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Engineering Notes

Comparison of Potential Flow-Based and Measured Pressure Distributions over Upwind Sails

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Introduction

TODAY, the use of vortex-lattice method (VLM) tools to design yacht sails for upwind conditions is common practice in the marine industry, while more sophisticated Reynolds-averaged Navier–Stokes equation (RANSE) codes are sometimes employed for the design of highly curved downwind sails with large areas of separated flow. Both VLM and RANSE codes are usually validated against *force* measurements from wind-tunnel tests [1,2] or full-scale investigations [3,4]. Although such force measurements can be used for code validation purposes, they cannot provide the same amount of detail as *pressure* measurements. VLM codes, for example, normally use image or mirror sails to model the influence of the sea surface and, depending on the exact location of the mirror plane, predicted aerodynamic load distributions can vary greatly [5]. Only pressure measurements can provide enough information to reliably validate codes to such a degree. However, very little research about pressures on sails seems to have been published. Recently, Viola and Flay [6] reviewed the situation and concluded that no wind-tunnel data on pressure distributions over upwind sails exist, while published full-scale results do not provide sufficient data to construct a full pressure map of the sails. The aim of the project summarized below was to fill this gap by conducting wind-tunnel measurements using a new (and we think innovative) type of pressure-tapped fiberglass sail models. The advantage of such rigid sails over cloth sails is that the shape is fixed and known. The experimental results are compared to VLM and extended lifting-line theory predictions, and excellent agreement is found.

Sail Models

Several conflicting requirements had to be balanced while designing the model sails: The models and their support structure have to be stiff enough not to deform appreciably under load, yet, at the same time, the models have to be thin enough to resemble real cloth sails, but there also needs to be enough room inside the models to accommodate a large number of pressure tubes. It was found that epoxy-fiberglass sandwich sails could meet these requirements when the sandwich core also houses multiple pneumatic tubes. For the present study, models of the flying shapes of sails for an America's Cup 33 yacht were laminated over male molds under vacuum pressure. At height D (Fig. 1) the headsail and mainsail have a maximum camber of 12 and 5.6%, respectively, and the positions of maximum camber are 31 and 44% of the chord length. Corrugated plastic (Corflute®) was used as the core material of the sandwich. This lightweight low-cost material is extruded from polypropylene and more commonly used for advertising signs. It features a high density of individually pressure-tight flutes (Fig. 1). The sail models were made from 2-mm-thick Corflute between two skins of 0.9 mm fiberglass. The resulting sails have approximately 200 usable flutes each. In the present study, only 41 and 86 flutes were used on the headsail and mainsail, respectively, and the pressure taps were arranged in rows B–K, as shown in Fig. 1.

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Experimental Setup and the Wind Tunnel

All experiments were conducted in the University of Auckland's Twisted Flow Wind Tunnel [7]. The sail models were supported by wires inside a frame, rather than being set on a yacht model (Fig. 2). This allowed trimming the models to several predefined positions very precisely and with good repeatability. It was found that this arrangement allows adjusting the angles of attack to within $\pm 0.3°$ [8]. The freestream dynamic pressure was $q = 32.5$ Pa, with a variation of ± 1 Pa in the vicinity of the sails. At $T_u = 3\%$ the freestream turbulence intensity was relatively high, although much lower than at low heights in the atmosphere. The Reynolds number based on the average chord length of $c_{\text{avg}} = 0.49$ m was $Re = 2.3 \cdot 10^5$. The pressure distributions over the sails were measured simultaneously using the 512-channel pressure system described in [9]. The piezoresistive sensors of this system are temperature-compensated Honeywell XSCL04DC transducers with an accuracy better than ± 0.5 Pa. With the above values the total experimental accuracy becomes about $\delta C_p = \pm 0.045$.

Load and Pressure Predictions

The measured pressure and load distributions have been used to validate two potential flow codes developed by the authors: namely, an extended lifting-line code (ELLC) and a vortex-lattice method code.

