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### Refinement of Yacht Superstructures with the Aid of Wind Tunnel Tests

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## ABSTRACT

The use of wind tunnels to study exhaust plumes from ship funnels is a well-established technique. What is rarely appreciated is the value of wind tunnel tests in addressing other operational aspects, such as levels of wind comfort around the decks. Higher speeds, and greater expectations of the owners and guests, have increased the importance of good aerodynamics. The techniques available for investigating the airflow around ships range from a simple wool tuft on a wand to a highly complex and costly laser doppler anemometry system. Similarly there are a bewildering variety of wind tunnel facilities in which tests might be conducted. This presentation will describe the techniques available, with illustrations from recent case studies.


## 1 TEST FACILITIES

### 1.1 Aeronautical Tunnel

Most tunnels have been constructed for aeronautical use, and have a working section designed for mounting wings or whole aircraft models at the centre. They are commonly used for testing models of ships, other vehicles and structures mounted on the floor of the working section.

These tunnels are designed to achieve a uniform velocity across the working section, but because of friction of the air over the walls and floor of the tunnel, the wind speed close to them is less than that at the centre. The result is a boundary layer with a velocity gradient varying from static air in contact with the floor, to the free stream wind velocity some distance from it. Typically the depth of this boundary layer is about 150mm.

Working sections vary is size with a width to height ratio of between 1 and 2.

Figure 1. View from the low to the high speed section of one of Southampton University's aeronautical tunnels

### 1.2 Environmental Tunnel

For testing building developments an environmental or boundary layer tunnel is used. The atmospheric boundary layer is a larger version of that in the wind tunnel described above. Because of the roughness of the earth's surface, the wind at ground level is much less than that at high altitude. The surface roughness also introduces turbulence into the wind. Higher grades of roughness, such as in a city, have a greater effect than low grades of roughness such as on an open prairie or a calm sea, and the velocity gradient and turbulence are highly dependent on this factor.

Figure 2. A model sailing yacht in a large environmental tunnel

Environmental tunnels incorporate turbulence stimulators and roughness elements on the floor to generate scale models of the atmospheric boundary layer. Building models and landscapes are then constructed to the appropriate scale to study a variety of issues such as the dispersion of the smoke plume from a power station, the dynamics of a bridge, or pedestrian comfort around a shopping mall.

These tunnels have long working sections in which to grow the boundary layer and may have width to height ratios of up to 4. Typically they model the atmospheric boundary layer at scales of between 1:100 and 1:1000.

## 1.3 Moving Ground Tunnel

In order to simulate the aerodynamics of a moving vehicle it is desirable to eliminate any boundary layer because in real life the vehicle is moving through relatively still air and so there is no velocity gradient to model. There are a number of ways to achieve this but the most common is the use of a moving ground facility in an aeronautical tunnel. This is simply a conveyor belt that moves at the same speed as the air, preferably with a suction box upstream of it to remove the boundary layer at that point. The vehicle model is then supported above the belt, often with wheels running on the belt if their effect on the airflow is significant, for example on a racing car.

