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System for the Measurement of the Attitude of Wind Tunnel Models

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Due to very large aerodynamic loads, deflections in the support systems of models tested in the RAE 5 m pressurized low-speed wind tunnel can be significant. For the continual measurement of the achieved model attitude a system, which includes a laser yaw meter for the measurement of attitude in the horizontal plane, has been developed. From simple geometry the yaw angle can be calculated and, for a model mounted on the mechanical balance, the equipment can also measure displacements from the balance calibration center. Attitude in pitch and roll is measured by an orthogonal set of accelerometers.

I. Introduction

THE 5 m pressurized low-speed wind tunnel, shown as Fig. 1, has been in operation at RAE Farnborough since December 1977. High-unit Reynolds number is achieved through a combination of working section size, a pressure range of up to 3 atm total pressure, and a large installed drive power. An independent control of Reynolds number over the Mach number range up to 0.34 enables the effects of scale and compressibility to be separated.[1]

Models are rigged on interchangeable carts, that allow rigging and preparation outside the tunnel working section. Normally the models are mounted on one of two standard carts; the first of these carries a quadrant assembly for force and pressure measurements on a sting-mounted model using an internal strain gage balance. The second carries an underfloor mechanical balance, on which the models are strut mounted from a turntable. In either case the aerodynamic loads on the model are so high that significant deflections are seen in the model support system and, during recent tests with a 1/13 scale model of A300b, deflections of up to 0.8 deg between the model and the sting mounting at the quadrant were measured.

It was necessary therefore, to develop a system for the continual measurement of the achieved model attitude in pitch, roll, and yaw; this measurement to be based on attitude sensors in the model to eliminate the effects of support deflection. In addition, it was necessary to measure the excursions of the model away from the calibration center of the mechanical balance in order to correct for the effects of strut deflection, and the consequent offset in moment center, on the measured aerodynamic moments.

The model attitude measurement (MAM) system forms one part of the complete instrumentation system of the tunnel, which is based on multiple minicomputers arranged in a two-tier network.[2] Three "front-end" machines are dedicated, one to each of the basic wind tunnel tasks: force measurement using an internal strain gage balance, force using the mechanical balance, and pressure distributions. A fourth machine controls the tunnel plant to achieve the desired conditions and pass this information to the front-ends. The fifth computer acts as a supervisory machine and controls all of the four computers in an integrated fashion. Data from the front-ends is available to the supervisory machine for detailed analysis and plotting.[3]

The two force-measurement packages carry an additional task, to control and measure the attitude of the model when mounted on the relevant cart. The MAM system was therefore developed, to be incorporated into the two packages. The method of attitude measurement is the same in both cases, although the model is restricted to pitch and yaw only when mounted on the mechanical balance. These two packages also control the setting of the model attitude either by moving roll gearboxes at either end of the sting plus quadrant rotation for internal strain gage balance models, or by a rotation of the balance turntable and extension of a tail strut in the case of the mechanical balance. In the full system, the measured achieved setting is used as an input to drive the model to the desired position, thereby eliminating the effects of sting or strut deflection (but not the effects of moment offset).[4]

II. Measurement of Model Attitude in Pitch and Roll

Measurement of model pitch and roll angle is by an orthogonal set of accelerometers mounted inside the model and acting as inclinometer devices. The triaxial mount is aligned along the centerline in the horizontal and vertical planes, the angle between the accelerometer axis and the model centerline being dictated by available mounting locations within the model. The information for measurement of pitch and roll is displayed to the operator in real time; in the present system, a comparison of the two measured values is used as a simple check on the performance of the system. For use in the 5 m tunnel, the accelerometers must be unaffected by pressure of up to 3 atm.

Analog information from the three accelerometers and from a temperature sensor is passed to the computer through identical channels comprising a variable gain differential amplifier, a variable cutoff low pass filter, and a digital panel meter used as a digitizer. The digital information is passed to the computer through a standard interface attached to a bus-structured digital data link that forms a part of the basic force package. This information, together with other necessary parameters, such as tunnel conditions, balance output, and yaw data, is then available for the calculation and display of aerodynamic coefficients in either wind or body axes.

