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Tuning the Rigging and Spars to Ensure Maximum Safety of Sailing Vessels

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ABSTRACT: Sailing vessels cannot sail straight into the wind, thus a voyage to a given destination point on one course only is rendered virtually impossible. The ship's master must sail close-hauled and change tacks periodically in order to get from point A to point B. This technique of sailing into the wind is known as "tacking". The sailing maneuver of tacking involves sailing close-hauled (beating to windward), sailing as close to the wind as possible, in order to have the least tack changes and least time and distance to overcome. The number and length of tacks depend on the distance between the starting and ending points of the route, the limits of the harbour area, the navigation situation and the change in wind direction during the passage. If sailing is to be carried out in tight quarters, the vessel must shift tacks every time she gets into proximity of the shore or may leave the fairway. If sailing takes place in high seas, the number of tacks tends to be less. A long tack ensures sailing the shortest distance to the mark. If there are navigational obstructions along the route, the vessel must be ready to short tack to avoid them. Sailing on a close-haul implies a certain angle of the sails to the wind and a certain ship's course into the wind. Finding the optimal course for the vessel means reaching the destination point the fastest way, making good maximum speed into the wind. The mean speed achieved by a sailing vessel is a good assessment criterion for the quality of sailing. Issues related to the optimal routeing of sailing vessels have been widely discussed in many researches. Most studies have focused on the trimming of sails to ensure top speed. Little consideration has been given to the problem of ship's speed alterations following different heeling angles due to different tuning of the rigging and its impact on ship's stability, irrespective of the maximum speed reached at a given tack. The present paper proposes a solution to this problem.

KEY WORDS: close-hauled, safety, sailing vessel, tacking.

I. INTRODUCTION

The reported cases of loss of ship's stability are always linked to the sailing vessel's response to external forces causing heeling in a longitudinal and transverse direction. Transverse stability is considered essential as the external heeling forces act on the width of the hull which is 2,5 - 5 times shorter than its length. Ship's stability is directly proportional to the displacement. Heavier vessels are able to withstand greater heeling moments than lighter vessels at one and the same metacentric height. To reduce the negative effect of the gravitational force, it is necessary to lower the centre of gravity of the ship. With proper ballasting the mass of the ship reaches 40 - 60% of displacement and the centre of gravity is low enough to create positive stability. [1], [2] A similar righting effect is achieved through crew shifting on the opposite side of the vessel, though this has a more dramatic effect on smaller sailing ships with a larger crew number. In event of high gusty winds, the deployment of crew members on high masts should be avoided. Better stability is achieved by lighter construction of the superstructures, reduction of their height, lowering of the height of the cockpit platforms and the wheelhouse. When sailing in stormy conditions the vessel must have full ballast tanks. The transverse stability value depends on the shape of the hull but most importantly on the width of the ship at the waterline and the coefficient of completeness. Larger breadth of the ship lowers the speed characteristics of the ship. [2], [4], [5] Masters of sailing vessels must be well acquainted with the sail trim variations as designed by the shipwrights and must strictly observe them with regards to the external factors. It should be borne in mind that the hull's speed potential is ultimately determined in the design consistent with the quality and strength of the sailing gear onboard. Any effort to reach speed other than the vessel's capabilities involves a risk of damage or loss of parts of the spars or rigging even at normal true wind speed. [2], [3]

II. MATHEMATICAL FORMULATION AND INFORMATION MODEL OF SPAR AND RIGGING CONTROL

The information model for sails control on board sailing vessels must contain guidelines defining the sails' optimal trim variations in line with the ship's potential within a permissible speed range, depending on wind force and direction. It is well known that sailing vessels make way through the water as a result of a system of forces acting on the craft. In sailing, the forces and moments, caused by the action of the wind on the sails, are in equilibrium with the combined hydrodynamic and gravitational forces and moments acting on the hull.

Mathematical formulation of the spar and rigging control: The forces occurring at the sails depend on the direction (W_A) and speed (V_A) of apparent wind, the drift angle (α), the angle of sails (K_S) relative to the ship's centre line (*CL*), the angle of attack (ζ) and the heel angle (θ). (Figure 1), [7] For the vessel to reach its running potential by tuning the rigging and spars, the information model must provide the conditions in which the forces and moments come in equilibrium: (Figure 1), [1], [6], [7]

$$F_x = R_h; \quad F_{yy} = R_y; \quad F_{yz} = R_z;$$

$$M_{trimFWD} = M\ trim; \qquad (1)$$

$$M_{heel} = M_{trim}; \quad M_{point} = M_{push};$$

where (Fx) is the thrust force along the True Course (*TC*), causing the vessel to trim by the head ($M_{trimFWD}$);

M_{point} - the moment pointing the vessel's bow towards the line of wind direction;

