

13.012 Hydrodynamics for Ocean Engineers

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Marine Propellers

Today, conventional marine propellers remain the standard propulsion mechanism for surface ships and underwater vehicles. Modifications of basic propeller geometries into water jet propulsors and alternate style thrusters on underwater vehicles, has not significantly changed how we determine and analyze propeller performance.

We still need propellers to generate adequate thrust to propel a vessel at some design speed with some care taken in ensuring some “reasonable” propulsive efficiency. Considerations are made to match the engine’s power and shaft speed, as well as the size of the vessel and the ship’s operating speed, with an appropriately designed propeller. Given that the above conditions are interdependent (ship speed depends on ship size, power required depends on desired speed, etc.) we must at least know *a priori* our desired operating speed for a given vessel. Following this we should understand the basic relationship between ship power, shaft torque and fuel consumption.

Power:

Power is simply force times velocity, where 1 HP (horsepower, english units) is equal to 0.7457 kW (kilowatt, metric) and 1kW = 1000 Newtons*meters/second.

$$P = F \cdot V$$

Effective Horsepower (EHP) is the power required to overcome a vessel's total resistance at a given speed, not including the power required to turn the propeller or operate any machinery (this is close to the power required to tow a vessel).

Indicated Horsepower (IHP) is the power required to *drive* a ship at a given speed, including the power required to turn the propeller and to overcome any additional friction inherent in the system. Typically the ratio of EHP/IHP is about 1:2 (or EHP is 50% of IHP).

Brake Horsepower (BHP) is the maximum power generated by an engine at a given RPM as determined by the engine manufacturer.

Shaft Horsepower (SHP) is the power delivered along the shaft to the propeller at a given RPM.

Regardless of how you think of engine power, as a general rule: the more power available the faster the ship should go all other factors being equal. There is a tradeoff between minimum required power, which would prevent the vessel operating at a fast enough speed, and excessive power, which could be wasteful in terms of fuel, space, cost, etc.

Torque:

To use the power provided by the power plant (engine) to propel the vessel it must be used to rotate the shaft connected between the engine and the propeller. Shaft horsepower is converted to a rotary force (or moment) applied to the propeller. This rotary force necessary to turn the shaft is simply torque.

Torque = Force * length (Newtons*meters)

When power is given in HP then torque can be found as

$$T = 5252.0 * HP / RPM$$

Where RPM is the revolutions per minute of the shaft and HP is the shaft horsepower. You can see here that for the same power, a slower turning propeller will generate more thrust.

Typically for engines and motors, power and available torque are provided as curves on performance data sheets as a plot of BHP, Torque, and fuel consumption as a function of RPM.

Speed of the vessel:

We have already laid the foundation for determining the resistance on a full scale ship based on model testing for a desired full scale ship speed. This is of course a function of the ship geometry and an important part of choosing the correct ship propeller.

Choosing a Propeller

To properly choose a propeller we must first understand some of the basic nomenclature used to describe propeller geometry. Figure 1 is taken from Gilmer and Johnson, Introduction to Naval Architecture.

Basic Nomenclature:

Hub The hub of a propeller is the solid center disk that mates with the propeller shaft and to which the blades are attached. Ideally the hub should be as small in diameter as possible to obtain maximum thrust, however there is a tradeoff between size and strength. Too small a hub ultimately will not be strong enough.

Blades Twisted fins or foils that protrude from the propeller hub. The shape of the blades and the speed at which they are driven dictates the torque a given propeller can deliver.

Blade Root and Blade Tip The root of a propeller blade is where the blade attaches to the hub. The tip is the outermost edge of the blade at a point furthest from the propeller shaft.

Blade Face and Back The face of a blade is considered to be the high-pressure side, or pressure face of the blade. This is the side that faces aft (backwards) and pushes the water when the vessel is in forward motion. The back of the blade is the low pressure side or the suction face of the blade. This is the side that faces upstream or towards the front of the vessel.

Leading and Trailing Edges The leading edge of a propeller blade or any foil is the side that cuts through the fluid. The trailing edge is the downstream edge of the foil.

Right Handed vs. Left Handed A propeller's "handedness" affects its shape. A right-handed propeller rotates clockwise when propelling a vessel forward, as viewed from the stern of the ship. A left-handed propeller rotates counter-clockwise, as viewed from the stern, when in a forward propulsion mode. When viewing a propeller from astern, the leading edges of the blades will always be farther away from you than the trailing edges. The propeller rotates clockwise, and is right-handed, if the leading edges are on the right. A propeller's handedness is fixed. A right-handed propeller can never be exchanged with a left handed propeller, and vice versa.

Most single screw vessels (one engine, one propeller) have right-handed propellers and clockwise rotating propeller shafts (as viewed from astern). Single propellers tend to naturally push the vessel to one side when going forward (and the opposite side when in reverse)—a right-handed prop will push the stern to starboard when in forward (and port when in reverse). Since Propellers are not ideally designed for reverse propulsion, this effect is somewhat exaggerated when operating a single-screw vessel in reverse. Twin screw vessels have counter rotating propellers with identical specifications. The port (left) side propeller is usually left-handed and the starboard (right) side propeller is usually right-handed.

