Experimental Study of a Directionally Stable Sailing Vehicle With a Free-Raking Rig and a Self-Trimming Sail

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ABSTRACT

There exists an exact dynamic analogy between a sailboat and a sailplane, if it can be assumed that the sail does not generate moment around the mast and that the yawing moment due to heel can also be eliminated. It is shown, both theoretically and experimentally, that a directionally stable sailboat can be realized. It is also shown that the above assumption of no-sail-moment can be realized by introducing a new type of mast which can elastically rake in the pitch direction and a wing sail which can freely rotate around the mast. The effectiveness of these sail and rig is verified by experiments.

INTRODUCTION

It is well known that the underwater part of the side view of a sailboat, when expanded symmetrically across the water line, is similar to the airplane plan form (e.g. Hoyt, 1986). The similarity exists not only in shape, but also in the systems of forces acting on a sailboat and a powerless airplane, a sailplane. The similarity becomes an exact dynamic analogy if it can be assumed that the moment produced by the sail is nonexistent.

One of the important characteristics of an airplane is that, if properly designed, it has a longitudinal, stick-fixed stability, i.e. it can fly along a straight path without moving the control stick (Etkin, 1994). A sailboat, on the other hand, does not usually have this level of stability and the skipper or an autopilot must steer it more or less actively in all points of sailing.

In the following, it is shown both theoretically and experimentally that a sailboat can obtain directional stability relative to the apparent wind if it can be assumed that the sail does not generate yawing moment around the mast and no additional yawing moment is produced by the sail force due to the heel of the boat.

The condition of no-sail-moment assumed above can be realized if the sail can be made to rotate around the mast freely and if the yawing moment due to heel can be eliminated. It is shown that this is possible by introducing a wing sail with a tail, called the self-trimming sail, and a new type of mast with an elastic degree of freedom in the pitch direction, called the free-raking rig.

THE DIRECTIONAL STABILITY OF A SAILBOAT

Dynamic Analogy between a Sailboat and a Sailplane

The underwater configuration of a sailboat is similar to the airplane plan form as in Figure 1. This similarity is even more striking when one considers the systems of forces and moments acting on a sailboat and on a sailplane.

As shown in Figure 2, the sail produces a force $F_y$ and a moment $M_y$. These are counteracted by the
forces \( F_H \) and \( F_R \) and the moment \( M_H \) which are generated by the water flowing across the hull-keel-rudder combination with the leeway angle \( \beta \).

The direction of the sail force \( F_S \) can be considered to be approximately fixed relative to the apparent wind direction. The approximation becomes better when the sail is not fixed to the boat but rotates around the mast keeping a fixed angle relative to the wind as with the self-trimming sail introduced later. Thus the angle \( \Gamma \) between the course-over-water (COW) and the normal to \( F_S \) approximately represents the course relative to the apparent wind direction.

If the sail moment \( M_S \), hence the counteracting fluid dynamic moment \( M_H \), is nonexistent, then the system of forces and moments acting on a sailboat is exactly similar to that on a sailplane, as shown on the right-hand-side diagram of Figure 2. With a sailplane, the gravitational force \( W \) is counteracted by the lift \( L \) and the drag \( D \) generated by the wing-tail-fuselage combination. The fuselage reference axis makes an angle of attack \( \alpha \) with the flight direction. The flight direction makes an angle \( \Gamma \) (glide path angle) with the horizon. This shows that, in the absence of the sail moment, the sailboat and the sailplane are dynamically analogous to each other and the following correspondence holds:

<table>
<thead>
<tr>
<th>Sailboat</th>
<th>Sailplane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Keel</td>
<td>Wing</td>
</tr>
<tr>
<td>Rudder</td>
<td>Tail</td>
</tr>
<tr>
<td>Sail Force</td>
<td>Weight</td>
</tr>
<tr>
<td>Leeway</td>
<td>Angle of Attack</td>
</tr>
<tr>
<td>CE of Sail Force</td>
<td>C.G.</td>
</tr>
<tr>
<td>Relative Curse</td>
<td>Glide Path</td>
</tr>
</tbody>
</table>

Any dynamical result that is valid in one system is also valid in the other.

