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Optimization of the Internal Structure and Shape of a 470 Dinghy Centerboard †

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Abstract: The purpose of this paper is to design an improved centerboard for the Olympic 470 sailing dinghy sailing upwind. The design is improved by introducing a composite design that makes the centerboard twist to windward when sailing upwind, thereby reducing the angle of attack of the hull. The results show that a beneficial twist up to 1.5° is possible to achieve without compromising the centerboard strength. According to our estimates, by utilizing the improved design it is possible to obtain a gain of up to 9 s per race in a world cup race.

Keywords: 470; sailing; hydrodynamics; induced resistance; twisted centerboard; composite design

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1. Introduction

Nowadays, professional sail races are very tight for several reasons. Firstly, the high-level competitors are very similar in skill. Secondly, the narrow limitations on the yacht design make the boats have very similar sailing performance. Therefore, the challenge to keep developing in the racing area has gone to focusing on the smaller details where it is still allowed to make small changes.

One detail that is often highlighted is the keel design. Over the years, several ways to develop the keel to reduce induced resistance have surfaced. One of these methods is the trim tab, which used to be popular in the Americas Cup where a trim tab was attached to the trailing edge of the keel as presented in Figure 1. The idea of this is that the crew can adjust the tab angle by a pivot and in this way redistribute the side force on the submerged body. By increasing the trim tab angle, the keel generates more side force and the hull less. Since the keel generates less induced resistance—per generated side force—than the hull [1], the total induced resistance is decreased with a trim tab [2] (see Figure 1).

Figure 1. Profile of keel with trim tab.

Inspired by this, this paper investigates the possibilities of reducing the induced resistance on the 470 dinghy which uses a centerboard and not a keel. With a smart composite design, where asymmetry in the layup creates a bending-twisting coupling, it is possible to obtain a centerboard that twists slightly to windward during upwind sailing, reducing the leeway angle of the hull. The induced resistance is then reduced in the same way as for the trim tab.

The purpose of this paper is to design an improved centerboard for the Olympic 470 sailing dinghy sailing upwind.

2. Background, Centerboard Dimensions, and Materials

The dimensions of the 470 centerboard follow the 2016 international class rules [3] from World Sailing (see Figure 2). The dashed area inside the centerboard contour should be a constant thickness between 20 and 24 mm, whereas the remaining area may have a varying thickness.

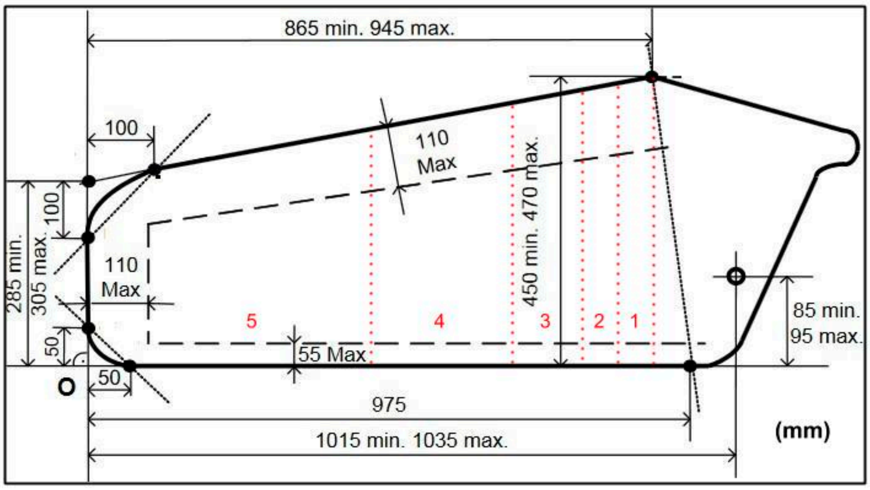

Figure 2. Dimension constraints on the centerboard [3]. Red numbers and lines show the five sector partitioning described in Section 3.

For the non-predetermined parameters, the important ones, in regards of performance, are:

- Centerboard depth: for a predetermined lift, the induced resistance is reduced with a larger depth (compare Figure 6.4 and 6.5 in [4]);
- Centerboard nose and tail: optimum shape of the nose is a parabolic shape [5] and the tail shall be slender to avoid flow separation (which causes increase resistance) from occurring [2];
- Centerboard material.

