S/V Catalpa

Comparison of Ten Sailboat Propellers

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Abstract

This study investigated the performance characteristics of ten different commercially available propellers typically seen on auxiliary sailboats. Included in the testing were two feathering propellers, three folding propellers, one self-pitching propeller, and four fixed-bladed propellers. All propellers were of the same pitch and diameter. Testing at the MIT Marine Hydrodynamics Laboratory consisted of three common boating situations: forward boatspeed, forward rotation (normal forward operation); forward boatspeed, reverse rotation (backing down); and forward boatspeed, no rotation (drag under sail). It was found that all ten propellers performed generally well in forward operation, but that large differences in performance existed in reverse and in drag. The text of this report is written with the lay audience in mind.

Introduction

As every sailor knows, wind comes and goes. And when it goes, the sailor must rely on other means of propulsion. Some sailors might have oars for their dinghies, and other stout sailors only a prayer for their souls. Yet most sailors fall somewhere in between and put their faith in a propeller. The purpose of this study is to investigate the performance characteristics of ten different propellers typical of those seen on small to midsize auxiliary sailboats.

The propellers included in this study are as follows:

- Michigan Wheel 2 bladed fixed pitch
- Campbell Sailer 2 bladed fixed pitch
- Martec 2 bladed folding
- Gori 2 bladed folding
- Max-Prop 2 bladed feathering
- Michigan Wheel 3 bladed fixed pitch
- Max-Prop 3 bladed feathering
- Campbell Sailer 3 bladed fixed pitch
- Autoprop 3 bladed self-pitching
- Trumbly 3 bladed folding

For purposes of comparison, the chosen propellers all have a diameter of 13 inches. It was felt that this was representative of small to midsize sailboats. Although the propellers tested in this experiment were identified as fixed, folding, or feathering, it is important to note that this differentiation refers to each propeller's physical configuration and not to its pitch. In fact, all but the Autoprop were either designed or set (in the case of the feathering Max-Props) with a fixed pitch of 10 inches, except for the Gori folding propeller, which had a designed pitch of 9 inches (the manufacturer did not expect any appreciable difference in its performance compared with a Gori designed with a 10 inch pitch).

The propellers were tested at the MIT Marine Hydrodynamics Laboratory Variable Pressure Water Tunnel. This water tunnel is a closed-loop tunnel driven by a single impeller connected to a 75 horsepower electric motor (figure 1). The pressure in the tunnel can be varied for cavitation experiments by a vacuum pump. The entire water tunnel has a square profile two stories high. The test section, which is at the top of the loop, is four feet long and has a cross-section twenty inches square. Maximum velocity of the water is about 30 feet/second. Upstream of the test section is a 5:1 contraction section fitted with a honeycomb mesh with cell size of 0.71 inches, and a wake screen to promote flow uniformity. The test section has removable

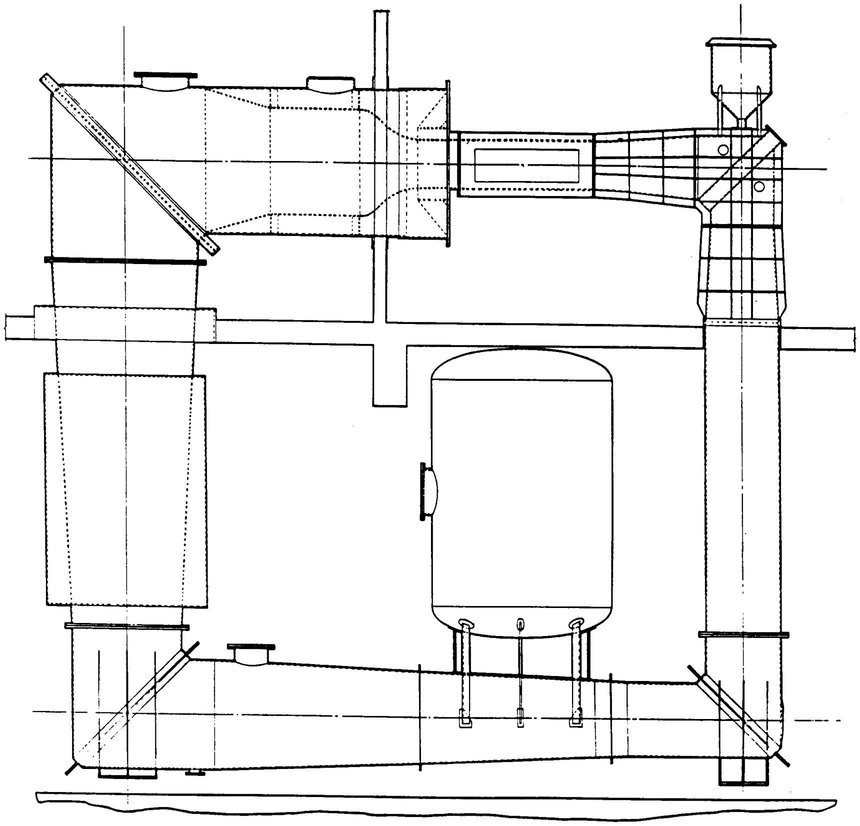

Figure 1: The MIT Variable Pressure Water Tunnel

Plexiglass windows on all four sides for ease of assembling and viewing experiments. The propellers are mounted on a retractable shaft that extends into the test section from upstream.

Performance of a propeller at various operating conditions can be simulated in the water tunnel by varying the impeller (water speed) and propeller (propeller RPM) settings. The nominal water speed in the tunnel test section is controlled by the impeller setting and is measured by a differential pressure cell in the contraction section. The propeller is driven by a 40 horsepower electric motor and is controlled by the propeller RPM setting. Thus, different combinations of forward boat velocity and propeller RPM can be examined and compared for each propeller.

It is important to note, though, that water speed past a propeller operating behind a boat is typically not the same as the speed of the boat through the water. Propellers operate in the viscous wake near and behind the boat where velocities past the boat have been reduced by frictional drag along the length of the hull and pressure forces due to the presence of the hull. Therefore, water velocities "seen" by the propeller are somewhat less than boat speed. The average water speed into a propeller is called the velocity of advance, V_A, and can be described as some fraction of boat speed or ship speed, V_S. Typically, for a propeller operating in an aperture,

$$V_A = 0.85 \times V_S$$

and for a propeller in the clear,

$$V_A = 0.90 \times V_S$$

For high speed planing hulls, V_A is often considered to be the same as V_S.[1] By controlling water speed in the test section one is, in effect, controlling the propeller's V_A.

