Engine Power Curves

Understanding Engine Performance and Engine Performance Curves, and Fuel Tankage and Range Calcuations

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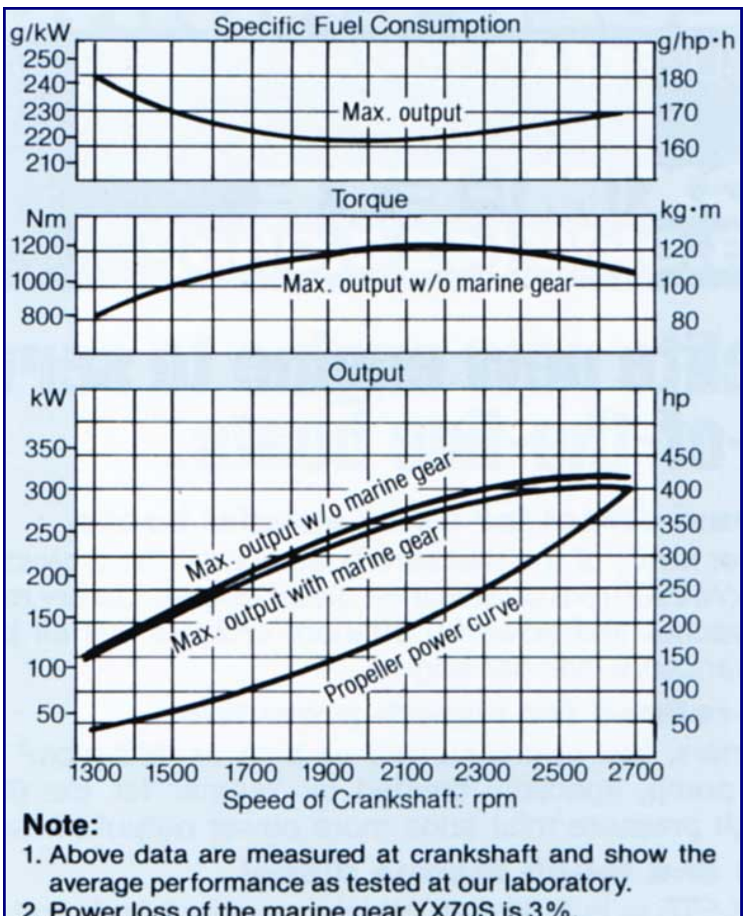
Deep in the bilge of the boat you're designing, building, surveying, repairing, or operating is her beating heart—her engine. The recipient of endless tuning, cleaning, and fuss, it's the boat's engine that drives her from anchorage to anchorage. Engines, however, come in a wide array of sizes, shapes, and flavors. Whether you're repowering, determining which propulsion-package option to install in a new boat, trying to optimize performance on an existing boat, or to understand why an engine isn't achieving full rated RPM, good information on engine behavior can seem hard to come by. The key to deciphering engine performance is the performance curves that are included with the engine manufacturer's literature. We'll examine these curves here.

Let's take a look at a fairly typical high-output diesel, the Yanmar 6CX(M)-ETE, and see what her curves will tell us. A pair of these might drive a 35-foot sportfisherman; or a single engine could propel a 65-foot motorcruiser. The info' sheets for this engine are handy because they happen to have all the usual curves. Some manufacturers don't include the torque curve or, sometimes, the fuel-consumption curve. At any rate, there are five standard performance curves:

1) Maximum output power without reduction gear
2) Maximum output power after marine reduction gear
3) Propeller power curve
4) Torque curve
5) Specific fuel consumption



Yanmar 6CX(M)-ETE Performance Curves

Between them, pretty much everything you need to know about this engine's performance is spelled out.

Maximum Output Power - BHP

The maximum output power curve is just what it says. It shows the maximum power that the engine can produce (in ideal conditions) at any given RPM. This is also called "brake horsepower" or BHP because in the old days it was measured on a gizmo termed a "Prony brake"— a form of dynamometer. These days other types of dynos are used, but the result is the same. Note that the brake horsepower is maximum in every regard—tested on a bench in a shop and before the reduction gear. Real power in the hot humid bilge of a boat may be somewhat lower. For our 420-HP CX Yanmar, the maximum rated BHP is 420 HP, at 2,700 RPM. The units for power on the graph are—as you'd expect—horsepower on the right and the metric equivalent on the left, kilowatts.

