Fourth AIAA SYMPOSIUM

INCREASED WINDWARD SPEED BY WINDMILLING

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Abstract

In the previous sailing symposium the author used correct reasoning to conclude that windmill-driven boats and conventional sailboats have essentially the same propulsive force mechanism. This view is shortsighted. As shown here for the case of speed to windward, the windmill-driven boat may have a much superior propulsive force mechanism, and the speed made good to windward might be as much as doubled. Performance in other directions is also shown to be different from that of a conventional boat.

1. INTRODUCTION

In the previous sailing symposium the author illustrated the similarities between a windmill-driven boat and a conventional sailboat by the use of a new type of sailing vehicle called a "windsail"[1]. This vehicle has two masts, two sails, and two keels plus a necessary hull and supporting structure. Its action in moving windward is much like that of two sailboats on opposite tacks from each other. These two elements are connected so as to eliminate heeling and leeway as well as to reduce hull drag, but their propulsive mechanism is essentially the same as a conventional sailboat.

A windmill-driven boat has windmill blades to play the role of sails and an underwater propeller to act as a keel. Hence, at first sight the windmill boat propulsive mechanism may appear to be essentially the same as that of a conventional boat or a windsail boat. In fact, they may be the same, but this holds true only for the special case where the lateral speed of the windmill blades is numerically equal to the lateral speed of the propeller blades. That is, the windmill blade element speed $\omega_w R_w$, illustrated in Figure 1, is equal to the propeller blade element speed, $\omega_p R_p$, illustrated in Figure 2.

In general, for the case where $\omega_w R_w$, is not equal to $\omega_p R_p$, the windmill-driven boat may have a greatly improved propulsive force mechanism, as illustrated in the figures below.

2. CONVENTIONAL SAILBOAT PERFORMANCE

The performance of the Gimcrack, a sloop of 2.92 tons displacement, has been carefully analyzed by Barkla[2] for the case of close-hauled sailing. This ship has a sail area of 450 square feet and a waterline length of 23.8 feet. For a true wind speed V_T of 11.0 knots, speed made good to windward is maximized at 4.40 knots when the heading γ is 35.0 degrees off the wind. The ship hull speed V_S is 5.37 knots, and the apparent wind V_A of 15.7 knots generates a sail lift L of 373 pounds with a drag D' of 61 pounds. These velocities and forces are drawn to scale in Figure 3. Figure 4, drawn to the same scale, shows the hull and keel lift L_H of 366 pounds and drag D_H of 94 pounds. These forces are only horizontal components of the complete force vectors, as may be appreciated by the heel angle of 25 degrees. The forces are, of course, in equilibrium. Of interest is the sail lift coefficient, $C_L = 0.98$.

This level of performance is believed to be typical of a 3 ton yacht. Now we will address the question of the performance of the Gimcrack hull when powered by a windmill.

3. WINDMILL-DRIVEN SHIP PERFORMANCE

3.1 Windmill and Propeller Mechanics

A windmill may be used to extract energy from the wind, as illustrated by the force and velocity vectors on a typical blade element in Figure 1. V_{Aw} is the apparent wind vector generated by the ship speed V_S, the wind V_T, and the lateral speed of the blade, which is the product of the element radius R_w and the windmill shaft speed ω_w. The apparent wind generates the blade lift L_w and drag D_w, which depend on the angle of attack α_w. As discussed in more detail in the Appendix, components of L_w and D_w generate a torque which drives the propeller, illustrated for a typical blade element in Figure 2. The wind vector is missing here, but the other vectors are analogous to Figure 1. Notice that α_p and L_p are defined in the positive direction so that a component of L_p acts in the forward or V_S direction. This component drives the ship forward, whereas D_p, L_w, and D_w as well as the hull drag D_H impede the forward progress.

Both the torque balance and the thrust balance of the windmill-propeller combination are detailed in the Appendix. The windmill torque is balanced by the propeller torque so that no torque is transmitted to the hull except for the slight torque due to shaft bearing friction. The bow will be lifted upward somewhat and the stem lowered to offset the couple produced by the windmill negative thrust acting near the center of the windmill and opposed by the propeller thrust and hull drag. Thus the windmill ship going to windward has essentially zero heeling moment but a finite pitching moment.

