MODEL SIMULATION OF WIND EFFECTS ON STRUCTURES

by

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1. INTRODUCTION

THIS paper attempts to set out briefly the similarity requirements which need to be observed in order that the results of tests carried out in a wind tunnel may be used to predict the behaviour of the full-scale prototype in the natural wind. These requirements will vary according to the problem under investigation. To achieve similarity it is necessary to represent in the wind tunnel the relevant physical properties of both the structure and of the natural wind.

In the first section of the paper non-dimensional parameters are introduced which may be used to define the properties of a model required to produce dynamic similarity with the full-scale structure. A separate section discusses the requirements for matching the airstream in the wind tunnel to that of the natural wind prevailing at the site of the structure. The paper is completed by a discussion of the errors introduced into force measurements on wind-tunnel models by an interference effect known as wake blockage. This effect is of particular significance for tests on building models owing to the wide wakes generated by such models. A correction procedure is introduced which permits the use of larger wind-tunnel models than would otherwise be possible without serious measurement errors being incurred.

2. LIST OF SYMBOLS

The suffices m and f are used to denote model and full-scale values respectively.

A	aspect ratio, suffices 1 and 2 refer to the values for the cross wind force-drag and lift-drag planes respectively

B	typical external linear dimension
C	area of wind-tunnel working section
C_L, C_D, C_C	lift, drag and cross wind force coefficients respectively
C_p, C_p, C_F, C_M	pressure, force and moment coefficients
c	model chord
D	diameter
E	modulus of elasticity
F	total wind force
g	gravitational acceleration
h	linear dimension used to define a moment coefficient
I	moment of inertia per unit span, suffices θ and z refer to torsional and bending modes respectively
K_s	structural damping coefficient
k	numerical constant in equation 5.3
M	overturning moment due to wind
m	mass per unit length
N	frequency
p, p_w	local surface pressure, suffix w refers to the windward face
Re	Reynolds number $\left(= \frac{\rho V B}{\mu} \right)$
S	area used to define the force and moment coefficients, suffices m and g relate respectively to the model and to any obstruction in the airstream not directly included in the model measurements
s	model span

t	wall thickness
V	wind speed, suffices z and z_o refer to wind speeds at these heights
z	height above ground, suffix o is used to denote a reference height
$^1/_\alpha$	exponent of wind-speed profile for long period means, and specifically for the mean-hourly speed
δ	logarithmic decrement, defined as the natural logarithm of the ratio of successive amplitudes of oscillation, suffices a and s refer to the aerodynamic and structural components respectively
μ	dynamic viscosity of air
ρ	density of air
σ	structural density

Other symbols used are defined where they appear in the text.

3. THE SIMILARITY REQUIREMENTS FOR AEROELASTIC SCALING

3.1 *The Non-Dimensional Parameters and Their Application to Model Scaling*

The laws which relate the results of model experiments to the behaviour of the full-scale structure are most easily and concisely determined by the method of dimensional analysis. Provided that all physical quantities involved in the phenomenon under consideration are incorporated into the analysis, the method provides the functional relationship between the non-dimensional values of these quantities and yields the similarity laws permitting full-scale predictions to be made from model-test results.

It can be postulated that the behaviour of a structure under steady uniform wind conditions will depend on the aerodynamic shape and on the following eight physical quantities:-

$$E,\ \rho,\ V,\ B,\ \mu,\ g,\ \sigma \text{ and } \delta_s$$

where each is defined in the list of symbols.

From these eight quantities the five non-dimensional parameters given in Table I can be derived. These parameters may be regarded qualitatively as ratios of forces or energies and the appropriate ratio for each parameter is shown in the Table.