To illustrate the accuracy of the instruments, results are presented for a recent test using a pitch-wing to measure the flow direction in the test section. This was part of the testing in support of the calibration of the tunnel. The wing has a symmetrical section, with an aspect ratio of 6 or 8 and is mounted on a short sting ahead of an internal strain gage balance. The wing is set at small geometric incidence and the

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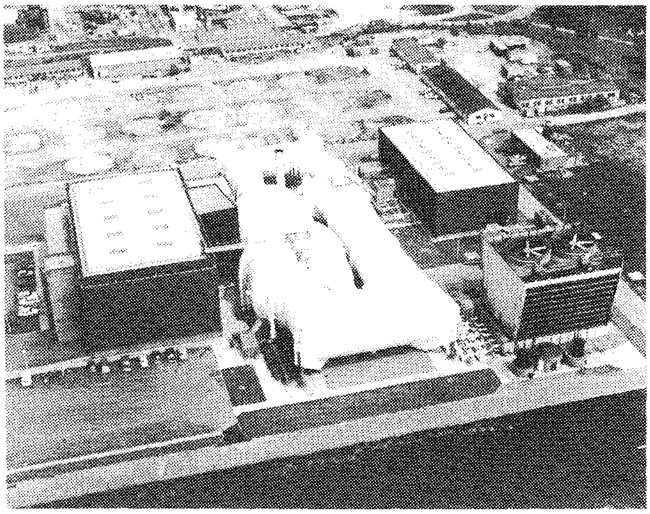

Fig. 1 Aerial view of the 5 m tunnel.

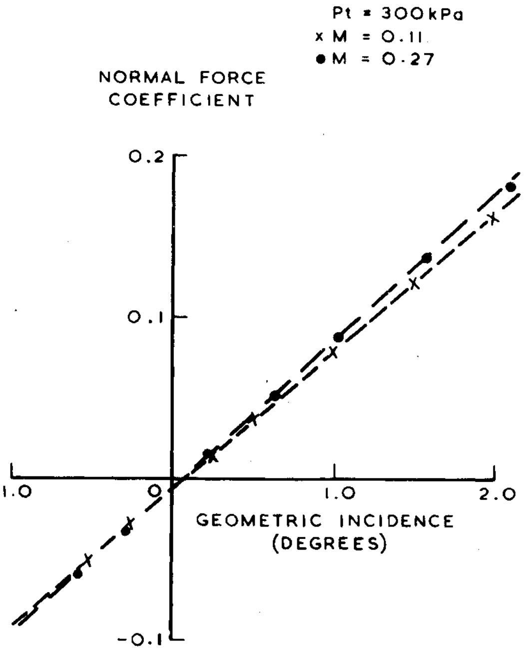

Fig. 2 Results from the pitch-wing experiment.

aerodynamic normal force measured. At conditions of zero load the wing is aligned with the flow thus the mean angle across the wing can be found.[5]

Figure 2 shows the results for a tunnel pressure of 3 atm at speeds of Mach 0.11 and 0.27. The variation of normal force, with small angles of incidence, is linear, thus the results demonstrate the ability of the onboard accelerometers to resolve very small angles. As a guide, the differences in measured incidence for the two tunnel speeds shown in Fig. 2 are an indication of the amount of sting deflection resulting from this speed change. The changes are of the order of 0.1 deg at the maximum, 2 deg incidence. The results demonstrate an accuracy greater than these 0.1 deg differences due to deflection of the support. During a static calibration, in which an inclinometer was used as the standard measure of pitch angle, the results agreed to 1 min of arc and this appears to have been confirmed by the tunnel test. For an aircraft model, accelerometer readings are reliable up to the stall, but beyond the stall the readings are unsteady. The signal conditioning on each of the three channels gives an averaged result that has been found to be consistent for different runs with the same stalled model under similar tunnel conditions.

