Marine Engine Application and Installation Guide

• Boat Performance

- Tolerances on Hull, Propeller and Engine
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Tolerances on Hull, Propeller and Engine

The performance of the boat is the result of a complex interaction of all three aspects of the installation; the engine, the hull, and the propeller.

Proper component sizing is very important to the life and performance of the entire propulsion system. There are tolerances in several aspects of the propulsion system. In worst-case conditions, the result can be short life and/or unsatisfactory performance. For example: the effect of these tolerances is shown below in Figure 2.1:

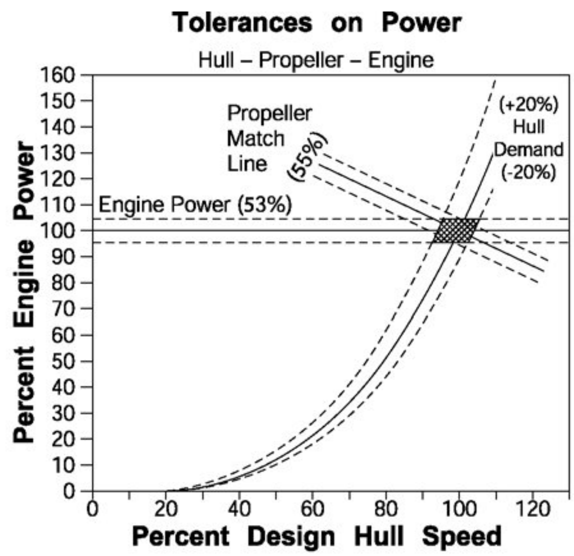

Figure 2.1

Mechanically controlled marine engine power may be expected to vary due to manufacturing tolerance by as much as 3% on either side of its rated or 100% power. Electronically controlled engines can easily be reset and all Caterpillar marine engines are reset at the factory for advertised rated power at rated speed.

The propeller power absorption may be as much as 5% higher or lower than originally expected. This could result from manufacturing tolerance in pitch, surface finish, and blade profile.

The hull resistance may vary as much as 20% from calculated values or previous experience due to inevitable differences in weight and shape.

Propeller Sizing

The propeller is as important as the hull or the engine to the performance of the boat. The propeller directly influences top speed, fuel efficiency, and engine life.

General Information

While many operators will choose to operate at reduced throttle settings while cruising, the engine must be able to reach its rated speed (rpm) when the boat is ready for sea; fully loaded with fuel, water, and stores. To achieve the ultimate in engine life and economy, most engines should operate approximately 1-3% over full load rated engine speed (rpm) at sea trail. This is done to compensate for anticipated boat loading and hull fouling. However, some engine models may require different target speed at sea trial. Refer to the Project Guide for your particular engine model for any special guidance on target speed at sea trial.

Table of Engine rpm at Sea Trials

Rated Speed (rpm)	Expected Engine Speed During Sea Trials* (rpm)
2800	2820-2850
2500	2520-2550
2400	2420-2450
2300	2320-2350
2100	2120-2150
1925	1945-1980
1800	1820-1850

*Unless otherwise specified in Engine Project Guide

Eliminating Engine Overloading on Over-wheeled Vessels

When the engine speed (rpm) measured during the sea trial of a vessel fails to attain the required sea trial speed, the reason generally is one of the following:

Excessive hull fouling — Solvable by cleaning the hull and re-running the sea trial.

Low engine power — Resolved by measuring and recording engine performance parameters such as inlet air temperature, exhaust backpressure, boost and fuel rate.

Incorrect transmission or propeller — A detailed listing of four alternative resolutions for this condition follows; these resolutions are restricted to fixed pitch propellers.

> **1) Engine fuel setting adjustment** — Many vessel operators and shipyards want to increase the engine fuel to the engine by changing the rack setting or, with electronic engines, change the FLS and FTS when their engine does not reach rated speed during sea trials. At first glance, this seems to be the easiest and least costly remedy. However, in such a situation, this solution is incorrect, even if the engine speed (rpm) does increase to the expected rated rpm. Increasing the fuel (rack) setting will result in reduced engine life, increased wear or, in worst case, early engine failure. The vessel operator's engine repair and maintenance costs will likely far exceed the cost of replacing or modifying the existing transmission or propeller.

2) High idle adjustment — Another often-considered alternative is increasing high idle engine speed on mechanical engines above the specified free running speed. This will not provide the desired results since the fuel stop is already at the maximum fuel position, and an increase in high idle will not result in any appreciable speed change.

3) Properly sized propeller and/or reduction ratio — The correct, but more costly, remedy is to re-pitch, or install a properly matched propeller and/or transmission ratio to allow the engine to operate within its rating guidelines.