Diameter The diameter (or radius) is a crucial geometric parameter in determining the amount of power that a propeller can absorb and deliver, and thus dictating the amount of thrust available for propulsion. With the exception of high speed (35 Knots+) vehicles the diameter is proportional to propeller efficiency (ie. Higher diameter equates to higher efficiency). In high speed vessels, however, larger diameter equates to high drag. For typical vessels a small increase in diameter translates into a dramatic increase in thrust and torque load on the engine shaft, thus the larger the diameter the slower the propeller will turn, limited by structural loading and engine rating.

Revolutions per Minute (RPMs) RPM is the number of full turns or rotations of a propeller in one minute. RPM is often designated by the variable N . High values of RPM are typically not efficient except on high speed vessels. For vessels operating under 35Knots speed, it is usual practice to reduce RPM, and increase diameter, to obtain higher torque from a reasonably sized power plant. Achieving low RPM from a typical engine usually requires a reduction gearbox.

Pitch The pitch of a propeller is defined similarly to that of a wood or machine screw. It indicates the distance the propeller would “drive forward” for each full rotation. If a propeller moves forward 10inches for every complete turn it has a 10inch *nominal pitch*. In reality since the propeller is attached to a shaft it will not actually move forward, but instead propel the ship forward. The distance the ship is propelled forward in one propeller rotation is actually less than the pitch. The difference between the *nominal pitch* and the *actual* distance traveled by the vessel in one rotation is called *slip*.

Typically blades are *twisted* to guarantee constant pitch along the blades from root to tip.

Often a *pitch ratio* will be supplied. This is simply the ratio of pitch to diameter, usually in millimeters, and typically falls between 0.5 and 2.5 with an optimal value for most vessels closer to 0.8 to 1.8.

Pitch effectively converts torque of the propeller shaft to thrust by deflecting or accelerating the water astern – simple Newton’s Second Law.

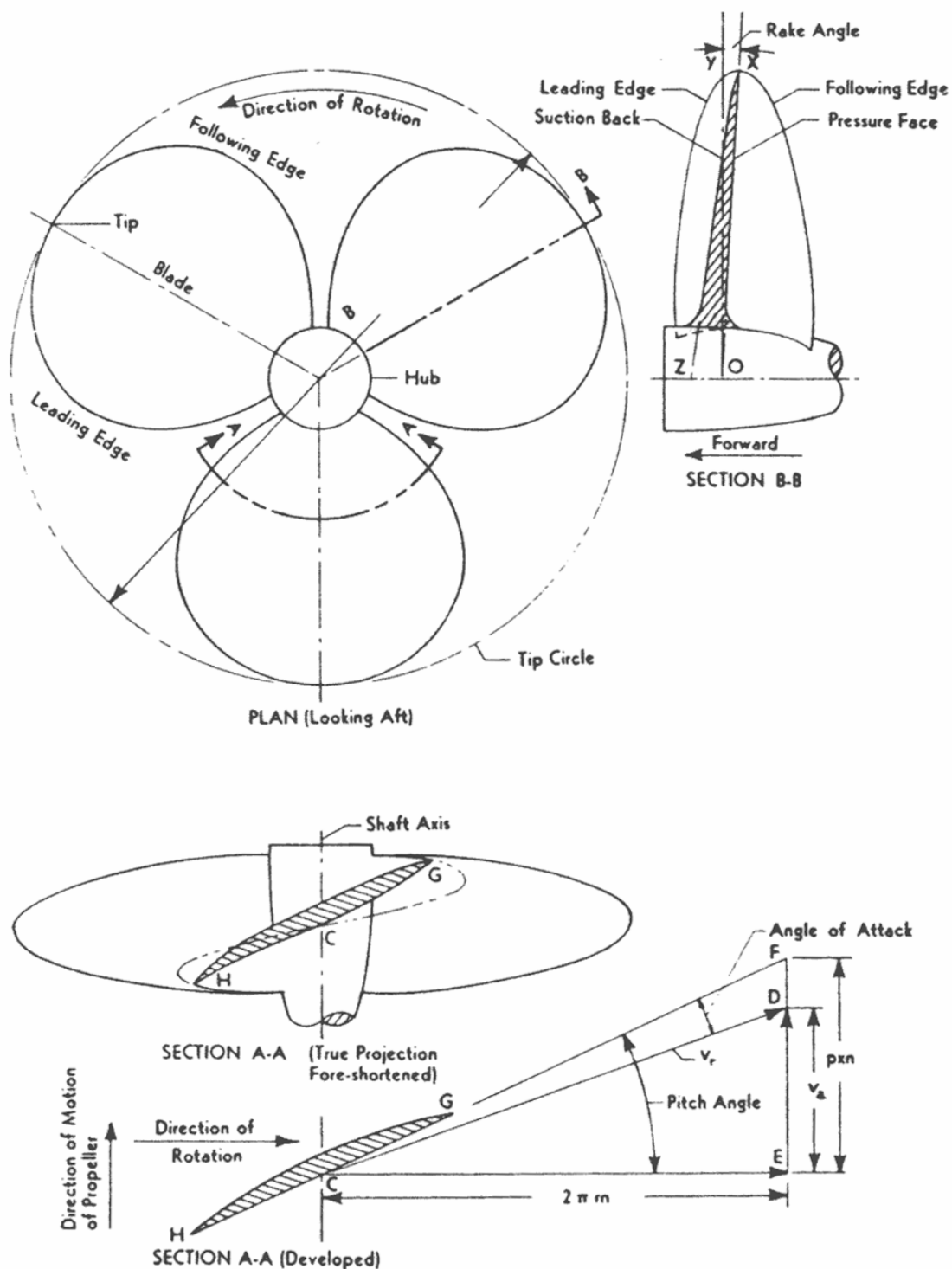


Figure 12–1. Propeller definition diagram (three-bladed, right-hand, constant-pitch propeller)

Figure 1

Propeller Section

Propeller section: A circular arc section cut through the blade at some radius. When this section is "flattened out" it looks like a foil section (see figure 2)

The following definitions apply to a propeller section :

Meanline: Half distance along a section between the upper and lower surfaces of the blade

Nose-Tail line: Straight line connecting the leading edge meanline point to the trailing edge meanline point.

