Advanced Wind Propulsion Devices—Current Status and Potential

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ABSTRACT: Wind propulsion has evolved over thousands of years to the basic Marconi or Bermuda rig commonly seen on yachts and small workboats. In recent times some radical and not quite so radical concepts have been proposed and demonstrated for wind propulsion. Three of these relatively new ideas are explained and their potential compared to existing designs: Magnus effect devices or Flettner rotors, rigid airfoils, and wind propellers. Each of the new concepts is discussed as to what has been done, is being done, or is planned. The merits and problems with the concepts are reviewed, and their potential for workboat and ship propulsion is evaluated. An appendix is included that reviews actual and potential marine applications of the Magnus effect other than for wind propulsion.

BACKGROUND

Surely sail propulsion dates back thousands of years to the time when an early sailor got tired of paddling and rigged a sail that was probably no more sophisticated than a bedsheet attached to some sort of pole (mast). Since those early times the sail has evolved into the relatively sophisticated form called either a Bermuda or Marconi Rig, currently in use on yachts. For more details on sail form evolution see Smith's fascinating book "The 40-Knot Sailboat." (1)

\[Figure 1: Flettner's first rotor ship - BADEN-BADEN\]

In 1924, a revolutionary sail form was introduced by Anton Flettner, a German entrepreneur. Flettner's device, which he called the Flettner Rotor, relies on a phenomenon discovered by Magnus before the turn of the century. Magnus' research was prompted by a desire on the part of the German military to find out why artillery projectiles would not stay on
course. Magnus established that a spinning projectile in a cross wind would move at right angles to the wind. (This is also the phenomenon which causes baseballs to curve when spun by the pitcher.) Flettner's rotor was designed to take advantage of this characteristics called the Magnus effect. Flettner mounted two of his rotors on a small ship, the BADEN-BADEN shown in Figure 1, which successfully crossed the Atlantic and during the crossing passed through a hurricane. Flettner also fitted a larger vessel "BARBARA", with two rotors. (2) Although both these experimental ships were successful, the very low cost of fossil fuel caused the investigations to end in the late 1920's.

Since World War II, the small high performance sailboat community - most especially Class C catamaran proponents - developed small rigid airfoil sails. (Figure 2) The Cross Bow - a 70 foot catamaran with an airfoil rig - currently holds the sail speed record of 33.8 knots. (4) Rigid airfoil sails have the advantage of significantly higher lift coefficients than soft sails.

Figure 2: Class C catamarans with wing sails. Patient Lady on the left is a U.S. design and Nicholas II is an Australian design. (3)
Since 1956, the Shipbuilding Institute, in Hamburg, German, has been studying a modern square rig system with cloth sails and in-the-mast roller reefing and furling called Dynaship. (5) (Figure 3) Unfortunately the Dynaship system has not progressed past the model stage.

**Figure 3:** Hamburg University Institute for Shipbuilding's Dynaship. An automated square rig design with in-the-mast roller furling. (5)

The Japanese have installed a unique rig on two ships, the SHIN AITUKO MARU and the AITUKO MURU. This rig is similar in form to Dynaship but uses rigid sails and is furled using a folding rather than a roller reef type system. (6) (Figure 4)

Wind Ship in Norwell, Mass., has installed a 3000 square foot (300 square meter) roller reefed cat rig on a small Greek flag tanker called MINI LACE. Fuel savings on this low speed coastal vessel have been on the order of 25 percent. (Figure 5)

Wind Ship has also built a 300 square foot (30 square meter) airfoil test rig which is currently undergoing limited testing. (9) (Figure 6) It is anticipated that the Government will underwrite extensive wind tunnel testing of this rig in the near future.
Figure 4: SHIN AITUKO MARU'S folding sails.(?)

Figure 5: MINIACE - Small coastal tanker under Greek Flag with U.S. design roller furled cat rig.(8)

Figure 6: Wind Ship's 300 square foot (30 square meter) airfoil model.
Dr. Blackford of Dalhousie University in Halifax, Nova Scotia, has built a windmill drive for a 12 foot (4 meter) catamaran which demonstrates the feasibility of windmill propulsion. (Figure 7)

Figure 7: Dalhousie University windmill boat (catamaran) sailing straight upwind. The wind turbine can be rotated about the vertical mast so as to face the apparent wind, allowing the boat to be sailed in any direction without tacking. $F_W$ is the backward force on the wind turbine. $F$ is the forward force produced by the underwater propeller and $F_D$ is the drag force of the water on the boat. The net force $(F-F_W)$ produces the forward speed, $u$, of the boat, at which $F-F_WF_D = 0$. The underwater hydrofoil at the rear of the boat counteracts the rearward pitching moment due to the forces $F_W$, $F$ and $F_D$. (10).

ONGOING EFFORTS

As previously noted, there are a number of ongoing efforts to develop advanced thrusters. The objective of most of these efforts is to establish feasibility and to find the best system from a life cycle cost basis for future sail assist applications.
Wind Ship is developing the technology needed to install large high lift airfoil sails for ships. Their designs are in the 3000 to 5000 square foot (300 to 500 square meter) range. (9) Studies indicate that of the forms investigated by Wind Ship for MARAD, the airfoil is the best. The French, having arrived at much the same conclusion as Wind Ship, are looking for even greater lift (11), the Japanese are sticking with their AITUKO MARU rig, however, they consider airfoils to be a close competitor, and the Germans continue to study the Dynaship form to the point that it seems that a rig could have been built and tested if much of the study cost had been put into hardware.

The Borg/Luther Group in Carpenteria, California, has been studying various configurations of Magnus effect devices for marine applications over the past four years. The potential applications include wind generators and thrusters, rudders, propellers, roll stabilizers, and tidal generators. Borg/Luther has applied for a number of patents and has done considerable small scale modeling.

Dr. Blackford of Dalhousie University is working on improving the efficiency of his propeller drive catamaran by evaluating such improvements as the use of variable pitch propellers.

**OBJECTIVES OF ADVANCED WIND PROPULSION DEVICES**

Table 1 was developed to compare wind thruster characteristics. The rigs listed include the now primitive square rig which made the so called "Yankee Clipper", which plied the oceans in the mid to late Nineteenth Century, the fastest sea transport of its time. The other end of the spectrum includes advanced forms such as airfoils, windmills and rotors. Three comparative measures are used. Lift per dollar takes into account the initial cost and the life cycle maintenance cost. (Estimated cost/square foot to build, install and maintain multiplied by the lift coefficient (12)) The second factor is upwind performance which is meaningful when the vessel is attempting to follow an upwind course. The third factor is Manning which is broken down into two parts - operational and shipboard maintenance. The maintenance Manning category is further broken down into two parts - numbers of personnel and skill levels. There are at least four other categories that should be considered but are not particularly amenable to tabular presentation. These four categories are: Stability, Stowability, Backfit Potential and Mission Compatability.

The old square rig besides having the poorest cost factor is Manning intensive, has poor upwind performance, requires more stability than most, is not particularly amenable to backfit, and tends to interfere with mission requirements. The stayed fore and aft rig represents the current state of the art and is being used for a number of sail assist applications. Hugh Lawrence's PATRICIA A., is probably the most significant example. The drawbacks of the fore and aft rig are relatively high operator Manning, stability and interference with mission requirements. Dynahips major drawbacks are poor upwind performance, high maintenance Manning because of the complexity of the furling mechanism, relatively high stability requirements and relative lack of
mission compatibility because of the yards. The SHIN AITUKO MARU rig and the unstayed cat rig's major drawback is the high maintenance skill levels required to maintain the actuators and controls.

