Third AIAA SYMPOSIUM

SAILING ALL POINTS OF THE COMPASS

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Abstract

Hammitt, Phillips, Barkla, Pierson, and Bauer have each expressed the idea that a windmill-driven boat could be used to sail on all points of the compass, perhaps as well as or better than a conventional sail-powered craft. The windmill-driven boat is shown to have essentially the same propulsive force mechanism as that of the conventional sailboat so that neither type of vehicle is inherently better than the other.

1. INTRODUCTION

The spirit of The Ancient Interface, as sponsored by the Los Angeles and the Orange County Sections of the AIAA, has been to apply modern technology to the art of sailing. Within this spirit a number of papers concerning the fundamentals of sailing propulsion have been presented. These papers have more in common than first meets the eye. Therefore, this brief survey has been assembled with the hope that these concepts may be illuminated.

Hammitt(1) has discussed the fundamentals of wind propulsion. He has calculated power coefficients in frictionless flow for both the conventional sail and for a windmill used to generate the propulsive power. These power coefficients are given for the optimum loading of the sail or windmill as a function of the angle γ between the boat velocity vector $\vec{V}_S$ and the true wind vector $\vec{V}_T$(2,3,4,5). The power coefficients are also a function of the ratio of boat speed to wind speed V_S/V_T. These parameters are illustrated in Figure 1. Hammitt's

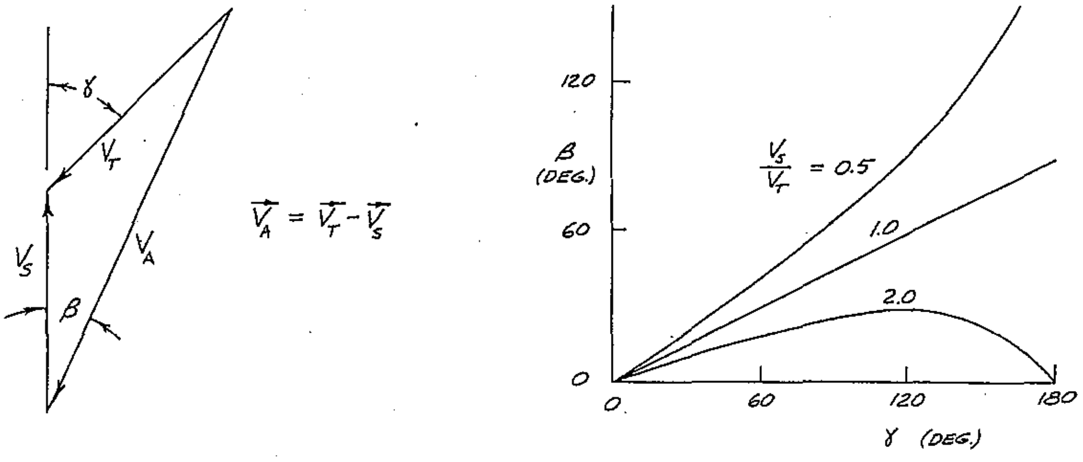


Figure 1. Relation between ship speed V_S, true wind speed V_T, apparent wind speed V_A, true heading γ, and apparent heading β.

calculations show the well-known fact that the power coefficient of a conventional sail goes to zero, even in frictionless flow, as γ goes to zero. On the other hand, for the windmill the power coefficient at γ near zero is very large, and it becomes small only as γ goes to 180 degrees, assuming that $V_S/V_T \leq 1$. Since the capability for sailing all points of the compass would be desirable, and since only the windmill powered ship can do this, does this mean that windmill-driven ships should be developed? Johnson(6) has suggested that this question might be at least partially answered if someone would work up a proof that the conventional sail-driven vehicle is more efficient than the windmilling vehicle. This paper has been written for the purpose of discussing the general nature of the relationship between windmill-driven and sail-driven ships.

2. A NEW TYPE OF SAILING VEHICLE

In order to show the related nature of windmill-driven and sail-driven ships, a new type of sailing vehicle has been invented, here called the "windsail," as illustrated in Figure 2. The windsail can be operated as either a windmill-driven or a sail-driven ship. Two hulls are used for lateral stability, and a long structural member, called boom A, extends ahead of the hulls. Attached to these booms is a spreader bar, and booms B are mounted on each end of the spreader bar. The booms B are free to rotate in a horizontal plane about the ends of the spreader bar. Each of these two booms carries a mast, a sail, and a keel.

This description should make obvious the point that the windsail may be operated in the manner of an ordinary sailboat by tying down the booms B so that they cannot move laterally. Then the sails may be trimmed for any sailing point between close hauled and running.

