A Good Screw for Your Luders 33

Bob Banzett (©1995)

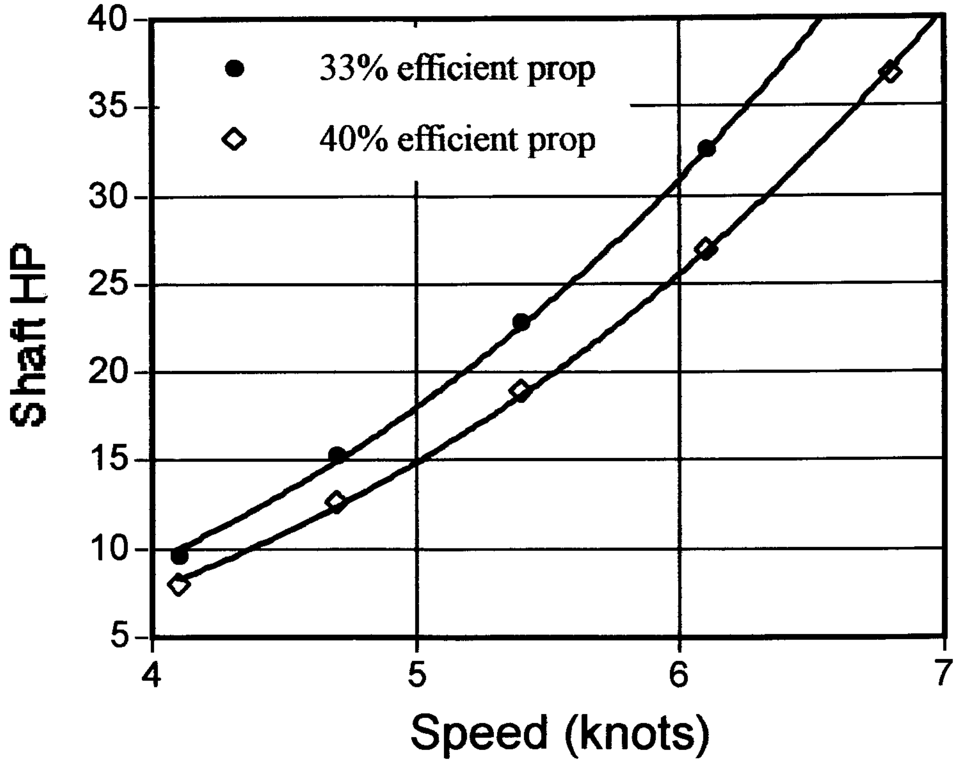
The device that enables your engine to drive the boat forward is called a 'screw propeller'. As many of you have discovered, selecting the propeller having the right characteristics is not always easy, and involves compromise, like everything about boats (or life, for that matter). The basic parameters involved in this compromise are 1) how much power the prop can transfer, 2) how efficiently the power is transferred, 3) how much drag the prop produces when the boat is under sail, 4) how much vibration the prop produces, and 5) (you knew this was coming) how much money you want to spend. I did a bit of research to find a better propeller for my boat, *Puff*. I discovered that most books that deal with sailboats stop short of actually telling one how to choose a propeller, while references on propeller selection concentrate on powerboats, treating sailboats as an aside. I based my prop selection mainly on formulae given in Dave Gerr's excellent Propeller Handbook, and used several other sources of information, such as Ted Brewer Explains Sailboat Design, Marine Diesel Engines by Nigel Calder, and The Ocean Sailing Yacht, Vol 1 & 2 by Donald Street, and an article 'Comparison of Ten Sailboat Propellers' by MIT grad students Beth Lurie and Todd Taylor which was summarized in the Jan 1, 1995 Practical Sailor (I read the full text of the paper presented to The Society of Naval Architects and Marine Engineers, kindly sent me by Dick Burke). In addition, several Luders owners told me about their experiences. After swimming through a sea of information, sorting out which formulas to use, and coming to a greater understanding about propeller performance, I felt I could make it all a bit simpler for you.

First, the boat: with crew, water and fuel, I figure the L/33 weighs about $6^1/_4$ tons. Although the static waterline length is 24 feet, because it has long overhangs, the effective waterline is closer to 26 feet. The waterline beam is about 9.25 ft. *Puff* is powered by a Westerbeke 4-107. Using *Puff* as the example, I will guide you through selection of a prop. I can't tell you what prop to buy because engines and transmissions vary, and sailors have different expectations of their boats. At the extremes we have those who want the best performance under power and those who want the best performance under sail (short of throwing away the engine altogether -- a solution I adopted for several years in my previous boat). I have tried to give enough information to enable other owners to see how to make their own decisions. Finding the perfect prop sometimes requires some trial and error -- propeller shops will often help out by loaning out used props ,or by giving you a trade in on your used prop. If you want more information, or need to solve a special problem, I highly recommend Gerr's book; although it is more technical than this article, it is clearly written. Even if you don't want to work your own solution, you will be better off if you can understand the advice you get from others, and understand the tradeoffs you can make. Propeller shops often have computer algorithms to make prop recommendations, but beware -- they don't always take all the important information into account.