For competitive sailing of the 470 sailing dinghy, the class rules require the centerboard to be made from wood, plywood, polyester reinforced with glass fiber, epoxy reinforced with glass fiber, plastic foam or any combination of these [3]. Generally, centerboards are constructed using either some composite material or wood. However, composite materials are becoming increasingly dominant, both to reduce weight and to enable customized design with more design freedom. The layup configuration (reinforcement orientation in each layer of the laminated composite) of the composite may be designed to obtain beneficial anisotropic properties, such as a bending-twisting coupling, for more specific applications.

The most commonly used glass fiber material is E-glass as it offers great strength properties and forming capabilities. An alternative to E-glass is S-2 glass, designed to provide even greater strength properties. As the interest of the current study is to utilize maximum strength of the material to achieve a maximum twist, high strength materials are desirable. In this study, E-glass and S-2 glass are compared against each other (for mechanical properties see [6,7]).

For the core material, the material to be used is the polymer foam Divinycell H45, with mechanical properties as presented in [8].

3. Design of Internal Structure for Optimal Twist

In composites it is possible to make the component twist when subjected to a bending moment [9]. This is achieved by having an asymmetric orientation of fibers—reinforcements on either side of the main bending axis. This way, the twisting of the centerboard may be maximized by adjusting the choice of laminate material and the orientation of the laminate plies. As a majority of the deformation consists of bending, a way of interpreting the twist angle from this deformation must be defined. The displacement along the z-axis of the leading and trailing edge are denoted as ΔL and ΔT, respectively (see Figure 3). The twist angle, α, is then defined as $\alpha = \tan^{-1}\left(\frac{\Delta L - \Delta T}{b}\right)$, where b is the centerboard chord (along the y-axis).

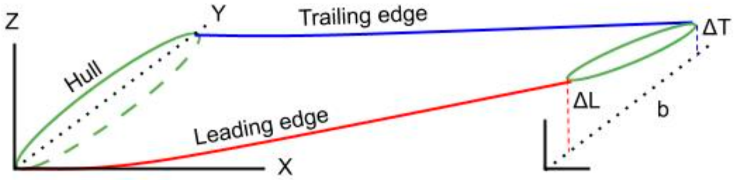

Figure 3. Definition of centerboard twist.

The maximum twist is obtained by optimizing the laminate material and orientation in the centerboard according to the load case of sailing. At the same time the laminate material and orientation must be designed so as to withstand the load case of righting which is the most severe load case in regard to sail racing and hence puts the highest restrictions on the centerboard strength. The challenge is to find a compromise between these two laminate designs since the load case of righting is somewhat contradictory to the twisting design.

The load case of upwind sailing is defined by the external pressure field on the centerboard from the incoming flow. This pressure field is determined by simulating the 470 dinghy in the fluid software STAR CCM+. The sailing conditions are based on 470 sail statistics [10], as well as research on the sailing behavior with similar hull shapes [1], which results in a leeway angle of 5° and a speed of 5.7 knots, at around 3 m/s wind speed. The leeway angle is defined as the angle between the hull centerline and the direction of motion.

The load case of righting is expected to occur in the case of capsizing. The sailors then flip the boat over by applying their weight at the end of the centerboard to induce a moment big enough to flip the sailing dinghy, thus righting it. This load constrains the dimensions of the composite, more specifically, the thickness of the laminate with corresponding core dimensions. In the case of righting, the centerboard may be approximated as a cantilever beam subject to a point load P. The maximal bending moments M and corresponding shear forces T are given by: $M_{MAX} = PL$ and $T_{MAX} = P$, where L (945 mm) is the depth of the centerboard and P is 1 kN (body weight of 100 kg). The laminates have to withstand these moments (M_{MAX} = 945 Nm) and the core has to withstand these shear forces (T_{MAX} = 1 kN). This load case will put the highest restrictions on centerboard strength

In order to simulate the deformation, the core and the two laminates are modeled separately in CATIA V5 and then imported to ABAQUS CAE where the layup, finite element discretization, and loads and boundary conditions are defined before solving the finite element problem. Here, contact surfaces are defined and constrained together using tie constraints. The upper part of the centerboard is constrained by a fixed boundary condition, representing the hull of the dinghy. The lower part of the centerboard is constrained by the load case of sailing by mapping the pressure field obtained from STAR CCM+ on the model in ABAQUS. The ABAQUS deformation simulation considers a safety factor of 1 in the failure analysis and the analysis is performed using the Hashin criterion [11].

