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

$$G = \frac{\omega_w}{\omega_p} \tag{A-1}$$

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

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

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

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

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

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:

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

where

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

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

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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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.

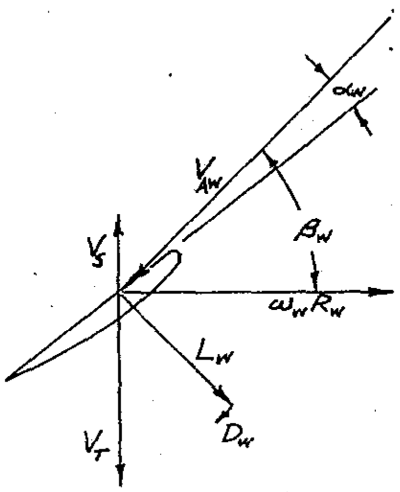

Figure 1
Force and Velocity Vectors
on a Windmill Blade Element

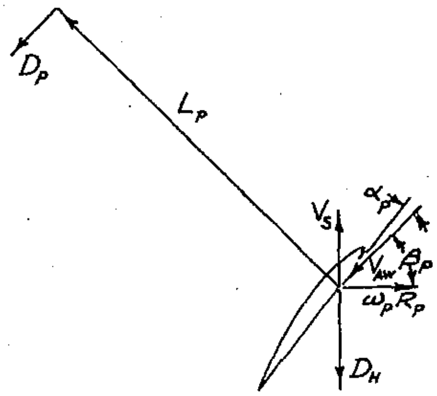

Figure 2
Force and Velocity Vectors
on a Propeller Blade Element

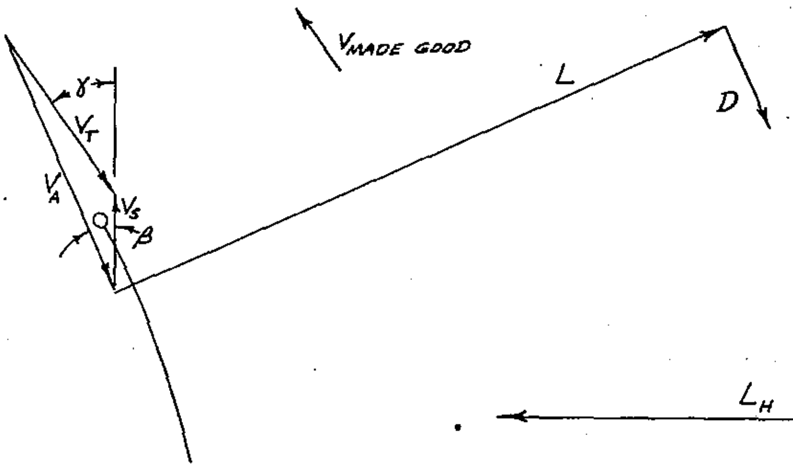

Figure 3
Force and Velocity Vectors
on a Sail Close-Hauled

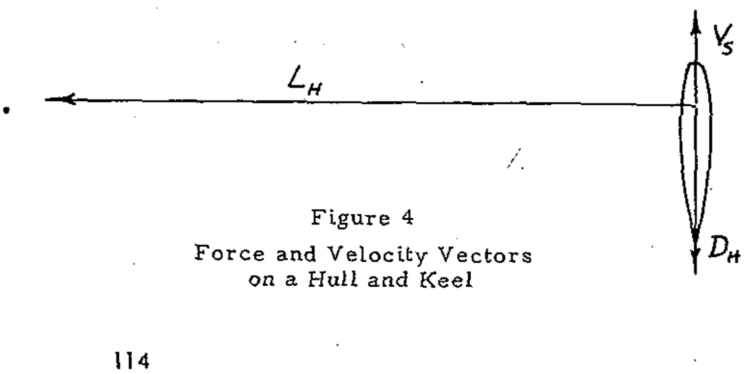

Figure 4
Force and Velocity Vectors
on a Hull and Keel

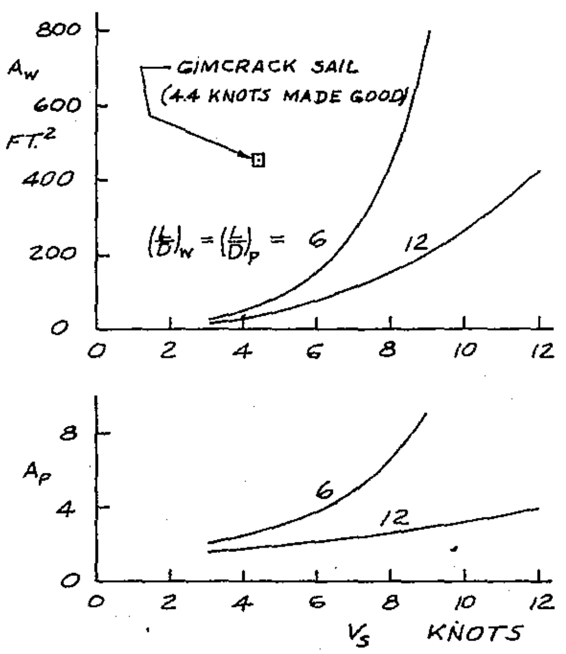

Figure 5

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

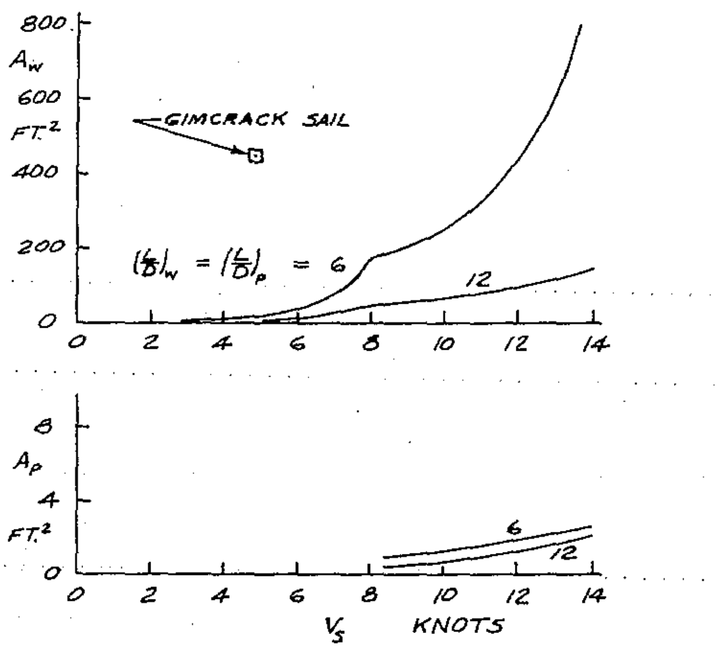

Figure 7

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

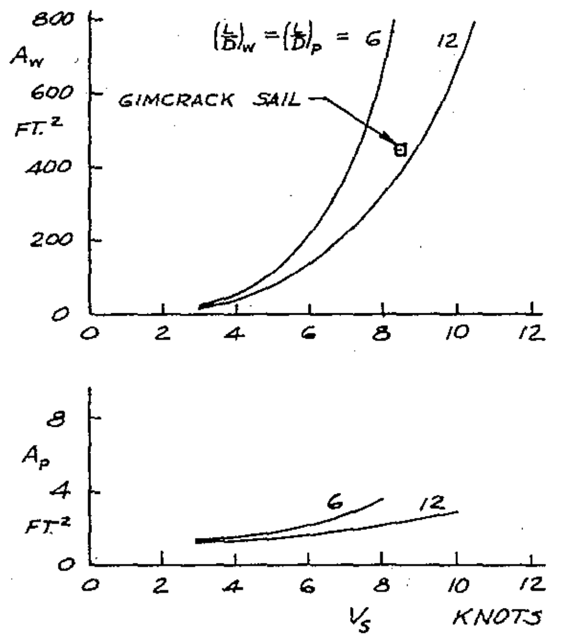

Figure 6

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

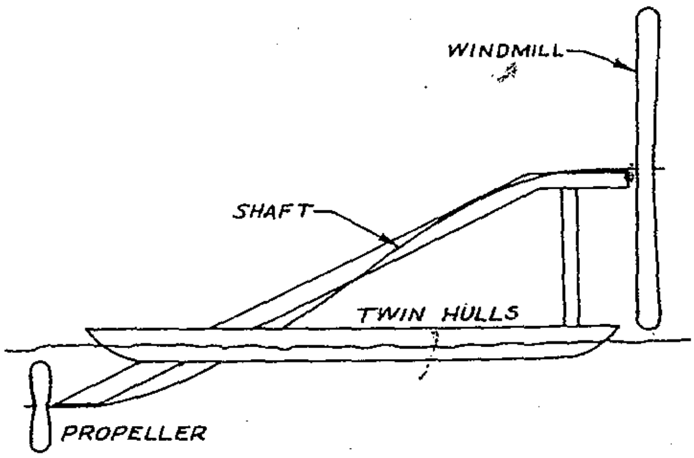

Figure 8
Model Windmill Boat