4) Avoiding driveline component changes — There is another alternative that we will consider in cases where driveline component changes cannot or will not be considered. This method consists of a reduction of both the engine fuel setting and the high idle speed. This can only be done with mechanically controlled engines. Of course, the engine power and rated speed are reduced in the process; however, we are taking advantage of the fact that the propeller's power demand drops off much faster than the engine power capability when engine and propeller speed is reduced (refer to Figure 2.2).

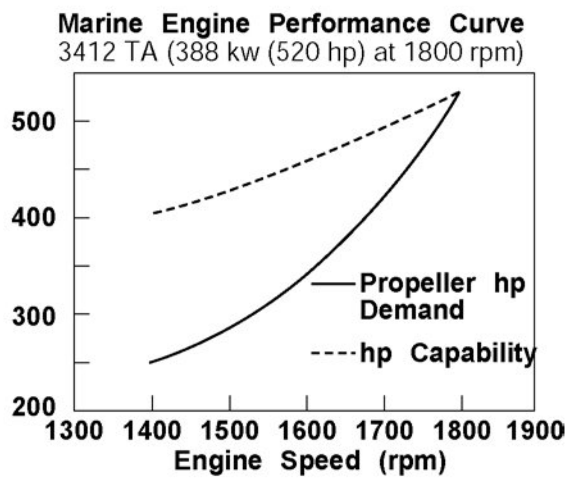

Figure 2.2

The net result is that the engine will perform within its application limits and the engine/propeller match is optimized. The following formula generally applies for a standard fixed pitch propeller:

$$\frac{\mathbf{hp}_1}{\mathbf{hp}_2} = \left[\frac{\mathbf{N}_1}{\mathbf{N}_2}\right]^3$$

or by rewriting the equation

$$\mathbf{hp}_2 = \mathbf{hp}_1 \times \left[\frac{\mathbf{N}_2}{\mathbf{N}_1}\right]^3$$

Where:

hp1 = Engine power produced at the full throttle speed recorded during the sea trial. This power level is determined by referring to the appropriate marine engine performance curve corresponding to the original engine rating sold by the dealer and reading the power on the curve at the recorded speed.

hp2 = Calculated propeller power demand at the new reduced engine speed (rpm) proposed for this application.

N1 = Engine speed (rpm) observed and recorded during the original sea trial — prior to fuel setting and high idle modifications. (This speed should always be measured with a precision tachometer.)

N2 = New, reduced engine speed (rpm) which must be determined in order to provide an acceptable engine, transmission, and propeller match.

For example: Consider a 3408B DITA engine, sold at a continuous rating of 365 hp at 1800 rpm. During the sea trial, the maximum attainable engine speed was only 1620 rpm. This engine was operating in an unacceptable overload (or *lug*) condition. The Marine Engine Performance Curve (for a continuous rating of 272 kw [365 hp] at 1800 rpm) indicates that the engine was producing (and the propeller was demanding) 344 hp at the limited speed of 1620 rpm. This power requirement exceeds the approved continuous rating of 330 hp at 1620 rpm. The solution is to further reduce the rpm until the approved engine rating, as shown on the 3408B marine engine rating maximum limit curve, exceeds the propeller demand.

For this example we will calculate the power required if the rated engine rpm was reduced to 1550.

$$\mathbf{hp}_2 = 334 \times \left[\frac{1550}{1620}\right]^3 = 301 \text{ hp}$$

Reducing the engine speed by 70 rpm has resulted in a decrease in propeller demand of 43 hp. The approved engine continuous rating at 1550 rpm is 314 hp and the propeller demand has been reduced to 301 hp.

At the initial trials, the recorded vessel speed was 10.2 knots for this 21 m long seiner. Resetting the engine from 344 hp @ 1620 rpm to 314 hp @ 1550 rpm would decrease the vessel speed to 9.7 knots, a relatively insignificant difference, especially considering the gain in engine life.

Propeller Pitch Correction

An over-pitched propeller must have its pitch reduced to allow the engine to reach rated rpm. The pitch must be reduced by an amount proportional to the engine rpm ratio. The following formula defines this relationship:

$$\text{P required} = \text{P present} \times \frac{\text{Engine rpm while over loaded}}{\text{Desired Engine rpm}}$$

Where:

P required = pitch the propeller must have to allow the engine to run at rated rpm

P present = pitch of the propeller which is preventing the engine from reaching its rated rpm

Engine rpm while overloaded = engine rpm under normal working conditions when equipped with the propeller whose pitch is too great

Desired Engine rpm = desired expected engine speed during sea trial (See Table p.3)

Propeller Errors and Propeller Measurement

Fast boats need more precise propellers than slow speed workboats. Propeller pitch errors that would be insignificant on a 10-knot river tow boat, will cost a high speed patrol boat or yacht 2 or 3 knots of its top speed.