Extended Lifting-Line Code

Recently, Junge et al. [10] used extended lifting-line theory (Weissinger's method) to predict the spanwise circulation distribution over an *isolated* mainsail. Subsequently, Fluck [8] extended this theory to the case of two *interacting* sails. Like Junge et al. [10], Fluck [8] also replaces the sail bound circulations by vortex distributions on the quarter-chords, calculates the downwash on the three-quarter-chord of each sail, and assumes that at this position the flow components normal to each sail vanish. Fluck, however, no longer models the wake of each of the sails as a planar vortex sheet, but assumes the wake to be shed parallel to the chord line. In this way, the geometric twist and the effect of the headsail wake on the mainsail are modeled more realistically. The problem formulation of no normal flow at the three-quarter-chord of each sail leads to two coupled integrodifferential equations. Fluck solves these using a modified Fourier-series representation (with typically about $n = 11$ terms). To account for the influence of the sea surface Fluck uses image sails, as in Junge et al. [10]. However, the headsail of a yacht usually seals against the deck. Therefore, the symmetry plane is located at deck level and not at the water surface, as it is in [10]. Consequently, the headsail and its image are considered to be one sail with a continuous deck-symmetrical circulation distribution. The

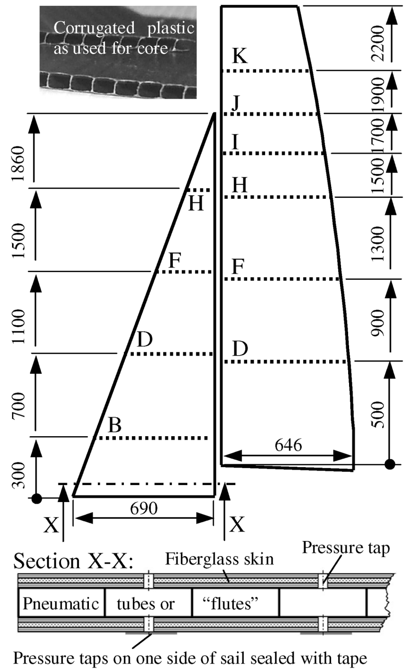

Fig. 1 Schematic drawing of sails and location of pressure tap rows.

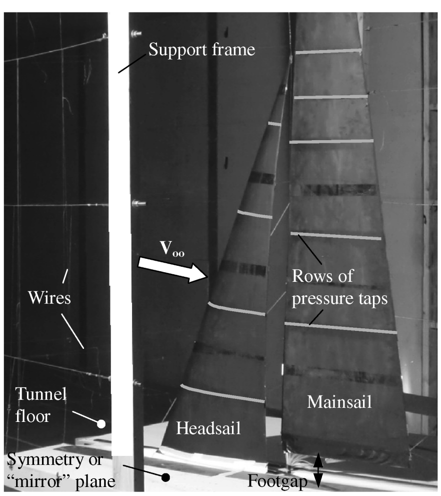

Fig. 2 Experimental setup in the wind tunnel.

foot gap under the mainsail (Fig. 2) is modeled as described by Junge et al.; its height, however, is reduced to the distance from the foot of the sail to the deck. Although this neglects the freeboard of the yacht, the experimental results justify this approach.

Vortex-Lattice Method Code

Based on the work of Fiddes and Gaydon [2], one of the authors (Pilate) recently developed a vortex-lattice method code for two interacting sails. Like the extended lifting-line method, the VLM code uses mirror images of the sails to model the influence of the sea surface. The code features three different methods to calculate the aerodynamic loading: pressure summation, Joukowksi method, and Trefftz-plane analysis. In the present Note only the first method is used, and 19×19 cosine-spaced panels represent both headsail and mainsail. The control points are located at the middle of each panel, and the wakes are planar and aligned with the incoming flow.

Results

Pressure Distributions

Figure 3 compares measured and predicted (VLM) pressure distributions at an apparent wind angle of $\beta_{\mathrm{AW}} = 19°$. The apparent