Of the five state of the art rigs discussed above, the stayed fore and aft rig, the unstayed cat rig and the SHIN AITUKO MARU rig appear to be the best choices for current applications with selection depending on factors such as first cost, mission peculiar requirements, and backfit constraints.

<table>
<thead>
<tr>
<th>RIG</th>
<th>LIFT/$*</th>
<th>MINIMUM ANGLE TO WIND</th>
<th>MANNEING OPERATORS NO.</th>
<th>MANNEING MAINTAINERS NO./SKILL</th>
</tr>
</thead>
<tbody>
<tr>
<td>SQUARE</td>
<td>9.9</td>
<td>45°</td>
<td>VERY HIGH</td>
<td>HIGH/LOW</td>
</tr>
<tr>
<td>STAYED FORE &amp; AFT</td>
<td>18.5</td>
<td>30°</td>
<td>HIGH</td>
<td>HIGH/LOW</td>
</tr>
<tr>
<td>UNSTATED CAT</td>
<td>13.2</td>
<td>30°</td>
<td>LOW</td>
<td>MOD/HIGH</td>
</tr>
<tr>
<td>DYNASHIP</td>
<td>21.1</td>
<td>40°</td>
<td>LOW</td>
<td>HIGH/HIGH</td>
</tr>
<tr>
<td>SHIN AITOKU MARU</td>
<td>22.5</td>
<td>20°</td>
<td>LOW</td>
<td>MOD/HIGH</td>
</tr>
<tr>
<td>AIRFOIL W/SIMPLE FLAP</td>
<td>34.5</td>
<td>15°</td>
<td>LOW</td>
<td>MOD/HIGH</td>
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</tr>
<tr>
<td>ROTOR</td>
<td>109.9</td>
<td>20°</td>
<td>LOW</td>
<td>MOD/HIGH</td>
</tr>
</tbody>
</table>

*CL/($1000/ft²)

Table 1: Rig Comparison Table. (2, 5, 6, 8, 9, 10, 11, 12, and 13)

The last four rigs in Table 1 are considered to be on the fringe of the current state of the art or beyond. Three out of four show a significant cost per unit of lift advantage. The fourth "rig" the windmill is not a lift device. The balance of this paper will focus on these high performance devices.
AIRFOILS

The airfoil is basically one half of an airplane wing. The physical laws that make it function are the same as those that apply to an airplane wing or a cloth fore and aft sail.

The main advantage of an airfoil over a cloth sail such as the unstayed cat rig is the higher lift coefficient that results from better control of the aerodynamic shape. The initial per square foot cost of an airfoil is greater than a cloth sail but life cycle cost is expected to be less. The major drawback of the airfoil is the low probability of making one that can be furled. To overcome this problem Wind Ship has designed an airfoil with a simple flap that can be set into the wind when not being used (feathered) without fluttering. With this design the airfoil sail does not need to be furled.

The tenth area model of an airfoil with a simple flap built by Wind Ship has demonstrated a lift coefficient of 2.0 in actual tests. (The best cloth sail rigs have lift coefficients of 1.5 to 1.6.) Although this 300 square foot model has the same area as the rigs being used on Class C catamarans, it is considerably heavier. The primary reason for the weight increase is that no relaxation of forces occurs when the wind hits an airfoil on a large stable ship whereas a small catamaran will heel, relieving the load on the rig.

Higher lift coefficients than 2.0 for an airfoil are considered feasible. Both references 11 and 14 indicate that a slotted entry design can result in lift coefficients in the range of 2.5 to 3.0.

References 9, 11 and 12 provide more detail on the merits and details of airfoil rigs.

WINDMILLS

In the Wind Ship report for the Maritime Administration (12), windmill propulsion was not seriously considered. Some of the reasons were: losses involved in converting windmill generated energy into propulsive energy, the large propeller size required to get enough power to drive a ship (200-300 foot diameters have been proposed), and the structural problems and bridge clearance problems with these large windmills. Table 1 does not include cost data on windmills in part because apparently no data on ship sized windmills has been generated.

However, even though windmills do not seem to show much promise at this time, there are factors that make them attractive and potential that has yet to be fully explored. As has been previously mentioned, Dr. Blackford of Dalhousie University, has developed a working small catamaran with a windmill/water propeller propulsion system. (10) With this small scale vehicle, he has achieved speeds on the order of 60 percent of wind speed regardless of wind direction. Although this does not compare favorably with conventional sail driven performance on most sailing points, with further improvements it has the potential for becoming more competitive, if not equal, to a conventionally rigged
catamaran. The use of advanced windmill forms, such as the Magnus effect windmill discussed later, may help improve performance as well as minimizing many of the problems outlined in reference 12.

If windmill performance cannot be increased to the point where it is competitive with the performance of fore and aft rigs or airfoils then the only unique feature of windmills - the ability to sail directly into the wind - will not be enough to make windmills competitive. The inability of other sail forms to sail directly into the wind can be overcome by techniques which will be discussed later.

MAGNUS EFFECT ROTORS

Table 1 ranks the rotor as the most cost effective of the all known ship wind propulsion devices. However, before the merits of the Magnus rotor are discussed, an explanation of what it is and how it works is in order.

The Magnus effect or Flettner rotor is a cylinder with flat end plates which is spun at surface velocities greater than the velocity of the apparent wind. The force to spin the rotor is usually provided from an auxiliary power source. However, recent work by Aydlett (15) and Borg indicate that a Magnus effect rotor can be spun at reasonable speeds by the apparent wind. The Magnus effect causes a partial vacuum to develop on the side of a spinning cylinder where the velocity of the spin combines with the velocity of the apparent wind. The vacuum developed permits the higher pressure air on the opposite side to push the rotor at right angles to the wind. As the velocity of the surface of the rotor increases, the pressure on the high velocity side decreases, thereby increasing the lift. The revolving cylinder will perform in the same fashion in a stream of flowing air or water but the magnitude of the lifting force will be relative to the mass-density of the fluid used.

![Graph: Magnus Rotor Lift vs Velocity Ratio (Experimental)](image)

Figure 8: Magnus Rotor Lift vs Velocity Ratio (Experimental). (17)
According to Swanson (16) the lift coefficient for a long slender Magnus rotor follows the curve in Figure 8 as the spinning velocity is increased. However, Flettner's experiments with relatively fat cylinders indicated a lift coefficient maximum of 10 at a velocity ratio of 5:1. Our practical capability to design and build tall thin rotors may make Flettner's conclusions more significant than Swanson's.

As previously noted, Aydlett and Borg have been experimenting with wind spun rotors. Aydlett considers a lift coefficient of about 2.7 to be the maximum for a wind spun rotor. Borg considers a lift coefficient of about 5 to be possible. Regardless of who is right, a wind spun rotor is comparable to or perhaps better than an airfoil concerning lift. Figure 9 shows a typical wind spun rotor which uses a self spinning principle inspired by the Flettner rotor and postulated by Savonius in the mid 1920's. (15) A self spinning rotor could be used on a small vessel to avoid the need for an auxiliary drive.

