1991
THE TENTH CHESAPEAKE SAILING YACHT SYMPOSIUM

MODEL TEST TECHNIQUES DEVELOPED TO INVESTIGATE THE WIND HEELING CHARACTERISTICS OF SAILING VESSELS AND THEIR RESPONSE TO GUSTS

Barry Deakin, Wolfson Unit, University of Southampton, England

ABSTRACT

During the development of new stability regulations for the U.K. Department of Transport, doubt was cast over many of the assumptions made when assessing the stability of sailing vessels. In order to investigate the traditional methods a programme of work was undertaken including wind tunnel tests and full scale data acquisition. The work resulted in a much improved understanding of the behaviour of sailing vessels and indeed indicated that the conventional methods of stability assessment are invalid, the rules now applied in the U.K. being very different to those in use elsewhere.

The paper concentrates on the model test techniques which were developed specifically for this project but which will have implications to other vessel types. The tests were of two kinds: measurement of the wind forces and moments on a sailing vessel; and investigation of the response of sailing vessels to gusts of wind.

For the force and moment measurements models were mounted in a tank of water on a six component balance and tested in a large boundary layer wind tunnel. Previous tests in wind tunnels have always concentrated on performance and the heeling moments have not normally been measured correctly. As the measurements of heeling moment at a range of heel angles was of prime importance a new balance and mounting system was developed which enabled the above water part of the vessel to be modelled correctly, the underwater part to be unaffected by the wind, and the interface to be correctly represented without interference. Various effects were investigated including rig type, sheeting, heading, heel angle and wind gradient.

The gust response tests were conducted with Froude scaled models floating in a pond set in the wind tunnel floor. A mechanism was installed in the tunnel which enabled gusts of various characteristics to be generated, and the roll response of the models was measured with a gyroscope. These tests provided information on the effects of inertia, damping, rolling and the characteristics of the gust.

Sample results are presented to illustrate the uses to which these techniques have been put.

INTRODUCTION

The Wolfson Unit at Southampton University has been involved in wind tunnel tests on sailing and motor vessels since the late 1960's, with a background of yacht research at the University preceding that by some years.

Recent contracts for wind tunnel tests to investigate the performance of a wide range of sailing vessel types, together with a growing interest in the wind forces on other marine vehicles, led to requirements which were difficult to fulfill with the existing facilities.

A large contract was awarded to the Wolfson Unit in 1988 by the UK Department of Transport, with the object of deriving stability standards for sail training vessels. The programme of work involved detailed wind tunnel studies which could not adequately be modelled with the facilities available. A new wind tunnel dynamometer was produced for this work, which is now used for all rig performance evaluation work, and a facility was developed in which the effects of gusts on sailing vessels could be studied.

These new facilities enabled realistic modelling of the wind forces in static and dynamic situations and led to a greater understanding of the mechanism of wind heeling. The recommendations resulting from this work have now been adopted by the Department of Transport in their Code of Practice for Sail Training Ships (1).

The facilities are equally suitable for studies on other vessel types and it is hoped that their use will benefit naval architects and authorities with interests other than sail power.

CONVENTIONAL TEST METHODS

When conducting tests to investigate the performance of aerodynamic systems, it is desirable to achieve Reynolds numbers as close as possible to the full scale values in order that the flow characteristics are closely modelled. In order to maintain the same Reynolds number when testing a small scale model, it is necessary to increase the wind speed by the inverse of the scale factor. This is often impractical and it is common practice to test models at the highest readily achievable wind speed to minimise the Reynolds number effects.

Most early sail tests were conducted on small sail models often comprising cambered metal plates, mounted on the existing dynamometers in high speed aeronautical wind tunnels. The limitations of these methods were very restricting and in the early 1960's a dynamometer was installed, specifically for model testing with large soft sails, in the 4.5m (15ft) x 3.5m (12ft) low speed working section of the Southampton University wind tunnel.

The yacht dynamometer was developed and used extensively for research by Mr C A Marchaj, and is well documented in his book (2). It comprised a turntable mounted flush with the tunnel floor, on a four component balance. The rig, or rig and hull combination, was secured to the turntable at the desired heel angle, normally by cutting through the model hull at the appropriate heeled waterline. Measurements were made of lift, drag and yaw moment, all referenced to the tunnel axes, and heeling moment about the model's centreline. The tare forces on the turntable were measured in the absence of the model and deducted from the test measurements.

Similar results could be achieved in other large tunnels, equipped with a three or six component dynamometer and turntable in the floor, onto which a yacht model could be fixed. This became the standard method and most of the published data derived from wind tunnel tests have been measured using the Southampton University dynamometer or a similar system elsewhere. It has also been used for tests on other types of vessel to determine wind resistance, heeling moments, and wind forces to be overcome when manoeuvring at low speed in confined quarters.

There are disadvantages of using this method, the significance of which vary according to the type of test being conducted. In recent years the prime causes of concern at the Wolfson Unit have been as follows:

a) The atmospheric boundary layer, with its significant velocity gradient, results in an increase in wind speed with increasing height above the sea surface. This is not modelled in an aeronautical wind tunnel and the distribution of load over the rig is therefore incorrect.

b) Mounting the model directly onto a turntable does not facilitate testing at different heel angles.

c) The presence of the model in the airstream causes a static pressure difference between the windward and leeward sides of the model. This contributes to the heeling moment acting on the model, which is to be measured, but also results in a heeling moment acting on the turntable. Since the model is connected indirectly to the dynamometer via the turntable, it is the sum of these moments that the dynamometer measures. The moment on the turntable, acting to windward, opposes the heeling moment on the model and thus
Measured Moment = Heeling Moment on Model − Moment on Turntable.

The turntable moment cannot be regarded as a tare to be corrected for later, since it cannot be measured (indeed does not exist) in the absence of the model.

This error may be insignificant when testing a high aspect ratio rig which is large in comparison to the turntable, but can result in a negative heeling moment when testing a low aspect rig or a motor vessel in a beam wind. If the test results are being used to assist in the selection of stability characteristics, the stability requirements will be underestimated.

ALTERNATIVE METHODS

The disadvantages raised in (a) above are most easily overcome by representing the atmospheric boundary layer in a purpose built boundary layer wind tunnel. A long working section enables the growth of a thick boundary layer with a velocity gradient and a high level of turbulence. Such tunnels are used primarily for investigations of the wind loads on buildings, bridges and other large structures.