Figure 3. Power boat model suspended over a moving ground belt

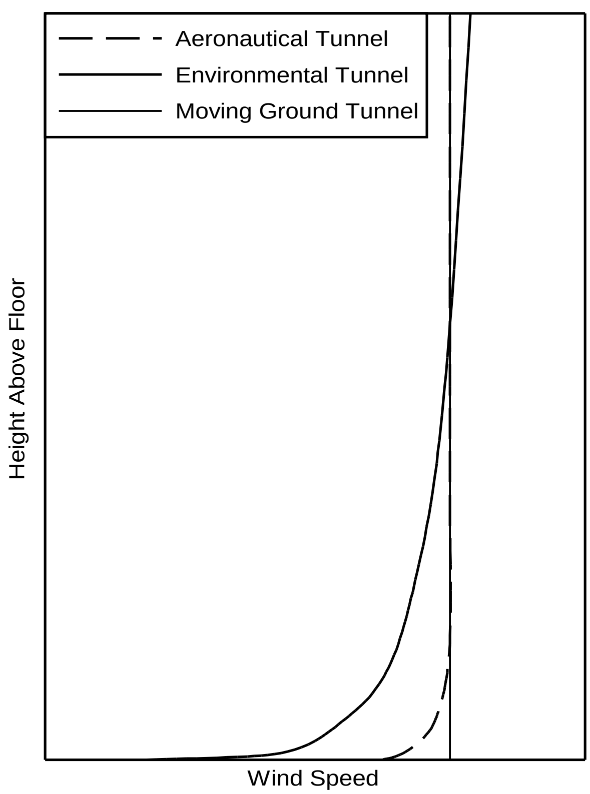


Figure 4. Typical velocity gradients found above the floors of wind tunnels

## 1.4 Application to Yacht Testing

All of these types of tunnels may be suitable for modelling ship aerodynamics and each offers certain benefits.

If the tests are to simulate conditions when the yacht is stationary, for example to study passenger comfort when at anchor, an environmental tunnel might offer the best aerodynamic representation. Unfortunately few tunnels of this type are large enough to enable tests at a scale adequate to model details and their effects with accuracy. For example, if a scale of 1:100 is the largest that can be achieved, a model of a 50 metre yacht will be just half a metre long, with the head of a seated person just a centimetre above the deck.

It is more likely that tests will be required to simulate conditions when the yacht is under way. When under way the yacht may be operating in an ambient wind from some heading, with a boundary layer and its associated velocity gradient. To this will be added a wind vector, which is constant with height, resulting from the forward speed of the yacht. If the ambient wind is from ahead the sum of these is simple to visualise, with a wind speed at ground level equal to the speed of the yacht, and with speed increasing with height, reaching a maximum at some point above the yacht. If the ambient wind is from some other heading, the sum of the two results in a twist in the apparent wind direction. For example, with the wind on the beam, the wind at ground level will be equal to the yacht's speed, and its apparent direction will be from ahead. At the mast head there will be the same component from ahead combined with the ambient beam wind component, resulting in an apparent wind of greater speed from off the bow. This twist in the wind is commonly referred to by yachtsmen as wind shear. To model this accurately is a difficult problem, which is now being tackled in specialised twisted flow wind tunnels, such as at Auckland University, for the purpose of racing sail development.

Figure 5. A racing yacht model in the Auckland University twisted flow tunnel

The potential number of combinations of yacht speed, ambient wind speed, and wind heading are infinite, and so going to extreme lengths to simulate one particular combination becomes rather unproductive.

The aeronautical tunnel offers a good compromise in simulating the situation on a moving yacht. There are a number of tunnels available with working sections large enough to model motor yachts at large scale, between 1:10 and 1:50. At such a scale the depth of the boundary layer is similar to the depth of the hull of the model, and the superstructure is in uniform flow.

If the yacht is capable of very high speed it may be appropriate to suspend it over a moving ground, particularly if the flow beneath the hull is of importance, perhaps for the measurement of aerodynamic lift and drag.

## 2 MODELS

It may be possible to press into service a display model of the yacht, but practical test constraints are likely to result in a dedicated wind tunnel model.

### 2.1 Scale

The scale will be dictated by the choice of test facility and the test requirements. For a study of the wind comfort the model should be built to the largest scale possible for the tunnel. If it is also required to measure forces the scale may be restricted by the capabilities of the measuring equipment.

### 2.2 Level of Detail

The level of detail will be governed to some extent by the scale, but it is unlikely to be worthwhile including fine details such as railings and small fixtures. Generally the model should incorporate features such as bulwarks, deck overhangs, coamings, structural pillars, tenders, masts, communication domes, etc. If the tests are to address the flow around seating or dining areas, the deck furniture should also be modelled.

### 2.3 Surface Finish

The growth of the boundary layer over the surface of the model is dependent on the Reynolds number and, ideally, tests should be conducted at the full scale Reynolds number in order to ensure that the flow is correctly represented.

Reynolds number = speed x length / viscosity.