Propellers on fast boats must be precisely manufactured if design performance is to be attained and they must remain within nearly new specifications to prevent severe performance deterioration. This is particularly true of propellers' leading and trailing edges. Tiny errors in profile, almost too small to be detected by feel, can constitute sites for initiation of cavitation. In severe cases, this can result in blade failure or loss after as little as 24 hours of high speed running.

Most industry professionals can relate instances where new propellers have been found to be several inches out of the specified pitch. When propellers are repaired or re-pitched, it is even more difficult to restore the necessary precision for highest performance vessels. The problem usually is the tooling. Most propeller pitch measurement machines cannot resolve or detect the small errors that prevent a boat from attaining first-class performance. All other things being equal, the skill of the propeller-finishing machinist will make the difference between barely-adequate and first-class boat performance.

Propeller Measurement Tools

There are several basic types of tools commonly used for propeller pitch measurement:

Swing Arm Type

This machine generally consists of a stand which supports the propeller in a horizontal position, a vertical column which passes through the center of the propeller's hub, a swing arm which rotates around the vertical column, and a vertical measuring rod which can slide in and out on the swing arm.

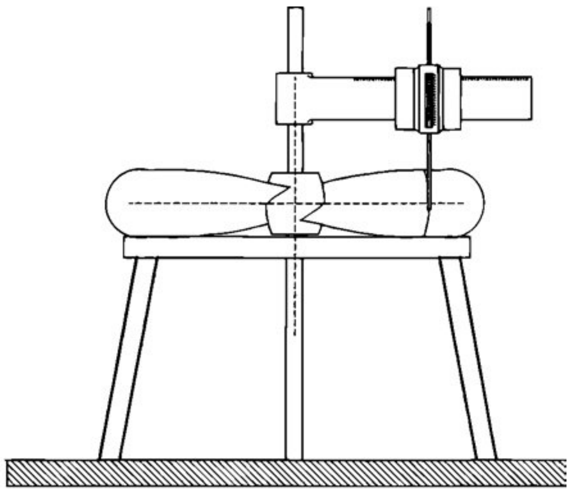

Figure 2.3

This machine reaches down from a horizontally mounted swing arm and "touches" the blade at several radial locations, at some standard increments of angle. The difference in elevation, the radial position, and the angular increment between readings allow pitch to be calculated between any two locations. The accuracy of this device is related to the rigidity of the swing arm and the degree of looseness in the required bearings. The potential accuracy of the propellers measured will be directly proportional to the number of measurements on each blade (places at which it touches each blade). For commercial (workboat) propellers, it is common to examine the blade at six to nine places per blade. On high-performance civilian propellers, it is common to examine each blade at twenty-five to fifty places while military propellers may be examined at several hundred places per blade. The skill of the machinist is applied in smoothing or "fairing" the areas between the measurements.

Pitch Blocks

Pitch blocks are precisely shaped anvils, against which individual propeller blades are hammered to repair or correct their shape. They can be used to measure propellers by comparing the shape of an unknown propeller to a set of incremental pitch blocks until a match is found.

Angle-Measuring Type

Angle-measuring devices relate the angle of a circumferential line on the blade to a horizontal reference plane and calculate the pitch from the angle and the radial position.

Ducted Propellers (Kort Nozzles)

The propeller duct, sometimes called a Kort nozzle is a ring, wrapped around a generally square-tipped, propeller. The ring has an airfoil-shaped cross section.

The ducted propeller is best used on vessels such as trawlers, tugs, and towboats with towing speeds of 3-10 knots. Ducted propellers should not be used on relatively fast vessels.

To aid in selection, perform the following calculation. If the result is less than 30, the use of the ducted propeller should not be considered as it may result in a net loss of vessel performance.

$$B_p = (\mathbf{srpm}) \left(\frac{\sqrt{\mathbf{shp}}}{(V_a)^{2.5}} \right)$$

Where:

Bp = Basic Propeller Design Variable
srpm = Propeller Shaft Speed (rpm)
shp = Shaft Horsepower (shp)
Va = Velocity of Advance of the Propeller (knots) generally equals 0.7 to 0.9 times boat speed

