Australian Wind Engineering Society
5th National Workshop on Wind Engineering
22-23 February 1996, Tanunda, South Australia

WAKE MEASUREMENTS USING A FIVE-HOLE PRESSURE PROBE

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THEORY

The project was under taken with the intention of measuring the lift and drag distributions of sails in a wind tunnel. The theory used in wake surveys has been developed and the technique has been proven overseas in the aircraft and car industries[1,2,3]. The theory derives from a control volume analysis with the resulting equations given below :

$$Lift_{1-2} = \rho U_{\infty} \int_{z_2}^{z_1} \left(\int_{z}^{z_{\infty}} \int_{y_{-\infty}}^{y_{\infty}} \xi \; dydz \right) dz \qquad where \quad \xi = \frac{\partial w}{\partial y} - \frac{\partial v}{\partial z}$$

$$Profile\ Drag,\ D_p = \int_{wake} (p_o - p_{o_e}) dA + \frac{\rho}{2} \int_{wake} (u^* - u_e)(u^* + u_e - 2u_{\infty}) dA$$

$$where \qquad u^* = \sqrt{\frac{2((p_o - p_{o_e}) + q_e}{\rho} - v_e^2 - w_e^2}$$

$$Vortex\ Drag,\ D_v = \frac{\rho}{2} \iint_{wake} (\psi \xi) dydz - \frac{\rho}{2} \iint_{exit\ plane} (\phi f) dydz - \frac{\rho}{2} \iint_{exit\ plane} u^2 dydz$$

The calculation of lift is related only to the vorticity, thus limiting the measurements to the viscous wake as shown by El-Ramely & Rainbird[4]. The profile drag and the first integral in the vortex drag comprise the major drag terms which are also limited to the viscous wake making the technique accurate in unseparated flows where the final two terms in the vortex drag are insignificant. These last two terms correct for cross flow velocities, included in the vortex drag, which are due to the source-like flow in the wake resulting from the loss in axial velocity due to profile drag and flow closure in the wake close to the model. When testing bluff bodies the 'correction terms' should ideally be evaluated over the entire plane downstream in the wake of the model although this is clearly impractical. While the perturbation velocity, u, and source density, f, are very small far away from the viscous wake region the contribution of these distant values are significant to the correction term when integrated over the large area they cover. In this study the accuracy of the measurements were insufficient to calculate these terms with any certainty and so were not included in final drag values.

A major difference between this study and those reported else where was the use of a slotted wall wind tunnel, which influenced the boundary conditions used to calculate the stream function, ψ, and the source density, f. The boundary conditions are important as they uniquely determine the stream function and source density function fields calculated. The slotted wall wind tunnel (49% open area ratio with a maximum blockage of 6%) was assumed to work ideally, that is, simulating an infinite flow in the vicinity of the model. The flow outside the viscous wake of the model could therefore be constructed from three potential component flows: a vorticity driven flow, a source induced flow and a uniform onset flow. The vorticity values, ξ_i, calculated from the wake measurements were treated as point vorticies, from which values of the stream function at the boundaries were calculated using the potential flow equation,

$$\psi_{point\ vortex} = -\frac{\Gamma}{2\pi}\ln(r) = -\frac{\int \xi dA}{2\pi}\ln(r)$$

Knowing the boundary values the ψ field was found by solving the governing equation for ψ, $\nabla^2\psi = -\xi$, using the method of the false transient[5]. The source density function is found in a similar manner except that ϕ replaces ψ, f replaces $-\xi$ and m (the source strength = $\int f\,dA$) replaces the circulation, Γ.