Chordlength: Length of Nose-tail line

Camber height: distance between nose-tail line and meanline normal to the nose-tail line (varies with chordwise position)

Max. Camber: Maximum camber height along the section

Meanline Distribution: A standard distribution of camber height as a function of chordwise position starting at the section leading edge. Quite often these are tabulated forms such as a NACA A=0.8 Meanline, and can be obtained from standard foil literature.

Thickness: Section thickness along a line normal to the meanline. Varies with chordwise position

Max. Thickness: Maximum section thickness

Thickness distribution: A standard distribution of thickness as a function of chord length quite often are tabulated forms such as NACA 66 thickness form that can be obtained from standard foil literature.

The following geometry definitions apply to the overall propeller geometry and are a function of radius:

Pitch: The axial distance traveled by the section if rotated on revolution and translated along the section nose-tail line (arc)

Midchord line: line produced from the midchords (i.e. Midpoint of section nose tail line) of each section along a propeller blade.

Rake: Axial distance from the midchord point at the hub section and the section of interest.

Skew or Skew Angle: Tangential component of the angle formed on the propeller between a radial line going through the hub section midchord point and a radial line going through the midchord of the section of interest and projected

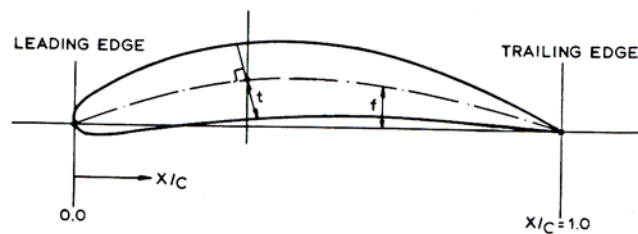


Fig. 5 Symbols defining shape of airfoil

Figure 2. Propeller blade cross section is similar to an airfoil

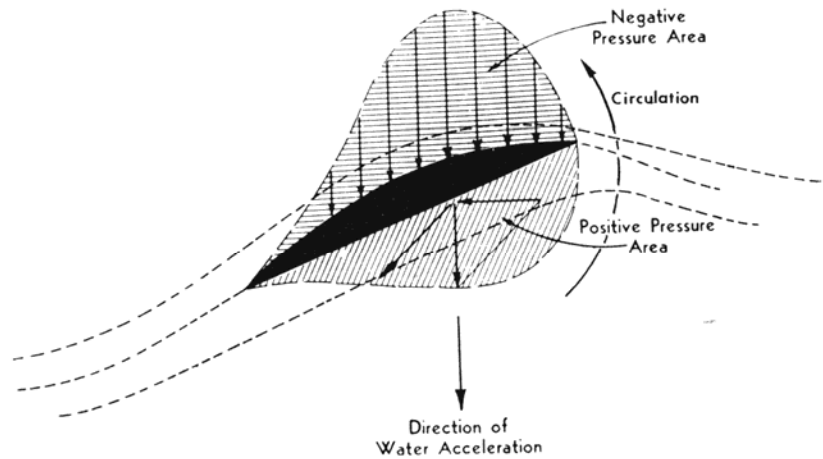
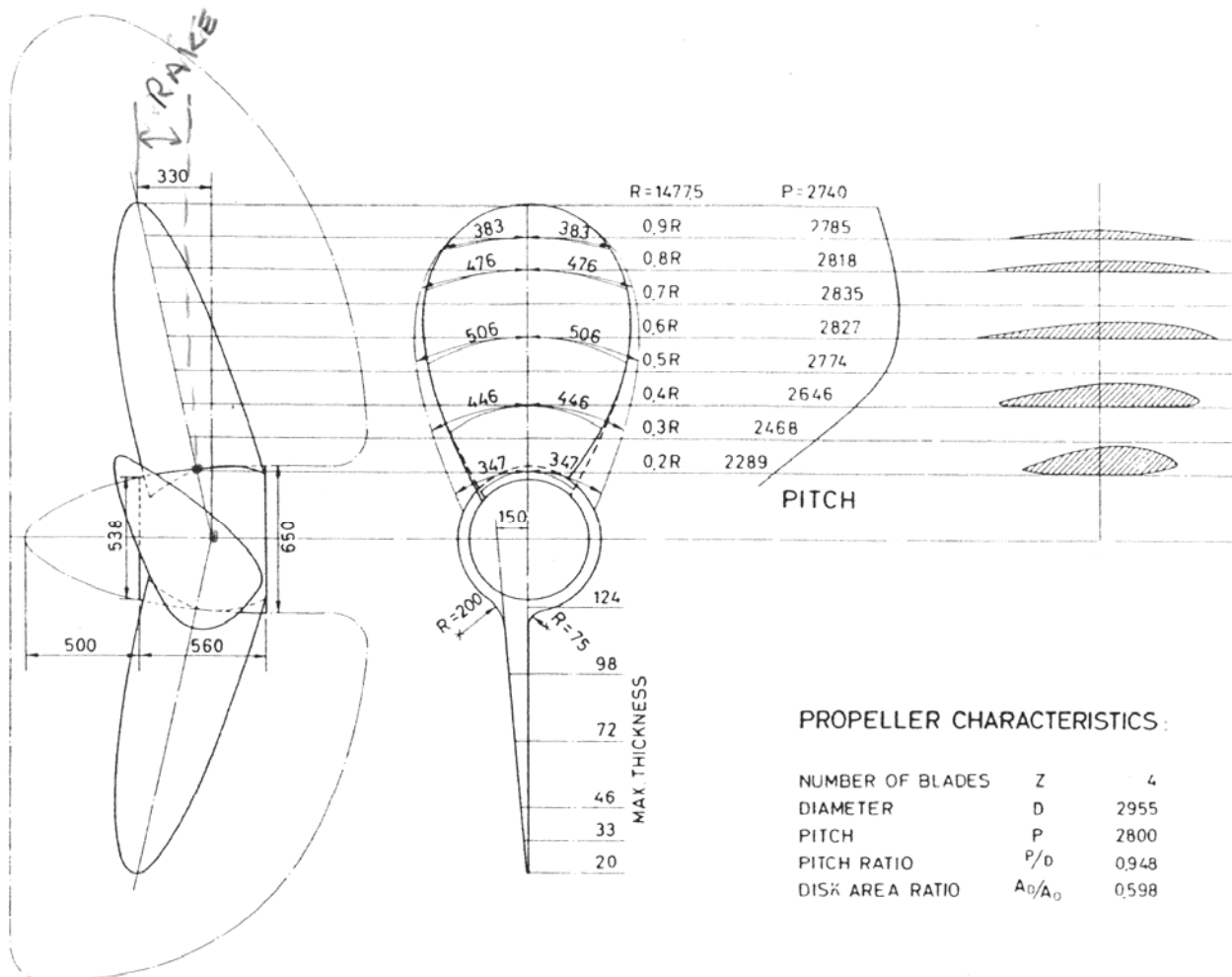