The major advantages of the Magnus rotor are ease of control (speed and direction of the rotor is the total control requirement), high lift, the ability to reduce air draft by telescoping the rotors, and simple cylindrical construction. A fore and aft pair of rotors, when used as a wind propulsion system is the lack of downwind performance. Figure 10 illustrates three possible arrangements of rotors. The first arrangement, which was the one Flettner used, performs reasonably well on a reach but as the wind comes around to the stern (downwind or running) the vessel will go sideways if both rotors are spun in the same direction or will turn in circles if the rotors are spun in opposite directions. By putting the two rotors side by side as shown in the second set of ships, Borg has postulated that some downwind capability will be obtained by the wind acting on the high pressure "wind wall" developed by the Magnus effect plus a pocket of low pressure expected to be between and extending somewhat forward of the rotors acting to let the force on the "wind wall" move the ship. The "four poster" arrangement is expected to perform in the same manner as the transverse arrangement but give more total thrust. The transverse dual rotor and "four poster" arrangements require considerable experimentation with diameters and spacing before Borg's theory can be proven. In all cases a broad reach is expected to generate a driving characteristics about the same as that for a close reach.
Figure 10: Magnus effect (Flettner) rotor arrangements. The fore and aft arrangement is the one used by Flettner on BADEN-BADEN and BARBARA (2). The transverse and "four poster" arrangements are theoretical (Borg/Luther February 17, 1983).
If Borg is wrong - and probably even if he is right - in his assumption, upwind performance can be improved by using the technique currently used by catamaran sailors to overcome cats notoriously dull downwind performance. Figure 11 illustrates the technique where the vessel is tacked downwind. In this case, where a very efficient hull form wind/speed diagram is used, the most effective course is 127 degrees and results in a speed made good downwind greater than wind speed. It should be noted that upwind performance with a high performance hull can be improved by coming off a point or close to the wind course, to a near reach. In the case shown in Figure 11, the optimum upwind course is 45 degrees which also produces an upwind speed greater than wind speed. Of course, tacking is not always possible in restricted waters, but large sail assist vessels would probably be under Diesel power when coming in or out of port. The technique of tacking up and downwind tends to reduce the significance of the windmill ships unique into the wind capability as well as diminishing the significance of the rotor's poor downwind performance.

Vt = True Wind Velocity

Figure 11: Downwind and Upwind routing of airfoil vessels for best speed to destination. Wind boat speed diagram (1) is for an almost frictionless hull form.
In the interest of boat sized testing of the Magnus rotor, to prove to those that weren't around in the mid 1920's that the rotor works, and to re-evaluate the limits of lift increase with rotor velocity increase, the Author plans to build and test the rig shown in Figure 12. The rig is designed to provide the same lift as the Hobie 16's stock rig (fully battened Marconi sloop rig) at a velocity ratio of 4:1. The Hobie was selected because: it has low resistance as shown in Figure 13 as compared to a mono-hull, it is the largest class of catamarans in the world which should provide numerous opportunities for comparing performance with its conventional rig, and the author happens to own one.

Figure 12: Hobie 16 foot catamaran with a powered Flettner Rotor and a wind generator. (Standard Hobie 16 sail shown in phantom.)

Figure 13: Hull Speed as a function of Width-to-Length. (17)

The Navy is currently negotiating with the Borg/Luther Group to study and develop a model test program to further evaluate applications of the Magnus effect to marine applications. The Flettner or Magnus rotor is the wind propulsion device under the proposed study which also includes rudders, propellers, wind generators and stabilizers which are discussed in the appendix to this paper. Lloyd Bergeson, president of Wind Ship also advises that Wind Ship is studying the Magnus effect.
CONCLUSION

The airfoil sail is almost ready for use for sail assist in large and small vessels. As previously noted, the government is considering underwriting wind tunnel tests of Wind Ship's one tenth scale model which should provide adequate data to permit full scale use for sail assist at minimum risk.

The windmill system has a long way to go. However, Dr. Blackford should be encouraged to continue his research. In addition, the use of the Magnus effect windmills discussed in the Appendix should be evaluated for their potential to drive a propeller.

The Magnus effect rotor has the greatest potential. However, considerably more research, modeling and testing must be done before full scale development is indicated.

With these three high performance systems as candidates our ability to demonstrate high performance full size advanced thrusters in the next decade is only constrained by economics. The availability of development, fabrication and installation dollars and the cost of oil will control the continued development of these devices for wind propulsion.

Appendix

Actual and Potential Applications of the Magnus Effect Other Than For Wind Propulsion

MAGNUS EFFECT RUDDERS

Cylindrical rudders designed by Borg/Luther have been used successfully on several vessels and are most advantageous for low speed, high thrust applications. (Figure A-1) The most obvious benefit is that no forward thrust is lost during a maneuver because the rotor does not act as a brake while a conventional rudder wastes large amounts of horsepower when hard over. (18)

The Magnus Rudder requires more horsepower for the rudder system than a conventional rudder, however the reduction in drag at a high speed of 10 or more degrees of rudder angle more than compensates by saving propulsion power. Although a higher power drive is required, the simplicity of the rotor as compared to a conventional

Figure A-1: Magnus Rudder. (19)
rudder results in the rotor system cost being comparable to a conventional rudder system. The simplicity of the rotor rudder also makes it inherently strong and relatively impervious to ice and floating debris.

The above characteristics make the Magnus Effect rudder ideal for amphibious craft, tugs, towboats, craft operating in ice, and fishing vessels pulling nets underwater.

MAGNUS EFFECT PROPELLERS

Within the past few months a successful model Magnus effect propeller has been tested by Borg/Luther proving that the principle will work. Calculations based upon Magnus effect hydrodynamic theory indicate such a propulsion device could deliver twice the thrust per horsepower as a conventional propeller for low vessel speed applications. This could result in cutting an operators fuel bill in half. (20)

![Diagram of Magnus Propeller](image)

**Figure A-2: Magnus Propeller (Borg drawing for pending patent).**

The Magnus effect propeller rotors shown in Figure A-2 can be driven in one of two ways. Either the rotors could be spun by a gear or friction drive in the shroud or by a separate drive through a concentric shaft in the tail shaft. The shape of the rotors could be cylindrical or conical, whichever is most efficient.
The cost of a Magnus propeller will be higher than a conventional propeller. If concentric shaft rotor drive is used, the cost will approach controllable pitch propeller costs.

Figure A-3 provides a comparison of the Magnus effect or Borg propeller to conventional, nozzled and vertical axis (Voith-Schneider) propellers. Tankers, Navy oilers, and most smaller vessels will save fuel with Magnus effect propellers if the theoretical curve for the rotor propeller proves to be accurate.

![Graph showing propeller efficiency](image)

**Figure A-3:** Propeller Efficiency Curves comparing Borg Rotor propellers with conventional, nozzled and vertical axis propellers. The curve compares the optimum propeller coefficient ($C_{p,\text{opt}}$) with Taylor's Power Coefficient ($B_p = \frac{NP}{V_o^{2.5}}$, were $N =$ RPM; $P =$ Horsepower; and $V_o =$ Speed of Advance) (21 and Borg circa March 1983).

Further testing is required to establish optimum rotor shape and the method for rotor spinning.

**MAGNUS EFFECT ROLL STABILIZERS**

Cylindrical stabilizers are still in the conceptual stage and have not yet been installed on any vessels. They are simple in design and
should cost a fraction of existing fin types. (Figure A-4) Considerable study and modeling will be required before the feasibility of using the Magnus effect for roll stabilization can be established. However, the potential of the device is too great to let it be overlooked.