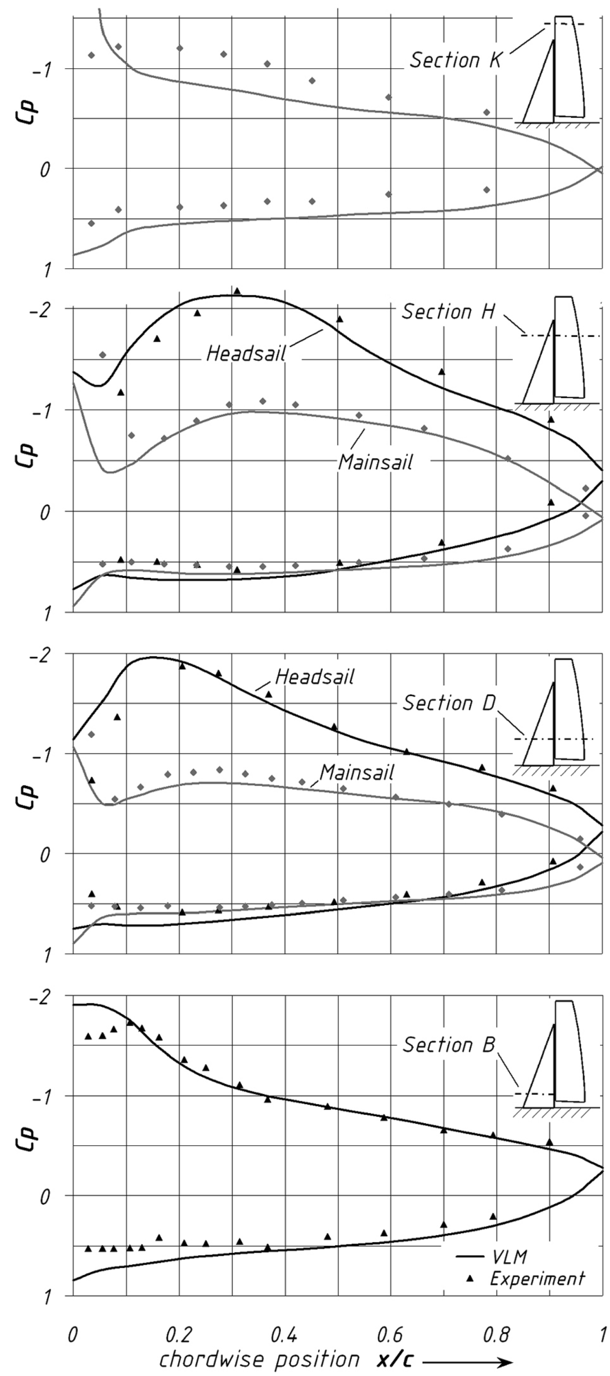

Fig. 3 Comparison between predicted (VLM) and measured chordwise pressure distributions at four different heights. Apparent wind angle $\beta_{\mathrm{AW}} = 19°$.

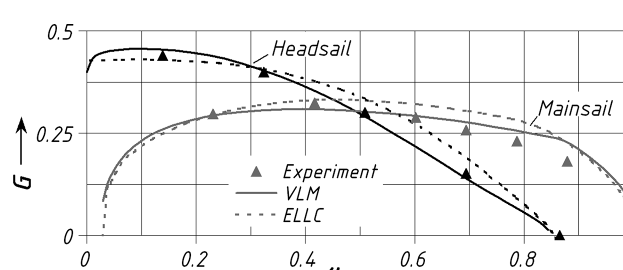

Fig. 4 Predicted and measured nondimensional spanwise circulation distributions $G = \Gamma/(bV_{\infty})$ at $\beta_{\mathrm{AW}} = 19°$.