Table I

The Non-Dimensional Parameters

Non-Dimensional Parameter	Symbolic Definition	Force or Energy Ratio
1. Logarithmic Decrement	δ_s	$\frac{\text{Energy dissipated per cycle}}{\text{Total energy of Oscillation}}$
2. Elasticity	$E/\rho V^2$ *	$\frac{\text{Elastic forces of the Structure}}{\text{Inertia forces of the air}}$
3. Density Ratio	σ/ρ *	$\frac{\text{Inertia forces of the structure}}{\text{Inertia forces of the air}}$
4. Gravitational	gB/V^2	$\frac{\text{Gravitational forces on the structure}}{\text{Inertia forces of the air}}$
5. Reynolds number	$\rho VB/\mu$	$\frac{\text{Inertia forces of the air}}{\text{Viscous forces of the air}}$

* either of these parameters may be replaced by $\frac{V}{NB}$

3.2 *The Design of Wind-Tunnel Models*

In practice it is rarely possible to satisfy all the non-dimensional parameters listed in Table I with a model of reduced linear scale tested in an atmospheric wind tunnel, both because the conditions imposed by the individual parameters are incompatible and because in general no materials for model construction are available with the physical properties demanded by the similarity requirements. For this reason it is usually necessary to relax the similarity requirements to some extent and to introduce compromise procedures which, while introducing uncertainties into the interpretation of the model results, still enable relevant data to be obtained.

The selection of the similarity parameters from those listed in Table I which need to be satisfied in any particular instance depends upon the nature of the problem to be investigated. A diagram showing the types of wind-tunnel model used for investigation of various wind loading problems is given in Fig. 1. In the following sections the similarity requirements for the three main types of model listed in Fig. 1 are considered in detail.

3.3 *Static Rigid Models*

Static rigid models are used for the determination of surface pressures and overall steady forces and moments experienced by a building or structure. Full-scale values of the Reynolds number cannot be achieved on reduced scale models tested in atmospheric wind tunnels and for each particular investigation it is therefore necessary to consider the extent to which the force and pressure coefficients (defined below) vary with Reynolds number. It has been shown by tests carried out over a wide range of Reynolds number that the airflow pattern around a sharp-edged body is substantially independent of this parameter because the positions of the flow separations are fixed by the sharp edges. Whether this independence extends to the extreme values of Reynolds number obtained on full-scale buildings is, as yet, unconfirmed and awaits the results of attempts to correlate model results with measurements on the full-scale. Nevertheless for many building shapes it is considered reasonable to assume an independence of the Reynolds number and to carry out tests in a wind tunnel on a model linearly scaled to be as large as possible without introducing unduly large interference effects due to constriction of the airflow by the wind-tunnel walls (see section 5).

For bodies of rounded shape, flow separation is not fixed by the presence of a sharp edge and the flow pattern may vary considerably with Reynolds number so that coefficients measured on a model at low Reynolds numbers may be significantly different from those experienced by the full-scale building. Attempts have been made to reproduce on models the flow conditions at high Reynolds numbers either by roughening the windward surface of the model or by using boundary-layer trip wires, so that the flow separations are induced to occur at similar positions on the model as on the full-scale, but the extent to which these devices are successful is in some doubt.

Measurements made on rigid models have their most general application when expressed in the form of non-dimensional coefficients. These coefficients, which may be used to determine the wind loading at any wind speed on structures of similar external shape, are generally defined as follows:-

(i) Pressure coefficient $C_p = \frac{p}{\frac{1}{2}\rho V^2}$

(ii) Force coefficient $C_F = \frac{F}{\frac{1}{2}\rho V^2 S}$

(iii) Moment coefficient $C_M = \frac{M}{\frac{1}{2}\rho V^2 Sh}$

where S and h refer to the frontal area and height of the building respectively.

3.4 *Dynamic Models*

Strictly, models used to examine the oscillatory behaviour of a structure in wind, should reproduce the correct values of all the structural parameters 1-4 in Table I together with the correct aerodynamic shape and value of the Reynolds Number. This last parameter will be subject to the same problems discussed in the section on static rigid models. For observations of static deflection and stress due to wind only the elastic and gravitational parameters need to be considered (see section 3.5) but for for dynamic studies both the inertial and the damping parameters have to be taken into account.

Two methods of test have been used to study the dynamic behaviour of structures in wind. The first involves the use of a model of the complete structure, termed a full model, in which the similarity parameters are satisfied either by a replica reproduction of full-scale in suitable materials or by a different type of construction chosen to yield the required mass and stiffness distribution. The alternative method uses spring-mounted rigid models of typical lengths of the structure which are termed sectional models. The use of such models is applicable to tests on structures such as long-span suspension bridges and tall lattice masts where the reduction in the linear scale required to accommodate the complete model in the wind tunnel would so reduce the dimensions of the individual components of the model that either its construction would be impracticable or the results would be subject to unacceptable Reynolds number effects.