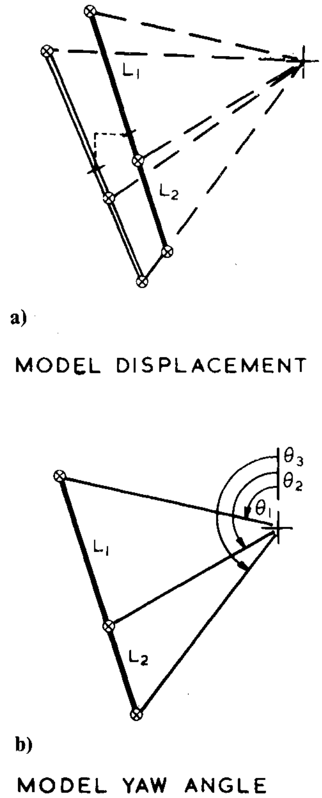

Fig. 3 a) Geometry for calculation of displacement; b) basic geometry for measurement of yaw angle.

III. Measurement of Model Attitude in Yaw

An optical method has been developed to measure both the model angular position in the horizontal plane and the displacement of the model center from the balance center under the very high aerodynamic load which causes the model support system to deflect. The aim was to produce a system that could resolve changes in yaw angle to 0.1 deg while updating the information fast enough to exceed the resonant frequency of the support system (in particular, the sting support with a frequency of around 15 Hz). Because the strain gage balance is mounted in the model and the tunnel flow has good uniformity, displacements are only important for a strut-mounted model on the mechanical balance. Under high aerodynamic loads the struts deflect and cause the model to displace sideways and back, moving the model center away from the calibration center of the balance as shown in Fig. 3a. Measurement of these displacements allows the balance loads to be adjusted back to the actual position of the model. For both support systems an accurate measurement of yaw angle is essential.

The system for the measurement of yaw angle and model displacement is based on a device to measure the angular position of three collinear points along, or near, the top centerline of a model relative to an offset center. The basic geometry is shown in Fig. 3b.

From simple geometry, based on the positions of the points along the model and the measured angular positions, the yaw angle can be calculated. It will be shown that the calculated yaw angle depends only on the ratio of the two lengths, L_1 and L_2, and the system is therefore independent of model incidence. In addition, the same basic system can be used to measure the rearward and sideway displacement of the model center under the action of the aerodynamic load.

The measurement of angular position of three points on the model centerline is made using a rotating fan of laser light which shines down onto the model from a point to one side of the tunnel center. Figure 4 shows a very simple schematic of the system. A beam of laser light is deflected vertically down

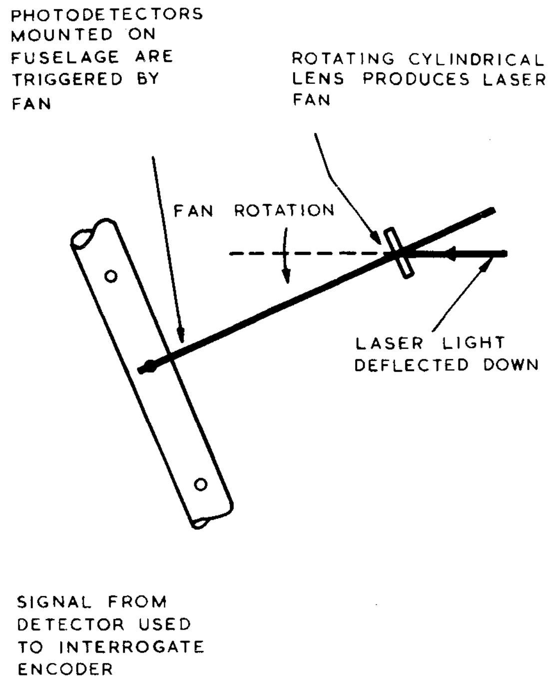

Fig. 4 Schematic of the laser yawmeter.