The so-called windmill mode of operation is novel and best illustrated by supposing that the ship is headed directly windward. The booms B are now freed to move laterally. To make windward progress the sails are first set as illustrated in Figure 3a. The sail force vectors F then move the sails away from the hulls. The forces F are balanced by the keel hydrodynamic forces, which have a forward component that drives the hulls forward at speed V_S, and the sails, keels and masts move with the velocity vectors $\vec{V}_M$, as shown in Figure 3a. The process is simply just like that of two independent sailboats sailing close-hauled but on opposite tacks with respect to the wind, but the boats are linked to the two hulls which are pulled along directly to windward.

Clearly this process can continue for only a short period before the masts and booms B are swung near the physical limits of their travel. Then the sails and keels must be retrimmed for the opposite tack, as shown in Figure 3b. This tack may continue for only a short time before the sails approach the hulls so closely that the tack of Figure 3a must be repeated. Thus, progress directly to windward requires a change in tack for every few hull lengths of travel.

This mode of operation is called the windmill mode inasmuch as the sail moves in the same manner with respect to the wind as does a windmill blade element. Furthermore, the keel operates with respect to the water in the same manner as that of a water propeller. Thus, in the windmill mode, the windmill vehicle operates to windward on exactly the same sort of aerodynamic and hydrodynamic forces as do the various forms of windmill-powered ships described by Phillips(7), Barkla(8), Pierson(9), and Bauer(10).

The tacking described above is directly analogous to periodically changing the direction of rotation of the windmill and propeller on a ship such as described by Phillips, Barkla, Pierson, or Bauer. Of course, there is no need to change the direction of rotation on these ships; to do so would be quite cumbersome and restrictive in the design of the blade elements. On the other hand, the windsail is forced to tack because of physical constraints. However, the windsail vehicle is not necessarily a more cumbersome vehicle than the others(7,8,9,10). We may note that the windsail has a much more efficient "transmission" than do the other