Various nondimensional parameters are used in the study of propellers. These numbers are useful as they allow comparison of characteristics of different propellers without depending on the specific conditions of each test. The parameters used in this study are:

Advance Coefficient, J_A:

$$\begin{aligned} J_A &= \frac{V_A}{(n \times D)} \\ where\ V_A &= velocity\ of\ advance,\ feet\ per\ second \\ n &= propeller\ rotations\ per\ second \\ D &= propeller\ diameter,\ feet \end{aligned}$$

Thrust Coefficient, K_T:

$$\begin{aligned} K_T &= \frac{T}{(density \times n^2 \times D^4)} \\ where\ T &= propeller\ thrust,\ lbs \\ density &= density\ of\ fresh\ water, 1.936\,\frac{lbs \times sec^2}{ft^4} \\ n &= propeller\ rotations\ per\ second \\ D &= propeller\ diameter,\ feet \end{aligned}$$

10 x Torque Coefficient, $10 \times K_Q$:

$$\begin{aligned} K_Q &= \frac{Q}{(density \times n^2 \times D^5)} \\ where\ Q &= propeller\ torque,\ foot - pounds \\ density &= density\ of\ fresh\ water, 1.936\,\frac{lbs \times sec^2}{ft^4} \\ n &= propeller\ rotations\ per\ second \\ D &= propeller\ diameter,\ feet \end{aligned}$$

Efficiency:

$$\begin{aligned} Efficiency &= \frac{(J_A \times K_T)}{(2\pi \times K_Q)} \\ where\ J_A &= Advance\ coefficient \\ K_T &= Thrust\ coefficient \\ \pi &= 3.1416 \\ K_Q &= Torque\ coefficient \end{aligned}$$

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[1] Kinney, F.S., ed., *Skene's Elements of Yacht Design*, New York: Dodd, Mead & Co., 1973, p. 140.

Values of K_T, K_Q, and efficiency are usually plotted against J_A to describe the performance of a propeller at various advance coefficients. Advance coefficient, J_A, for a given propeller is determined by V_A and propeller rotational speed. Note that when a propeller of a particular diameter is operating at 5 knots and 1000 RPM, it has the same advance coefficient as when it is operating at 10 knots and 2000 RPM: the propeller responds to neither speed nor RPM alone but rather to the ratio of the two numbers. Thus, different propellers can be compared (in terms of K_T, K_Q, and efficiency) if they are tested at the same J_A. Also, using the above formulas for K_T, K_Q, and efficiency, an owner can enter values for a particular vessel and get expected values for thrust and torque at different operating conditions.

It can be dangerous to directly compare and rate propellers in terms of their efficiency curves. A more useful method for judging the efficiency attributes of propellers in forward is detailed in the section on Forward Performance.

About the Propellers

The Autoprop was the one propeller without a designed fixed pitch. Instead, manufacturer literature describes the Autoprop as "self-pitching." Each of the three blades of the propeller is mounted to the hub on its own separate bearing, allowing the blades to move independently. Whether the propeller is spun by the engine or just trailed while sailing, each blade assumes an orientation relative to the moving water based on a balance of "centrifugal and hydrodynamic forces;" that is, the blades respond to the combination of accelerations: due to spin around the shaft and due to the pressure of the water on the blades.

While sailing, the propeller is not being spun and the blades should feather in line with the moving water, thus decreasing drag. While motoring or motor-sailing, the blades are designed to constantly repitch themselves in order for the blades to maintain a positive angle of attack with respect to the incoming flow. The Autoprop is designed without any sort of stops to arrest the pivoting of a blade around its bearings, thus allowing the blades a 360 degree range of rotation: upon reversing, the blades spin about their bearing so that the leading edge of each blade in reverse is the same as the leading edge in forward.

One note about the Autoprop is that a potential owner should include the cost of the manufacturer-supplied "propeller-puller" for removing the propeller from the shaft. A standard-sized gear puller will not do the trick: you run the risk of damaging the propeller without the right tool.

The Campbell Sailer and Michigan Wheel propellers are standard two and three bladed fixed propellers. The Campbells appear to have relatively narrow blades when compared with their Michigan Wheel counterparts.

The Martec folding propeller has its blades pinned together within the hub, permitting independent opening and closing of the blades. Unlike the Martec, the Gori folding propeller has blades that are geared together within a somewhat larger hub. The gearing forces the blades to open and close in unison. A drawback of pinned blades, such as the Martec, is that the independent action of the blades allows the possibility of one blade opening before the other, causing uneven sideways loads on the shaft, sterntube, and drivetrain until the other blade opens. Over time, it is possible that these uneven loads could do damage. While sailing, a pinned blade folding prop can come to rest with one of its blades facing downward and the weight of the blade can cause the blade to fall open and remain open, increasing drag. Of course, this drag problem can be solved by sending a hearty member of the crew over the side to put a rubber band around the blades until the the race or passage is over, or by marking the propeller shaft inside the boat so the skipper can be sure that the propeller has stopped with its hinge pin situated vertically to prevent a blade from falling open. But the Gori seems to eliminate these problems by gearing the blades together. Simultaneous opening and closing is assured, and while sailing, the gearing allows the weight of the closing top blade to lift the bottom blade up and closed as well.

An interesting additional feature of the Gori is the manner in which the blades open in forward. Unlike the Martec folding prop where the blades slam loudly against stops when the blades spin into their open position, no slamming was observed with the Gori under the test conditions. The Gori propeller has stops that allow the blades to open farther than perpendicular to the shaft. It appears that the Gori engineers designed their propeller so that upon opening, the blades find their operating position prior to banging against the stops. Slamming from a propeller is bothersome at best and could possibly be detrimental to engine thrust bearings.

The Max-Prop feathering propellers are designed with planar blades that feather in line with the incoming water when the boat is under sail, that is, when the propeller is not being spun. The flatness of the blades allows the prop to perform similarly in forward and reverse. The pitch of the propeller can be changed by the owner only when the boat is out of the water.