### The Longitudinal Stability of a Sailplane

Let us briefly recapitulate the basic theory of stability of longitudinal motions (motions in the symmetry plane) of a sailplane. In the reference condition, which is called the trim condition in the field of flight mechanics, the sailplane flies on a straight course, with the lift and the drag counteracting the weight and the aerodynamic moment around the center of gravity C.G. being zero. If the angle of attack \( \alpha \) is changed by a small amount by some disturbance in the air, the resulting aerodynamic moment around the C.G. must be such that it tends to pitch the vehicle in the direction opposing the change of the angle of attack. The necessary and sufficient condition for this stability is that the C.G. lies in front of a specific point called the neutral point, i.e.

\[
h < h_n
\]

in which \( h \) is the position of C.G. from the leading edge of the reference wing chord (mean aerodynamic chord \( c \) ) made nondimensional by \( c \) and \( h_n \) which is the position of a specific point on the fore-and-aft axis called the stick-fixed neutral point. \( h_n \) can be interpreted as a point at which the pitching moment around C.G. is independent of \( \alpha \). Its position is given by

\[
h_n = h_{n,0} + \frac{a_H}{a} \bar{V}_H \left(1 - \varepsilon_\alpha \right)
\]

where \( h_{n,0} \) is the aerodynamic center (a fixed point around which the aerodynamic moment is independent of \( \alpha \)) of the wingbody (combination of the wing and the fuselage), \( a \) and \( a_H \) the lift-curve slope of the whole vehicle and the tail respectively, \( \bar{V}_H \) the tail volume ratio defined as

\[
\bar{V}_H = \bar{I}_s \frac{S_t}{cS}
\]

in which \( \bar{I}_s \) is the distance between the aerodynamic centers of the wingbody and the tail, and \( S \) and \( S_t \) the areas of the wing and the tail, respectively. \( \varepsilon_\alpha \) is the slope of the wing downwash with respect to \( \alpha \). The name “stick-fixed stability” signifies that the airplane has the tendency to return to the original angle of attack after some disturbance without the pilot intervention (stick fixed).

Equation 1 states that a sailplane has a tendency to hold a steady \( \alpha \) if the C.G. is in front of a specific point. This is the same kind of stability as that of an arrow or a wind vane which always points to the incoming flow if the C.G. or the axis of rotation is well before the vane. The static stability does not, however, ensures that the vehicle flies on a straight path. Even with a constant \( \alpha \),
The flight path can oscillate to upward or downward of the reference straight path, losing speed and gaining altitude or vice versa, respectively. This oscillatory motion is a result of an exchange between the kinetic energy of flight and the potential energy. It is the same as the oscillation of a pendulum and is called the phugoid motion. Just as the pendulum motion is damped out by the friction at the pivot, the phugoid motion is damped out by aerodynamic drag of the aircraft. Thus, for a sailplane that has no power plant, the static stability is also the necessary and sufficient condition for the vehicle to have the phugoid stability, in other words, to have a tendency to return to the straight flight path after being disturbed from it by the turbulence of the atmosphere.

The Directional Stability of a Sailplane

In view of the dynamic analogy between a sailboat and a sailplane, it follows that a sailboat has the static stability if and only if the point of action of the sail force (CE) is in front of the neutral point of the keel-hull-rudder combination. Note that, in the absence of the sail moment, CE coincides with the mast step position. This is also the necessary and sufficient condition for the sailboat to have the course stability, i.e. to have the tendency to return to a fixed course with respect to the direction of the sail force after it has experienced some kind of disturbance, due to waves, for example. If the direction of the sail force is assumed to be independent of the boat motion, this ensures that the sailboat has a tendency to sail on a constant course with respect to the wind as shown in Figure 3.

Although the exact position of the neutral point of a sailboat must be determined with regard to a reference state in which the boat is heeled and the rudder is deflected by a specific amount to hold a straight course, it approximately coincides with the CLR of the upright hull. Although the traditional geometric method of using the centroid of the keel, hull and rudder as CLR has no theoretical background, a few useful methods have been proposed for the theoretical determination of CLR. Gerritsma considered the influence of the keel and rudder (Gerritsma, 1971), while Nomoto also included the influence of the canoe body (Nomoto, 1979). A better way is to apply the method used by the aeronautical engineers to determine the neutral point position (Hoak and Finck, 1978), in which the effects of the wing, tail and the fuselage configurations are considered both theoretically and empirically.

These methods are compared with the tank test result of a model of a quarter-tonner by Gerritsma (Gerritsma, 1981) in Figure 4. The point marked as Airplane Theory uses the method of Hoak and Finck in which the hull effect is approximated by a potential flow around an elliptic body (Schlichting and Truckenbrodt, 1979). Both the method of Nomoto and that of Hoak and Finck show satisfactory agreement with the tank test, while the geometric method is useless.

