13th Australasian Fluid Mechanics Conference
Monash University, Melbourne, Australia
13-18 December 1998

THE IMPORTANCE OF FROUDE AND REYNOLDS NUMBERS IN MODELLING DOWNWIND SAILS

Peter JACKSON and Peter HAWKINS

Department of Mechanical Engineering
University of Auckland, Auckland, NEW ZEALAND

ABSTRACT

This paper investigates the scaling problems associated with testing models of downwind sails in a wind tunnel. Besides the usual problems of scaling Reynolds number correctly, a Froude parameter is identified which measures the ratio of sail weight per unit area to the dynamic pressure. Specific experiments were devised to analyse separately the effects of each non-dimensional number. In order to isolate Reynolds number effects the sail shape was held constant by constructing rigid sails from sheet metal. To alter the Froude number at fixed Reynolds number, point load weights were added to fabric spinnakers and gennakers.

The results indicated significant Reynolds number effects at model scale up to a value of about 7×10^5. However large changes in Froude number made no appreciable changes in the drag coefficient for downwind sails, even though changes in sail shape were observable. Measurements on spinnakers and gennakers trimmed for maximumthrust at a fixed angle of attack reinforced these conclusions.

INTRODUCTION

Wind tunnels have been used for some time to study the fundamental aerodynamics of different sail configurations; a good introduction and summary of measurements is given by Marchaj (1979). More recently sail designers have adopted wind tunnels as a means of refining their designs, sometimes with considerable success; Fallow (1996) for example, reported that Team New Zealand obtained a 15% increase in driving force during their sail testing program. Different facilities around the world have adopted different approaches to sail testing, and as yet there is little common agreement on how best to obtain useful and reliable results. This paper clarifies the effects of two of the most important nondimensional parameters involved in testing downwind sails; the Reynolds and Froude numbers. Two kinds of sail are of interest - symmetric spinnakers for sailing close to dead downwind, and asymmetric gennakers used for higher points of sail. Both are used in conjunction with a mainsail (as in Figure 3).

For downwind sails the variables of principal interest are the lift and drag coefficient and, in particular, the thrust coefficient - their net component in the direction of motion of the yacht. The independent parameters include those concerned with the incident wind - its velocity profile, turbulence characteristics and ratio of boat speed to windspeed - all of which have been discussed in this context by Flay and Jackson (1992). Richards (1997) has used CFD to examine the effect of wind shear and twist on spinnakers, but the effect of Reynolds number on downwind sails does not appear to have been discussed at all. Nor have those nondimensional numbers relating to the properties of the sail fabric been discussed - four separate such numbers may be formed from the air speed and density, the sail chord and the thickness, mass per unit area, stiffness and fold height of the sailcloth.

Of the latter, since in practice sail stretch is small, the only number of any consequence is the sail Froude number - the ratio of dynamic pressure to the sail weight per surface area. As this number decreases the self-weight of the sail begins to cause its shape to 'sag', which happens quite visibly on a full-size yacht in light winds. In testing at the University of Auckland, the practice has been to use the actual fabric to make the model sails and then to test close to the actual relative wind speed, when this Froude number is automatically preserved. However the Reynolds number is then too low. If the tunnel speed is increased to improve the matching of Reynolds number, the correct Froude number could be recovered by also increasing the weight of the sail fabric. Whether either or both of these steps is necessary depends upon the effect of these two numbers on the thrust coefficient, and the following experiments were designed to determine these.

WIND TUNNEL TESTS

As noted above, for a downwind sail the nondimensional function of most interest is the thrust coefficient;

$$\frac{T}{qA} = C_T\left(shape, trim, Re\ , Fr\right)$$

where $Re = \frac{Uh}{\nu}$, $Fr = \frac{q}{mg}$, U is the apparent (or wind tunnel) speed at the mast height h, q is the corresponding dynamic pressure, m the mass per unit area of the sail and A the reference area (taken as nominal projected area). Here "shape' means the shape built into the sail as constructed, whereas "trim" means the shape adjustments which can subsequently be made when the sail is hoisted. Typical fullscale values are in the range 10^6 to 10^7 for the Reynolds number, and 0.03 to 0.3 for the Froude number.

Clearly it is not possible to vary the Reynolds and Froude numbers independently on a fabric sail by varying the speed, so in order to isolate the effects of Reynolds number tests were carried out on rigid sail shapes. These were fabricated from sheet metal, first using a CAD program to generate the developed surfaces needed to approximate a spinnaker shape supplied by North Sails NZ. Two identical shapes were made, 1.0 m and 2.0 m high. These were mounted on a frame which as far as possible was made from sharp-edged sections to avoid *Re*-dependent tare drag, and tested over a range of speeds and angles of attack. Fabric sails were then made from the same pattern and tested in the same way, along with fabric models of a gennaker with the same projected area. More complete details of these tests are given by Hawkins (1998).