Finally, the Trumbly Tri-Blade is a three-bladed folding propeller. The hub of the Trumbly is relatively large for the propeller diameter.

It is important to note that the Max-Prop, the Trumbly, and the Autoprop propellers all have intricate mechanisms contained within relatively large hubs. It is likely that propellers of a larger diameter by these manufacturers would show fewer losses in efficiency due to the oversized hubs than the propellers of the diameter tested.

Forward Performance

The propellers were tested in forward rotation with forward water speed, the conditions for normal motoring or motor-sailing. Measurements of thrust and torque were acquired by taking data throughout a finely spaced range of flow speeds and propeller RPM's. The standard format for presenting propeller data is K_T, $10 \times K_Q$, and efficiency as functions of J_A. The curves for the ten test propellers are shown in figures 2 through 11.

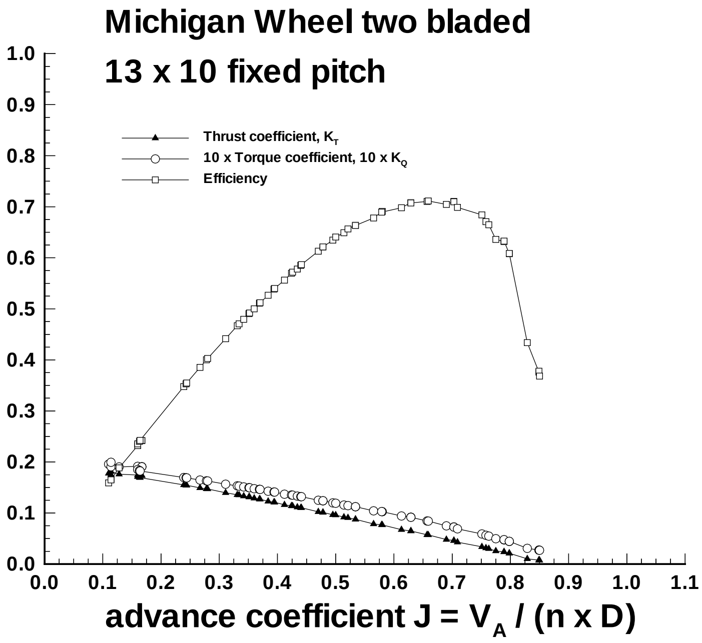

Figure 2: Michigan Wheel 2 blade fixed

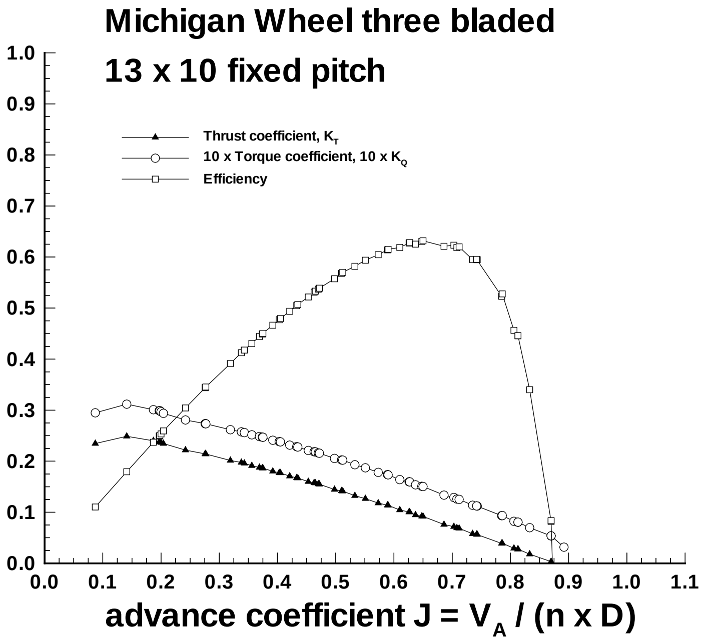

Figure 3: Michigan Wheel 3 blade fixed

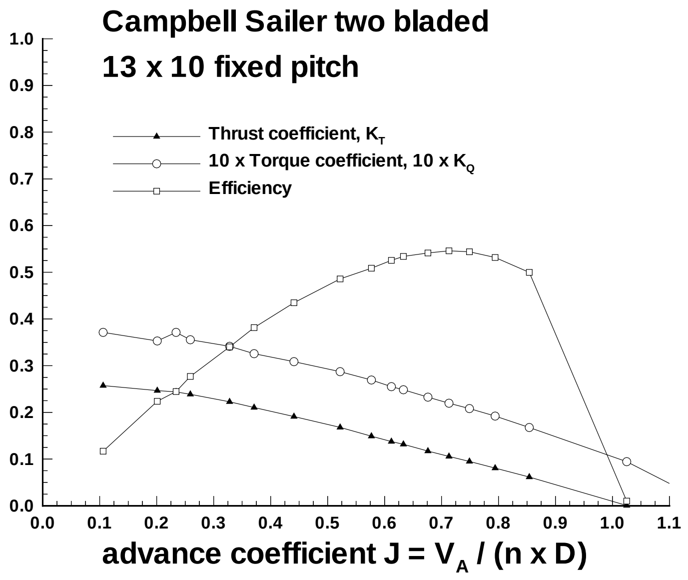

Figure 4: Campbell 2 bladed fixed

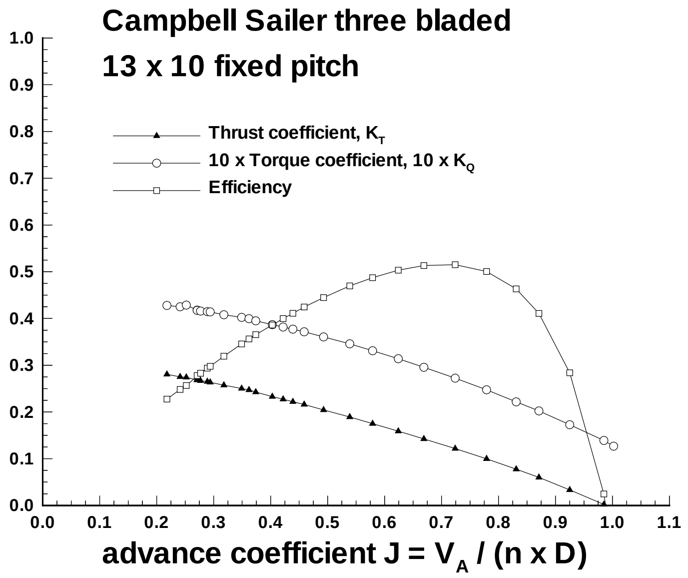

Figure 5: Campbell 3 bladed fixed

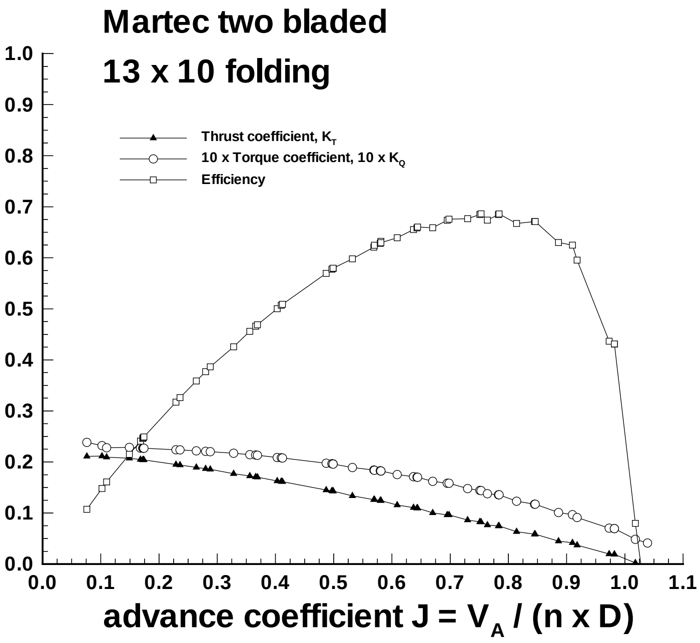

Figure 6: Martec 2 bladed folding

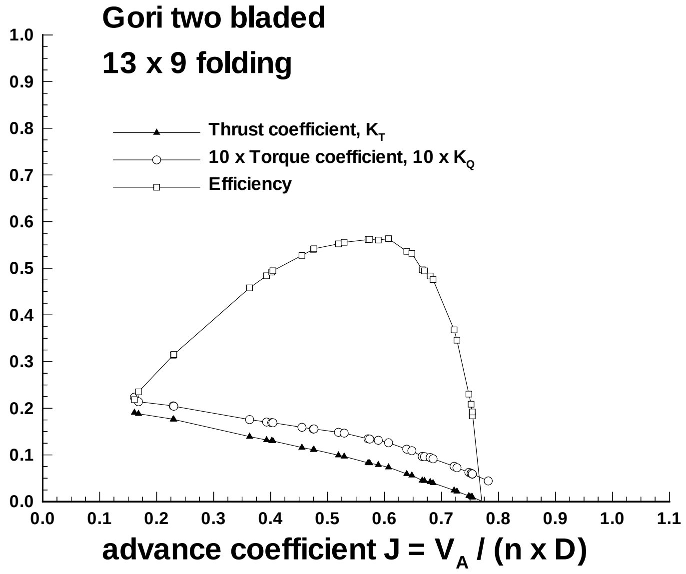

Figure 7: Gori 2 bladed folding

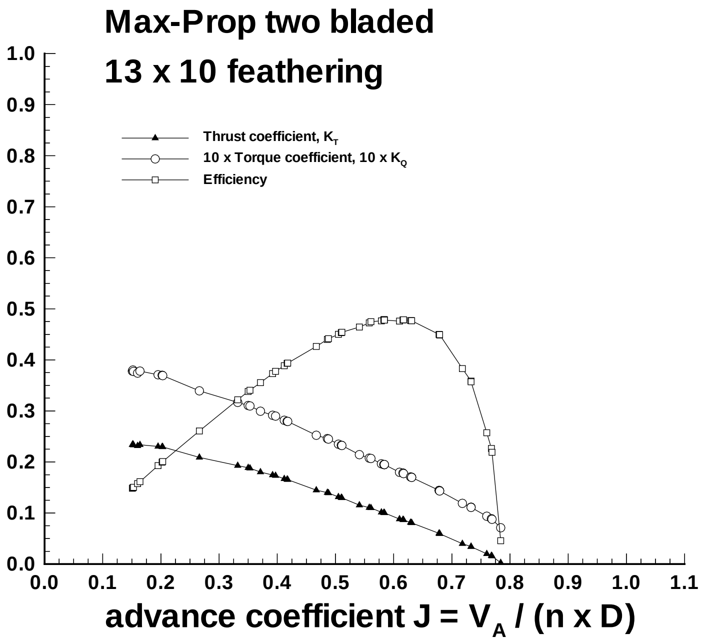

Figure 8: Max-Prop 2 bladed feathering

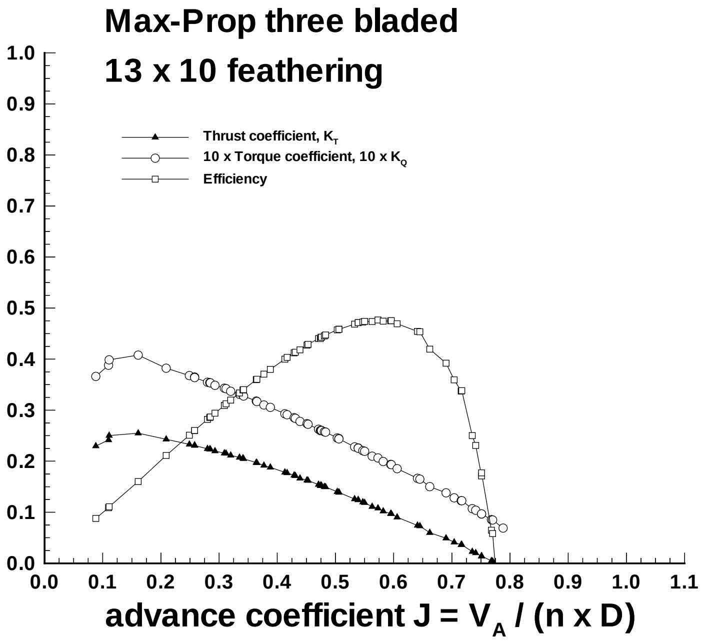

Figure 9: Max-Prop 3 bladed feathering

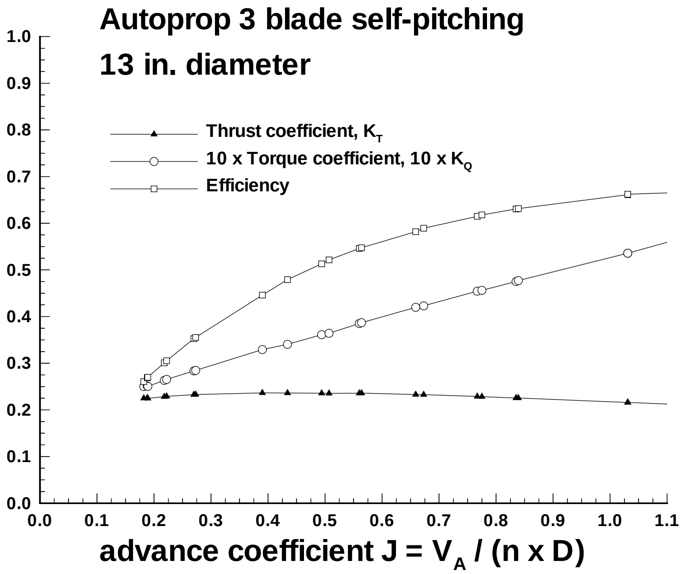

Figure 10: Autoprop self-pitching

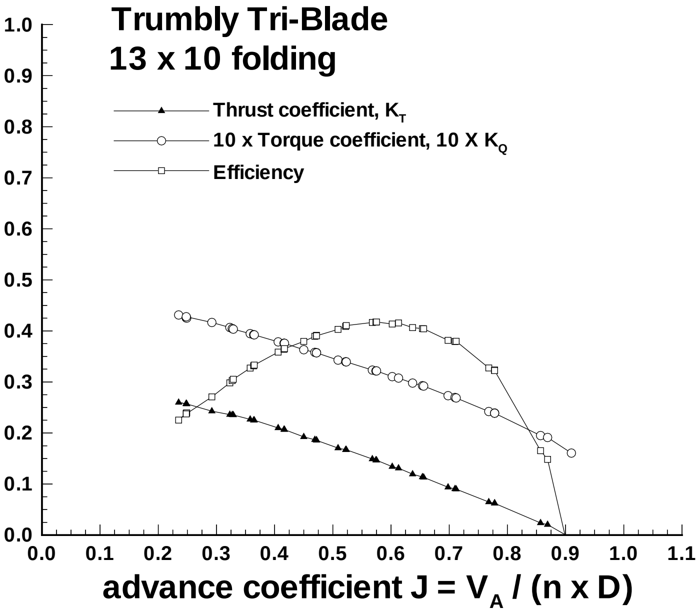

Figure 11: Trumbly Tri-Blade folding

The angle of attack relative to the passing water "felt" by a propeller blade is related to the ratio of boat speed to propeller RPM. At the risk of oversimplification, the blades must maintain a positive angle of attack in order to continue producing lift and providing thrust, in the same way that an airplane wing