**Figure A-4:** Magnus effect stabilizer system. (Stabilizer system shown oversize for clarity.) (The author circa September 1982. Sketch by Borg/Iuther February 17, 1983).

The factors that make further investigation worthwhile are:

- The high lift and low hydrodynamic resistance of rotors as compared to traditional foils.
- The simplicity of the structure of a rotor as compared to a foil.
- The ease with which a rotor can be retracted into a stowed position.
- The possibility of using electric rotor and retraction drives in lieu of complex hydraulics.

**MAGNUS EFFECT WIND TURBINES**

Although Flettner constructed Magnus Effect wind turbines in the mid-1920's, they seem not to have enjoyed much popularity. Perhaps
the complexities of the rotor drives and relatively low RPM at which they turned contributed to their lack of acceptance. The powerful torque they produced is another story. Model tests indicate that the more load they have to overcome, the harder they work.

2 ROTOR, MAGNUS EFFECT WIND GENERATOR

2 BLADE, TURBINE WIND GENERATOR

SIZE COMPARISON OF MAGNUS EFFECT AND TURBINE WIND GENERATORS OF EQUAL POWER

Figure A-5: Size comparison of horizontal axis Magnus effect and conventional wind generators of equal power. (Borg/Luther February 17, 1983).

Auto-rotating horizontal axis Magnus effect wind energy converters are about one fifth the size of comparable conventional blade types and power driven rotor units would be even smaller.

It is safe to say that a Magnus effect wind energy converter can presently be designed and constructed to serve any applications that are being considered for more conventional wind turbines, such as generator drives, pump drives, and as an alternate to the conventional propeller ship drive discussed earlier and in reference 10.

Figure A-5 shows Flettner's original (horizontal axis) form for a Magnus effect wind turbine and Figure A-6, shows Borg's recent vertical axis design. The vertical axis design although more complex than Flettner's design is expected to be more efficient for some applications.
Figure A-6: Vertical Axis Magnus Effect Wind Generator.
(Borg drawing for patent pending.)
Crimi, in reference 22, indicates that the size and simplicity of construction will make Flettner wind turbines competitive with more conventional wind turbine designs.

**MAGNUS EFFECT TIDAL GENERATORS**

![Diagram of Magnus Effect Tidal Generator](image)

*Figure A-7: Magnus Effect Tidal Generator - Uses vertical axis Magnus effect generator (Borg drawing for patent pending).*

Figure A-7 is a patent drawing for the application of a vertical axis Magnus effect water turbine of essentially the same design as the vertical axis wind turbine shown in Figure A-6. The vertical axis configuration lends itself to this application because of its balanced design which does not generate large bending movements in the vertical shaft.

**APPENDIX SUMMARY**

With the exception of Borg's Magnus effect rudder, all the designs discussed in this appendix require further study, modeling, and small scale testing before their full potential can be established. Because this is so, the contract that the Navy is currently negotiating with the Borg/Luther Group includes work on these devices as well as the basic Magnus effect ship propulsion rotor.
REFERENCES:


14. Correspondence between Oscar Owinger (Consultant in Structural Dynamics, Aeroelasticity and Fatigue) and Wind Ship, October 23, 1982.


GLOSSARY:

Airfoil - A shape that takes advantage of the difference in wind velocity from one side to the other in order to create a pressure differential and therefore a lifting force.

Apparent Wind - The wind speed and direction as seen by a moving vessel.

Broad Reach - Sailing with the wind ranging from perpendicular to the ship to 45 degrees aft of perpendicular.

Catamaran - A vessel with two symmetrical hulls.

Class C Catamaran - A catamaran with hulls not longer than 25 feet (7.6 meters), beam not in excess of 14 feet (4.2 meters) and 300 square feet (30 square meters) of sail area.

Downwind - Sailing with the wind behind the vessel.

Dynaship Rig - A sail form of the square-sail type that furls and unfurls the sails horizontally in and out of the mast while constrained by fixed spars.

Flettner Rotor - A vertical, cylindically-shaped sail used to drive a vessel. The Flettner rotor must be spun by auxiliary machinery to gain the lift required to provide a driving force.

Fore and Aft Sails - Sails fitted parallel to the ship's centerline.

Furling - Stowing sails (unfurling is breaking out sails).
Lift Coefficient - The ratio of the lifting force per unit area (i.e. pounds per square foot or kilograms per square meter) to the pressure that results when the air is stopped by a flat surface perpendicular to the flow (12).

Magnus Effect - The phenomena where lift occurs on a spinning cylinder at right angles to fluid flow. The lift occurs in the direction of the side where the fluid flow and the cylinder are going in the same direction.

Magnus Rotor - A lift device using the Magnus effect. The Flettner rotor is a Magnus rotor.

Marconi Rig - A fore and aft sail plan which uses sails which are triangular in form, with the point at the top, and cut to provide an airfoil effect when the wind passes across it. Sometimes called a Bermuda sail.

Point - To go as close to into the wind as possible without losing the wind in the sails (luffing).

Reach - To sail with the wind off the beam or at right angles to the centerline of the craft or ship.

Reefing - To shorten sail. This is accomplished in a variety of ways such as using reef points (lines attached to the sail) to put part of the sail around the boom or spar, or by rolling part of the sail up on the boom. This is done to limit heel by reducing sail area in high winds.

Run - To sail downwind (with the wind astern or behind the vessel).

Savonius Rotor - A Magnus effect device conceived by the Finnish inventor Sigurd Savonius in the early 1920's. (Figure 9)

Sloop - A single-masted craft with a small triangular sail called a jib forward of the mast and a larger sail, called the mainsail, aft of the mast.

Square Rig - A rig with sails at right angles to the centerline of the vessel. The sails were traditionally hung from spars and furled by manually gathering the sails up to the spars. The full-rigged ship typified by the Clippers of the early nineteenth century, were rigged with square sails on three masts.

Spars - Horizontal beams, hung on a mast at right angles to the vessel's centerline, used to support square rigged sails.

Tack - A technique used by sailing vessel operators to get to a location which is upwind of the vessel's position. The vessel is sailed as close to the wind as possible with the wind coming from the right (starboard) and alternately shifted so that the wind is coming in from the left (port). By tacking to port and starboard the vessel can (slowly) arrive at a destination directly upwind of the starting point.

True Wind - The speed and direction of wind seen by a stationary object.
Upwind - Sailing into the wind.
Wing Sails - Airfoils used as sails.

THE AUTHOR

Graduated from the New York State Maritime College in 1956, receiving his degree in Marine Engineering. While attending the Maritime College he was active in intercollegiate sailing. He then reported to the Navy's Bureau of Ships where he was assigned to the Hull Mechanical Section in the Hull Design Branch. During this period he was involved in the contract design of various materials handling features of naval ships including vehicle and cargo handling for amphibious ships, electronic equipment handling, and underway replenishment, and, in addition, managed the Design Division's computer installation. In 1964, he was the Hull Project Coordinator for the AOR 1 Class, AO(J) 51 Class, and the AOE 3 Class ships. From 1965 until 1974 he was the Program Manager for the FAST System and the Missile/Cargo STREAM System in the Underway Replenishment Project Office. In April 1974 he became Head of the Underway Replenishment Improvement Branch in the Amphibious and Combat Support Ship Logistics Division. In July 1979, he was transferred, along with the management of the Underway Replenishment Improvement Program, to the Deck and Replenishment Systems Division as Head of the Underway Replenishment Systems Branch, the position he now holds in the Naval Sea Systems Command. In addition to his duties concerning underway replenishment, he has been active in sailing ship research and the promotion of sail assist for Navy ships. He has presented two papers on sail assist to Navy oriented technical societies. The author is an active member of the Society of Naval Architects and Marine Engineers and the Association of Scientists and Engineers.

