# "A CRITICAL INVESTIGATION INTO THE VALIDITY OF CURRENT PRACTICE IN SIMULATING THE VELOCITY PROFILE OF THE NATURAL WIND IN WIND-TUNNELS."

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## VOLUME I

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# GENERAL SUMMARY

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A variety of techniques are currently being advocated and employed in simulating the velocity profile of the natural wind in wind-tunnels when testing model buildings and structures. The writer holds the belief that serious inconsistencies are occurring in the results being produced using certain of these profile generating techniques. The reason being that the character of the turbulence in a wind-tunnel air-stream greatly influences the shearing and flow separation behaviour in the flow around any body under test.

A wind-tunnel investigation was made into the effects on the results of flow visualisation and pressure distribution studies on two model buildings. Air-streams without any induced velocity profile, then with velocity profiles of various forms, generated by both the graded screen and the surface roughness methods, were employed. The anticipated marked variations were found in the results.

These studies were followed by experiments in the field in which a large model (18 ft. x 18 ft. on plan and 6 ft. high) was constructed on a pivoted base. The velocity profile in the natural wind over the field station was obtained by erecting a 40 ft. instrument mast on which were mounted cup anemometers linked to automatic data recording equipment.

The velocity profiles measured over the site have themselves produced some interesting indications in the present uncertainty as to the exact form of natural wind profiles. The results favour the lower exponents being advocated for use in the Power Law for calculating the form of natural wind profiles.

It had been anticipated that the results from the field model would have been capable of being related to the wind-tunnel results, using Jensen's Model Law to account for scale differences. However,

it was found that this could not be done satisfactorily and has led to conclusions concerning possible weaknesses in the Model Law. Furthermore, unexpected features were found in the detailed pressure measurements from the field model. These features can be partly explained by micro-meteorological effects but their failure to appear in the wind-tunnel results required further study.

The possibility that wind-tunnel design could have had a significant influence on the results was then examined. Consequently, further studies were carried out in a second wind-tunnel of entirely different design. The results obtained in this tunnel differed in certain significant respects from the first wind-tunnel results and showed a more pronounced similarity with the results from the field model.

This has led to the examination of the possibility that acoustical resonance of the air column in the second wind-tunnel influenced the results. Although this phenomenon is already known to affect aeroelastic models, only further experiment will establish to what extent it can influence the pressures around rigid models. It is possible, using the idea of an "energy store", that the fluctuations in the natural wind caused by gusts could be at least partly simulated by means of induced acoustic air resonance.

# INTRODUCTION

# INTRODUCTION.

It was not until late in the 19th century that wind-tunnels were constructed, capable of producing air-flow under controlled conditions for the purpose of studying, in detail, the effects of wind pressure.

Prior to this period, tests to assess the effects of wind pressure on objects such as buildings and similar structures had to be carried out in the field using the natural wind. This field work was, however, remarkably successful in certain cases. The early work of Smeaton (1759) and of Duchemin (1842) produced results which form part of the basis of the generally accepted formulae in current use. Probably the most significant formula to emerge from this work was the following, which allowed the pressure on inclined surfaces to be calculated (36):-

$$pn = \frac{\rho^{2} \sin \theta}{1 + \sin \theta}$$

where:- pn = intensity of pressure on the inclined surface

$\rho$ = intensity at right angles to the wind

$\theta$ = the angle of the inclination to the horizontal

The first wind-tunnel experiments on model buildings were carried out by Irminger in 1895 (48). Eiffel followed in 1914 with tests on flat plates.

Shortly after this period, however, the rapid developments in the field of aeronautics began to demand that priority be given to research of this nature. The use and development of wind-tunnels became almost exclusively for this purpose. Little serious wind-tunnel study of the effect of wind movement on buildings and their environment was undertaken in the succeeding twenty years.

Noteworthy exceptions in this period were the extensive investigations of Dryden and Hill, in 1926 (27) and the tests on the model of the Empire State Building (42) in 1934.

The work by Prandtl and Betz - (1920-1923) and by Flachsbart (1927-1932) (89) on open frame and trussed structures paved the way to the study of wind effects on bridges and similar structures.

Between the years of 1930 and 1936 Irminger and Nøkkentved, in Denmark, made a long series of fundamental investigations into the nature of air movement over buildings. A large part of their work was concerned with assessing the accuracy of the methods of reproducing the flow patterns in the wind-tunnel (48).

Probably their most important work was in refuting the belief, held until that time, that model buildings, like model aircraft, should be mounted in wind-tunnels outside the wall boundary layers, in the undisturbed air-stream. The experiments carried out in this work showed that mounting models in the undisturbed air-stream did not establish the correct flow pattern around the model, even when provided with a polished plate beneath them extending some distance upstream and downstream. Similarly discarded was the "double image" arrangement in which the model was mounted in the centre of the wind-tunnel with an exact replica mounted immediately beneath it. The correct upstream separation point and downstream reattachment position could only be obtained, it was shown, by mounting the model on the floor of the wind-tunnel.

This use of the floor of the wind-tunnel to simulate the ground area around a building quickly became adopted as standard procedure by almost all workers in this branch of research.

Nøkkentved continued with research into the reproduction of natural conditions in the wind-tunnel and was subsequently followed by Martin Jensen. Jensen was not satisfied that by simply mounting a a model of a building on the floor of the wind-tunnel the natural conditions experienced by a full sized building standing in varied surroundings were fulfilled. Extensive investigation into the effect of varying the turbulence produced by the wind passing over rough terrain in nature, led to his publishing his Model Law in 1958 (50).

The necessity to reproduce the velocity gradient of the natural wind had been recognised by others who had approached the problem using different methods (5). In Jensen's method a wind-tunnel with an extremely long working section is employed using coverings of material, varying in size of roughness, on the upstream tunnel floor. Not only does this cause heavy frictional drag on the air-stream but appreciably thickens the boundary layer by means of the vortices shed by the rough material.

This differs considerably from the the method of profile generation employed by Baines and others (6). In this alternative method, screens or vertical grids of varied resistance are used to slow down the air-flow near the boundary, allowing progressively faster movement of the air as the height above the boundary increases. As a result the maximum air movement is allowed to occur at some point near the centre of the flow. Above this point the velocity distribution is uniform.

Attempts to recreate atmospheric turbulence in the wind-tunnel have been hindered by lack of adequate meteorological data. Information on the exact form of the velocity profiles of the natural wind, which exist over terrain of varying degrees of roughness, and the range and distribution of the eddy sizes in the flow is still incomplete and not yet fully reliable. Experimental work to gain more knowledge of these phenomena has been carried out both by meterological authorities and by individual groups (25) (53) (61), with increasing intensity in recent years but much still remains to be learned.

Velocity Gradients.

The first formula which allowed a calculation of the velocity gradient was produced by Hellman (10) (1915). After a prolonged period of study of the frictional resistance of the ground surface on air-flow, he devised the following formula which corrected the wind speed for changes in height:-

$$\frac{V_H}{V_{10}} = 0.2337 \left[ 1.00 + 2.81 \log (H + 4.75) \right]$$

Where:- $V_H$ = the wind velocity at any height

$V_{10}$ = the wind velocity at a height of 10 metres

H = the height above ground in metres.

Further attempts have been made to arrive at a more refined and accurate calculation of wind profile velocities. This work has been assisted by the growing volume of information on the measured velocities in the natural wind over different types of terrain, provided by meteorological offices and other authorities.

One approach is to employ a formula having a variable index. This is the, so called, Power Law. However, at present an argument still ensues as to which is the more accurate version. The formula supported by Shellard (A) is a development of that originated by Hellman and takes the form:-

$$\frac{V_h}{V_{10}} = \left(\frac{h}{10}\right)^{\alpha}$$

$V_h$ and $V_{10}$ are the mean speeds at h metres and at the meteorological standard height of 10 metres above ground, respectively. The power $\alpha$ varies from 0.1 to 0.4 (A value of 0.17 has been advocated for use throughout Britain).

Davenport (B) developed his own version of this formula, which depends on the height and velocity of the gradient wind:-

$$\frac{V_Z}{V_G} = \left(\frac{Z}{Z_G}\right)^{\alpha}$$

Where:- $V_Z$ = the velocity at any height Z

$V_G$ = the velocity of the gradient wind

$Z_G$ = the height of the gradient wind

$\alpha$ = a variable power, of value between 0.16 and 0,40

Jensen (52), however, supports the theory that the velocity profile follows the form:-

$$\frac{V_Z}{V_*} = \frac{1}{K} \ln. \frac{Z + Z_o}{Z_o}$$

In this formula $V_Z$ is the velocity at any height Z, K is von Karman's constant (0.4), $Z_o$ is the roughness parameter (or position of zero flow) and $V_*$ (the friction velocity)

$$= \sqrt{\frac{\tau_o}{\rho}}$$ where $\tau_o$ = the Reynolds stress

$$= \sqrt{\varepsilon \frac{dV}{dz}}$$ and $\rho$ = the eddy vicosity

The above formula has been developed from the work of Nikuradse and others (89) which has shown that the velocity profile at the boundary in pipes and ducts depends upon the roughness of the wall surface.

In 1937, Paesche made experimental studies of the turbulence in the natural wind. From his results he was able to show that the motion of the natural wind was also controlled by the laws of friction governing the flow of fluid in rough walled pipes. That is, the effective roughness of the ground surface could be determined by measurements of the velocity distribution in the wind at heights immediately above the surface of the earth. This led to his obtaining values of the roughness parameter which varied between 3 and 130 cms., depending on the terrain.

About this time, in 1933, another important discovery was made. Millikan and Klein (C) found, from experiments made in the natural wind, that the scale of the turbulence to that of the objects over which the wind flows is of considerable importance. They found that the pressures experienced by an object in the flow remained unaffected by increases in the turbulence, provided that the scale of turbulence was large in relation to the size of the object. If the turbulence was small in relation to the object then the pressures experienced by the object altered rapidly with increases in the turbulence of the flow.

## Jensen's Model Law.

Following this work and from the logarithmic formula above, Jensen has shown that a graph of the naturallog. of the heights in the profile plotted against their respective velocities, expressed as a percentage of the maximum, will be a straight line. The point at which this straight line graph cuts the vertical axis can be regarded as the position of zero flow, i.e. the roughness parameter $Z_o$.

After analysing the results of extensive field and wind-tunnel experiments, Jensen formed the conclusion that the value of $Z_o$ is the key to the correct simulation of natural conditions in the wind-tunnel. He claims that experiments in wind-tunnels must be carried out in air-flows in which are created the correct velocity profiles (50).

To obtain the necessary velocity profiles, it is claimed that the air-stream must be passed over a long "fetch" of rough material. The velocity profile so generated by frictional drag will have a form dependant upon the roughness of the material placed in the wind-tunnel. The straight line logarithmic graph of this profile, as stated earlier,

(C) Millikan, C.B. & Klein, A.L. - "The Effect of Turbulence," Aircraft Eng. 169, Aug. 1933.

will cut the vertical axis at a point representing the position of $z_o$ in the wind-tunnel air-flow.

The velocity profile over terrain with a corresponding roughness in full-scale is next plotted on a log. graph. From this graph is obtained the roughness parameter in nature, $Z_o$.

For model tests in wind-tunnels the Model Law rules that the ratio of the size of the model to that of the full-scale building must be exactly equal to the ratio of the roughness parameter in the wind-tunnel to the roughness parameter of the corresponding natural wind. That is:-

$$\frac{Z_o}{z_o} = \frac{D}{d}$$

$Z_o$ being the roughness parameter in nature, $z_o$ the roughness parameter in the wind-tunnel; D is the height of the full sized building and d the height of the model building.

## Experiments in the Field.

Even with increasing care in producing the supposedly correct conditions in wind-tunnels, discrepancies have been obvious between the results obtained in different tunnels and between these results and those available from experiments in nature. It has become obvious that more information is necessary on the variations between the results obtained from wind-tunnel research and those obtained from measurements in full-scale conditions.

Although Galileo and Newton, in the 17th century, considered wind loading on buildings (9), the work of Smeaton and Duchemin in the first half of the 19th century produced the first usable information from measurements in the natural wind.

Following the Tay Bridge disaster, Sir Benjamin Baker conducted experiments between 1884 and 1890 in the natural wind for consideration in the design and construction of the Forth Rail Bridge. These experiments, on two pressure boards, one $1\frac{1}{2}$ sq. ft. and the other 300 sq. ft. in area, led to the conclusion that the wind pressure per unit area on small vertical surfaces is greater than that on large surfaces.

However, Stanton (1912) whose principal experiments were carried out on the high level footways of Tower Bridge, London, disputed this theory. Stanton's conclusions were that the same intensity of wind pressure is experienced by a large surface area as a small area.

Only isolated cases of wind measurements on and around buildings are recorded in the 40 years following Stanton's work. By far the most detailed and noteworthy example, in this period, was the work carried out on the Empire State Building. In addition to extensive model tests, prior to construction, field experiments on the building itself were carried out. The results of this work are, in themselves, interesting but one of the major contributions it made was to show that the techniques used in the field measurements were unsatisfactory. More accurate methods of measuring simultaneously the pressure distribution on the surfaces of very large buildings have since been developed.

Once again, the work of Jensen in this field of research has made a major contribution. In recent years a considerable increase has occurred in the volume of research being carried out in the field. Jensen's work was probably one of the first and most significant in the recent research. This work covered the effects of shelter and the effects of wind pressure on buildings (49) (52).

Cabron (14), Nägeli (72) and others (39) have carried out work of significance in the sphere of shelter effects. Davenport (D) has made pressure measurements in connection with his work. Interesting

(D) Paper 9 of reference (73)

work on the measurement in nature of velocity profiles above urban areas, together with the wind effects to be expected at ground level in these areas, has been carried out at Liverpool University.

Perhaps the most important and extensive research programme, currently being undertaken, is that of the Building Research Station. In this programme, measurements from the full-scale are being made on large buildings in London. Among these are State House, Millbank Tower and the G.P.O. circular transmission tower. Simultaneous pressure measuring devices (E), consisting of circular aluminium pressure plates set flush with the external walls and windows, allow the simultaneous recording of pressure measurements from large areas of the external surfaces of the buildings. One of the most interesting sections of this work will be the comparison of the results obtained from the field with those obtained from simulated conditions in the wind-tunnel.

## The Problem.

It can be seen that the problem at issue is composed of three interdependant sections. Firstly, the assessment of information concerning natural wind profiles and turbulence, in general, and over specific sites in particular. Then the problems of simulating natural conditions in wind-tunnels. Finally, relating the results of wind-tunnel measurements to those obtained from full-scale conditions on the specific sites.

(E) Paper 13 of reference (73)

# CHAPTER I

# CHAPTER 1.

## OBJECTS OF THE INVESTIGATION.

In the field of aero- and hydro-dynamics the criterion for obtaining the correct scale conditions in wind-tunnels is the Reynolds' number:- $Re = \frac{\rho v d}{\mu}$

Where:- $\rho$ is the fluid density,
$v$ is the undisturbed velocity of the flow,
$d$ is a typical dimension of the object,
$\mu$ is the fluid viscosity.

With regard to wind-tunnel tests on model buildings, the Reynolds' number is not the sole criterion to be considered. It can be seen that if the Reynolds' number associated with a full-scale building 30 ft. high in a 70 m.p.h. wind were to be created for a model building 2 ft. high in a wind-tunnel, it would require an air-flow of 1,050 m.p.h. Wind-tunnels of this capacity are not feasible for research into wind effects on buildings.

Fortunately, it is not necessary to recreate the correct Reynolds' number for wind-tunnel tests on sharp edged bodies, such as straight walled buildings (but may be necessary for testing curved walled buildings). The reason for this is that the natural wind in the atmosphere of the earth is nearly always turbulent from the surface of the ground up to heights of 1,500 ft. and more. That is, the natural wind is a roughness flow, with the turbulence caused by the irregular ground surface over which it passes.

Reynolds' number does not apply to the velocity profile of a fully turbulent flow. Provided that no positive nor negative thermal effects exist, the scale of turbulence in the wind depends solely on the degree of roughness of the terrain over which it is passing.

The problem therefore resolves itself into establishing the relevant parameters for testing rigid models in turbulent air-streams which are, the necessary intensity of turbulence, the required scales of turbulence and the correct velocity profile.

Nevertheless, there still exists a body of opinion which claims that wind-tunnel investigations of wind movement around buildings and other structures, constructed on the ground, should be carried out in an air-flow which is free from significant turbulence (A). This opinion is, however, fast giving way to a school of thought which considers that the growing experimental evidence indicates that it is necessary to create velocity profiles in the wind-tunnel air-flow. Within this school of thought, however, there is a divergence of opinion.

To generate a velocity profile in a wind-tunnel by the surface roughness method, advocated by Jensen, as required by his Model Law, it is necessary to have a working section which has a length of at least 9 to 9.5 times its height. Indeed, there are indications from certain field work (B) that an up-stream fetch of roughness 100 times the required profile height may be necessary.

There are extremely few wind-tunnels with working sections of this length. From 2 to 3 times the height is the average length of working section in most wind-tunnels. This restriction in working section length has been the main reason for the objections to Jensen's technique and has resulted in the development of the graded resistance method of profile generation.

The graded resistance takes the form of either a wire mesh screen, whose density increases progressively down to the wind-tunnel floor, or a vertical arrangement of solid rods. The rods are so arranged that the gap between them is gradually decreased down to the tunnel floor, thereby increasing the blockage to the air-flow.

(A) Paper 5 of reference (73)
(B) Meteorological Office Research Unit, Cambridge

It is the theory underlying the investigation outlined in the following work that these methods of profile generation produce air-streams of a fundamentally different character. The profile created behind a screen of graded resistance can be equated to the velocity profile in a purely laminar flow, as first measured by Prandtl (90). The air passing through the screen is split up into a series of laminations, each lamination having a progressively greater velocity the further it is from the wind-tunnel floor. It is known that there is no intermixing of these laminations for a considerable distance downstream of the screen (31). The boundaries between the laminations are formed by the wakes behind the wires making up the screen and there is no mixing of these wakes with the laminations nor grouping of the wakes until the distance from the screen already stated.

The type of air-stream described above is completely different from that produced by passing an air-current over a considerable area of rough material. In this case the reduction of horizontal energy in the lower areas of the flow is a result of the conversion of horizontal energy into vertical energy, due to the large scale eddying and mixing in the flow. This turbulence is caused by the drag of the rough surface and by the shedding of eddies from the obstacles at the boundary.

Hence, by these two methods, two distinctly different air currents are produced. The first having its velocity variation across the flow caused by the drag of the restricted portion of the screen and the acceleration through the open portion of the screen. In the second, the variation in horizontal velocity is due to the large scale conversion of horizontal kinetic energy in the flow into vertical kinetic energy, resulting in fully developed turbulence.

It has been argued that this should not substantially alter the acceleration of the flow around a body placed in the air-stream nor alter the general form of the flow pattern around the body. This has been said to mean that since the curvature of the flow pattern around the body remains, in effect, the same then the pressures on the body will be the same. In this argument a particularly important factor is neglected; that is, the shearing effect which takes place in the flow immediately behind the sharp edges of the model building form. On curved model forms it will mean an alteration in the position of the flow separation point.

An example of the effect of this considerable variation in the character of the flow can easily be drawn. In an air-flow in which all the kinetic energy of the flow is horizontal, all this energy can be quickly translated into a circular motion, for example, in the vortex streams generated by a sharp corner penetrating the flow. When a large proportion of the kinetic energy in an air-flow is, however, moving across the flow, in a non-horizontal direction either vertically or laterally, then the simple translation of the flow to a circular motion cannot easily take place. The result, in the second case, is a rapid breakdown of the vortices with a considerable corresponding reduction in the negative pressures experienced by the surfaces adjacent to these vortices.

The investigation described in this thesis was designed to test the theory concerning the probable variations in pressure distribution on models caused by using the three techniques at present used in wind-tunnel studies. That is, air-streams without velocity profiles, air-streams having velocity profiles generated by the surface roughness method and air-streams having velocity profiles generated by graded screens. It was considered that the technique using the fetches of rough material would produce results much closer to those experienced in full-scale than those results obtained from the other two methods.

To test this probability and to assess the shortcomings of the surface roughness method, a major field experiment was included. In the field experiment an instrumented mast was employed to measure the velocity profiles over the site on which a large model was constructed. Pressure measurements were carried out on this field model, similar to those made on the wind-tunnel models, which are described later.

# CHAPTER 2

# CHAPTER 2.

## MODIFICATION OF THE WIND-TUNNEL AND PREPARATION OF THE MODELS AND INSTRUMENTS

The wind-tunnel which was used in the investigation was of the N.P.L. open circuit, closed jet type and is shown in fig. (1). It had a working section of 1'-9" x 1'-9" square in cross section and was situated in the Department of Building of the Heriot-Watt University.

In its original form its overall length was 22 ft. 7 ins., having a working section length of 4 ft. 9 ins. The wind-tunnel which had been used by Jensen, in the experiments leading to the formulation of his Model Law, had been of very similar design. However, due to his need to have an extremely long working section, Jensen's tunnel was 10 metres long with a working section 60 cms. x 60 cms. in cross-section and 5.5 metres long. This gave a working section length to height ratio of 9.11:1.

The square cross-section of the Heriot-Watt wind-tunnel was well suited to the work to be carried out since it gave the maximum floor area in the working section for mounting model buildings and reduced constriction effects to the minimum. However, the length of the working section was completely inadequate for the purpose of generating velocity profiles by means of the roughness method. Since the working section was only 4 ft. 9 ins. long the ratio of length to height was only 2.72:1. This restriction necessitated the redesigning of the wind-tunnel so that Jensen's methods could be recreated exactly, for the purposes of comparison.

In redesigning the wind-tunnel certain sections, namely the inlet effuser, the two circular exhaust sections either side of the fan casing and the canvas anti-vibration section, were shortened. The working section was extended by 15 ft. 5 ins. to give a total working section length of 16 ft. 3 ins. that is, giving a length to height ratio of 9.3:1. Since this ratio was a little greater than that of the wind-tunnel which Jensen had employed it was considered to be satisfactory. The final design of the wind-tunnel is shown in fig. (2).

To permit the extension to its length, the wind-tunnel was moved from the basement laboratory, in which it was first situated, to very much more spacious accommodation (an empty room 36 ft. 3 ins. long, 25 ft. wide with a ceiling height of 15 ft.).

The power unit of the tunnel was an eight bladed 35 in. diameter, high efficiency fan driven by a 4 H.P. D.C. electric motor capable of working at up to 1,400 r.p.m.. When the redesigned wind-tunnel had been erected in its new situation the power unit was overhauled and connected to the power supply. The necessary D.C. supply was obtained by passing the 440 v.3 phase output from a star-star transformer through a large plate rectifier which produced a final direct current of 300 volts.

The control of the speed of the motor was effected by means of a three staged main switch gear, thus giving three principal fan running speeds. In addition, variable resistances were incorporated to give fine control of the lowest and the highest ranges of speed. On the lowest speed range a heavy duty variable resistance (of 7 amps. capacity, total resistance 150 ohms in 51 increments) and the two fixed coils of the motor starter were arranged in series thereby producing the strongest field. By arranging the two fixed coils in parallel, the middle speed range was obtained and by arranging a heavy rheostat in parallel with one of the starter resistances a variable control of the top running speed of the motor was achieved. With this rheostat adjusted to its minimum value the weakest motor field strength was created, thereby producing the maximum fan speed.

As can be seen from the figures given below fine adjustment was possible, by this arrangement, over almost the complete range of fan speeds.