3.2 Matching the Gimcrack Performance

In order to match the Gimcrack performance of 4.40 knots to windward, the appendix equations have been solved for the case where $L_w/D_w = L_p/D_p = 6$, equal to L/D for the Gimcrack sail. Both β_w and β_p are taken to be 45 degrees; other design point values are $C_{L_w} = 1.0$, $C_{L_p} = 0.8$, and $V_T = 11$ knots. Also, throughout the following analysis it will be assumed that D_H in pounds is equal to $3V_S^2$, where V_S is in knots. This matches the Gimcrack hull drag for 5.4 knots, but it smooths out the hump that occurs at $V_S = 9$ knots due to wave drag. This smoothing will be useful in relating the results to the topic of this paper, windmill performance, rather than to hull performance.

Using the above, a windmill blade area of only 55 square feet is needed to match the Gimcrack windward performance. L_w is only 89 pounds, compared to an L of 373 pounds for the Gimcrack. Thus, with a windmill type of sail, only 12 percent as much sail area is required, and the sail lift is only 24 percent of the Gimcrack value!

Other parameters of interest in this calculation are the propeller blade area, $A_p = 2.6$ square feet, and the gearing parameter, $GR_w/R_p = GB = 3.5$.

The force vectors in Figures 1 and 2 are drawn to the same scale as those in Figures 3 and 4. Notice how much smaller the forces are for the windmill case. For the conventional sail L must be very large to move the ship forward because it is turned at a large angle, 66.3 degrees, with respect to V_S. Because L is large, D is correspondingly large, opposing the ship motion. For the windmill case the drag of the blades also reduces the performance, but the proper choice of GB enables β_w and β_p to be such that the forces lie at more favorable angles.

3.3 Windward Performance as a Function of Windmill Blade Area

Much faster windward performance may be obtained by increasing the windmill and propeller areas and by improving the blade lift-to-drag ratios. The required windmill blade area is plotted in Figure 5 as a function of the windward or ship speed. The corresponding propeller blade area is also given. With $(L/D)_w$ values of 12, a V_S of 10 knots may be reached using only 260 square feet of windmill area, less than the Gimcrack sail area of 450 square feet, but L_w is 773 pounds, greater than the Gimcrack L of 373 pounds.

3.4 Windmill Performance at a Heading of $\gamma = 90$ Degrees

The appendix equations when modified for the case of a heading 90 degrees off the wind gives the windmill area required for propulsion as shown in Figure 6. On this heading the Gimcrack can make $V_S = 8.5$ knots, assuming, somewhat optimistically, that hull drag is $3V_S^2$ for V_S in knots plus a small allowance for heeling. The windmill ship can match this speed by using a very large windmill blade area, 880 square feet if $(L/D)_w = 6$, and 385 square feet if $(L/D)_w = 12$.

3.5 Windmill Performance at a Heading of $\gamma = 180$ Degrees

The Appendix equations may be modified for a heading directly downwind, and the corresponding windmill blade area required is shown in Figure 7. The mechanics of this operation are quite different than those of $\gamma = 0^\circ$ or $\gamma = 90^\circ$ where β_w and β_p were both taken to be 45 degrees. Such angles could be used at $\gamma = 180^\circ$, but this would result in much larger blade areas than given in Figure 7. The mode of operation is as follows:

1. For $0 \leq V_S \leq 8$ knots the propeller is disconnected from the windmill and the windmill runs free. The angle β_w is brought to $\tan^{-1}(D_w/L_w)$, a small angle which results in a large rate of windmill rotation and a large windmill force in the direction that the ship is moving. Therefore, only very small values of blade area are needed, as shown in Figure 7.

2. For $V_S = V_T = 11$ knots the "windmill" must play the role of a propeller which is powered by the energy obtained by using the underwater "propeller" as a windmill. For this case it is obvious that the windmill cannot be used to drive the propeller, as no energy may be extracted from a windmill where there is no wind; i.e., where $V_S = V_T$. The angle β_w was taken to be zero for the results shown in Figure 7, and β_p was 45 degrees.

3. For the entire range of $V_S > 8$ knots the "windmill" was assumed to be driven by the underwater propeller. The angle β_w was small, whereas, β_p was taken as 45 degrees.