Output Power With Marine Gear - SHP

Of course, almost all engines engine have a reverse/reduction gear mounted on their tails. The reduction gear not only allows the boat to back up (which I'm told is useful), but it's what allows you, the designer, to match the torque characteristics of the engine to the optimum propeller. All this is both proper and also unavoidable. Like all other machines, however (and the reduction gear is nothing more than a machine with lots of moving parts) reduction gears have built in power losses due to friction. Standard marine gears fritter

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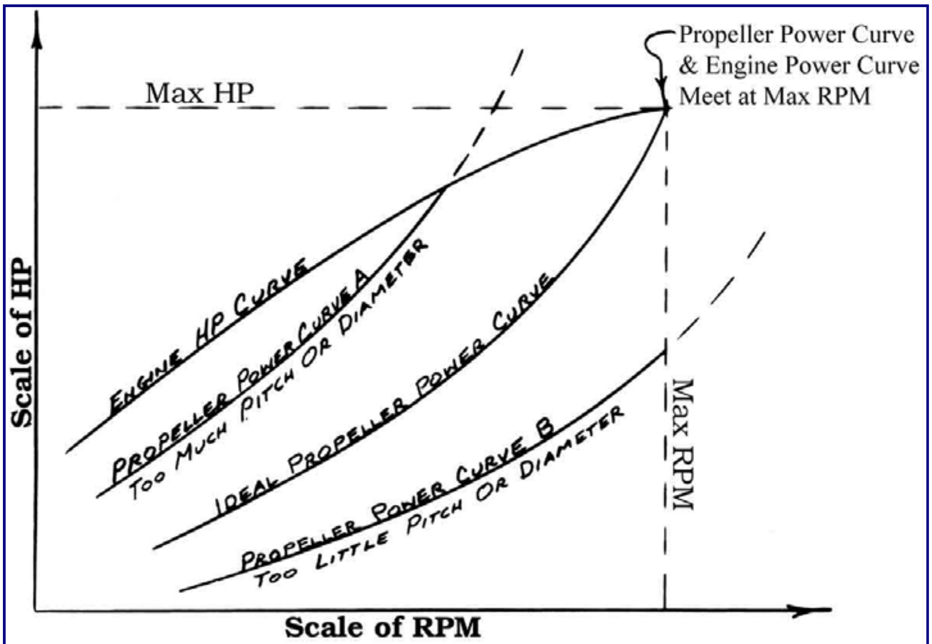
away about 3 percent of power as they do their required job. This means that the maximum "output power with marine gear" or the SHP is reduced to 407.4 HP [420 HP x 0.97 = 407.4 HP.] This is sometimes called "shaft horsepower" or SHP. It is what the curve just below the maximum output power curve is showing—the maximum power at each RPM, minus 3 percent.
In reality, this isn't true shaft horsepower. There is still another source of loss due to friction—the shaft bearings. Generally, you lose about 0.5 percent of power for each bearing, so—with one or two shaft bearings—the true power the propeller sees is about 96 percent of brake horsepower or 403 HP for this engine. (If there's a remote V-drive, subtract another 2 percent of power for it.)

Propeller Power Curve

So far so good, but the propeller power curve makes things more entertaining. What is it showing? Well, remember that the BHP curve is generated by testing the engine in a lab to get the maximum power that the engine can deliver at each RPM. The word "can" is crucial. The fact is that the power the boat's propeller demands or absorbs increases or changes at a very different rate relative to RPMs than does the output power that your engine can deliver. What the propeller power curve shows is *approximately* the power that a standard propeller would be using at any given engine RPM. You can see just how different the shape between the two curves is—between the BHP (or SHP) curve and the propeller curve.



Propeller Power Curve Variations

This is unfortunate in a way as it controls a lot of things about propeller selection. If you installed a propeller that was too large in diameter or that had too much pitch, then the propeller curve (Propeller Power Curve A) would be shorter and steeper and would intersect the engine power curve at some point less than maximum 2,700 RPM, perhaps at 2,100 RPM. In this case, the propeller would be overloading the engine and lugging it down. This would limit speed, and would be bad for the engine. In fact, most engine warranties require that the propeller allow the engine to spin up to maximum RPMs or nearly so, otherwise any engine damage is likely to be blamed on overloading the engine and the warranty considered void.

Conversely, if the propeller had too little diameter or pitch the propeller power curve would flatten and extend out beyond and/or below the engine power curve (Propeller Power Curve B). In this case, the engine would spin up to max RPM with ease, but the prop would be too small to do useful work and, again, wouldn't drive the boat effectively.

The goal is to have the propeller sized and selected so its maximum power demand exactly matches the maximum power (shaft horsepower) produced by the engine and maximum rated RPM. Because the curves are such different shape, they can't meet at any other point, so this is a compromise, but the only one possible, and it's one that works well.

The way to make the power curves match up more closely at other RPMs is to use a controllable-pitch propeller. This is quite useful for vessels that operate under varying loads or run for long periods at different speeds, but the extra expense is not called for on most average boats.

