Folding prop *gear test*

Folding propellors are perhaps the most expensive and least understood gear under the water line. In this must read article, Nigel Calder, well-known author, tests leading folding propellors for fuel efficiency and explains the factors that affect them.

RIGHT: Barnacle growth on any prop will dramatically reduce efficiency.

FOR THE PAST three years the European Union funded HYbrid MARine (HYMAR) project has enabled me to collect a mass of performance data from a conventional displacement hull. This data is being used as a baseline against which we are comparing the performance of hybrid propulsion systems. The data we have collected so far provides excellent insights into the relationship between propellers, hull resistance curves, engine fuel maps, and efficiency.

The test boat

Our test boat, 'Nada', is a Malo 46 sailboat built in Sweden. The engine is a Volvo-Penta D2-75, which uses a 2.2 liter turbocharged Perkins block with about as good fuel efficiency as anything on the market in this power range. The engine operates at a maximum 3,000 rpm, as opposed to the more common 3,600 rpm, and drives the propeller through a 2.74:1 reduction gear, which is somewhat higher than is typical. The net result is to slow the shaft speed down over similar installations, enabling us to swing a larger diameter, and thus inherently more efficient, propeller than would be the norm.

The propellers we have tested are:

- A latest generation Volvo-Penta 22"x18" 4-bladed folding propeller
- A Bruntons Propellers 566 mm diameter 'Autoprop'
- A Bruntons Propellers 590 mm 'Autoprop'
- A Gori 22"x17" 3-bladed folding propeller on which the blades rotate to create two different pitches, which I will refer to as the 'normal' mode and the 'overdrive' mode
- A 23" MaxProp 4-bladed feathering propeller with adjustable pitch, which we set to 20", 22" and 24" pitch
- A Varifold 22"x15" 4-bladed folding propeller
- A Flex-O-Fold 22"x17" 3-bladed folding propeller
- A 19"x14" conventional fixed 3-bladed propeller

These propellers include a variety of technologies, and cover the range from under propping (the fixed propeller – the engine overspeeded and was still well below its full rated power output), 'correct' propping (the engine just reached full speed, at which point it was fully loaded), and 'over' propping (the prop load was such that the engine could not reach full speed).

We have a torque and rpm meter on the propeller shaft which enables us to accurately measure the power at the shaft (power is a function of torque x rpm). We also have an accurate fuel measuring device. During tests, we disable the alternators so that the only load is the propeller.