Figure 12-5. Pressure distribution about propeller blade section



Propeller Geometry Definitions

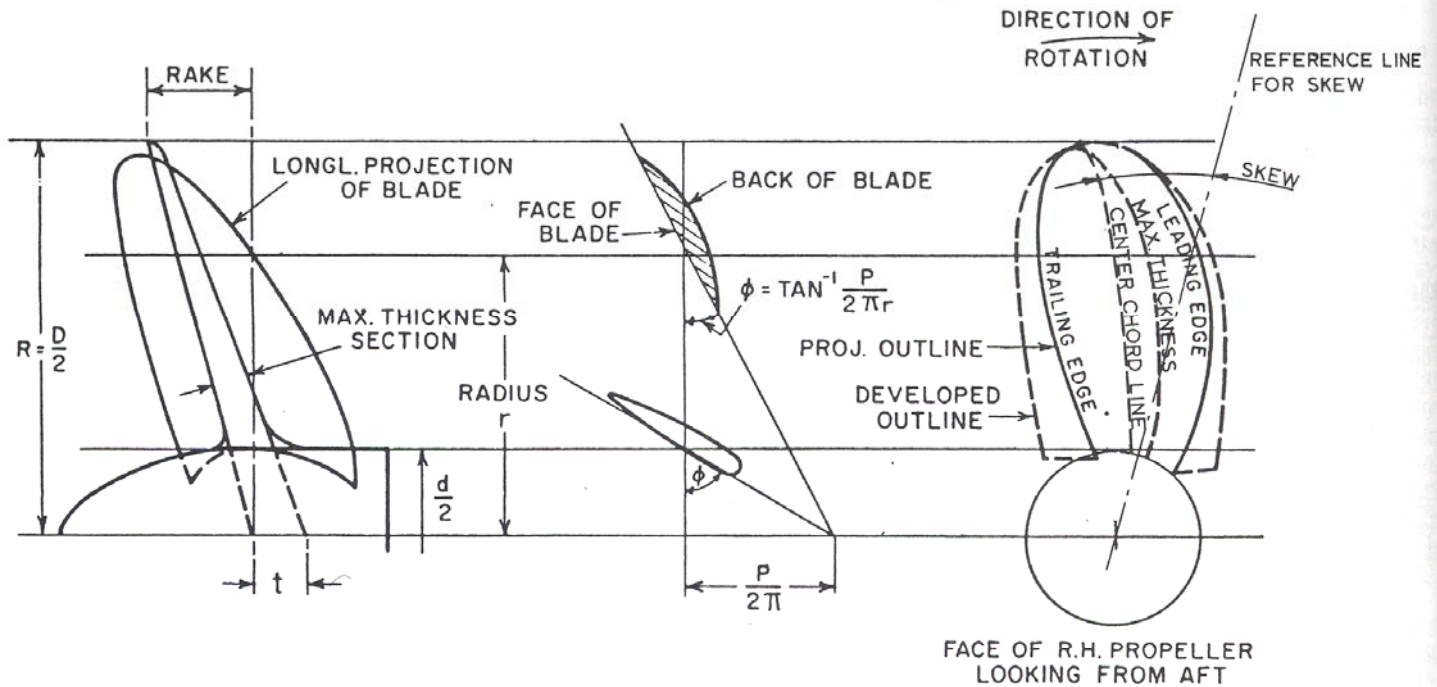


Fig. 8 Typical propeller drawing

Diameter D	Pitch ratio $= \frac{P}{D}$
Pitch P	Blade thickness ratio $= \frac{t}{D}$
No. of blades 4	Pitch angle $= \phi$
Disk area = area of tip circle $= \frac{\pi}{4} D^2 = A_o$	
Developed area of blades, outside hub $= A_D$	
Developed area ratio $= DAR = \frac{A_D}{A_o}$	
Projected area of blades (on transverse plane) outside hub $= A_P$	
Projected area ratio $= PAR = \frac{A_P}{A_o}$	
Blade width ratio $= BWR = \frac{\text{Max. blade width}}{D}$	