Because the length of the object is reduced by the model scale, the wind speed should be increased by the same factor. This is not practical and so tests are conducted at Reynolds numbers significantly less than full scale. This may cause problems with flow over smooth contoured surfaces, such as found on some modern yacht superstructures. The effects are minimised by increasing the roughness of the model surface relative to that at full scale.

Construction using foam insulation slabs offers the advantages that they are simple to shape and have a texture that gives the model the required degree of surface roughness.

If smoke flow visualisation is to be used the model will need to be finished in dark colours to provide a suitable background. If laser flow measurement techniques are to be used the finish will need to be black.

### 2.4 Alternative Arrangements

It is normally fairly straightforward to model any alternative superstructure configurations that are being considered, using removable modules and components.

If some feature of the design appears to generate undesirable flow conditions it is normal practice to try a number of modifications to it during the course of the tests. It is convenient to use readily available materials such as tape, card, aluminium plate or plasticene with which one can quickly fashion some modification and assess its effect. Such modifications to the yacht, even if constructed in prototype form using disposable materials, might cost more than a modest wind tunnel programme, and it would be more difficult to assess and measure their effect outside the controlled environment of the tunnel.

## 3 FLOW VISUALISATION

Measurements of the flow are very important, but the experimenter and designer will quickly gain a much more comprehensive understanding of the airflow if they can see it. There are many ways of visualising flow, the following being the most commonly used in ship testing.

### 3.1 Tufts

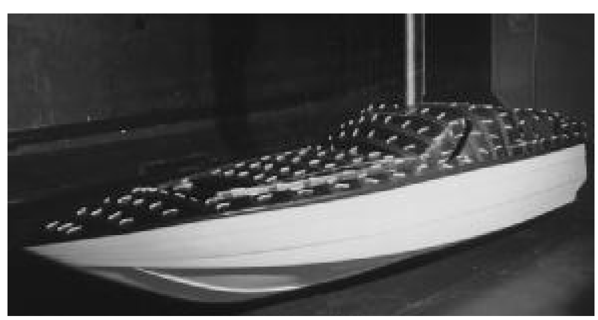

Figure 6. Wool tufts to visualise surface flow pattern

The simplest form of flow visualisation is by the use of tufts of wool, magnetic audio tape, or similar lightweight material about 50mm long. These may be attached to the model to indicate the local flow direction on the surface, or to a wand that the experimenter can move around the model to explore the flow off the surface.

### 3.2 Smoke Wand

With a smoke wand the experimenter can observe the flow direction and turbulence along a streamline over the model. This gives a clearer image of the flow characteristics than a wool tuft on a wand, particularly because of the greater useful length of the smoke trail, which may be up to a metre.

Figure 7. Yacht designer David Pedrick using a hand held smoke wand

### 3.3 Exhaust Smoke

To study the trajectory of engine exhausts, a theatrical smoke generator is connected to the model exhaust outlets via a fan and valve system to control the exhaust flow rate. Observations of the smoke plume provide information on its trajectory and degree of mixing with clean air.

## 4 LOCAL VELOCITY MEASUREMENT

### 4.1 Hot Wire Anemometry

The hot wire anemometer is one of the commonly used methods of measuring local wind speed and turbulence. It incorporates a very fine wire a few millimetres long mounted on a forked probe. A current is passed through the wire and its resistance is monitored. Air flow over the wire cools it and alters the resistance. Unfortunately the relationship between flow speed and resistance is complex and so the instrumentation is expensive and calibration must be conducted carefully. The probes are very suitable when a traversing mechanism is used to position them precisely, but they are extremely delicate and not ideally suited to being placed manually into confined locations on a model.

### 4.2 Thermal Anemometry

The thermal anemometer represents a more recent development. It incorporates a small thermistor in a bead, usually mounted in a flexible probe on a telescopic wand. This is a much more robust probe and will tolerate the knocks of a quite careless experimenter. The instrument may not be as precise as a hot wire anemometer, and does not give information on turbulence, but is a very practical tool with adequate accuracy for the measurements required in yacht testing.