Low Setting:- From 15.1 ft./sec. to 73.87 ft./sec.
(10.30 m.p.h. to 50.37 m.p.h.)
Mid Setting:- 85.39 ft./sec. (58.22 m.p.h.)
Top Setting:- 88.2 ft./sec. to 140 ft./sec.
(60.15 m.p.h. to 95.4 m.p.h.)

As will be seen later, it was found to be most convenient to work in the lowest range of running speeds. The maximum speed in this range, i.e. 74 ft./sec., was found to be suitable for pressure readings, producing sufficiently clearly defined readings in the manometers employed.

## Instrumentation

Certain instruments were already available at the start of this work. These included a hot-wire anemometer, a tilting multitube manometer, two small inclined tube manometers, with ranges of up to 1 in. w.g. and 3.5 ins. w.g. respectively. Three N.P.L. type pitot-static tubes were also available together with two micro-pitot tubes and two vane anemometers.

A more sensitive manometer with a wider range was later obtained to allow more accurate velocity measurements to be made when the velocity profiles, generated by the various methods, were being explored. The longer of the two manometer tubes could be set in 4 different positions to give a range of sensitivities from 0.2 in w.g. to 20 ins. w.g.

By far the most important instrument, in the work under discussion, was the multitube manometer. This manometer had 15 pressure tubes mounted on a scale graduated in inches and one tenth of an inch and was capable of inclining through 90°, from the vertical to the horizontal. Of the 15 pressure tubes, 14 were used to make pressure measurements from the model under test, the 15th tube was used to measure the total head pressure of the free stream in the working section. The static tapping in the roof of the working section was connected to the reservoir at the rear of the manometer.

In this way, by measuring and recording the free stream dynamic pressure simultaneously with the measurements being taken from the model, any variations in the wind-tunnel air-speed would be recorded and accounted for. This was felt to be important for although very little short term variation in the voltage supply, and hence in the fan running speed, was obvious, a slow drift in the running speed of the electric motor did occur over a considerable period of time. This was due, primarily, to a slow heating of the resistances in the switch and control gear.

What was more important about the arrangement of recording the dynamic pressure of the free stream simultaneously with the pressure measurements from the model was the means of arriving at the pressure coefficients for each point on the model. All that was required was to divide the height of the column recording each pressure measurement from the model by the height of the column measuring the dynamic pressure of the air-stream. This was due to the arrangement in which the static pressure acting on the surface of the liquid in the manometer reservoir is automatically deducted from all the manometer readings, leaving the results as straight-forward dynamic pressure readings.

The static tapping used in all the experiments was a 0.5 m.m. diameter hole in a polished brass plate, 4 ins. by 3 ins. in area, set into the roof of the working section, flush with the surface. It was positioned 18 ins. forward of the model test position and 8 ins. away from the tunnel wall. Adjacent to the static tapping was mounted one of the micro-pitot tubes, 3 ins. from the tapping and projecting 4 ins. into the flow.

Positioned where they were, it was considered that the readings from the tapping and the pitot tube were close enough to the model test area to show negligible effect from the longitudinal pressure gradient in the long working section. Also, they were sufficiently far forward of the test position not to be influenced by any minor blockage effects which might result from the presence of the model in the air-stream.

The micro-pitot tubes, used in the various experiments, were produced from stainless steel hypodermic tubing of 1.35 m.m. external diameter and 0.72 m.m. internal bore. Each pitot tube was $5\frac{1}{2}$ ins. long with a $\frac{1}{2}$ in. long head. The inlet face of each head was accurately machined and its calibration later checked against one of the N.P.L. pitot-static tubes. A brass connection nipple was used to secure the hypodermic tubing and facilitated the connection of the rubber pressure tubing.

## The Wind-Tunnel Models

Two model buildings were employed in the wind-tunnel experiments. These models were not constructed specifically for the experiments to be carried out but were two models selected from a set of fourteen which had been used in a previous investigation. (121)

It was considered that the design of these models offered a number of desirable features, having been based on certain rationalised concepts. They were designed on a simple form which depended upon a fixed module of $1\frac{7}{8}$ ins. The first requirement was that the models should have a symmetrical plan form, in order that when rotated through 360° in the wind-tunnel, the aspect presented to the air-stream would be identical at each test position. For this reason, the models were square on plan.

Flat roofs were chosen in their design for two reasons. A low pitched roof experiences the greatest and most clearly defined negative pressure effects and a flat roof produces the shortest downstream vortex pocket (18) (121), which had a very important bearing on the next design feature.

Each model had a central patio and it was considered that this characteristic of the design offered a unique and important possibility. As was stated in Chapter 1, it was anticipated that the nature of the vortices generated in the air-stream behind the leading edges of the model roofs would be affected by the character of the turbulence in the air-stream. As a result, it was considered that the variation in the breakdown of the vortices in the various flow conditions would have a direct effect on the air penetrating to the central patios, which would be readily apparent in the pressure measurements from the patio walls.

Using a scale of 5/32 in. = 1 ft., the $1\frac{7}{8}$ in. module represents 12 ft. The smaller model was $1\frac{7}{8}$ ins. high, representing a single storeyed building, and was $5\frac{5}{8}$ ins. x $5\frac{5}{8}$ ins. on plan, with a central patio $1\frac{7}{8}$ ins. x $1\frac{7}{8}$ ins. on plan and $1\frac{7}{8}$ ins. high. The larger model had exactly the same plan form, including patio, and represented a three storey high building. Its external dimensions therefore comprised a $5\frac{5}{8}$ ins. cube.

It must be noted that for ease of reference, a convention was adopted in which the design module was referred to as 'A' and both models were identified by their patio size. Therefore, the smaller model was identified as A x A x A and the larger model as A x A x 3A.

The plan and vertical cross-section of the smaller of the two models are shown in fig. (4). The pressure tappings, which are shown, were positioned on the models in such a way that they covered one quarter of the external surface areas of the models and that by rotating the models through $360^{\circ}$ the pressure patterns on the complete surface area could be measured.

In constructing the models, clear Perspex sheet 3/16 in. thick, had been employed, cemented together using chloroform as a solvent-binder. By using this material, the drilling of certain of the more awkwardly positioned pressure tappings was greatly assisted. In drilling such tappings, considerable difficulty was experienced since the pressure holes frequently had to be drilled in the 3/16 in. thickness of the Perspex and taken several inches from the tapping point. This often required several changes in the direction of the pressure hole to bring it out at a position where a nipple connection point could be cemented on.

The tapping holes were 0.055 in. in diameter except at the edges of the model where they were 0.029 in. in diameter. The tappings were positioned on a basic ½ in. grid but the spacing was reduced near the edges to 5/16 in. and the last rows of holes were positioned 1/16 in from the edges of the surfaces bearing the tapping holes.

An additional row of pressure tappings ⅛ in. from the edges was provided in the roof surfaces. This was necessitated by the fact that the pressure variations around the edges of roofs take place so rapidly that extremely close spacing of pressure tappings in these areas is essential to be able to measure the variation. It was the close spacing of the two rows of holes round the roof edges which required the diameter to be reduced. For within the thickness of the Perspex sheet forming the model wall, two tappings had to be drilled vertically, side by side, to meet a secondary hole leading to the connection point.

Since 14 pressure tubes, leading to the manometer, had to be accommodated in the hollow interior of the models, this tubing had to be of relatively small bore. For this reason ⅛ in. I.D. rubber tubing was employed. Connection with the rubber manometer tubing was facilitated by gluing nipple connectors, cut from 3/16 in. O.D. Perspex tubing, over the inside positions at the tapping holes. After gluing, every nipple was tested for air leaks by a suction of 25 ins. of mercury delivered from an air pump. All leaks thus detected were carefully sealed and the connectors retested.

In mounting the models for testing in the wind-tunnel, the model under test was secured by a clamp provided in the working section turntable. When clamped in this position the hollow interior of the model was positioned over a one inch square hole in the turntable which was just large enough to allow the 14 pressure tubes from the manometer to pass through into the body of the model for distribution and connection to the various pressure points.

# CHAPTER 3

# CHAPTER 3.

## GENERATING THE VELOCITY PROFILES IN THE WIND-TUNNEL

Immediately after reconstructing the modified wind-tunnel, tests were carried out to determine whether there were any disturbances or inconsistencies in the air-stream within the working section. Using a micro-pitot tube connected to the sensitive inclined tube manometer, 3 traverses were made transversely across the working section, each traverse positioned at $\frac{1}{4}$, $\frac{1}{2}$ and $\frac{3}{4}$ of the height. Another set of 3 traverses were made vertically across the working section, positioned at $\frac{1}{4}$, $\frac{1}{2}$ and $\frac{3}{4}$ of the width.

No measurable disturbances were discovered in the cross-section of the air-stream at the working section. This was most probably due to the considerable settling length provided by the very long working section. However, as can be seen in fig. (5) a very clearly defined boundary layer existed at the wall surfaces. This 3 ins. deep boundary layer resulted from the untreated nature of the surface of the plywood forming the wind-tunnel walls. Although the plywood had been sand papered smooth, no attempt had been made to varnish the surfaces nor to polish them and bring them to a high aero-dynamic smoothness. This decision had been taken deliberately since it was known that various methods of profile generation would be employed and that a heavy boundary layer would assist in creating the profiles.

It was noted during the preliminary measurements that little short period fluctuation was evident in the manometer readings. This was a significant improvement in the performance of the wind-tunnel since marked fluctuations in the readings were evident when the wind-tunnel was situated in its previous position, in the basement laboratory. The improved performance of the tunnel was almost certainly due to the much improved recirculation provided by the more spacious accommodation. Minor contributions may have been made by the stability of the increased electrical supply voltage and by the slightly heavier load imposed on the fan by the increased length of the wind-tunnel.

## Profile Generation by the Surface Roughness Method.

### A. HEAVY PROFILE.

As stated previously, it was planned that in addition to testing the models in the wind-tunnel with an air-stream having no induced profile, they would be tested in air-streams having velocity profiles of three distinct forms. The form of the profiles would, in turn, be light, moderate and heavy and would correspond to the profiles found in the natural wind over smooth terrain, moderately rough terrain (dotted with woods, villages and obstructions of similar size) and over extremely rough terrain (such as the centre of a city). Jensen's surface roughness method was to be used first, followed by screens of graded resistance, to produce the required profiles.

The results obtained from the smaller wind-tunnel model, measured under the same velocity profile conditions as measured in the field, would be compared with the results from the large-scale field model. By doing so, the validity of the methods of creating the wind-tunnel profiles would be tested.

In selecting which form the velocity profiles should take and the means of creating the profiles, it was decided to adopt the techniques used by Jensen. In this way, the intention of investigating the conflicting existing theories on profile generation in wind-tunnels would be further pursued.

Therefore, wherever possible, the exact roughness methods employed by Jensen were adopted (50). It was decided to attempt to produce a heavy profile first, similar in form to the heaviest profile produced by Jensen.

To produce the velocity profile found over cities and similar densely built-up areas, Jensen employed timber bars 2.9 cms. wide and 7.0 cms. high. The tops of the bars were shaped to the form of double pitched roofs with 45° slopes. The bars were placed across the full width of the tunnel at random angles between 70° and 90°. This variation of the angle at which the air-flow passed over the bars was designed to avoid any cumulative effects in the turbulence produced in the flow. Spacing of the bars was arranged to obtain a density of 25% of the floor area. The boundary layer produced by this method was 30 cms. high.

Because the wind-tunnel to be used in the experiments was somewhat smaller in cross-section than that employed by Jensen (21 ins. $^2$ as opposed to 60 cms. $^2$) it was decided to reduce the size of the timber bars by a corresponding amount. The bars were, therefore, prepared 1 in. wide and $2\frac{1}{2}$ ins. high. Their top surfaces were prepared to the double 45° roof pitch.

By arranging the bars in the wind-tunnel in the same manner as Jensen, with their centre positions 4 to 5 ins. apart on the centre line of the tunnel, minor adjustments of the velocity profile could be achieved by varying the spacing between the bars.

However, the major factor governing the form of the velocity profile over the model test position was the position of the last timber bar. The nearer to the test position this bar was located the higher the position of zero flow (or negative back flow) became. Various positions of this bar were tested before a satisfactory profile, as shown in fig. (6), was obtained. To achieve this profile the last bar of the roughness grid had to be positioned 16 ins. from the front edge of the model test area.

The profile thus obtained was plotted on a straight line logarithmic graph, see fig. (7) in which the horizontal axis is the relative velocity and the vertical axis is the natural log. of the heights of the points of measurement in the flow. The position of zero flow or the roughness parameter $z_0$, was obtained from the point at which the graph cuts the vertical axis. In this case the graph cut the axis at 1.5 that is a $z_0$ of $1\frac{1}{2}$ ins.

As will be seen later, the information obtained from the natural log. graphs was essential when comparing the results obtained from the wind-tunnel model with the pressure measurements from the field model.

## B. MODERATE PROFILE

Following the technique used by Jensen to create a moderate velocity profile in his wind-tunnel, in which 2 cms. x 2.5 cms. wooden fillets were employed, wooden bars 1 in. high and 13/16 in. wide were prepared. These bars were wedged across the floor of the tunnel for the full length of the working section. They were positioned at random between 6 ins. and 9 ins. apart with their positions varied up to 20° from 90° to the axis of the wind-tunnel.

It was found that some of these timber bars had a tendency to be dislodged by the air-stream in the working section and to avoid any possibility of their being carried into the fan, some means of anchorage had to be arranged. Two lengths of strong thin cord were anchored, close to the tunnel walls, immediately downstream of the honeycomb stabiliser. These were passed over the top of the ends of the bars for the length of the tunnel and secured, again close to the wind-tunnel sides, just short of the turntable of the model test area.

The position of the last bar of this length of roughness was 21 ins. from the front edge of the model test position. Measurements of the velocity profile produced in the air-flow over the test position by this means were made, as in the case of the heavy profile, using a micro-pitot tube connected to the sensitive inclined tube manometer. Measurement of the static pressure of the flow was obtained from the static tapping in the roof of the working section.

These measurements showed the velocity profile to have the form shown in fig. (6), with a total height of 10 ins. This profile gave a straight line logarithmic graph of the form shown in fig. (7). The graph cuts the vertical axis at the 0.62 mark, which represents a $z_0$ in the flow of approximately $\frac{5}{8}$ in.

## C. LIGHT VELOCITY PROFILE

After completing work on preparing the technique of reproducing the moderate velocity profile, attention was turned to the light velocity profile.

In producing velocity profiles of this form, Jensen had not used bars of material across the wind-tunnel but had densely covered the working section floor with large angular stones. When considering this method it was decided that since the roughness material would have to be removed from the working section then replaced again several times, the method employing stones was not suitable. The reason being the lengthy process involved and the uncertainty of replacing the material exactly as it had been before.

It was decided, therefore, to attempt to produce the required profile using, once more, a series of bars of some suitable material. A large number of bars were cut from $\frac{3}{8}$ in. thick plywood, to a depth of $\frac{1}{2}$ in. These were wedged across the floor of the tunnel working section in exactly the same manner as before. The centres of the bars were varied at random from $1\frac{1}{8}$ ins. to $1\frac{1}{2}$ ins. apart.

Measurements of the velocities in the air-stream above the model test area showed that this system of roughness produced a profile 8 ins. high. The form of the profile had the desired light curvature, as shown in fig. (6). The straight line logarithmic graph of this profile is shown in relation to the graphs from the other two methods in fig.(7) and shows the $z_0$ of the profile to have been 0.116 in.

## Profile Generation by Wire Mesh Screens

Reports are available of velocity profiles being created in wind-tunnel air-streams by two methods of graded resistance. The first uses wire mesh screens either curved in side elevation (6) (31) or mesh screens of graded resistance (107). The second method employs a vertically positioned row of horizontal spars or rods. Graded resistance to the flow is achieved by spacing the rods more closely together near the floor of the tunnel and spacing them at an ever increasing distance as the height above the floor increases (76)

Both of these methods were given careful consideration and it was decided that although both would produce fundamentally the same type of flow system, there would be significantly more wake behind the rods (8) than behind the mesh screens. For this reason it was considered that the wire mesh screens would be a better choice since the profiles produced by them would illustrate more clearly the anticipated variations in the results.

The next choice which had to be made was whether to employ screens which were vertical in side elevation and which were graded in blockage or to employ screens whose side elevations were curved, thereby closing the horizontal aspect of the screen apertures progressively towards the bottom. Because it was considered that greater control could be had, and to avoid the possibilities of secondary disturbances it was decided to employ curved screens.

However, it soon became evident that this method was unsuitable. A reasonable degree of success was achieved using an interwoven steel mesh screen with $\frac{1}{8}$ in. square apertures. Although profiles of the desired form were obtained up to 12 ins. high, it was found that it was impossible to control the air-flow above the profile. The volume of air which was prevented from passing through the restricted apertures at the bottom of the screen rose to the centre of the tunnel and escaped through the centre of the screen.

This meant that immediately above the velocity profile was an area of accelerated flow. Numerous methods were employed in attempting to remove this undesirable feature of the flow. The screens were first curved downstream then were curved upstream. The upper portions of the screens were also curved to give that part of the screen a graded resistance in attempting to spread the escape of the displaced air. Deflectors, barriers and additional, superimposed sections of wire mesh were employed but without significant success.

As a result, this method of profile generation was abandoned. It was considered that if measurements on the models to be tested had been made in the air-streams having profiles generated by curved wire screens, the results would have been seriously affected. The area of accelerated flow which existed above the velocity profiles would have had a restricting effect on the vortex sheets formed behind the models. The curvature of the vortex sheets and their position of recontact downstream of the model, on which a large proportion of the pressure effects on the model depends, would have been appreciably altered.

This left the screens of graded resistance as the only alternative and work began on investigating the characteristics of the flow produced behind these screens.

It had been feared that because of the method employed in constructing these screens the flow produced by them would be irregular in character. Although some irregularities were produced in the early stages of preparing the screens, it was found that by adjusting the various parts of the screens or by changing sections of the wire mesh, surprisingly good control was obtained over the form of the profiles produced by the screens.

The method employed in producing the screens was to use a piece of wire mesh of very wide weave, with say $\frac{3}{4}$ in. or $1\frac{1}{2}$ ins. openings, as a vertical support onto which were secured secondary bands of wire mesh.

In producing the first screen, for the light profile, numerous attempts, based simply on increasing experience, were made to prepare a suitable screen. By means of either increasing or decreasing the widths of the secondary strips of wire mesh or by replacing certain strips of mesh with others of greater or lesser density, as required, the height and shape of the profile produced by the compositescreen could be controlled. The fine adjustment of the profiles, achieved by this method was quite remarkable.

The same procedure was followed for each of the profiles with equal success. In two of the profiles, however, minor irregularities occurred in spite of all attempts to adjust the sections of mesh to get rid of them. These profiles were the light profile, simulating the wind gradient over smooth, flat terrain, and the heavy profile, representing the wind gradient over extremely rough areas of ground surface, such as the centre of cities.

The reason for the irregularities was the acceleration of the air-flow either through joints in the screens or the excessive escape over the top of an extremely dense section of the wire mesh screen.

Various methods were employed in attempts to remove the irregularities. Since the accelerated sections of the flow were narrow in width, it was eventually found most successful to introduce across the screen, at the necessary height a length of stout cotton twine. The twine was interwoven with the mesh of the screen, horizontally across the width of the wind-tunnel and can be seen in the photographs shown in figs. (9a, b & c).

As can be seen from the graphs in figs. (6) and (7), the forms of the profiles produced by the screens, although of slightly heavier curvature, were kept as close as possible to those produced by the roughness method of profile generation. The reason was to facilitate the comparison of the results from the two models, produced by the two methods of profile generation.

None of the feared irregularities remained after the screen had been finally modified. The bands of accelerated air and the bands of air at uniform speed had been dispersed from each air-flow. What remained were velocity profiles which took the form of almost smooth curves. The graded resistance of the screen, even although the grading did not follow a uniform progression, allowed a gradually accelerated escape of air through the screen which resulted in a smooth, even profile.

The completion of the three screens marked the end of the preparatory stage of the wind-tunnel and apparatus. Work was then begun on testing the models in the various flow conditions to be investigated.

# CHAPTER 4

## CHAPTER 4.

## FLOW VISUALISATION EXPERIMENTS

### Methods Employing Smoke

In order to attempt to make a visual assessment of the anticipated variations in the air-flow patterns produced around the model buildings by the various flow characteristics, a series of flow visualisation experiments was planned. It was expected that the differences in the vortex behaviour behind the leading edges of the models would produce clearly defined modifications to the shape of the vortex pockets surrounding the models.

To allow these effects to be studied and photographed it was planned to use smoke tracers. In the first attempt to photograph the air movements, a smoke generator, manufactured by Taylor Electronics Ltd., was employed. For a number of reasons this method was not fully satisfactory. Although the apparatus, using a mixture of carbon dioxide and vapourised oil, produced large volumes of smoke, it proved extremely difficult, because of the design of the pressure equalisation system of the apparatus, to inject the smoke in the required quantity into the desired position in the wind-tunnel.

After some minor modifications to the apparatus, however, followed by careful testing of different procedures, it was found possible to improve the performance and to introduce sufficient quantities of smoke into the wind-tunnel. At first the smoke was simply injected at the chosen point as a single continuous plume. Later, in attempts to make this method succeed, a smoke comb was used.

Regrettably, however, it was found that neither visual observation nor photography using this method of smoke generation, would allow any conclusive assessment to be made of what was happening in the air-flow around the models. No improvement was obtained by moving the point at which the smoke was injected from a position at considerable distance upstream of the model by stages until it was close to the windward wall of the model. The clarity of the smoke forms was not improved by introducing the smoke at various heights between the floor of the tunnel and the roof of the model. Neither did injecting the smoke through the smoke comb, in the form of fine filaments produce significantly improved results.

Consequently, it was decided to discontinue this method and to adopt the well tried methods employing titanium tetrachloride. This liquid, which decomposes to give off dense white fumes on exposure to the moisture in the atmosphere, is often best employed when small quantities of the liquid are placed at chosen positions in the wind-tunnel and allowed to decompose. In this way, it is often possible to introduce smoke streams to difficult positions without risking disturbances in the flow arising from the intrusion of injecting tubing or of streams of air at a higher velocity transporting the smoke.

Following this method, small quantities of titanium tetrachloride were placed at various positions in front of the models when under test. The results obtained by this means were no better than those from the first method, being very obscure and indefinite. A change in technique was therefore necessary.

A series of studies was then made in which small quantities of titanium tetrachloride were dropped onto the roof surfaces of the models. This method at once produced a marked improvement in the definition of the form of the vortex movements above the roofs of the models. Not only was the vortex sheet above the model at 6° (see fig. (11) for illustration of model positions) much more clearly defined but a very good illustration was obtained of the twin vortices produced behind the leading corner of the roof when the models were positioned at 30° and 45°. This can be seen in figs. (12a & b).

These two photographs give, in addition, some indication of how the air circulating within the patio(121) left it again at the rear corner. More discussion will take place on these effects in Chapter 5.

On further investigation, using this technique, disappointment was again experienced. Although during the early stages of the studies it was thought that the expected effects could be seen in the flow patterns, the subsequent observations and photographs were inconclusive. If the theory under investigation was correct and the different methods of profile generation did produce variations in the breakdown of the vortices behind the leading edges of the models, this should have affected the height of the vortex sheet above each model. Under conditions of least turbulent intermixing in the flow it was anticipated that the vortex sheets would pass at their highest levels above the roofs of the models. Conversely, when there was greatest turbulence in the air-flow this would cause the quickest break up of the vortices on the roofs thereby causing the vortex sheets to pass at a lower level over the models.