Mean width ratio $= MWR = \frac{A_D / \text{length of blades (outside hub)}}{D}$	

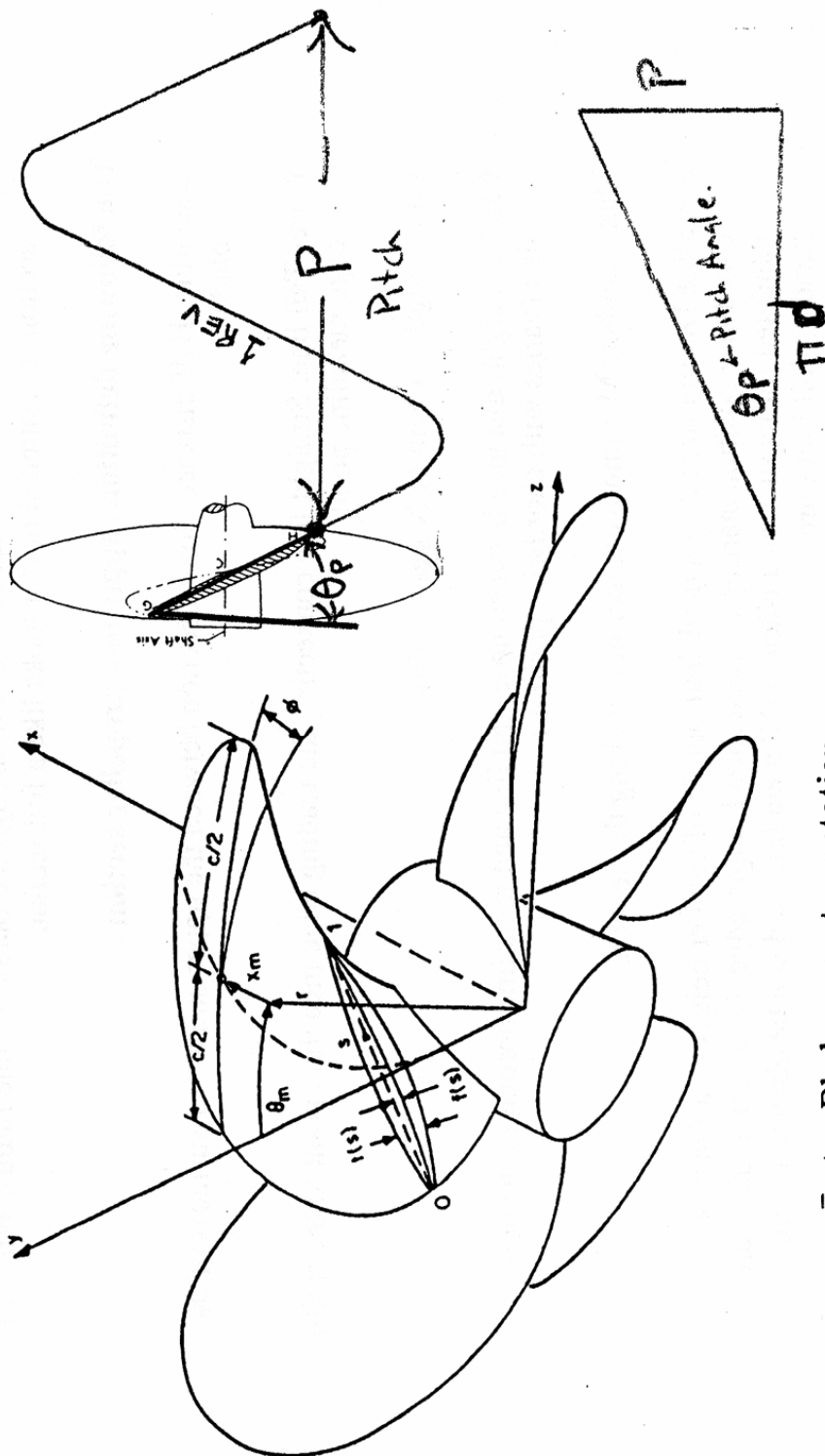


FIG. 1 Blade geometry notation

Propeller Performance Characterization

Dimensional Attributes:

Diameter	D	Overall diameter of the propeller
Rotation rate	N	Rotational speed of the propeller in rev/sec
Density	ρ	Fluid density
Thrust	T	Propeller axial thrust force
Torque	Q	Propeller shaft torque
Ship Speed	V_s	Ship velocity
Inflow Velocity	V_a	Mean inflow velocity

Non-Dimensional Characterization of propeller performance:

Advance Coef: $J = V_a / (ND)$

Thrust Coef.: $K_t = T / (\rho N^2 D^4)$

Thrust Coef.: $C_t = 2T / (\rho A V_a^2)$ (A= Propulsor area)