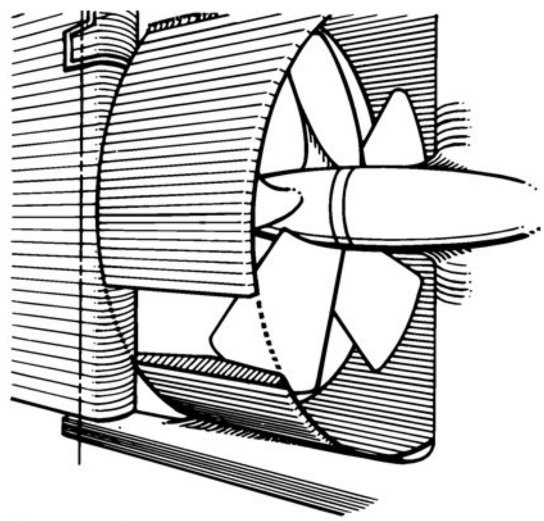

Figure 2.4

The nozzle configuration or profile most often used is a No. 19A nozzle although a No. 37 specifically designed for backing is obtainable. Nozzles are made of mild steel with a stainless steel liner to stand up to erosion. They may be mounted to steel, wood, or fiberglass hulls.

A comparison of bollard pull ahead and astern for the open water propeller versus the No. 19A (taken as 100% in ahead) and the No. 37 nozzle follows.

	Ahead	Astern
Nozzle No. 19A	100%	59%
Nozzle No. 37	99%	82%
Open Propeller (B4.70 Type)	69%	55%

These are actual figures for a 1491 kW (2000 hp) installation with 2007 mm (79 inch) diameter propellers. A larger diameter open propeller would show up somewhat better, though not as good as the nozzles.

More specific information on ducted propeller systems generally can be obtained from propeller manufacturers, many of which also manufacture propeller ducts.

Hull Types

All hull types discussed here refer only to the portion of the hull below the waterline. What is above the waterline concerns seaworthiness, seakindliness, stability, comfort, and eye appeal, but has little impact on the propulsion machinery.

There are two basic types of hulls: Displacement Hulls and Planing Hulls. There are also some special types of hulls. These include the Semi-Displacement Hull, Catamaran, Wave-Piercing Catamaran, Hydrofoil, Surface Effects Ship (with both flexible skirts and rigid sidewalls), and the Small-Waterplane-Area-Twin-Hull (SWATH) Ship.

Displacement Hull

A displacement hull can be described in most basic terms as a block, with tapered ends. To illustrate the basic shapes this allows, five blocks in what are rearranged to form four simple, but fundamental forms cover most all displacement hull forms.

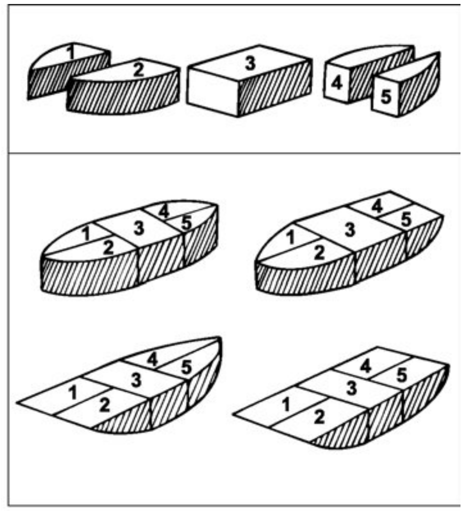

Figure 2.5

Keep in mind that this discussion concerns only the portion of the hull below the waterline and that the blocks represent only the submerged part of the hull.

When any one of the hulls shown above moves through the water, waves form. The bow pushes the water aside, forming a bow wave. The momentum imparted to the water carries it beyond the boundaries of the hull, leaving a hollow behind it. The wave surges back, into the hollow. At slow speeds, this causes the return surge to bounce off the hull, starting the familiar diverging pattern of troughs and crests originating with the bow wave.

Relation of Hull Length to Boat Speed

The length of a displacement hull determines its eventual top speed. It is literally possible to measure the length of a displacement hull and calculate its highest practical top speed based on this measurement. This is due to the relationship of boat speed, boat length and wave-length.

Boat Length and Wave Length

Wave-length and wave speed are directly proportional: the faster a wave, the longer its length. Since the movement of the hull causes the bow wave, the faster the hull moves, the faster the speed of the bow wave . . . and the longer its length.

As the boat increases its speed, the length of the bow wave will eventually approach the length of the hull. The speed at which the length of the bow wave equals the hull length is called the hull speed limit.

Further increases in hull speed, beyond the hull speed limit, will cause the stern of the hull to drop into the trough of the bow wave.