As may be seen in the Figure, the windmill-powered boat can go much faster than the Gimcrack's speed of 4.8 knots. For example, with A_w equal to 225 square feet, half the Gimcrack sail area, $V_S = 9.2$ knots if we assume $(L/D)_w = 6$. If $(L/D)_w = 12$, V_S becomes 14 knots with A_w no more than 140 square feet.

4. GENERAL REMARKS ON WINDMILL-DRIVEN SHIP PERFORMANCE

The windmill-driven ship is able to travel fastest for headings near zero degrees and near 180 degrees, whereas the conventional ship goes fastest for headings near ± 90 degrees. The reason for this with the conventional ship is well known, having to do with the apparent wind vector V_A. The windmill ship reacts to this same V_A in a different manner. It can be shown that windmill propulsion is most useful when the magnitudes of V_A and V_S are much different. When V_A is larger than V_S, the windmill should be used to drive the underwater propeller, as is always the case for γ near zero degrees. When V_S is larger than V_A, the underwater "propeller" should be used to drive the "windmill", as happens when γ is near 180 degrees. When V_S and V_A are equal or nearly equal the windmill propulsive method is least effective. This cannot happen unless V_S has a magnitude approaching that of V_T; that is, the windmill is quite effective for any γ so long as V_S is a good deal less than V_T. This means that quite moderate values of A_w are required for windmill propulsion at, say, V_S equal to 4 knots when V_T is 11 knots, as shown by Figures 5, 6, 7.

5. MODEL BOAT TRIALS

The writer has built and sailed the model windmill boat shown in Figure 8. The boat has a displacement of one pound, a windmill blade area of 66 square inches, and a windmill diameter of 22 inches. The propeller is driven by a flexible shaft from the windmill. Five different peopellers of various shapes with diameters ranging from 5 to 7 inches were used; all were supplied by a model airplane supply dealer. The boat was sailed successfully in a breeze of up to about 7 knots using each of the propellers. As expected, faster windward progress was made with the propellers of larger pitch, $\beta_p + \alpha_p$. In no case was the effective $\beta_p + \alpha_p$ larger than about 30 degrees, as this was the largest blade angle that could be purchased. The windmill $\beta_w - \alpha_w$ was 40 degrees. Since the windmill was at the stern and the propeller ahead of the bow, the boat turned naturally windward. Thus, it performed much like the earlier windmill-powered model boat by Phillips.[3]

6. CONCLUDING REMARKS

The windmill-powered ship requires much less "sail" or windmill area than a conventional ship when sailing at headings of near zero and 180 degrees; with only half the area of the conventional ship, the windmill-powered ship is much faster. However, for heading angles near ± 90 degrees the tables are turned, and the windmill ship may not keep up with the conventional one even if the windmill area is equal to the sail area.

Since it is obvious that sail area might be much easier to design into a ship than the same amount of windmill area, one should not compare the two one a one-to-one basis. Therefore, the actual performance of a windmill ship will depend on the ability of the naval architect to put a sizeable amount of windmill area into a well-configured design.

APPENDIX

WINDMILL AND PROPELLER THRUST AND TORQUE RELATIONS FOR GOING TO WINDWARD

A number of useful relations are derived here for the purpose of predicting the performance of windmill-powered boats. The windmill is used to drive an underwater propeller. In general, the windmill and propeller are geared with a ratio G defined as

$$G = \frac{\omega_w}{\omega_p} \qquad \text{(A-1)}$$

where ω_w is the rotational speed of the windmill shaft and ω_p is the same for the propeller shaft.

Before proceeding further, two assumptions are made which will greatly simplify the results at some expense in accuracy for the sake of a greatly increased clarity in understanding the physical mechanisms involved. First, the mechanical friction of the windmill-propeller shafting and gearing is taken to be zero. This may be justified to a certain extent by assuming the hydrodynamic drag of the propeller and windmill blade elements to be a little larger than is met in practice. Secondly, the windmill and propeller blade forces are assumed to act at a single point on each blade. The blade element at 70 percent of the blade tip radius is assumed to be typical of that of the entire blade, and the forces of the blade as assumed to act through that blade element. Thus, the usual practice of integrating forces over the entire blade is greatly simplified. This simplification is justified in part because the great complexity of the flow problem over a typical blade is such that the forces cannot be accurately predicted to begin with. Without these simplifications, the physical relationships between the air, the windmill, the propeller, and the water might not be clear.