How a propeller propels. The propeller shoves the boat forward by shoving water backwards (as Newton said, for every action there is an equal and opposite reaction). The force or "thrust" developed by the prop is equal to the mass of water ejected times the acceleration (f=ma, another of Isaac's gems). You can develop the same force by accelerating a small quantity of water to a high velocity with a small fast turning prop, or by accelerating a large amount of water to a smaller velocity with a large prop that turns slower. The reasons are complicated, but the larger, slower prop is more efficient. The difference between the forward speed of the boat and the speed of the stream the propeller spews backwards is often called 'slip' -- a somewhat misleading term.

Power Requirements. First you must decide how fast you want the boat to go under power. For a given displacement and waterline length (*LWL*), the power requirement (*propHP*) for driving the boat increases with the cube of the speed desired. Assuming smooth water and 100% propeller efficiency, it requires 15 propeller horsepower to drive the Luders 33 at 6.8 knots ('hull speed'). You can go faster than this, but it takes a lot of power -- another knot takes 50% more power. Reducing speed to 80% of hull speed (5.4 knots) reduces the power required to 8 horsepower (engine horsepower will need to be 2-3 times higher than prop horsepower due to prop inefficiency, discussed below, and a few horsepower must be allowed for transmission losses, powering the alternator, raw water pump, etc.). Remember that more power will be needed to maintain speed in the face of chop or headwinds.

An important consideration when calculating needed power is the efficiency of power transfer from propeller to water. Unfortunately, efficiency isn't easily calculated. Fortunately, the range of efficiency encountered in auxiliary sailboats is not great -- ranging from around 50% to around 33%. If you are able to swing a fairly large prop (see Diameter, below), efficiency will be near 50%, but it would take major surgery to the aperture to achieve this efficiency in the Luders 33. The 12" prop fitted to most L/33s is probably about 33% efficient, necessitating an engine having three times the propeller horsepower. *Puff*'s 35 HP (continuous duty) Westerbeke with a 33% efficient prop ought to push her to about 6.4 knots. The graph below shows how horsepower requirements depend on speed for a boat the size and weight of the L/33.

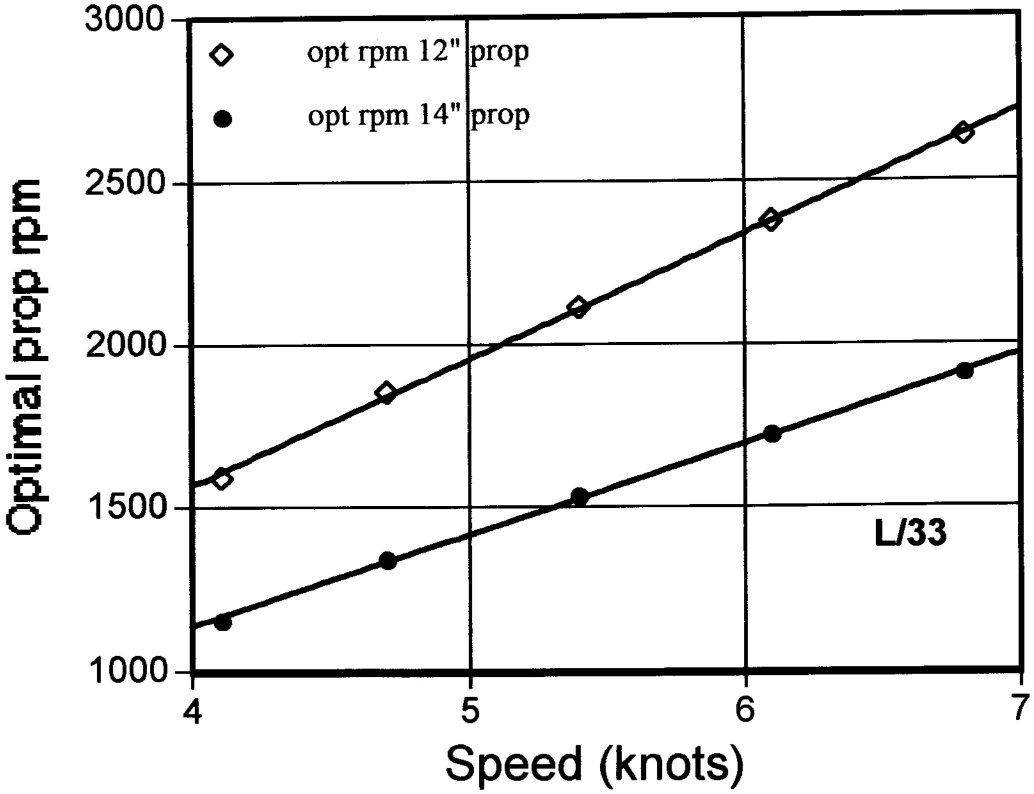


Number of Blades. Boats in this range are almost always driven by two or three bladed props (four-blade props in the appropriate size and pitch are tough to find, and one-blade props have proven notably unpopular). Two-blade props have an advantage on some boats like the Luders because the stopped blades can be lined up behind the keel deadwood while sailing, reducing drag (you have to mark the shaft or coupling while the boat is out, then each time you stop the engine you crawl in and check its alignment, nudging the engine with the starter till it is lined up). Even when they are not lined up, the two blades may have less area (depending on blade width), thus present less drag. On the other hand, two-blade props tend to produce more vibration under power because both blades move into the relatively still water behind the deadwood simultaneously. On the Luders 33, which has a wide deadwood and little blade clearance, this vibration is reported to be strong, and most cruisers are not willing to put up with it, though racers are. Everyone agrees that a three blade prop gives better thrust in reverse.