Even after attempting to improve the results by varying the running speed of the wind-tunnel and by trying various camera shutter speeds, no significant improvement could be made in the results. Although it was often thought that the anticipated variations in the patterns could be seen, it was uncertain and could not be photographed. When a fast camera shutter speed was used, temporary variations in the height of the vortex sheet were recorded, thereby showing an irregular pattern of results. The photographs in figs. (13) and (14) show the effect which was sought; the wind-tunnel air-flow in each case contained a moderate velocity profile. Figures (13 a & b) show photographs of the smoke above the smaller model in an air-flow in which the moderate velocity profile was generated by the wire screen. In figures (14 a & b) can be seen the apparent difference in the flow patterns produced by the same velocity profile but created, in this case, by the roughness method. In the latter case, the vortex sheets above the models are very much more disturbed.

Unfortunately, the validity of such results is brought into considerable doubt when results such as those shown in fig. (15 a & b) and in (16 a & b) are examined. These two pairs of photographs were each taken under exactly the same air-flow conditions (A) with a heavy velocity profile produced by the roughness method. As can be seen, there is no consistency in the results.

When slower camera shutter speeds were used, in attempting to average out the variations, the photographs produced were blurred and indistinct. It had become obvious that methods using smoke were much too unreliable. In addition to the above difficulties, it had also been noted that variations in the volume of smoke present or in the relative position of the camera to the models together with its distance from them during photography also caused confusion in the results. This method was therefore abandoned, with the question of the validity of the investigation still in dispute.

However, some aspects of this technique had proved of interest, such as the previously mentioned photographs of the vortices on the roofs of the models and the photographs shown in figs. (17a) to (17d). These demonstrate the air movement around the smaller model in a heavy profile when generated by the roughness method and show the extremely disturbed pattern of the air-movement produced by the heavy velocity profile created by this method. Many of these photographs later proved of interest in relation to subsequently measured results.

(A) All photographs shown were taken with a single lens/reflex camera, shutter speed 1/60th sec. aperture f 2.8 using a wind-tunnel air speed of 5 m.p.h. The film used was Ilford F.P.3., 125A.S.A. black and white film.

## Oil Film Technique.

Having failed in the early attempts to obtain proof of the inaccuracies in the wind-tunnel data, thought to result from variations in wind-tunnel technique, concern was experienced. However, before commencing studies using pressure measuring methods, it was considered desirable to attempt further flow visualisation.

In order to provide both information on the behaviour of the air-flow close to the model roof surfaces and to give assistance in the plotting of the pressure diagrams, it was decided to carry out oil film studies. Experiments using this technique are valuable in revealing the positions of vortex streams on model roof surfaces. The method employed has been used extensively by the National Physical Laboratory.

This method of flow visualisation makes use of a white viscous oil which is brushed onto the roofs of the models in a smooth, even film. The roof surfaces must first have been coloured black. Because the models being used were made of Perspex and it was necessary to preserve their transparency, permanent colouring, such as paint, was avoided. Instead, the pressure tappings in the roof surfaces were first covered over with cellotape then the model roofs were coated with a dense black substance, similar to that used to coat the inside of camera bellows.

The oil used in these experiments was a suspension of finely ground titanium oxide in a misture of oleic acid and paraffin. Shortly before a test was to be carried out, the roof surface of the model to be tested was given an even coating of the white oil. In the early stages of these experiments it was necessary to make tests to determine the best proportions of oleic acid and paraffin in the mixture to obtain the correct vicosity. Thus it was ensured that the oil flowed sufficiently well to illustrate the vortex positions but was not too fluid so that patterns disappeared whenever the wind-tunel was switched off to allow the removal and photographing of the model.

The procedure was, therefore, to run the wind-tunnel at 73.9 ft. per sec., with the model in position and the required means of profile generation installed, until the patterns were clearly established in the oil film on the model roof. Once the patterns could clearly be seen the tunnel was stopped, the model removed, studied and photographed.

In this way, both models were tested under each of the air-flow conditions being investigated. That is, in air-streams in which there were no induced velocity profiles, then in air-streams having velocity profiles of light, moderate and heavy curvature produced first by the wire mesh screens of graded resistance, then produced by the roughness method.

It quickly became obvious that much more tangible results could be had from this experimental method than with the methods employing smoke.

## Oil Film Results.

Both models were tested in the wind-tunnel at three positions in relation to the air-flow, at 0°, 45° and 30° (see fig. (11). The positions of 0° and 45° were regarded as standard positions in which to test the models. Tests at the angle of 30° were considered essential since an earlier investigation (121) had shown that at or very close to this angle, under certain flow conditions, interesting air movements could be found in the model patios. This was caused by one of the two vortex streams, generated behind the leading corner of the roof, passing over the patio whereupon it expanded downward and struck one of the rear patio walls. This resulted in a continuous, spiralling movement of air into and out of the patio. Consequently, the pressures on the patio walls were considerably affected.

By careful study of the results obtained from the models at this angle to the air-flow, it was anticipated that differences in the sets of results could be readily detected. Not only was this expected to be seen in the oil film patterns but also in the pressure measurements from the patio walls.

Model AxAxA

MODEL POSITIONED AT $0^{\circ}$:-

On examination of the photographs in figures (18a) to (18d) it can be seen that there is a clearly defined area behind the front edge of the model roof which has been swept by the vortex roll which existed immediately behind the edge. Between that position and the rear roof area, which had been swept where the vortex sheet above the roof had made recontact with the surface, there can be seen a crescent shaped area of relatively undisturbed oil where the flow had divided. Taking first the pattern produced by the air-stream without any velocity profile and comparing it with the patterns produced in turn by the light roughness profile, the moderate roughness profile and the heavy roughness profile, an obvious trend can be seen. The recontact area of the vortex sheet and the position occupied by the forward vortex roll can be seen to move closer each time to the front edge of the roof until, in the case of the pattern produced by the heavy roughness profile, the two areas appear to have merged.

This result is exactly in keeping with what had been anticipated. The break-down and recontact of the vortex sheet being influenced by the amount of turbulence in the air-stream. More information on why the two areas on the roof merged in the case of the pattern from the heavy roughness profile was later obtained from the pressure measurements and was shown to be caused by the leeward vortices from the last bar of the roughness grid impinging on the model roof, causing distinct areas of positive pressure.

The first clear indication of the success of the investigation is had by comparing the above mentioned photographs with those from (19a) to (19c), produced by the velocity profiles generated by the graded screens. The positions of the vortex movement on the roofs began by being further back on the roof surface than they were with the roughness profiles and did not move forward, towards the leading edge, so rapidly with changes in the form of the profile. Indeed, the pattern produced by the heavy screen profile can be compared with that produced by the light roughness profile.

## MODEL POSITIONED AT 30°:-

By examining the traces left by the twin vortices created behind the leading corner of the roof, at this angle, in the same sequence as was followed with the model at <u>0°</u>, a similar effect can be seen in figs. (20a) to (20d). The vortices became less intense, less clearly defined and progressively broader in form as the turbulence in the flow increased. Again, the pattern produced by the vortices completely disappeared from the roof of the model when it was tested in an air-stream with a heavy roughness profile.

The patterns produced by the velocity profiles generated by the graded screens show exactly the same deviation from the results of the tests in the roughness profiles as was noted in the results at <u>0°</u>, as can be seen in figs. (21a) to (21c). In this case, the patterns caused by the twin vortices remain clearly defined and narrowly confined in every case. They do display a distinct tendency to widen and become less intense but not nearly so obviously as in the patterns produced by the roughness profiles. When the oil pattern produced by the heavy screen profile is considered it can be seen to show characteristics somewhere between those of the light roughness pattern and that from the moderate roughness profile.

## MODEL POSITIONED AT 45°:-

By studying the photographs in the established sequence it can be seen that the oil patterns obtained from the model at this angle are in every way similar to those produced at 30°. (Figs. (22a) to (23c) ).

The reduction in intensity and the spread of the vortices occurs in both the results from the roughness profiles and from the screen profiles. However, the results from the screen profiles can be seen to have a particular intensity. The pattern produced by the light screen profile is much more pronounced than even the pattern from the air-flow which had no velocity profile. This appears to be very clear evidence in support of the theory under investigation. That is, the air-stream having passed through the graded screen is closer to laminar flow than even the undisturbed air-stream in the wind-tunnel without any velocity profile.

As before, the pattern from the model when tested in the heavy screen profile is as intense as that from the light roughness profile.

## Model ΛxΛx3Λ

When the oil patterns produced on the roof of this model are examined in precisely the same sequence as with model Λx Λx Λ it can be seen that they have been influenced in every respect in a completely identical manner (see figs. (24a) to (29c) ).

Every statement made about the results from model Λx Λx Λ and every conclusion drawn can be made from the results from model Λx Λx 3Λ in every exact detail. The confirmation, produced by these results, of the conclusions drawn from the results from model Λx Λx Λ provided substantial evidence in support of the theory of the variations produced by the different air-flow characteristics and the effects which would be caused.

# CHAPTER 5

# CHAPTER 5.

## PRESSURE MEASUREMENTS ON THE MODEL BUILDINGS.

Having obtained the first clear indications from the oil film experiments that the predicted variations in the results were taking place, it was then necessary to carry out experiments of a quantitative nature. By doing so, it was anticipated that the precise form which the variations were taking could be defined.

By making detailed pressure measurements on the model surfaces, accurate information was expected on how the vortices around the models were affected by the different turbulence levels in the air-flow. If the predictions were correct, the increased turbulence, produced by the roughness methods, would cause a reduction in the intensity of the pressures created by the vortices. In addition, when these results were compared with those obtained in air-streams having velocity profiles generated by mesh screens of graded resistance, it was expected that distinct differences would be found between results obtained under supposedly similar flow conditions.

The method adopted, in making the pressure measurements, involved first covering all the pressure tappings with cellotape on the model to be tested, except those to which the manometer was to be connected. In this way, local disturbances in the air-flow, caused by small streams of air passing through the tapping holes not in use, was avoided. Fourteen of the multitube manometer gauges were then connected, by means of the $\frac{1}{8}$ in. I.D. rubber tubing, to fourteen nipple connections at tappings on the model. The fifteenth manometer tube was connected to the micro-pitot tube measuring the free flow total head pressure. Finally, the pressure point on the manometer reservoir was connected to the static tapping in the working section roof. The model was then clamped to the turn-table in the working section and the wind-tunnel run at an air-speed of 73.9 ft. sec. The positions of the pressure tappings were noted, in a coded sequence on a chart, to facilitate their subsequent plotting, and the pressures measured were recorded against their coded numbers.

At first, a photographic method of recording the liquid levels in the multitube manometer was adopted. This method, although satisfactory, proved to be slightly more time consuming than the manual method and was discontinued. This was because the time involved in loading large quantities of film, developing the film after recording, then projecting it to allow readings to be made, was a more lengthy process. However, this method had the distinct advantage that the time consumed at the actual recording was very much shorter than the visual/manual method and it was later employed under difficult conditions in which the time available for readings was extremely limited. Indeed, this later proved to be the only possible method of recording the pressure measurements from the field model.

Once all the pressure measurements were recorded from the total external surface area of the model, at each of the three positions in relation to the air-flow $0^\circ$, $30^\circ$ and $45^\circ$, the results were prepared and the pressure coefficients at all points calculated. Each of the coefficients was plotted carefully on a plan at the point on the model surface from which it had been measured. When all the coefficients had been plotted, interpolation was carried out between the points and the lines of equal pressure were drawn up at intervals of 0.1. The pressure diagrams produced in this manner are shown in figs. (30a) to (41c).

The method of calculating the pressure coefficients, as already discussed in Chapter 2, was very much simplified by the procedure employed in recording the results. This allowed the coefficients to be calculated merely by relating the heights of the columns of liquid in the manometer tubes recording the pressures to the height of the fifteenth column measuring the free stream dynamic pressure, as follows:-

Total pressure of the approaching airstream

$$H_o = p_o + \tfrac{1}{2}\rho V^2$$

where $p_o$ is the static pressure of the airstream

and $\frac{1}{2}\rho V^2$ is the dynamic pressure of the airstream.

Total pressure at a point on the surface of the body immersed in the airstream is

$$p_s = p_o + \Delta p$$

The pressure difference $\Delta p$ can be positive or negative and its coefficient

$$C_p = \frac{\Delta p}{\frac{1}{2}\rho V^2}$$

$$= \frac{p_s - p_o}{H_o - p_o} = \frac{h_2}{h_1}$$

In spite of the simplicity of calculation, because of the extremely large numbers of pressure measurements involved (including the measurements later obtained from the field model and from the Edinburgh University Department of Mechanical Engineering wind-tunnel, a total of over 50,600 pressure readings were processed), the Heriot-Watt University's Sirius digital computer was employed. By using this computer to calculate the coefficients, although a very considerable time was required to punch the measured results onto data tapes, a very large saving in time was achieved and the reliability of the results ensured.

Both of the models were tested in turn in air-streams without any induced velocity profile, then in air-streams having the three intensities of velocity profile generated first by the roughness method then by the wire screens of graded resistance. Each time, the results were recorded, calculated and plotted in the manner described.

## Comparison of Results.

Before any discussion of the results can take place, it is necessary that the degree of accuracy achieved in recording the results be examined. Inconsistencies in the results could possibly have arisen from two sources. The first caused by the methods of recording the results and the second from the manner in which the models were mounted and rotated on the turntable in the working section of the wind-tunnel.

The standard method of recording the results was to read the levels of the liquid in the manometer tubes visually after which they were written into a suitable manual. Because some fluctuation occurred in the levels in the manometer tubes during recording, the practice adopted was to assess the modal point in each level, which was then recorded. Therefore, a slight variation could occur between one result taken at one point in time and an identical result taken at a later time. Due to force of circumstances, photographic means of recording the manometer readings had to be employed with the results from the field model and with certain sets of results obtained from the models when tested in the Edinburgh University Department of Mechanical Engineering wind-tunnel. When photographic records of the results were made, it was not possible to record the modal point of the pressure measurements. Since the liquid levels of the manometer varied in an irregular manner, when a photographic recording was made some of the levels would be at their maximum, some at their minimum and some levels would be moving. Therefore, minor differences in the results did occur, caused by this variation in recording procedure. However, as will be discussed later, the differences were small and could be taken into account when making comparisons.

For the purposes of the comparisons to be made in this chapter, the photographic method of recording can be temporarily ignored since none of the results to be considered were recorded by this means. The method of mounting the models on the turntable must, however, be considered. Due to factors such as the means of pivoting the turntable and the varying plan size of models to be attached to it, the clamp on the turntable was positioned $5\frac{1}{4}$ ins. away from the centre point. As a result, when each model was being rotated, in order to pick up the pressures on all the surfaces, it moved backwards in the working section, that is in a downstream direction. For example, the outer wall surface of the model under test, containing the pressure tappings, moved the maximum distance of 11 inches between measuring the air-pressures on the front wall and those on the back wall of the model. This meant that it was $5\frac{3}{8}$ ins. out of the position, when measuring the back wall pressures, that it would have been in if the model had been located centrally over the turntable pivot point.

Measurements had shown that minor alterations in the form of the velocity profiles, generated by the two methods under investigation, occurred progressively downstream in the working section. Therefore, because of the movement of the models in a downstream direction when under test, caused by their positions on the turntable, small variations were caused in the pressure readings.

As a result of the manner in which the pressure tappings were positioned on the models, the measurements made on one of the quarters of the external surfaces overlapped those of the adjoining quarters. This allowed a quantitative assessment to be made of the variations produced in the results. On examination of the results it was found, by this means, that one reading might vary by as much as 5%. This takes the worst possible view of the results and this percentage may, at first consideration, appear a substantial variation in one result. However, in terms of the full range of values covered by all the results in one set this variation is extremely small, only approximately 0.2%.

In practical terms of what effect such a variation would have on a set of results, when they were drawn up as a pressure diagram, the pressure line affected by the reading under consideration would be moved slightly out of position. The movement would probably only be approximately $1/16$ in. on the full sized diagram. Therefore, no serious distortion of the results occurred and it can be certain that no pressure line failed to appear on any pressure diagram as a result of such a variation.

However, it must be remembered that those variations occurred on the rear half of the model surfaces. The areas of major importance, in these comparisons, were the windward external wall surfaces and the front areas of the model roofs. The pressure measurements from these surfaces were made with the models in exactly the same positions for each set of flow conditions. As a result, the only variations which could have arisen in the readings taken at such positions were caused by inaccuracies during recording. These inaccuracies probably occurred in the second decimal place of the pressure readings and would be very much smaller than those, already discussed, which arose from the movement of the model with the turntable. Consequently, these small inaccuracies are of very much less importance.

By using the digital computer, not only was the calculation of the large quantities of pressure coefficients speeded up but further inaccuracies were avoided at this stage in the preparation of the results.

## Velocity Profiles Produced by the Surface Roughness Method Model AxAxA.

### MODEL POSITIONED AT 0°

Figures (30a) to (30d) show the pressure diagrams obtained from the model in air-flow conditions which in the first set had no induced velocity profile, in the second set had a light velocity profile generated by the surface roughness method, in the third set had a moderate roughness profile and in the fourth set had a heavy roughness profile.

The anticipated results, as already indicated by the results of the flow visualisation experiments using the oil film technique, are clearly evident. As the degree of turbulence in the air-stream increased, the vortices around the model, particularly those in front of the windward walls and on the roof surfaces immediately behind the front edge, broke down more rapidly thereby reducing the pressure effects.

For ease of reference and to highlight the differences in the results more clearly, the range of pressures, from maximum positive to maximum negative on the windward surfaces and from maximum negative to minimum negative on the roof surfaces, leeward walls, side walls and patio walls, have been abstracted from the pressure diagrams and drawn up in the tables shown in figs. (42) and (43).

Considering first the front wall surface of the model when positioned at the angle under consideration, the range of pressures experienced by the wall surface can be seen to have been progressively reduced as the turbulence in the air-stream increased. In the case of the air-stream with no induced velocity profile the pressure coefficients vary from + 0.61 to $\bar{0}.21$ across the wall surface whereas the coefficients obtained from the air-stream with the heavy roughness profile only ranged from + 0.10 to 0.00.

When the coefficients from the pressure measurements on the roof are considered, exactly the same effect can be seen. The coefficients obtained in the flow with no profile, ranged from a maximum of $\bar{1}.01$ to a minimum of $\bar{0}.15$. The range of pressures measured from the roof surface rapidly decreased as the turbulence in the flow increased. As had been shown by the oil film experiments, not only was the intensity of the vortex behind the leading edge of the roof decreased in value but the area of roof surface affected by it was reduced as the turbulence in the air-flow increased.

By far the most remarkable feature of the results from the model when tested in the air-stream having the heavy roughness profile was the large, clearly distinguishable areas of low value positive pressure (up to + 0.04) measured on the roof surface. This was the reason for the indistinct result from the oil film studies under this set of flow conditions. As already discussed, the cause was the leeward eddies from the last bar of the heavy roughness grid descending onto the model roof. This set of conditions is perfectly valid since exactly the same air-flow behaviour, producing precisely the same effects, can occur in full-scale urban areas.

What is of considerable importance is, as will be proved later in this chapter, that this result could not possibly have been achieved in an air-stream having an equally heavy, or even much heavier, velocity profile generated by a mesh screen of graded resistance. This conclusion, even by itself, is a major piece of evidence for the case against the use of graded screens to produce velocity profiles supposedly to represent the profiles of the natural wind.

When considering the results from the model in this position in relation to the air-flow, there is another set of vortices which can profitably be examined. These are the vortices which existed on the two side walls, immediately behind the vertical edges of the front wall.

The vortices in this position behaved in exactly the same manner as those on the roof surfaces. As the turbulence in the flow increased, the areas affected by the vortices were reduced, as was the intensity of the negative pressures produced by the vortices. The maximum range of pressures experienced by these wall surfaces of the model occurred, as expected, in the flow without a profile with values from $\bar{1}.12$ to $\bar{0}.12$. The behaviour of the pressure patterns on these wall surfaces can be seen to have been extremely similar to that which occurred on the roof of the model. In the air-stream with the heavy roughness profile, the pressure range was finally reduced to as little as $\bar{0}.07$ to +0.03.

Once again, areas of low value positive pressure were found on these side wall surfaces, produced by the heavy roughness profile. These pressures only reached a maximum of + 0.03 on one of the side walls but their presence is even more remarkable and significant than the positive pressures on the roof surface.

## MODEL POSITIONED AT 30°

On examining the results of the pressure measurements obtained from the model at this angle, an even clearer indication is had of how the progressively increasing turbulence in the air-flow affected the readings. On the roof surfaces, the two vortices generated behind the leading corner produced closely confined areas of high negative pressure when there was least turbulence in the air-flow. As the turbulence level increased, the areas covered by the vortices broadened and the negative pressures were rapidly reduced.

When the results from the model tested in the air-stream without a velocity profile are examined, the range of pressures measured on the roof surfaces and the windward wall surfaces are found to be $\bar{2}.59$ to $\bar{0}.16$ and + 0.70 to $\bar{0}.23$ respectively. Considering the range of pressures in these results it is remarkable to find them reduced to that of $\bar{0}.70$ to $\bar{0}.07$ and + 0.31 to $\bar{0}.09$ respectively on the model tested in the moderate roughness profile.

However, it is even more remarkable to find the pressure ranges further reduced to $\bar{0}.08$ to $+ 0.04$ and $+ 0.10$ to $\bar{0}.06$ respectively under the flow conditions having a heavy roughness profile. Large areas of low value positive pressure were again measured on the roof surfaces of the model under these heavily turbulent flow conditions.

## MODEL POSITIONED AT 45°.

As can be seen from the pressure diagrams and from the tabulated ranges of pressure, the results obtained from model Ax Ax A at this angle were affected, in all respects, in the same way as at the 30° position.

## PATIO WALL SURFACES.

As has already been discussed, it was anticipated that the air movement inside the patios of the models would be influenced to a very great extent by the variations in the turbulence of the air-stream in the wind-tunnel. It had been found in a previous investigation (121) that the pressures experienced by the patio wall surfaces were very sensitive to minor alterations in the air-flow above the model roofs. As can be seen from the results, the pressures on the patio walls were indeed greatly affected by the variations in the air-flow characteristics.

Under the influence of the increasing turbulence in the flow, the vortices on the model roof broke down more quickly as they passed over the patio, thereby penetrating into the patio area to an ever increasing extent. This caused the pockets of positive pressure, produced by the expanded lower section of the vortices impinging on the rear patio walls, to increase progressively with the increases in the air-flow turbulence. Simultaneously with increase in area of the positive pressures on the patio walls, the size of the areas on the patio walls which experienced negative pressure was accordingly decreased and the intensity of the negative pressures was reduced.

The reduced range of pressure measured on the patio walls, in each case, is clearly illustrated in the tabulated results. One minor exception to this general behaviour pattern is seen in the results from the model positioned at $30^{\circ}$ in the air-stream which had no induced velocity profile. In this particular case, the vortex which passed over the patio was so closely confined and vigorous that when its lower area encountered the rear patio wall it caused a small area of high positive pressure. The accompanying acceleration of the air movement in the patio produced a wide variation in the pressure range, from $+ 0.35$ to $\overline{0}.28$.