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The view expressed herein are the personal opinions of the author and are not necessarily the official views of the Department of Defense or a military department.
THE TUNNY RIG - A VARIABLE CAMBER FLEXIBLE WING SAIL

By E W H Gifford
Gifford Technology, Southampton

SUMMARY

A prime need for the rig for a sailing fishing boat is that it should not obstruct the handling of the fishing gear. It should also be efficient, robust, and easy to handle. If damage occurs, it should be simply repaired. It is well known that traditional and conventional modern rigs fail to meet one or more of the above requirements.

The Tunny rig, invented by the Combewrights, and being further developed by the author's company, meets them all. It is a wing sail with a double surface of sailcloth shaped by fish-shaped battens (the "tunnies") which are warped to the required asymmetrical shape by an internal system of lines. Wide chord shapes are used giving space for a cantilever mast and a safe crew access throughout the inside of the sail. Multiple sheets are used, as in the junk rig, so that sail and rigging loads are small but the asymmetric aerofoil ensures that the lift is high.

The prototype rig has recently reached the United States from England on a double-hulled boat crewed by the two inventors, who have their six month old child with them.

A second prototype rig, shaped to the NASA GA(W)1 profile, is now being fitted to a Sandskipper double-hulled beach fishing boat. This is described in the paper but trial results will be reported at the Conference.

The paper also describes a proposed gill-netter for Western Scotland carrying a single Tunny sail.

INTRODUCTION

This paper is an account of another person's invention and successful first voyage and the author's plans for future development, the first results of which have been presented verbally at the Conference.

The Combewrights, Wayland and Aruna, wished to visit the West coast of America and to stay there for some time. They decided that the cheapest way to do this was to design and build a boat, which they did for $3,000! They crossed the Atlantic during last November, averaging 4 knots, with just the two of them as crew and yet with a 6 month baby, thus demonstrating the capabilities of their invention in terms of weatherliness and ease of handling.

They chose to build a double-hulled boat, in Irish curragh style of multi-layered tarred canvas on cleft ash framing but that will be described by them elsewhere.
For the rig they considered the Chinese lug but felt that its handiness was offset by its poor windward performance so, having little previous knowledge of sailing, they talked to many experts, aerodynamicists among them, and read a great deal, and produced a scheme for a fully battened, double-skinned sail. They did not like the idea of symmetrical fixed camber (they knew nothing of Jack Manners-Spence's work at this time) so they decided on an ingenious method of warping the sail, which Orville Wright would surely have approved, so that it presents an asymmetric aerofoil of appropriate shape on either tack (Fig 1 and 2).

They built a one-fifth scale model which performed so well that they built the full size boat, 40ft by 20ft (12m x 6m) straight off this and it too works well.

The hull forms are not ideal, they are too blunt at entry and too tucked up in the stern, so the maximum speed attained of 6½ knots is all that can be expected but a remarkable quality of the rig is that it continues to draw up to within 30° of the apparent wind and has satisfactory lift characteristics, and it is really docile and easy to handle. Reefing is simple and on the whole voyage across there was no chafe.

The author learned of the venture when it was nearly complete and so had no influence on anything but was so attracted by the idea that the Combewrights agreed that whilst they were sailing to America etc., the author could develop the idea scientifically.

It so happened that Gifford Technology are working on timber windmill blades which are of the NASA GA(W)1 section.

A little simple geometry showed that a close approximation to the required asymmetric form could be achieved by simply warping a symmetrical shape. This particular aerofoil is designed to be relatively insensitive to surface roughness and it is hoped that it will be equally tolerant of slight deviations from its proper form.

In addition to the close windedness of the rig, equivalent to a first class Bermudan rig but without all the high rigging loads and complication, wind tunnel tests on the wing section have given a lift coefficient of 1.60 which, if realised with the sail, should give excellent speed to windward.

The rig is also very seamanlike for, in addition to its low chafe, it is fully accessible from the inside at any time as a seaman can climb aloft in good shelter and comfort whilst the sail is fully set and drawing.

DEVELOPMENT OF THE RIG

A sail of simple rectangular profile using battens to give the required shape (Fig 3) is being fitted to a standard Sandskipper 24ft (7.3m) hull. This particular layout is intended for use in artisanal fisheries but the data obtained will be directly transferable to more elaborate applications. The mast is a simple cantilever ply-wood box, the lower part of which is fitted with

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straingauges to enable the direction of thrust of the rig to be calculated. The actual thrust on the longitudinal axis of the boat will be determined by measuring boat speed, the speed/drag characteristic of the boat being known. Thus the main characteristic of the rig dynamics can be obtained.

The boat speed and course made good will be measured from shore stations and wind speeds will be electronically averaged.

To increase drag, when sailing down wind a "flap" rather like a triangular bonnet will be hoisted at the trailing edge of the sail. This has not yet been tried but, if successful, will reduce the need for special running sails which, for simple fishing use, are an unwelcome complication. The rig is virtually complete at the time of writing this paper and so it is hoped to present first trial results at the Conference.

FUTURE DEVELOPMENT

Gifford Technology have been invited by Mr Ian Nicholson, a senior partner of Alfred Mylne & Company, the famous Scottish naval architects, to join with them in the design of a motor sailing gillnetter to operate out of Mallaig in Western Scotland where conditions of wind and sea are very severe. The client is a successful working fisherman with a scientific education.

The rig shown in Figure 4 is a straight development of that of the experimental Sandskipper rig but of substantially larger area and with an increased aspect ratio. The mast will be a cantilevered hollow round section and it should be noted that the rig does not obstruct the deck as gear can be handled at any point over the rail; even the sheets lead to the top of the wheelhouse and leave the stern free for lines or net shooting. Such freedom could not be obtained with any conventional rig requiring stayed masts.

As the sail can be readily lowered and stowed in a neat package above the head level on deck, it is considered that this would be the best approach when proceeding to windward under power in heavy weather. The alternative advocated for rigid wing sails, namely feathering the full sail aloft, seems likely to produce problems of oscillation unless the roll periods of the vessel can be kept well out of match with the "flutter" of the rig and this might sometimes be difficult.

Applications for an energy saving grant in addition to the standard UK fishing grants are at present being considered and if sufficient money is available then the project will go ahead as soon as sufficient rig data has been obtained from the Sandskipper experiment.

CONCLUSION

This brief paper outlines a new rig which appears to offer very real possibilities of considerable aerodynamic improvement combined with good seamanship.
Fig. 1 BATTEN OF TUNNY SAIL IN SYMMETRICAL POSITION
Fig. 2 BATTEN WARPED TO NASA GA(W) 1 PROFILE
FIG. 3 EXPERIMENTAL TUNNY RIG ON SANDSKIPPER
WINDMILL THRUSTERS FOR COMMERCIAL FISHING CRAFT

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ABSTRACT

This paper discusses the theoretical design of windmill thrusters for assisting the conventional propulsion system on commercial fishing craft. The windmill thruster consists of a windmill mechanically coupled to an underwater propeller. Kinetic energy extracted from the wind by the windmill is used by the underwater propeller to produce a net forward thrust. This can be achieved in all relative wind directions, even when the boat is proceeding directly against the wind. Using the theory of these devices, quantitative estimates are given of the expected thrust under a variety of operating conditions. Some consideration is also given to the best type of hull configuration for this application. A comparison between a windmill thruster and an aerofoil sail is given in the appendix.