In the following paragraphs the methods of satisfying the similarity requirements on models will be discussed for two types of structure.

3.4.1 *Full Models of Suspension Bridges*

The full model must have an external shape similar to that of the full-scale although true reproduction of the internal structural details is not necessary provided the inertial and elastic stiffness requirements can be maintained. Model and full-scale air densities are the same for tests in an atmospheric wind tunnel. The effect of this is twofold. Firstly the correct representation of Reynolds number is not possible and the remarks made in the previous section concerning the justification for the neglect of this parameter are applicable. Secondly, for consistency of the density ratio, the structural densities at all corresponding positions must be the same on the model as on the full-scale.

Velocity scaling is prescribed by the gravitational parameter as,

$$\left[\frac{gB}{V^2}\right]_m = \left[\frac{gB}{V^2}\right]_f \qquad \ldots (3.1)$$

and since the gravitational acceleration must be the same for both systems,

$$\frac{V_m}{V_f} = \sqrt{\frac{B_m}{B_f}} \qquad \ldots (3.2)$$

To be compatible with this prescribed velocity scale the required elastic properties can only be achieved on a replica model by the use of materials for model construction with moduli of elasticity given by

$$\left[\frac{E}{\rho V^2}\right]_m = \left[\frac{E}{\rho V^2}\right]_f \qquad \ldots (3.3)$$

so that

$$\frac{E_m}{E_f} = \frac{B_m}{B_f} \qquad \ldots (3.4)$$

Suitable materials are not usually available and compromise procedures have to be adopted which yield an equivalent stiffness effect. These usually involve either an overall reduction in the cross-sectional areas of the elastic members; (the necessary restoration of the external shape and mass distribution being achieved by the addition of discrete fairings and masses), or by the adoption of an entirely different method of construction. In the construction of their full model Frazer and Scruton[1] adopted the former method for the model suspension cable, the stiffness properties of which were obtained by a steel wire of area reduced by the ratio B_M/B_f from that of the dimensionally-scaled model cable, and the shape and mass distribution were restored by the point attachment of brass cylinders along the length of the cable. The latter principle was adopted for the suspended structure; the road decks and stiffening trusses being made up of short rigid segments of the correct external shape and interconnected by small steel springs to provide the correct overall elastic stiffnesses.

The introduction of a representative amount of structural damping into the model tests presents certain fundamental difficulties since it is neither possible to predict a value of the full-scale damping nor to adopt a model construction which automatically achieves the correct value of this parameter. The uncertainties surrounding the structural damping cannot be adequately resolved and, in order that the stability predictions may err on the safe side, tests on models need to be performed with values of damping well below the minimum value likely to occur on the full-scale bridge.

3.4.2. *Sectional Models of Suspension Bridges*

In this method of test the conditions for complete dynamic similarity are obviously not observed. It is assumed that the aerodynamic forces which cause the various modes of oscillation of the full-scale structure are the same as those producing the rigid-body oscillations of the sectional model. The validity of this assumption has been demonstrated experimentally by Frazer and Scruton[1]. They show that for sectional models, the similarity requirements are that the external shape and the following non-dimensional parameters (the equivalent expressions for parameters 1, 2 and 3 in Table I) shall be the same for model as for full-scale:-

(a) Damping - $\delta_{\theta s}$, δ_{zs}

(b) Reduced Velocity - $\dfrac{V}{N_\theta B}$, $\dfrac{V}{N_z B}$

(c) Inertia - $\dfrac{I_\theta{}^*}{\rho B^4}$, $\dfrac{I_z{}^*}{\rho B^2}$

where the suffices θ and z refer to torsional and bending modes of oscillation.

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* The values of I_θ and I_z are the values per unit span of the bridge and include the contributions of the cables. For both vertical bending and torsional oscillation the cables are assumed to move vertically.

Rigid sectional models are usually of the light-weight construction required to reproduce the inertial characteristics of the full-scale bridge as specified by parameter (c). They are mounted across the wind tunnel on a spring suspension so that two-dimensional flow conditions are maintained over the entire length of the model, and oscillation can take place in vertical or pitching motions, representing respectively the vertical bending and torsional oscillation of the full-scale bridge. The stiffnesses and arrangement of the supporting springs are chosen to provide the appropriate frequency ratio N_θ/N_z with values of N_θ and N_z giving a convenient wind-speed scale. The suspension is designed to have as low a value of damping as possible, well below the expected full-scale value, so that various values of controlled external damping may be applied to the model.

