TWIN DISC
POWER TRANSMISSION EQUIPMENT ®

TWIN DISC SURFACE DRIVES

Technical Notes On Propeller Analysis and Selection

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ANALYSIS

For any given set of propeller specifications and operating conditions, there are really only two major unknown quantities: torque absorbed by the propeller, and thrust produced by the propeller. By expressing torque and thrust as non-dimensional parameters, the results of experiments performed on model propellers can be applied to full-scale applications. Torque coefficient (Kq) is expressed as:

Kq = Torque/(rho*n^2*D^5)

where rho = density of fluid
n = rotation per second
D = diameter

This is equivalent to representing torque as proportional to the torque coefficient, Kq, and also proportional to rho*n^2*D^5.

It is worth examining this coefficient briefly on an intuitive basis, using familiar relationships for aerodynamic forces on lifting surfaces.

Clearly, force on the propeller blades will be proportional to density of the fluid, so rho should appear in the coefficient to the first power. And force on the blades is also proportional to velocity squared, so for a given diameter, n^2 should appear. Dependency on diameter to the fifth power, however, requires some thought. If propeller diameter increases, but the shape remains geometrically similar, then total blade area will increase by an amount equal to the square of the diameter increase, so there is a D^2 term. Average velocity of the blade through the water will increase by an amount equal to the diameter increase. (Remember that RPM is now being held constant - that was accounted for in the n^2 term.) Since force on the blade is dependent on velocity squared, this results in a second D^2 term. Now consider the moment arm of the force about the shaft. For geometrically similar propellers, this will be proportional to the first power of diameter, so there is another power of D multiplied in. The result is D^2*D^2*D, or D^5. This all assumes that the blades are operating at a constant angle of attack through the fluid, and this must be represented by another parameter. (We are neglecting the effects of variation in cavitation number for simplicity.)

The torque coefficient, Torque/(rho*n^2*D^5), should now make some intuitive sense. If two propellers are operating at the same value of rho*n^2*D^5 and the blades are moving at the same angle of attack through the water, then they should be absorbing the same amount of torque. Any difference is a result of individual propeller design features, such as number of blades, blade area, blade selection shape, etc.

We mentioned that a parameter is needed to represent angle of attack of the blades through the fluid, and several are available. "Slip" is the most common, defined as the ratio of actual propeller advance through the fluid divided by theoretical advance through the fluid, if the advance was equal to one propeller pitch for each revolution; this ratio is subtracted from one and usually expressed in percent. "Advance coefficient" (J) is the parameter more commonly used in the technical literature. This is defined simply as V/(n*d). For propellers of equal pitch/diameter ratio, it can be thought of as determining the angle of attack of the blades.

The conventional method of representing the torque-absorbing characteristics of any given propeller design, then, is to show a plot of torque coefficient versus advance coefficient, or Kq versus J. Any two propellers with the same P/D ratio, regardless of size, speed, power, or RPM will have Kq-J curves that differ only due to differences in design details.

The thrust developed by a propeller can be treated in a similar manner, with thrust coefficient (Kt) expressed as:

$$\mathbf{Kt = Thrust/(rho*n^2*D^4)}$$

where rho = density of fluid
n = rotation per second
D = diameter

The factors are similar to the Kq factors, except that diameter is only raised to the fourth power because the moment arm term is absent.

Thrust coefficient is usually shown on the same plot with torque coefficient, both as a function of advance coefficient. Efficiency, which is simply the useful work done by thrust (thrust times advance velocity) divided by the work absorbed (torque times angular velocity) works out to Kt*J/(Kq*2*pi), can also be plotted along with thrust and torque. These plots, usually derived from instrumented flow channel test of propeller models, are referred to as propeller curves.

For the special case of surface propellers, Hadler & Hecker have published some of the most useful data to date. Although their experiments did not include a complete family of propeller designs, the models that were tested can be used as benchmarks from which the thrust, torque, and efficiency characteristics of a reasonable range of propellers can be estimated. The published data is for three-bladed, superventilating designs, having expanded blade area ratios of around 0.50. P/D (pitch/diameter) ratios are 1.180 and 1.628.

METHODOLOGY

Propulsion analysis and propeller selection begins by estimating the resistance of the vessel at design speed. When resistance data cannot be supplied by the vessel designer or builder, Twin Disc calculates resistance by one of several standard analysis tools. By far, the most common for high-speed planing craft is the Savitsky method. This is a set of semi-empirical equations that predicts planing hull resistance based on vessel dimensions and mass properties. Twin Disc applies a correction developed by Blount and Fox, also known as the "M factor", which seems to improve the accuracy of results for heavier vessels in the transitional speed range. In addition, Twin Disc has developed its own correction for high dead-rise hulls operating at high speed. This correction reduces frictional resistance based on bottom aeration, and trial data indicates that it represents a significant improvement over the unmodified Savitsky equations.

Resistance can also be represented as effective horsepower, which is simply the product of resistance and speed, converted to units of 550 ft-lb/sec.

Once vessel resistance is established, a set of propellers must be selected that produces thrust in excess of resistance. The propeller analysis program now in use allows for instantaneous trial of candidate propellers, gear ratios, drive trim angle, and power input until the most satisfactory design is achieved.

This program is based on the Kq and Kt curves for the two propeller models, as reported by Hadler & Hecker. After calculating advance coefficient for each model to match the slip of the real propeller, Kq and Kt are interpolated based on the actual P/D. Empirical adjustments are made to account for number of blades, differences in expanded blade area ratio, and cavitation (really ventilation) number. An upper limit is set on allowable propeller slip, based on mid-range performance problems that can sometimes arise if the propeller is strictly optimized for design speed only.

The accuracy of this method is, of course, somewhat limited due to the scarcity of data points. However, there has been considerable progress in the detail design of surface-piercing propellers since this data was published in 1968. Propeller performance estimates, therefore, tend to be somewhat conservative, despite the limitations of the method.

It should be noted that the analysis technique does not distinguish among the three principal families of propeller designs currently used for surface-piercing applications. The choice of "Lo-rake", Hi-rake", or "Cleaver" style is based on vessel speed, cavitation number, and experience with successful applications.

In general, Lo-rake propellers, which bear a superficial resemblance to conventional fully-submerged propellers, are recommended for vessels up to approximately 50 knots. Lo-rake propellers have been used successfully, however, at speeds up to 70 knots. For speeds above 60 knots, Cleaver style propellers are generally preferred. The Hi-rake style, which is a development of the cleaver, is sometimes recommended for the 45-60 knot speed range.

Peak efficiency at rated engine power and RPM is only one of the objectives of propeller selection. Cruise efficiency, ability to achieve planing speed, and margin for power reduction due to gear losses and off-nominal ambient conditions must all be considered. Although there is a need for more reliable and complete open-water tank data for surface-piercing propellers, Twin Disc has had considerable success in predicting the performance of surface-piercing propellers based on the limited data that is available.