## MODEL Ax Ax 3A.

All that has been said of the results from model Ax Ax A is equally valid for the results from model Ax Ax 3A at each of the 3 test positions. The velocity profiles, generated by the method under consideration, had exactly the same effect. As the turbulence in the air-stream increased, the intensity of the pressure effects produced on the model decreased.

As can be seen from the tabulated results obtained from the model when positioned at $0^{\circ}$, very small areas of extremely light positive pressure were measured on the model roof in the air-stream with the heavy roughness profile. Reference to the relevant pressure diagram (36d) shows, however, that these areas of light positive pressure were extremely small. It seems certain that they were not caused, as in the case of the smaller model, by the leeward eddies shed by the grid of roughness but were due to the recontact of the vortex sheet with the rear roof area. This recontact must have had increased vigour due to the turbulent motion of the air-stream having a horizontal axis across the working section of the wind-tunnel.

No positive pressure was measured on the roof surface of this model at the other two test positions although, in the air-stream with the heavy roughness profile, in very large areas of the roof surfaces the pressures were reduced below a coefficient of $\bar{0}.10$. In general, the pressures measured under the conditions of heavy roughness flow were very low indeed for this model.

## PATIO WALL SURFACES.

The range of pressures obtained from the patio walls are given in the same tabulated form as for model Ax Ax A. The progressive reduction in the intensity of the vortices on the model roof, caused by the reasons already discussed, can be seen to have influenced the pressures on the patio walls of this model in exactly the same manner as with model Ax Ax A.

As the turbulence in the air-flow passing over the roof of the model increased, the penetration to the patio increased correspondingly. The high negative pressures were reduced, reaching the minimum value in the case of the model tested in the air-stream with the heavy roughness profile. The areas of low negative pressure were changed to areas of positive pressure which increased in size and intensity.

An exception to these general conditions can again be found in the results from the model when tested at the $30^{\circ}$ position. When these results are examined, it can be seen that the conditions described above were maintained until the last set of results, that is those obtained in the air-stream with the heavy roughness profile. Under the influence of the heavy turbulence in the flow, the vortices on the roof were so weakened that they could no longer produce the high positive pressure on the patio walls. The result was a general reduction in the range of pressures experienced by the patio walls with a $\bar{0}.12$ to $+0.15$ range signifying a major reduction of the air movement inside the patio.

## Velocity Profiles Produced By the Wire Mesh Screens of Graded Resistance

### MODEL Ax Ax A

ROOF SURFACES

It can be seen from the tables of results extracted from the pressure diagrams that at each of the three test positions, the ranges of pressure measured on the model were significantly different from those obtained in the air-streams with velocity profiles produced by the surface roughness method. Not only were the maximum negative pressures very much greater when using this method of profile generation than in the exact counterparts when using the surface roughness method, but the whole range of pressures in each case was of much higher value. This is particularly evident in the results obtained at the angles of 30° and 45°.

This finding is additionally emphasised by the fact that the profiles produced by the graded screens were even heavier than those produced by the roughness method. For example, if the results from the light screen profile (the curvature of which lay between that of the light roughness and the moderate roughness profiles) are compared with the results from the moderate roughness profile the differences in the results are seen to be even greater.

One other characteristic of the results from the roof surfaces is that, although the maximum negative pressures were reduced progressively as the velocity profile in the flow became heavier, the minor negative pressures at the lower ends of the pressure ranges varied by very little, only between $\overline{0}.29$ & $\overline{0}.22$. What is more important is that in the air-flow which had a velocity profile even slightly heavier than the heaviest roughness profile, the roof pressures do not correspond in any way with those of the roof pressures in the heavy roughness flow. Indeed, they are so much greater as to be very nearly equivalent to the pressures measured in the moderate roughness profile.

In general, it can be seen from the tables and from the pressure diagrams that on the roof surfaces of this model the negative pressures were very much higher and the vortices very much more narrowly confined, in agreement with the manner predicted by the oil film experiments.

## EXTERNAL WALL SURFACES

At the 0° position the pressures obtained behaved, once again, in a similar manner to those on the roof at this position. The negative pressures were again greater than those measured in the air-streams with the roughness profiles. What has already been said about the roof pressures is applicable to these pressures, with the measurements made in the heavy screen profile being similar but slightly higher than the pressures obtained from the moderate roughness profile.

When the measurements made from the windward wall surfaces at the three test positions are examined, a rather unexpected feature is found. The maximum positive pressures were lower than those found in the roughness profiles except in the sets of results recorded in the light screen profile with the model in the 30° and 45° positions, when the maximum positive pressures were the same as in the light roughness profile. However, the negative pressures on these surfaces were greater than those from the roughness profiles and in the heavy profile generated by the graded screen no positive pressures at all were found on the windward wall faces.

Once again, as with the minimum negative pressures on the roof surfaces, the variation in the maximum negative pressures from the windward walls showed little variation. Unlike those in the roughness profiles, these pressures only varied between $\overline{0}.31$ and $\overline{0}.41$.

Part of this effect may have been caused by the profiles from the graded screens being slightly heavier than the equivalent profiles produced by the roughness method. However, these conditions would appear to indicate that less air movement took place in front of the model in the air-streams having profiles produced by the graded screens than in the air-streams with roughness profiles. The air-flow, it can be deduced, separated from the tunnel floor at a point further upstream, than with the roughness profiles, and passed with increased velocity over the model roof.

PATIO WALL SURFACES.

A striking feature of the results obtained from these surfaces is that in only one case, the model positioned at 30° in the light screen profile, was positive pressure measured. When compared with the corresponding results from the roughness profiles, the pressure coefficients are markedly different. The negative pressures are very much greater than those recorded in the model patio under the influence of the air-streams with roughness profiles.

In addition to the one case of positive pressure stated above there is only one other instance in which evidence of some degree of air-flow penetration to the patio can be seen. This occurs at 30° in the moderate profile, by graded screen, where the minimum negative pressure coefficient is $\bar{0}.08$. In all the other cases, in the various test positions and conditions of air-flow, the negative pressures remain very high.

In general, therefore, the vortices above the roof surfaces must have been vigorous and closely confined to the leading edges of the roof at each test position. The two cases with the model at 30° being exceptions.

## MODEL Ax Ax 3A

ROOF SURFACES.

It had been anticipated that the pressures which would be measured on the roof surfaces would be significantly greater than from the same model in the roughness profiles. This was indeed found at the 45° position and, to a lesser extent, at the 0° position. However, at the 30° position the results show that in the air-flows with light and moderate profiles the negative pressures were not as high as in the corresponding roughness profiles. At the same position in the heavy profile the pressures were, however, greater than with the roughness flow.

What is most unusual about the results at each test position is the lack of variation in the pressure ranges obtained at each angle in the varying flow conditions. At the 0° and 30° positions there was virtually no difference between the maximum pressure in the light profile and the maximum pressure in the heavy profile. Even at 45° the maximum negative pressure only varies from $\bar{5}.75$ in the light profile to $\bar{5}.68$ in the moderate profile and finally to $\bar{3}.25$ in the heavy profile.

In addition, comparatively little variation can be seen in the minimum pressures experienced by the roof surfaces,

Since the height of the model was approximately half that of the velocity profile in each case, the model was always fully immersed in the profiles. It must be deduced, therefore, that at the height of the model roof there was very little difference in the turbulence within the three profiles. This is in agreement with the predicted character of the flow behind the graded screens.

## EXTERNAL WALL SURFACES.

The conspicuous lack of variation in the roof pressures under the various profile conditions is again apparent in the measurements from the side walls with the model positioned at 0°. The pressures were all higher than those obtained in the roughness profiles and the maximum pressures only varied from $\bar{1}.26$ in the light profile to $\bar{1}.05$ in the heavy profile.

As had been found in the smaller model, the positive pressures on the windward faces in the profiles generated by the screens were slightly less than those obtained in the roughness profiles. The reduction in the positive pressures was small and not as great as was found in model AxAxA.

Once again, the lower end of the range of pressures found on each of the external walls was higher than for the similar case in the roughness profiles. The explanation must once again have been that which was offered for the same effects in model AxAxA. That is, primarily, more escape of air over the model caused by a separation of the flow from the tunnel floor upstream of the screens.

## PATIO WALL SURFACES.

When the results obtained from the patio walls of this model in the profiles produced by the graded screens are compared with those obtained from the roughness profiles, a considerable difference between the two sets of results is obvious. The most important indication of this is that no positive pressures were measured on these wall surfaces in the air-streams with the screen profiles. Indeed, except for the case of the model positioned at 30° in the heavy screen profile, where the minimum negative pressure was $\overline{0}.08$, there is virtually no evidence of flow penetration to the patio area. This is completely different from the results measured in the roughness profiles, which produced positive pressures of up to + 0.41 on the patio walls of this model.

The maximum negative pressures measured on those walls were all extremely high, significantly higher than in the air-streams with the roughness profiles. In addition, there was very little reduction in the pressures measured with increases in the gradient induced in the air-flow in the wind-tunnel.

## General.

The results of the pressure measurements showed, beyond any doubt, that the two methods of profile generation produced results of greatly different character. All of the negative pressures measured on the roof surfaces of the two models, on the external wall surfaces and on the patio walls were very much higher in the air-stream with screen generated velocity profiles than in the air-streams with roughness profiles.

One strange feature of the findings of these experiments was that the positive pressures from the windward surfaces of the models in the roughness profiles were slightly higher than in the screen generated profiles. However, this feature of the results is in itself significant, as previously discussed.

Furthermore, it has been seen that the heavy velocity profile generated by the graded screen produced widely different results from those obtained in the heavy roughness profile, particularly in the case of the smaller model.

Further comment on these results cannot be made until the results obtained from the experiments in the field are considered.

# CHAPTER 6

# CHAPTER 6.

## CHOOSING THE SITE AND CONSTRUCTING THE FIELD MODEL

### Designing the Field Model.

In order to provide means of assessing the validity of the results obtained in the wind-tunnel and to investigate which method of profile generation was the more correct, it was necessary to carry out a major investigation in the field. This investigation, it was planned, should take the form of experiments conducted on a large model, constructed on a suitable area of land.

The investigation in the field consisted of two separate and distinct problems. The first involved determining the velocity profile in the natural wind over the chosen site and the second consisted of designing and erecting a large model on which pressure measurements would be made. This model had to be an exact replica of one of the wind-tunnel models. To allow direct comparisons to be made of the results from the field model with those from the wind-tunnel, the field model had to be of such a design as to permit the same experiments to be carried out upon it as were carried out in the wind-tunnel.

Little difficulty was envisaged in constructing the model and in providing the necessary pressure tappings but a major problem arose from the question of how to position the field model in relation to the mean direction of the wind. In the wind-tunnel this, of course, was perfectly simple since the model was mounted on a turntable, capable of being rotated through 360°.

Even if it had been possible to position the field model in a static position, exactly in line with the prevailing wind, the model would have been required to have pressure tappings over the whole of its entire surface area. Furthermore, enormous delay would have resulted from waiting until the mean wind direction approached the model in precisely the correct direction. In addition, if both of these major requirements were fulfilled, it would have only been possible to test the model at the $0^{\circ}$ position, that is, in only one of the three positions.

These problems are the main reasons that there has been very little experimental work carried out on model buildings in the field. Furthermore, the little research which has been carried out (49) has again been directly limited by these problems. The result has been a small model, in a stationary position having a single row of pressure tappings along the line of the centre section of the model placed axially with the mean direction of the wind. This has produced results which are severely limited in quantity and scope.

To minimise the difficulties of interpretation produced by scale effects, it was decided to make the model as large as practicable. The choice then lay between the two models. It was felt that if the larger model were chosen the size would have had to be restricted. This would have been necessary to reduce the height of the model and, thereby, the physical problems involved in making the pressure measurements. Also, as will be seen later, in mounting the field model for testing, a physical limit was imposed on the size and weight of the model.

Having selected the smaller model for reproduction in the field, it only remained to decide on the overall size of the model and to draw up a suitable design. In considering the size of the model, it was decided, that since the smaller model was representative of a single storeyed building, to construct the field model to half full-size. A complete full-scale replica, 12 ft. high and 36 ft. x 36 ft. on plan, would have been impracticable, again mainly because of the method of mounting the model. A half full-size model would be 6 ft. high and 18 ft. square on plan, this was thought to be the maximum practicable plan size and the minimum convenient height to allow sufficient head room inside the model for the purposes of moving around when attending to instruments and making pressure readings.

To facilitate the alignment of the model with the mean direction of the wind, it was planned to construct the model on a mounting which could be rotated through 360°. The method of constructing such a mounting was given careful consideration and several possibilities were examined. The various methods were based on two different approaches to the problem. The first required a large platform turntable, sunk into the ground, on which the building could be constructed. The second approach was based on the requirement of a structurally rigid model which would have its own pivot mounting. Because of the necessary economy of materials and time it was decided not to employ a turntable.

Initially, the design of the model took the form of a timber structure with a central pivot point and large rollers or castors at intervals around the perimeter. Unfortunately, it became obvious that this design, to be at all satisfactory, would still require a heavy sub-structure on which to travel. A reappraisal of the design showed that if the model were sufficiently rigid it could be mounted on a single central pivot and be freely rotatable about that point.

By now, the design of the model had taken on a distinct form. A rigid and substantial base was required on which would be built the main structure of the model which, although rigid, would have to be as light as possible. As can be seen from fig. (44), the model building was designed to be constructed of 2" x 2" timber framing clad with oil bound hardboard sheeting. The major difficulty envisaged in using the hardboard was that it would not be suitable to carry pressure tappings due to its flexibility between supports and because it was only $\frac{1}{8}$ in. thick. Provision was made, therefore, to replace the hardboard with $\frac{1}{2}$ in. thick resin bonded plywood on those surface areas of the model which had to carry pressure tappings. The base of this structure was designed in 4" x 2" timber framing.

It was not considered feasible to construct a base which would be completely rigid. The problem arose of how to prevent the 18 ft. wide base from collapsing over the pivot point under the weight of the superstructure, since much of the weight occurred at the periphery. The problem was further increased by the requirement that nothing should project above or beyond the outside surfaces of the model.

The solution devised required a large block of concrete, below ground surface level, into which would be cast the bottom bearing of the pivot mounting. The top pivot of the mounting would be positioned beneath the centre point of the model patio. Immediately above the pivot point, a 4 in. x 4 in. vertical post, 2 ft. 3 in. high would brace wire tensile supports to the edges of the base. These four wires would pass diagonally across the model and from the centre of one outer edge to the centre of the opposite outer edge, in each case over the top of the centre post. By providing a means of tensioning these wires, it was anticipated that they would be able to support the outer edges of the model and transfer the resultant thrust onto the centre pivot. To take the weight off the wires when the model was stationary and to prevent the model from swinging in heavy winds it was envisaged that large folding wedges would be driven under the edges of the base.

## Choosing the Site.

Having arrived at a design for the field model, the next requirement was to find a suitable site. Care was necessary in the choice of a field site since the results to be obtained from the model erected on it were to be compared with those from the wind-tunnel. It was considered that a site in open country might have a velocity profile of a very light form making measurement and comparison of results difficult. Going to the other extreme, a city site, even if this could be found, could have produced considerable pressure effects, on the model, which were caused by purely localised characteristics in the wind over the site, due to nearby obstructions.

It was considered that a city suburban site offered the best possibilities. The velocity profile in the wind would be clearly established and have a sufficiently significant effect on the pressure measurements, thereby allowing a clear comparison of the results with those from the wind-tunnel experiments carried out under similar conditions.

A search was then begun for a site of the required type, within the suburbs of Edinburgh. A number of sites were considered in the suburban areas of the city. Many of those considered were eliminated because of their unsuitability due to such reasons as obstructions blocking the approach to the site from the southwesterly direction of the prevailing wind, to inaccessibility and to the crowded nature of the site surroundings. This would have given rise to the danger of peculiarities arising in the results due to local disturbances in the wind. The decision was reduced to two possibilities, an area of ground within the precincts of the Redford Road military barracks or an area of land forming part of the playing fields of the Heriot-Watt University, at Paties' Road.

The latter site was chosen after due consideration. It was accessible by road to within 300 yards of where the model would be situated. This allowed easy access for the transportation of materials and equipment, which was of importance with regard to the instrument mast. The open, flat area meant that the model was removed from the possibilities of local disturbances.

Along one side of the site was a row of deciduous trees up to 70 ft. in height, which ruled out wind measurements from that direction. However, the boundary flanked by these trees was on the north westerly side of the site and it was considered that it would be seldom that suitable winds would blow from that direction, the prevailing winds being from the west or south west. In addition the ground beyond the trees sloped downwards very steeply, making measurements in the wind from that direction undesirable.

The approaches to the site on all the other sides were relatively opem and unobstructed. All of these approaches lay over built-up areas which were interspersed with trees. The situation of the site in relation to its surroundings can be seen in fig. (45). The approaches to the model position are to be seen in fig. (46), photographed from the model position.

There was no objection to this site being used for the experimental work because approximately two thirds of the playing field area were undergoing extensive treatment. It had been ploughed over and was lying fallow for the winter. This situation represented one difficulty for the site had to be cleared and all apparatus dismantled by April 1966. If favourable weather conditions, including strong winds, did not occur in the anticipated spring period or if long periods of snowy weather were encountered, then serious difficulties would arise. Since construction work began on the model building early in December 1965, little difficulty in completing the work in time was envisaged.

One of the greatest advantages offered by the Paties' Road site was that one of the groundsmen was in residence in the nearby sports pavilion. As a result, the experimental station could be kept under surveillance and tampering with the apparatus, much of which was vulnerable, by unauthorised persons could be prevented.

The area (of approximately 20 acres) occupied by the playing fields was almost rectangular on plan, with the longer axis of the rectangle aligned roughly north east and south west. The position chosen for the model and mast was as close as possible to the centre of the whole area, as can be seen on the plan. This position was no more than 90 yards from the sports pavilion, which was a considerable advantage. In severe weather conditions, particularly during the construction, shelter and warmth could be sought in the pavilion. Also, an electric cable could easily be run out from the pavilion to the model to provide light and heat.

## Construction of the Model Building.

After ordering the necessary materials and having them delivered to the playing fields, work began on constructing the model. The base was the first section to be assembled. The 17 ft. 8 ins. long 4" x 2" joists were set out at 18 ins. centres and their ends secured to 4" x 2" edge beams. Rows of 4" x 1½" noggings were then used at 3 ft. centres to give rigidity and a solid timber bearing block 18 ins. square was formed exactly at the centre of the base, on which would be mounted the metal pivot.

For ease of transportation, assembly and eventual removal, the superstructure of the model building was constructed in sections. These sections were fabricated from 2" x 2" timber framing at 18 ins. centres, with 2" x 1½" cross framing at 2 ft. centres. To this framing was securely nailed the oil bound hardboard. Before nailing on the hardboard, it was thoroughly soaked with water a short time in advance. This swelled the material so that after being nailed in position it dried and shrank, making the outer surface of the model flat and taut. This removed the danger of the hardboard buckling in wet weather.

For the reasons already stated, the areas of wall and roof surface which were to carry the pressure tappings were covered in resin bonded exterior quality plywood.

A steel pivot mounting was fabricated in which an end bearing was fitted to one end of a steel pivot which was bolted to the underside of the floor of the model. When the floor of the model was placed in position on the site, the spindle fitted into a tubular steel socket set into a concrete base which had been cast below ground level. Thus mounted, the floor section of the model was 1 in. below the average ground surface level. For this purpose, the ploughed surface of the ground around the model was levelled and a shallow circular depression formed to allow the model to rotate. This can be seen in fig. (44). On completing the fabrication of the model sections, these were transported and erected on the prepared position.

When the base had been mounted and wedged up until it was level, the various sections of the model were erected and bolted together. The next requirement was to insert and tension the four $\frac{1}{4}$ in. thick stranded wire straining cables to support the edges of the model base and prevent them sagging. These were anchored in position, each being run over the top of the support post at the centre of the patio. When the wires were tensioned sufficient support was given to the model base to allow the whole structure to be freely rotated through 360°. The means of positioning the model was by the two long removable levers shown in fig. (44). The folding wedges were used to hold the model in position when stationary and to take the weight of people moving around inside the model off the support wires. After forming 6 ft. x 2 ft. 6 ins. access doors in the rear wall of the model and in one of the patio walls, the structure of the model was complete.

## Pressure Tappings.

Little difficulty was experienced in forming the pressure tappings in the model surfaces. The required positions were set out in an identical pattern to that of the wind-tunnel model.

Copper tubing, of $3/16$ in. external diameter and $\frac{1}{8}$ in. internal bore, was obtained and cut to the required lengths. Holes of $5/32$ in. diameter were then drilled through the $\frac{1}{2}$ in. plywood faces of the models in the required positions. The pieces of copper tubing were inserted in turn into these holes and driven through the plywood until they were exactly flush with the external face, leaving $\frac{1}{2}$ in. of the tubing protruding from the internal face, to allow the connection of the manometer rubber connection tubing. A total of 136 pressure tappings were inserted in the model, 45 in the front wall, 64 in the roof and 27 in the patio walls.

Exactly the same experimental procedure was planned in making the pressure measurements from the field model as had been employed with the wind-tunnel model. Indeed, to reduce the possibility of discrepancies arising from experimental procedure, the same multitube manometer was employed.

As already shown, this procedure required the measurement of the dynamic and static pressures of the air-flow simultaneously with the pressure measurements from the model. This presented certain difficulties for although these measurements were easily obtained in the wind-tunnel, with the pitot tube and static tapping mounted in the tunnel roof outside the velocity profile, an entirely different set of circumstances existed in the field. The first problem arose from the obvious fact that the wind would not approach the model from a constant direction. The second problem was that the required pressure measuring device could not be mounted above the velocity profile in the natural wind, for this was many hundreds of feet above ground level. Finally, if the measuring device were positioned at a great distance from the model, errors in the results would occur due to the time lapse between the measurement of the pressure at the device and the registration of that pressure on the manometer. Obviously, this would arise from the extreme length of the air column in the inter-connecting rubber tubing.

A Dynes pressure head was the first solution considered and, since it was self aligning, would measure dynamic and static pressures simultaneously and could be mounted high above ground level. This was subsequently rejected on the advice of the Instruments Development Department of the Meteorological Office. It was considered that this instrument was obsolete and for the purposes for which it would have been employed it would have had a serious time lag in recording due to the very considerable size of the pressure connection tubing which it requires.

On further consideration, it was realised that the point of pressure measurement could not be very far from the model building. The reason being that the eddies which would engulf the model during a strong wind could not be expected to be more than 50 ft. across, on plan. This meant that the pressure head had to be close to the model. Since the instrument mast could not be positioned within this distance of the model, because of interaction effects, a separate mounting was necessary.

As was subsequently proved, there existed one further difficulty. Since natural wind veers in direction about its mean path this had to be considered when aligning the model in preparation for pressure measurement. The mean wind direction would have to be found and the model aligned, in the required position, with it. Having done this and prepared to make pressure measurements, even with external assistance, it would be no easy matter to choose the times to record the measurements to coincide with the precise time when the direction of the wind was exactly along the mean direction line. This would be virtually impossible during the hours of darkness.

The dictates of the foregoing problems demanded that certain conditions be met. The measuring device had to be as close to the model as possible, positioned in such a way that the presence of the model did not affect the readings. It had to be within reach of the ground and, although being capable of alignment with the wind, had to maintain a fixed position after being set up. This will be discussed later, since it allowed the dynamic pressure of the wind to be followed and its position of maximum value used to indicate when the wind was aligned with the pressure head, at which time the required pressure measurements would be made on the model.