Figure 1 illustrates the forces and velocity vectors acting on a typical windmill blade element for the case of the ship going directly to windward so that $\gamma = 0^o$. Here R_w is the radius of the blade element, and $\omega_w R_w$ is the blade speed in the plane of the windmill, which is perpendicular to the ship speed V_S. The apparent wind vector is

V_{Aw} and the blade lift is L_w with drag D_w. Since the angle between $\omega_w R_w$ and V_{Aw} is defined as β_w, there exists the relation

$$\tan \beta_w = \frac{V_S + V_T}{\omega_w R_w} \qquad \text{(A-2)}$$

The propeller, acting in the water, has a related set of velocity and force vectors as shown in Figure 2. Since the propeller flow is not influenced by the wind speed, we have the relation

$$\tan \beta_p = \frac{V_S}{\omega_p R_p} \qquad \text{(A-3)}$$

where V_T does not appear as in the windmill cases. Another difference from the windmill case is the angle of attack α_p of the propeller blade. In Figure 2 the blade element is designed so as to provide a component of the lift L_p in the V_S direction. This is the propulsive force on the ship whereas all other forces retard the ship's forward motion, including a component of the windmill lift L_w.

We can now see the forces and torques acting on the ship. Of primary interest and the only case considered here is that of steady motion so that V_S and ω_w are constant in time. Then the torque generated by the windmill is balanced by the gearing system and propeller torque. That is,

$$\omega_w R_w (L_w \sin \beta_w - D_w \cos \beta_w) = \omega_p R_p (L_p \sin \beta_p + D_p \cos \beta_p) \qquad \text{(A-4)}$$

The excess thrust T_e available to overcome the hull drag and/or inertia is

$$T_e = L_p \cos \beta_p - D_p \sin \beta_p - L_w \cos \beta_w - D_w \sin \beta_w \qquad \text{(A-5)}$$

Since we are interested here only in windward travel, it turns out that we will have sufficient generality by limiting our attention to cases where L_w, L_p, and all the sine and cosine terms are positive, that is, cases where β_w and β_p are between 0 and 90 degrees. Then it is clear that L_p must be sufficiently large to render T_e positive in order to propel the ship. Also, it is necessary to have G or ω_w/ω_p positive, as may be understood when equations (A-1) through (A-3) are combined to eliminate ω_w and ω_p. Then we have

$$\frac{V_S}{V_S + V_T} = \frac{\tan \beta_p}{GB \tan \beta_w} \qquad \text{(A-6)}$$

where

$$B = \frac{R_w}{R_p} \qquad \text{(A-7)}$$

Since V_S must be positive, and since V_T and B are positive by definition, all terms in equation (A-6) are positive. Equation (A-6) shows clearly how the angles β_p and β_w are related to the windward speed ratio $V_S/(V_S + V_T)$.

The torque balance equation, (A-4) may be written in non-dimensional form as

$$\frac{L_p}{L_w} = MG^3 B^3 A \qquad \text{(A-8)}$$

where

$$L_p = \frac{C_{L_p} \sin \beta_p + C_{D_p} \cos \beta_p}{\cos^2 \beta_p} \qquad \text{(A-9)}$$

$$L_w = \frac{C_{L_w} \sin \beta_w - C_{D_w} \cos \beta_w}{\cos^2 \beta_w} \qquad \text{(A-10)}$$

$$A = \frac{A_w}{A_p} \qquad \text{(A-11)}$$

$$M = \frac{\rho_w}{\rho_p} \qquad \text{(A-12)}$$

and the force coefficients are defined in terms of the apparent wind speeds

$$V_{Aw} = \frac{\omega_w R_w}{\cos \beta_w} \qquad \text{(A-13)}$$

$$V_{Ap} = \frac{\omega_p R_p}{\cos \beta_p} \qquad \text{(A-14)}$$

so that

$$C_{L_w} = \frac{2 L_w}{\rho_w V_{Aw}^2 A_w} \qquad \text{(A-15)}$$

$$C_{D_w} = \frac{2 D_w}{\rho_w V_{A_w}^2 A_w} \qquad (A-16)$$

$$C_{L_p} = \frac{2 L_p}{\rho_p V_{A_p}^2 A_p} \qquad (A-17)$$

$$C_{D_p} = \frac{2 D_p}{\rho_p V_{A_p}^2 A_p} \qquad (A-18)$$

and A_w and A_p are the blade areas of the windmill and propeller.