to pass through a cylindrical lens aligned in the horizontal plane and free to rotate about a vertical axis. Figure 5 shows the ray path through the lens; a thin fan of laser light is produced, normal to the axis of the lens, as shown. The lens assembly is rotated by a motor and so the fan sweeps over the model and illuminates three photodetectors, in turn, mounted in the model. The lens assembly is mounted on a position encoder and the pulse from the detector is used as a trigger to interrogate the encoder thus measuring the angular position of the three detectors. From this, and knowing the spacing of the detectors, the yaw angle and model displacement can be found. As shown in Fig. 5, when the laser beam passes through the center of the cylindrical lens, a symmetrical fan is formed and the two halves of the beam each cross the detectors during one revolution of the lens, effectively doubling the measurement rate of the system.

A. Calculation of Yaw Angle and Model Displacement

The system for the measurement of yaw is based on the same set of simple geometric expressions, whichever support system is used. The laser yawmeter measures the three angles, as shown in the text, between the centerline through the laser axis and the three photodetector positions. From the following expression, yaw angle can be calculated and the result is available to the package for further calculation; the measured angle is updated twice per revolution of the laser fan. The expression, Eq. (1), is derived for three collinear detectors.

The angle depends on the ratio of lengths between the photodetectors and is therefore independent of model incidence. When the model is mounted on the mechanical balance the wings remain horizontal in roll. However, on the sting support the model can be rolled and in this case the fuselage cross section is important. The A300b model already tested in the tunnel, and the first model to use the yaw-measuring system, has a parallel cylindrical body and so the yaw angle is copied by the line through the detectors as the model rolls.

yaw angle, β

$$= \tan^{-1}\left(\frac{(L_2/L_1)\sin\theta_1\sin(\theta_3-\theta_2)-\sin\theta_3\sin(\theta_2-\theta_1)}{\cos\theta_3\sin(\theta_2-\theta_1)+(L_2/L_1)\cos\theta_1\sin(\theta_3-\theta_2)}\right) \qquad (1)$$

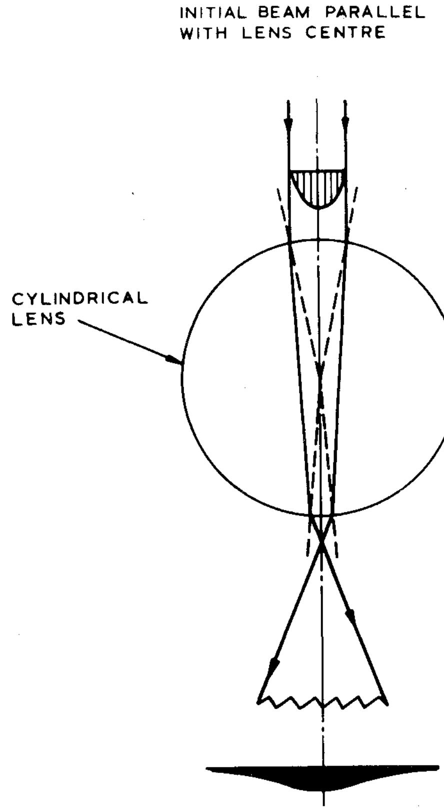

Fig. 5 Mechanism to produce a symmetrical laser fan.

For a conical fuselage, the taper angle contributes to the yaw angle measured, and for a fuselage of arbitrary cross section the method would break down since the detectors are no longer collinear. In these cases different expressions would be used to calculate the yaw angle based on sectional information for the fuselage cross section.