Torque Coef. : $K_q = Q / (\rho N^2 D^5)$

Propeller Efficiency: $\eta_0 = (T * V_a) / (2\pi N Q)$

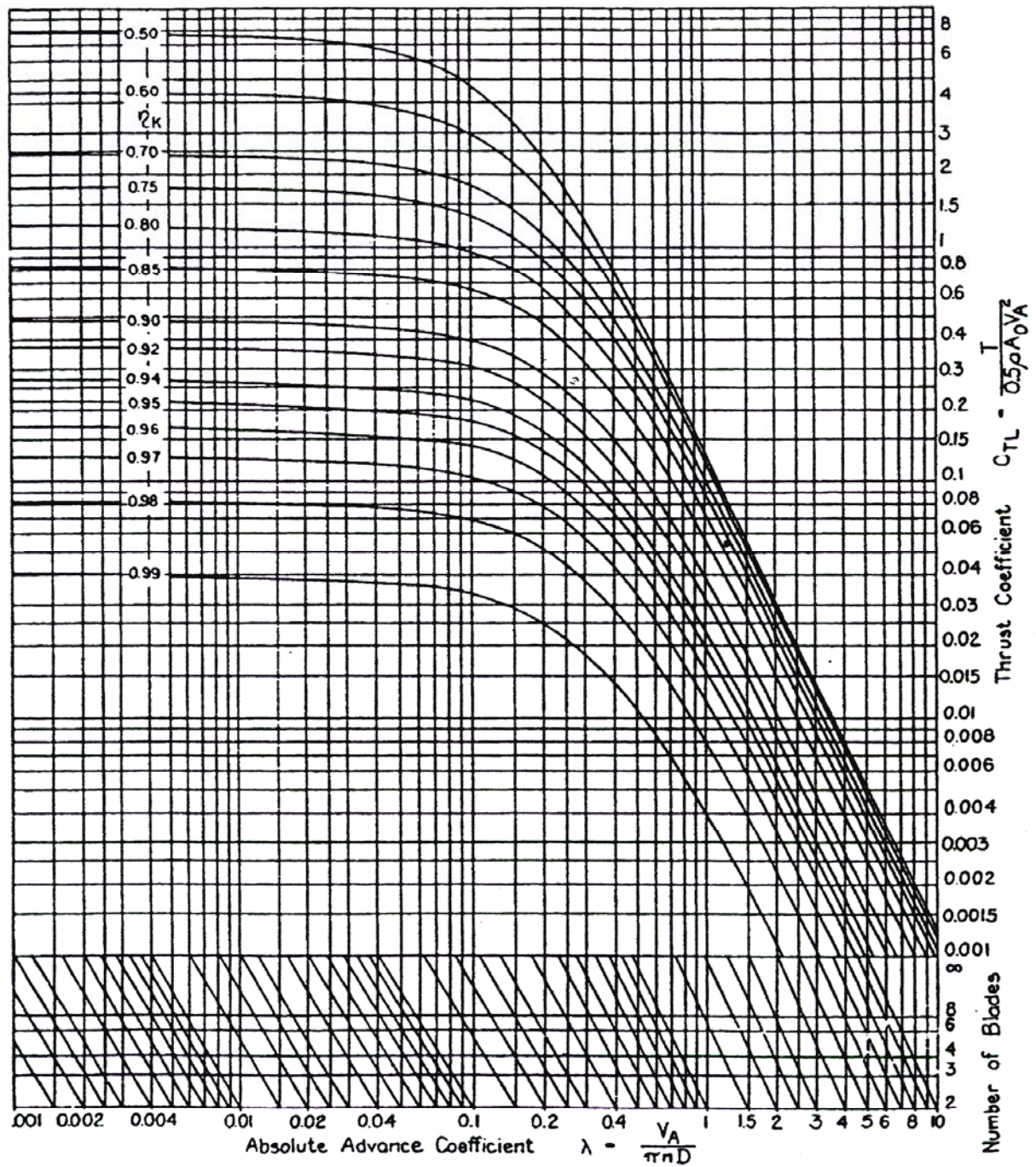
Propulsive Efficiency: $\eta_t = (R_t * V_s) / (2\pi N Q)$ R_t = Total Ship resistance

Ideal Propellers and the Kramer Diagram

Unlike the actuator disc a propeller requires that the power be input into the fluid via a shaft and thus must apply a torque to the fluid. To balance this torque the flow must contain tangential velocity, or swirl, to counteract this torque. The kinetic energy in the swirl velocity, if not recovered by a stator or downstream blade row, is lost. *Therefore the efficiency of an ideal propeller will be less than an actuator disc efficiency.* For a propeller in uniform flow this ideal efficiency can be computed given the advance coefficient, J , and the thrust coefficient, C_t . The graphical chart of these results is depicted in the Kramer diagram, which also has correction for losses due to finite blade number. This chart does NOT include viscous losses and gives the maximum achievable efficiency for a real propeller in uniform inflow.

To use Kramer's diagram:

- Need to Know: T = thrust to propel ship (need to know ship's total resistance)
- Find C_t based on your chosen propeller area.
- Choose the number of blades
- Know Va , D , N
- Use chart:
 - Start with λ = Absolute advance coefficient ($\lambda = Va / (\pi n D) = J/\pi$)
 - Follow up diagonal line until you hit the horizontal line that corresponds to your number of blades.
 - Next go DIRECTLY up to the next horizontal line that corresponds to your known value of C_t which you calculated earlier.
 - Then choose the closest efficiency curve or interpolate between curves for η .