Hence, the RHS of (A-8) contains only fluid and geometric constants, whereas, the LHS contains only force coefficients and trigonometric functions of β_w and β_p.

The thrust equation may also be non-dimensionalized as follows:

$$\phi = \frac{2 T_e \tan^2 \beta_p}{N_w \rho_p V_S^2 A_p} = \frac{N_p}{N_w} - MG^2B^2A \qquad (A-19)$$

where

$$N_p = \frac{C_{L_p} \cos \beta_p - C_{D_p} \sin \beta_p}{\cos^2 \beta_p} \qquad (A-20)$$

$$N_w = \frac{C_{L_w} \cos \beta_w + C_{D_w} \sin \beta_w}{\cos^2 \beta_w} \qquad (A-21)$$

The above equations may be used to describe some general physical features of the windmill-propeller action as follows. Suppose that the ship is standing still with wind V_T acting on the windmill but with the windmill not turning. The windmill will then turn from the wind action. This is, if α_p is kept small enough, C_{L_p} will also be zero and C_{D_p} small; L_p and D_p will be correspondingly small. The torque equations (A-4) and (A-8) will be out of balance so that the windmill lift in terms of C_{L_w} or L_w can quickly increase the ω_w and ω_p until the equations are in balance. Here we assume that the propeller pitch, as represented by the angle $\alpha_p + \beta_p$, is variable over a wide range. Then if α_p is increased C_{L_p} and L_p will increase to drive the ship forward into the wind. So long as V_S is small compared to V_T it is easy to balance the torque equations even with large values of C_{L_p} or L_p. This is because β_p is small, by equation (A-6), whenever V_S is small. Then it is also easy to obtain a positive value of excess thrust, T_e, as given by equation (A-19). T_e is used to increase V_S up to the equilibrium speed where T_e becomes equal to the hull drag D_H.

In the above it was tacitly assumed that the windmill blade angle $\beta_w - \alpha_w$ was fixed. In actual practice it would be almost mandatory that $\beta_w - \alpha_w$ be varied and controlled so that the windmill speed might be controlled or stopped as needed. Changing $(\beta_w - \alpha_w)$ to near 90 degrees would stop the windmill action so that the windmill blade or sail area might be reefed for high wind conditions. Also, if $\beta_w - \alpha_w$ is variable, the propeller pitch $\alpha_p + \beta_p$ could be fixed at some intermediate value. This would simplify the propeller design at some expense in the ship overall performance.

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3. Phillips, W. H., Letter addressed to R. M. Pierson, July 10, 1965.

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BIOGRAPHY

Andrew B. Bauer began his sailing career by writing the paper "Faster than the Wind"[4] in 1969. Prior to this, his education was primarily in fluid mechanics. In this discipline he obtained graduate degrees from the Ohio State University, California Institute of Technology, and Stanford University. He spent one year with Arthur D. Little, Inc. and and four years with Philco Ford working on problems in acoustics, machinery dynamics, heat transfer, and experimental aerodynamics. Dr. Bauer is now working in the Aerodynamics Research Group at Douglas Aircraft Company, and he resides with his wife and two children in Orange, California.