Diameter. Considerations in determining diameter include efficiency (larger diameters are generally more efficient), blade area, and clearance between the prop and the boat. According to the formula in Gerr's book, the L/33 should have an 18" diameter prop for an efficiency of 50-60%. Sailboats almost always have props smaller than this 'target' diameter. On *Puff*, clearance in the keel/rudder aperture is the limiting factor -- the minimum radius of this aperture (on the upper edge of the aperture) is only about $7^1/_4$". The distance between the prop tips and the hull or keel should be about 10% of the prop diameter to prevent vibration from interaction between hull and prop -- this allows only a 12" prop on the Luders 33 (I think Bill Luders kept the prop and aperture small to optimize sailing performance). Even if I had space for an 18" prop, I would opt for something smaller to reduce the drag penalty when sailing. The small diameter prop is has an efficiency of only 33%, thus *Puff* would require 45 "shaft horsepower" to reach hull speed (shaft horsepower is engine power minus power to run the generator, and a few percent lost in the transmission). Steve Bowes (who sent me some excellent data) has a 14" prop on *Esprit*, Hull #48. (I presume someone has enlarged the aperture.) He can reach 6.5 knots with a Westerbeke 21, which is capable of a maximum of 30 horsepower at the engine speed he shows. (This is really pushing that engine -- he gets a bit of black smoke at that speed; Steve wisely cruises a bit slower.) Nevertheless, this demonstrates the greater efficiency of a larger diameter prop -- about 40%.

Blade Area & Cavitation. If the total blade area is too small, the propeller runs the risk of 'cavitation.' Cavitation occurs when the water on the front side of the blade literally boils. Water boils at lower temperatures when pressure is lower, and the pressure on the forward side of the prop can get low enough to boil water at sea temperature; bubbles form and collapse rapidly, making noise and eroding the metal propeller. The required blade area is determined by the thrust needed. The blade works like a wing or a sail -- by virtue of its shape and angle of attack, it develops a pressure difference. We can think of the boat as being propelled by the pressure difference between the front of the blade and the back of the blade. The estimated thrust to drive the Luders 33 to hull speed is about 880 pounds. The pressure difference (in pounds per square inch) equals 880 pounds divided by the blade area (in square inches). With the wide three-blade 12" Michigan prop I selected, the total blade area is about 90 square inches, therefore the average pressure difference is about 10 psi. Experience has shown that this may lead to local pressures on the forward side of the blade that cause cavitation bubbles. Cavitation is more likely if the prop is rough, or if the deadwood causes uneven flow past the blades. Sure enough, *Puff*'s prop cavitates at speeds over about $5^1/_4$ knots (it makes a rumbling/rattling sound). Dick Burke reports cavitation at about the same speed with a narrow three-blade 13" Michigan wheel on *Water Witch*. Cavitation is less likely with a larger blade, say a wide-blade 13" or 14" diameter prop, but I might have to enlarge the aperture to avoid vibration arising from insufficient tip clearance; in addition, the larger prop would reduce sailing performance further. Some owners report higher speeds without mentioning cavitation -- I don't know whether they don't experience it, or just don't report it. I cut away quite a bit of fiberglass to fair the deadwood and rudder aperture, but there was only a small improvement. Fairing the rudder alone is not too hard, and might get you most of the benefit. Remember to coat the new surface with epoxy to prevent blistering.

RPM and Reduction Gears. Given the power and prop diameter *D* determined above, there is an optimum propeller shaft rpm. However, we must meet another requirement -- the engine must turn at the proper RPM -- if the engine turns too slowly, it will not develop the needed power; at the upper end, engine speed is limited by the manufacturers redline . Running at the lowest possible engine RPM that develops the needed horsepower will be quieter, and save wear and fuel. To properly determine engine RPM you should have the manufacturer's power curve. Use it to determine the minimum speed you must run the engine to develop the power needed. For instance, the Westerbeke 4-107 is rated for continuous output of 35HP at 3000 RPM, not quite enough to push *Puff* to hull speed (with her inefficient small prop). (Although the 4-107 can develop intermittent output of 40 HP at 3000 RPM, its life will be short if I ask it to do that for long periods) *Puff*'s current engine ought to push the boat 6.4 knots with a 33% efficient prop (from the first graph). The graph below shows the optimum prop RPM for 12' and 14" propellers on the Luders 33 (I have taken into account the different efficiencies of these props in making the graph–interpolate for a 13" prop):