In some cases it may not be possible to construct a model light enough to satisfy the inertial requirements and at the same time be rigid enough for the purposes of the tests. In such instances, Scruton[2] has shown that it is permissible to combine the parameters (a) and (c) above to form a single parameter

$$\frac{I_\theta \delta_{\theta s}}{\rho B^4} \quad , \quad \frac{I_z \delta_{zs}}{\rho B^2}$$

provided that the frequency of oscillation does not vary with wind speed, thus indicating that the in-phase component of the aerodynamic force is negligibly small.

The alternative scaling procedure may be used for the different modes of oscillation provided that the modes occur in isolation. For the study of oscillatory behaviour involving coupling between different modes, or if the results of the tests are to be used for amplitude predicition, then proper inertial scaling is required.

3.4.3 *Full Models of Slender Towers and Stacks*

The discussion of the similarity requirements given in section 3.4.1 is equally applicable to the problem of reproducing the oscillatory behaviour of towers and stacks on models of reduced linear scale. For towers and stacks the influence of the gravitational parameter is usually insignificant and the similarity parameters to be satisfied on the model may be expressed as follows:-

(1) δ_s

(2) $\frac{Et}{\rho V^2 B}$ (equivalent to $\frac{E}{\rho V^2}$ in Table I)

(3) $\frac{m}{\rho B^2}$ (equivalent to $\frac{\sigma}{\rho}$ in Table I)

(4) $\frac{\rho VB}{\mu}$

The use of the alternative form of the elasticity parameter is applicable to thin-walled structures and to lattice towers where the distance of the stress bearing members from the neutral axis is large compared with the thickness t. It is useful in that it enables convenient materials of construction and wind-speed scales to be adopted since the requisite stiffness effect Et may be obtained on the model by adjustment of the thickness scale.

A model designed to satisfy the stiffness requirement will not, in general, satisfy the inertial requirement $\frac{m}{\rho B^2}$ (where m is the mass per unit length). Provided that the inertial value has not already been exceeded in achieving the required stiffness then it is possible to increase the inertia by the addition of discrete masses at intervals along the height of the model. The location and value of each of these added masses are calculated to bring the energy of oscillation of the significant modes up to the required value. As for the bridge models, independent scaling of the inertia and damping parameters is not essential if there is no frequency change with wind speed so that (1) and (3) above may be combined to form a single parameter $\frac{m\delta_s}{\rho B^2}$. If inertial scaling is not attempted then the speed scale is no longer prescribed by the elastic scaling parameter but only by the reduced velocity parameter $\frac{V}{NB}$ so that

$$\frac{V_m}{V_f} = \frac{N_m}{N_f} \cdot \frac{B_m}{B_f} \qquad \ldots (3.5)$$

3.4.4 *Sectional Models of Slender Towers and Stacks*

The similarity requirements for the sectional-model testing of towers and stacks are the same as those discussed in the section 3.4.2 for suspension bridges. However, the objectives of the test are usually somewhat different. The suspended structure of a bridge is uniform across the whole span so that tests can be limited to a small range of wind direction with respect to the spanwise axis, and structurally acceptable modifications of the shape to improve the aerodynamic stability are readily made. Tests on bridges are therefore usually directed towards ensuring stability by modification to the aerodynamic shape. The same consideration does not apply to slender towers and stacks, and tests of these structures are usually directed towards the measurement of the aerodynamic excitation so that a stability prediction can be made by taking into account the anticipated amount of structural damping. To obtain the total aerodynamic excitation experienced by a full-scale tower it is necessary to measure the excitation on a number of sectional models each representing a different typical section of the tower and to integrate, using a strip theory, this excitation over the full height. For this purpose calculated frequencies and modal shapes are used.

3.5 *Static Aeroelastic Models*

The distortions and stresses in the structural members of a proposed building or structure due to wind may be determined by wind-tunnel tests of an aeroelastic model, provided that the model is built as a replica of the full-scale with all the relevant structural detail reproduced. The similarity requirements for static aeroelastic models differ from those for the dynamic aeroelastic types discussed in sections 3.4.1 and 3.4.3 in that, for the static model, the density and gravitational effects have only a minor influence. Consequently parameters 3 and 4 in Table I may be disregarded. Dynamic models which satisfy the condition of replica aeroelastic construction are, of course, equally suitable for distortion and stress measurements.