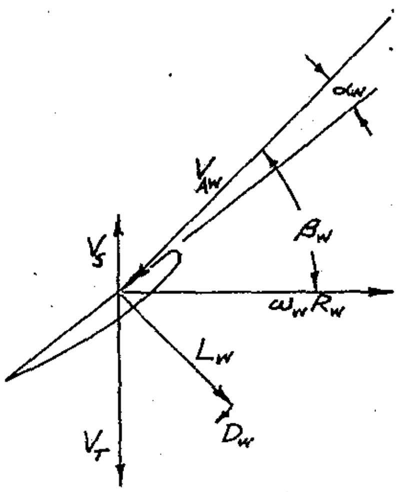

Figure 1
Force and Velocity Vectors
on a Windmill Blade Element

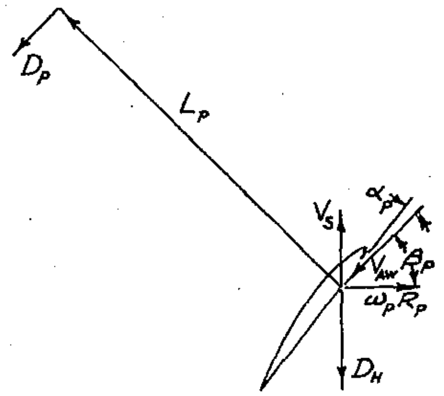

Figure 2
Force and Velocity Vectors
on a Propeller Blade Element

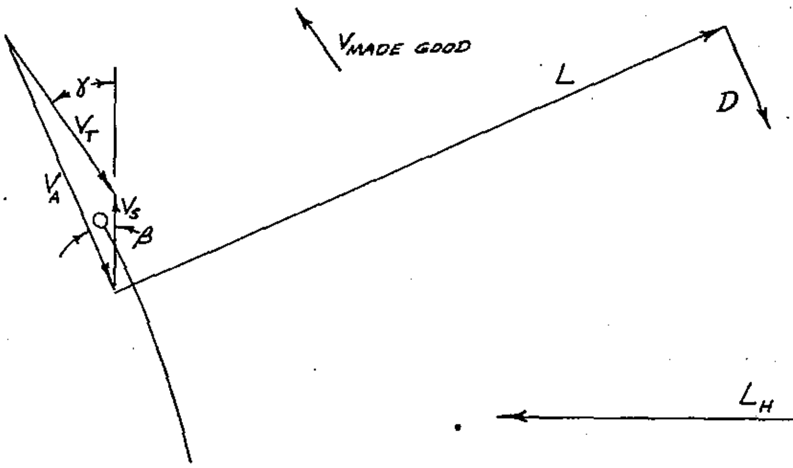

Figure 3
Force and Velocity Vectors
on a Sail Close-Hauled

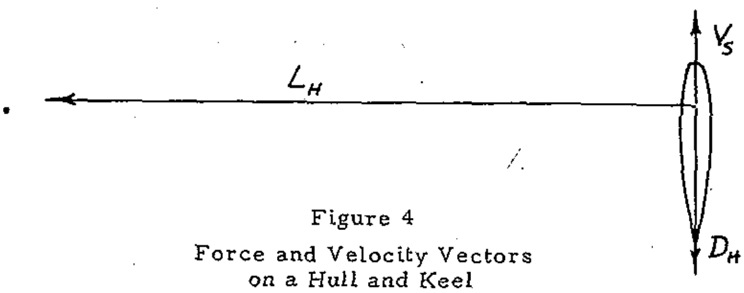

Figure 4
Force and Velocity Vectors
on a Hull and Keel

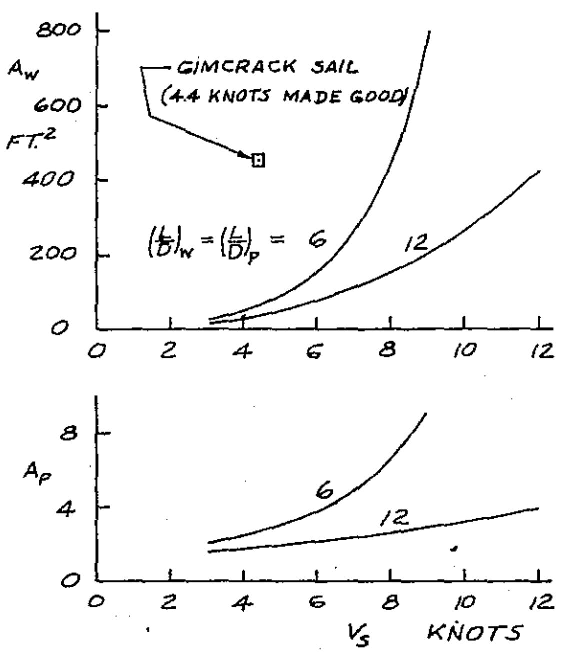

Figure 5

Windmill and Propeller Area Required
to Propel the Ship Versus Ship Speed
for γ = 0 Degrees