EXPERIMENTAL VERIFICATION OF THE DIRECTIONAL STABILITY OF A SAILBOAT

In the case of an airplane, it can be shown that the deflection of the elevator (the control surface on the horizontal tail) which is necessary for a straight (trimmed) flight is given by

$$\delta = -B - C_{r_{\text{trim}}} \frac{\partial h}{h}$$

(Etkin, 1994). This means that, when the C.G. is nearer the neutral point, less stick movement is required to change the trim flight speed. When the C.G. is at the neutral point,

$$\frac{d\delta_{\text{trim}}}{dC_{r_{\text{trim}}}} = 0$$

(Etkin, 1994). This means that, when the C.G. is nearer the neutral point, less stick movement is required to change the trim flight speed. When the C.G. is at the neutral point,
and the correspondence between the stick position and the flight speed disappears.

This relationship was utilized to experimentally determine the neutral position of a model of a ten-meter sailing cruiser shown in Figure 5. The boat was towed by a line attached to a point on the fore-and-aft axis of the deck. The direction $\theta$ and the strength $F$ of the line tension, which is an analogue of the sail force, was measured by a rotary encoder and a load cell. The rudder angle $\delta_R$ needed to keep the relative course angle $\theta$ constant even when the boat speed or the towing force is disturbed. When the tow point is moved aft of the neutral point as in (b), the boat becomes directionally unstable.

Figure 7 shows examples of measured data. In (a), the tow position given by the nondimensional position $h$ is well before the neutral point and the boat is theoretically stable. It shows the tendency to hold the relative course angle $\theta$ constant even when the boat speed or the towing force is disturbed. When the tow point is moved aft of the neutral point as in (b), the boat becomes directionally unstable.

From the stable results as in Figure 7(a), the relationships between the steady rudder angle and the keel lift coefficient for various tow point positions ($h$) are obtained as in Fig. 8. The lift coefficient is taken positive when the lift is working to port. The measured data include both the starboard tack results (line tension to starboard, keel lift positive to port, and rudder angle positive) and the port tack results.

This experimentally obtained position of CLR is compared with the theoretical predictions in Figure 10.
and Table 2. In this case, too, the airplane theory of Hoak and Finck gives the best agreement, while agreement of the method of Nomoto is not as good as in the case of the model quarter-tonner in Figure 4. This is perhaps because only the influence of the forward half of the canoe body is considered in his method and the result strongly depends on the selection of the half-body point.

<table>
<thead>
<tr>
<th>Neutral point positions</th>
<th>Experimental</th>
<th>Airplane Method</th>
<th>Gerritsma</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.90</td>
<td>0.92</td>
<td>0.96</td>
</tr>
</tbody>
</table>

The tow test has shown that the concept of the longitudinal static stability of an airplane can be successfully applied to the analysis of the relative directional stability of a sailboat, and the theoretical estimation of the neutral point (CLR) by the method used in the airplane flight mechanics agrees very well with the experimental result.

Weather Helm vs. Lee Helm

It must be noted that, if the mast is stepped before CLR to ensure directional stability, then the sail force acting on the mast step generates yawing moment that tends to yaw the boat into the sail force direction, i.e. downwind. In other word, a directionally stable sailboat has a lee helm. This is in agreement with the tendency of a stable airplane in which the gravity force acting in front of the neutral point generates a nose-down moment. This must be counteracted by the downward lift produced by the horizontal tail.

This does not mean, however, that the conventional sailboat with weather helm is necessarily directionally unstable, since the above stability analysis is based on the assumption that no yawing moment is produced around the mast nor by the heel of the boat.

THE SELF-TRIMMING SAIL AND THE FREE-RAKING RIG

Origin of the Sail Moment

The above analysis, however, depends upon the assumption that the sail produces no yawing moment, which is not true with the conventional sailboat. There are two origins for the sail moment. First, conventional sails are attached by various lines to the deck and the aerodynamic moment produced by the sail is transferred to the hull by them. This moment can be eliminated by allowing the sail to rotate freely around the mast. This is the concept of the free-trimming sail.

When the boat is heeled, second kind of yawing moment is produced even when the sail does not generate moment around the mast. This is because the heeled mast generates a moment arm between the sail force and the keel force. This second type of moment can be eliminated by adopting the new, free-raking rig.

Self-Trimming Sail

The self-trimming sail consists of a wing sail and a tail as shown in Figure 11. The sail rotates freely around the mast, and its angle relative to the wind, i.e. the angle of attack, is determined by the deflection of the tail, just as the angle of attack of an airplane is determined by the elevator.

A similar concept has been proposed, for example, by Newman and Fekete (Newman and Fekete, 1983).