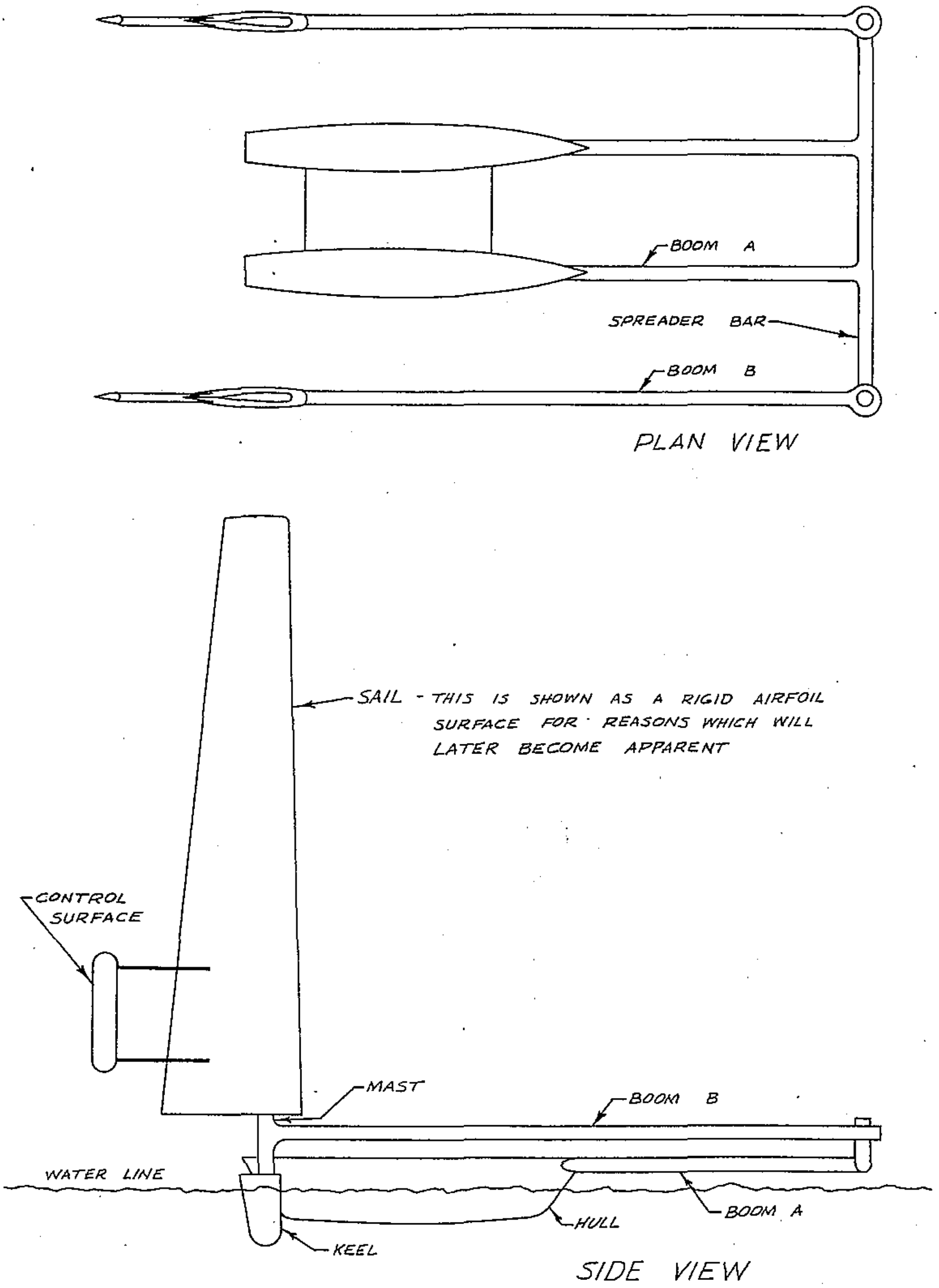


Figure 2. Schematic diagram of a "windsail."

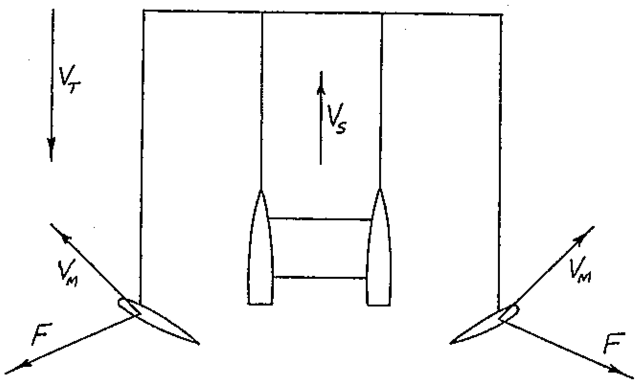


Figure 3a. Sailing directly to windward with masts moving away from the hulls.

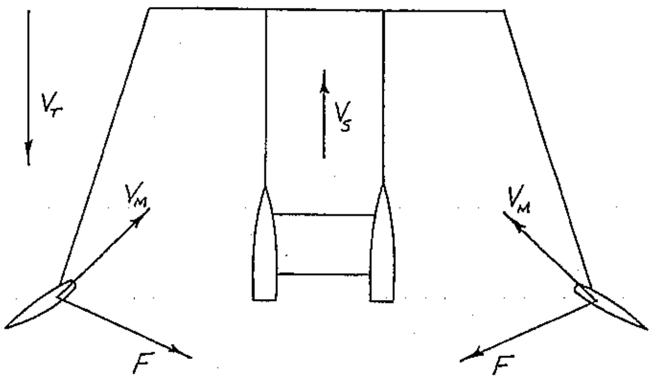
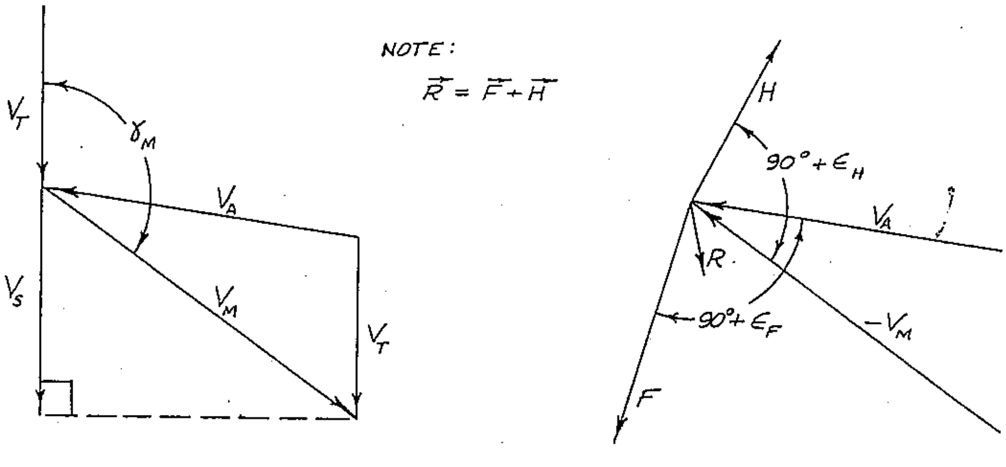