Velocity gradients have sometimes been introduced in aeronautical tunnels by installing a temporary grid of battens upstream of the model. Although the turbulence levels would not be adequate for precise tests on building structures, the wind gradients thus achieved may give a reasonable simulation of the velocity gradient and improve the load distribution on the sails.

In order to overcome the errors introduced by measuring forces on the turntable and model as a unit, the model may be mounted through a hole in the turntable, and attached directly to the dynamometer. This also enables a complete hull model to be used, and testing at different heel angles may be possible. This method introduces further problems however. Wind tunnel turntables are frequently set in the floor of the tunnel with the air beneath at atmospheric pressure, and the air above at a different static pressure, either higher or lower depending upon the type of tunnel and its arrangement. There will therefore be a vertical force on the model when it is mounted through the tunnel floor, and a leakage of air around the waterline. This is further complicated by the flow of air induced, through the gap between the model and the turntable, by the wind. This gap cannot be fully closed without causing interference between the model and turntable which would affect the force measurements.

THE WOLFSON UNIT'S WIND TUNNEL BALANCE

Requirements

In order to be suited to the range of test programmes envisaged over the foreseeable future the new design was required to satisfy the following conditions:

a) Capable of measuring three orthogonal force components aligned with model axes.
b) Capable of measuring three moments about model axes.
c) Should incorporate a turntable enabling a 360 degree range of headings.
d) Should incorporate a model mounting system enabling a 90 degree range of heel angles.
e) Should enable the model to be sealed to the turntable, representing the sea surface, with no air gap.
f) The model should be mounted independently from the turntable with no interference between them.
g) Models of approximately 2m (6ft) overall length should be accommodated.
h) The whole system should be portable for installation in a variety of wind tunnels.

The Adopted Solution

A system was constructed as illustrated in Figure 1, which satisfied all of these requirements. It comprises a turntable, of composite construction to ensure rigidity, recessed into the false floor of the wind tunnel. The turntable incorporates a rectangular trough of water large enough to accommodate a model hull up to 1.6m (5.25ft) long on the waterline, and rotates on wheels rolling on a circular track secured to the wind tunnel floor. The preferred wind tunnel has a false floor 0.3m (1ft) above the solid floor, and when the system is used in an alternative tunnel a temporary false floor is installed at the same height.

The model apparently floats in the water trough but is in fact free to flood, to minimise hydrostatic forces, and is supported at the correct waterline by the dynamometer. The support frame consists of a rod fixed in the bow of the model parallel to the centreline to provide a roll pivot and bow support, and a rod passing transversely through the hull aft of midships to provide a roll restraint and stern support. The hull of the model is pre-drilled with appropriate holes such that the transverse rod, which always remains horizontal, passes through a pair of holes to fix the model at the desired heel angle. The three outboard ends of the rods are connected, through small holes in the turntable, to a system of seven force blocks mounted on the underside of the turntable.

The use of the tank of water enables the hull to be correctly modelled at all heel angles and provides a true representation of the air flow around the hull at sea level without any interference to the forces. The only parts of the system which might interfere with the air flow around the model are the support rods. These however are small in comparison with the model and are located close to the tunnel floor where, due to the boundary layer, the flow speed is low.

A: Aluminium angle rolled into a circular track
B: Turntable
C: Water trough
D: Flexures to which model is attached
E: Force blocks
F: Dynamometer frame
G: Dynamometer supports
H: Tunnel false floor

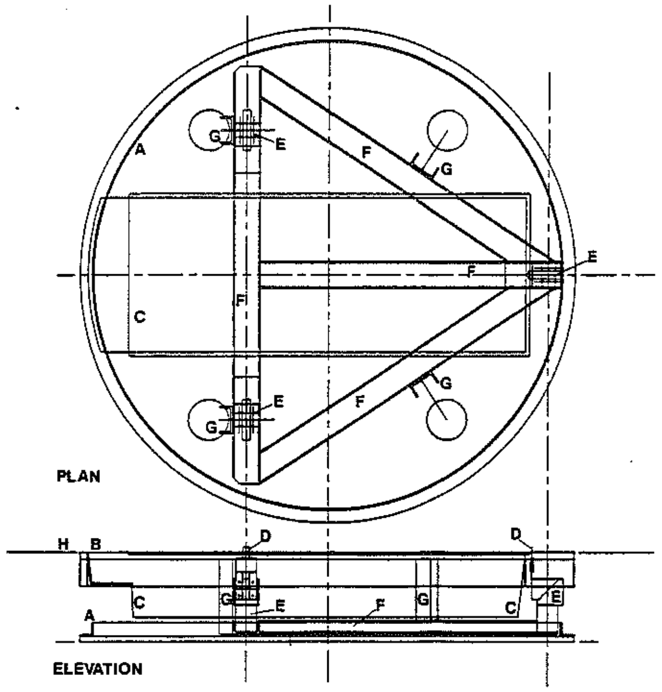

Fig. 1 Dynamometer arrangement

The force blocks are identical units designed by the Wolfson Unit for general force measurement and model testing applications. Each comprises a cage of flexures and a displacement transducer enabling an individual loading ± 400N (90 lbf). They are assembled with different orientations and are connected to the model via one rigid support and two flexures, the resulting seven forces being resolved to derive the required six components. See Figure 2. The transducers may be wired via an analogue to digital converter to a suitable computer which enables averaging of the signals and resolution of the forces.

By mounting the force blocks on the turntable the measured forces remain aligned to the required axis system, that is: driving force along the model centreline; heeling force horizontal and at 90 degrees to the centreline; and vertical force remaining vertical. Heeling moment, pitching moment and yawing moment are measured about these axes.