The Missing Power Mystery

Okay, you may ask, but what about all that extra power that the engine is producing? If you look at the 420 CX Yanmar curves, it indicates that propeller power at 2,300 RPM is 250, but that the engine is putting out about 380 HP at that same speed. What happened to the missing 130 horsepower? The answer is that the engine isn't generating it. A diesel engine's power at any RPM is controlled by how much fuel is metered into the injectors. This engine could produce 380 HP at 2,300 RPM, but since the propeller is only absorbing 250 HP, less fuel is being injected into the cylinders and less fuel means less power—even at the same RPMs.

Of course, if you added an auxiliary load (perhaps a high-output alternator) then this could add another 15 HP of load

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above the propeller load. In this case, more fuel would automatically be injected to keep engine at our throttle-set 2,300 RPM and add an extra 15 HP of output power. You could keep on adding loads at this RPM until you reached the maximum rated 380 HP, at which time the engine would be overloaded, and you'd have to increase RPMs. Eventually, as you increase RPMs the propeller curve gradually rises until it crosses the engine power curve and there's no more extra power available.

In fact, the extra power we've been discussing here is a minor consideration. The reality is that the two upper power curves aren't what your propeller sees or uses. It's the propeller power curve that governs things. But you do want to reach maximum rated engine RPMs, or pretty darn close.

The Torque Curve

Toque is the twisting force on your prop shaft. You could have all the power in the world, but if the shaft didn't spin you'd have no torque and no go. Torque is actually defined mathematically with the formula:

Torque, in pound-feet = (5252 x HP) ÷ RPM
Or
Torque, KGM = (975.175 x kW) ÷ RPM

The torque curve shows the torque generated by this engine at various RPMs. The interesting thing is that maximum torque on normal internal-combustion engines doesn't occur at maximum engine rated power and RPM. In fact, the torque curve of the 420 CX Yanmar is pretty typical. The maximum torque occurs at about 77 percent of maximum RPM, or 2,100 RPM. Indeed, on most engines maximum torque falls somewhere between about 55 percent and 80 percent of max RPM. (Light gas engines tend to have peak torque at lower engine RPMs and heavy diesels at higher RPMs.) The units for the torque curve are in kgm (kilogram meters) and Nm (Newton meters). This is the metric equivalent of pound feet. We're not particularly concerned with the absolute numbers; however, we're simply interested in where torque is highest.

It simple terms, the 420 CX Yanmar is delivering the most oomph per gallon of fuel consumed from 2,100 RPM. This wouldn't be a bad low-cruising speed, but you don't unnecessarily want to limit operating speed this much. Let's see how fuel consumption fits into the picture.

Units of Torque

In the English system torque is measured in rather consistent "pound-feet." The Yanmar (being a Japanese engine) has its torque measured in metric units. For torque the engine graph reads in "kg·m" on one side and in "Nm" on the other side. These are (currently) the two standard metric units for torque. kg·m is kilogram meters (the old metric torque measure commonly noted as kgm), while Nm is Newton meters (the new metric torque measure). Kilograms are units of weight or force and, to be absolutely accurate, engineers should use the designation "kgf" (kilograms of force) rather than just plain "kg." Of course, it's usually omitted because it's obvious. Newtons are the new metric measure of force only. Newtons can't ever be mass. This makes them technically "better." The bottom line is that pound-feet, kg·m, and Nm are all measures of torque.

Specific Fuel Consumption

The specific fuel consumption curve reads—as is often the case—in rather inconvenient units. In this instance, in grams per horsepower per hour (g/hp·h) and in grams per kilowatt per hour (g/kW). For the moment, though, what we're really interested in is the shape of the curve and where fuel consumption is lowest for the output power and torque. In other words—just the opposite of the power and torque curves—the best spot on the specific fuel consumption curve is where it's lowest. For the 420 CX Yanmar, this is at 2,000 RPM.

Since we already know that the optimum torque is at 2,100 RPM, you could say that you'd get the most bang for the buck out of this engine at 2,050 RPM — a combination of best fuel efficiency and most oomph.

As for the curve of specific fuel consumption, this is inconvenient in more ways than simply converting grams per horsepower hour to sensible units such as liters per kilowatt per hour or gallons per horsepower hour. This isn't because the conversion is difficult (it isn't) but because almost every engine's specific fuel consumption curve seems to understate the real-world, in-the-boat fuel consumption.

In practice, I've found that almost all diesel engines consume approximately 0.054 gallons per horsepower per hour. Or (restated to make things simpler still) simply divide the propeller power curve power at any RPM by 18.5 to find fuel consumption in real service in gallons per hour.