### 4.3 Laser Doppler Anemometry (LDA)

When accurate measurements of the flow are required, and the presence of an experimenter near the model, or a probe at the measurement site, would have an unacceptable effect on the flow, laser doppler anemometry may offer the solution.

A laser beam is split and focussed at the location of interest and the flow through that area is seeded with a tracer, such as smoke particles. An optical receiver detects light reflected from the tracer particles and instrumentation interprets the interference patterns produced to determine the flow speed and direction. Continuous sampling enables a study of the time history and turbulence in the flow at that location.

The technique provides a high level of accuracy but alignment of the optical equipment is critical and can prove extremely time consuming. A precision traversing system is required to enable measurements at a series of points so that information can be built up over a region of the flow.

The technique is appropriate for extensive research projects or contracts with a large budget, as might be the case for a naval ship, but is unlikely to be cost effective for a yacht.

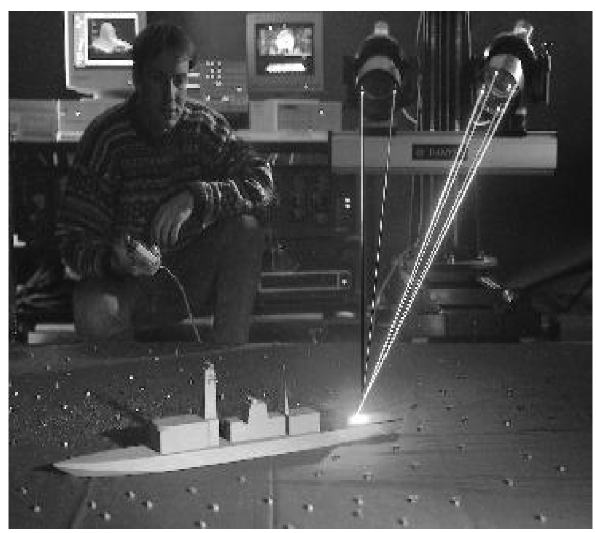

Figure 8. Laser doppler anemometry on a flight deck in the Bristol University tunnel

### 4.4 Particle Image Velocimetry (PIV)

This technique also uses a laser and smoke to seed the flow, but the laser is focussed into a thin sheet in the region of interest. The laser sheet is viewed by a camera controlled by a computer, which acquires two images in rapid succession. By tracking the movement of smoke particles across the plane, the system determines the flow speed and direction within the plane.

As with LDA, this system still requires careful alignment and setting up of the optical components, but it has substantial benefits, in particular the information is obtained for the flow across an entire plane, at perhaps 200 points simultaneously, rather than at a single point. The measurement is 2 dimensional, and there is no measure of the flow orthogonal to the plane, so three dimensional measurements require the use of orthogonal planes. Traversing the system to obtain images of successive planes gives comprehensive information on the flow through a three dimensional volume. The image gives an instantaneous measure of the flow, and successive images enable a measure of the turbulence, although the sampling rate is much lower than that of LDA.

## 5 LOCAL PRESSURE MEASUREMENT

It may be of interest to determine the local pressures at certain locations. This is common practice on building developments to determine the fastenings required for cladding a structure, but this is unlikely to be the case on a yacht. Pressures at exhaust outlets and vent locations may be of great assistance in specifying ventilation system components and designing exhaust arrangements.

It is a simple matter to install a small tube in the model, with an opening flush with the surface at the location of interest, and monitor the pressure with a sensitive transducer.

## 6 EXHAUST PLUME TESTS

These tests indicate whether the exhaust gases are likely to result in soiling of the yacht's structure, cause a nuisance on working or recreational areas of exposed decks, or be drawn into ventilation inlets.

Generator exhausts, as well as those of the main engines, should be modelled, and perhaps even vent outlets, such as those from the galley, are worthy of consideration if they might impinge on recreational areas.