must maintain an upward angle of attack in order to climb. If a propeller is not spinning fast enough for a given water speed, the propeller will not be able to keep up and will, in a sense, be "outrun" by the passing water; the prop will no longer be producing forward thrust; instead, it causes drag. The situation is analogous to a person jumping out of a speeding car and trying to get his or her legs moving quickly enough to continue running at the same speed as the car: the person will not be able to aid in propelling the car and will instead be a weight to be (literally) dragged. A more realistic example is when a boat under power is throttled back substantially: momentarily the boat is still travelling at the speed associated with the previous higher propeller RPM, even though the propeller is now spinning more slowly. The water passing the boat is outrunning the propeller; the prop acts as a brake until the boat has slowed down enough so that the propeller can once again get a bite on the water, produce lift, and resume propelling the boat at the new lower speed.

This behavior can be seen on the K_T versus J_A curves. The crossing from thrust to drag for a propeller occurs at the value of J_A where K_T, which is based on thrust, changes from positive (forward thrust) to negative (reverse thrust, or drag).

It is in this context that the advantage of the Autoprop is manifested. First, as stated before, the Autoprop repitches itself automatically for a change in conditions; boat speed and/or RPM, so that its blades maintain a positive angle of attack to the oncoming flow. It can provide lift up to extremely high values of J_A: note that the Autoprop K_T curve shows a K_T value that appears to decrease only slightly with increasing J_A. This feature would be helpful to a skipper who is motorsailing: it would not be necessary to spin an Autoprop (and hence the engine) at an RPM as high as for the other propellers in these tests, other conditions being equal, in order to get the same boost from the propeller. Second, when