The sketch, Fig. 3a, also shows the way in which the model, and the line of photodetectors, would translate sideways and backward when the strut support system deflects under the influence of the very large aerodynamic load. To measure the excursions away from the balance center, wind-off measurements of the original angles are needed, together with the corresponding positions with the wind on. From this information, together with the model geometry information relating to the position of the photodetectors, which is also necessary for the calculation of yaw angle, the displacements can be found. Of course, under the aerodynamic load, the achieved yaw angle will be changed and the actual lengths, in the horizontal plane, between photodetectors must be known. This is found from the original geometry information along with the measured incidence, found from the set of accelerometers. The calculated model displacements are then used as offsets to relate the measured aerodynamic loads to the calibration center of the balance.

B. Initial Test with a Prototype System

A prototype test rig was built, powered by a 25 mW helium neon gas laser, to assess the performance of different types of photodetector and cylindrical lenses of different diameter. At the end of these tests, which confirmed that a system based on a single fan in conjunction with three single-segment photodetectors gave the best results, a developed version was built for use in the 5 m wind tunnel. One critical feature was that the system should operate under normal lighting conditions in the working section, so that television cameras could still be used to monitor the model under test. During these initial tests a method was found to offset the beam, to concentrate the light in the fan on one side of the vertical

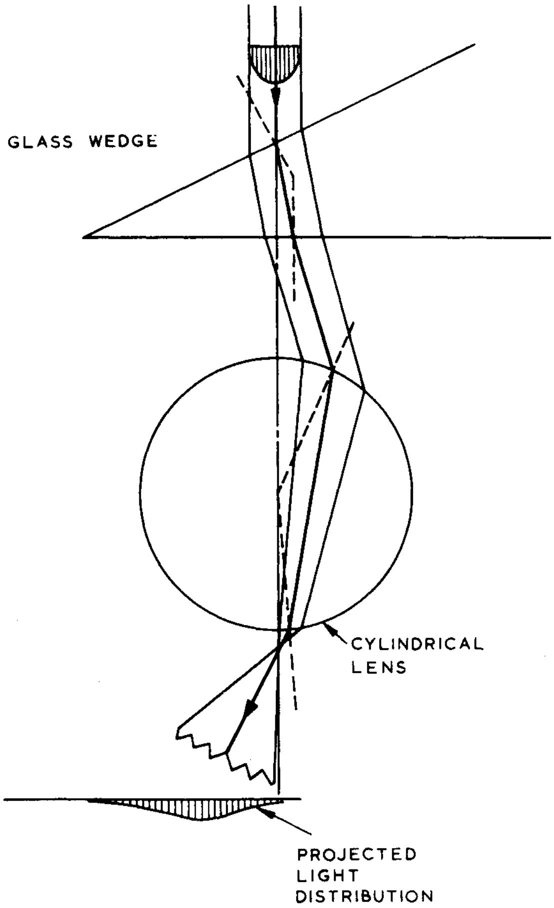

Fig. 6 Mechanism to produce an offset laser fan.

center so that light, in the form of an annulus, passed over the detectors and enhanced the performance in ambient light conditions. However, this change from a symmetrical beam, where the detectors are illuminated twice for each revolution of the cylindrical lens, lead to a slower system. With the beam offset to one side, the concentrated annulus swept the detectors only once for each revolution of the lens and the measurement speed was effectively halved; the performance under normal lighting conditions was much improved.

The prototype test rig comprised a horizontal support for a 25 mW helium neon laser, a mirror to deflect the horizontal beam vertically down, and an arrangement for rotating the cylindrical lens with the curved surface normal to the beam. This lens assembly, together with the fan of laser light, was rotated by an electric motor. The encoder was fixed to, and rotated with, the lens and the detector pulse, when the beam passed over, was used to trigger the encoder thus measuring the angular positions of the three detectors. The encoder was designed for a maximum throughput of 100 kHz: during the prototype tests a resolution of 10,000 counts gave a maximum rotational speed of 10 Hz. In the final system the optical disk was replaced with a unit having less resolution and the speed was increased to maintain the same maximum throughput. In the case of an offset fan, this was the maximum operating speed; for the symmetrical fan the operating speed was effectively doubled, but at the expense of reduced lighting levels in the working section.