The technique used is to match the mass flow rate of the exhaust to that of the ambient wind. There are of course an infinite number of combinations of apparent wind speed, heading, and engine duty, and to attempt to cover these with a matrix of tunnel speeds, headings and exhaust flow rates would generate a very costly test programme. At the Wolfson Unit, it has been found most efficient to fix the exhaust flow rate, and progressively increase the wind tunnel speed until the exhaust plume is seen to interfere with some part of the yacht. This combination then represents the critical ratio of exhaust flow rate to apparent wind speed at that heading.

The critical ratio may be representative of operation in a low wind speed with the engines at low power, or at full duty in a strong wind. Armed with this information the designer can decide whether the critical ratio is likely to be encountered frequently and therefore whether the situation justifies relocation of the exhaust or modification of the adjacent structure.

The wind speed at the critical ratio may be representative of a full scale speed at which the exhaust trajectory is no longer a concern. For example, the exhaust plume from a funnel will have a progressively lower trajectory as wind speed from ahead increases. It may reach the level of the sun deck with an apparent wind speed of 40 knots, but at this speed guests are unlikely to be out on the exposed deck and the only consideration would be possible soiling of the structure there.

It is not practical to model the buoyancy effects of a hot exhaust in a conventional wind tunnel, but the buoyancy tends to influence the far field trajectory and mixing of the plume, and it is generally the near field that is of interest on a yacht.


Figure 9. Exhaust plume trajectory interfering with the aft end of the sun deck

Figure 9 illustrates the problems that may occur with exhausts from funnels above the superstructure. This is a model of a 76m motor yacht for DML, with naval architecture by Laurent Giles. Adjustments to details of the funnel structure eliminated the problem.

Figure 10 shows tests for Martin Francis, designer of Eco and the modifications to transform it to Katana. The possibility of moving the gas turbine exhausts to the aft end of the owner's deck were studied, and the photographs show two options for exhaust outlet configurations, with very different plume behaviour.

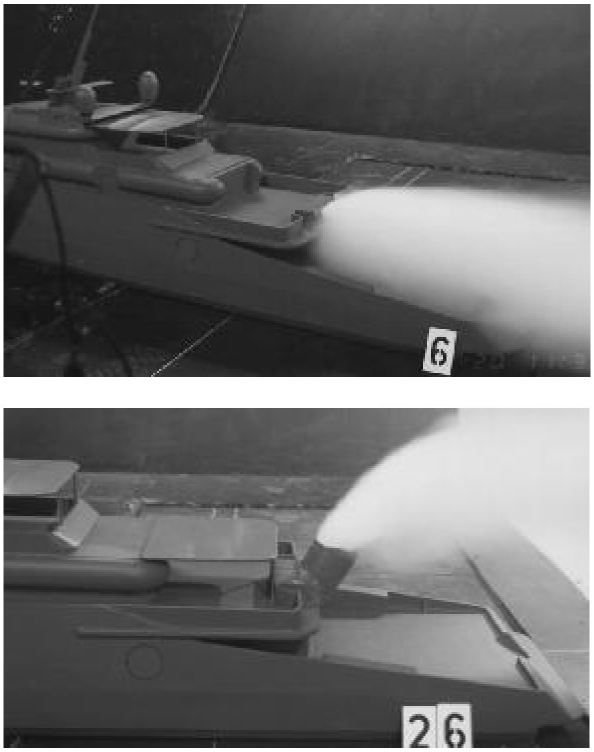


Figure 10. Study of alternative gas turbine exhaust arrangements

## 7 PASSENGER COMFORT TESTS

Passengers' perception of environmental comfort is affected by the temperature, humidity, sunlight and wind speed. Of these, temperature is of surprisingly little importance, whereas wind speed is fundamental.

Measurements can be made of the local wind speed at a number of locations at which passengers might relax, dine, sunbathe or move about the decks. The measured velocities are compared with a reference value, usually in the free stream ahead of the model at the standard height of 10 metres which is used by meteorologists for quoted wind speeds. The local wind speeds typically will be less than the free stream value, except where the flow is accelerated over some part of the yacht that has little or no shelter, or funnelled into a restricted area.

As with exhaust plume tests, the possible combinations of yacht speed, wind speed and heading are infinite, but it is sufficient to conduct tests at discrete headings for a single wind tunnel speed. The ratios of local wind speed to free stream speed will remain valid for all speeds.