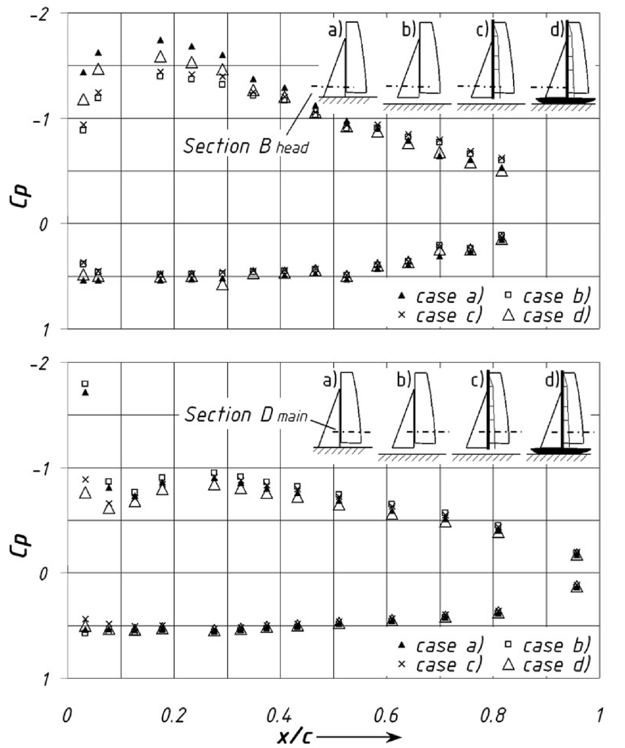

Fig. 5 Influence of foot gap and mast on experimental chordwise pressure distributions.

wind angle is the angle between the incident flow and centerline of yacht, and the value of 19° was chosen because most modern yachts sail at $17° \leq \beta_{\mathrm{AW}} \leq 20°$ when beating to windward. By and large, the agreement between calculated and measured pressures in Fig. 3 is very good. The shapes of the theoretical pressure distributions indicate that sections D and H operate at near-ideal incidence. The VLM predicts that section D_{main}, for example, operates slightly above ideal incidence; i.e., the theoretical pressure distribution for the suction side exhibits a high but narrow suction peak near the leading edge, followed by a second much flatter peak at about 30% chord. A theoretical analysis shows that the sharp first peak is caused by the angle of attack, while the second peak is due to the camberline shape. The experimental results for section D_{main} closely follow this theoretical trend.

The agreement for section K on the mainsail is not so good. Whether the noticeable difference between measured and predicted distributions on the suction side of section K is caused by flow separation or simply by an experimental error (e.g., angle of attack too low or too much camber at this location) is still being investigated.

The experimental and theoretical results both show that $Cp < 0$ in the vicinity of the trailing edge of the headsail. This is caused by the overlap of the sails; i.e., the trailing edge of the headsail operates in the low-pressure region of the mainsail.

Spanwise Loading

Figure 4 shows theoretical and experimental spanwise circulation distributions. The latter have been calculated by integrating the measured pressures along the chord. As can be seen, the agreement with the experimental results is good: in particular, for the VLM. The ELLC slightly overpredicts the loads for $0.25 \leq y/h_{\mathrm{mast}} \leq 0.9$, because this much simpler method cannot model the interaction between the two sails as well as the VLM.

Influence of Mast and Hull

In the above experiments, the simplified symmetry plane geometry of the ELLC and VLM calculations was replicated (Fig. 2). Such an arrangement neglects the influence of hull, rig, and freeboard. To quantify the resulting error, more experiments with the pressure-tapped sails were carried out (see also [8]). Starting from the experimental setup in Fig. 2 (case a), the symmetry plane was lowered (case b), the mast was attached (case c), and the hull was introduced (case d). Figure 5 shows the corresponding chordwise pressure distributions for one representative section on each of the sails. As can be seen, the mast only affects the leading 15% of the mainsail by reducing the suction peak. A wider foot gap, on the other hand, mainly reduces the load at the bottom of the headsail. This effect is well known to sailors and was also studied theoretically in [5]. On the headsail, the most realistic pressure distribution from case d is not very different from case a, which is modeled in the VLM and ELLC. The resulting difference in the sectional lift coefficients C_l is only 4.8% for the headsail, but it is 7.6% for the mainsail, where the mast has an effect. The pressures on the other sail sections show very similar behavior, and the resulting differences in the total lift coefficients C_L of cases a and d become 3% for the headsail and 7% for the mainsail.

Conclusions

Rigid fiberglass sail models with internal pressure tubes have been designed and were used for a study of the aerodynamics of upwind sails. Predicted pressures from a VLM code and wind-tunnel results generally agree well, but some local differences exist near the top of the mainsail. A comparison of experimentally derived spanwise load distributions and distributions from a VLM and an extended lifting-line code shows good agreement for the VLM code, while the extended lifting-line code seems to overpredict the loads near the midspan of the sails slightly. Experimental results also indicate that the mast and hull, which are ignored in the theoretical analysis, lead to only a 3% reduction in lift of the headsail, but to a 7% reduction for the mainsail.

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