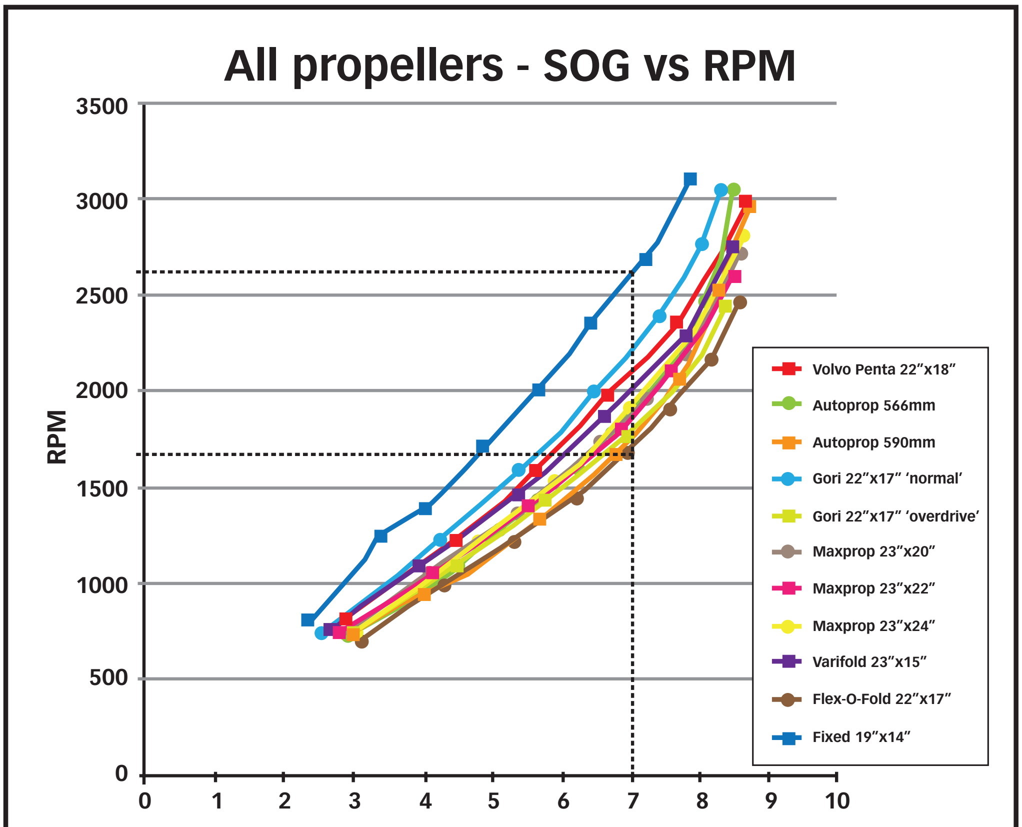


FIGURE 1

ABOVE: At 7 knots speed the RPM required to achieve this varied from 1,700 to 2,625 RPM.

RIGHT: The props tested are pictured at right.

OPPOSITE BELOW: Figure 2 shows for a given speed how much shaft energy was required to get there.

With power at the shaft and fuel flow rates we can calculate specific fuel consumption (SFC), which is the amount of fuel it takes to produce each unit of energy used. Since this is a European project, we are working in Newton-meters (Nm), kilowatts (kW) and liters (l).

Test procedures

From day one we discovered how difficult it is to do objective in-the-water testing. We had initially thought the ideal conditions would be no wind and flat water. However, if there is no wind, the faster you go the more apparent wind you create, and this has an effect on the results. Our preferred mode of operation is now flat water with a 10-20 knot beam wind, which is not an easy set of conditions to find. With the wind this strong, regardless of boat speed we can still keep it on the beam where it has little effect on the measurements.

Our methodology is to run back and forth over the same ground to cancel out tide effects. We start at engine idle speed and work up to full speed in increments of 200 rpm. At each engine speed we record three sets of readings in each direction. We are not getting laboratory-quality data, but what we are getting is about as good as can be done in the real world.

Next, we take the boat out into the open sea and drive 'Nada' straight into the waves to record 'rough water' performance. We have had unusually stormy summers in Sweden, so we have had plenty of rough water. At higher speeds, the boat sometimes slams violently. It's punishing work on us and the boat. The conditions are way too variable to collect objective data, so what we are trying to do is to gauge relative performance when the going gets tough.

We now have many megabytes of incomparable data that we are parsing for critical insights. This year we will do this all over again with an electric propulsion motor and diesel-driven generator. We will then be in a position to determine how best to optimize hybrid propulsion systems.

Engine speed versus boat speed

As you would expect given the wide variety of propellers, and the wide range in terms of how well they are matched to the engine, there is a wide variation in the engine speed needed to achieve a given boat speed. For example, at 7 knots the engine speed varies from 1700 rpm to 2625 rpm. The fixed 19" x 14" propeller stands out in as much as it was particularly undersized. The engine ran much faster for a given boat speed, and the top boat speed achieved was up to a knot slower than with the other propellers (see Figure 1). All the other propellers achieved similar top boat speeds, with the over-propped ones doing it at slower engine speeds than the properly-matched propellers.

It's tempting to think that those propellers which achieve a higher boat speed for a given engine speed are more efficient. It's an assumption made by many boat owners. However, it's far more complicated than this.

Boat speed versus shaft power

Figure 2 shows propeller shaft kilowatts (kW) for a given boat speed (SOG) for each propeller. Take a look at the undersized fixed propeller. It is right in the middle of the pack! In other words, in spite of the

fact that the engine is running much faster for a given boat speed, the amount of energy at the shaft that is required to get to that boat speed is pretty much the same as with the other propellers. When you think about it, this makes sense. It's not the engine speed that determines boat speed, but the amount of energy that is being put into the water. The more powerful propellers get to a given level of energy at a slower engine speed than the less powerful propellers.

Figure 2 provides us with a measure of relative propeller efficiency in this application (not system efficiency – this is something different, as we will see in a moment). If we take a given boat speed, we can see how much shaft energy it takes to get there with the different propellers. For example, at 7 knots this varies from 16 to 20 kW, which is a