INTRODUCTION

A windmill boat is a wind-driven boat in which a windmill type air turbine is mechanically coupled to an underwater propeller. Kinetic energy extracted from the wind by the windmill blades is used by the underwater propeller to push the boat directly against the wind, Fig. 1. The boat moves forward because the momentum added to the water can be greater than that removed from the air, despite unavoidable energy losses in the system. In a similar manner, a wheeled vehicle can move against the wind by coupling the windmill blades to a driving wheel. In addition to the capability of sailing directly upwind, windmill boats and vehicles can also sail at any other direction relative to the wind, by orienting the windmill blade to face the apparent wind, Fig. 1.

Historically, the concept of windmill boats and vehicles can be traced back to the early 1900's by numerous patents and published articles in Europe and America.(1) More recently, interest in wind propulsion was revived by the "oil crisis" and the subsequent search for alternative energy sources.(2),(3),(4). During the past several years we have worked on the theory of windmill boats and vehicles and have carried out numerous experiments(5)-(9). Our objective was to develop a fundamental understanding of these devices and, thereby, to identify the parameters which are important for their efficient, fast operation.

In the present paper, the theory is used to design windmill thrusters for possible use on commercial fishing craft. Quantitative thrust predictions are given for a variety of wind speeds, boat speeds, apparent wind directions and underwater propeller efficiencies. The theory shows that the efficiency of the underwater propeller is of the
utmost importance, especially when proceeding against the wind where it is desirable that it be greater than 80%. To achieve such high propeller efficiencies requires a considerably larger diameter propeller than would normally be used on conventional fishing boats. This is an intrinsic problem that could be overcome by designing deeper draft boats or by using an independent, retractable propeller for the windmill thruster.

**BACKGROUND THEORY**

The theory of windmill boats and vehicles has been presented previously\(^\text{(5)-(9)}\), including a comprehensive account of blade design, for sailing at arbitrary directions with respect to the wind\(^\text{(9)}\). For the present purpose the power output, \(P\), from the windmill and, more importantly, the forces \(F_W\), \(F\) and \(F_{NET}\) are of interest. Here \(F_W\) is the longitudinal component of the downwind force on the wind turbine and \(F\) is forward force produced by the underwater propeller, as shown in Fig. 1. \(F_{NET} = F - F_W\) is the net forward force effective at propelling the boat.

Expressions for the above quantities can be written as follows\(^\text{(9)}\),

\[
\frac{P}{4\pi R^2 W^3} = \frac{(U/W)^3}{S^2} \int_0^S (1-a) a' s^3 ds \quad (1)
\]

\[
\frac{F_W}{4\pi R^2 W^2} = \frac{(U/W)^2 \cos \delta}{S^2} \int_0^S (1-a) s \, ds \quad (2)
\]

and

\[
\frac{F_{NET}}{4\pi R^2 W^2} = \frac{(U/W)^2}{S^2} \int_0^S \frac{U_k}{U} a' s^2 \cos \delta \, ds \
\]

where

\[
\frac{U}{W} = \left(1 + f^2 + 2f \cos \theta \right)^{1/2} \quad (4)
\]

as shown in Fig (2), and

\[
\cos \delta' = \pm \left(1 - \frac{(W \sin \delta)^2}{U^2} \right)^{1/2} \quad (5)
\]

In Eqn. (5) the +th sign is to be used for \(0 < \delta' < \pi/2\) and the -th sign for \(\pi/2 < \delta' < \pi\). The various parameters appearing in Eqns. (1)-(5) are defined as follows:

- \(a\) = wind speed reduction factor at the blade element.
- \(a'\) = wind rotation factor at the blade element.
- \(f\) = \(U/W\) = boat speed/wind speed.
- \(r\) = radius of blade element measured from rotation axis.
- \(R\) = radius of blade tip.
- \(s\) = \(\pi r/U\) = dimensionless speed ratio.
- \(S\) = \(\pi R/U\) = tip speed ratio.

(continued)
\[ u = \text{boat speed with respect to the water, Fig. (2).} \]
\[ U = \text{apparent windspeed with respect to the boat, Fig. (2).} \]
\[ W = \text{true windspeed with respect to the water, Fig. (2).} \]
\[ \varepsilon = \text{drag/lift ratio of the wind turbine blades.} \]
\[ \rho = \text{air density} \]
\[ \theta = \text{angle between true wind and boat course, Fig. (2)} \]
\[ \theta' = \text{angle between apparent wind and boat course, Fig. (2)} \]
\[ \Omega = \text{wind turbine rotation rate, (rad/sec)} \]
\[ \zeta = \text{efficiency factor of drive train, including water propeller} \]

The factors \( \alpha \) and \( \alpha' \) both depend upon radius, and therefore on \( s \), and are functionally related to each other by

\[ a'(s) = -\frac{1}{2}(1+\varepsilon/s) + \frac{1}{2} \sqrt{(1+\varepsilon/s)^2 + 4a[(1-\alpha)/s^2-\varepsilon/s]} \]  \( (6) \)

It is assumed, with considerable justification\(^8\),\(^9\), that \( a(s) \) is of the form

\[ a(s) = a_0(1-\exp(-2s)) \]  \( (7) \)

where \( a_0 \) is a constant to be chosen so as to maximize the net thrust.

A correction factor for a finite number of blades\(^9\),\(^10\) can be introduced by replacing \( a \) with \( aG \) in all of the preceding equations, where \( G(s) \) is given by

\[ G = \frac{2}{\pi} \arccos (\exp(-g)) \]  \( (8) \)

and

\[ g = \frac{N}{2} \left(1-s/S\right) \sqrt{1+s^2} \]  \( (9) \)

The efficiency factor of the underwater propeller, which is the major part of \( \zeta \), is a very important factor in determining the net thrust, as can be seen from Eqn. (3). To calculate this efficiency, the computational procedure worked out by Larrabee\(^10\) can be used. The necessary input parameters are shaft power, shaft rotational speed, boat speed, propeller radius and the drag/lift ratio of the blades used. Once \( \zeta \) is known, the various thrusts can be calculated using Eqns. (1)-(9).

**DESIGN DESCRIPTIONS**

Three different hull types are considered: (a) a medium displacement, shallow draft monohull capable of semi-planing operation; (b) a heavy displacement, deep draft monohull operating at hull speed and; (c) a shallow draft catamaran hull operating at hull speed. All three are currently used by the fishing industry, but the catamaran is not very common. Sketches of the three different types are shown in Fig. 3 (a,b,c), respectively.
Referring to Fig. 3, the horizontal axis wind turbine is mounted on top of a vertical mast and drives, through a 90° gear box, a vertical concentric shaft inside the mast. The mast can be rotated through 360° about the vertical so as to position the wind turbine to face the apparent wind. For the monohulls, Fig. 3(a,b), the power from the wind turbine is coupled to the drive shaft of the existing underwater propeller, through a gearbox and clutch mechanism. For the catamaran hull, Fig. 3(c), the wind turbine drives an independent underwater propeller which can be pivoted up out of the water between the two hulls when not in use. The latter ability would be useful for operating in shallow water and for reducing the water drag during operation in calm weather.