If the tests are to simulate comfort with the yacht under way, it is unlikely that an apparent wind direction from abaft the beam will be relevant, and the tests should be predominantly for head and bow wind headings. This is particularly true for high speed craft, as the polar plots of Figure 11 demonstrate. The left hand graph presents the apparent wind speed and heading for a yacht under way in 15 knots of true wind. An apparent wind from ahead is denoted 0 degrees. For a yacht travelling at 10 knots into the wind the apparent wind from ahead is 25 knots, and as the yacht turns downwind the wind speed progressively reduces until it is 5 knots from astern. If the yacht increased its speed to 20 knots and repeated the manoeuvre, the apparent wind direction would remain within the range of 0 to 45 degrees from ahead. With further increases in the yacht's speed the apparent wind speed and direction are dominated by it, until at a speed of 40 knots the apparent wind direction remains less than 25 degrees off the bow.

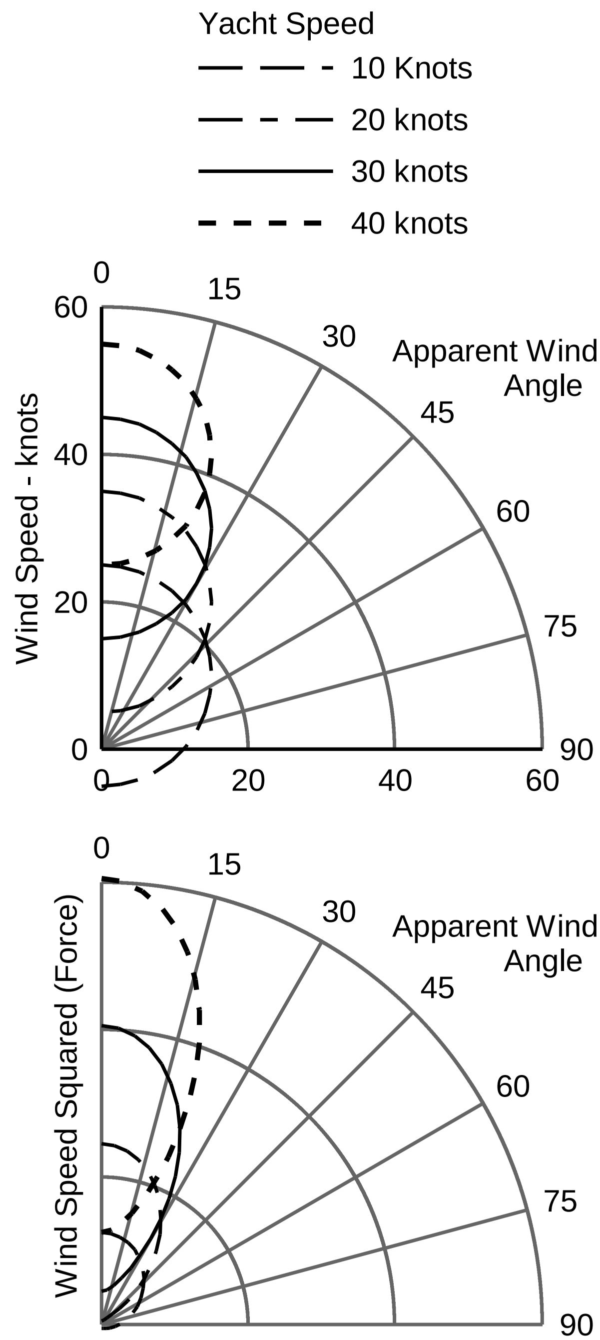


Figure 11. The apparent wind speed and direction on board a yacht travelling in 15 knots true wind, with true wind angles ranging from ahead to astern.

The second plot of Figure 11 presents the same data, but with the wind speed squared. This is representative of the wind pressure or force, and is therefore more relevant to the perception of a person walking about the decks of a high speed vessel. It is interesting to note how this further reduces the relative magnitude when the apparent wind is from aft or on the beam, reinforcing the argument that it may not be appropriate to test high speed craft at wind headings of more than 30 degrees.