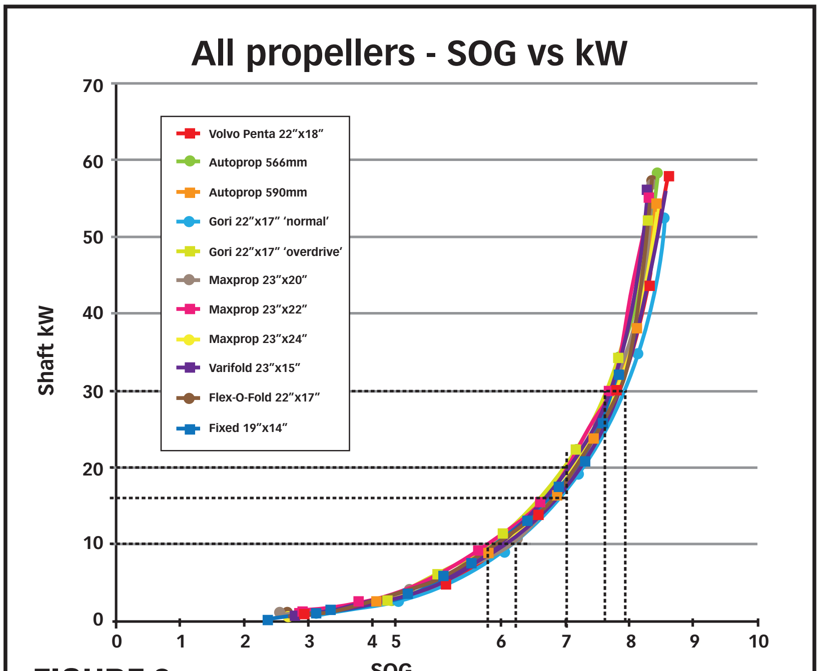


FIGURE 2

RIGHT (Figure 3): Note that the fixed prop offers substantially less fuel economy.

BELOW RIGHT (Figure 4): The fuel map shows how much fuel an engine burns per unit of energy produced and different engine speeds and loads.

MAIN IMAGE: Our test boat, *Nada*, being hauled and the props changed.

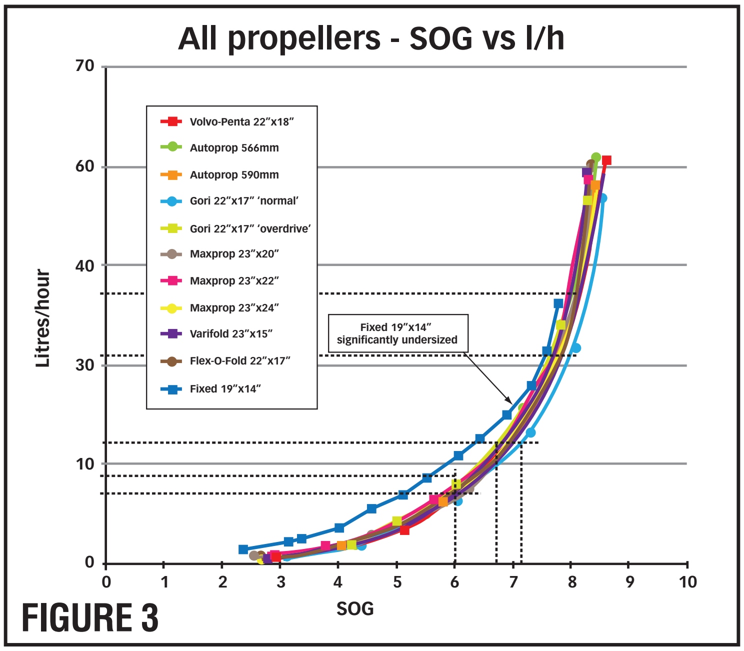


FIGURE 3

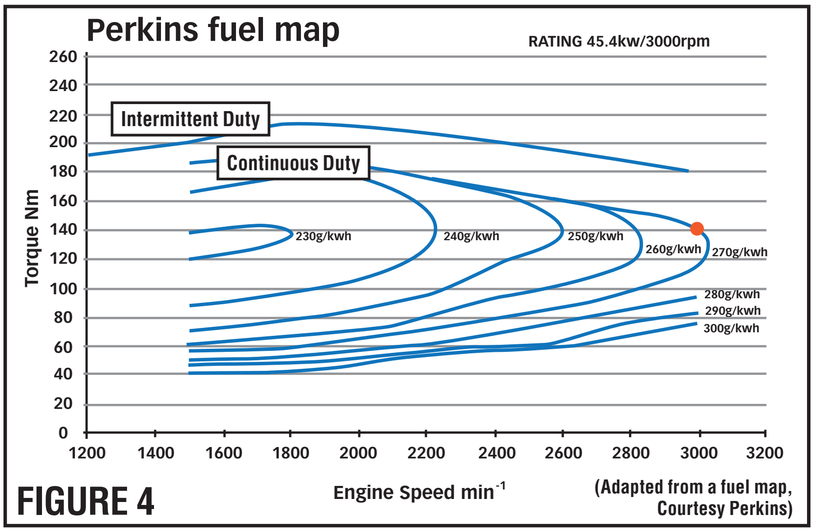


FIGURE 4

(Adapted from a fuel map, Courtesy Perkins)