MEASUREMENTS

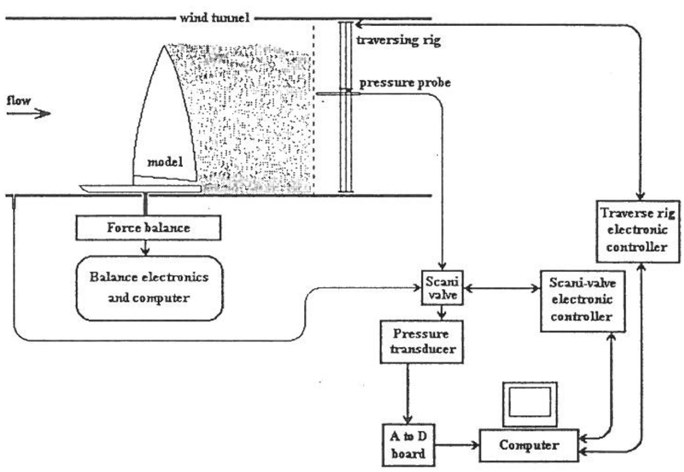

Diagram of the wake survey measuring system.

The above theory required the velocity (u, v & w) and the total pressure loss (p_o-p_{oc}) to be measured in wake of the model. As flow angles in the wake were not expected to exceed ±30° an existing 5-hole, hemispherical head (diameter =5mm), non-nulling, pressure probe was used to take the measurements. A non-nulling probe is one which has a fixed orientation in the wind tunnel (usually with its axis orientated along the tunnel), making the probe and its support less intrusive to flow. However, an extensive calibration is required to relate the differences in pressures between holes in the probe head to the flow properties: q_L (local dynamic pressure), α (pitch angle), β (yaw angle) and Δp_o (total pressure loss). While 7-hole probes have been developed that can measure large flow angles, limiting the measuring range to ±30° allowed the use of a simplified calibration[6]. The calibration essentially

generated maps relating probe pressures to q_L, α, β and Δp_o. The maps were initially defined using 3rd and 4th order bivariate polynomials fitted to the calibration data using a least squares fit. Comparing values recalculated from the calibration with the original data gave unacceptably high errors of ±2° in α and β and errors of ±4Pa in q_L and Δp_o. To get a better fit, bi-cubic smoothing splines were used to define the maps which produced errors of ±0.24° in α and β and ±0.6Pa in q_L and Δp_o when compared to the calibration data. Although these errors are satisfactory, comparison of the net lift and drag forces calculated from wake surveys with those measured using a force balance suggested poor probe performance in flows where large velocity gradients exist. Most of the studies reported elsewhere have successfully used conical head probes to take the flow measurements. The velocity can be measured using alternate means such as thermal anemometry or LDV but measuring the total pressure loss still requires some sort of pressure probe (although less complex) to be used. The probe is clearly one of the most important parts of the system and requires careful selection. The wake traversing system used to collect the wind tunnel data is illustrated in the diagram.
Wake measurements were first taken behind a rectangular wing (section profile NACA 0015), mounted vertically above a ground board. These measurements showed a significant influence from the floor boundary layer on the wake flow and on the profile drag distribution, as high loss flow from the floor boundary layer was entrained in the wake (see also Figures 2 and 4). A higher than expected net lift force was calculated which was attributed to poor measurement accuracy in the narrow viscous wake region. Sail wake surveys were taken for a 40th scale IACC model yacht, tested in a uniform flow, with $Re=6.2\times10^5$ (based on mast height = 0.81m). The hull was set at an angle of 36° to the flow and a heel angle of 20°. The sails where adjusted, using tufts, to give attached flow over most of the sail area. The wake was scanned 365mm down stream of the mast base of the model over a 41x61 grid. Results of the wake survey are shown in Figures 1 to 4.

CONCLUSION

The lift and drag distributions of yacht sails were measured using a five hole pressure probe. The force distributions and contour plots provided useful insight into the flow around yacht sails. The apparent inaccuracy of the probe limited the value of the absolute forces measured.