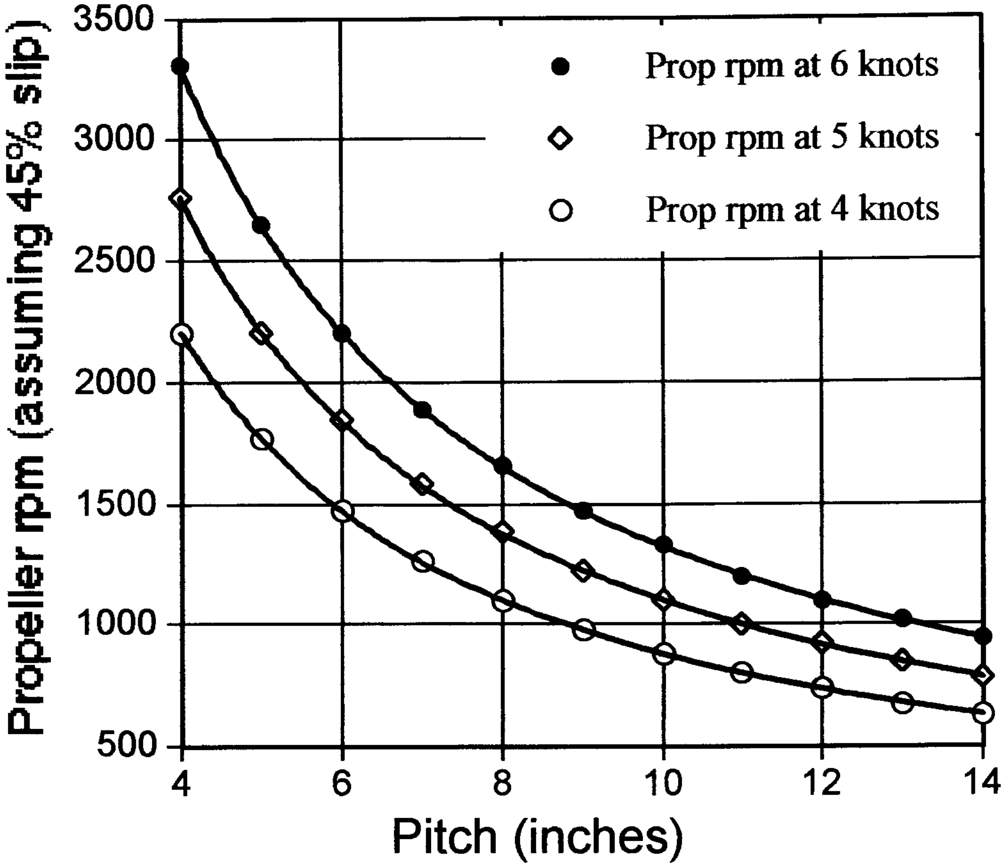
To drive a Luders 33 at 6.4 knots with a 12" prop, the ideal shaft speed is 2500 RPM (Using above graph). This is pretty close to the engine RPM that produces maximum horsepower, so the 1:1 transmission gearing that's in *Puff* is pretty good (the perfect ratio would be 1.2:1). If I chose to enlarge the aperture to take a 14" prop, the maximum speed would increase to 6.8 knots (because of greater efficiency) and the optimal shaft speed would decline to 1880 RPM. A 1.5:1 transmission reduction would be perfect. In reality, I would rather sacrifice some speed to make it easier on the engine and reduce the noise and fuel consumption. To make $5^1/_2$ knots she requires 24HP, which the Westerbeke achieves at about 1800 RPM. Optimal propeller shaft speed at this speed and power is about 2100 RPM.

Pitch. Finally, we turn to determining pitch. There are at least two ways to do this -- the simpler one was developed by George Crouch, and is entirely empirical. To begin with, we calculate the pitch that would be required to move the boat at the desired speed if there was no 'slip', that is, if the boat moved forward exactly the pitch measurement with each revolution of the prop, i.e., if the pitch is 6", the boat moves 6" for one revolution of the shaft, or a nautical mile for each 12152 revolutions. (There are 72912 inches in a nautical mile.) We then turn the revolutions and motion into speeds by dividing by time:

$$pitch = (Boat\ speed \times 72912) \div (prop\ RPM \times 60)$$

But of course, propellers don't work that way -- they appear to slip (really they eject water backwards to propel the boat forward), and this must be taken into account when determining pitch. The best way to determine slip is to measure the shaft RPM and the speed over a measured course. If you know the current pitch of your prop, you can determine the apparent slip by comparing the speed predicted by the above formula to that measured (I found a slip of about 45% at 5.7 knots). This slip measurement should hold true as long as you don't change the diameter or blade width. Fortunately, there are good predictions of slip to use as a starting point -- auxiliary sailboats tend to have slip values of about 45%, so we need to multiply the pitch value above by 145%. This yields a pitch of 4.5" for *Puff*, using the optimum <u>propeller</u> RPM. Steve

Bowes also sent data on slip -- with a 3-blade 14" prop slip was 42% at 5.7 knots and 50% at 6.4 knots, with a 2 blade 14" prop, he observed a bit more slip: at 6.4 knots slip was 58%. The graph below shows what prop rpm to expect with various prop pitches, assuming 45% slip. To get engine RPM multiply propeller RPM by gearbox ratio.



Engine power changes with RPM, but it doesn't follow the same curve as required power. Because gearboxes are seldom available in the exact ratio needed, we usually must make a slight adjustment in pitch to obtain the engine RPM that will deliver the correct power for the speed we select. According to the power curve for the Westerbeke/Perkins 4-107, the engine needs to turn only 1800 RPM to produce the 23 HP needed to push the boat at 5.4 knots; This RPM will be obtained with a pitch of 5.2"; this pitch is still pretty close to the optimum calculated above, but will let the engine run a little slower, reducing noise and fuel consumption. To let *Puff*'s engine turn fast enough to develop full power at the calculated maximum continuous speed (6.4 knots) the correct pitch is 3.7". Here we see the usual pitch dilemma - the best pitch changes with speed. If your boat has the wrong transmission ratio, you may be stuck with a pitch and prop RPM far from the optimal value. The most elegant way to solve this is with a variable pitch propeller, but this is not practical unless you repower with an engine equipped with variable pitch propeller, such as the Sabb (not Saab, though they make wonderful cars and airplanes).