The investigation shows that a non-uniform composite configuration using S-2 glass laminates gives the largest twist while still providing sufficient safety margins for failure in the righting load case. The optimal layup orientation, Θ, is given as a positive and negative rotation around the z-axis in Figure 3 (unsymmetrical layup to make the centerboard twist).

The centerboard is partitioned in five sectors from the top (the hull) to the bottom (see Figure 2) and four plies (laminate thickness = 4 × 0.125 = 0.5 mm) are used.

Table 1 shows Θ for each of the plies in the five sectors. The max twist angle is found to be 1.435° and the centerboard is close to the failure limit. To reach a safety factor of 2, the investigation shows that eight plies are needed, which gives a somewhat altered Θ scheme and a maximal twist of 0.81°.

Table 1. The optimal layup orientation for the four plies in each partitioning of the centerboard.

	1 (top)	**2**	**3**	**4**	**5 (bottom)**
$\Theta\ ^{\circ}\ _{\text{plies}}$	$28_1/7_2/28_1$	$28_2/7_1/28_1$	$28_2/7_1/28_1$	$28_2/14_1/28_1$	28_4

4. Analysis of Performance from Twist, Method, and Results

4.1. Sail Performance

In order to understand the impact of twist on sailing performance, the initial performance of the dinghy needs to be investigated. In the initial state of the dinghy during upwind sailing, the side force generated by the submerged body is equal to the side force generated by the sail [4]. When the centerboard starts to twist, it starts to generate more side force. As a result, the hull will generate less side force in order for the submerged body to still be in equilibrium with the side force from the sails. As stated in the introduction, it is the side force redistribution that reduces the induced resistance. Since the magnitude of the generated side force of the submerged body depends on the leeway angle, the reduction of the induced resistance can be determined by computing the side force for the 470 dinghy with the twisted centerboard at 5° and 3° of leeway and interpolating to the leeway angle that gives the same side force as the original centerboard at 5°. This turned out to be 4.32°, and a new computation of the total drag was made at this angle. The new total drag was then compared with the original one at 5° and a reduction of 0.8% was found (see Tables 2 and 3).

Table 2. Side forces for different dinghy leeway angles.

Dinghy Position	**Side Force (N)**
Dinghy with twisted centerboard, leeway 5°	1072.74
Dinghy with twisted centerboard, leeway 3°	801.5
Dinghy with Original centerboard, leeway 5°	979.97
Twisted centerboard interpolated, leeway 4.32°	982.35

Table 3. Total reduced drag.

Dinghy Position	**Total Drag (N)**	**Diff. (%)**
Original centerboard, leeway 5°	185.61	0
Twisted centerboard, leeway 4.32°	184.12	−0.8

By determining the relation between the total drag and speed of the dinghy, the reduced drag of 0.8% can be translated to an increased velocity of 0.4% which results in a gain of up to 9 s when applying it to a 470 sail race [10].

4.2. Parametric Twist Study

It is of interest to analyze how much the total drag could be reduced, considering no limitations on the internal structure, in order to evaluate the total effect from the deformed twist. This is done by carrying out a parametric twist study and comparing the parametric results with the deformed twist from ABAQUS. This study determines the reduced drag following the same calculation process as described in Section 4.1 where the reference side force for the interpolation is equal to the side force generated by the dingy using an original centerboard with a 5° leeway angle as presented in Table 3. The twist is considered linear with no bending from 0 to 10° within steps of 2° and the reduced drag is determined as shown in Figure 4. The study shows that the optimal twist is around 8° where the total drag is reduced by 1.42%. Figure 4 shows that more than half of the reduction in drag is obtained at 2° of twist and then the reduction speed slows down. After 8°, the drag on the centerboard increases more than the drag on the hull decreases. This results in a lower reduction of the total drag.