M_{push} - the moment pushing the ship's bow away from the line of wind direction;

R_H - hydrodynamic resistance;

M_{trim} - trimming moment;

M_{heel} - heeling moment balanced by the righting moment (M_R);

F_y - aerodynamic force perpendicular to centre line (*CL*). It is broken down to two components (equations 2 and 3):

Fyy - causing the drift (α) and the heeling of the vessel (θ);

Fyz - a component increasing the weight of the sailing ship.

$$Fyy = Fy \,.\, \cos\theta \qquad (2)$$

$$Fyz = Fy \,.\, \sin\theta \qquad (3)$$

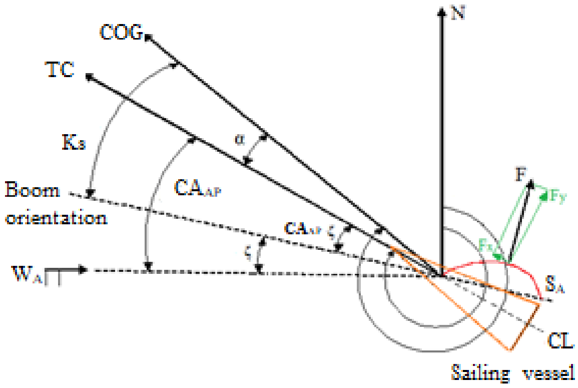

Fig. 1 Breakdown of the aerodynamic wind force (*F*)

Information model of the spar and rigging control :

The information model provides:

1. Aerodynamic data on the sail trimming, i.e. how the aerodynamic wind force (*F*) changes depending on the apparent wind force, the angle of attack, the angle of the sail relative to the centre line (*CL*) and the sail area (S_A).
2. The hull's hydrodynamic characteristics, i.e. how the response force (*R*) varies depending on the ship's speed (V_X) and the drift angle (α).

The Information Model Checks The Status Of Hoisted Sails On The Basis Of Set Criteria For The Permissible Values Of The Force Perpendicular To The Centre Line – (Fyper), Which Ensures The Spars And Rigging Integrity And The Heel Angle (Θper) When The Heeling And Righting Moments Are In Equilibrium. The Model Offers A Wind Configuration That Provides Maximum Speed Along The Course Over Ground (COG). (Figure 2)

III. TUNING THE RIGGING AND SPARS TO ENSURE MAXIMUM SAFETY OF SAILING VESSELS

The critical heel angles, i.e. the angle of flooding and the capsizing angle are taken from specific points on the static stability diagram.The diagram and the position of the specific points depend on the hull form and the point of centre of gravity. Typically, the maximum righting arm corresponds to the heel angle at which the deck edge is immersed into the water. Then, the beam of the waterline under heel is the greatest. Therefore, the higher the freeboard, the larger the heel angles at which adequate transverse stability is maintained.