25% range if we take 16 kW as the starting point, and a 20% range if we take 20 kW as the starting point. We can look at this another way, which is to take a given level of power at the propeller shaft and see how much the speed varies. For example, at 10 kW the range is from 5.8 to 6.2 knots for a variation of just 6-7%, while at 30 kW the range is from 7.6 to just under 8 knots for a variation of 4-5%. Clearly, depending on what point you want to prove, you can use the data in all kinds of different ways! In any event, to make detailed comparisons we would want to divide the propellers into three groups – under-sized, properly matched, and over-sized – and compare the propellers within each group, in which case the differences are less pronounced.

For propellers that were about equally matched to the boat and engine, the biggest factor in propeller efficiency seems to be blade shape. The latest generation of folding propellers (the Volvo-Penta, Flex-O-Fold, and Varifold in our test) all have blades with substantial camber and all performed consistently well. The MaxProp feathering propeller, which has very flat blades, lagged a little. However, there are things the folding propellers cannot do which the feathering can. Most important from the perspective of the HYMAR project is the ability to 'trick' a feathering propeller into remaining open when under sail so that it can be used to generate power off a free-wheeling propeller. This is difficult, and perhaps impossible, to do with the folding propellers (we will run some experiments on this later this year).

Fuel consumption

Now let's look at fuel consumption versus boat speed (Figure 3). This gives us a more accurate measure of the overall system efficiency with the different propellers.

The thing that really jumps out is the undersized fixed propeller, which was in the middle of the pack in terms of SOG v kW, but is now shown to have a substantially worse fuel economy. However, let's ignore this for the moment and look at the rest of the propellers. Once again, we can parse the data in a couple of different ways, looking at the amount of fuel consumed for a given boat speed, or the boat speed achieved for a given level of fuel consumption. For example, at 6 knots the fuel consumption is between 3.5 and 4.5 liters per hour while at 8 knots fuel consumption is between 10.5 and 13.5 liters. In both cases, this gives a variation of 22-30% (depending on whether you calculate this from the lower or the upper rate), which is quite significant. At 6 liters per hour fuel consumption, the speed ranges from 6.7 to 7.1 knots

for a variation of around 6%, which is not particularly significant. If we look at the numbers one way, there's a big difference in efficiency, and if we look at them another way, there's not much!

Fuel maps

Let's return to the undersized propeller and see what is going on here. For a given boat speed it required the same shaft kilowatts as the other propellers, so why is the engine burning significantly more fuel? To understand this, we need to look at the engine fuel map (Figure 4).

A fuel map shows us how much fuel an engine burns per unit of energy produced at different engine speeds and loads. The energy is measured at the flywheel rather than the propeller shaft and as such does not take account of losses in the drive train. In Figure 4, we have torque on the vertical axis and engine speed on the horizontal. The graph would be easier to understand if we had kilowatts on the vertical axis, but unfortunately I don't have this map (any kind of a fuel map is hard to obtain – the engine manufacturers tend to keep them close to their chests).

For those who want to go through the exercise, we can translate any part of the fuel map into kilowatts (at the flywheel) as follows: take the torque in Nm, multiply it by the rpm, and divide by 9549. For example, if we take the point circled on the fuel map at which the 140 Nm line intersects the 1800 rpm line we get: (140 x 1800)/9549 = 26.39 kW

At this point on the graph, we can see the engine is burning 230 grams per kilowatt-hour (g/kWh). The total hourly fuel consumption is therefore 26.39 x 230 = 6069.7 grams. There are approximately 840 grams in a liter, so this equates to 7.23 liters. If we refer back to the previous graphs we will see that this translates to around 7.5 knots, which translates to something over 25 shaft kW, so the pieces fit together as well as can be expected given that we don't know the losses between the flywheel and the propeller shaft, and also bearing in mind that the fuel map is derived in the laboratory and will be different to what is experienced in real life.

In Table 1 I have the measured propeller shaft torque at different engine speeds for three propellers. The Flex-O-Fold is too big for the boat: the engine cannot get above 2,471 rpm. If we were to run the boat at full speed for any length of time we would probably damage the engine. The Volvo-Penta propeller is well matched to the engine: it allows the engine to reach just under its full rated speed. The fixed propeller is way too small: the engine overspeeds and is still nowhere near fully loaded.

RIGHT: This table shows the propeller shaft torque at different engine speeds. The Volvo-Penta (V-P) is the best suited as it generates a large amount of torque at close to the maximum engine speed.