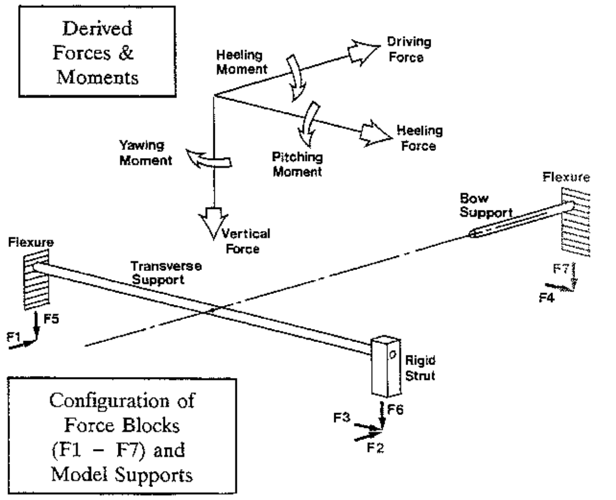

Fig. 2 Force block schematic arrangement

The Wind Tunnel Facility

The facility currently used by the Wolfson Unit for sail testing is the boundary layer wind tunnel operated by the Central Electricity Generating Board's Marchwood Engineering Laboratories.

The tunnel is unusually large with a rectangular working section 9.1m (30ft) wide, 2.7m (9ft) high and 23.5m (77ft) long. The 900 kw (1200 HP) centrifugal fan enables a maximum speed of 14m/s (50ft/s). The arrangement is an open circuit with smoothing screens and honeycombs at the inlet. The atmospheric boundary layer can be modelled at a range of scales by incorporating appropriately sized roughness elements on the floor, a castellated wall to accelerate the initial growth of, and effectively extend the fetch of the boundary layer, and vortex generators to stimulate turbulence and mixing within the boundary layer. These features can be seen in Figure 3. This method of atmospheric boundary layer simulation is described in detail elsewhere (3). Figure 4 presents a comparison of the tunnel wind gradient over the turntable with the log law gradient normally found over the sea. Wind speeds are normally quoted at a height of 10m (33ft) and this nominal speed has been used to non-dimensionalise the local speeds over the height of the test section. The same boundary layer has been used for tests at both 1:25 and 1:30 scale and hence the representations differ slightly when scaled to full size. The comparison with the assumed full scale gradient reveals discrepancies of less than 5% in local velocity and is considered to be satisfactory, since far greater variations are found at full scale.

A wind speed of about 7m/s (23ft/s) at a nominal height equivalent to 10m (33ft) is normally used, being best suited to the strength of the models, and results in forces well within the measurement range of the dynamometer. This is of the same order as typical full scale wind speeds and hence the model Reynolds number is lower than the full scale Reynolds number by a factor equal to the scale ratio.

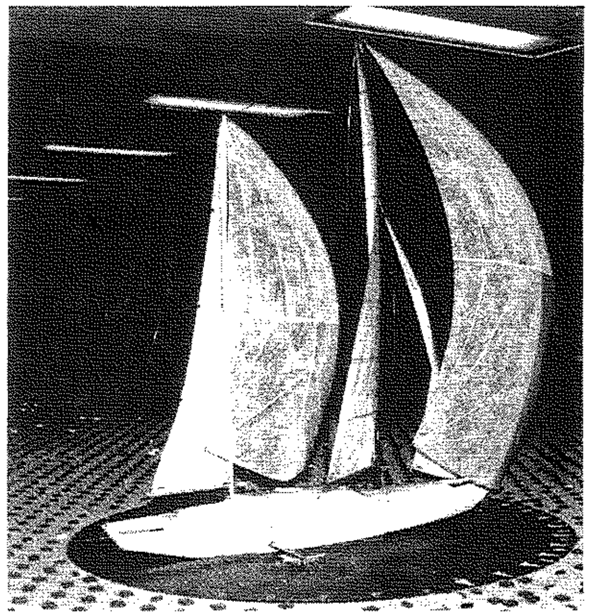

Fig. 3 42.5m Fast Cruising Ketch under tests. Courtesy Ed Dubois.

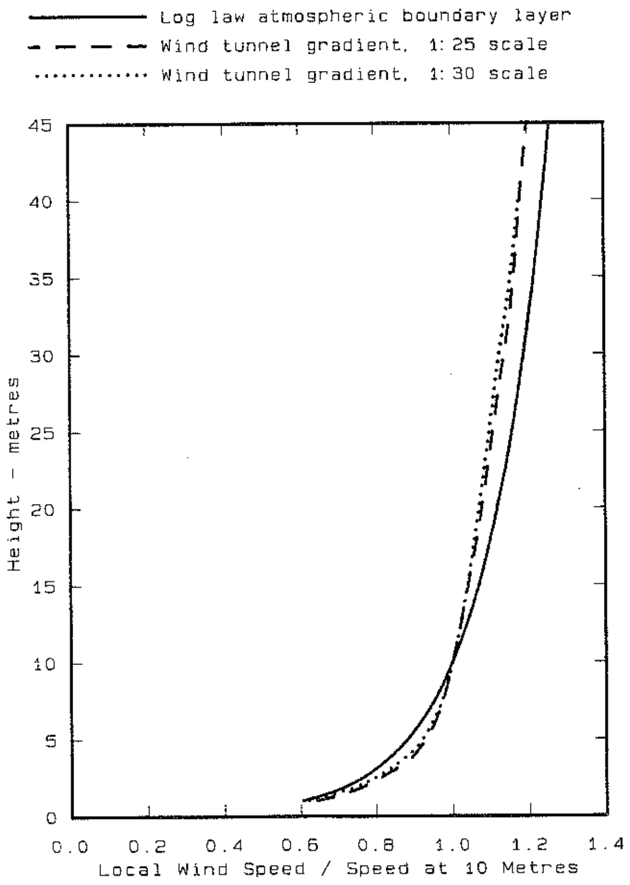

Fig. 4 Comparison of the boundary layer used in the wind tunnel with the assumed atmospheric boundary layer.

Test Techniques and Sample Results

When testing the performance of sailing vessels it is important to ensure that the sails are sheeted to optimise their performance for the apparent wind angle of the model, just as the sailor attempts to do with the full scale vessel. The technique employed to facilitate this is to: first set the model to the desired heel angle and apparent wind angle; sheet the sails to what appears to be the optimum setting, using tufts attached to the sails as a visual aid; then to measure the forces at a range of apparent wind angles. The model is yawed into the wind until the sails are luffed, and then yawed off the wind until they are stalled. In this way, if the sails were not sheeted to their optimum setting, the optimum apparent wind angle will be in the range covered. This procedure is repeated at a range of apparent wind angle settings by, for example, progressively easing the sheets, to provide data for all points of sailing.