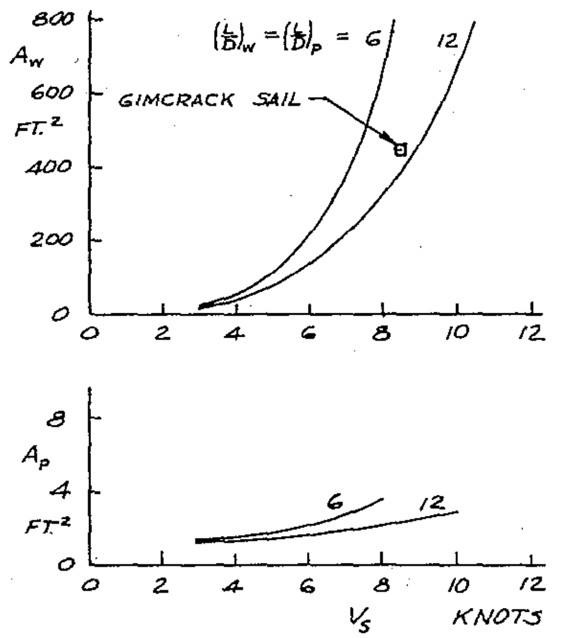

Figure 6

Windmill and Propeller Area Required
to Propel the Ship Versus Ship Speed
for γ = 90 Degrees

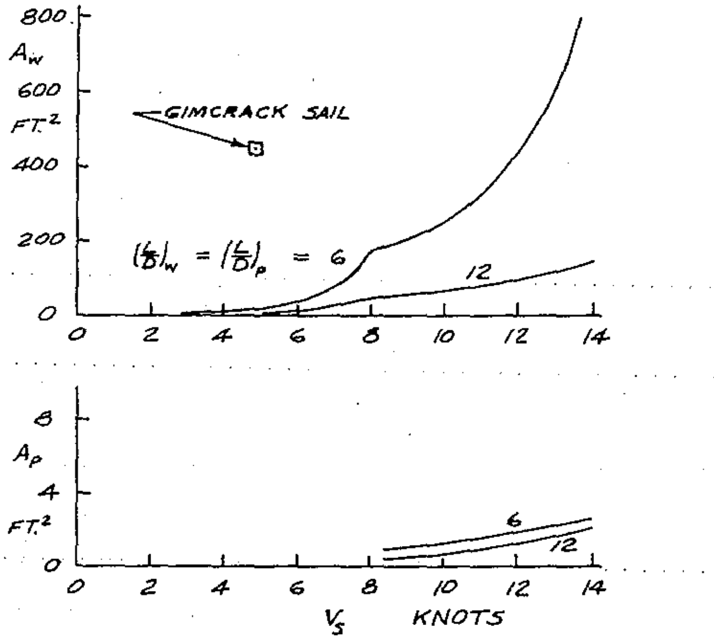

Figure 7

Windmill and Propeller Area Required
to Propel the Ship Versus Ship Speed
for γ = 180 Degrees

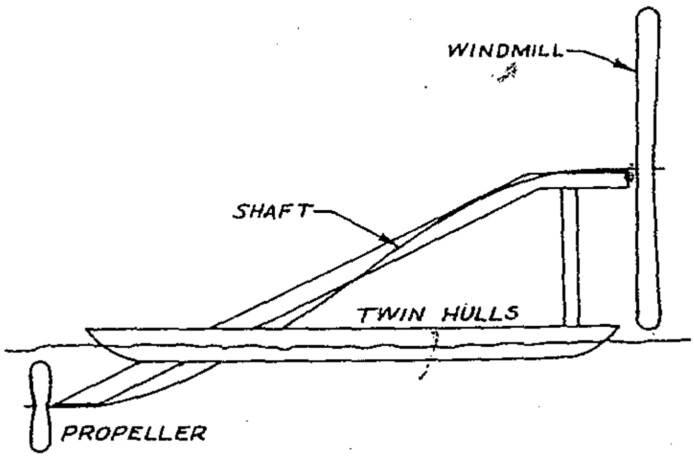

Figure 8

Model Windmill Boat