powering into head seas or heavy wind with any propeller, for a given RPM the boat will move at a speed that is lower than that for calm water and wind. Lower boat speed corresponds to a lower advance coefficient, J_A, and hence to larger angles of attack on the fixed blades. This increases the torque necessary to continue to turn the propeller, resulting in an engine that may be laboring. Since the Autoprop will decrease pitch in this situation, providing smaller blade angles of attack, the engine is able to continue usual operation.

A warning is appropriate regarding the apparent advantage of thrust from an Autoprop at high advance coefficients. It is crucial to remember that almost all boats that might use an Autoprop are displacement hulls. Displacement hulls, unlike high-speed planing hulls that skim across the surface of the water, are limited in their maximum speed (the theoretical "hull speed") by bow and stern wave formations accompanying their passage through the water. As the boat gets close to hull speed, the force required to continue moving the boat any faster increases very rapidly. Short of hiring

propeller	J_A	*efficiency*
Michigan Wheel 2 blade fixed	0.43	0.59
Autoprop self-pitching	0.64	0.58
Martec 2 blade folding	0.49	0.58
Michigan Wheel 3 blade fixed	0.49	0.56
Gori 2 blade folding	0.45	0.53
Campbell Sailer 2 blade fixed	0.53	0.49
Campbell Sailer 3 blade fixed	0.56	0.48
Max Prop 3 blade feathering	0.49	0.46
Max Prop 2 blade feathering	0.49	0.44
Trumbly Tri-Blade	0.53	0.41

Table 1: Propeller efficiencies for a representative sailboat

a tug to pull your boat or surfing down the face of a wave, no propeller will enable you to break out of displacement hull speed. Even though it is tempting to envision an Autoprop as the revolutionary means to doubling one's top motoring or motorsailing speed, it is simply not the case! For most of us, engine power is a limited resource: having an Autoprop which can maintain a proper angle of attack even for very large RPM's has no practical application.