Figure 5 presents data obtained in this way for the square rigged vessel shown in Figure 6. Only the driving force and heeling force are shown here, derived with four different sail settings. Such a diagram is drawn as the tests proceed in order to ensure that the curves form a family and hence that the sails have been sheeted consistently. The dotted line indicates the maximum driving force available at a given apparent wind angle, and the dashed line shows the corresponding heeling force.

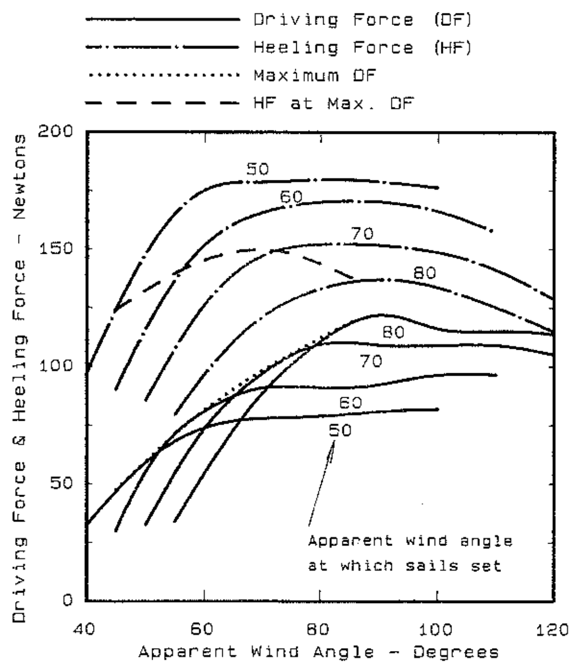

Fig. 5 Variation of driving force and heeling force with apparent wind angle. Data are presented for the sails sheeted at four different apparent wind angles, from 50° to 80°.

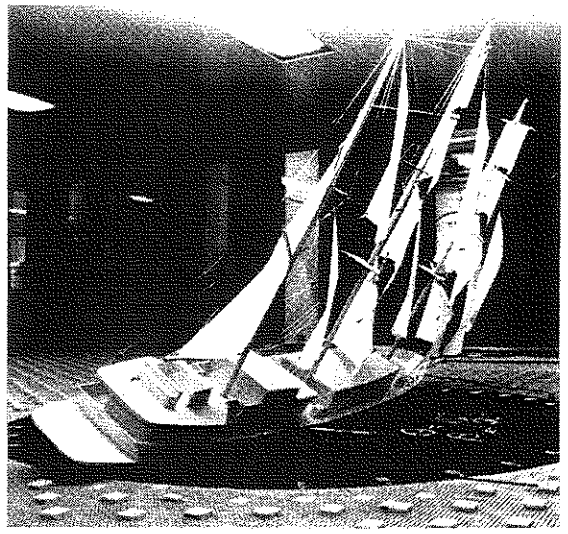

Fig. 6 Sail Training Ship 'Lord Nelson' being tested at a heel angle of 15°.

If the tests are being conducted to determine the maximum likely heeling moment, as was the case for the Department of Transport, it has been found that the model need only be tested with the sails sheeted for the lowest apparent wind angle likely to be sailed. This setting must however be tested at a range of apparent wind angles, since the heeling moment is maximised as the apparent wind angle is increased with the sails sheeted in tight. Whilst such a situation might seem unrepresentative of normal sailing conditions, it might occur if, when sailing close hauled, a vessel is struck by a gust on the beam, or is required to alter course suddenly, perhaps to avoid a collision.

One of the aims of the stability study was to determine the relationship between heel angle and wind heeling moment, which is conventionally assumed to vary according to $\cos^2$ (heel angle). Figure 7 shows test results for the square rigged model with a variety of sail plans set. The data indicate a reduction in heeling moment with increasing heel angle, and the curves which give the best fit to the data are of the form: Heeling moment = Upright heeling moment x $\cos^{1.3}$ (heel angle). The apparent scatter in these data is predominantly the result of changes in the pattern of flow around the sails and through the various slots, rather than measurement inaccuracies. With a simpler fore and aft rig the scatter is much reduced. In the case with bare poles only, the data indicate an increase in heeling moment between upright and the first heeled position at 18 degrees. This is because, when upright, the yards are aligned to the flow and as the vessel heels their projected area increases. As sails are added to the rig this effect becomes comparatively small and with full sail is not noticeable.

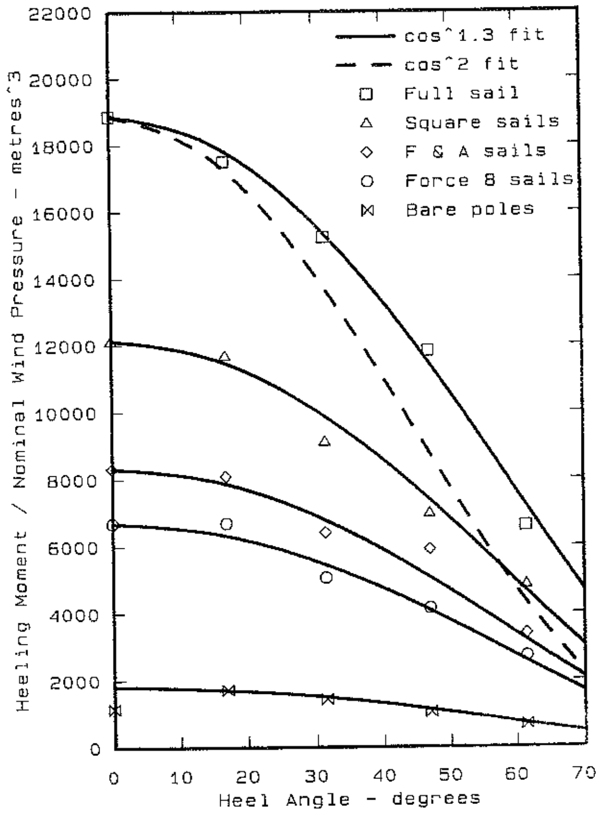

Fig. 7 Variation of heeling moment with heel angle. Wind tunnel test results for the barque 'Lord Nelson'. Sails set at 50 degrees apparent wind angle and tested with an apparent wind angle of 90 degrees.