MAIN IMAGE: Nada's nav station and the computers we used to monitor the shaft speed and fuel usage.

Table 1: RPM vs Nm for selected propellers

Volvo-Penta		Flex-O-Fold		Fixed	
RPM	Nm	RPM	Nm	RPM	Nm
797	12	708	14		
1096	21	1070	34		
1178	24	1215	43	1234	14
1415	35	1427	62	1400	18
1595	44	1628	82	1599	24
1814	57	1832	109	1818	31
2003	72	1985	131	1992	38
2177	86	2158	155	2174	45
2379	106	2381	189	2366	54
2566	127	2471	203	2564	65
2760	151			2767	73
2984	186			2904	84
				3096	100

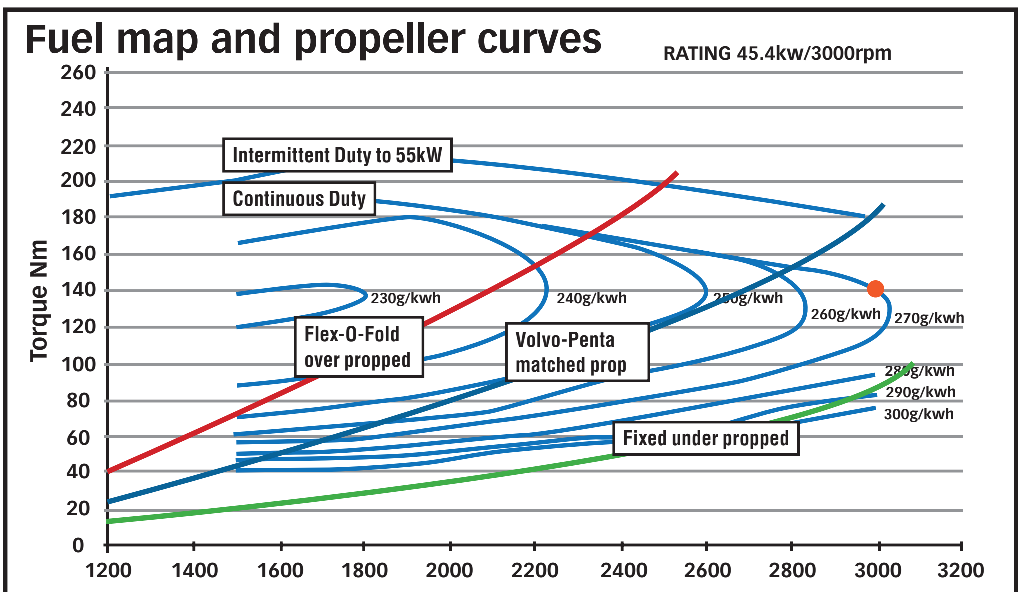


FIGURE 5

ABOVE: The fuel map above presents a conumdrum in that the less efficient propeller in terms of kWs at a given boat speed is the most efficient in terms of fuel usage.

In Figure 5 I have plotted the three propeller curves on the fuel map without accounting for drive train losses. Now we see the answer to the fuel efficiency question. The over-propped Flex-O-Fold is close to the highest efficiency part of the fuel map over most of its operating range. The well-matched Volvo-Penta is close at higher loads, but falls off somewhat at lower loads: in practice, we won't see a great deal of difference between it and the Flex-O-Fold. The under-sized fixed propeller is always in inefficient areas of the fuel map – for a given amount of energy at the propeller shaft, it will burn significantly more fuel. Although my plotted propeller curves need to be shifted by some unknown amount to account for the drive train losses, and the differences between laboratory testing and the real world, the relationships between the three curves will remain pretty much the same.

Figure 5 presents a conundrum. The only way to get a conventional propeller to operate in the most efficient part of the fuel map for the marine engines I have looked at is to over-prop the engine to the point at which engine damage is possible, and may even be likely.

Figure 5 illustrates another interesting possibility. We could have a propeller that is less efficient than another propeller in terms of how many kilowatts it takes to get a boat up to a given speed, but which operates in a more efficient part of the fuel map such that the overall system efficiency (as measured in terms of fuel consumption) is higher. In other words, the less efficient propeller turns out to be more efficient overall. Optimum efficiency is achieved by matching a high efficiency propeller to the highest efficiency part of the fuel map that is practicable without incurring the risk of engine damage.