An optical rail was mounted below the lens assembly on a surface table, so that the line of photodetectors could be arranged in a way that represented a model in the 5 m tunnel. The distance of the rail below the lens was roughly the same as the distance between the working section roof and the model in the wind tunnel. Excitation of the photodetectors, by the fan beam, produced signals that could interrupt and simultaneously record the output from the encoder, marking

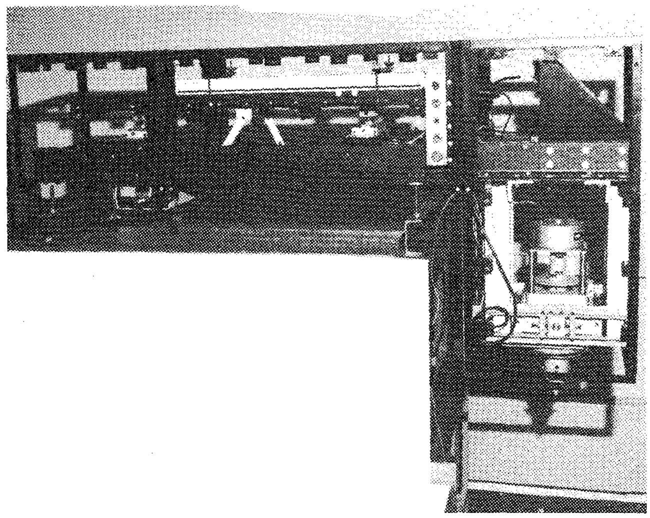

Fig. 7 Laser yawmeter assembly.

specific rotational positions of the cylindrical lens and hence of the laser fan.

Cylindrical lenses of different diameters were used in order to select the optimum diameter to give the greatest beam spread while maintaining sufficient light intensity within the beam to energize the photodetectors. An attenuated 25 mW helium neon laser, having an initial beam diameter of about 1.5 mm, gave an effective beam spread of 1.0 m at a projected distance of 2.5 m for a 6-mm-diam cylindrical lens. Smaller diameter lenses gave a more diverged fan, but it was then more difficult to align the laser beam with the lens. (Alignment probes were used to set the incident beam normal and central to the lens so that the fan rotated concentrically on a vertical axis.) A complete assessment of the distribution of light was made using a silicon cell which traversed across the fan.

In the prototype system, to evaluate the possibilities for displacing the beam to produce an offset fan, a convex lens was placed above the cylindrical lens. In the final system a glass wedge was used because the wedge gave a larger offset without the problems of beam convergence which were found with a convex lens. Figure 6 shows the ray paths and the mechanism to produce a fan, offset to one side of the vertical axis. The effect was to displace the symmetrical fan by about 0.5 m, concentrating the light at the position of the detectors.

C. Design of the System for Use in the Tunnel

Based on the tests with the prototype system, a rigid frame was designed and made to form the main optical assembly to be mounted in the roof of the working section. The laser was mounted horizontally and the beam reflected by a silvered plane mirror down through a hollow shaft encoder, the lens assembly, and out into the tunnel through a glass window in the working section roof. A 15 mW helium neon laser was chosen, this being of sufficient power to excite the photodetectors on the model against the ambient light background. This power level was such that the anticipated light intensity in the fan at this position of the model was below 2.5 mW/cm^2, allowing indirect viewing and accidental exposure protection within the test section.[6]

The hollow-shaft encoder allowed direct connection to the lens assembly. The resolution was decreased and the rotation speed increased by using an encoder with 4000 counts per revolution and a maximum throughout of 100 kHz. The lens unit was belt driven by a dc motor which could drive at speeds between 10 and 3000 rpm. The whole assembly is shown in Fig. 7. Adjustments were provided for levelling the whole unit and for aligning the beam with the optics before the cylindrical lens was added to the elements. The laser was fitted