The blades of the wind turbine must be mounted on a controllable pitch hub. This is necessary for two reasons: (a) to achieve the optimal blade pitch, and thereby maximum thrust(9), in all wind directions, and (b) to feather the blade for safety purposes when winds become too strong.

Streamlining of the pilot house and forward section of the boat would be desirable for delivering a clear air flow to the wind turbine.

THRUSt PREDICTIONS

To work with a specific example, an overall boat length of 15 m (-50 ft) was used for each of the hull configurations in Fig. (3). In each case the diameter of the wind turbine was assumed to be 11 m (36 ft) which is about 75% of the boat length. Thrust predictions were calculated for wind speeds of 7 m/s (14 knots) and 10 m/s (20 knots). The results for each type of hull configuration are as follows:

(a) Shallow Draft Monohull.

For this semi-planing hull the cruising speed is assumed to be 6 m/s (12 knots), which is somewhat greater than hull speed. This is achieved normally by a 190 KW (250 HP) engine, driving a 0.75 m (30") diameter 4-bladed propeller at 105 rad/sec (1000 rpm). Using the procedure of Larrabee(10) the propeller efficiency is found to be 57% and the thrust of the propeller is 18,000 Newtons (4000 lbf). Thus a net forward thrust of 4000 lbf is needed to propel the boat at 12 knots. Now the wind turbine is added to the boat and the power from it is coupled to the same underwater propeller, as shown in Fig (3a). The wind turbine is assumed to operate at a tip speed ratio of S=4 when going upwind, S=5 when going at e=90° to the true wind and S=6 when going downwind at e=180°, respectively(9). The results are summarized in Table 1.

Examination of Table 1 shows that when the boat speed is u = 6 m/s(12 knots) the presence of the wind turbine would be detrimental, except when proceeding down wind in a wind of 10 m/s (20 knots) where the engine power could be reduced from 190 to 180 KW. The situation is worst when proceeding upwind in a wind of 10 m/s, where the engine power would have to be increased from 190 to 240 KW because of the wind turbine.
Note that the wave and wind drag forces on the hull and superstructure of the boat were ignored in this study in order to show the effect of the wind turbine. Power train losses, typically a few percent, were also ignored.

For $u = 2 \text{ m/s}$ the situation is somewhat better. For $\theta = 90^\circ$ and $180^\circ$ the thrust derived from the wind turbine is more than adequate and no power is required from the engine. However, for $\theta = 0^\circ$, the wind turbine is a detriment.

(b) Deep Draft Monohull

For this case, heavy displacement hull, the cruising speed is assumed to be 5 m/s (10 knots), which is the hull speed. This is achieved normally by a 230 kW (300 HP) engine driving a 1.52 m (60") diameter 4-bladed propeller at 52 rad/sec (500 rpm). Using the procedure of Larrabee [10] the propeller efficiency is found to be 69% and the thrust of the propeller is 31,800 Newtons (7200 lbf). Now add the wind turbine and couple the power from it to the same underwater propeller, as shown in Fig. (3b). The results are summarized in Table 2.

Examination of Table 2 shows that the situation is somewhat better than for Table 1. This is mainly due to the increased efficiency derived from the larger diameter underwater propeller. For $u = 5 \text{ m/s}$, the wind turbine leads to a slight reduction of engine power, except when proceeding upwind in a wind of $W = 7 \text{ m/s}$ where the required engine power is increased from 230 to 234 kW. For $u = 2 \text{ m/s}$, the wind turbine leads to a substantial reduction in engine power for $W = 7 \text{ m/s}$ and produces more than enough thrust when $W = 10 \text{ m/s}$.

(c) Shallow Draft Catamaran.

For this case the cruising speed is again assumed to be 5 m/s (10 knots), which is the hull speed. However, the drag force is less than for the heavy displacement hull (b) and consequently the cruising speed can be achieved with 2 - 76 kW (100 HP) engines, each driving a 0.65 m (26") diameter propeller at a shaft speed of 104 rad/sec (1000 rpm). The propeller efficiency in this case 57% and the thrust of each propeller is 8700 Newtons (1950 lbf). Thus a total thrust of 17,400 Newtons (3,900 lb) is required to move the boat at $u = 5 \text{ m/s}$.

The wind turbine in this case is coupled to its own underwater propeller, 3-bladed and having a large diameter of 2.5 m (98"), as shown in Fig. (3c). The underwater propeller rotates 2.0 times faster than the wind turbine. The results for this case are summarized in Table 3.

Examination of Table 3 shows that the situation is much better than for Tables 1 and 2. For $u = 5 \text{ m/s}$ the required engine power is reduced in all cases and substantially so (nearly 50%) when proceeding upwind in a wind of $W = 10 \text{ m/s}$. For $u = 2 \text{ m/s}$ the windmill thruster produces more than enough thrust for all cases considered. This is particularly true for $W = 10 \text{ m/s}$, for which the thrust is 3 times the minimum amount required to move the catamaran at $u = 2 \text{ m/s}$. 

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CONCLUSIONS

The conclusions to be drawn from this study are:

(a) The use of a wind turbine on a commercial fishing boat in which the power output from the wind turbine is coupled to the existing underwater propeller is not recommended. The size of the propeller used on a conventional fishing boat is too small to realize the high propeller efficiencies which are needed to make the wind thruster of practical value. The situation would be improved considerably by using a much larger propeller in cases where there is no need to operate in shallow water.

(b) An alternative, recommended procedure is to couple the wind turbine to an independent propeller of sufficiently large diameter, i.e. about 20-25% of the diameter of the wind turbine. The predicted results for this case are encouraging, and suggest that the system would be of practical value. The large propeller would be retracted when not in use or when operating in shallow water. This system could be installed on a monohull, but the catamaran would be more ideally suited. In the latter case the large propeller could be pivoted out of the water and stored between the two hulls. The catamaran has the additional advantage of a very large initial stability which would minimize the heeling caused by the wind turbine.
### TABLE 1

<table>
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<tr>
<th>Speed W(m/s)</th>
<th>Direction θ(deg)</th>
<th>Power P (KW)</th>
<th>Force F(_W) (10(^3) N)</th>
<th>Thrust (10(^3) N)</th>
<th>Engine Power (KW)</th>
<th>Efficiency</th>
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Table 1. Thrust and power predictions for a wind turbine mounted on a shallow draft monohull and coupled to the existing engine propeller, as shown in Fig. (3a). \( \theta = 0^\circ \) corresponds to going upwind and \( \theta \) is against the boat motion. The required net thrust is 18,000 Newtons (4,000 lbf) at \( u = 6 \) m/s and 2,000 Newtons (450 lbf) at \( u = 2 \) m/s. See text for further discussion.
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<th>Speed W(m/s)</th>
<th>Direction $\theta$(deg)</th>
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<th>Force $F_W(10^3\text{ N})$</th>
<th>Thrust $F_T(10^3\text{ N})$</th>
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Table 2. Thrust and power predictions for a wind turbine mounted on a deep draft monohull and coupled to the existing engine propeller, as shown in Fig. (3b). The required net thrust is 31,800 Newtons (7,150 lbf) at $u = 5\text{ m/s}$ and 5,300 Newtons (1,200 lbf) at $u = 2\text{ m/s}$. See text for further discussion.
### Table 3