'Specialist' propellers

The Gori propeller is intriguing in as much as the blades can be opened out in two different directions, presenting a different leading edge to the water. There is a substantial difference in pitch between the two operating modes, which I call 'normal' and 'overdrive'. In overdrive mode, the propeller we tested had a similar performance to that shown for the

"Optimum efficiency is achieved by matching a high efficiency propeller to the highest efficiency part of the fuel map that is practicable without incuring risk of engine damage."

Flex-O-Fold, including overpowering the engine at higher engine speeds, and as such was one of the more efficient propellers but could damage the engine if used improperly (see Figure 6). In normal mode the Gori was a little undersized for the boat and marginally less efficient than some of the better matched propellers. A slightly larger propeller would have pushed the overdrive side even harder while providing a better match to the boat in the normal mode. Clearly, with judicious use of the propeller a boat operator can achieve high levels of efficiency much of the time, but this takes a certain amount of operator management and there is the risk of engine damage if the propeller is used improperly.

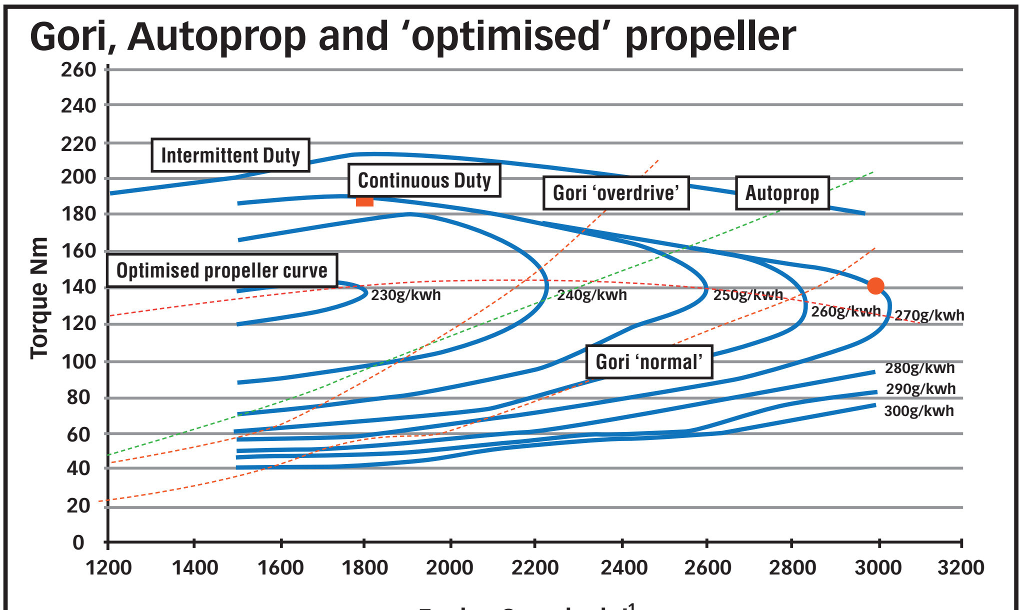


FIGURE 6

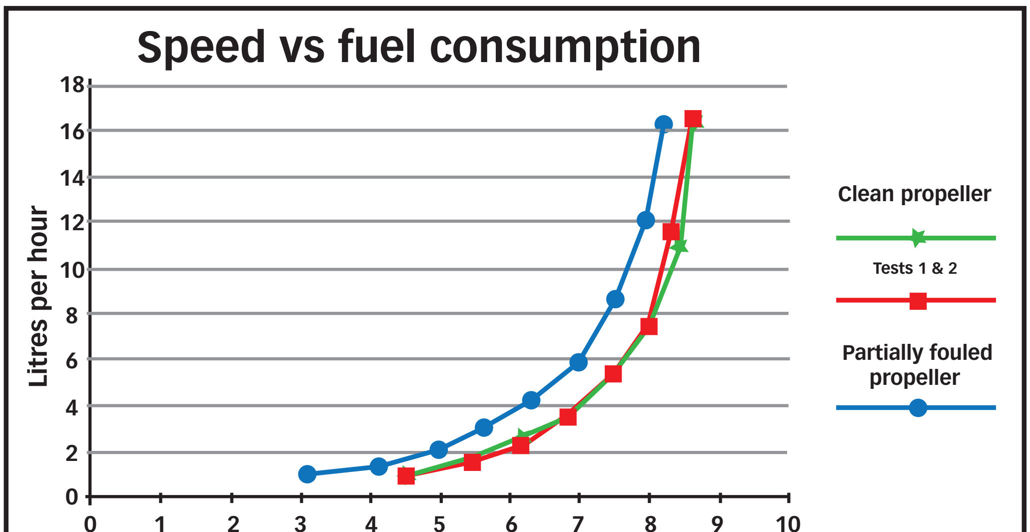
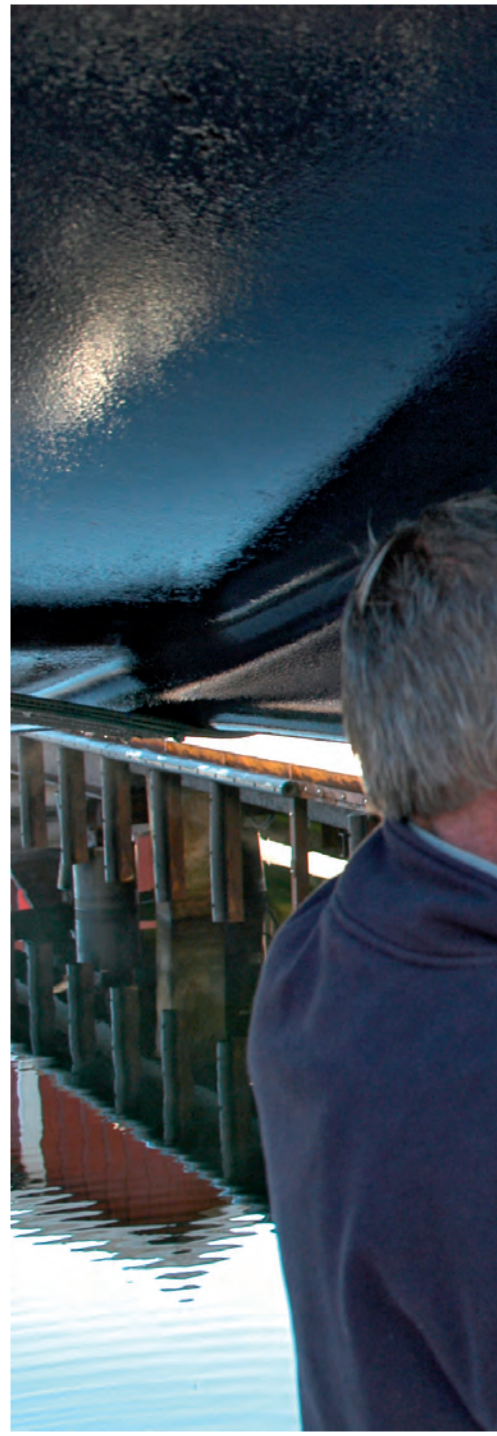


FIGURE 7



The Bruntons 'Autoprop' is another interesting propeller. It is a self-pitching propeller, adjusting the pitch according to the blade loading. This results in a considerably different, much flatter propeller curve than with other propellers that creates greater opportunities for efficiency optimization. In terms of the fuel map used in this article, an idealized propeller curve from an efficiency perspective would be as shown in Figure 7, although this is unacceptable in practice in as much as it sacrifices considerable power at the high end (full power falls from 55 kW to 38 kW).