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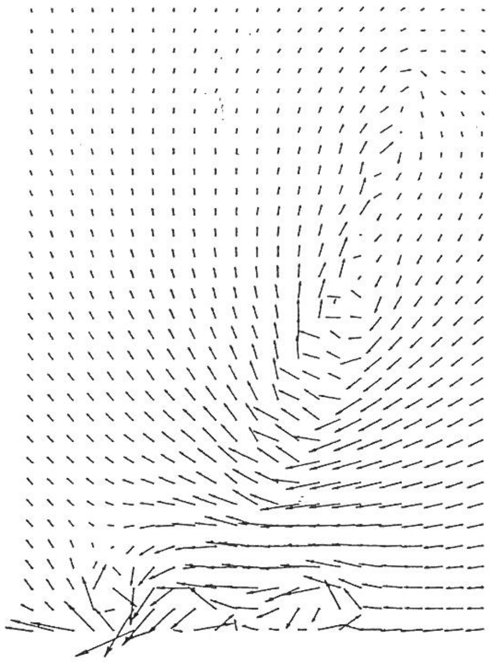

Figure 1. Crossflow velocity vectors in the sail wake.

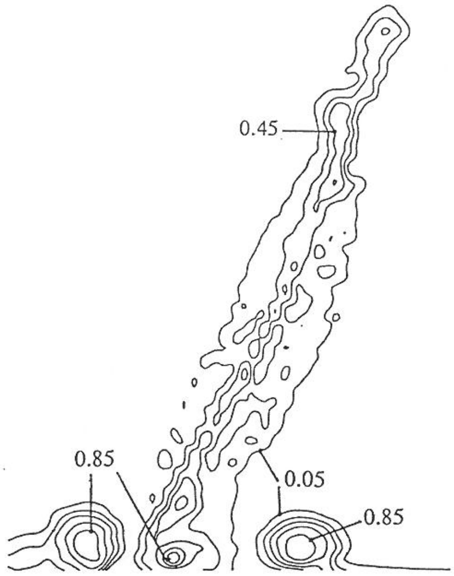

Figure 2. Total pressure loss in the sail wake, $(p_o-p_{oe})/q_\infty$.

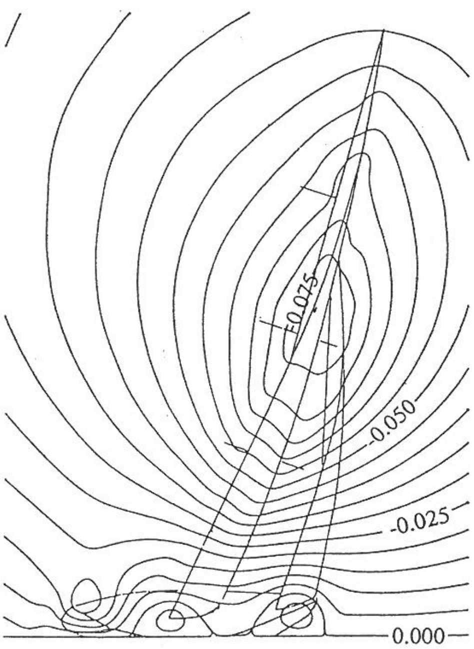

Figure 3. Streamfunction contours in the sail wake, ψ/bU_∞ (yacht outline superimposed)

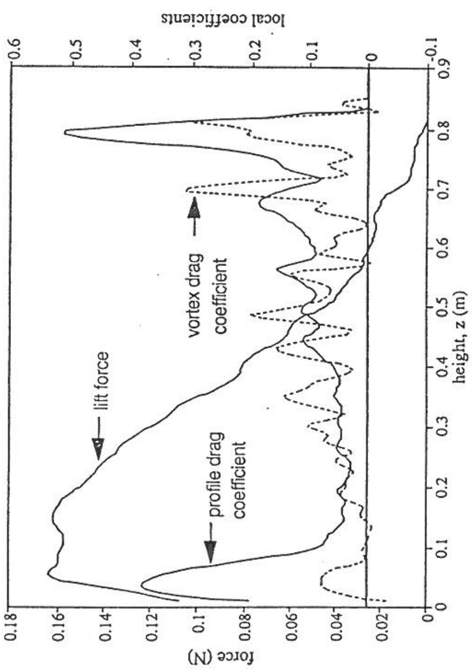

Figure 4. Distribution of lift force and drag coefficients.