To satisfy these conditions, a 12 ins. long N.P.L. type pitot-static tube was provided with a suitable clamp mounting. This device was fitted to a 5 ft. 6 ins. high post, provided with guy wires, which was set up 20 ft. from the model building. Two 30 ft. lengths of $\frac{1}{4}$ in. internal bore rubber tubing were used to carry the required dynamic and static wind pressures to the inside of the model, where they were connected to the multitube manometer.

A length of white coloured light silk streamer was attached to the shaft of the pitot-static tube. This allowed the head to be aligned with the mean wind direction at the same time as the model was positioned and anchored. This procedure was followed before pressure measurements were begun on each occasion and at intervals during long periods of pressure measurement.

# CHAPTER 7

# CHAPTER 7.

## PREPARING THE INSTRUMENT MAST AND CUP ANEMOMETERS

### The Mast.

Since it was necessary in the work under discussion, for the apparatus employed in the wind profile measurement to function continuously, it was decided that the most suitable method was to erect an instrumented mast. This method of profile measurement has undergone lengthy development and has, in the past, proved satisfactory (61) (73).

By far the best type of mast for mounting instruments in the natural wind, with rigidity and convenience of access, is a metal lattice structure. However, for the limited time of the programme of measurements and with the limited capital resources available, it was considered that such an acquisition was not justified. A suitable substitute was then sought.

It was decided that if, as it was planned, automatic recording apparatus were employed in measuring the wind profile, it would be unnecessary to provide means of regular access. Therefore, provided that adequate means of ensuring stability were provided, a much simpler mast for supporting the instruments, in the form of a large diameter timber pole, would be satisfactory. The necessity of ensuring rigidity was of considerable importance since if the mast were to sway in the wind the movement would have the effect of distorting the results from the velocity measurements.

The physical difficulties involved in erecting and ensuring the rigidity of an extremely tall mast imposed limitations on the height of the proposed mast. After considering all the factors involved it was decided that measurements up to 40 ft. above ground level would be sufficient to establish clearly the velocity profile which was produced in the natural wind over the site surrounding the field model. To assist in plotting and interpreting the data, it was planned that sampling points would be positioned on the mast at 5 ft., 10 ft., 20 ft., and 40 ft. above ground level.

A source of a stout timber mast was then sought. This proved no real difficulty. A number of timber producing estates were visited and a stand of suitable cedar was located at the estates of the Right Honourable the Earl of Rosebery, in Queensferry. A good sturdy straight trunk was selected for felling, trimming and delivery.

When delivered, this trunk was 17 ins. in diameter at the bole and of 4½ ins. diameter at the top, with an over-all length of 45 ft. The additional 5 ft. was considered necessary so that the mast could be sunk into the ground to that depth to fix its position and assist in providing rigidity. After removing the remaining protrusions, preparations were made to attach the brackets, necessary to carry the instruments, to the mast.

The brackets provided were formed from 4" x 1¼" hardwood and extended 3 ft. from the mast. Since it was planned to erect the mast with the brackets pointing outwards from it in a south easterly direction, this would place the mast between the instruments and the undesirable north westerly direction. This meant that all winds, except those which passed over the boundary of tall trees, had an unobstructed approach to the instruments. The instruments were particularly well placed, in this way, to measure the winds from the south westerly direction, which were anticipated as being the winds which would produce suitable conditions for pressure measurements on the model building.

## Preparing the Instruments

In designing a suitable system of instruments for the purpose under consideration, the main problem lay in making provision for a reliable means of recording the results continuously. In the past, Dines head anemometers have been employed, recording by means of an anemograph.

As previously mentioned, the Dines head has fallen out of use and has been replaced by fast response cup anemometers. In the early stages of their development, anemometers were considered unsuitable for velocity measurement in the natural wind, owing to their alleged response characteristics to the gusts in the wind. However, as a result of studies made by Shrenk in 1937, it was shown that even in measuring maximum gust speeds in strong winds they are capable of high accuracy.

The most suitable type of anemometer for the study which was to be carried out was the sensitive type IV anemometer designed by Sheppard (110) and subsequently modified and manufactured by Cassela of London. The sensitivity of this anemometer is achieved by the light nature of its construction. It employsa 3 cup rotor of 3 ins. cup centre line radius. The spindle supporting the cup rotor is lightly geared to either a counting mechanism or a display dial.

The calibration of this instrument has been shown to be linear and it has been found to have a satisfactory performance in fluctuating winds. Due to the light nature of its construction, the total frictional torque, it is claimed, is only 20 dynes/cm., which results in a stopping speed of 0.3 ft./sec. An approximate verification of this was later made in the wind-tunnel. Although these anemometers are sensitive at low wind speeds they are capable of withstanding exposure to winds of 88 ft./sec. (60 m.p.h.)

In making continuous recordings from such instruments, in the past, it has been necessary to photograph the counter displays either on a continuous basis or at predetermined intervals to give the necessary time scale. This was considered too elaborate and it was decided to seek a simpler means of recording. This was indeed proved possible and the solution to the whole problem was achieved by the very real generosity of the Department of Forestry and Natural Resources of the University of Edinburgh.

It was found that this department was developing a system of automatically recording wind speeds, operating on a continuous basis, for the purposes of their own research (67). This system of instruments was centred around modified cup anemometers of the Cassela type (15). These cup anemometers originally had had dial displays in which three dials had indicated the units of wind length in 10,000 ft. units, 1,000 ft. units and 100 ft. units. The anemometers had been converted in such a way that the dial displays had been removed. In place of the 10,000 unit dial a small low torque (700 dyne/cm.) 357° toroidally wound potentiometer had been inserted in each instrument. The existing gearing was then employed to drive a light wiper arm around the potentiometer. Great care had been taken in the design of the potentiometer to ensure that the unavoidable gap in the circular form, between the input and output ends of the coil, was kept to the minimum. In this way there was no loss of readings when the wiper arm produced an open circuit as it passed the gap, for the wiper arm was able to short the gap. (A current limiting resistor of 1.5 K $\Omega$ was included in the circuit as a result). Therefore, it was quite impossible for the recording device. sampling at a pre-set time interval, to make two consecutive readings from the potentiometer with the wiper lying stationary in the gap, except under conditions of complete calm.

It is of importance further to note that the speed of rotation of the wiper arm round the potentiometer, in relation to the 15 minute sampling interval of the recorder, was such that it was not possible for the wiper arm to pass the gap twice in the interval between two samplings, even under the strongest of winds. This prevented confusion in the interpretation of the recorded results.

The means of recording the readings from the anemometer heads was provided by battery operated, data logging equipment. A standardised-5 volts potential difference was applied to the circuit passing through the potentiometer. As the wiper arm was driven round the potentiometer by the cups, the voltage of the circuit was reduced. Therefore, by measuring the drop in voltage over a given period the mean wind speed passing the anemometer head during that period could be determined.

As a result of this system, by simply providing suitably long electrical leads, it was possible to position the recording apparatus a very considerable distance from the anemometer heads. The automatic recording apparatus was basically a magnetic tape recorder, manufactured and marketed by "d-mac" Ltd., Glasgow, under the proprietory name of the "Limpet Logger".

A schematic diagram of this instrument is seen in fig. (47) together with the related electrical circuit. In principle, a number of input channels (the first logger employed had 4 channels but a 10 channel logger later replaced it) were connected through a multiple selector device which was connected to an electro-mechanical timer. At predetermined intervals the timer activated the selector which closed the circuit of each input channel in turn and the voltage of each channel, from the relevant anemometer, was recorded consecutively on the magnetic tape, which had been simultaneously switched on and which ran for the short period of recording. As a consequence of the short period of tape run, little tape length was consumed in making each set of readings which meant that some 35,000 readings were possible from each tape, representing 2,180 hours of continuous recording.

Each of the electrical circuits supplying the individual anemometer heads included its own electrical dry battery supply. This meant, in the event of failure of one battery, only one circuit was temporarily affected and the other 3 circuits continued to function normally. The batteries used were 8.1 v., 6-RM4R (3400 m.a.hrs.) Mallory Cells. These batteries had the essential characteristic that when nearing the end of their life their output did not drop but continued producing 8.1 volts until all the energy was exhausted, whereupon the battery instantaneously ceased to function. As a result, no erroneous variations in the voltage readings of the recordings could arise from this source. These batteries had, in themselves, considerably long lives and since current was only drawn from them for approximately 1 sec. every 15 mins., during each sampling, the replacement time for each battery was suitably lengthy.

To allow the voltage in each circuit to be reduced from the 8.1 v. supply to the required standardised 5 v. in the circuits, each circuit was provided with a 2.5 K$\Omega$ variable resistance. This resistance allowed the voltage in each circuit to be exactly standardised before recordings were begun and allowed periodic checks and adjustments to be made during the long measurement runs. A junction box was provided in which each battery was housed together with the variable resistance and by providing a watertight seal to this box, the battery and connections were protected from the severe weather conditions encountered in the field. On the outer casing of each junction box were provided soldered connections, for the attachment of the circuit wires to the battery terminals together with a lockable adjustment point.

Reference to the photograph in fig. (48a) will show the completed circuit, ready to have the final connection (on right of photograph) made to the multiple connector of the limpet logger. The pin connectors shown to the left of the photograph were necessary in order to either remove a faulty anemometer head from the mast or to switch the connection of one logger channel from one anemometer head on the mast to another. As will be seen later, this was essential under certain emergency conditions. The final important fact shown by this photograph is the casing provided to each anemometer.

This casing was necessary because serious doubts were raised about the weather proofing of these anemometers. Instruments of a similar type had proved extremely troublesome during a programme of research carried out by Liverpool University and also by Lettau & Davidson (61). The weaknesses were further increased by the modifications which had been made to the instruments for the purposes being discussed. As a result, each of the anemometer heads was enclosed within a $4\frac{1}{2}$ ins. diameter, 8 ins. deep metal cannister. The cannister, which was sealed at all points and rendered water-tight, was firmly screwed to a hardwood base 6 ins. x 12 in . and 1 in. thick. Each base was subsequently provided with 3 bolt holes to allow securing and positioning of the instruments on the brackets of the mast, as shown in fig. (48b).

Since the clamp which secured the cup rotors to the spindle of the anemometers was provided with a depp shroud, which considerably overlapped the hollow shaft around the spindle, no water penetration was expected at that point. The shaft and rotor spindle projected 4 ins. above the top of the cannister. The maximum possible projection above the cannister was arranged in order that the cups would be as high as possible above the vortex sheet which would result from the wind passing over the cannister top.

## Testing the Instruments.

After having completed all the modifications and the preparation of the instruments it was considered necessary, as a precautionary measure, before mounting the instruments on the erected mast, to check the accuracy of the instruments in the wind-tunnel. Four anemometers were to be mounted on the mast and a further two were prepared, to serve as replacements, should the need arise, as indeed it did.

Each anemometer, complete in its cannister, was mounted, in turn, in the working section of the wind-tunnel. The projected frontal area of each anemometer was 38 sq. ins. or approximately 11% of the cross-sectional area of the working section. As a result, blockage effects must have occurred, causing some local acceleration of the flow around each instrument. However, each instrument tested was identical in shape and form which meant that the flow conditions would be the same around each and would not affect the comparison of the performance of the instruments which was the object of the test.

After mounting each anemometer an Avometer was connected across the terminals of its circuit junction box and by means of the variable resistance the voltage was standardised at 5 volts. The wind-tunnel was then run at a steady 50 m.p.h. for exactly 30 mins. during which time the behaviour of the wiper arm passing round the anemometer potentiometer was studied by means of the Avometer. Precisely at the end of the 30 min. run the voltage across the circuit was noted and the voltage drop in the period was determined.

On completing the test runs on all the anemometers the results were assessed and the mean result recorded was calculated. On inspection, it was found that the maximum variation between the fastest and the slowest result was exactly 4.9% of the mean. The maximum permissible deviation of the system had been assessed as 5% and, although a slightly better performance had been anticipated, it was considered that the results were satisfactory. From the 6 anemometers tested, the 4 with most similar characteristics were selected.

During the tests on the instruments, the limpet logger had not been employed to record the results, although the recorder had been tested on its own and was found to be in a satisfactory condition. The reason for not using the recorder in obtaining the results was the difficulty in translating the data. After results were recorded on the tape of the logger it was necessary for these to be "read" by a specially designed translating apparatus. Since no such apparatus was to be conveniently had, the tapes were returned to the manufacturer of the logger for translation. Although this was a fairly lengthy procedure it had a distinct advantage. When the results were returned, not only was a print-out provided but all the results were recorded on punched tape in a pre-selected code.

The results from the mast readings were subsequently punched, on request, in 5 hole Sirius autocode. This allowed these tapes to be used straight off as data tapes together with a suitable programme, on the Sirius computer which was employed in calculating the pressure coefficients from the various models. In the handling of the masses of data which was accumulated, this resulted in a considerable over-all saving in time.

It could be argued that in failing to test the limpet logger in conjunction with the wind-tunnel tests on the anemometers, a risk was run in not detecting distortions in the velocities recorded, due to the characteristics of the logger. This possibility was considered at the time and it was decided that since any distortions produced would appear in the recordings from all the instruments on the mast, no difficulties would result. The reason being that each reading would be expressed as a percentage of the reading from the topmost instrument on the mast. However, no variations, produced by the logger recorder, were ever detected in the results subsequently obtained.

## Erecting & Instrumenting the Mast.

The major problem involved in setting up the instrumented mast was in securing and adjusting the topmost anemometer, 40 ft. above ground level. It was considered that even if, when the mast was set up, it was possible to obtain a ladder sufficiently long to reach the top of the mast the weight of someone resting on the ladder at the top of the mast would push it out of position. The result would be that when the weight of ladder and man were removed from the mast it would return to the vertical thereby resulting in the spindle of the anemometer being tilted from the vertical.

A solution was obtained in deciding to secure the topmost anemometer to the mast before erection. In addition, in case of failure of this anemometer, it was considered necessary to provide two instruments at this top level. For this purpose the top bracket was extended across the mast, forming a 6 ft. wide bracket across the mast top. On each end of this bracket, 3 ft. from the mast on either side, were mounted the two anemometer heads. These were securely bolted down and by means of lock nuts on the bolts, the spindle shafts of the heads were aligned, as close as possible, with the longitudinal axis of the timber mast.

When prepared, the mast was transported to its final position and hauled upright with its base set in a 5 ft. deep foundation hole. Support for the mast was provided by eight 3/16 in. stranded wire cables, four at the top and four $\frac{5}{8}$ ths. of its length from the bottom, 25 ft. above ground level. These cables were secured to 4" x 4" timber stakes securely driven into the ground at the 8 anchor points.

By using a theodelite and taking great care over the final securing of the eight anchoring cables, the spindle shafts of the two premounted top anemometers were brought to the vertical position.

When this had been done, the 3 remaining anemometers were mounted at the 20 ft., 10 ft., and 5 ft., positions. Access was had by means of a ladder and each anemometer head was correctly positioned vertically by means of the locknuts on the three bolts of each base. The electric leads from each anemometer head were identified by a colour code and securely taped to the mast to prevent wind damage.

Although the limpet logger was provided with a clamped watertight metal casing (capable of being buried in the ground without damage), this instrument was provided with a large timber box housing. This timber housing was given a weather resisting internal lining of bituminous felt and a central shelf on which to place the logger, battery junction boxes and all their related electrical parts. A large access door completed this housing.

Providing a shelter from the weather for this apparatus was essential since it frequently had to be opened up for the purposes of replacing recording tape, checking battery settings and switching on and off the logger each day recordings were made.

The final piece of apparatus to be provided was a wind direction indicator. This was fabricated from aluminium tubing and sheet, provided with a spindle mounting set above a base showing all the points of the compass. Ideally this direction indicator should have been provided with a means of electrically recording the wind direction. However, the logger being employed at this time had only 4 recording channels (although a 10 channel logger had to be employed later) each of which was taken up by an anemometer.

Readings of wind direction had to be made visually and recorded manually at the start and finish of each set of recordings made on the logger. Whenever there was a shift in wind direction, intermediate recordings were made.

# CHAPTER 8

# CHAPTER 8

## RESULTS FROM THE FIELD MODEL

### Experimental Procedure

After making unsuccessful attempts to make pressure measurements on the model in light and moderate winds, it eventually became apparent that to obtain satisfactory and clearly defined results, strong to gale force winds were necessary. The reason for this was that the readings produced in the manometer tubes by pressure measurements in light winds were very low, with very small differences in the heights of the columns of liquid. Even minor errors and inaccuracies in recording these liquid levels could have resulted in significant errors in the final results. All measurements were subsequently made with wind velocities of 30 m.p.h. and over.

Whenever a strong wind occurred, its mean wind direction was established and, when it was found to be in a favourable direction, pressure measurements were made. During the period of February to April 1966, all the strong and gale force winds were from a Southwesterly direction. This was fortunate since it avoided the possibility of discrepancies arising in the results due to recordings having been made in winds which had passed over terrains with different roughness characteristics.

The only difficulty experienced with regard to the wind direction was a frequent tendency for the wind to commence in a direction between S.S.W. and S.W. then to veer first to W.S.W. then to a direction a little west of W.S.W. When this wind behaviour was evident, great care had to be taken to readjust the alignment of the model. At the point when the wind passed the W.S.W. position it began to approach the field model over the end of the line of tall trees which bounded the North-westerly side of the site. This resulted in the recording of the pressure readings being discontinued in case the leeward eddies from the trees affected the readings.

Due to the very considerable length of time necessary to make even one complete set of pressure readings and because readings could not be made when rain was falling, every possible opportunity had to be taken to obtain pressure measurements, not infrequently this meant returning to the site in the middle of the night when conditions were favourable.

When wind conditions were suitable the procedure followed necessitated the head of the pitot-static tube to be carefully aligned with the mean wind direction. This was done using the streamer of light silk as a guide. Next, the line of the mean wind direction was set out on the ground along the side of the model. If the model was to be positioned at the 0° position, a line at 90° to the mean wind line was set out in front of the windward face of the field model and the model front face set parallel to it. When the model was set in the 45° position, the distance from the leading corner and the rear corner to the wind direction line were made equivalent. The greatest care had to be exercised when positioning the model at 30° to the wind. This again required a line to be set at 90° to the mean wind line. The 90° angle was then carefully divided into three equivalent parts and a line drawn at 30° to the 90° line. The front face of the model had finally to be set parallel with this 30° line.

Inside the model the same multitube manometer as had been used to obtain the pressure readings from the wind-tunnel model was set up on top of the base frame forming the floor of the model. The same manometer was employed in order that variations arising from different instrument characteristics would be avoided.

Each one of the pressure tappings was identified by an alphabetical and numerical series and the positions plotted on a chart. Each time that a set of 14 pressure readings was to be recorded, the tappings were first cleared of any rainwater blocking them. The rubber pressure tubes from the manometer were next connected to the inner end of the copper tubes forming the pressure holes. When this had been done, the pressure readings were recorded.

Since the lengths of pressure tubing from the manometer could not be made too long, in order to avoid the possibility of delay effects, the manometer had frequently to be moved. This particular feature of the recording process was very time consuming. In order to make all 136 readings from one quarter of the model surface area the manometer had to be moved 3 times, requiring to be carefully set up after each move. When measurements were completed for one quarter of the model surface area the model was rotated through 90°, carefully re-aligned with the wind direction and anchored in position by means of the folding wedges. Following this, the manometer was reset and the recording process continued.

## Recording and Preparing the Results.

As already discussed, the fixed alignment of the pitot-static tube, which measured the dynamic and static pressures of the wind during the recording of the pressure readings from the field model, was essential. When each set of 14 pressures were about to be recorded from the manometer a careful watch was kept on the level in the fifteenth manometer tube which displayed the dynamic pressure of the wind, as measured at the pitot-static head. As each gust front passed over the model the dynamic pressure measurement was carefully studied. If there was only a relatively small movement in the level of the liquid in the manometer tube this indicated that at that time the wind had temporarily veered from the mean wind direction.

When a considerable depression was observed in the level in the fifteenth manometer tube indicating the dynamic pressure, as a gust front passed over the model, the manometer readings were recorded. Since the full impact of the gust front only lasted for the space of a few seconds, the levels of the liquid in the manometer tubes had to be recorded photographically. The photography was carried out using a single lens reflex camera, loaded with 35 m.m. F.P.3. film allowing a shutter speed of 1/60 th. second with an aperture of f 2.8. Illumination was by means of a single photoflood lamp suspended above the manometer.

There were two additional factors which had to be guarded against when recording the results by this means. A short delay period of two or three seconds had to be given after the pressure measurements appeared in the manometer tubes, in order to make sure that the gust front had completely enveloped the whole model together with the pitot-static tube and to reduce surge effects in the manometer.

It can be certain that the short delay before recording minimised the surge effects but subsequent tests showed that minor effects may have remained in the results. That is, if a manometer tube which was measuring a high negative pressure were situated beside a tube which was measuring a very low negative pressure (or even a positive pressure) then instead of the inflow of liquid to the long column of liquid all coming from the main reservoir, some of it tended to be drawn from the adjacent liquid column on which only low pressure was being exerted. The design of the manometer tended to contribute to this effect since the manometer tubes were not individually connected to the reservoir but were all connected to a common $\frac{3}{4}$" diameter feed tube running along the bottom of the battery of glass tubes (a standard feature of manometer design).

The main tendency of these surge effects was to lower the value of low negative measurements and to increase the value of positive measurements which were made at the same time as negative measurements. For this reason, two safeguards were practised. Firstly, three distinctly separate sets of recordings were made of each group of 14 pressure measurements. Secondly, when there was any doubt as to whether low negative readings or low positive readings had been affected by surge effects they were remeasured by themselves.

It can be seen that the process of recording, with its necessary safeguards, added considerable time to the already lengthy period required to obtain the correct wind and weather conditions, to position the model and to set up the instruments.

After the filmed records of the measurements had been developed they were mounted in a 35 m.m. slide projector. When projected onto a suitable screen the recordings were read off and punched immediately onto data tapes. This was followed by computation, plotting and interpolation to produce the pressure diagrams in the same manner as for the wind-tunnel results.

## Correction for Scale Effects.

One major correction had to be applied to the results before plotting. This correction resulted from the fact that the dynamic and static pressures of the natural wind had been measured at a different height, in relation to the model, than had the dynamic and static pressures in the wind-tunnel. This required to be corrected for the purposes of comparison.

The correction applied was based on the relationship of the profiles generated in the wind-tunnel air-stream to the natural wind profile. The wind-tunnel profiles were considered as 10 ins. high and pitot-static measurements were made outside the profile, in an air-stream of velocity equivalent to that at the top of the 10 ins. high profile.

Since the size of the wind-tunnel model, in relation to the field model, represented a scale 5/16 ins. reps. 1 ft., the height of measurement, at 10 ins., of the dynamic and static pressure in the wind-tunnel represented a height of 32 ft. in the natural wind. That is, the velocity profile which had been generated in the wind-tunnel air-stream was considered to be only the bottom section of a profile which continued to a height of 1,000 ft. or more. Hence the reason for assuming that measurements made in the air-stream, at a height where the velocity was equivalent to that at 10 ins. above the tunnel floor, were equivalent to those made at a height of 32 ft. in the profile of the natural wind.

The reference pressures obtained from the natural wind at the time of making the pressure measurements from the field model were recorded at a height of 5 ft. 6 ins. This meant that the dynamic pressure measured by the fifteenth manometer tube was considerably less than the corresponding pressure measured in the wind-tunnel and required a correction to be applied.