The current prop on *Puff* has a 6" pitch; this works reasonably well, giving 1900 RPM at 5.3 knot cruise (the knot meter and tachometer have not been carefully calibrated), and a top speed of 5.7K at 2100 RPM (engine and prop speed are the same on *Puff*). Not surprisingly, the engine shows signs of overloading (black smoke, rising coolant temperature) when I try to push faster than 5.6 knots (remember, it's cavitating at this speed anyway). For better performance under power I could go to a 13" wide blade prop; the larger blades should raise the speed at which cavitation occurs, and the larger diameter would be slightly more efficient. At the same time, reducing pitch to 4" or 5" pitch would allow the engine to turn faster and develop more horsepower. Steve Bowes has a 2:1 transmission and has settled on a 14x12 three blade prop that gives a cruise speed of 5.5 K at 1800 engine RPM and maximum speed of about 6.6 knots at 2700 engine RPM (1350 prop RPM). (Remember that a 14" diameter prop may not clear your aperture.) Calculations can get you pretty close to the right pitch, but there is still some art and luck involved. Fortunately, a good prop shop can tweak the pitch 1" in either direction.

Drag Under Sail. First, let's deal with the old debate about whether to allow the prop to freewheel. I have yet to see the definitive study. I have seen believable information says that relatively shallow-pitch propellers found on sailboats produces more drag when freewheeling -- although this may seem to defy common sense, the fluid dynamic principles are sound. Other experts say freewheeling propellers produce less drag. However, freewheeling causes extra wear on the driveline, and may even damage some kinds of hydraulic transmissions. I suspect that there is little difference in drag, and prefer to stop the prop to avoid wear, tear, and vibration. The drag of a stopped propeller is mainly related to the blade area. If clearance permits, you are better off getting the blade area you need with a larger diameter and narrower blades, as this gives better efficiency without much of a drag penalty, but with the small aperture of the L/33 you need the largest diameter and the widest blade that fits to avoid cavitation over 5 or $5^1/_2$ knots.

As you can see from the above discussion, a large prop is good for performance under power -- large diameter yields higher efficiency, allowing a small engine to move the boat faster, and greater blade area prevents cavitation; unfortunately these features are bad for performance under sail. The prop and the aperture itself present considerable drag, which increases with prop size. As mentioned above, two bladed props mounted in apertures may be lined up behind the deadwood to reduce drag. Unfortunately, the sort of boat that carries the prop in an aperture is usually a heavy, full keel design that needs the power of a three bladed wheel. In addition, the wide deadwood that can effectively hide the stopped blades from water flow during sailing will also cause vibration under power as both blades simultaneously move in and out of the shelter of the deadwood, experiencing sudden changes in loading. Boats that carry the prop on an open shaft with strut have the option of a two-blade folding prop -- under sail, the water flow folds the blades back parallel to the shaft, under power, centrifugal force opens the blades. Folding props produce very little drag under sail, but have less than optimal performance under power, especially in reverse; these props won't fit in the Luders aperture without drastic modification. A more elegant solution is the feathering prop -- under sail, the water flow causes the blades to swivel into alignment with the flow. Because their blades are flat, and they have a relatively large hub, these props are not quite as efficient as solid props in forward, but they provide better thrust in reverse, and will fit in most apertures. Ken Smith just bought a feathering Max-Prop for *Polaris*, so we should have a first-hand report next Spring. A more sophisticated variation is the controllable-pitch prop; these not only feather, but their pitch can be adjusted from the cockpit to suit any speed/power combination. Why doesn't every boat have a feathering or adjustable pitch prop? Money -- these beauties cost ten times as much as solid props. Feathering props cost as much as a new mainsail, adjustable-pitch props cost more, and will not fit most engine/transmissions. So, as usual, you have to compromise between performance and bucks -- your choice.

Re-powering Puff - Part 2 – Propeller and Aperture

by Bob Banzett

The key to performance

The propeller is the thing that actually pushes the boat, so it shouldn't be a surprise that the propeller is one of the most important determinants of performance under power. Performance under power could be improved in almost all Luders33's by propeller/aperture modifications, regardless of engine power. The small aperture in the Luders is an important limitation – but you can fix this if you are willing to do some work. If you want better performance under power, enlarge the aperture and fit a bigger diameter prop.

Selecting a propeller

One important decision is whether to employ a feathering or folding prop in place of the fixed prop. I reviewed the basic considerations in my earlier article on props. These props are said to give less drag when the boat is sailing. Folding props have very poor thrust in reverse, while feathering props have better reverse thrust than fixed props. Both folding and feathering props are less efficient than fixed props because of the compromises in blade shape. The aperture in the L33 must be lengthened substantially in the aft direction to accommodate the correct size folding or feathering prop. This requires removal of a substantial amount of the rudder, so I elected not to do it. These props are also much more expensive than fixed props (up to 10 times the cost of fixed props).