Limitations

The only significant limitation of the wind tunnel tests is that, because the model is stationary, unlike the full scale vessel, there is no boat speed vector to add to the true wind vector in producing the apparent wind. At full scale the boat speed, being constant, when added at an angle to the true wind, which increases with height, creates a twist in the apparent wind. This is not simulated in any wind tunnel and hence the twist required in the sails is less than would be used at full scale, in order that they are correctly loaded. This requires an awareness, when sheeting the model sails, that the normal amount of twist may be reduced.

GUST RESPONSE TESTS

Requirements

An important aspect of a sailing vessel's stability is its ability to withstand gusts of wind. This ability is conventionally assessed by means of an energy balance method, and an important part of the work for the Department of Transport, was to investigate the validity of this method for sailing vessels. The tests were required to investigate the responses of different vessels to gusts of various types, and to assess the effects of stability, inertia and damping on their behaviour.

No record could be found of any tests of this nature having been conducted in the past, and so the apparatus and techniques had to be developed as the tests progressed. Before any of the main objectives could be addressed therefore, a system had to be developed to produce a sudden and repeatable gust with which to compare the response of a model in different configurations, whilst the model needed to be floating unrestrained in roll and sway, with its roll angle monitored continuously. These requirements necessitate Froude scaling, which results in low wind speeds at model scale, since speed is reduced by the square root of the scale.

Gust Test Facility

These tests were conducted in the same wind tunnel section as is used for the force and moment measurements described above. The gust facility was constructed temporarily and dismantled at the completion of the tests.

A section of the false floor at one side of the working section was removed, and in its place a tank of water was installed. Constructed of timber with a vinyl lining, the tank measured 2.4m (8ft) x 2.4m x 0.3m (1ft) deep, with the water surface level with the tunnel floor. Around the tank sides, concealed beneath the false floor, domestic guttering was fitted to catch spillage from the tank during tests. A wooden partition was fitted alongside the tank and this, together with the existing side wall of the tunnel, formed a duct spanning one third of the tunnel's cross section. At the downstream end of the duct an array of shutters were installed to control the flow of air through it. The shutters comprised flat rectangular flaps pivoting on rods and coupled together to a single control outside the tunnel. By closing the shutters, flow through the test section was blocked and hence diverted through the unused portion of the wind tunnel. When the shutters were opened the flow could again pass through the test section and the increase in velocity thus produced, created a gust. The arrangement is illustrated in Figure 8.

Fig. 8 Gust test facility with the model being prepared for testing.

The shutter aperture was calibrated at a number of wind tunnel speeds to enable wind and gust velocities to be pre – selected, and by varying the shutter speed the rise time of the gust could be changed.

The wind tunnel boundary layer vortex generators, which produce the normal levels of boundary layer turbulence, were removed so that the flow was smooth and the gusts would be more clearly defined and controlled. The velocity gradient was maintained although, with the vortex generators removed, the local speed differed by up to 10% from that over the turntable used for the force and moment measurements. The wind speed was monitored by a roof mounted pitot static tube connected, via a micromanometer with a high frequency response, to the data acquisition computer.

The confined space available in the tank required that the model be restrained from sailing forwards. It would have been beyond the budget of this research to have constructed a facility to enable a free sailing model to be subjected to controlled gusts, and whilst it is well known that the hydrodynamic damping is highly dependent upon the speed of the vessel, it is minimised when the vessel is stationary and this therefore represents the worst case. There have in fact been instances of sailing vessels being heeled to large angles when stationary in the water, one such being the loss of the 'Isaac Evans' in 1984 (4). It was considered necessary however, to allow the model to drift sideways in response to the gust, and of course it must be unrestrained in roll. To confine the model to these two degrees of freedom, it was coupled to wires stretched along the tank, parallel to the wind direction and located just forward of the bow, and aft of the stern of the model. Light lines attached to the bow and stern just below the waterline were connected to small pulley blocks running on the restraint wires. The aft restraint prevented the model from sailing forwards and the bow restraint was found to be necessary to prevent the model from yawing in the steady wind prior to the gust strike.

The model contained a roll position gyro to measure the roll angle. This remained unaffected by the sideways motion and accelerations of the model, which would have rendered a pendulum type device inaccurate. The gyro was connected to its power supply, and to the data acquisition system outside the tunnel, via an umbilical taken out through the stern of the model above the waterline.

A video camera was mounted beside the tank to provide a record of the tests and assist with interpretation of the results.

Gust Test Models

Two models were used in this series of tests. One was a model of the barque 'Lord Nelson', built to the same scale as that used for the force and moment measurements, of 1:25, Figure 9. The other was a 1:9 scale model of a Nicholson 55 cutter, a yacht used extensively in the UK for sail training, Figure 10.

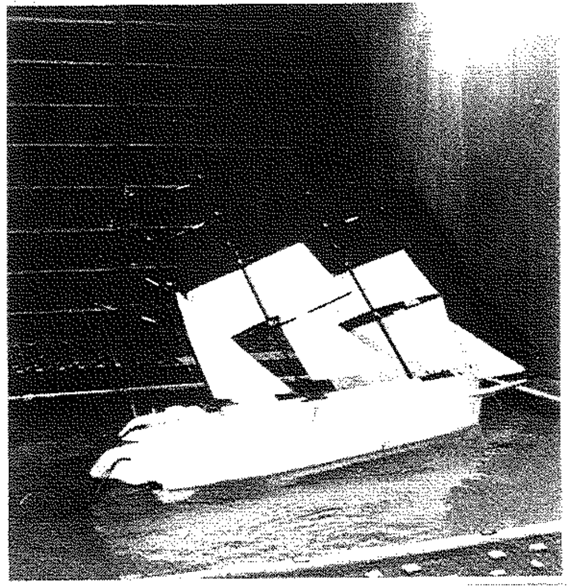

Fig. 9 Model of 'Lord Nelson' responding to a severe gust under reduced sail.