Figure 12 shows an example of the kind of information that can be acquired quickly with a thermal anemometer, and its value in optimising detailed design. Local wind velocities were measured over a range of heights at the fly bridge helm position to study the effectiveness of the windscreen. With the screen moved forward 500 mm the wind speed at normal head height, 1.6 to 1.8 metres, was reduced by about 50%. This will represent a significant benefit in comfort for the helmsman and anyone accompanying him. The effects of such a modification to the yacht would have been difficult to predict, and such a modification at full scale might have been extremely costly. The tests occupied less than an hour of wind tunnel time, including the model adjustments, and therefore represent very good value as part of the overall programme.

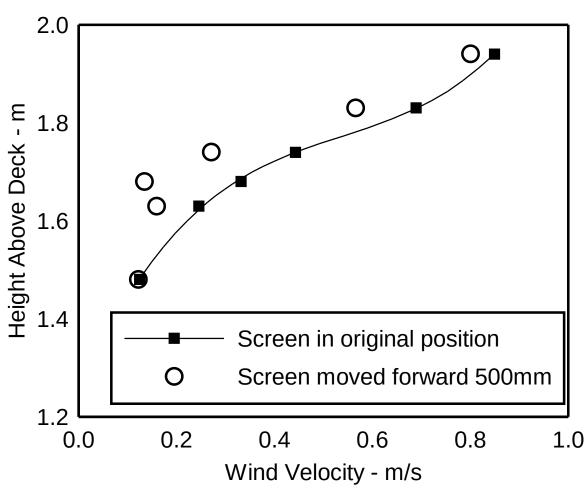


Figure 12. Variation of local wind speed with height at the fly bridge helm position

A typical model modification, one that was quickly fitted and assessed, is illustrated in Figure 13. An area designed for relaxation, which would be rather exposed when motoring, was improved by a simple vertical screen. The wind speeds at head height of seated guests were reduced to about 25% of their values without the screen.

Using the model shown in Figure 7, twenty five different model configurations were assessed during a two day wind tunnel programme. These included a variety of windscreen, cockpit screen and bimini designs. The design was for a 42 metre motor-sailer capable of 25 knots under power. With the owner's desire to maintain open style cockpits typical of conventional sailing yachts, wind comfort was given a high priority.

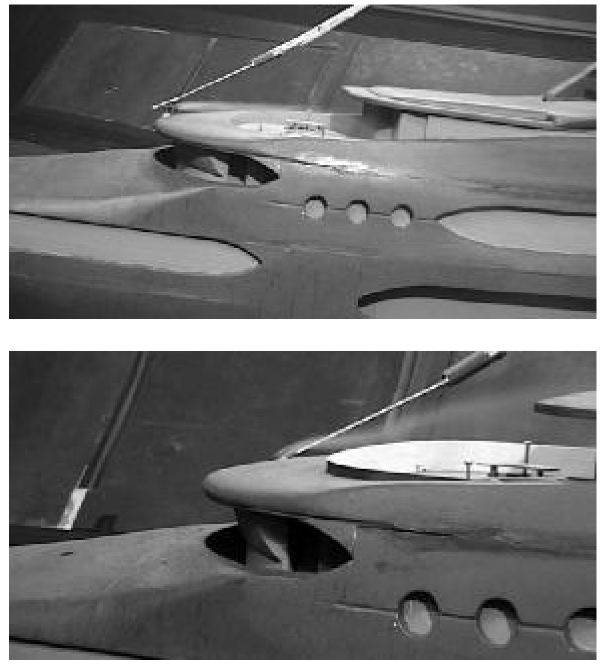

Figure 13. A screen fitted to deflect wind upwards and improve the wind comfort in an area of exposed seating

## 8 HELICOPTER OPERATIONS

The wind velocity and distribution over the flight deck may be studied using the simple techniques described above, but this may not be adequate for a vessel that is very reliant on its helicopter operations, be it for business or naval use.