Since the wing sail is free to rotate around the mast, the force transferred from the hull to the sail is analogous to the gravity force $W$ acting on a sailplane as shown in Figure 2. The airplane stability theory can again be applied to this case, which states that the system of the wing sail and the tail is statically stable when the mast is placed before the neutral point. The steady angle of attack of the wing system relative to the apparent wind is determined only by the amount of the deflection of the
Free-Raking Rig

The reason that a heeled sail produces strong yawing moment lies in the fact that the boat heels much more easily than it pitches. Which means that the mast, in general, does not tilt in the direction of the sail force acting on it, and the resulting moment arm between the sail force acting on the mast and the hydrodynamic force on the keel produces yawing moment, as shown in Figure 12. However, if a boat is round-bottomed and can heel in any direction with equal ease as in Figure 13, the mast would tilt in the direction of the sail force and no moment arm, hence no yawing moment, would be produced.

This condition can be approximately realized if the mast is given an elastic degree of freedom at the mast step and allowed to pitch with nearly equal ease as when it heels with the hull, as shown in Figure 14. Combined with the self-trimming sail which produces no moment around the mast, the sail force is always aligned with the mast step with this rig, and no extra yawing moment is produced when the boat is heeled. This also means that the stability concept defined with regard to the distance between the mast step and the CLR is also valid when the boat is heeled. This new concept of stepping the mast is called the free-raking rig.

EXPERIMENTS WITH THE SELF-TRIMMING SAIL AND THE FREE-RAKING RIG

Effectiveness of the Free-Raking Rig

To test the effectiveness of the free-raking rig in eliminating the yawing moment due to heel, the boat used in the tow test shown in Figure 5 was give a stubby mast with an elastic joint at the mast step as shown in Figure 15. The height of the mast approximated that of the center of effort of the wing sail to be used in sailing tests. The mast step was positioned well before the neutral point to ensure directional stability. The boat was towed from the mast top by an inflatable dinghy and the direction and strength of the line tension were measured along with the position, speed, course and heading of the boat, its heel angle, and the mast pitch angle.

The graphs in Figure 16(a) and (b) show the time histories of the line tension, course relative to the wind, mast pitch angle and heel angle of the boat. The rudder angle was fixed during the measurement.
Graphs in Figure 16(a) are the result with the mast raking mechanism held inoperative. As the line tension is increased, so is the heel of the boat, and the relative course starts to veer due to the yawing moment produced by the heel. In 16(b), however, the mast raking mechanism is operative, and the relative course is held fairly constant in spite of a large change in the line tension and the heel angle.

Sailing Test

A preliminary sailing test with both the self-trimming sail and the free-raking rig revealed that the form stability of the boat was insufficient. The latter is caused by the scaling law which states that the restoring moment by the hull decreases as the fourth power of the representative length while the heeling moment by the sail decreases only as the third power. A new test boat with a longer keel and a modified raking mechanism as shown in Figures 17 and 18 has been constructed and sailing tests as in Figure 19 are underway.

Preliminary experiments has also revealed that sufficient damping of the pitching movement of the mast was necessary. This is because the elastic restoring moment at the mast step of the free-raking rig and the large moment of inertia generated by the tall wing sail constitute a vibrational system. It will also mean that such a rig might not be practical on a full-scale boat which must sail in any kind of seas.

CONCLUSIONS

It has been shown that there exists an exact dynamic analogy between a sailboat and a sailplane if no yawing moment is produced either directly by the sail or indirectly by the sail force when the boat is heeled.

It has been shown theoretically that the sailboat can
have directional stability relative to the apparent wind, as an analogy to the longitudinal stability of a sailplane. This has also been proved by a towing experiment. The position of CLR (the neutral point of stability analysis) obtained by the experiment agreed very well with the theoretical estimate by the method used in the flight mechanics.

It has been shown that the sail moment around the mast can be eliminated when a wing sail with a tail that rotates freely around the mast, the self-trimming sail, is employed and that the yawing moment due to heel can be eliminated by using a new type of mast, the free-raking rig, that can elastically rake with a same stiffness as that of the boat in heeling. The effectiveness of the free-raking rig was verified by a towing test. Sailing experiments using a test boat with the self-trimming sail and the free-raking rig is in progress.

ACKNOWLEDGEMENTS

We wish to thank Prof. Yutaka Masuyama of Kanazawa Institute of Technology, Japan, who has warmly helped us in many aspects of the research and has offered us the use of the mold of a quarter-scale model of a sailing cruiser he himself designed.

We also wish to extend special thanks to the late Prof. Kensaku Nomoto, who died last July in a sailing accident. He had shown continued interest in this study and the discussions we enjoyed with him on several occasions will always remain as fond memories in our hearts.

REFERENCES