For the 420 CX Yanmar, propeller output power at 2,300 RPM is 250 HP, so fuel consumption at this RPM (assuming the propeller is properly matched) is 13.5 gal./hr. [250 HP ÷ 18.5 = 13.5 gal./hr.], while at maximum 2,700 RPM fuel consumption is 22.7 gal./hr. (The shape of the specific fuel consumption curve and its point of maximum and minimum consumption are usually quite accurate in service, just not the absolute consumption numbers indicated.)

Determining Optimum Cruising Speed

So far, we've seen what the engine performance curves mean and that maximum oomph and fuel efficiency occur for this engine at between 2,000 and 2,100 RPM. Is this the proper cruising speed? Well, an argument can be made for

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this in terms of sheer efficiency, but it'd be a bit slow. Instead, we can look at the performance curves to determine where the best compromise between efficiency and speed falls. In this case, 2,300 RPM looks like a good bet. At 2,300, torque is still high, specific fuel consumption is still low, and we're getting a reasonable 250 HP at the propeller. Low cruise, for quiet, efficiency, and maximum range would be around 2,000 RPM, and you'd only open her up to 2,700 from time to time to show off or outrun a storm.

Estimating Fuel Tankage and Range

For either power or sailboats, once you've determined the size of the engine(s) you will install, you need to determine how much fuel to carry in order to meet the range requirements of your design.

For gasoline engines fuel consumption can be estimated as:

Gal./hr. = 0.10 x HP
or
Liters/hr. = 0.508 x KWprop

For diesel engines fuel consumption can be estimated as:

Gal./hr. = 0.054 x HP
Or
Liters/hr. = 0.274 x KWprop

Where:
HP = Propeller Horsepower, from prop-HP curve
KWprop = Kilowatts, from prop-power curve

Though performance curves from some engine manufacturers may indicate thriftier fuel consumption, my experience is that, in the real world, the above numbers are usually about right. They are a bit conservative (normally, the numbers above slightly overestimate consumption, but this is good as you want to ensure you have enough fuel on board to meet the range requirements for the design.

Keep in mind that boats are not run constantly at full throttle. You can assume that diesels will be cruised at 80% of maximum RPM and gasoline engines at about 70% of maximum RPM. This is not 80% and 70% of power output. In fact, engine power falls off very quickly.

Look at the power curves for the 420-hp (313 kw) Yanmar diesel. You'll see there are two power curves—the engine power curve (with and without gear, in this case) and the propeller power curve. The propeller power curve is the one that indicates approximately how much power the propeller will be drawing at any given engine speed (assuming the propeller has been properly selected to allow the engine to reach maximum rated RPM). You can see from the propeller power curve that this engine delivers 420 hp (313 kw), at 2,700 rpm, but at 80% of max RPM (2,160), the propeller power curve shows that it's only delivering 217 hp (162 kw). This, in fact would be the power for cruising speed. You need to:

- Calculate the speed the boat will go at this power (cruising speed)
- Calculate the gallons per hour at this horsepower (at cruising horsepower)
- Determine how many gallons you need to make the required range at this speed (cruising speed)

Assume that this is a 30-foot (9 m) LOA planing hull. Your speed calculations show that top speed (at full power) is 30.5 knots, at which speed consumption is:

0.054 x 420 BHP = 22.7 Gal./hr.
Or
0.274 x 313 KWengine = 85.7 Liters/hr.

At cruise speed (2,160 RPM and 217 hp—162 kw) speed will be 20.3 knots, and consumption is:

0.054 x 217 BHP = 11.7 Gal./hr.
Or
0.274 x 162 KWengine = 44.47 Liters/hr.

Say you want a range of 750 nautical miles.
750 miles ÷ 20.3 knots = 36.9 hours running time
36.9 hours x 11.7 gal./hr. = 432 gal.
Always add a 10% reserve so
432 gal. x 1.1 = 475 gal. diesel

or

Say, you wanted a range of 750 nautical miles.
750 miles ÷ 20.3 knots = 36.9 hours running time
36.9 hours x 44.4 l/hr. = 1638 l
Always add a 10% reserve so
1638 l x 1.1 = 1802 l diesel

On a boat of this size and type, the fuel would usually be carried in twin wing tanks of 238 gallons or 900 liters each.

NOTE: If you don't have any engine curves available, you can estimate that the propeller power at various RPMs as follows:

90% of max RPM = about 68% of max rated engine power
80% of max RPM = about 48% of max rated engine power
70% of max RPM = about 30% of max rated engine power
60% of max RPM = about 22% of max rated engine power
50% of max RPM = about 15% of max rated engine power
40% of max RPM = about 11% of max rated engine power