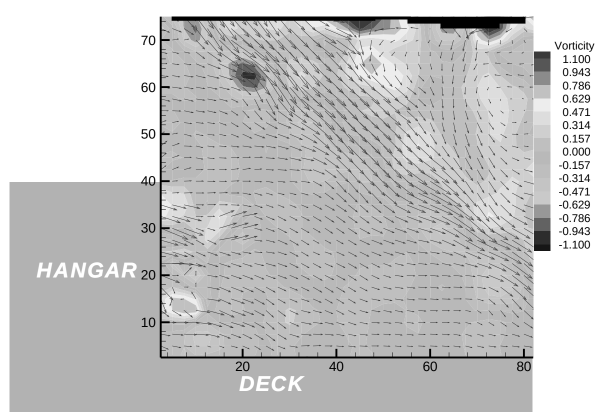


Figure 14. PIV measurement on the centreline plane of a naval vessel during helicopter approach

PIV measurements of the wind field offer excellent analysis and imaging opportunities. They provide information for the designer and the helicopter operator on the conditions on deck and along typical flight paths. Figure 14 presents a PIV measurement obtained with a model of a naval ship and a helicopter rotor in the wind tunnel. It shows the flow on a vertical plane, on the centreline, over the flight deck, with the apparent wind from ahead, that is from the left, and the helicopter hovering above the deck. The interaction between the flow over the superstructure and the down draught from the rotor is clear.

## 9 FORCE MEASUREMENTS

Aerodynamic forces are generally less than hydrodynamic ones for a motor vessel, and so wind tunnel tests to measure forces are not common.

They may be worthwhile for very fast craft to provide information on power requirements, pitch stability or handling. An example is that illustrated in Figure 3 and Figure 6, a 22 metre luxury powerboat design by Tony Castro and Peter Birkett. The model is suspended on struts from a 3 component overhead balance, to measure the drag, lift and pitch moment at a range of trim attitudes over the moving ground.

Figure 15 shows a 110 metre wave piercing ferry for Aluminium Shipbuilders Ltd. being tested in a boundary layer tunnel. There was concern regarding the manoeuvring and handling of the ferry in the confined waters of the ports during strong winds, and the tests provided data on the forces and moments which the propulsion and thruster systems would be required to overcome. Because the vessel would be stationary or at very low speed, the boundary layer tunnel gave an appropriate wind gradient. The model was larger than would normally be selected for such tests, and required adaptation of the turntable and balance, but it was based on a towing tank hull model to minimise modelling costs. The tests also included a study of some different funnel configurations to determine the best with regard to exhaust plume trajectory, and the large scale was beneficial in that respect.

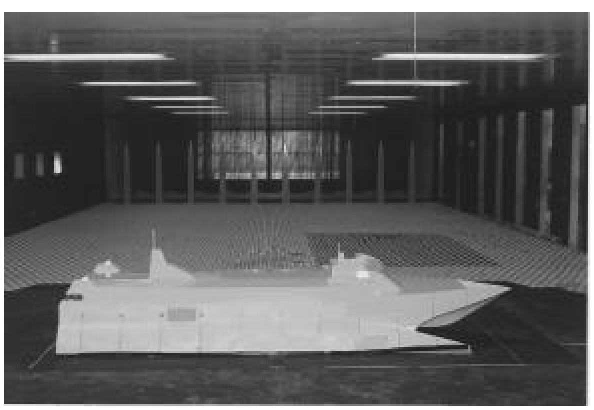

Figure 15. A catamaran ferry on a 6 component balance in the tunnel floor

## 10 CONCLUSION

Wind tunnels can offer valuable contributions at the design stage of a new project. They are also powerful tools for assessing potential solutions to problems with exhaust, ventilation and wind comfort on existing yachts.

Wind tunnel studies can involve expensive models and extensive test programmes, but many sound decisions have been made on the basis of ‘quick and dirty’ tests conducted in a single day of wind tunnel time.

Models can incorporate alternative modules, and can be modified with ease, to refine and optimise the detailed design of features that have a significant effect on the aerodynamics.