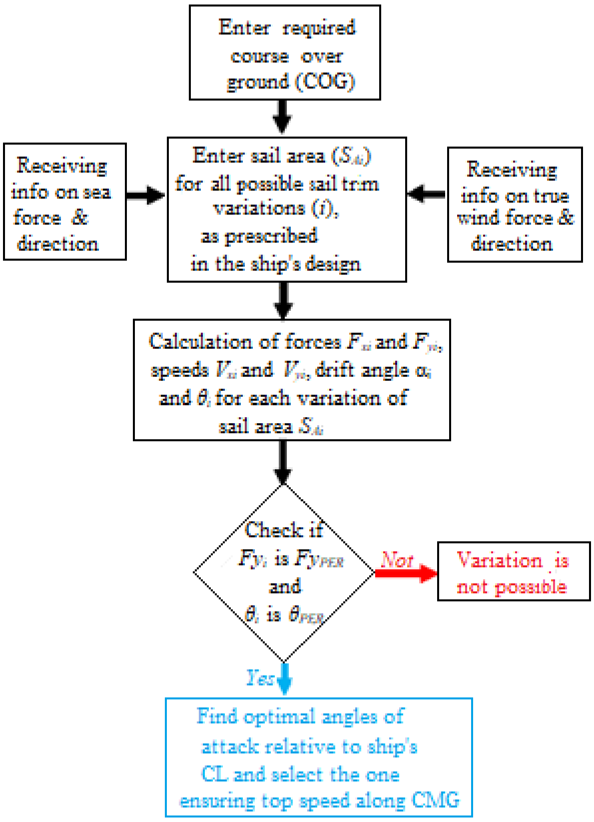

Fig. 2 Block diagram of the information mode

Apart from the well-know statistical data on the effects of the heeling moment, sailing vessels are faced, to a much greater extent compared to other ships, with the dynamic action of external forces, where the maximum heeling moment can reach the minimum overturning moment within a relatively short timeframe (almost instantly). This could happen with sudden violent gusts of wind (squalls) or heavy wave action on the windward side. The heeling moment is important as is the kinetic energy imparted to the ship and absorbed by the righting moment. The height of the freeboard and the heeling angle at which the vessel will start shipping water are also of great significance. The presence of water or other liquids in the ship's hold should not be overlooked at any time. The free surface effect affects the metacentric height. Water in the holds of flat-bottomed sailing vessels can be particularly dangerous and when sailing in stormy conditions it must be discharged into the sea. If the sailing ship has fuel tanks and cisterns, they must be separated by longitudinal bulkheads into watertight compartments and have top overflow openings.

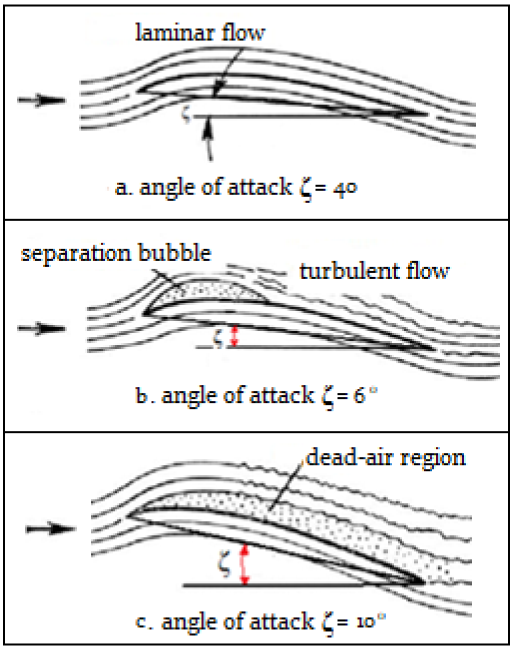

Fig. 3 Air flow over the sails and reduced pressure distribution over the width of the sail profile at different angles of attack (ζ)

The stability of a sailing vessel limits the force of the drift. Therefore, stability is closely linked to the permissible force of the apparent wind as well as the ship's speed at which the vessel will remain in a seaworthy condition.
If the ship is sailing at a sharp angle to the wind, the efficiency of the sail trim is dependent on:
- the sail area;
- the cross-sectional area of the sails;
- the angle of attack;
- the aerodynamic extension and outline of the sail.

If the angle of attack is relatively small, the point of contact with the flow shifts from the windward side of the sail and the airflow meets the leading edge of the sail at a great force. (Figure 3) As a result, near the leading edge (luff) of the sail at the leeward side, adverse pressure forms which causes the laminar boundary layer to separate (physically detach from the sail surface) and leads to the formation of a vortex-like bubble.At a high enough force of the apparent wind, the airflow rapidly absorbs the energy of the vortex and the airflow re-attaches to the sail at some point aft of the luff. As the angle of attack increases, the size of the vortex bubble grows. At an angle of attack of $\zeta = 5^\circ$, the airflow separates close to the trailing edge. At an angle of attack of $\zeta = 6^\circ$, the adverse pressure decreases, and the airflow distribution on the sail surface is more even. In this case, the bubble covers 25% of the chord length, as seen in Figure 3b. By further increasing of the angle of attack to $\zeta = 9^\circ$, the bubble covers the entire width of the sail profile and the lift of the sail drops by 2,5 times as compared to $\zeta = 4^\circ$.

With real sails the more tightened the sheets, the higher the angle of attack (ζ), and the larger area of the leeward side of the sail is covered by the vortex. The value of the critical angle at which the lift of the sail stalls depends on the depth of the sail profile, its aerodynamic extension (the ratio of the sail height and the mean chord), the size of the mast cross section or the diameter of the stays. The more flowing the sail and the greater its extension, at smaller angles of attack the stream collapses. With weaker winds, the stream collapses at smaller angles of attack as compared to stronger winds. This is also caused by the presence of a mast. With intense air flow, setting a jib ahead of the mainsail shifts the moment of collapse of the stream to larger angles of attack. For Bermuda rigged sailing ships with average luff length, the best angles of attack to broad reach are in the range of 16° - 10°, and to close haul the angles of attack are 5° - 8°. Increasing the angle of attack (ζ) above the critical angle, the lift drops with the increasing head-on resistance.

IV. CONCLUSIONS

The point of sail relative not only to the apparent wind, but also to the course angle (*CA*) (angle on the bow), makes it easier to program the points in sail trimming for different hydrometeorological conditions and especially when there is a change in the wind direction and force in the area. The key in resolving the problem of safety of sailing vessels is determining the angle of the type of rigging, taking into account the point of the sail area relative to the course over ground.

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