The biggest improvement you can make is to go to a larger diameter prop. The larger the prop diameter, the greater the thrust, and the greater the efficiency (i.e., a greater percentage of the engine's power will be applied to driving the boat). So even with the same engine a larger diameter prop can push the boat faster, drive her into a head sea better, and/or improve fuel economy. One calculation shows that the ideal prop for a Luders 33 would be 17" in diameter. The original prop on most L33s is 12" in diameter, some people have squeezed 12.5 or 13" props into the stock aperture, and a few of us have enlarged the aperture. With a small diameter prop there is another problem: the blade area may be inadequate, leading to cavitation (the pressure on the forward side of the prop drops so low that the water boils). Wider blades help (e.g., the Michigan MP series), as does adding more blades (three is the maximum available in the size & type of prop we use). Most L33s are currently equipped with 3 blade props. But adding blade area does not increase efficiency, and has a smaller effect on thrust than increasing diameter. Two blade props are said to have an advantage because the blades can be lined up in behind the keel deadwood when the boat is sailing, thus reducing drag (because the water here is being dragged along with the boat, thus the flow velocity over the stopped blades is less). Two-blade props also vibrate more under power because the two blades simultaneously move from the free water to the water behind the deadwood, but skewed blade prop designs help reduce the vibration.

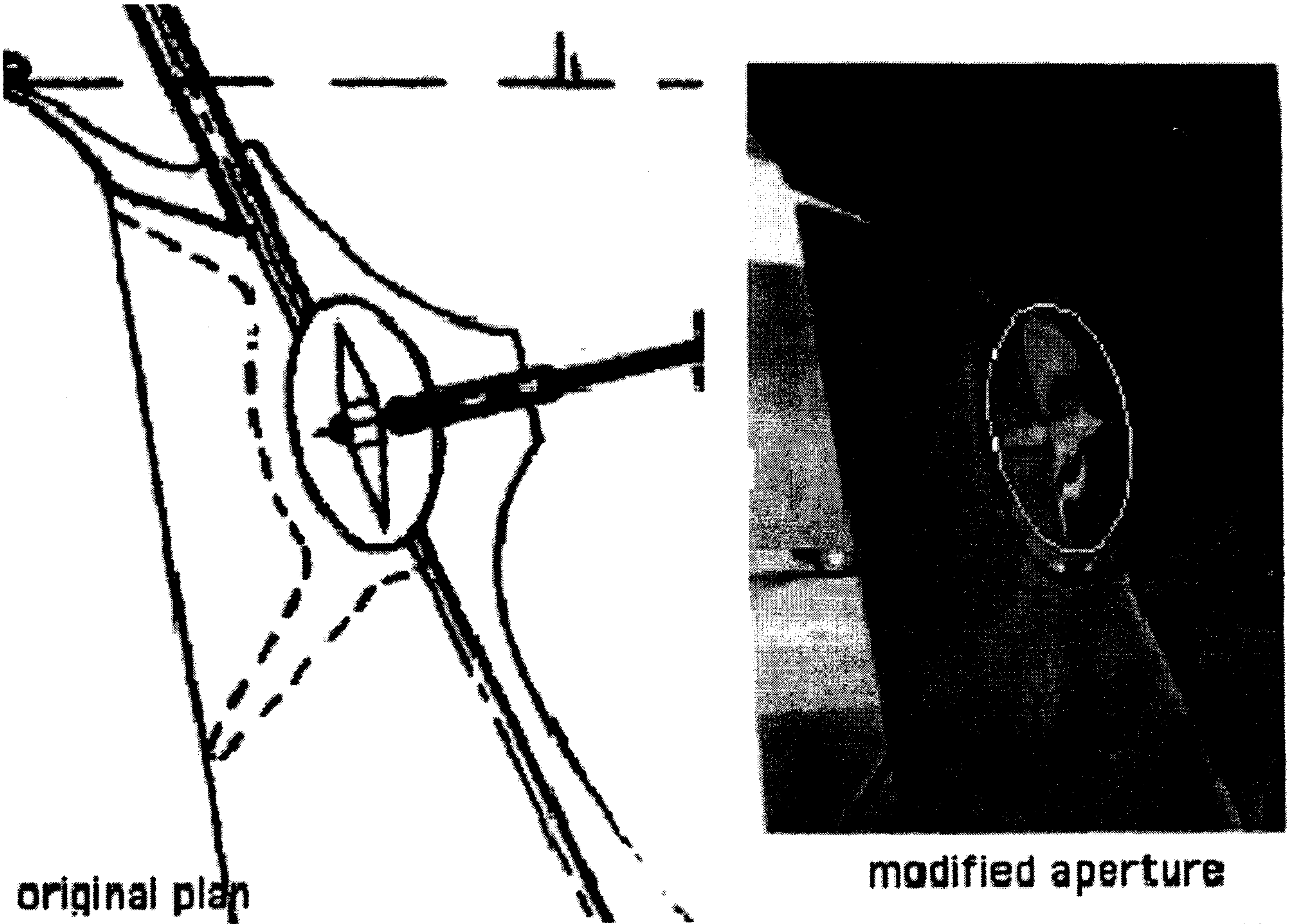
I had been using a 3-blade Michigan MP style wide-blade prop on Puff, and had tried both 12 and 13 inch diameters. The 13" was an improvement, but even with the 13" prop, the largest that could fit in the aperture, cavitation limited top speed. Thus when I did the engine refit, I also decided to enlarge the aperture to accommodate a 14.5" prop (cut down from a 15" prop). (Blade tip clearance should be about 10% of prop diameter, or 1.5"). As an experiment, I decided to try a 2-blade prop, but one with 'skewed' blades that reduce vibration. I chose a 14 $^1/_2$ inch diameter, 13" pitch Teignbridge prop (made by Mikado, supplied by General Propeller, Bradenton, FL 941-748-1527) *IT WORKS GREAT!* (Note in the picture this prop has a little rake, which must be allowed for when specifying shaft length.)