The best way to compare the efficiencies of the propellers is not to look simply at which propeller has the efficiency curve with the highest peak efficiency: considering only peak efficiency disregards the fact that it is usually impossible to operate a propeller/boat at the point of highest efficiency. The characteristics of the boat in question *must* be considered. A boat will require some amount of forward thrust to overcome hydrodynamic drag forces of the passing water. These forces increase as boat speed increases and thus the push from the propeller must increase to maintain higher speeds. When the boat is underway at a constant speed, the propeller provides the forward thrust (push) to exactly balance the drag (force trying to slow the boat down) felt by the hull for that speed.

In figure 12 is a curve related to the thrust, as a function of J_A, required to propel a typical 30-footer. This boat curve is shown on the same plot as the thrust coefficient and efficiency curves for the ten propellers. Where this "typical boat" line crosses the lines of propeller K_T are the actual operating points of each propeller with our hypothetical 30-footer. This tells us the advance coefficient at which thrust from the propeller and hydrodynamic drag on the boat are in balance, resulting in constant forward boat speed. A propeller with a higher J_A value needs fewer RPM's than one with a lower J_A value for the same boat speed. Then, one can look straight up the dashed lines on the plot to find the corresponding efficiency of each propeller at this advance coefficient to see which propeller is most efficient at its particular operating condition. Shown here is the dashed line for the Campbell Sailer 2-bladed prop only. The efficiency results for the ten propellers are shown in table 1.

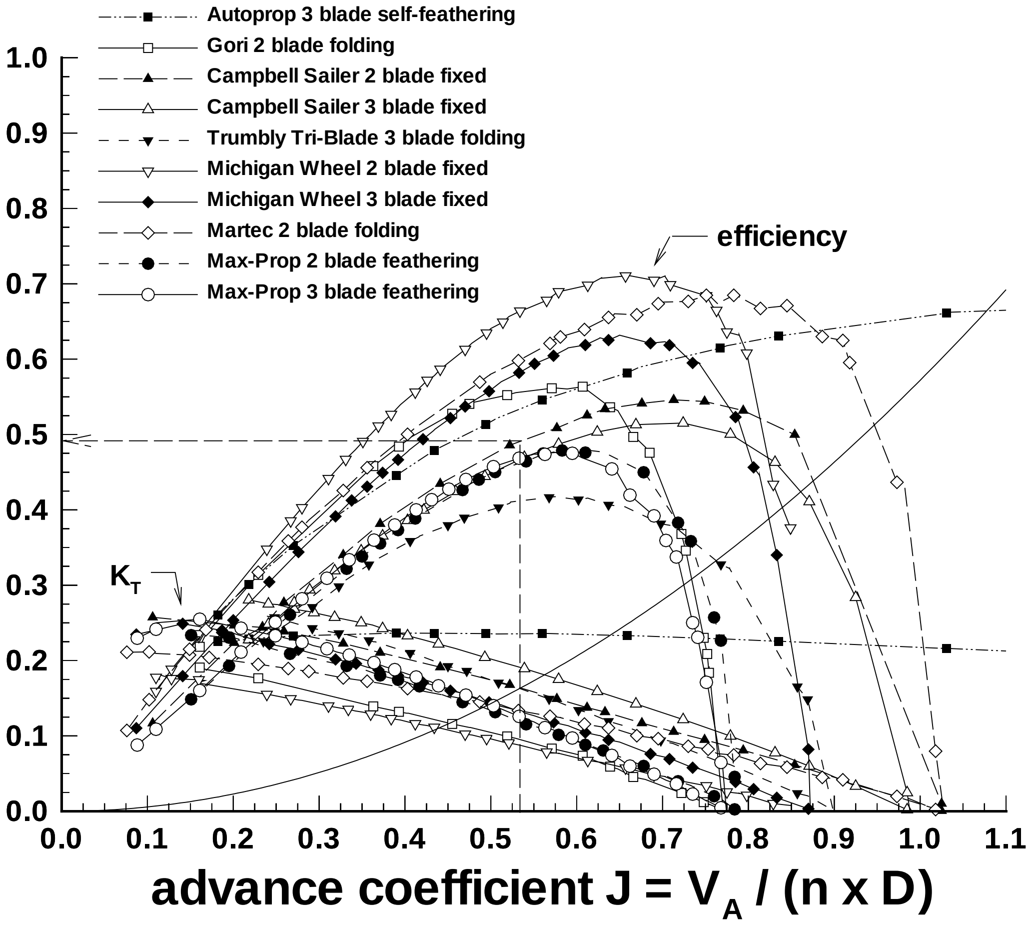

Figure 12: Determination of Propeller Efficiencies

Reverse Performance

The reverse thrusting ability of the ten propellers was tested. This proved to be not so straightforward a task as one might imagine. As mentioned previously, the water speed through the tunnel is measured by a differential pressure cell located in the contraction section. When the tunnel impeller is run in reverse, or when the impeller is run in forward but the propeller is run in reverse (which also pushes large amounts of water in the reverse direction), the water moves in the wrong direction (upstream) through the contraction section, making that area act as a diffuser. For higher water speeds the flow separates from the walls as the section widens, causing inconsistent velocity readings by the pressure cells. In order to prevent this from occurring, it is important to balance the forward speed of the water through the tunnel and the reverse thrust of the propeller. The combination of reverse propeller/reverse flow could not be accurately tested.

The technique that was developed to take data is as follows: the water speed was set to a constant forward 3 knots, and the propeller turned on in reverse and set to some rotational speed. Data was then taken as quickly as possible before there was flow reversal induced by the reverse spinning propeller. Once thrust readings had been taken, the propeller was turned off and the water allowed to reach a forward speed of 3 knots again, before the next run.

The decision was made to test at a forward speed of 3 knots and "gunning" the propeller in reverse because this simulates the action taken by the skipper when approaching a dock or mooring too quickly. It is in this situation that reverse performance makes the difference between safe docking and gelcoat repair. Also, very few skippers go any distance in reverse.