Figure 3b. Sailing directly to windward with masts moving toward the hulls.

boats$^{(7,8,9,10)}$. This transmission is just the mast which connects the sail and the keel. This simplicity eliminates most of the transmission losses, whereas transmission losses from shafting and gearing can be quite significant$^{(7,8,9,10)}$. Thus, the windsail configuration or "linear windmill"$^{(11)}$ is different from the earlier windmill power concepts through mechanical constraints rather than any fundamental change in the hydrodynamic and aerodynamic forces which generate the propulsive energy.

In sailing directly downwind the windsail can, of course, be operated in the manner of a conventional sailboat, which means that V_s must always be less than V_T. Nevertheless, it is quite possible to increase V_s to faster than the wind speed$^{(10)}$ V_T by operating the windsail in the so-called windmill mode. This is illustrated by the vector diagram, Figure 4, which shows one mast velocity vector $\vec{V}_M$ on one of the two tacks. The hull speed V_s, which is equal to $-V_M \cos \gamma_M$, is greater than V_T. That the forces are in balance so that this speed can be maintained is shown on the force vector diagram, where F is the total sail force and H is the total keel force. These forces are at an angle of 90° + ε with respect to the apparent wind and apparent water speeds, V_A and $-V_M$, respectively, where ε is the so-called drag angle. The sum of $\vec{F}$ plus $\vec{H}$ is given by $\vec{R}$; this is the force which balances the hull drag and/or the vehicle



NOTE: $\vec{R} = \vec{F} + \vec{H}$

Figure 4. Vector diagrams describing the windsail going directly downwind faster than the wind.

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(10).

Sailing on other points of the compass can be done by using the windmill mode of operation, which is possible for any γ, and by using the sailboat mode for γ's greater than about 40°. At certain γ'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. Neverthless, 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, $\gamma = 0°$ 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(12). 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 δ_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 α is given by $\alpha = -\delta_E$. This is not an unrealistic relationship. Then, if the helmsman wishes to tack by changing α from +10° to -10°, he can simply change δ_E geometrically from -10° to +10°. 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 δ_E can be made between two suitable stops. The moment that δ_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 α_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 α_K at the same time that δ_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.

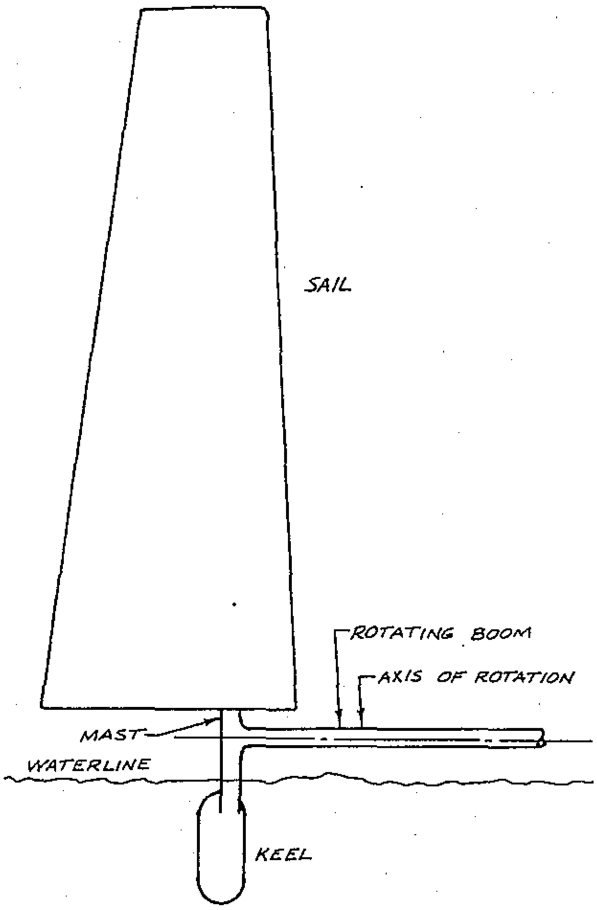


Figure 5. Schematic diagram of a rotating windsail

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$^{(13)}$.

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 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(6), Smith(14), and Barkla(15) 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"(6) 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(1) 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

Andrew B. Bauer began his sailing career by writing the paper "Faster than the Wind"(10) 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 four years with Philco Ford working on problems in acoustics, machinery dynamics, heat transfer, and experimental aerodynamics.

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