When arriving at the necessary correction factor, the velocity profile obtained from the anemometer mast in a S.W. wind was employed. The difference between the dynamic pressure at 5 ft. 6 ins. and at 32 ft. in this profile was 16.3%. Therefore, when calculating the pressure coefficients for the pressures measured from the field model the value of the recorded dynamic pressure, for each set of results, was increased by 16.3%. This had the effect of reducing the value of the pressure coefficients.

The gust speed of the wind in which pressure measurements were taken from the field model varied considerably. No measurements were made in gust speeds less than 30 m.p.h. and the maximum gust speed recorded was between 60 and 65 m.p.h. Since very few measurements were taken in the slower gust speeds and since only on a few isolated occasions were gusts of over 50 m.p.h. recorded, pressure recordings were normally made in wind speeds of between 35 and 50 m.p.h. This compares with the wind-tunnel air speed of 50.37 m.p.h. employed to test the two wind-tunnel models.

There is a possibility that the form of the wind profile differed in the short gust periods, in which the pressure measurements were recorded on the field model, from the 20 minute mean profiles recorded by the anemometers. However, there is no available evidence to support or refute this possibility. A pressure diagram showing the values of the uncorrected coefficients is shown in fig. (49). After the corrected coefficients had been calculated they were carefully studied. Since each set of results had been recorded in triplicate, as discussed, it allowed any obviously erroneous results to be discarded. The remaining sets of results were matched as closely as possible when being plotted.

## Smoke Tests.

Before the field model was finally dismantled, a number of smoke tests were made in an attempt to gain further information on the behaviour of the air-flow around the model. The first tests were carried out using the Taylor smoke generator but this proved unsatisfactory since insufficient quantities of smoke were produced. The smoke was very rapidly dispersed and could not be clearly photographed.

The next attempt at producing smoke of sufficient quantity was more successful. This required a large fire to be lit approximately 50 ft. up-wind of the model. When the fire was burning well, quantities of old rubber were thrown onto it. This produced large volumes of very dark and dense smoke.

Unfortunately, in spite of the dense nature of the smoke, the photographs obtained were very disappointing. The flow patterns were not at all clear and corresponded very closely with those unsatisfactory photographs which had been obtained in the wind-tunnel when the smoke was injected upstream of the model.

The only well defined photograph obtained from these tests is shown in fig. (50b). In this case the model was positioned at 0° to the wind direction. The very distinct down-curl of the wind would appear to support the conclusion of a rapid and vigorous recontact with the roof surface of the vortex behind the leading edge of the roof. This vigorous recontact is noted in the following appraisal of the results of the pressure measurements.

## Results of Pressure Measurements from the Field Model.

Figures (51a) to (51c) show the pressure diagrams produced from the pressure measurements. In the table in fig. (52) the range of pressures experienced by each surface of the model is shown.

The most striking feature of these results is the large areas of positive pressures measured on the roof surfaces. These positive pressures varied in intensity from + 0.18, in the case of the model positioned at 45°, to the surprisingly large value of + 0.63, when the model was positioned at 0°.

One other significant characteristic of the results is the extremely high positive pressure obtained from the front face of the model at the 0° position. This value of + 1.00 (stagnation pressure) is indeed very high, much higher than thought possible for a relatively small surface area with a small aspect ratio. In addition, no negative pressure was measured on this front face and the two areas of zero pressure are exceedingly small. This indicates that flow separation did not take place on the front face but occurred at the edges.

On further examination of the results from the 0° position, it can be seen that small areas of zero pressure were found on the side walls. This, together with the distinct areas of positive pressure on the front and rear patio walls, gives further evidence of the recontact of the air-flow with the surfaces of the model.

This is a different set of flow conditions from those obtained in the wind-tunnel, except for those in the air-stream with the heavy profile generated by the roughness method.

## Review of Field Results.

The conclusions to be drawn from the pressure measurements from the field model are that there was extremely vigorous eddying in front of the model when positioned at 0°. Not one but two areas of peak positive pressure are found on the front wall surface, positioned beneath the two areas of maximum negative pressure at the front of the roof surface. This indicates that not one but two alternating vortices existed against the front wall.

In all cases the recontact of the flow with the model surfaces was extremely rapid, particularly with the roof surfaces. In addition, the low negative pressures on the side and the back walls of the model show that the vortex pocket which formed around the model was relatively small.

The reason would appear to be primarily centred upon the character of the air movement within the structure of the natural wind. The gusts in which the measurements were obtained from the model had their axes of rotation in the horizontal plane. As a result, the direction of the air-flow over the model was not truly horizontal but had an angular component in the vertical plane, directed towards the ground.

It is considered that it was this factor which caused the vigorous recontact of the air-flow with the model roof, trapped the windward vortex firmly against the front wall and reduced the size of the vortex pocket formed around the model.

## Comparison of Field Results with those from the Wind-Tunnel.

### 0° POSITION

On comparing the maximum and minimum results obtained from the roof surface of the field model at this position, as tabulated in fig. (52), with those from the wind-tunnel model, as given in the table in fig. (42), it can be seen that the closest set of results was obtained from the model when tested in the air-stream with the light roughness profile. However, the patterns of the lines of equivalent pressure on the two roof surfaces as seen in figs. (30b) and (51a), are not at all similar. The lines on the roof of the field model are split into two areas, one on the left and the other on the right side of the roof. Pockets of positive pressure lie between and behind the two areas.

When the front wall surface of the field model is considered, none of the results from the wind-tunnel model are at all similar, not even the results obtained in the air-stream without an induced velocity profile. The maximum positive pressure obtained in the air-stream without a profile was + 0.61, whereas the maximum from the field model was + 1.00 (and no negative pressures were obtained from the front wall surface).

The maximum pressures from the side walls of the field model were slightly higher than those obtained from the wind-tunnel model tested in the air-flow with the light roughness profile. However, the minimum pressure, of 0.00, was very much less than the $\bar{0}.14$ measured on the wind-tunnel model side walls in the light roughness profile.

The range of pressures from the patio walls of the field model, i.e. $\bar{0}.37$ to + 0.06, is extremely similar to that obtained from the wind-tunnel model in the light roughness profile ($\bar{0}.37$ to + 0.03).

## 30° POSITION

The general form of the pressure distribution across all the surfaces of the model in this position was extremely similar to that of the smaller wind-tunnel model tested at the same position in the light roughness profile, see figs. (32b) and (51b). The pressures from the windward faces and from the patio walls are extremely similar together with the general configuration and values of the roof pressures.

More detailed scrutiny shows certain important exceptions to this general similarity. The most obvious is the areas of positive pressure recorded on the roof. These positive pressures lie along the sides of the twin vortices created behind the leading corner and reach a maximum of + 0.23 in the larger of the two locations.

Secondly, the maximum negative pressure of $\bar{0}.93$ from the leading corner of the roof was lower than that from the wind-tunnel model tested in the light roughness profile, the value for which was $\bar{1}.11$. But this value from the field model was not as low as the pressure of $\bar{0}.70$ from the leading corner of the wind-tunnel model in the moderate roughness profile. The close proximity of an area of low positive pressure on the field model roof has caused an expansion of the larger, critical vortex immediately after its formation. This appears to have been the cause of the reduction in the peak negative pressure.

Finally, the leeward wall pressures ($\bar{0}.20$ to 0.00) from the field model were less than those from the corresponding positions on the wind-tunnel model in all but the heavy roughness profile.

## 45° POSITION

The maximum negative pressure measured on the field model roof at this angle was $\bar{2}.05$. This is a relatively high negative pressure, when the results from the wind-tunnel model are considered. Considering the range of pressures measured, the results from the field model must be taken to lie, very generally, between the results obtained in the air-stream without any induced profile and the stream with the light roughness profile.

However, the stream lines of the two vortices from the roof of the field model are shorter and more closely confined than those from the roofs of the wind-tunnel models.

An extremely close similarity can be seen in the ranges of pressure from the windward wall surfaces of the field model and the wind-tunnel model in the light roughness profile. But areas of high negative pressure were measured on either side of the leading corner of the field model at this angle, indicating heavy negative curvature in the air-flow on either side of the corner.

The patio wall pressures from the field model cannot be equated with any of the sets of pressures measured in the wind-tunnel. The maximum negative pressure ($\bar{0}.34$) is greater than any negative pressure measured from the model patio walls in any of the roughness profiles (but is the same as the max. negative pressure obtained in the heavy screen profile). Whereas the maximum positive pressure of + 0.15 exceeded even the highest positive pressure of + 0.10 measured from the wind-tunnel model in the heavy roughness profile.

## Discussion.

An over-all appraisal of the foregoing comparison of the results from the field model with those from the wind-tunnel model leads to the conclusion that in many respects the field model results are closer to the results from model A x A x A obtained in the air-stream with the light roughness profile than any other set of wind-tunnel results.

This is broadly in agreement with the form of the velocity profile which was measured in the natural wind over the field site, as is discussed in the following chapter.

However, certain of the discrepancies between the results from the field model experiments and the wind-tunnel results, even those obtained in the light roughness profile, are considerable and require careful consideration. The main factors requiring explanation are as follows:-

(a) The occurrence of positive pressures on the roof of the field model.

(b) Very high positive pressures on the front wall surface of the field model at the $0^\circ$ position.

(c) Areas of zero pressure on the side walls and leeward walls of the field model.

(d) Distortion of the pressure lines in the pressure diagrams prepared from the results obtained from the field model.

It is considered that three influences have, singly or jointly, contributed towards producing the above features of the results.

1) ---- As already discussed, the turbulence in the natural wind had, due to the extremely large eddies of which the wind was composed, a vertical component, angled towards the ground. This was largely responsible for the areas of positive pressure on the field model roof and for the greatly increased positive pressure on the front wall of the model. The reasons being the vigorous recontact of the vortices above the roof with the roof surface and the trapping of the windward vortex against the front wall of the model.

At first it was considered that the angular movement of the air in the wind had prevented the formation of the windward vortex at the $0^\circ$ position, thereby exposing the wall surface to the total potential, pressure energy of the wind. However, if this had been the case, the escape of the air at the vertical edges of the front wall would have produced areas of high negative pressure down the sides of the front wall but these areas of negative pressure were not found in the results.

The smoke tests later showed that a vortex roll did form against the front face of the model, Fig. (50a). It can be deduced, therefore, that this windward vortex was extremely vigorous, causing the high positive pressures. That two alternating vortices formed before the front face, with their centres located on either side of the mid-point of the wall, would explain the divided pressure areas and the lack of negative pressure at the edges.

It is considered that the angular movement (in the vertical plane) of the mean wind direction also had the effect of reducing the vortex pockets along the side walls of the model when positioned at 0° and behind the leeward walls at the 30° and 45° positions. The total effect was to produce a much smaller over-all vortex pattern around the whole model than would have existed if a flow pattern similar to that which was produced in the wind-tunnel had developed.

Proof of this behaviour can be had from the pressures measured from the back wall and leeward wall surfaces. The ranges of pressures experienced by these walls have been abstracted from the pressure diagrams and included in the tables in figs. (42) and (52). It can be seen that the pressures obtained from the back and leeward walls at 0° and 30° were lower than all of the wind-tunnel results except those measured in the heavy roughness profile.

2) —— The alterations or distortions in the form of the patterns of lines drawn up in the pressure diagrams were mainly produced by the effects discussed above. That is, areas of positive pressure were produced at the boundaries of the vortices on the roof and the size and form of the vortices were reduced and altered due to the accelerated recontact of the air-flow with the roof surface.

However, in addition, the photographic method employed to record the pressure measurements from the field model contributed to the differences between the pressure diagrams produced from the field model results and those from the wind-tunnel results. By waiting two or three seconds after each gust of the wind engulfed the field model before photographing, the manometer readings thus approximated to the method of assessing the modal position in the readings when recording the wind-tunnel results. But whereas in the latter case the visual reading and manual recording process allowed the modal value of each separate measurement to be obtained, the photographic records can be considered to have captured most of the readings in their modal position but that a minority of the readings were recorded above or below the desired position.

Quite certainly, fluctuations in the position of the vortices in the flow around the model must take place. By obtaining the modal value of the pressure readings the mean position of the pressure patterns around the model is obtained and the resultant pressure lines in the pressure diagrams are smooth and of uniform shape.

Pressure measurements recorded above or below the modal position would cause the movement of the pressure lines to one side or the other or would occasionally cause abnormally high or low results at random positions in the pressure diagrams. Therefore these effects contributed to the variations in the form of the pressure diagrams from the field results.

3) --- Even after considering the variations between the field and wind-tunnel results in relation to the full effects of the two foregoing influences, it was considered that the differences had not been fully explained. Consequently, attention was turned to the possibility of the design of individual wind-tunnels having an influence on the results produced.

Minor considerations, such as the effect of differences in the turbulence level, must always be taken into account and will be discussed later. However, a more fundamental issue was raised in order to fully explain the considerable differences between the results from the field model and those obtained in the wind-tunnel. In particular, the low positive pressures from the front face of the wind-tunnel model positioned at $0^{o}$ and the fact that no areas of positive pressure or even low negative pressure were found in association with high negative pressures on the roof of the wind-tunnel model, under any of the air-flow conditions, required further examination.

As explained, the wind-tunnel employed in the experiments discussed in Chapter 5 was of the N.P.L. open circuit type. In order to explore the possibilities being considered, a wind-tunnel with a completely different design was required. That is, the wind-tunnel had to have the fan and motor mounted at the inlet, thereby creating a static pressure greater than atmospheric; whereas the wind-tunnel previously used had the power unit mounted at its outlet and moved the air through the tunnel by reducing the static pressure below atmospheric.

The experimental work concerned with investigating this variation in wind-tunnel design and the results obtained are discussed in Chapter 10.

# CHAPTER 9

# CHAPTER 9

## RESULTS FROM THE INSTRUMENT MAST

### Measurement of the Velocity Profile over the Site.

After erecting the instrument mast and connecting the electrical circuits of the cup anemometers to the limpet logger, no further difficulties, beyond the day to day operation of the apparatus, should have been encountered. However, a number of difficulties were experienced which caused considerable delay and inconvenience.

During the first two weeks of operation, the system appeared to function normally. At the end of this period, after one daily recording run, it was found that the timing mechanism of the limpet logger had malfunctioned causing all of the recording tape to wind onto the take up spool. When this tape was sent for translation, it was found that no usable material had been recorded.

The faulty four channel logger was then replaced by a larger, ten channel instrument of a slightly modified design. This logger subsequently functioned faultlessly throughout the remainder of the recording period.

Freezing fog was the next problem which delayed recordings. This froze the instruments solid and caused so much ice to accumulate around the anemometer heads that even when a fresh wind developed some 36 hours later it took almost two days for the anemometers to thaw out and begin to function again. There was a shorter repeat of this occurrence ten days later.

No attempt was made to measure the temperature or the relative humidity at the various heights on the mast. The reason being that since pressure recordings from the field model were only to be made in strong winds the air would be thoroughly mixed and the temperature and humidity would be virtually uniform throughout the flow. Thus, influences from such variables could not affect the field model results.

When the strong winds of early spring began to make their appearance the anemometers were occasionally subjected to considerable stress. Although the maximum mean hourly wind speed recorded was 25.2 m.p.h. and the fastest 20 minute wind speed which appeared on the records was 28.1 m.p.h. this indicates that the 2 to 3 second gust speeds exceeded 60 m.p.h. (i.e. probably reaching 65 m.p.h.). That is, the maximum design speed of the anemometers was exceeded for short periods during heavy gusts.

No effect of this short term overloading was ever apparent in the operation of the main mechanism of the anemometers. However the rotor cups did show the effects of the buffeting. After one particularly long period of heavy winds it was discovered that one of the three rotor cups of the bottom (5 ft.) anemometer had been wrenched off its support arm and was lying on the ground. The two small rivets which had secured it had worked loose in their fixing holes until they had been pulled out through the holes.

Further examination showed that two cups on the rotor of the 10 ft. anemometer were also loose but that the cups of the anemometers at higher levels showed no sign of damage. The two lower cup rotors were replaced and subsequently gave no further trouble. It can only be concluded that the increased small scale turbulence in the flow near the ground produced a buffeting period which caused a considerable increase in the flexing or vibration of the lower cup rotors.

After a further recording period it was found that the maximum voltage occurring across two of the circuits, from the 20 ft. and 40 ft. anemometer heads, was less than the required 5 v. Investigation showed that in the case of the circuit to the 20 ft. anemometer, the fault lay in the battery box. This was subsequently replaced.

The fault in the 40 ft. anemometer appeared to lie in the circuitry of the head itself. As a result, recordings were switched to the second anemometer head which had been positioned at the 40 ft. height on the mast. This anemometer functioned satisfactorily for the remainder of the profile recording programme.

An examination of the faulty battery box from the 20 ft. anemometer showed that the increased resistance of the circuit was caused by damage to the soldered connections between the circuit wiring and the battery terminals. This was subsequently also found to have been the trouble with connections in the 40 ft. anemometer head.

The damage to the soldered connections was probably caused by frost action assisted by minor flexing vibration of the wires during heavy winds.

Shortly before the profile measuring programme was terminated, that is after the first velocity profiles which had been measured by the instruments were plotted, it was decided to place another anemometer head at the bottom of the mast, 1 ft. 6 ins. above the surface of the ground. The reason for this was that the first profiles plotted from the measurements were much more lightly curved than had been anticipated.

The reason for the form of the wind profiles being lighter than anticipated possibly was the area of relatively open ground which stretched for some 350 yards upstream of the field model. In addition, the ground sloped very gradually downwards in this open area. These two factors probably combined to cause the profile, built up over the suburban area, to decay and reform into the lighter form recorded.

As can be seen from the graphs of the velocity profiles over the site, given in fig. (53), the measurements obtained from the 1 ft. 6 ins. anemometer did not in any way conflict with the results from the other instrument heads.

As a final check, additional sets of readings were obtained by disconnecting the anemometer circuits from the automatic logger and reconnecting to a multi-channel device with a dial display. This device allowed the potential of each anemometer circuit to be monitored at any chosen time. Using the display system and with the aid of a stop watch, readings of the wind speeds were manually recorded over one hour periods, taking sample readings at 15 minute intervals.

A close agreement was found between the results thus obtained and those which had been recorded automatically.

## Preparation of the Results.

As previously stated, the magnetic tapes from the logger were returned for translation to the manufacturer of the limpet logger. On translation the results were punched onto data tapes for computer conversion and accompanied by a print-out of what the tapes contained.

In the form which the translation of the magnetic tape readings took, one complete rotation of the potentiometer wiper arm was represented by a scale of 100 numbers. That is, on a scale descending from 99 to 00, one complete potentiometer revolution was represented by a movement of 100 places. Therefore, because of the instrument calibration, one complete potentiometer revolution integrated over a 15 minute period represented a mean wind speed of 55 m.p.h.

Since the recording interval of the second logger which had been employed was 20 minutes, the average wind speed over the 20 min. period was found by taking the number of places descended on the scale (N) and using the following procedure:-

$$\text{Mean 20 min. wind speed} = \frac{15}{20} \ (N) \times 0{,}55 \text{ m.p.h.}$$

Where:- N = 20 min. displacement on the scale

$\frac{15}{20}$ = conversion to 15 min. interval

0.55 m.p.h. = speed represented by one decrement on the scale, for a 15 min. interval.

As 0.55 m.p.h. was the lowest average speed detectable by this means, it also represented the greatest accuracy with which the average speed could be indicated.

After computing the wind speeds, typical sets of readings from the various wind directions encountered were selected and plotted as percentage velocities at their respective heights adopting the 40 ft. velocities as 100%. The graphs produced are shown in fig. (53).

The profiles measured in winds from a southerly direction contained distortions, which were almost certainly due to eddies produced in the wind as it passed over the sports pavilion. This gave an indication of the sensitivity of the recording system.

As a further check, the profiles measured over the field site were compared with Davenport's Power Law (A):-

$$\frac{V_z}{V_G} = \left(\frac{Z}{Z_G}\right)^{\alpha}$$

Where:- $V_Z$ = the velocity at any height Z

$V_G$ = the velocity of the gradient wind at height $Z_G$

$\alpha$ = an exponent whose value depends on the roughness of the terrain.

Using the gradient wind heights calculated by Davenport (A) the theoretical profiles were found to agree well with the measured profiles. The exponents which produced the closest agreement with the measured profiles lay between 0.13 and 0.17. This supported the conclusion that the form of the profiles was lighter than had been anticipated, for Davenport has predicted that exponents with values around 0.25 would produce profiles which would fit those the the natural wind over terrain of the type which surrounded the field station.

However, Shellard (B) has disagreed with Davenport and has advocated that the exponents required to calculate the profiles over

(A) Paper 2 of reference (73)
(B) Paper 1 of reference (73)

such terrain should be around 0.17. It can be seen that this agrees with the E.S.E. profile measured over the site.

That instrument characteristics have an influence on the results of such wind profile measurements cannot be disputed. A good illustration of this can be had by referring to the work reported by Lettau and Davidson (61) in which the velocity profile in the natural wind over the great plains of Nebraska was measured by groups from a number of American universities. Each group employed a different system of instrumentation and considerable variations in their results are obvious. If the Power Law is applied to the profiles which were measured in this work, it is found that exponents between 0.13 and 0.17 again produce graphs which closely conform to the natural wind profiles.

## Comparison of Field Results with Wind-Tunnel Results.

To provide a basis for the comparison of the forms of the natural wind profiles with those which were generated in the wind-tunnel, it was necessary to draw up the logarithmic graphs. These are shown in fig. (54), in which the relative velocities of the natural profiles have been plotted against the logarithms of their respective heights. The log. graphs of the Power Law profiles, having exponents of 0.13, 0.17 and 0.25, are included for comparison.

These graphs allow the scale relationship between wind-tunnel model and the field model to be examined more critically. In the Model Law developed by Jensen (50) the scale relationship between wind-tunnel and field models is based upon the roughness parameters of the velocity profiles in the wind-tunnel and in nature:-

$$\frac{z_o}{Z_o} = \frac{d}{D}$$ as already discussed in the introductory chapter.

From the log. graphs of the natural wind profiles the value of the roughness parameter ($Z_o$) lies between 0.70 in. for the E.S.E. profile and 0.024 in. for the S.S.W. profile. This corresponds closely with the roughness parameter for the Power Law graphs with exponents of 0.17 and 0.13, being 0.50 in. and 0.022 in. respectively.

When the roughness parameter of the S.S.W. wind is used in Jensen s Model Law and using the tunnel model height of $1\frac{7}{8}$ ins. together with the field model height 72 ins., as d and D respectively, a value for $z_o$ of 0.00063 in. is obtained. Alternatively, if the $Z_o$ of the heavier E.S.E. wind is adopted then $z_o$ becomes 0.013 in.

The roughness parameter of the lightest profile generated in the wind-tunnel, i.e. the light roughness profile, as shown in fig. (6), was 0.11 in. Therefore, a roughness parameter of even 0.013, much less 0.00063 in., could only be produced by a profile of the size of a very small boundary layer. Indeed, when the heavy boundary layer which existed in the wind-tunnel is plotted in a similar manner to the velocity profiles the roughness parameter obtained is 0.07 in. It can be estimated that a boundary layer with a $z_o$ of even 0.013 in. would only be approximately $\frac{1}{2}$ in. high.

Since the Power Law profiles showed a marked similarity with the natural wind profiles, producing almost the same roughness parameters, and since the results from the field model were closer to the wind-tunnel results obtained in the light roughness profile than to any other set of wind-tunnel results, a critical examination of the validity of the Model Law becomes necessary.