The results are presented in figure 13. For each of the propellers, best-fit lines were drawn to the data in order to enhance the readability of the trends. Overall the Max-Prop 2 bladed feathering, Campbell 2 bladed fixed, Campbell 3 bladed fixed, Michigan Wheel 3 bladed fixed, and Max-Prop 3 bladed feathering propellers had similar reverse performance; less thrust was generated by the Michigan Wheel 2 bladed fixed and Autoprop propellers, followed by the Gori and then the Martec folding propellers. It appears that at higher RPM's the Autoprop would turn in a better performance than any of the propellers. It was noted that neither the Martec folding propeller nor the Gori folding propeller opened completely for any combination of reverse RPM and forward flow speed. This is due to the tendency of the backwards thrust on the blades trying to close the blades even though the rotating shaft is trying to throw the blades open.

Finally, we experienced difficulty testing the reverse performance of the Trumbly. Therefore, those results are not included in this report.

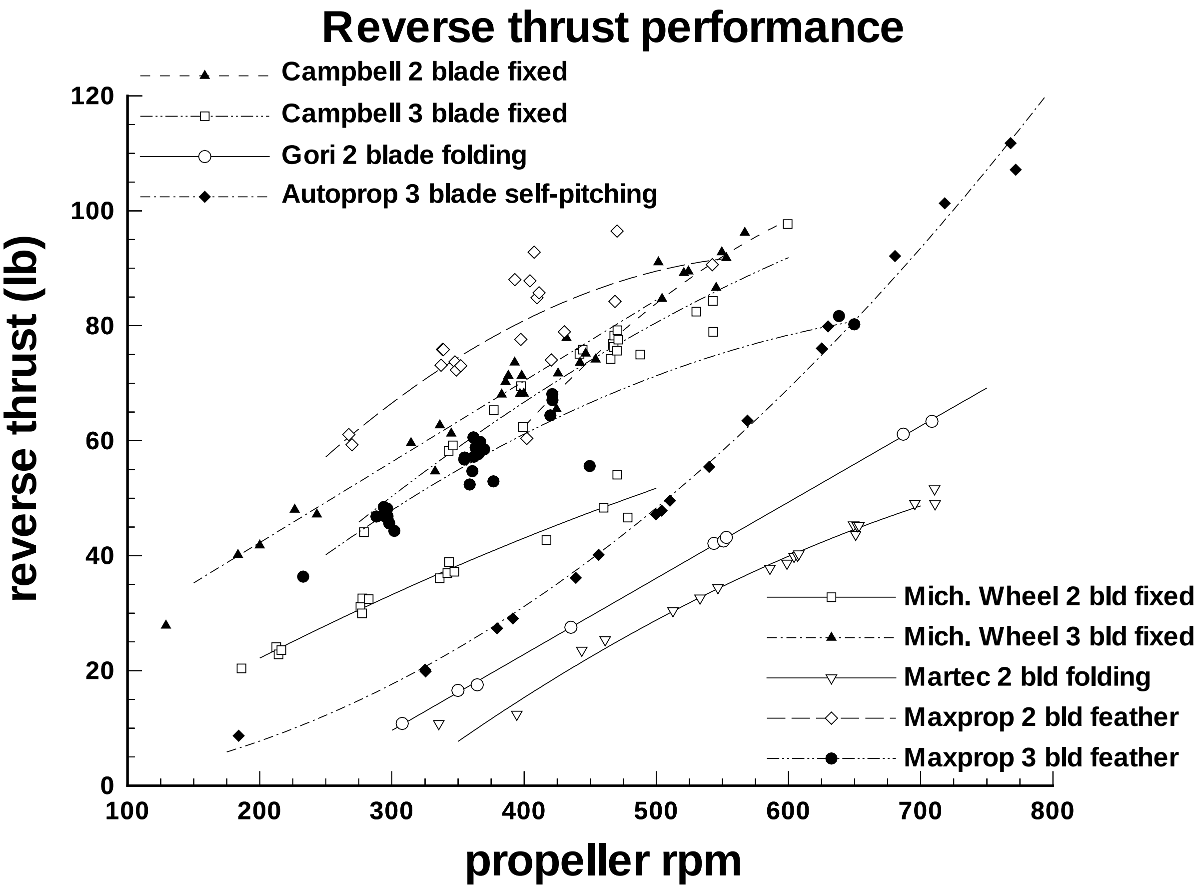

Figure 13: Reverse Performance

Drag Under Sail

An important consideration to many sailors is the amount of drag (the force which slows a boat down) caused by a propeller when sailing. Typically, while sailing, the boat-owner will choose to either lock the shaft and propeller in place or allow the propeller to "free-wheel." Due to the experimental set-up, allowing the propellers to "free-wheel" was not possible.

Drag measurements were taken while the propellers were held essentially still, analogous to locking the shaft in place. The propellers were spun at a very low RPM, less than 1 rotation every 8 seconds, in order to keep the water lubricated bearings around the shaft from sticking and interfering with the measurements. Though the propellers were spinning, their rotational speeds were so low that the propellers could be considered as fixed in place.

Drag was measured for each propeller at various water speeds. The results are shown in figure 14. At low speeds, the drag readings for the feathering propellers, the folding propellers, and the Autoprop were small enough to be hidden in the electronic noise of the test equipment. Thus those readings were not included. Still, the general trends for the drag characteristics for each propeller, relative to the other propellers, are very clear.

The lowest drag can be achieved with a folding or feathering propeller. You must be sure, though, that a folding propeller like the Martec or the Trumbly is prevented from having one of its blades fall open, which increases the drag. Next best performance in drag comes from the Autoprop, which balances water forces and gravity forces on the blades in an effort to feather the blades. Finally, drag from fixed propellers turned out as expected with three blades showing more drag than two, and broader blades creating more drag than narrower blades, all other thing being equal.