Kramer Diagram for Ideal Propeller Efficiency

¹Kramer, K.N., "Induzierte Wirkungsgrade von Best-Luftschrauben endlicher Blattform", Luftfahrtforschung, July 1938, Vol 15. An English translation appears in NACA TM 884, January, 1939

Propeller Series

A common way to choose propellers as a first cut at a design is to choose propellers from a standard propeller series such as the B-series propellers shown below. These are essentially propeller curves for a variety of propellers of varying loading indicated in the form of pitch. If J and K_t are known then one can pick the propeller in the series that gives the best efficiency, for example, by reading directly off the chart.

Example:

Suppose one has a propeller application with the following requirements:

Thrust = 14,000 N
 Ship speed $V_s = 10$ m/s
 Density water = 1000 kg/m^3
 Diameter = 1.0 meters
 Max. Shaft RPM = 600
 4-bladed propeller

Compute the ideal (actuator disc) efficiency:

$$C_t = 2 (14,000) / (1000 * 3.1415 * (1^2 / 4) * 10^2) = 0.357$$

$$\text{Ideal efficiency} = 2 / (1 + (1.357)^{1/2}) = 0.923 \text{ or } 92.3\%$$

Given a maximum Shaft speed of 600 RPM (10 rps)

$$J = 10/10/1 = 1 \quad (\text{Lambda} = 0.318)$$

$$\text{Ideal prop. Eff.} = 0.86 \text{ or } 86\%$$

$$K_t = 14000/1000/10/10/1 = 0.14$$

From the B-series Data:

$$J = 1.0 \text{ and } K_t = 0.14$$

$$\text{Gives a } P/D = 1.2 \text{ and a propeller efficiency of } 0.75 \text{ or } 75\%$$

You can see the actual propeller is much less efficient than either the ideal propeller or the actuator disc result.

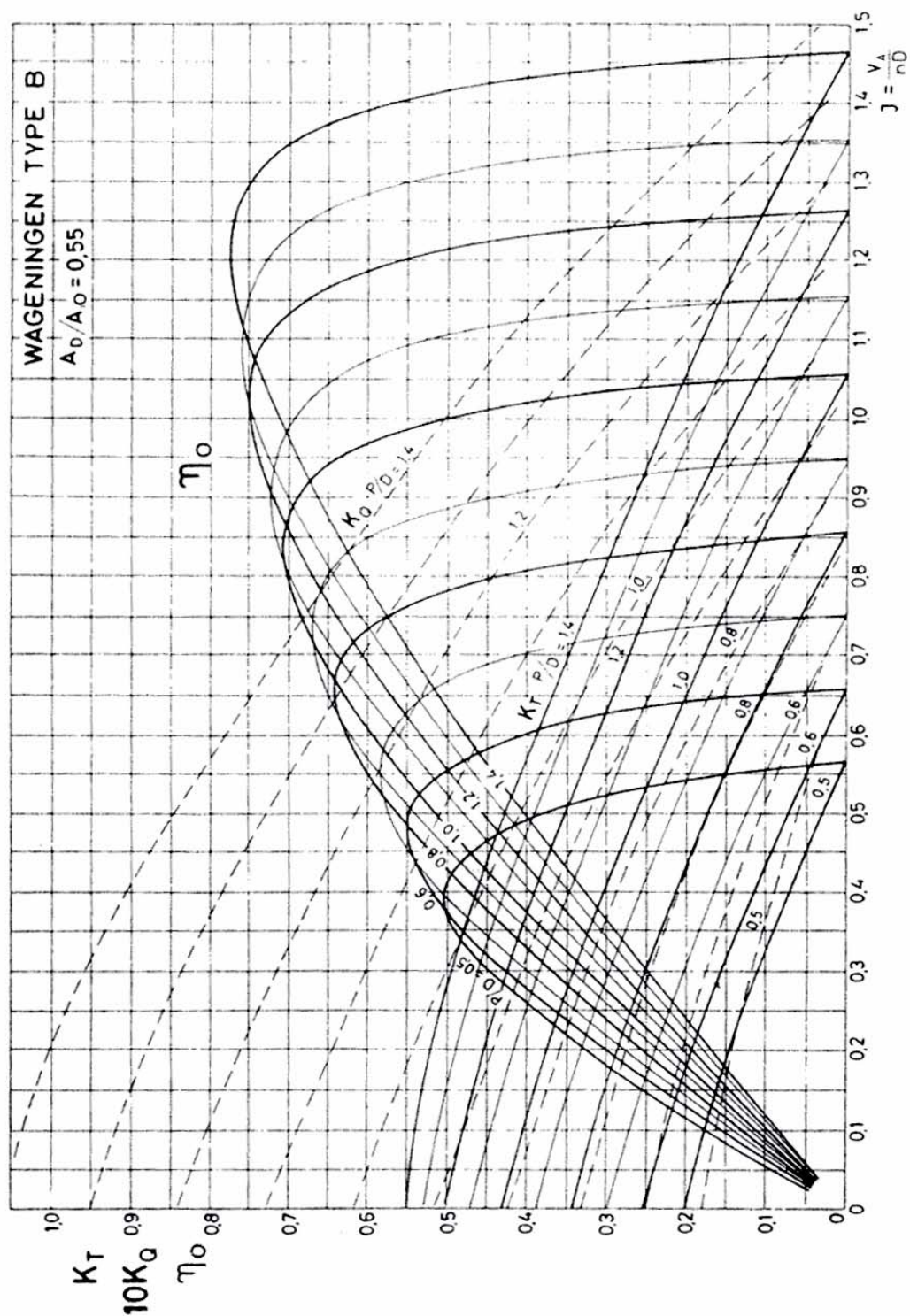


Figure 6.3.10. Results of open-water tests on four-bladed model propellers of the Wageningen B 4-55 type.