I now routinely motor at 6+ knots @ 1800 rpm (about 20 Hp according to the published engine power curve), with no audible cavitation, and less vibration & noise than with my old 3-blade prop. The top speed is 6.8 K @ 2200 rpm (about 26 Hp); a finer pitch prop might raise this a little, but the boat is already going a bit above hull speed, and there is a little cavitation. (These speeds are determined with GPS, average of two-way runs.) The boat will also make good way into a headwind – one day last October I made 5$^1/_2$ knots straight into 35-40 K wind and 2 foot steep chop. The boat now accelerates and stops faster and there is good power in reverse, making maneuvering & docking easier. The improvement in motoring performance is delightful, and I have not noticed any decline in sailing performance (drag on a stopped prop is largely a function of blade area, and the new 2 blade prop has the same blade area as the old 3 blade).

Before you put a larger prop on, be sure the gear ratio is adequate to allow the engine to turn fast enough with the larger diameter prop. If you are happy with your current engine but the gearing is too high, it may be possible to change the gearbox ratio without spending too much. To some extent you can adjust engine RPM by altering prop pitch, but you don't want to have pitch too low (less than 8 or 9" pitch is less than ideal).

Enlarging the aperture

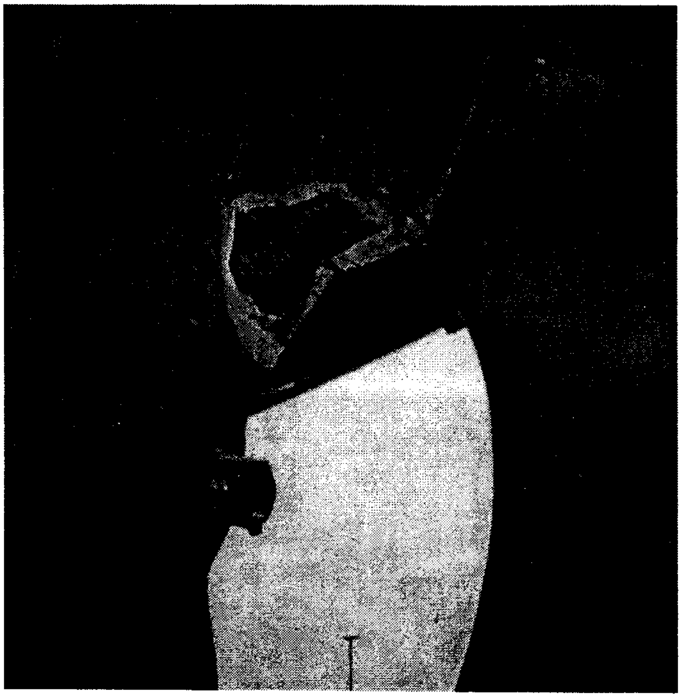
Enlarging the aperture is a little easier when the engine is out so you can get to the inside for fiberglassing, but it could be done from the outside. To do the entire job from outside you will have to cut away a bit more of the boat to account for the fiberglass you will add back. A 4" or 4.5" angle grinder with a sanding disc and 40 grit paper makes short work of it (but cover yourself well – it makes a lot of fiberglass dust). The enlarged aperture is pictured below. The distance from shaft centerline to the top & bottom of the new aperture at the fore-aft position of the prop tips is 8.5". I also lengthened the aperture in the fore-aft direction; the distance from stern tube to rudder in line with the shaft is 7.0". (The stern tube projects 2.0" from the deadwood). It's best to get the new prop (and shaft if that's being changed) ahead of time. After you think you have removed enough fiberglass, temporarily fit the prop and check clearances – don't forget to check clearance through the full range of prop and rudder motion. Take enough glass off to allow for the buildup when you apply the new glass.