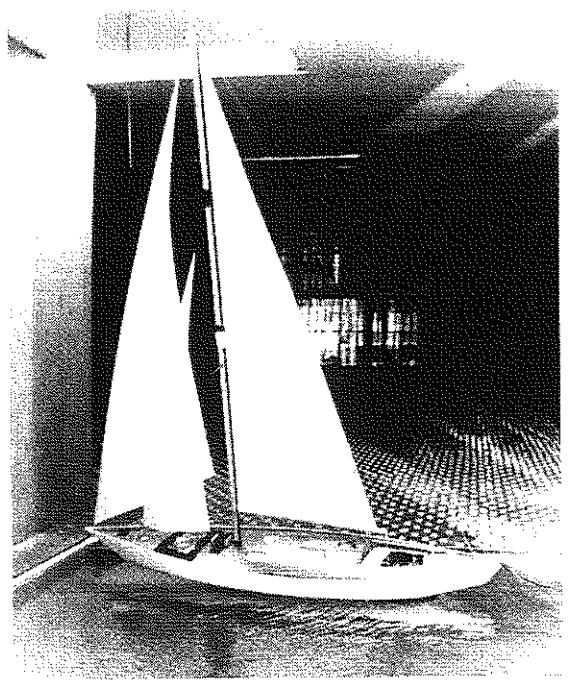

Fig. 10 Nicholson 55 Cutter model prepared for testing.

The size of the models was a compromise between the desire for a large model, with a substantial displacement for ease of ballasting and inertia variation, and a small model with which wind tunnel blockage effects would be minimised. It was considered that, because the response of the model to a relative increase in wind pressure was the main concern, the blockage effects would not have any significant bearing on the conclusions drawn. It was decided therefore to use the largest models which could be comfortably accommodated in the tunnel. The scales chosen gave model weights of 28 and 31 kg (62 and 68 lb) which enabled sufficiently rugged models to be constructed, with cast lead keels of scale weight, and about 9 kg (20 lb) of residual ballast for adjustment of stability and inertia. The weight of the gyro was 0.8 kg (1.8 lb).

The models were rigged with spars of the correct dimensions and with light fabric sails, but with simplified rigging to minimise the weight aloft. With wind speeds significantly lower than those normally used for wind tunnel testing, rig strength was not a problem.

The models were constructed of wood and GRP with watertight hatches in the decks for access to the movable ballast inside. Two vertical studs were fixed inside each model with a 2.5 kg (5.5 lb) weight on each. These could be finely adjusted for tuning of the stability and inertia, and other weights were secured in the bilge or at deck level to obtain coarse adjustments. For very high inertia conditions, weights could be attached to the masts.

Gust Test Techniques

For each configuration to be tested the model was ballasted to the correct displacement and LCG, with the movable weights adjusted to give the desired VCG and inertia. VCG was measured by an inclining experiment, and the inertia by rolling the model in water with the gyro active. The free rolling test also enabled a roll decrement curve to be obtained from the gyro as a measure of the damping. The models' inertias were also measured while rolling in air about a pivot. This result when compared with the inertia in water gave a measure of the added inertia of the water entrained around the hull and keel. These preliminary rolling tests were conducted in a towing tank, rather than the small gust tank where wave reflection made free rolling over sufficient number of cycles impossible.

For each test the model was first tethered to the upwind side of the tank, beam on to the wind with the shutters closed to the desired aperture. With the air flow steady the model was released to drift sideways across the tank. The shutters were then opened to create the desired increase in wind speed and the model response was monitored by the gyro and video recorder.

The characteristics of the gusts could be varied to give a slow or fast increase in wind speed followed by either a continued steady strong wind or a return to the original lower wind speed. Gusts could be generated which were representative of the strongest to be found in the turbulent atmospheric boundary layer, typically up to 40% greater than the hourly mean wind speed, or alternatively very severe gusts could be generated to simulate the arrival of the strong winds associated with a line squall in otherwise light wind conditions.

Typical gust test records are presented in Figures 11 and 12.

The facility enabled investigation of the effects of beam winds and gusts when rolling, by forcing the model to roll prior to the gust strike, and by releasing the model from a windward or leeward heel angle in a steady wind. A record of the latter type of test is presented in Figure 13. The model was restrained at a heel angle of 40 degrees to windward by a line attached to the masthead, and released manually.

Gust Test Results

No attempt was made to calculate the wind heeling moments during the tests since, with an accurate measure of the heel angle and the model's stability, the actual heeling moment was measured.

Conventional theory suggests that, when a gust strikes, the vessel will heel until the area beneath the wind heeling moment curve is equal to the area beneath the righting moment curve, and will settle back after the impact at the steady heel angle corresponding to the wind speed after the gust.

The most conspicuous feature of the observed gust responses was the lack of heel angle overshoot beyond the final steady heel angle. The cases where a small overshoot was measured, were with a much reduced sail plan set, when the model had significantly less aerodynamic damping.

Figure 14 presents the data derived from Figure 12 in the familiar format. The initial heel angle was measured by the gyro, and the heeling arm curve is thus defined as the $\cos^{1.3}\theta$ function which intersects the GZ curve at that point. The measured gust factor is applied to the heeling arm curve and the gust heeling arm curve can be drawn. The intersection of this curve with the GZ curve indicates the heel angle which would be predicted for a steady wind at the gust velocity. The measured gust response never exceeded the predicted steady heel angle due to the gust by more than 10%, and these tests therefore indicated current theories, with their numerous assumptions, to be inadequate.

The reasons for this, much lower, gust response are two fold. Gusts do not strike a vessel with a sudden impact, their rise time normally being greater than the period of a quarter of a roll cycle, that is the time taken to roll naturally from upright to the extreme angle (typically 1 to 2 seconds for sailing vessels). The vessel is therefore able to adjust its heel angle steadily as the wind speed increases. The aerodynamic damping takes over in cases where the rise time is particularly short,