An adjustable pitch propeller also offers the opportunity to manipulate the propeller curve by changing the pitch on the blades. However, without sophisticated software and adjustment procedures, it would be a bit of a hit and miss affair as to whether or not fuel efficiency was optimized.

Hull resistance curves

Figure 7 shows speed versus fuel consumption for a couple of runs with a representative, well-matched propeller (it's the Volvo-Penta).

A couple of things are striking. One is how little fuel it takes to move the boat at slow speeds, which is a function of how little energy it takes (refer back to Figure 2: Speed Over the Ground v Shaft Kilowatts). The other is how rapidly the fuel consumption increases above a certain speed. For example, at 6 knots fuel consumption is approximately 2.4 liters an hour; at 7 knots it's 4 liters; at 8 knots it's 7.6 liters; and at 8.6 knots it's 16.4 liters.

What we are seeing here is the impact of the hull resistance curves associated with displacement hulls. At slow speeds, the principal resistance to motion is friction between the wetted surface area of the boat and the water. So long as the boat's bottom is clean, this resistance is low and as a result it takes little energy to move a displacement boat in calm water.

As the boat moves through the water, it makes waves. At slow speeds these waves are small and close together but with increasing speed the waves increase in size and lengthen until we arrive at a point at which there is a wave at the bow and one at the stern with a clearly defined trough between them – in other words, the length of the waves the boat is making is the

same as the waterline length of the boat.

It takes energy to make these waves. Initially not much, but rising rapidly as the wave length approaches the waterline length. Thereafter it takes enormous amounts of energy (whether from the sails or an engine) to gain ever smaller increases in speed.