Finally, in order to isolate the effects of the Froude number, small weights were distributed over the surface of the fabric sails to change the effective mass of the sail fabric. Since the speed range varied by a factor of 3, the dynamic pressure varied by a factor of 9 and so the weight added needed to be up to 8 times the sail weight to remain at fixed *Fr*.

The apparent wind seen by a yacht varies with height in both speed and direction. Here the velocity profile chosen was a power law with an exponent of 0.22, which was shown by Hawkins (1998) to give a reasonable approximation to what is found in practice. The wind tunnel was built specifically for sail testing and so does have the ability to generate a twisted onset flow, but here a uniform direction was used. The tunnel test section is 6m x 3m, and has a 6-component balance to which the test rig was fitted. A full description of the tunnel is given by Flay (1996).

THE EFFECTS OF REYNOLDS NUMBER

Lift and drag coefficients of the "tin" spinnakers for angles of attack in the range 90° to 220° were measured at five speeds with no mainsail, corresponding to Reynolds numbers from 3×10^5 to 10×10^5. Since transition might be expected within this range the sails were also tested with a roughened strip near the leading edge. Inspection with tufts indicated that the flow was almost wholly attached up to an angle of attack of 120°, and almost wholly separated at angles above 160°.

As expected the maximum drag occurred at 180° when the full sail area is exposed, and the minimum drag at 90°. The lift peaked at 120° and diminished almost linearly to zero at 180°. The thrust coefficient also peaked at 120°, and then decreased slowly to a weak minimum at 180°. There was strong evidence of Reynolds numbers effects, most noticeably, and not surprisingly, in the range 100-140° when the lift is near to its maximum and the flow is neither fully attached nor fully separated.

The results for the sails with roughness strips were similar, but unexpectedly showed slightly more pronounced Reynolds Number effects although the results were more consistent with a clearer trend. These effects are illustrated in Figures 1 and 2, with more details available in Hawkins (1998).

For the fabric sails Reynolds numbers effects were less apparent except at low speeds or angles near to 130°, below which angle the sails collapsed. Overall, good agreement was obtained between the thrust coefficients for the rigid and membrane sails. It is concluded that Reynolds numbers effects may be significant below a value of 10^6 based on sail height.

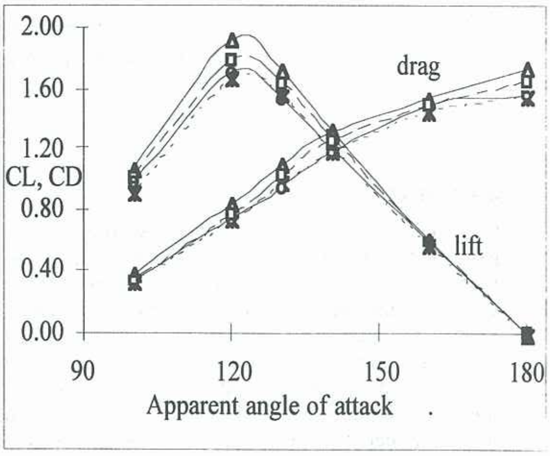

Figure 1 : Lift and drag coefficients versus angle of attack for a rigid spinnaker with roughness strips (Re x 10^{-5}: —△, 3;—□ , 4.5;—○, 7.5;- - ✳ , 10.5)

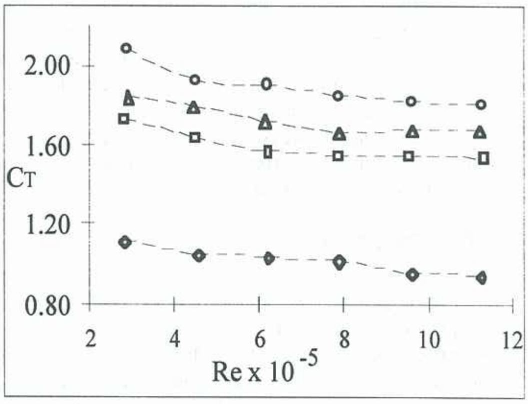

Figure 2 : Thrust coefficient versus Reynolds number for a rigid spinnaker with roughness strip at various angles of attack.
(—◇ , 100°, — ○ , 120°, —△ , 140°; — □ , 180°)

THE EFFECTS OF FROUDE NUMBER

The weighted fabric sails were initially tested with no mainsail and with all three corners of the sail fixed, so that the only variables would be the apparent angle of attack and weight/pressure ratio (*Fr*). The sail was weighted with an extra 1, 2, 4 and 8 times the original sail fabric weight and tested over a range of angles from 130° to 180°. It was found that once the wind speed was sufficiently high to inflate the sail, there were no significant differences in the force coefficients observed, even though the sails of different weights took on shapes of visibly different profile.