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Table 3. Thrust and power predictions for a wind turbine mounted on a shallow draft catamaran and coupled to a large (2.5 m) diameter propeller which is independent of the engine propeller. The required net thrust is 17,400 Newtons (3,910 lbf) at u = 5 m/s and 2,800 Newtons (630 lbf) at u = 2 m/s. See text for further discussion.
BIOGRAPHY

Brad Blackford is a native of Nova Scotia. He graduated from Acadia University in 1961 with B.S honours degree in physics. In 1963 he received an M.S degree in physics from the Massachusetts Institute of Technology and in 1969 a Ph.D in physics from Dalhousie University. Research topics have ranged from fluid dynamics to high temperature thermionic emission, to low temperature superconductivity phenomena. He is an active sailor and finds the application of physics to windmill boats and vehicles an interesting topic. He is associate professor of Physics at Dalhousie University, and is currently on sabatical leave at the Institute of Ocean Sciences in Sidney, British Columbia.

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REFERENCES

Fig. 1. Sketch of a windmill boat (catamaran) sailing straight upwind. The wind turbine can be rotated about the vertical mast so as to face the apparent wind, allowing the boat to be sailed in any direction without tacking. $F_W$ is the backward force on the wind turbine, $F$ is the forward force produced by the underwater propeller and $F_D$ is the drag force of the water on the boat. The net force $(F-F_W)$ produces the forward speed, $u$, of the boat, at which $F-F_W-F_D = 0$. The underwater hydrofoil at the rear of the boat produces a lifting force which counteracts the rearward pitching moment due to the forces $F_W$, $F$ and $F_D$.

Fig. 2. Sketch of a windmill boat sailing at an angle $\theta$ with respect to the true wind. $U$ is the apparent windspeed, which makes an angle $\theta'$ with respect to the boat's course.
Fig. 3(a). Wind turbine mounted on a medium displacement, shallow draft boat. The power output from the wind turbine is coupled to the same propeller used by the engine.
Fig. 3(b). Wind turbine mounted on a heavy displacement, deep draft boat. The power from the wind turbine is coupled to the same propeller as that used by the boat's engine.
Fig. 3(c). Wind turbine mounted on a catamaran hull and coupled to an independent propeller which can be pivoted out of the water between the hulls when not in use.
APPENDIX

Comparison of a Windmill Thruster and an Aerofoil Sail

The net forward thrusts produced by a windmill thruster and by an aerofoil sail, respectively, will be compared for all sailing directions, φ. Consider an aerofoil sail mounted on a boat which is proceeding at a speed \( u \) and whose course makes an angle \( φ \) with respect to the true wind, Fig. (2). The lift force, \( F_L \), produced by the sail is perpendicular to the apparent wind, \( \mathbf{U} \), and is given by

\[
F_L = \frac{1}{2} \rho C_L AU^2 \tag{10}
\]

where \( C_L \) is the lift coefficient of the sail, \( A \) the sail area, and \( U \) is obtained from Eqn. (4). Similarly, the drag force, \( F_D \), which is parallel to \( \mathbf{U} \), is given by

\[
F_D = \frac{1}{2} \rho C_D AU^2 \tag{11}
\]

The net force propelling the boat forward is given by

\[
F = F_L \sin \phi' - F_D \cos \phi' \tag{12}
\]

where \( \phi' \) is given by Eqn. (5). For comparison purposes, the normalized forward force will be of interest,

\[
F_{\text{forward}} = \frac{1}{\rho AW^2} \left[ \frac{U}{W} \right]^2 \left[ C_L \sin \phi' - C_D \cos \phi' \right] \tag{13}
\]

In a realistic situation \( C_L \) and \( C_D \) will depend on the apparent wind angle \( \phi' \) and the following forms were used here:

For \( 0 < \phi' < 90^\circ \), \( C_L = 1.5 \) and \( C_D = 0.3 \)

\[
90^\circ < \phi' < 180^\circ \), \( C_L = 1.5(1 + \cos \phi') \) and \( C_D = 0.3 - \cos \phi' \tag{14}
\]

The lift coefficient maintains a high constant value, 1.5, up to \( \phi' = 90^\circ \) and thereafter decreases to zero at \( \phi' = 180^\circ \). The drag coefficient maintains a constant value of 0.3 up to \( \phi' = 90^\circ \) and then increases to 1.3 at \( \phi' = 180^\circ \). Note that these values of \( C_L \) and \( C_D \) are about the best that one could hope for.

The normalized net forward force produced by the aerofoil sail is plotted as curve (a) in Fig. (4), for a boat traveling at a speed \( u = W/2 \). The thrust is negative for small values of \( \phi \) and increases to its maximum value for \( \phi = 90^\circ \).

Now consider the case of the windmill thruster, for which the net forward force is given by Eqn. (3). The effective area of the windmill is taken to be \( \pi R^2 \), the swept-out area. The appropriate normalized
force is then $F_{\text{net}}/\rho \pi R^2 W^2$, so that the factor of 4 in Eqn. (3) must be taken to the right hand side.

To obtain optimal net thrust from the windmill, the wind speed reduction factor $a_0$, Eqn. (7), and the tip speed ratio $S$ must be allowed to vary with $\theta$, as discussed in references (8,9). To take this effect into account, the following approximate forms were used for $a_0(\theta)$ and $S(\theta)$,

$$a_0(\theta) = 0.21 + 0.24 \left(\frac{\theta}{180}\right)^2$$  \hspace{1cm} (15)

when $u/W = 0.5$, and

$$S(\theta) = 4 + \theta/90$$  \hspace{1cm} (16)

The efficiency factor, $\zeta$, of the underwater propeller, and the drag/lift ratio, $\epsilon$, of the windmill blades were chosen to be $\zeta = 0.95$ and $\epsilon = 0.01$, which again are about the best values that one could hope to achieve.

The normalized net thrust produced by the windmill thruster is plotted as curve (b) in Fig. (4). In contrast to the sail, the thrust is maximum for $\theta = 0^\circ$ and remains high in the interval $0^\circ < \theta < 45^\circ$, which is normally forbidden to a conventional sailboat. On the other hand, for $45^\circ < \theta < 135^\circ$ the windmill produces less thrust than the sail, as much as 35% less. For $135^\circ < \theta < 180^\circ$ the windmill produces somewhat more thrust.

The comparison depends strongly on the boat speed ratio $u/W$ as can be seen from Fig. (5), where the normalized thrusts are given for $u/W = 0.75$. In this case, the aerofoil sail is much better than the windmill thruster for $45^\circ < \theta < 135^\circ$. For larger values of $u/W$ the windmill thruster becomes progressively worse. On the other hand, for $u/W < 0.33$, the windmill thruster is better than the sail for all $\theta$.

The general conclusion here is that; the windmill thruster would likely be a superior propulsion system to the aerofoil sail for $u/W < 0.5$, whereas the opposite is true for $u/W > 0.5$. 
Fig. (4). Normalized net forward force versus wind angle $\theta$ for an aerofoil sail (a) and a windmill thruster (b). The boat is travelling at $u = 0.5W$.

Fig. (5). Same as Fig. (4), but with $u = 0.75W$. 