For years, we've all been taught to think in terms of the maximum or 'hull speed' for most displacement boats (I am not addressing racing boats here) being that point at which the wavelength more-or-less equals the waterline length. This is defined by the formula: 1.34 x √(waterline length in feet). It takes surfing conditions for most displacement boats to significantly exceed this speed.

'Nada' has a waterline length of 12.05 meters = 39.56 feet. The square root is 6.29 feet, so this gives us a nominal hull speed of 1.34 x 6.18 = 8.43 knots. We can tell when we reach this speed because the stern wave we are generating is under the stern counter. If we go any faster, this wave starts to move aft of the boat until we are dragging it behind us, which requires enormous amounts of energy.

This definition of hull speed puts us well up on the hull resistance curve at which point fuel consumption is above 14 liters an hour and is rising more-or-less logarithmically. If we accept a top speed of just one knot less, the fuel consumption drops to less than half and if we back off another knot it is down to one quarter! In other words, to get the last two knots takes three times as much power as is needed for the first 6.43 knots. To put this in perspective from a financial point of view, at $3.00 a gallon that last two knots is costing around $8 an hour or $4 a mile, whereas the first 6.5 knots is costing 35c a mile.

The cost of barnacles

We've also run some tests with a mildly barnacled propeller, and then the same propeller in a polished state, to see what effect a few barnacles would have on performance, and it really was just a few. It was equally shocking (see Figures 8 and 9). At any given speed, the fuel consumption was approximately 50% higher with the barnacled propeller while for any given level of fuel consumption the speed fell anywhere from half a knot (at higher levels of fuel consumption) to a full knot (at slower boat speeds and lower levels of fuel consumption). For example, at 7 knots fuel consumption went from around 4 liters an hour without bar-

ABOVE: Prop technicians helped fit the props to ensure it was done properly.

OPPOSITE TOP: Figure 6 shows the difference in performance when the pitch of the Gori is adjusted.

OPPOSITE BOTTOM: This figure looks at fuel consumption versus speed. Note how much fuel consumption rises above certain speeds.

RIGHT: Figure 8 shows that for any given speed fuel consumption can be up to 50% higher for a barnacled prop.

nacles to around 6 liters an hour with barnacles. If we pegged the fuel consumption at a steady 3 liters an hour, the speed fell from around 6.5 knots without barnacles to around 5.5 knots with barnacles.

Improving fuel efficiency

For those who are interesting in achieving higher fuel economies and in reducing their carbon footprint, there are two clear 'take home' messages from our testing so far:

- Keep the propeller clean;
- Slow down a knot or two.

We have found that additional improvements in fuel efficiency with conventional propulsion systems can be achieved by careful matching of propeller curves and engine fuel maps. We also know that in many applications we can achieve further improvements with optimized hybrids. However, both of these approaches require significant technical resources.

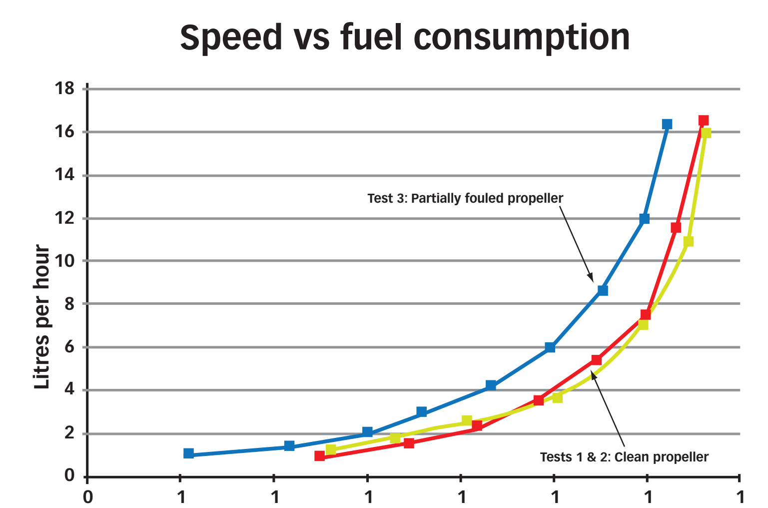


FIGURE 8

Ironically, the single greatest conservation measure we could probably apply to boating at the present time is ridiculously simple and non technical. It is to install a nautical mile per litre (or litres per nautical mile!) meter or even a 'cost-per-nautical mile' meter, at the helm station. Most owners, especially of displacement vessels, would be truly shocked at the doubling and quadrupling of fuel consumption and costs that occur when they try to squeeze out the last knot or two of boat speed. That last bit of speed is incredibly costly in terms of fuel consumption. They would immediately ease up on the throttle.