Changes were therefore made to make the tests more realistic. First, the sails were rigged as they would be in practice; the clew of the spinnaker was correctly sheeted (ie, attached to a long rope) allowing this corner of the sail two degrees of freedom, and a mainsail was also added. The mainsail and gennaker are shown being tested in Figure 3. Second, as described below, the test procedure was altered to allow the maximum thrust to be determined at each apparent angle of the wind to the yacht centreline (rather than the angle relative to the sail).

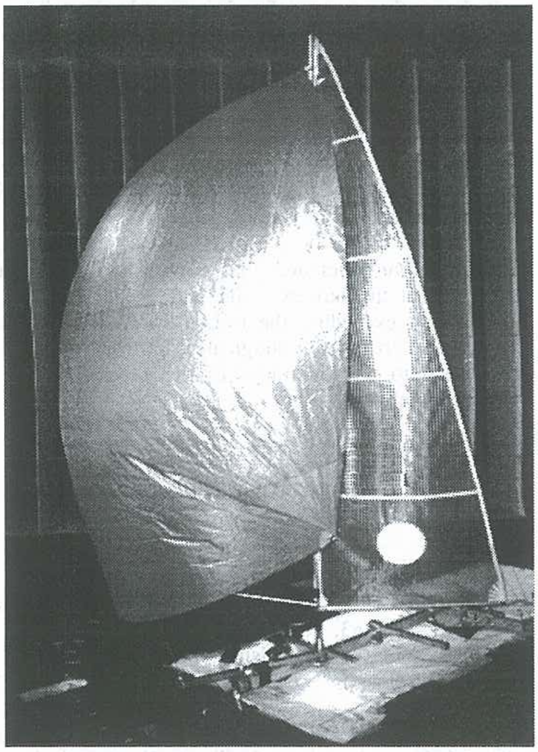

Figure 3 : Wind tunnel set up for a gennaker test.

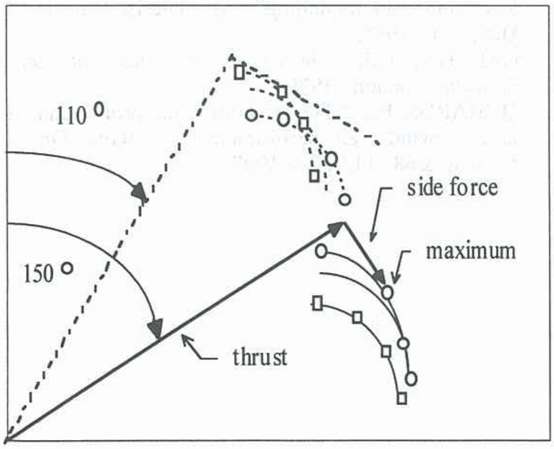

Figure 4 : Method for finding the maximum thrust at each sailing angle. Each curve is for a series of measurements at different sail trim, with speed and overall angle of incidence held fixed.

For each sail weight, sailing angle and speed, four or five measurements were made with the sails in different trim positions. With the spinnaker pole fixed, the mainsail angle was adjusted until the maximum thrust was obtained, and this data point was recorded. The pole angle was then moved to a new position and the procedure repeated, until sufficient points were obtained to allow the point of maximum thrust to be obtained from the sail polar using the construction shown in Figure 4.

Figure 5 shows the results for the heaviest spinnaker (weighted eight times), the different curves showing results at different speeds. For clarity, only two wind directions are shown. It is clear here that the data *are* dependent on wind speed but since both *Fr* and *Re* are changing it is not possible to determine the relative importance of each from this figure.

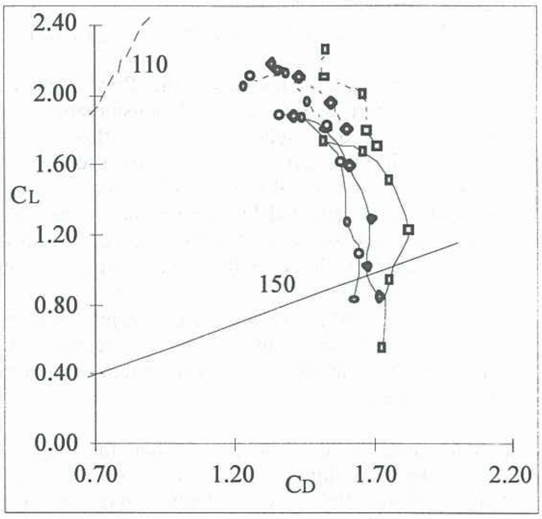

Figure 5: Lift/drag polar for a spinnaker with eight times weight-added. (——, 150°; - - - - , 110°: (Re x 10^{-5}: —□ , 4.5; —◇ , 6.0; —○ , 7.5)

The construction of Figure 4 was therefore used to find the peak thrust at each sailing angle, and these were then plotted at fixed speed (*Re*) for sails of different weight (*Fr*). Two typical data sets for the gennaker and mainsail are shown below.