A popular debate regarding the drag on fixed pitch sailboat propellers concerns the practice of "free-wheeling" the propeller when under sail. By placing the boat's engine in neutral while under sail, a skipper can allow the propeller to spin on its own due to the hydrodynamic forces of the water passing by. Ideally, the propeller shaft would have no torque applied to it by the boat or engine while free-wheeling, and hence the propeller would spin at an RPM strictly governed by the sailing speed at the moment: this would correspond to points on the K_T, $10 \times K_Q$, and efficiency curves where $10 \times K_Q$ (torque) is zero. In reality, zero torque is impossible, as small amounts of friction from the sterntube bearings, stuffing box, and engine prevent the propeller from free-wheeling as fast as it would like. Looking back at the definition of J_A, this lower RPM at a given V_A (proportional to current sailing speed) will result in a larger value of the advance coefficient. An example of what all these free-wheeling details would produce in terms of changes in drag is as follows.

From figure 14, the drag on a 3 bladed fixed propeller at 6 knots is about 40 pounds when not spinning. If the torque holding the propeller in place is now removed, the propeller will begin to free-wheel. Due to the friction mentioned above, the propeller will not be able to spin exactly at the point of zero torque, but instead at a slightly lower RPM and thus a slightly

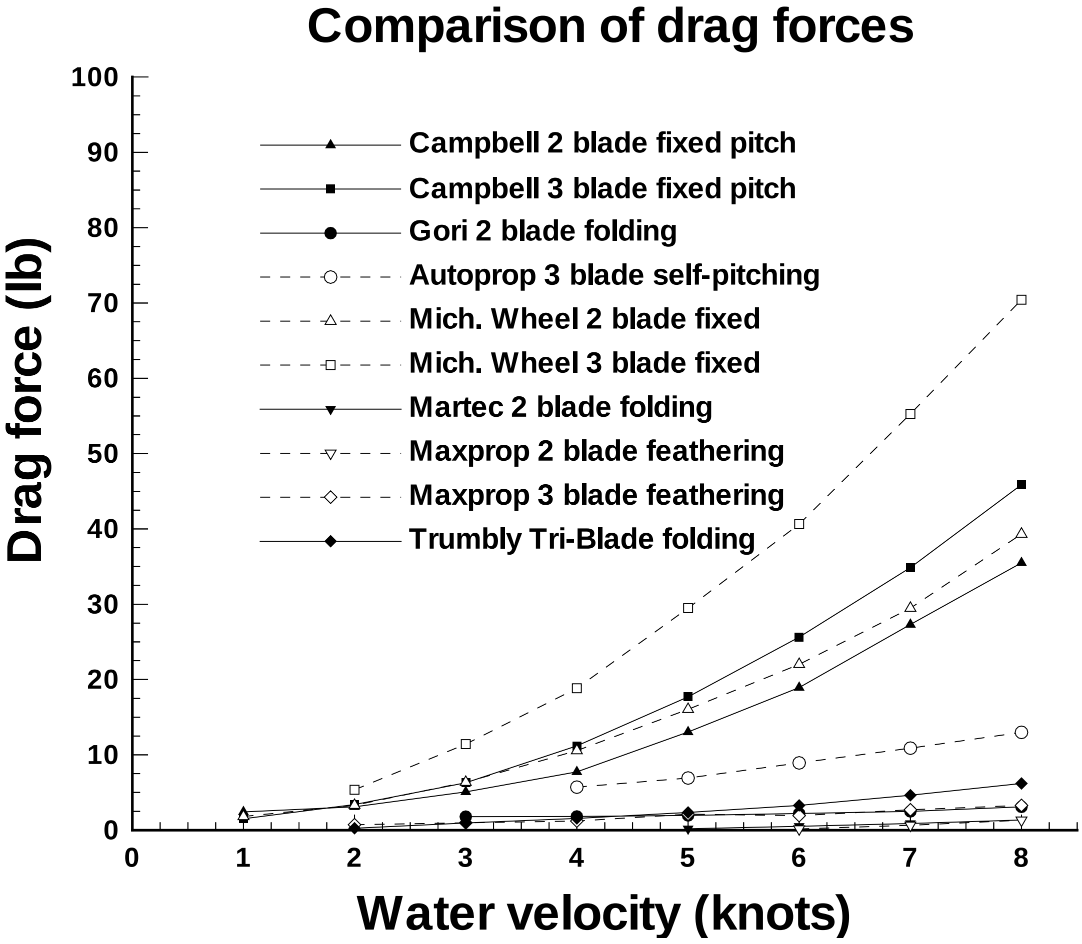

Figure 14: Comparison of drag forces

higher advance coefficient. In figure 3, the $10 \times K_Q$ curve can be extended to the right by eye to the point where it passes through zero torque. Zero torque ($10 \times K_Q = 0$), corresponding to no friction on the shaft from the boat, would fall at about $J_A = 0.95$. A reasonable approximation for the advance coefficient that accounts for the bearing friction therefore might be $J_A = 1.05$. Extending the K_T curve as well, the value of K_T is about -0.1. Using the formula for K_T, the thrust is about -21 pounds (this is 21 pounds of drag on the boat, since K_T is negative). Clearly, the decreased drag for this situation is worthy of consideration. The conclusion from these calculations is that a substantial reduction in drag, and thus gains in boatspeed, can be realized when a fixed pitch propeller is allowed to free-wheel. The decision to free-wheel or not, though, must also take into account the factors of noise and wear and tear on the engine and bearings.

Conclusions

Ten sailboat propellers were tested in three operating conditions: forward rotation, forward water speed (normal forward operation); reverse rotation, forward water speed (simulated backing down); and no rotation, forward water speed (drag with shaft held in place while sailing).

In forward operation, all propellers tested here are capable of propelling a typical 30-foot displacement sailboat, though at different relative RPMs as shown by the J values in table 1 (a propeller with a higher J value can be considered to need fewer RPMs than one with a lower J, for similar thrust). In reverse operation, the Maxprop 2 bladed feathering propeller appears to perform well for these test conditions, while the folding propellers produced the least thrust for the RPM's tested. Under sail, the fixed propellers were found to have more drag than the feathering/folding models, which can be considered to have negligible drag. The actual relative drag performance from each model can be seen in the figure in the section on drag.

The choice of a propeller is therefore heavily dependent on the needs of the individual owner. Choosing between a fixed, folding, or feathering propeller necessitates consideration of all performance requirements. Each skipper will care more or less about the different performance characteristics for a given propeller. Clearly there is not one propeller that is best in every category or for every owner.

Acknowledgments

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