original plan

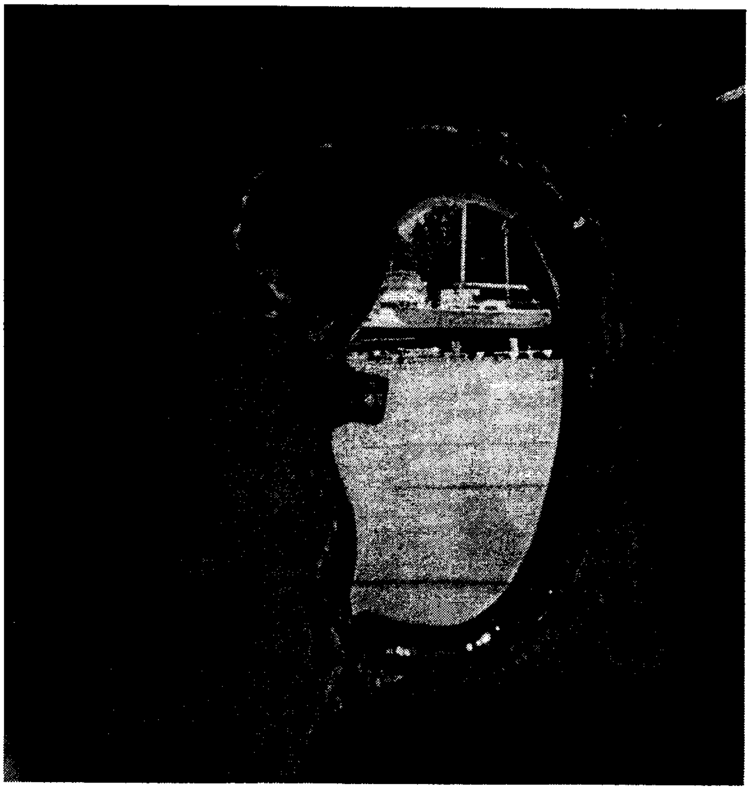
modified aperture

The Figure shows the original L33 plan (left), compared to a photo of Puff's new aperture (right-with the old aperture traced in white). On the upper side, cutting an aperture this large will make a sizable hole in the boat just forward of the rudder shaft (see picture below) that must be closed with fiberglass. Since I did this job with the engine out, I did the glassing inside so that it didn't reduce the aperture size. I made a 'mold' to hold the first layers of glass by wedging a round plastic gallon bottle against the top of the aperture (See picture below). If you are not changing engines, just cut away a bit more glass and build up from the outside. I built up about a half inch of glass. On the rudder is solid, so all that is needed after shaping is a couple layers of glass and epoxy to protect the laminate from water ingress. If you cut too far into the rudder you may encounter the bronze armature – stop there. This all sounds dramatic (I know many people shudder to think of making a hole in the bottom of the boat) but fiberglass/resin construction is wonderful stuff, and it will be good as new when it's done. Always use a good marine epoxy for any critical work – it bonds better to the existing glass than polyester resin, blocks water ingress that could cause blistering, and emits less toxic fumes (important if you do the job from inside). I like West System epoxy, partly because it is formulated to minimize toxicity.

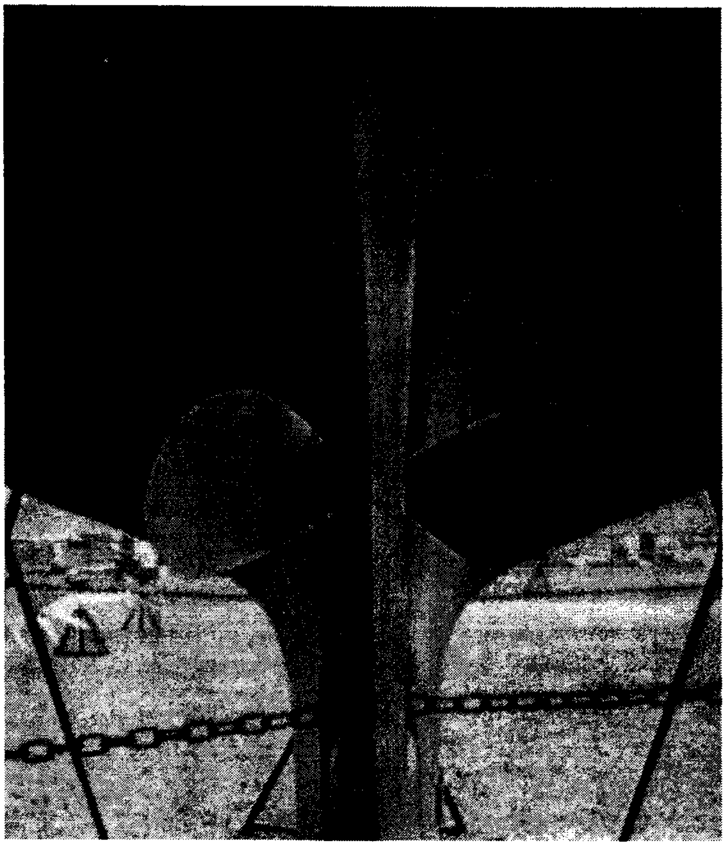


This picture shows the hole resulting from enlarging the top of the aperture – you can see a vent hose inside. (You may also notice that I narrowed the deadwood a bit in an earlier attempt to get better flow over the prop.) I did this rough cut with a sawzall, then shaped with an angle grinder with 40 grit paper on a rubber disc. In retrospect it would have been easier to do the whole thing with the grinder.

This picture shows the jug/mold held in place for glassing from the inside (fill the bottle with water to prevent it melting when the resin gets hot). If you are glassing from the outside, you can make an armature out of wire screen to hold the first layer of glass.



This picture shows the new aperture after glassing but before painting. Notice that the leading edge of the rudder has been rounded to improve flow.



This picture shows the new 2 blade prop in place – this photo shows the 'skew' of the blades that minimizes vibration.

I always stop the prop when sailing by putting the engine in gear (less drag and less wear on the gears. I marked the shaft coupling before launch so I could line up the prop with the deadwood to minimize drag. The photo shows what ought to be the maximum drag position. I have been unable to see any actual difference in sailing performance between this and the ideal position.

Good luck!!!