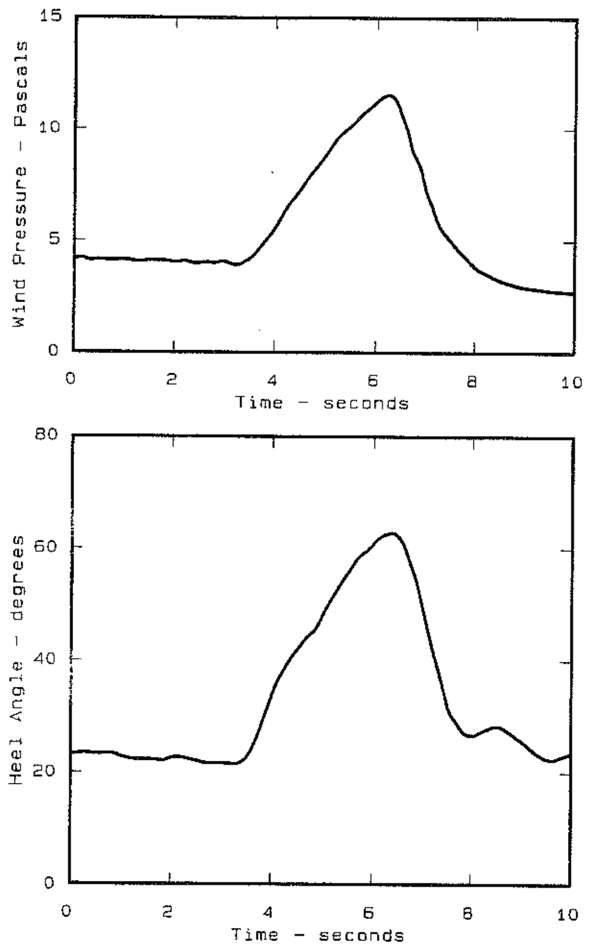

Fig. 11 Gust test records of wind pressure and heel angle.
Barque 'Lord Nelson'.
Standard condition. Brief gust.

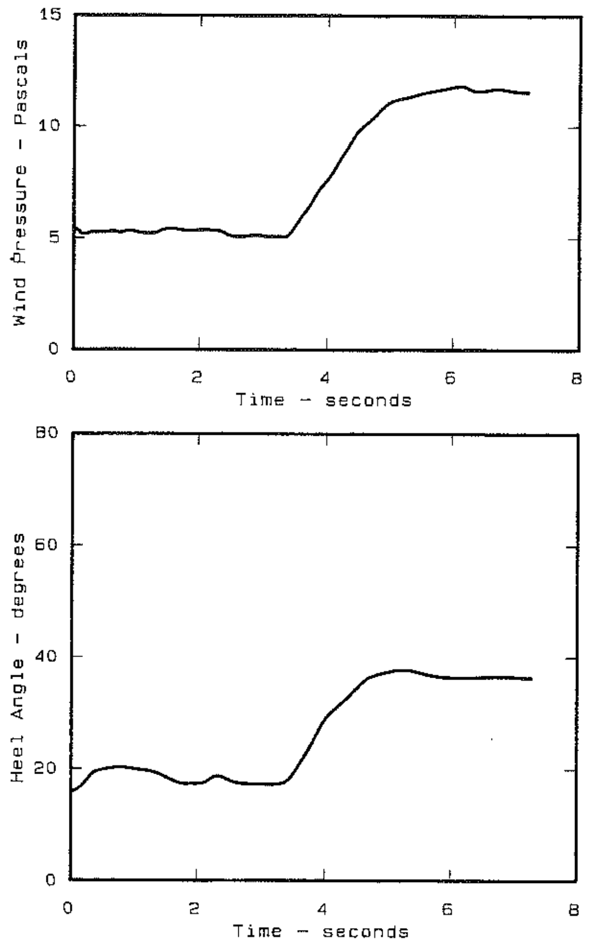

Fig. 12 Gust test records of wind pressure and heel angle.
Nicholson 55 cutter 'Kukri'.
Standard keel. High KG. Prolonged gust.

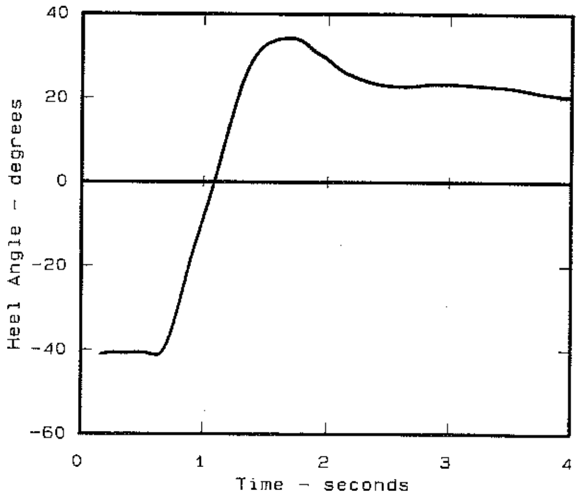

Fig. 13a Heel angle record with the Nich. 55 model released from 40° to windward in a steady wind.

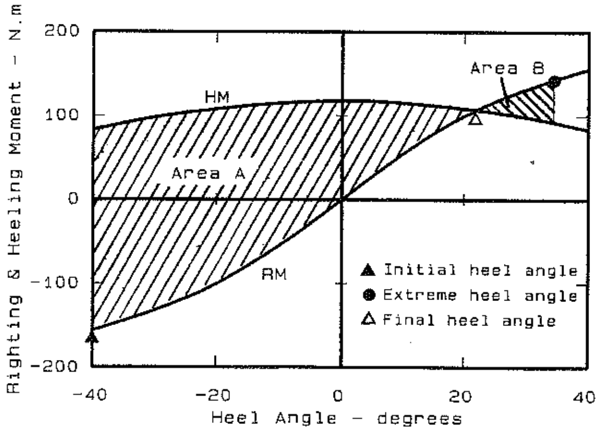

Fig. 13b The above result presented in the conventional form of the energy balance method.

and prevents a large heel angle overshoot, as demonstrated in Figure 13. In this instance conventional theory would predict a maximum heel angle at which area B is equal to area A, whereas the observed result shows this to be grossly inaccurate.

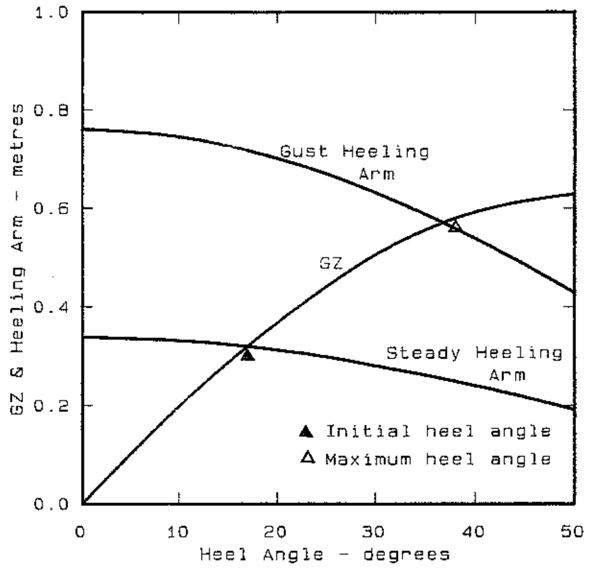

Fig. 14 Analysis of the gust test data presented in Figure 12.