## Examination of the Model Law.

When the straight line log. graphs of the velocity profiles generated in the wind-tunnel air-streams and of the velocity profiles measured in the field are examined it can immediately be seen that the mean slopes of these two sets of graphs differ considerably. It is considered that this points to a weakness in the Model Law.

The profiles of the natural wind, and therefore the slope of their log. graphs, together with their position of zero flow, i.e. the roughness parameter, can be influenced in a number of ways. The velocity gradient in the profile becomes established after the wind has passed over a certain length of a particular terrain (considered by some authorities to be around 100 times the height of the profile). When a change in the condition of the terrain is encountered the form of the profile begins immediately to alter. Obvious examples of this would be either when the flow encountered a wide belt of trees - when the curvature at the bottom of the profile would be increased - or when the flow began to pass over ground which sloped downwards - in which case the bottom of the profile would be "opened up" or reduced in curvature.

It should be noted that the ground surface which lay to the S.W. of the field model sloped gently down to the model position and this may well have been part of the reason that the profiles measured above the field site were rather more lightly curved than had been anticipated.

Furthermore, the relationship between the slope of the log. graph and the roughness parameter ($z_0$) of the profile can be distorted. When the wind passes over fields of growing grain, situated in flat unbroken country, the turbulence produced by surface roughness is of a small magnitude and the curvature of the profile produced is light. However, the position of zero flow would be as much as 18 ins. above the surface of the earth, due to the closely spaced nature of the stalks of grain.

On the other hand, the turbulence produced in a wind passing over similar flat terrain which was strewn with rocks and other small obstructions would be greater and the curvature of the profile rather more heavy. But the position of zero flow would be closer to the surface of the earth, at a height of say - 2 to 3 ins.

Therefore, the slope of the log. graph of the first profile would be steeper than the second, due to its lighter curvature, but the position at which it cut the vertical axis of the graph would be higher (indicating a greater roughness parameter) than the graph of the second profile. In such a way the roughness parameter of the first profile would be indicated at an artificially high point in relation to the general character of the air-flow.

Thus what is probably the principal weakness of the Model Law is that it cannot take account of the spacing of the material producing the rough surface. This can result, under certain circumstances, as illustrated above, in an erroneous relationship between the roughness parameter and the turbulence character of the flow. That is, it is possible to have a set of conditions in which the roughness parameter is large (indicating an air-flow with heavy turbulence characteristics), caused by the close spacing of the objects covering the ground, and the turbulence inherent in the air-flow is light in character (caused by the closely spaced objects being of very similar height, thereby reducing the aerodynamic roughness).

It is considered that whereas it can give a general indication of the model and full-scale relationship, the Model Law cannot be completely depended upon to give an accurate correlation of the model and full-scale conditions.

Although it is a rather more difficult and lengthy process to achieve, a much more accurate means of establishing the precise relationship between full-scale and model test conditions would be to consider the spectral density of the turbulence in the two air-streams. Dependence would then be on the relationship between the scale of the turbulence in the natural wind and in the wind-tunnel air-stream. This could be adjusted to be in the same scale relationship as the full-sized and model buildings.

The criterion would then be the turbulence spectrum of each flow rather than the roughness parameter.

# CHAPTER 10

# CHAPTER 10

## EXPERIMENTS INTO THE EFFECTS OF VARIATIONS IN WIND-TUNNEL DESIGN

### Consideration of Wind-Tunnel Design.

On further examination of the unusual features found in the field model results, it was considered that the design of the wind-tunnel which had been employed in the laboratory work might have contributed to the discrepancies between the laboratory and field results.

Since the Heriot-Watt University wind-tunnel, which had been used, was of the form producing a sub-atmospheric static pressure, it was decided to make an initial study of results produced by a wind-tunnel which functioned by means of positive static pressure. A wind-tunnel of the desired type was therefore sought out.

A large, well designed tunnel was located in the Department of Mechanical Engineering of the University of Edinburgh and was generously made available for the necessary experiments.

Figs. (55) to (57) show the design of this wind-tunnel. The total length of the tunnel was 35 ft. 11 ins., with a working section length of 4 ft. The working section was an irregular octagon consisting of a 24 ins. square cross-section with 6 ins. broad inserts across the four corners. An unusual aspect of the design was the power unit which consisted of an eight bladed centrifugal fan. It was for this reason, to remove the turbulence produced by the impeller, that the large settling chamber with a large number of fine mesh screens was necessary in the design. The effectiveness of the design was proved by the low turbulence level of 0.27% in the working section.

Due to the high pressure developed by the centrifugal fan, air speeds of up to 115 m.p.h. could be obtained in the working section.

## Profile Generation.

The only problem presented by the design of this wind-tunnel was the restricted length of its working section, i.e. 4 ft. This made profile generation by the roughness method extremely difficult and made the possibility of the comparison of results with those from the Heriot-Watt tunnel remote.

The solution to the problem was obtained by referring to the results of a previous investigation (121). This work had been carried out in the Heriot-Watt University wind-tunnel before the modifications described in Chapter 2 had been carried out. Since the working section of the Heriot-Watt tunnel had, at that time, only been 4 ft. 2 ins. long, a short length of roughness 25¾ ins. long composed of ½ in. deep bars of ¼ in. thick perspex spaced at 1 3/16 ins. centres, had been employed to create a light velocity profile. The models tested in this air-stream had included the two models used in the study under consideration and detailed pressure measurements, exactly similar to those under discussion, had been carried out on them.

Therefore, it was decided to create a velocity profile in the Mechanical Engineering wind-tunnel by identical means. This would allow the results to be compared with those from the earlier study.

A grid composed of plywood bars ¼ in. thick and ½ in. deep spaced at 1 3/16 ins. centres was then prepared to a length of 25¾ ins. When firmly anchored in the floor of the working section immediately upstream of the model test position this grid of roughness produced a velocity profile in the air-stream of the form shown in fig. (6). The total depth of this profile was 8½ ins., compared to the 8 ins. of the profile produced in the earlier study, also shown in the same figure. The straight line log. graphs of these profiles are shown in fig. (7).

## Oil Film Tests.

Before experiments were begun, a turntable had to be prepared, with a suitable pivot, model anchorage and arrangement for access for the pressure tubing. It had then to be fitted into the floor of the working section.

When this had been done it was decided to carry out preliminary tests using the oil-film method described in Chapter 4. These tests were carried out on both models at the three test positions, first in the air-stream without an induced velocity profile then in the air-stream with the light roughness profile.

The photographs of the oil-films produced are shown in figs. (58a) to (63b). It can be seen that the vortices on the roof surfaces appear to have behaved in the same manner, under the influence of the increased turbulence in the flow, as was previously found. However, without the full range of conditions covered by the previous study discussed in Chapter 4, the results are less conclusive and are certainly unable to show up the subtle differences being sought to support the theory of variations produced by differences of wind-tunnel design.

In the case of model AxAxA at the 0° position the increased turbulence caused recontact of the air-flow with the roof surface closer to the front edge. With this model positioned at the 30° and 45° angles to the air-stream the vortices above the roof were broader and less narrowly confined in the results from the air-stream with the light roughness profile than in the air-stream without an induced velocity profile. This is in keeping with the results obtained in the Heriot-Watt wind-tunnel.

The same effects can be seen in the case of model AxAx3A, with the vortices produced in the light roughness flow broader than those produced in the undisturbed air-stream. The differences are not quite so marked as with model AxAxA, which can be attributed to the larger model not being so deeply immersed in the roughness flow as the smaller model had been.

## Pressure Readings.

Care was taken in preparing to make the pressure readings on the models to ensure that exactly the same procedure, using the same techniques and instruments, was employed as with the previous pressure measurements. The same multitube manometer was used, which had been unmodified in any way since the studies in the original Heriot-Watt wind-tunnel had been made. The same micro-pitot tube was used to measure the dynamic pressure of the air-stream and it was mounted in approximately the same position in relation to the model position. A choice had to be made between the air-speed of 70.5 ft./sec. which had been used in the unmodified wind-tunnel or of 73.9 ft./sec. which was used in the tunnel after modification.

This was an extremely small matter (especially in the light of considerations related to Reynolds' number effects which were investigated later) but for the sake of continuity the slower speed was adopted since the comparison of the results to be obtained would be with the results from the unmodified Heriot-Watt tunnel.

The pressure measurements were then made on each model in turn first in the air-stream without any induced velocity profile then in the air-stream with the light roughness profile. The measurements were recorded, calculated, plotted and drawn up in the form of pressure diagrams in exactly the same manner as had been done before.

Since doubts are still expressed from time to time about the validity of ignoring the Reynolds' number, when testing model buildings and similar sharp edged objects in wind-tunnels, it was decided to take the opportunity afforded by the high maximum air-speed of the Mechanical Engineering Department tunnel to carry out tests. If some of the variations which had been noted between the field and the wind-tunnel results had been scale effects caused by differences in Reynolds' number then it was hoped, by this means, to bring this to light.

# Comparison of Results

## Model AXAXA

### Air-Stream without induced Velocity Profile - 0° POSITION

A table of the abstracted pressure ranges obtained in both the Dept. of Mech. Eng. wind-tunnel and in the unmodified Heriot-Watt tunnel are shown in figs. (76) to (79). The pressure diagrams produced from the results are shown in figs. (64a) to (69b). The results from the earlier study in the unmodified Heriot-Watt tunnel are given in figs. (70a) to (75).

At the 0° position the positive pressures measured from the front face of the model in the Mech. Eng. tunnel were considerably greater than from the model in the unmodified Heriot-Watt tunnel. The maximum pressures were +0.94 and +0.59 respectively.

In addition, the negative pressures from the side walls were higher in the Mech. Eng. tunnel, reaching a maximum of $\bar{1}.31$ compared to a maximum of $\bar{0}.76$ from the Heriot-Watt tunnel.

However, the roof pressures were lower from the Dept. of Mech. Eng. tunnel than from the Heriot-Watt tunnel, with maximum results of $\bar{0}.99$ and $\bar{1}.14$ respectively. The area of high negative pressure was confined closer to the front edge of the roof in the case of the results from the Heriot-Watt tunnel than in the Mech. Eng. tunnel results. But there was a larger area of low pressure at the back of the roof surface in the results from the Dept. of Mech. Eng. tunnel.

Consequently, the negative pressures from the patio walls were higher in the results from the Dept. of Mech. Eng. tunnel, $\bar{0}.71$ to $\bar{0}.53$ compared to $\bar{0}.39$ to $\bar{0}.18$ from the Heriot-Watt tunnel.

The back wall pressures were similar, indicating that the over-all size of the vortex pocket surrounding the model in each case was approximately the same.

What is of significance from the results is that, in addition to being of higher value, the maximum positive pressures on the front face of the model in the Dept. of Mech. Eng. tunnel were grouped into two separate pockets. These pockets occurred on either side of the front face, directly beneath the positions of maximum negative pressure on the roof. This characteristic is very similar to that which was noted from the field model results. However, the maximum positive pressures from the Mech. Eng. tunnel are not quite as great as those from the field model and the negative pressures found at the edges of the front face of the wind-tunnel model show that, unlike the field model, separation of the flow occurred on the face.

Although no positive pressures were found on the model roof at this position in the Mech. Eng. tunnel, the values of the negative pressure in certain areas of the roof were low, with a minimum of $\bar{0}.12$.

### 30° POSITION.

The principal differences in the results from the two wind-tunnels at this position were that the pressures measured in all the areas of major significance were of greater value in the Mech. Eng. tunnel than in the Heriot-Watt tunnel.

The respective maximum values from the Mech. Eng. and Heriot-Watt tunnels were: +0.97 and +0.70 from the windward wall surfaces; $\bar{3}.59$ and $\bar{2}.45$ from the roofs; +0.83 to $\bar{0}.61$ and +0.08 to $\bar{0}.30$ from the patio walls.

From these values and from the intensity of the configuration of the pressure distribution in the results from the Dept. of Mech. Eng. tunnel, it is obvious that the vortex activity which took place around the model in that tunnel was much more intense. This is possibly attributable to the lower turbulence level of the Dept. of Mech. Eng. tunnel - this matter will be discussed later in this chapter.

## Positive Roof Pressure.

By far the most important feature of these results is the small but well defined area of positive pressure which was found on the roof, lying at the front edge of the patio wall, between the positions of the two vortex streams. In addition, pockets of very low negative pressure were found on other parts of the roof surface, reaching a minimum of $\bar{0}.08$ in a small area close to one of the leeward roof edges.

This indicates that an extremely vigorous recontact of the vortices with the roof surfaces occurred, in the same manner as found on the field model roof.

## 45° POSITION

Again, in this position, the maximum pressures from the areas of principal importance were greater from the model when tested in the Dept. of Mech. Eng. tunnel than in the Heriot-Watt tunnel, being: +0.92 and +0.63 from the windward walls; $\bar{4}.02$ and $\bar{2}.21$ from the roofs; +0.01 to $\bar{0}.44$ and $\bar{0}.18$ to $\bar{0}.30$ from the patio walls, respectively.

Similarly, the evidence of the pressure diagrams again shows the vortices in the Dept. of Mech. Eng. tunnel to have been more vigorously established around the model.

Although no positive pressures were measured on the model roof at this position in the Dept. of Mech. Eng. tunnel, two small positions of extremely low negative pressure were found. The minimum values in these positions were $\bar{0}.04$ and $\bar{0}.07$, their positions can be seen to lie along the inner boundary of one of the vortex streams. That is, approximately in the same position as in the case of the field model positioned at the same angle in relation to the direction of the air-flow.

## Air-Stream with Light Roughness Profile - All Positions.

When the tabulated pressure ranges, shown in fig. (76) and (78), together with the pressure diagrams produced from the results obtained from the model in the Dept. of Mech. Eng. and unmodified Heriot-Watt tunnels are examined in detail, it is found that the introduction of the light roughness profile brought the sets of results very much closer to similarity. The pressures obtained from the Mech. Eng. tunnel are seen to be still slightly greater than those from the Heriot-Watt tunnel but by only a small margin.

## MODEL AXAX3A

### Air Stream without Induced Velocity Profile.

Unfortunately, no measurements were made on this model in the original programme of experiments in the unmodified Heriot-Watt tunnel using an air-stream without an induced velocity profile. The only results available from that tunnel on model AxAx3A were obtained in the light roughness profile described above. This, of course, prevents comparison but does not invalidate any appraisal of the results from the Dept. of Mech. Eng. tunnel with the profile-free air-stream.

The main features of the results which required greatest attention were the pressures measured on the windward model faces together with those measured from the roof surfaces. The object was to determine whether or not the increased positive pressures on the windward faces and the reduced minimum pressures on the roof were in evidence.

On examining the results (pressure tables figs. (77) and (79), pressure diagrams figs. (67) to (75)) it can be seen that the positive pressures from the windward faces are extremely high, reaching stagnation pressure at the $0^{\circ}$ and $30^{\circ}$ positions, and distributed over large areas. However, in the light of the subsequent results obtained in the air-stream with the light roughness profile, these features cannot be regarded as being in any way unusual.

No striking features can be found in the sets of results obtained at the three test positions from the model roof, as was found in the smaller model. The minimum pressures measured at the 30° and 45° positions i.e. $\bar{0}.48$ and $\bar{0}.30$ respectively, can be regarded as being of relatively low value. This is borne out by the results obtained in the light roughness profile.

However, no areas of extremely low negative pressure, much less positive pressure, were found. This is considered to have a significant bearing on the discussion which will follow in the next chapter.

### Air-Stream with Light Roughness Profile.

In the same manner as had been found with the results from model AxAxA., the results from the larger model when tested in the light roughness profile in the Dept. of Mech. Eng. tunnel were found to be very similar, in all respects, to those from the unmodified H eriot-Watt tunnel. The differences were relatively minor. Indeed, in certain cases the values of the results from the Heriot-Watt tunnel were greater and in other cases the values from the Dept. of Mech. Eng. tunnel were greater.

The two sets of results can be considered to have been in fairly close agreement. This point will be included in the discussion which is contained in the following chapter.

### Measurements in Air-Stream of Increased Speed.

Since the possibility of differences in Reynolds' number affecting the air-flow behaviour around bluff bodies is still discussed from time to time, it was considered desirable to make at least one test of this possibility. This was done by testing the smaller model in the Dept. of Mech. Eng. tunnel at a greatly increased speed.

Pressure measurements were made from the model in an air-stream with a speed of 170 ft./sec. No attempt was made to induce a velocity profile in the flow, in order to prevent secondary effects occurring.

The results from this test have been listed in the table in fig. (76) and the pressure diagrams produced are shown in figs. (64) to (66). Very close agreement is evident between this set of results and those from the air-stream without an induced profile at the lower speed of 70.5 ft./sec.

## $0^{\circ}$ POSITION.

Virtually no difference can be found in the results obtained from the model at this position in the two air-streams of different speed. The only detectable variation in the results is that the pressures measured in the patio of the model in the faster flowing air-stream were slightly less than those from the slower air-stream, with a range $\bar{0}.65$ to $\bar{0}.45$ compared to $\bar{0}.71$ to $\bar{0}.53$.

## $30^{\circ}$ POSITION.

Once again, as with the results at $0^{\circ}$, little or no difference can be found in the pressures measured from the model at this position in the two air-streams. One feature is, however, worthy of examination. That is, in the faster air-stream the small pocket of positive pressure which was found on the model roof at the slower speed did not appear. A similar small pocket, in the same position, was found in which the negative pressures were extremely low, going down to $\bar{0}.15$. It is considered that this feature of the results has significance and will be discussed.

## $45^{\circ}$ POSITION.

An examination of the patterns of pressure distribution produced on the model at this position in the two air-streams of different speed shows them to have been, once again, extremely similar in form and value. The only exception was the peak negative pressure measured on the roof surface behind the leading corner. In the slower air-stream the value of this pressure was $\bar{4}.02$, whereas in the faster airflow the value was $\bar{3}.43$.

This discrepancy may have arisen from the fact that the surface area on which the peak negative pressures were found was extremely small. Since there had to be a finite spacing between the pressure tappings (the holes being $\frac{3}{8}$ in. apart at the position under consideration) there was a risk that the very small area of maximum negative pressure might have occurred between the pressure tapping holes.

Further discussion will be entered into concerning this and other variations when the possible effects of acoustical air resonance are examined in the following chapter.

# CHAPTER 11

## CHAPTER 11

## THE PRESENCE OF SOUND WAVES IN WIND-TUNNELS

### Acoustic Resonance of the Air Column in Wind-Tunnels.

The small variations which have been shown by the comparison of the two sets of results from the air-streams of different speed in the Dept. of Mech. Eng. wind-tunnel, are possibly partly attributable to experimental error and partly to differences in turbulence levels of the air-streams. What is now thought to have been the more probable cause is the effect of acoustic resonance in the air-stream.

After careful consideration of the results from the two wind-tunnels and after comparing these results with those obtained from the field model, it was deduced that forces, hitherto unconsidered, were at play. The variations in the pressure distribution over the model external surfaces indicated that the vortex shedding behaviour around the models, particularly the smaller, had been influenced by certain characteristics of the air-streams employed.

A considerable volume of sound energy is generated in the air columns of wind-tunnels of the closed throat, open circuit type used in the investigations. Under certain conditions, much of this sound could be generated by the acoustic resonance of the air column enclosed by the wind-tunnel.

An obvious analogy is the resonance of the air column in a large organ pipe. The analogy can be carried further. The period of the vortices shed at the lip in the mouth of the organ pipe is influenced by the superior energy of the acoustic resonance in the pipe to match its resonant period. Similarly, the vortex shedding period from a model in a wind-tunnel could be forced to correspond with the frequency of the acoustic resonance of the wind-tunnel air column.

It has not yet been established to what extent large quantities of acoustical pressure energy at any random frequency, or combination of frequencies, passing down a wind-tunnel will influence the flow behaviour, and hence the pressure distribution, around a model in the air-stream. However, it is considered that the effects on the flow behaviour around the model would be at a maximum when the acoustical frequency of the sound in the tunnel was similar to, or slightly slower than, the frequency of the vortex shedding period from the model. When the vortex shedding frequency did not exactly match the acoustical frequency, the shedding frequency would be "locked into" the acoustical frequency due to its superior energy. This could occur at vortex shedding frequencies both above and below the acoustical frequency.

There is in existence a very small amount of evidence (94) (125) to support the above conclusion, but this is still far from sufficient to establish to what extent the acoustical and vortex shedding frequencies can be mis-matched before the "locking" behaviour is destroyed. This must obviously depend upon the amount of energy contained in the critical acoustical frequency. In turn, the strength of any particular acoustical frequency will depend upon its origin. If the origin of the sound is solely from the fan blades ("siren" effect) then the pitch and intensity of the sound will be dependent upon the speed of the blades. On the other hand, if the main sound source is the harmonic resonance of the wind-tunnel air column (excited by the fan blade pulses), the predominant frequency in the harmonic range would depend upon the physical size and shape of the wind-tunnel.

Although it is entirely possible that the total amount of sound energy present in the air-stream could have a major effect on the flow behaviour around a model, no evidence is yet available to evaluate the effect. If the sound were low in pitch and of a high intensity then it would certainly affect any large eddies which were shed from the model. In the same way, if the sound were of high pitch it is more likely to have its effect on smaller sized vortices. This, of course, means taking a much more general view of the vortex frequency considerations and would apply where the sound was more complex in structure, rather than pure tones in a harmonic range.

## Effects of Acoustic Resonance.

It is considered that certain features of the pressure results can be attributed to the effects of acoustic resonance. The most significant of these is the increased positive pressure on the windward walls of the small model, particularly at the $0^{\circ}$ position, together with the pockets of very low pressure found on the roof of this model. As noted in the preceding chapter, this low pressure was replaced with a pocket of positive pressure on the model roof in the set of results obtained at the $30^{\circ}$ position in the low speed air-stream without any induced velocity profile.

The possibility of blockage effects causing the differences in the results has been examined. However, both of the models had cross-sectional areas less than 6% of the working section area, the cross-section of the smaller model was only 0.652% of the sectional area. In addition, the positive pressures on the windward walls and the negative pressures on the roofs and side walls of the models were greater in the larger wind-tunnel, which runs counter to the effects to be expected from blockage.

Secondly, the effects of the turbulence level in the wind-tunnel must be examined. The turbulence level in the unmodified Heriot-Watt tunnel was approximately 0.5% whereas in the Mechanical Engineering Dept. tunnel it was 0.27%. This variation must obviously account for some of the differences between the results obtained from the two wind-tunnels.

However, in arguments centred around differences in wind-tunnel turbulence, 'fan noise' and 'fan pulses' are included as part of the spectrum of turbulence and seldom is any attempt made to differentiate between turbulent mixing of the flow and longitudinal pressure fluctuations.

Indeed, after considering the arguments which are outlined in this chapter it is entirely probable that the presence of very low frequency acoustical signals in a wind-tunnel would eliminate fan blade pulses and fan noise, would dampen out many other secondary disturbances and thereby greatly reduce the measurable "turbulence" level in the wind-tunnel.

As already discussed, a small amount of evidence is avilable which indicates that at least at certain critical Strouhal numbers, depending upon the acoustical frequency, the vortex shedding behaviour from a model will be altered by longitudinal sound waves. In addition, the results of studies on aeroelastic models have shown that longitudinal acoustic effects in the wind-tunnel can excite the model. (125).