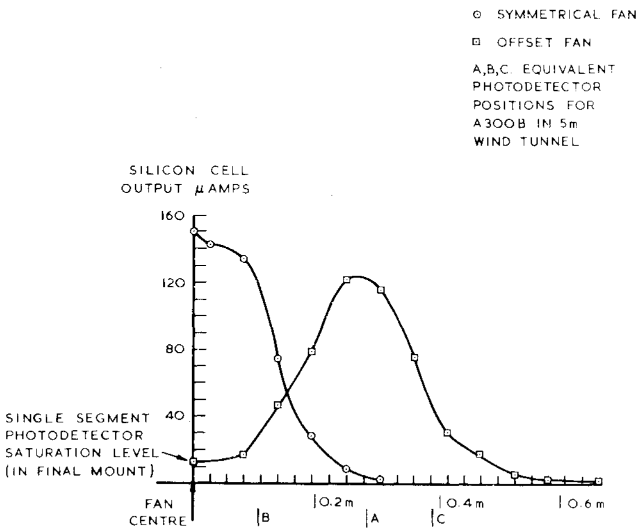

Fig. 8 Light intensity across the laser fan.

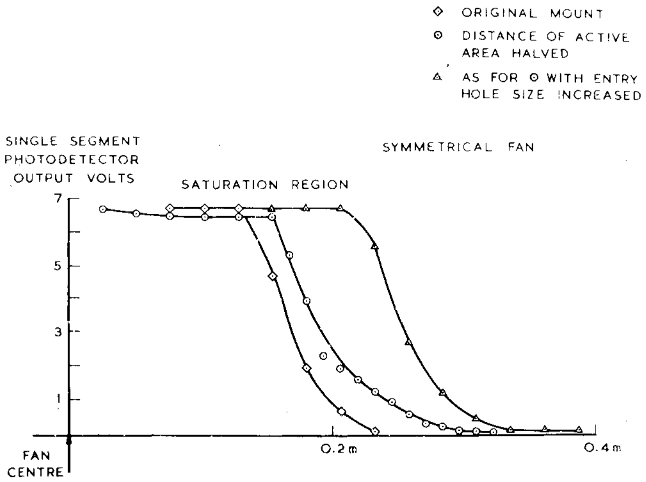

Fig. 9 Performance of photodetector masks.

with a remote-controlled shutter which was built into the tunnel interlock circuits so that the unit only could be operated with the access doors closed. A power meter was also included to monitor the performance of the laser unit.

To enable the fan to reach the photodetectors using the optimized 6-mm cylindrical lens, the yawmeter assembly had to be placed close to the tunnel centerline, within the structure of the upper turntable in the test section roof. It was necessary to offset the beam to concentrate the light over the photodetectors as previously discussed. Calculations showed that a 1.5 deg glass wedge placed 7.6 mm ahead of the 6-mm cylindrical lens would concentrate the light in the right place. A wedge of thickness 0.25 mm was made and mounted at the correct distance ahead of the lens. By reverting to the offset fan the maximum operating speed was reduced to 25 Hz, only just above the natural frequency of the sting, but the light was concentrated in an annulus above the detectors. At the expense of reduced ambient light levels, the system can be changed back to a symmetrical fan and the operating speed increased to 50 Hz, by removing the wedge.

Before being installed in the 5 m tunnel, the complete system was assembled at RAE Bedford and was checked in a way that simulated the tunnel at Farnborough. However, the photodetectors were placed at only half the distance below the lens, compared with the installation in the tunnel, to simplify the mounting assembly. Measurements were made of the distribution of light across the fan and Fig. 8 shows this distribution both with and without the offsetting wedge in place. The horizontal scale is roughly half the scale for the tunnel installation but typical positions for the three photodetectors have been shown. Without the wedge there is insufficient light at the third section but by displacing the fan center, there is then enough light at all three positions to saturate the single segment photodetector, with the final design of mask in place over the detector.

