

acceleration. Notice that the direction of  $R$  can be altered over a rather wide range just by adjusting the sail and keel angles of attack so that the relative magnitudes of  $F$  and  $H$  are altered. This may be done without any large change in the drag angles. In general, the angles of attack need to be such that the magnitude of  $F$  is larger than  $H$  so that  $R$  will be pulling in the direction of the ship speed  $V_s$ . This illustrates the essential details of going downwind faster than the wind<sup>(10)</sup>.

Sailing on other points of the compass can be done by using the windmill mode of operation, which is possible for any  $\gamma$ , and by using the sailboat mode for  $\gamma$ 's greater than about  $40^\circ$ . At certain  $\gamma$ 's some combination of these two modes may be beneficial. The analysis and performance predictions for such combinations are too lengthy to appear here, but it is clear that the windsail configuration, as presented schematically in Figure 2, is capable of sailing all points of the compass.

### 3. COMMENTS ON THE PRACTICALITY OF THE WINDSAIL CONFIGURATION

The windsail configuration is intended to be instructive in the possible mechanics of sailing propulsion rather than serve as a model for a practical yachting design. The windsail has two striking weaknesses — the necessity for much tacking and for the related long booms which support the masts, keels, and sails. Nevertheless, it has redeeming features. The windsail can possibly be designed to have a larger  $V_{mg}$ , speed made good to windward, than any other type of sailboat.

The reason for this is the fact that in sailing windward,  $\gamma = 0^\circ$  as illustrated in Figure 3, the total heeling moments are zero. This means that sail area is unlimited by heeling considerations. Furthermore, because the hulls move through the water at  $V_{mg} = V_s$  instead of the speed  $V_M$ , hull drag is greatly reduced in comparison to a conventional ship. Also, hull drag due to heeling is now zero, and leeway is also zero. Thus the windsail fulfills all of the "four primary goals of sailcraft design" as put forth by Baker and

Douglas<sup>(12)</sup>. These are:

- (1) Maximization of aerodynamic thrust.
- (2) Minimization of hydrodynamic drag.
- (3) Minimization of heeling.
- (4) Minimization of leeway.

The maximization of aerodynamic thrust cannot be made good without an efficient method of tacking. This is the reason for the control surface shown behind the sail in Figure 2. Also, the sail is designed as a rigid airfoil surface, and is pivoted about the mast. By proper design of the sail and the control surface, the sail angle of attack to the relative wind will be only a function of the geometric angle  $\delta_E$  of the control surface with respect to the booms connecting the control surface to the sail. Suppose that the design is such that the sail angle of attack  $\alpha$  is given by  $\alpha = -\delta_E$ . This is not an unrealistic relationship. Then, if the helmsman wishes to tack by changing  $\alpha$  from  $+10^\circ$  to  $-10^\circ$ , he can simply change  $\delta_E$  geometrically from  $-10^\circ$  to  $+10^\circ$ . He can move the small control surface through this range very rapidly from the hull by suitable control cables. The small size of the control surface is an advantage to moving rapidly, and the switch in  $\delta_E$  can be made between two suitable stops. The moment that  $\delta_E$  is changed the aerodynamic force on the control surface will quickly turn the sail to the new tack. This tacking can be much more rapid than on an ordinary boat since only the sails and keel move, not the entire boat.

The keel angle of attack  $\alpha_K$  must also be controlled for optimum results. On a normal boat, this is done by rotating the entire hull. For a windsail keel a small control surface analogous to the one on the sail can be used to control  $\alpha_K$  at the same time that  $\delta_E$  is changed.

By such means the job of tacking might be accomplished before the boat has moved forward by as little as one chord length of the sail. Then, if the boom structure can be made sufficiently strong to carry the sail loads and the two equal but opposite heeling torques, one might have a very good windward sailboat. The writer is not at all sure that the structure can be built that strong.

One way of eliminating these large boom torques is to mount the sail, mast, and keel unit so that it is free to rotate about a horizontal axis, as illustrated in Figure 5, and hereafter called a "rotating windsail." The rotating boom is attached directly to but free to rotate with respect to the hull. In operation directly to windward, the sail angle of attack is controlled so that the wind rotates the sail, mast, and keel about the horizontal axis of rotation. The keel angle of attack is also regulated to produce the forward thrust necessary to drive forward. Thus, the sail and the keel really are portions of a windmill and a water propeller mounted on a common axis. When the sail becomes heeled over close to the water, it is necessary to tack or reverse the angles of attack until the sail swings over

the top to the other side where a second tack brings the process back to the starting point. Also, because side loads at the axis of rotation are large, it would be best to counteract these by having a second rotating sail, mast, and keel unit operating 180° out of phase with the first unit. This second unit could be located on the same axis of rotation and ideally at the same fore and aft location as the first unit. One major problem is the proper control of the angles of attack on the sail and keel. Unlike the windsail configuration, the rotating windsail will have a large variation in angle of attack along the spans of the sail and keel, so that it would be desirable to twist the sail and keel as they rotate. Then it might be possible to have an efficient rotating windsail ship.