FULL SCALE TRIALS CORRELATION

Two sailing vessels were fitted with data acquisition and recording systems to collect apparent wind speed, apparent wind direction and heel angle data during the 1988 season. The vessels used were those modelled in the gust tests and these full scale data showed good correlation with the model test results, reinforcing their findings.

Figure 15 presents a typical trace for the 'Lord Nelson'. The apparent wind angle is 270 degrees, that is on the port beam. The oscillations on the data have a period of about 7 seconds and are due to the ship rolling, at close to its natural frequency in the beam seas, the ship having little aerodynamic damping with only three sails set.

The wind speed trace reveals a gust with a duration of about 50 seconds and an increase in the apparent wind speed from 17 to 21 m/s, an increase of 50% in wind pressure. The mean heel angle increased from 8 to 12 degrees which, since the vessel is operating on the linear part of the GZ curve, indicates a 50% increase in righting moment. There is obviously no overshoot beyond the new steady heel angle, despite the relatively low damping.

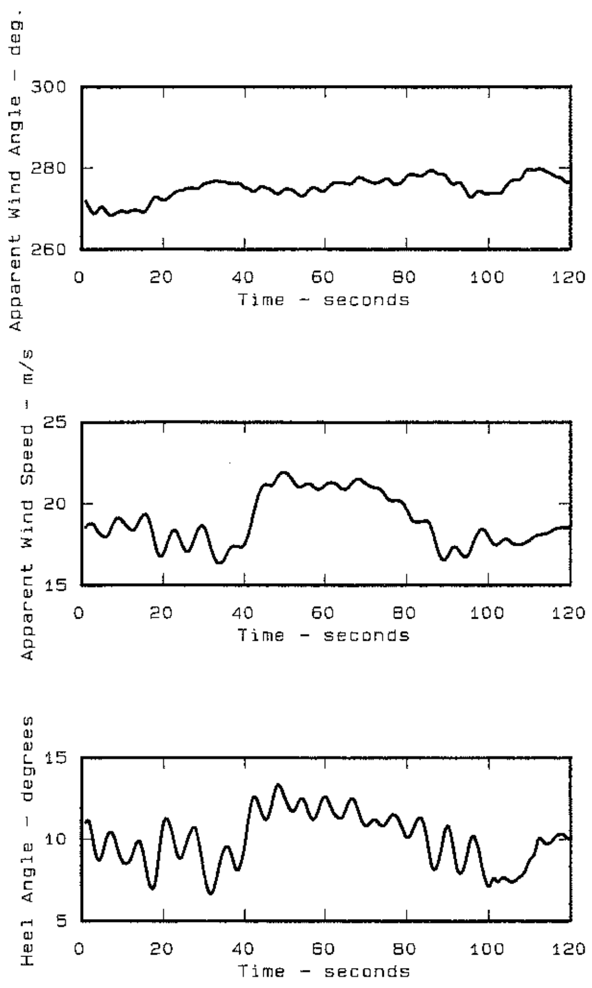

Fig. 15 Full scale data records of apparent wind angle, apparent wind speed and heel angle.
Barque 'Lord Nelson', with Inner jib, fore topsail, and main topsail set.

USE OF TEST RESULTS

Performance testing of sailing rigs enables the comparison of rig types, or of the effects of various design options and refinements to a particular rig. The performance data, particularly if combined with the results of towing tank tests on the hull, will enable accurate velocity predictions to be undertaken, enhancing the chances of racing success. Beside the driving force and side force information, the wind tunnel data will include heeling moments to assist selection of stability parameters, and centre of effort locations for use in achieving helm balance.

Setting and sheeting the sails for a range of headings also enables problems with sheet leads, or interference with parts of the rig or other sails, to be highlighted and rectified at an early stage, although it must be borne in mind that, in the absence of forward speed, sail twist is not modelled accurately.

Results of the gust tests conducted for the Department of Transport, and their use in deriving new stability standards, were discussed fully at the 1990 RINA Spring Meetings (5). The test results led to a much improved understanding of the gust response of sailing vessels, which in turn enabled a very simple set of stability standards to be introduced.

These incorporate a requirement for information to be carried on board sailing vessels, which enables the master to quantify his level of safety from capsizing at all times, with the aid of an anemometer and inclinometer. This method has put the safety of the vessel in the masters hands rather than those of the regulatory authority, who might otherwise require a reduction in the sail plan to meet some arbitrary wind heeling condition.

CONCLUSIONS

The dynamometer described in this paper has enabled more accurate measurements to be made on sailing rigs than has previously been possible. The system measures all six components correctly, and is sufficiently versatile for use with other vessel types. The tests conducted so far, in addition to providing valuable data on a number of new designs, have revealed new information on heeling moment characteristics, in particular their variation with heel angle.

The gust test facility also described, has enabled the investigation of some of the dynamic aspects of sailing vessel behaviour. Realistic gusts are produced in the wind tunnel, and test results on two vessels very different in size, hull shape and rig, have been verified by full scale trials.

Together these model test techniques have provided a greater understanding of the behaviour and safety of sailing vessels and have given rise to new techniques for their assessment.

ACKNOWLEDGEMENTS

This paper is based on work conducted by the Wolfson Unit M.T.I.A. The assistance of members of the unit in developing the experimental techniques and carrying out the tests is gratefully acknowledged by the author.

REFERENCES

1. Department of Transport.
   Code of Practice for the Construction, Machinery, Equipment, Stability and Survey of Sail Training Ships between 7 metres and 24 metres in Length.

   London HMSO. 1990.

2. Marchaj, C. A.
   Sailing Theory and Practice.
   Adlard Coles Ltd. 1964.

3. Cook, N. J.
   The Designers Guide to Wind Loading of Building Structures, Part 1.
   Building Research Establishment. Butterworths. 1985.

4. Accident Report on the Sinking of the Isaac H. Evans.
   U.S. Coast Guard. 1985

5. Deakin, B.
   The Development of Stability Standards for U.K. Sailing Vessels.
   R.I.N.A. Spring Meetings. 1990.