In order that an assessment can be made of the possibility of acoustical effects being present in the results under discussion, the designs of the wind-tunnels must be examined. In fig. (80) the basic shapes of all three wind-tunnels are shown. An examination of the shape of the unmodified Heriot-Watt wind-tunnel reveals that the fundamental resonance of its air column lies, theoretically, at around 14 c./s. However, the narrow width of the tunnel in relation to its length, would virtually eliminate the lower harmonics in the resonance of the air column.

The model test position in this tunnel was located close to a point where an antinode of the second harmonic (i.e. 70 c./s.) occurred; this has been sketched on the diagram in fig. (80). Because of the design of the tunnel it is probable that this harmonic would not be vigorously established.

The width of the extended Heriot-Watt tunnel remained the same but in relation to the increased length it made the proportions of the tunnel very narrow. Therefore, although the fundamental resonance of this tunnel was theoretically lower (10 c./s.) the design discouraged even further the lower harmonics of any air resonance. In this case the model test position was situated close to an antinode of the 4th harmonic, having a frequency of 85 c./s.

A different set of conditions is found when the design of the Mechanical Engineering Dept. wind-tunnel is studied. The considerable width of this tunnel, in relation to its length, would mean that the fundamental tone of 8 c./s. in any harmonic resonance would be greatly encouraged together with the other lower harmonics. Indeed, it was observed that the sound eminating from this tunnel during operation was very low in pitch.

Contrary to the influence of the design of the Heriot-Watt wind-tunnel, in which the narrow tunnel width would discourage the lower harmonics, the Dept. of Mech. Eng. tunnel was of a form which would suppress the upper and encourage the lower harmonics of the air resonance. Returning to the analogy of the organ pipe, this wind-tunnel design, with a large body width in relation to its length and a restricted cross-section at its open end, can be likened to those organ pipes which are constructed in a similar manner to reduce the upper harmonics and achieve almost pure tones of the lower harmonics (e.g. the flute-toned pipes).

Furthermore, the shape of this wind-tunnel design would appear to assist the emphasis of the acoustical effects under discussion. The gradual expansion of the wind-tunnel behind the fan would behave like an acoustical horn, allowing the maximum pressure energy to pass down the tunnel. The contraction into the working section, at the end of the tunnel, was of the order of 9:1 and evidence is available that little reflection of the energy takes place from such a contraction. Thus the pressure energy would be condensed as it passed into the working section.

A further important difference in the design of the two types of wind-tunnel is the position of the fan. In the Heriot-Watt wind-tunnel the fan was positioned at the outlet, whereas in the Dept. of Mech. Eng. tunnel the fan was positioned at the inlet. A direct consequence of this would be that the acoustical pressure would be carried down the Dept. of Mech. Eng. tunnel by the air-stream with little loss of energy, until it passed through the working section and out into the surrounding room. On the other hand in the Heriot-Watt tunnel the acoustical energy had to travel against the displacement caused by the air-stream moving in the opposite direction. Thus a further dissipation of the acoustical energy in the Heriot-Watt tunnel must have occurred.

Since the model test position in the working section was located near the outlet of the Dept. of Mech. Eng. wind-tunnel, it was situated close to the antinode of the fundamental tone of any harmonic resonance. This fact, together with the over-all design of the wind-tunnel, gives rise to the strong belief that considerable acoustical energy reached the models under test.

## Influences Experienced by the Models.

By calculating the Reynolds' numbers for the two air-streams employed in the investigations (i.e. 197,500 and 476,000 for the 70.5 ft./sec. and 170 ft./sec. flows respectively) the relevant Strouhal numbers of 0.18 for the slower and 0.225 for the faster air streams were obtained from figure (81). (59) Using these two values in turn for S in the formula $S = \frac{nD}{V}$, together with the width of the models

0.464 ft., as the typical dimension D, and the velocities 70.5 ft./sec. and 170 ft./sec., in turn, for the velocity V then the shedding frequencies (n) for the slower and faster air-streams were found to be 28.1 c./s. and 82.4 c./s. respectively.

Since the Strouhal numbers for the air-streams lay in a region of instability the above calculated shedding frequencies would be unstable and, therefore, liable to be easily influenced by any force tending to modify them. With a fundamental frequency of 8 c./s. the first, third, fifth, seventh, ninth and eleventh overtones would be 24 c./s., 40 c./s., 56 c./s., 72 c./s., 88 c./s. and 104 c./s. in the Dept. of Mech. Eng. tunnel. Following the argument which has gone before, the lower harmonic partials would be stronger in any harmonic range in that wind-tunnel.

If the acoustical frequencies are compared to the natural vortex shedding frequencies around both models in the two air-streams, the shedding may have been locked to the 24 c./s. frequency in the slower air-flow and to 56 c./s. in the faster flow. However, since the shedding frequencies were unstable and if the fundamental resonance of 8 c./s. were very strongly established, as would appear to be suggested from the examination of the wind-tunnel design, this would have had a significant effect.

Under normal conditions, the vortex pocket above the roof of the model under test must have been enlarged and reduced in size each time a vortex from one of the sides developed and detached at the rear of the model. Whether or not pockets of air were released from the roof vortex on a random or periodic basis, as has been observed in other three dimensional flows, cannot be determined.

The pressure fronts of the sound waves would have a considerable influence on this behaviour, particularly if the vortex shedding frequency from the rear sides of the model were slowed in the manner estimated. This would have a particularly important influence on the smaller model AxAxA, producing the alterations in the pressures experienced by the windward faces, roof surfaces and rear areas of the side walls, previously discussed.

In the case of model AxAx3A, its greater height (i.e. three times that of model AxAxA) would mean that a much smaller proportion of the air-flow passed over the roof and correspondly more air escaped around the walls. Consequently, any alteration to the vortex pocket above the roof of this model, caused by acoustical energy, would be less distinct. The greatest effects of any acoustical influence would be experienced by the vortex behaviour around the side walls.

The arguments advanced for the effects of the acoustical resonance influencing vortex shedding in an air-stream obviously must also apply in the case of the air-flow containing the velocity profile generated by the grid of roughness. However, in this case the vortex shedding edge which would be affected would not be that of the model but would be the leading edge of the first bar in the grid of bars providing the floor roughness. Since the model was fully immersed in a very turbulent layer, the pressures experienced by it would be governed by the vortices shed from the bars of roughness which would tend to obscure, if not obliterate, the acoustical effects.

The differences in the sets of results from the two tunnels tested using the roughness profiles are so small as to make it impossible to embark upon any examination of whether they were caused by acoustical resonance, or by variations in the roughness profile caused by acoustical resonance, or by the differences in the turbulence levels of the two wind-tunnels, or simply by errors in experimental technique when making the measurements or (what is more probable) when setting up the roughness profile conditions in the Dept. of Mech. Eng. tunnel.

High frequency acoustical energy could only effect the vortex shedding behaviour from a body in an air-current if such energy were able to influence the vortices. Little or no information appears to exist on this possibility but the effects of high frequency acoustical energy fed transversely into a wind-tunnel (70) have been found to have a considerable influence on boundary layer behaviour. It is clear from the argument advanced for the effects of low frequency acoustical energy that high frequency energy would have the same effect if the vortex periodicity were high enough to be "locked" to the acoustical frequency. However, if sufficient high frequency acoustical energy were present it is considered to be entirely possible for it to agitate either the whole air mass in the vortex pocket or the boundary layers at the separation points and thereby produce a modification in the vortex shedding behaviour.

## Possible Uses of Acoustical Energy in Wind-tunnels.

It has been found that acoustical energy induced transversely in the working section of wind-tunnel effects the boundary layer thickness and separation point in the flow around a body. Mention has already been made of reference (70), which contains descriptions of successful experiments into the control of boundary layer behaviour by means of transversely induced acoustical energy.

As already shown, the sets of results obtained from the Mechanical Engineering Dept. wind-tunnel which contained features similar to those found in the results of the pressure measurements from the field model were those sets which were recorded from the model in the air-stream without any induced velocity profile particularly at the speed of 70.5 ft./sec. The reason for this can be explained if the idea of an "Energy Store" is considered.

Instead of the natural wind blowing as a steady current it contains turbulence, much of which occurs in the form of large eddies. The energy is "stored" in vortices which form around and break away from the obstructions on the ground. Subsequently, the air-flow passes over any object in the form of pulses or gusts.

In an air-stream containing low frequency acoustical energy the flow also passes over any object immersed in it in a series of pulses. These pulses are of smaller magnitude and contain less energy but could have the same effect. That is, the vortices would be shed from the body at a slower rate and would be larger. This would explain the increased positive pressure found on the windward faces of the model and the areas of reduced pressure and positive pressure on the roof surfaces. The vortex in front of the model would first become enlarged then would break away, passing over the model. As each vortex passed over the model it would contain a larger quantity of "stored" air which would be prevented from escaping upwards by the accelerated flow above the model and would be confined close to the roof and wall surfaces of the model causing a greatly emphasised recontact of the flow with those surfaces.

It is, therefore, possible that low frequency acoustical energy induced longitudinally in a wind-tunnel could assist in simulating the the effects of the large eddies in the natural wind. Sound waves might possibly be used to excite oscillations in aero-elastic models, since these models have already been shown to be sensitive to such excitation. The frequency and amplitude of the sound waves would be readily adjustable and, therefore, easily matched with the periodicity of the critical section of the turbulence spectrum in the natural wind.

In the case of static models, the passage of the low frequency sound waves over the model, and its estimated effect on the vortex shedding behaviour, could prove to be of considerable advantage in assisting the simulation of the effects of large scale turbulence on wind-tunnel models.

From the foregoing discussion, it is evident that much more information is required on the behaviour of sound waves, and acoustical energy in general, in wind-tunnels. The sources of sound, the processes of propagation, the interaction of acoustical signals and the effects produced in the working section of wind-tunnels all require further study.

Furthermore, research into the possibility of employing acoustical pressures in wind-tunnels to assist in simulating the correct full-scale flow separation behaviour around objects in the natural wind would appear to merit very serious consideration.

# CHAPTER 12

# CHAPTER 12

## SUMMARY OF AND CONCLUSIONS FROM RESULTS

### Objects of the Investigation.

The investigation embodied in this thesis set out to determine the effects on the results from experiments on model buildings and structures of applying the three widely differing theories for establishing the correct air-flow conditions in wind-tunnels, currently advocated by different authorities.

In the investigations, two main lines of procedure were followed. Firstly, the variations produced in the results of experiments on model buildings by using air-streams having the three different characteristics dictated by the three concepts of model testing procedure were established. Secondly, experiments were carried out on a large model in the field in order to attempt to establish which concept is valid.

A third stage was later added in which a study was made of variations produced in the results from model experiments by differences in wind-tunnel design.

### Flow Visualisation Experiments.

The first method of flow visualisation, using smoke tracers, was found to be inconclusive and was abandoned. The second method, using an oil-film technique, proved much more satisfactory.

By photographing the patterns formed by this method, clear evidence was obtained of the differences in the behaviour of the vortices over the model roof surfaces brought about by the variations in the character of the turbulence in the air-streams.

### Pressure Measurements on the Wind-Tunnel Models.

In the results obtained in the air-streams with velocity profiles produced by the surface roughness method, the pressures experienced by the two models decreased in intensity successively with the increased curvature of each of the three profiles. This is precisely what was expected with the increased turbulence in the flow and was entirely in agreement with theory.

The results of the pressure measurements taken from the two models in the air-streams with the three velocity profiles generated by the graded wire mesh screens showed striking variations from the results obtained in the roughness profiles. The negative pressures measured on the roofs were much greater than those recorded in the roughness profiles. Furthermore, the intensity of the roof pressures from model AxAx3A, did not rapidly decrease, as before, with the increased curvature of the profiles. This showed that at the level of the taller model (which was roughly 50% of the height of each profile) very little variation took place in the turbulence level of the air-streams.

.Further evidence of the considerable differences in the character of the air-flow regimes produced by the two different methods of profile generation was provided by the windward walls of the two models. A clear indication was obtained from the pressures measured on these walls that the greater escape of air through the upper areas of the screens caused the air-flow to rise upstream of the screens, producing a separation point of the flow from the tunnel floor far upstream from the model position.

With regard to the measurements taken in the air-stream without any induced velocity profile, the results obtained were markedly different, in all respects, from those from the other two air-flow regimes. The pressures measured at all points on the models were greater in every way.

## Results of Profile Measurement in the Field.

The profiles recorded were rather lighter in form than had at first been anticipated. Calculations made using the Power Law, with exponents between 0.13 and 0.17, agreed with the form of the profiles and straight line log. graphs of the Power Law calculations also agreed with those from the field profiles. The relatively low values of 0.13 to 0.17 of the Power Law exponents confirmed the opinion of the curvature of the profiles.

However, a comparison with other available data on wind profiles over similar types of terrain showed that they too agreed with Power Law curves with exponents between 0.13 and 0.17. Furthermore, these findings agree with the natural wind profiles which have been predicted by Shellard for similar types of terrain. But it is estimated that the measured profiles were lightened slightly by the lie of the land, which sloped gently in the upwind direction down to the position occupied by the mast and model, and by the relatively unobstructed nature of the area of ground which lay between the model and the city suburb which surrounded it.

When the roughness parameters of the natural wind profiles were compared with the roughness parameters of the wind-tunnel profiles, using Jensen's Model Law, it was found that the roughness parameter of even the lightest of the wind-tunnel profiles was too high to fit this relationship.

This failure to correlate the results of the wind-tunnel and field experiments by means of the Model Law has raised certain doubts concerning its validity.

## Results from the Field Model.

The results of the pressure measurements on the field model proved to have certain interesting features. In the main, these results broadly corresponded with those from model AxAxA when tested in the light velocity profile generated in the wind-tunnel by the roughness method.

This assessment can be considered to be satisfactory since the profile of the S.W. wind, in which the readings were obtained, was found to be closest to the form of the light roughness profile.

However, there were notable deviations from this general similarity, the most striking of which were the areas of strongly defined positive pressures found on the roof surface. This positive pressure was found on the roof of the model at all three positions in which the model was tested. Linked to this discovery was the evidence of greater flow penetration to the central patio.

The very high positive pressure found on the model front face at the 0° position in addition to the low side wall and leeward wall pressures together form what is regarded as the second strongly characteristic feature of the field model results.

It has been deduced that the main cause of the above variations in the field-model results was the gust behaviour of the natural wind. Due to the fact that the axis of rotation of the gusts was horizontal, the mean direction of the wind had an angular component directed downward towards the ground. This angular movement of the air in the wind appears to have trapped a large vortex pocket in front of the model, caused the over-all size of the total vortex pocket around the model to be somewhat smaller than in the case of the wind-tunnel model and induced rapid recontact of the air flow with the model surfaces, particularly the roof.

After taking all the above factors into account it was still considered that the full explanation for the differences between the wind-tunnel and field results had not been fully uncovered.

## Experiments into the Effects of Variations in the Design of Wind Tunnels.

A second wind-tunnel of a completely different design from that of the first tunnel employed was sought out. This wind-tunnel was of a highly suitable design but had one disadvantage, which was that its working section was very short. Consequently, any direct comparison of results with those from the Heriot-Watt tunnel was ruled out.

A solution was found by employing the results from a previous study carried out in the Heriot-Watt wind-tunnel before it had been lengthened and by making the test conditions as similar as possible. Both flow visualisation studies and pressure measurements were carried out on the two models first in an air-stream without any induced velocity profile than in an air-stream with a light roughness profile. A third set of measurements was made from the smaller model at a greatly increased air-speed, without any velocity profile, in order to examine the possibility of Reynolds' number effects.

The results from the larger model showed certain interesting characteristics of a minor nature. However, in the results from the smaller model, tested in an air-stream without any velocity profile, certain striking features were found. That is, principally, evidence of positive pressure on the roof and high positive pressure on the windward faces.

These features were slightly modified when the results from the air-stream of higher speed were obtained and were heavily modified, bringing the results from this model into much closer agreement with those from the Heriot-Watt tunnel, when the model was tested in the light roughness velocity profile.

An examination was then necessary of the reason for the differences in the results from the two wind-tunnels.

## The Presence of Sound Waves in Wind-tunnels.

What is now considered to have been the reason was the presence of strong acoustical energy in the working section of the Department of

Mechanical Engineering wind-tunnel. It would appear that the air-column resonated harmonically under the excitation of the fan blade pulses. The design of this wind-tunnel would encourage the establishment of the lower partials of this harmonic resonance, probably giving greatest emphasis to the fundamental tone of 8 c./s.

The effect appears to have had a major influence on the vortex shedding which took place in the air-flow around the model. Working from the Reynolds' and Strouhal numbers for the air-streams, it has been shown that the critical vortex shedding frequencies from the models were slow. The shedding was sufficiently slow to have "locked" into the slower frequency of the first harmonic of the resonance or even the fundamental.

Resulting from the slowing of the shedding frequency, the vortices shed were larger causing the increased positive pressures on the model windward faces and the pockets of low pressure on the roof.

In the faster air-stream the shedding frequency was too great to "lock" into a low acoustical frequency. Hence the reason for the differences in the model pressure readings obtained in the air-streams of different speed.

When the grid of roughness was employed to create the light velocity profile the acoustic effects were obscured. This was because the vortex shedding which was affected was that from the leading edge of the first bar of roughness and the turbulence produced by the grid engulfed the model making secondary effects from the sound waves negligible.

# CONCLUSIONS.

The results of the experiments in the Heriot-Watt University wind-tunnel have proved, beyond any shadow of doubt, the principal contention which initiated this work. The character of the turbulence produced in a velocity profile generated in a wind-tunnel, to simulate the natural wind profile, has a fundamental effect on the shearing behaviour at the separation points in the flow around a model immersed in it.

Pressure effects on a model are greatest when no velocity profile is created in a wind-tunnel air-stream. Although velocity profiles generated by wire mesh screens of graded resistance are adjusted to be the same as those produced by a fetch of roughness material, the pressures experienced by a model under test are considerably greater. Pressure effects on a model are lowest when tested in velocity profiles produced by the roughness method.

It has been shown that curved mesh screens are unsuitable for generating velocity profiles in a wind-tunnel. Contrary to reports which have been prominently published it was found impossible to achieve the necessary profiles by means of curved mesh screens.

The field model results proved to be similar to the results obtained from the wind-tunnel model in a velocity profile produced by the roughness method to a form close to that of the natural wind profile. Consequently, the roughness method of profile generation has been demonstrated to be the more accurate method.

However, gust effects appear to have influenced the results from the field model in a manner which is not normally possible to produce in a wind-tunnel. These effects require to be investigated further. Very much more information is required on the effects of the natural wind on field models and on full-scale buildings.

One additional factor which requires further study has been brought to light by recent investigations carried out by the Building Research Station. This work (64) has shown that the permeability of a model has a significant effect on the pressure distribution on its external surfaces. When a model is adjusted to have the same permeability as a full-scale building the pressure measurements obtained from it become much more similar to those from the building.

In correlating the field model results with those from the wind-tunnel model, difficulty was experienced due to the inadequacy of the information which currently exists on the form of the velocity profiles in the natural wind. The Power Law was in agreement with the results obtained from the instrumented mast. However, confusion still exists concerning the exact form of the profile which is produced over various types of terrain and the exponents for the Power Law which fit these profiles.

The field measurements recorded agreed with those exponents advocated by Shellard, as did other experimental data consulted. On the other hand, in the argument concerning the heights to which natural wind profiles reach, Davenport's assertions are in closer agreement with boundary layer theory. It is to be hoped that current investigations of natural wind profiles will soon disclose the true nature of conditions.

Probably the most important factor revealed by the correlation of the wind-tunnel and field data was the failure of Jensen's Model Law to show the exact scale relationship. It now seems clear that the weakness in this law is its total dependence on the roughness parameters of the wind-tunnel and natural wind profiles and its disregard for the density of the roughness. A much more satisfactory and dependable basis on which to construct the proper scale relationship would be to consider the turbulence spectrum of the two flows. Greater accuracy would be achieved if the spectral density of the flows were used as the criterion for comparison and the relationship of the scale of the turbulence to the model were adjusted to be the same as in the full-sized condition.

No evidence was found in any of the experimental work that variations in the Reynolds' number of the air-streams employed had any effect on the results produced - in spite of deliberate attempts to find such effects.

Turning to the consideration of wind-tunnel design, it has been shown that this can have a very great influence on model test results. Not only does the control of the air-flow require to be complete but the detailed characteristics of the flow must be fully investigated.

The results of the experiments conducted in the Department of Mechanical Engineering wind-tunnel have strongly suggested that the presence of intense acoustical energy (particularly of a low frequency) can have a major influence on the pressures experienced by a model under test. It has been deduced that such acoustical energy is likely to have greatest energy and produce the maximum effect when it is propagated by the harmonic resonance of the column of air enclosed by the wind-tunnel.

Differences in the quantity of acoustical energy, from one wind-tunnel to another would have noticeable effects, and differences in the pitch of the acoustical signal could be of major importance. The effects of high frequency acoustical pressures, possibly caused by fan blade noise, would be different from the effects of low pitched sound waves.

What is the most interesting aspect of the influences asserted by the acoustical effects is that they brought the wind-tunnel model results much closer to those from the field model. This led to the detailed consideration of the flow behaviour which caused this and brought about the "Energy Store" idea. That is, in the same manner as the energy of the natural wind is held up and stored in gusts the energy in a wind-tunnel flow could be stored in low frequency acoustical pressure fronts. Just as wind gusts pass over a building in a series of pulses, the acoustical pressure would pass over the model in a series of pulses and could modify the vortex behaviour around the building and model in a like manner.

Evidence already exists of acoustical energy in a wind-tunnel exciting aeroelastic models. Since the reproduction of the large scale turbulence, which are termed gusts, has never yet been successfully achieved in wind-tunnels, it would appear that the "Energy Store" idea warrants further detailed investigation. Further hope of success with this method is had from other recent experimental work in which acoustical energy has been used to control boundary layer separation over flat and curved bodies.

Much more work is essential on the generation of turbulence in wind-tunnels in order to reproduce turbulence characteristics in close similarity with those of the natural wind. This is particularly important with regard to the reproduction of gust behaviour, which has long been recognised as of great importance when studying the behaviour of aeroelastic models.

Work is now going on (2) in which triangular prisms are being used to induce turbulence in wind-tunnel air-streams. This carries Jensen's roughness method one stage further by producing eddies in the air-stream with their axes of rotation vertical as well as horizontal. Provided that the fetch of this rough material in the wind-tunnel is long enough, this method promises to produce clear improvements in the ability to create the desired turbulence spectra.

Other work (62) (63) is being carried out on the effectiveness of flat plates, with and without turbulence generators on their surfaces, in producing velocity profiles in the wind-tunnel. This method appears to have the same fundamental weakness as the method employing a vertical grid of bars. It is to be seriously hoped that careful study will be made of the results obtained from models tested in profiles created by this and the prism technique before these two methods are brought into general practice.

It is still doubtful if either the prism technique or the plate method can introduce the full range of the turbulence spectrum of the natural wind into the wind-tunnel air-flow. For this reason a supplementary method of introducing the 'gust' effects will be necessary. Such a method could be based on the "Energy Store" idea with the additional pulse energy supplied acoustically.

Alternatively an injection method in which jets of high speed air are forced transversely across the main flow direction in an upstream position could cause large scale eddying in the flow which could behave like wind gusts.

A very great deal of work still requires to be carried out on wind-tunnel technique in this area of research. Only after the inaccuracies and uncertainties described above have been thoroughly investigated and reliable information made available for application in the wind-tunnel testing of model buildings will the results produced be sufficiently accurate to be considered fully dependable.

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