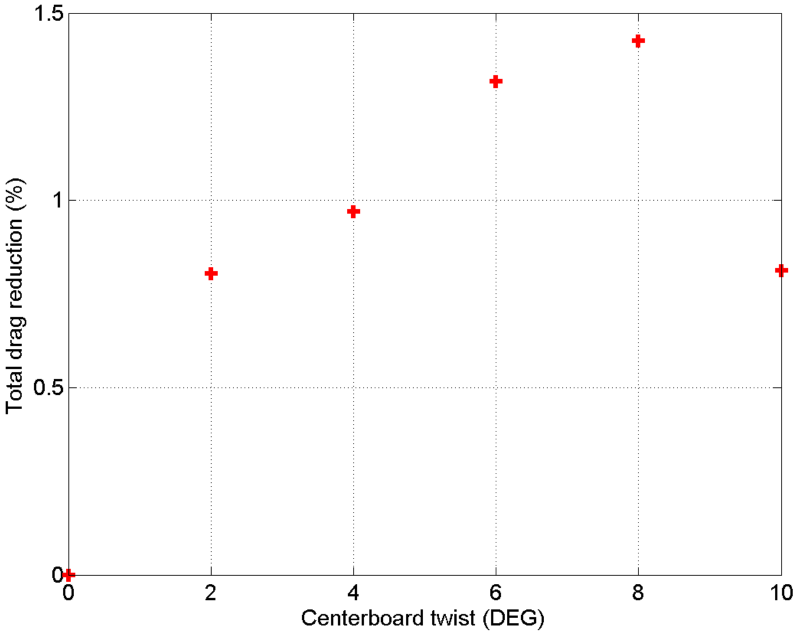

Figure 4. Parametric twist study.

5. Conclusions

The purpose with this paper was to design an improved centerboard for the Olympic 470 sailing dinghy upwind by introducing a composite design that makes the centerboard twist to windward. In addition to this, it was investigated how large twist is achievable by optimizing the internal structure, such as composite layup orientation and thickness. By optimizing the internal structure, a twist of 1.435° at most was achieved. This resulted in a predicted velocity gain of 0.4% when sailing upwind equivalent to a maximum time gain of 9 s in a real race case which corresponds to an advance of one or several positions. This states that the twist provides beneficial properties in relation to a straight centerboard. Comparing the achieved results to the parametric twist study, it can be seen that if the twist could be around four times larger, the reduction in drag would be twice as large. However, the parametric twist study assumes a linear twist which is far from the real case and the comparison shall therefore be considered carefully.

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Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Lindstrand Levin, R. Strongly Coupled Performance Prediction for Sailing Yachts Based on CFD. Licentiate Thesis, Department Shipping and Marine Technology, Chalmers University of Technology: Göteborg, Sweden, 2016.
2. Van Oossanen, P. America's Cup Yachts–Recent Design Developments, Journal: RINA. 2003. Available online: https://www.oossanen.nl/beheer/wp-content/uploads/2012/01/petervanoossanen_-_americas_cup_yachts_-_recent_design_developments.pdf (accessed on 18 November 2019).
3. *International 470 Class Rules 2016*; World Sailing: London, UK, 2016.
4. Larsson, L.; Eliasson, R.; Orych, M. *Principles of Yacht Design*; Bloomsbury Publishing: London, UK, 2014.
5. Marchaj, C.A. *Sailing Theory and Practice*; Adlard Coles Limited: Southampton, UK, 1982.

6. Performance Composites. 2016. Available online: http://www.performance-composites.com/ (accessed on 18 November 2019).
7. High Strength Glass Fibers. 2016. Available online: http://www.agy.com/wp-content/uploads/2014/03/High_Strength_Glass_Fibers-Technical.pdf (accessed on 18 November 2019).
8. Diab. 2017. Available online: http://www.diabgroup.com/en-GB/Products-and-services/Core-Material/Divinycell-H (accessed on 18 November 2019).
9. Agarwal, B.D.; Broutman, L.J.; Chandrashekhara, K. *Analysis and Performance of Fiber Composites*, 3rd ed.; John Wiley & Sons: Hoboken, NJ, USA, 2006.
10. 470 Men Race R2-Sailing World Cup. 2017. Available online: https://swc2017-hyeres.sapsailing.com/gwt/RaceBoard.html?regattaName=SWC+2017+Hyeres+-+470+Men&raceName=R2+(470+Men)&leaderboardName=SWC+2017+Hyeres+-+470+Men&leaderboardGroupName=Sailing+World+Cup+2017+-+Hyeres&mode=FULL_ANALYSIS&canReplayDuringLiveRaces=true (accessed on 18 November 2019).
11. Autodesk. Available online: http://help.autodesk.com/view/ACMPAN/2015/ENU/?guid=GUID-A2597BFC-606B-4C21-ABCA-8F34D37FBC41 (accessed on 18 November 2019).