B-Series Propeller Data for Wageningen B 4-55 type propeller series (From Harvald; Resistance and Propulsion of Ships, 1983 ed. Wiley)

Interaction with hull on performance:

An actual ship propeller often operates in the wake of a ship as shown below. Therefore the "freestream" velocity as seen by the propeller is lower than the ship speed.

The Wake fraction is defined as

$$w = 1 - V_a / V_s$$

and is the percentage of the ship velocity seen at the propeller

The propeller, if close to the hull can also induce a low pressure on the hull which increases its drag. Thus the propeller thrust must be higher to overcome this additional drag. The thrust deduction coefficient is defined as:

$$t = 1 - R_t / T$$

where R_t is the total ship resistance and T is the propeller thrust. Note that prop efficiency is simply

$$\eta_0 = (T * V_a) / (2\pi NQ)$$

and the propulsive efficiency is

$$\therefore$$

$$\eta_t = (R_t * V_s) / (2\pi NQ)$$

If the torque in each equation is assumed the same then we can show that

$$\eta_t = (1-t)/(1-w) * \eta_0$$

From this result we can see that the propulsive efficiency can increase if the propeller is put in the wake of the ship (if t is small). In fact it is possible to have a propulsive efficiency for a propeller system of greater than 1.0! This doesn't violate any physical laws but merely states that the propeller has "reduced" the ship resistance by taking advantage of its wake.

Propeller Cavitation

Cavitation occurs when the local absolute pressure is less than local vapor pressure for the fluid medium.

Cavitation Number (Inflow Velocity Based) is defined as:

$$\sigma_v = \frac{2(P - P_{\text{vap}})}{\rho A V_a^2}$$

Sometimes Propeller Cavitation Number is defined based on Propeller tip Speed:

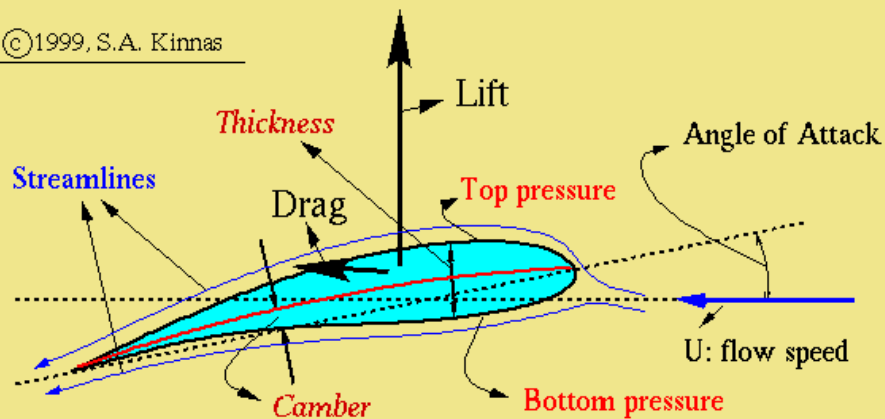
$$\sigma_{\text{ND}} = \frac{(P - P_{\text{vap}})}{(\rho N^2 D^2)}$$

The Critical measurement for cavitation performance is the cavitation inception point which is the conditions (i.e. Cavitation number) for which cavitation is first observed anywhere on the propeller.

Typically the Inception cavitation number as a function of K_t or J is plotted for a given propeller which defines the cavitation free operation boundary. This boundary typically has a bucket shape which is referred to as the cavitation bucket.

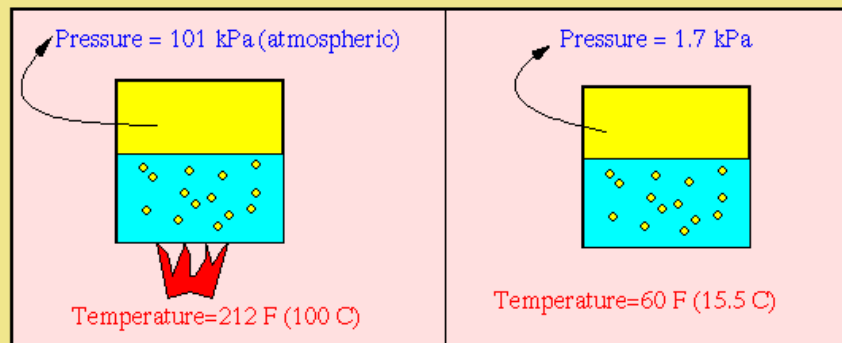
Flow around a hydrofoil (blade section)

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- ▶ Top pressure LOWER than bottom pressure
- ▶ Lift increases with U^2 , Angle of Attack, Camber
- ▶ Top pressure DECREASES as Lift (or U) increases

REMEMBER WATER BOILS WHEN ...



BOILING OF WATER AT NORMAL TEMPERATURES IS CAUSING ...

CAVITATION

