have software and special equipment to aid in selection. Subscribe to our newsletter. Thank you for subscribing. New Bronze Propeller For Boat and Small Ship. $10.50-$11.00/ Kilogram. 3000 Kilograms(Min. 2 For any technical problems we have professional engineers to offer solutions for you . 4 We have our own shipping forwarders to arrange shipment and save you troubles looking for shipping company . We are happy to deal with any problems you meet with before /during/after buying from us . 1/4.

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