Figure 9 shows the results of traversing the beam with different masks above the single segment detector. In the design of the original mount the detector is 8.2 mm from the model surface with a pin hole of 0.75-mm diameter. The effect of moving the detector closer to the surface and then increasing the hole size to 2.0 mm is shown in Fig. 9. These changes improved the acceptance angle of the detectors and, together with the offset fan, produced a system that would work under normal lighting conditions in the 5 m tunnel, once the threshold level of the detection circuitry had been adjusted to the ambient levels.

The final check before installation was to mount three detectors on a straight beam in positions corresponding to those proposed for the A300b model in the 5 m tunnel. The beam was held on a small turntable with a readout of angular position. The encoder was connected to its instrumentation and the fan rotated at a speed of 400 rpm. The beam carrying the detectors was incremented in 5 deg steps and the measured yaw angle was calculated from the encoder outputs. Over a 130 deg angular range the agreement was within 0.5 deg and over 10 deg increments near the straight ahead position the measured yaw angle increment was within 0.1 deg of the set value. The absolute errors caused by slight eccentricity of the beam are increased for large angular measurements. For a given turntable position the results repeated for the same turntable angle, within the resolution of the encoder. When a data point was repeated the calculated angles varied by ± 0.1 deg. This variation in the results was due to the eccentricity of the fan and to errors in the spacing of the detectors on the beam. However, there was sufficient confidence to go ahead and install the system in the 5 m tunnel even though the specified accuracy had not been achieved in this very quick and simple check before installation. Errors due to a slightly nonvertical beam onto the glass wedge, spacing of the detectors, and to limited accuracy of the turntable accounted for these inaccuracies.

D. Results from the Yawmeter Installed in the 5 m Tunnel

Initial tests in the tunnel were concerned with checks on the operation of the laser under increased pressure. Since the laser unit is mounted above the working section within the tunnel pressure vessel, it is subjected to the full working pressure up to a maximum of 3 atm. During these tests the beam intensity reduced with increased pressure.

The laser had Brewster windows at the end of the main tube, with the laser mirrors mounted outside the windows and an air space between. Changes in air pressure caused the refractive index of the air to change from 1.00029 at 1 bar to 1.00087 at 3 bars. The setting of the window at the end of the tube could be adjusted, for a given tunnel pressure, so that the beam travelled back along the same line. However, without this adjustment the laser path gradually diverged and, having been adjusted to operate at atmospheric pressure, at tunnel pressures of 2 bars and above the beam was not returned by the mirror and operation ceased. To correct the laser and thus give operation over the complete pressure range, the laser is housed in a tube with an exit window and operated under a constant pressure, independent of the changes in tunnel pressurization.

IV. Conclusions

Due to very large aerodynamic loads, deflections in the support systems of models tested in the RAE 5 m pressurized low-speed wind tunnel can be significant. A system has been developed to measure the achieved model attitude using onboard instrumentation. Accelerometers are used to measure pitch and roll to an accuracy of 0.02 deg. A new instrument, based on a rotating fan of laser light, has been made to measure yaw angle, continually, to an accuracy of 0.1 deg. It can also be used to measure the translation of the center of a strut-mounted model away from the balance calibration center.

A series of tests and experiments has refined the design of the laser yawmeter and the associated detectors in the model. Computer software and the instrumentation interfaces are now being tested with a model in the wind tunnel. Initial results show that the system will meet the original specification in terms of accuracy but, because an offset fan of light is being used to enable the system to operate under normal lighting conditions, the system is limited to a measuring rate of 25 Hz. A maximum speed of double this could be restored by using a more powerful laser, with additional safety implications, or by reducing the working section lighting levels to a subdued state which would still allow television cameras to operate. One further problem is that the laser will not continue to operate over the full 3 atm range of the tunnel pressurization. The reason for this has been identified and a solution found.

Although developed for use on the 5 m tunnel, the system is designed to be used on any facility with space for the laser unit and sufficient space to mount photodetectors and detector electronics in the model.

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