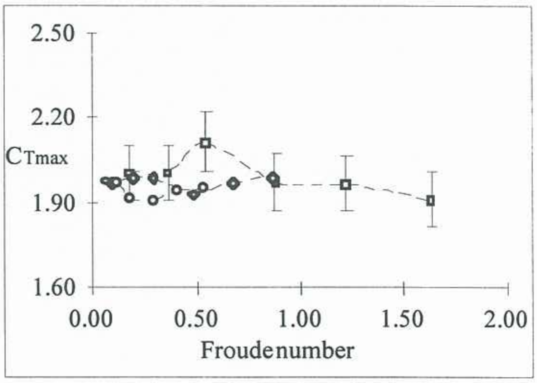

Figure 6a : Maximum C_T versus *Fr* and *Re* for a sailing angle of 70° apparent.

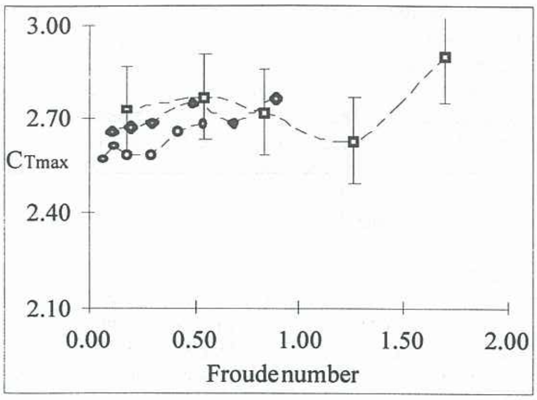

Figure 6b : Maximum C_T versus *Fr* and *Re* for a sailing angle of 130° apparent.
(Re x 10^{-5}: —□ , 4.5; —◇ , 6.0; —○ , 7.5)

At the lower angle of incidence the flow is attached over a large part of the sail, and considerable lift is generated. At the higher angle the flow is more separated with less lift, and so the pressure difference across the sail is generally less. One would therefore expect to see the effect of Froude number being less at the smaller angle and indeed while Figure 6b shows a slight increase in thrust with Froude number, Figure 6a shows no discernible trend. However the effect of the Reynolds number is somewhat stronger, as in both cases the maximum thrust tends to decrease with increasing Re (unlike an airfoil, where the thrust would increase).

In both cases it must be noted that the trends lie within the experimental error (5% error bars are shown). While this error is higher than one would like, it is high because the data shown is the result of a considerable number of measurements and a process of curve-fitting, and because the tests are made at quite low speeds (a few m/s) which reduces the accuracy of all the force and pressure measurements.

CONCLUSIONS

The measured lift and drag coefficients for the rigid spinnakers exhibited a characteristic typical of a lifting body, in that significant Reynolds number effects were observed near to maximum lift. Comparisons of measurements between rigid and fabric sails suggested that fabric sails show similar behaviour.

The weighted sails did not show any significant signs of Froude number effects when all three corners were fixed, probably because such over-constrained sails do not have the proper freedom to change shape in response to changes in pressure distribution. With the sails rigged more realistically and tested to allow the maximum thrust for each sailing angle to be extracted, the effects of Froude number effects on the thrust were still small and their magnitude appeared to depend upon the angle of incidence. However these tests on peak thrust again suggested that Reynolds number effects are the more significant.

It is therefore concluded that downwind sails should be tested at the largest scale and speed possible (of course, not exceeding the fullscale *Re*), and that sails should be artificially roughened. However there is less need to pay attention to the proper scaling of Froude number.

ACKNOWLEDGMENT

The authors wish to acknowledge North Sails NZ for their advice and assistance with sail construction.

REFERENCES

FALLOW, J.B, “Americas Cup sail design”, *J. Wind Eng Ind Aero.*, **63**, 183-192, 1996.

FLAY, R.G.F., “A twisted flow wind tunnel for testing yacht sails”, *J. Wind Eng Ind Aero.*, **63**, 171-182, 1996.

FLAY, R.G.F. and JACKSON, P. S. “Flow simulation for wind-tunnel studies of sail aerodynamics”, *J. Wind Eng. Ind. Aero.*, **41-44**, 2703-2714, 1992

HAWKINS, P. “Nondimensionsal number effects on downwind sail modelling”, ME Thesis, University of Auckland, 1998.

MARCHAJ, C.R. *Aero-Hydrodynamics of Sailing,* Granada, London, 1979.

RICHARDS, P.J. “The effect of wind profile and twist on downwind sail performance” , *J. Wind Eng. Ind. Aero.*, **67&68**, 113-321, 1997.