Another variation of the windsail idea would be a rearrangement of the component parts of Figure 2 so that one mast is on each end of a very long horizontal boom. The center of the boom would be supported by a vertical pivot at the midpoint between the two hulls. In operation directly to windward, one mast, sail, and keel unit would be upwind of the hulls and moving with the velocity vector and forces illustrated by the left-hand unit in Figure 3a. The second mast, sail, and keel unit would be downwind of the hulls and operating like the right-hand unit in Figure 3a. After a short time it would be necessary to reverse the tack so that the velocities and forces are similar to those in Figure 3b. The long boom would carry the equal and opposite heeling torques of the two sails. This idea is much like two sailboats connected by a long boom.

The above system could also be designed so that the boom would rotate continuously in one direction; then the sail and keel actions would be those of a Voith-Schneider propeller<sup>(13)</sup>.

#### 4. CONCLUSIONS

This paper does not pretend to answer the question of whether some sort of windmill- or windsail-driven boats should be developed. Since sailing is a sport and/or hobby rather than strictly a

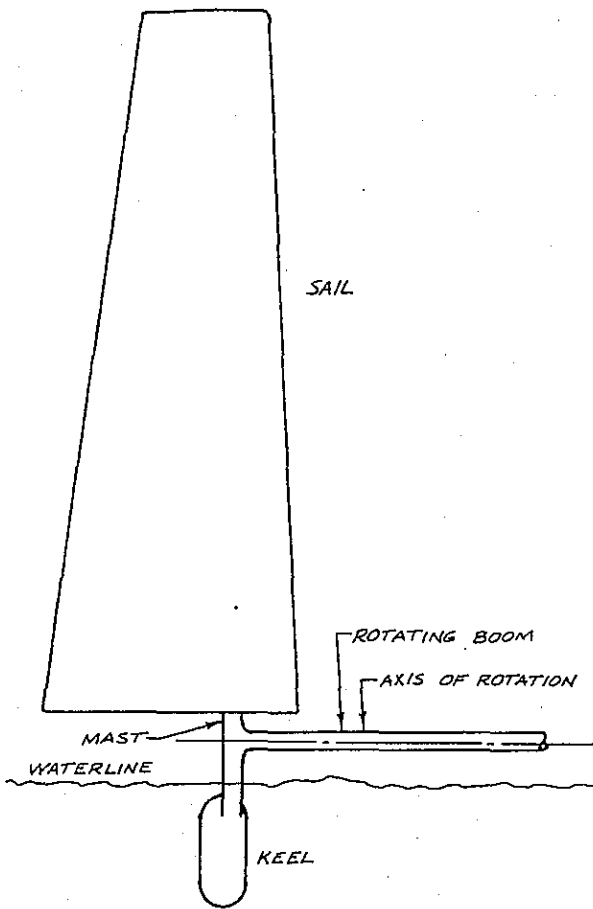


Figure 5. Schematic diagram of a rotating windsail

commercial venture, the argument as to what type of sailboat should be built rests on the sporting whims of the enthusiast. It seems that conventional sailboats do move people about with a great deal of reliability against the sometimes treacherous seas, and probably we should be happy with this. Of course, the ideas of Johnson<sup>(6)</sup>, Smith<sup>(14)</sup>, and Barkla<sup>(15)</sup> in finding configurations for which larger values of aerodynamic and hydrodynamic lift-to-drag ratios may be realized in sailboats without complex rotating parts should be utilized to the best advantage in future sailcraft design.

The real lesson to learn from this exercise is that the windmill-driven and the sail-driven boats both are alike in that they both derive their motion from sails and/or airfoils whose angles with respect to the relative wind and the relative water velocity are essentially the same in both cases. Therefore, we cannot prove that "the opposing force vector vehicle is more efficient than the energy transfer vehicle"<sup>(6)</sup> or vice versa. The relative merits of the two types of vehicle depend more on how well they are engineered and developed than on their inherent efficiencies. In traveling from point A to point B they may each do equally well in elapsed time, although they may travel on different points of the compass. As Hammitt<sup>(1)</sup> has so aptly stated, "this change of velocity of the air through the propeller is the same mechanism as the turning by the airfoil."

#### 5. REFERENCES

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## 6. BIOGRAPHY

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