This has the following bad effects:

- air can enter the displacement hull's propeller(s) (reducing propeller thrust)
- the belly of the hull is exposed to the oncoming waves (increasing hull resistance)
- the increased incline of the propeller shaft(s) reduces the amount of shaft thrust for forward motion (part of the forward component of propeller thrust is wasted in holding up the stern of the boat).

This greatly increases the hull's resistance-to-further-speed-increase. To go faster, the displacement hull must climb the crest of its own bow wave. For example, the last 10% of a displacement hull's top speed costs 27% of its engine power (and fuel consumption).

Mathematical Representation of Hull Speed Ratio

This relationship can be described mathematically.

$$\text{Hull Speed Ratio (SLR)} = \frac{\text{Boat Speed}}{\sqrt{\text{Hull Length}}}$$

When the bow wave length is equal to the hull length, the speed length ratio formula can be expressed as follows:

$$4.5 \sqrt{(\text{Hull Length}_{\text{meters}})} = (\text{Boat Speed}_{\text{km/hr}})$$

or

$$1.34 \sqrt{(\text{Hull Length}_{\text{feet}})} = (\text{Boat Speed}_{\text{knots}})$$

Planing Hull

The planing hull skims over the surface of the water with relatively little disturbance of the water. The main resistance to planing hull speed is the skin friction. Hulls of this type are very sensitive to the smoothness of the hull, making good hull maintenance essential for top performance. Planing hulls are very sensitive to boat weight.

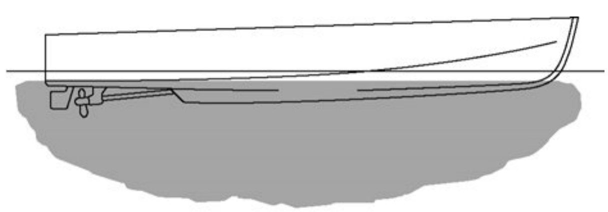

Figure 2.6

Semi-Displacement Hull

The semi-displacement hull looks very much like the planing hull and is easily mistaken for the planing hull. Semi-displacement hulls can be described as having characteristics of both planing and displacement hulls but are not one or the other.

Displacement hulls have trouble with speed length ratios above 4.5 (1.34) due to their hull shape. The planing hulls have difficulties below speed length ratios of approximately 8.4 (2.5) because of their straight fore-and-aft lines.

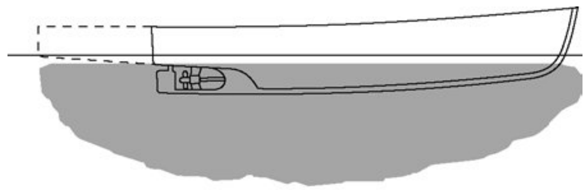

Figure 2.7

Semi-displacement hulls are designed to operate well in this speed range.

Semi-displacement hulls are characterized by the angle of the quarter-beam after-body buttock line. Visualize a pair of vertical, parallel planes intersecting the hull — midway from the longitudinal center of the hull — to the waterline at the side of the boat. The intersection of the planes — with the bottom of the hull near the stern — form the quarter-beam after-body buttock line (there are two, one on each side, but they have the same shape). The angle of the quarter-beam buttock line is formed between it and a line parallel to the at-rest waterline, fig. 2.8.

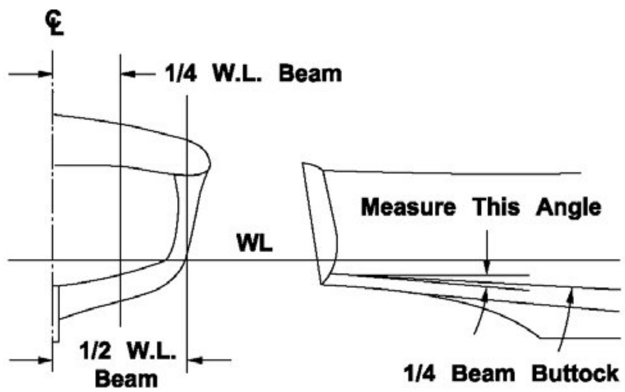

Figure 2.8

If the angle of the quarter-beam buttock line is very small (less than 2 degrees), the hull is capable of planing performance. At an angle of 4 degrees, the limiting speed length ratio will be around 2.0. An angle of 7 degrees will limit the speed to length ratios of 1.5, or just above displacement hull speeds. These angles should be measured relative to the hull's waterline at rest.

Rules of Thumb

Power to Reach Hull Speed

A useful rule of thumb for vessels below 100 tons displacement is:

Power to Reach Hull Speed horsepower = 5 x [Displacement long tons]

Fuel Consumption

A useful rule of thumb for basic budgetary purposes is:

Fuel Consumption = 1 Liter per hour per 5 horsepower