A dynamic aeroelastic model of a tall building block has been built in perspex at the NPL[3] and used for a wind-tunnel study of the distortion and stresses in structural members due to wind. The dynamic scaling of the model also enabled observations of aerodynamic stability to be included as part of the investigation.

4. THE REPRESENTATION OF NATURAL WIND CHARACTERISTICS IN THE WIND TUNNEL

4.1 *The Vertical Gradient of Velocity and Its Effect on Airflow around Structures*

Apart from thermal effects the variation in speed of the natural wind with height, known generally as the vertical wind gradient, is dependent on the relative roughness of the local terrain. Measurements of the gradient in different localities have shown that it is reasonable to represent the variation of speed (V_z) with height (z) as a simple power law variation of the form

$$V_z = V_{z_o} \left(\frac{z}{z_o}\right)^{1/\alpha} \qquad \ldots (4.1)$$

where V_{z_o} is the speed at a reference height z_o. For mean-hourly wind speeds Davenport[4] has suggested values of $^1/\alpha$ ranging from $^1/7.5$ for open grassland to $^1/4$ for heavily built-up areas; these exponents are decreased for wind speeds averaged over a shorter period.

Many of the shape and pressure coefficients used to specify wind loading on buildings and structures have been obtained from tests in wind tunnels with wind streams uniform except for the natural boundary layer of the wind tunnel. Attempts to deduce the wind loading on a building immersed in an airstream with a vertical velocity gradient from results obtained in a uniform stream, have been based on the simple assumption that the gradient produces no overall change in the flow pattern, so that the wind load per unit length at any height (z), is proportional to the square of the speed of the approaching wind at that height.

$$\text{i.e.} \quad \text{Force per unit length} = \tfrac{1}{2}\rho V_z^2 C_F \qquad \ldots (4.2)$$

where C_F is the overall shape factor for the building which has been determined from tests in a uniform wind.

Wind-tunnel tests have shown that this procedure is unsound since the variation of the wind load with height is felt only by the windward face, while the suction on the leeward face is approximately constant in magnitude over the entire height. Baines's[5] investigation on a tall building immersed in an airstream with a vertical velocity gradient showed that the measured pressure distribution on the windward face was in reasonable agreement with the distribution predicted by

$$p_w = \tfrac{1}{2}\rho V_z^2 C_{p_w} \qquad \ldots (4.3)$$

where C_{p_w} is the pressure coefficient on the windward face determined from tests in a uniform wind. In addition Baines[5] has suggested that pressures on the leeward face in a wind gradient can be taken as some 60% of the values recorded in tests in a uniform airstream where the reference velocity is taken as that corresponding to the top of the building.

Jensen[6], on the other hand, is of the opinion that wind-tunnel tests on low buildings under uniform wind conditions are misleading and that a correct representation of the 'Model Law' is essential.

4.2 *The Production of a Velocity Gradient in the Wind Tunnel*

The methods so far used in wind-tunnel investigations rely, in the main, on the introduction of a graduated resistance into an initially uniform airstream so that for some considerable distance downstream a steady velocity gradient is maintained with a uniform static pressure throughout. In some cases a simple empirical approach has yielded good results. O'Neill[7] produced the required graduation in resistance by spacing rods of different diameters in a plane normal to the airstream. Baines[5] used a similar empirical approach by introducing a curved wire-mesh screen some distance ahead of a model to produce a gradient having an exponent $^1/\alpha = {}^1/6$. Jensen's Model Law[6] suggests a somewhat different approach which involves representing the correct scale of ground roughness for a considerable distance upstream of the model so that the wind gradient is formed in similar manner to that of the natural wind. The disadvantage of this method appears to be that, in order to reproduce the ground roughness effect for a reasonable full-scale distance upstream of the model in the limited length of working section available in most wind tunnels, very small-scale models have to be used. This restriction does not apply to the methods used by O'Neill[7] and Baines[5] although their purely empirical approach has the disadvantage that considerable time is usually expended in obtaining the required velocity profile. The analytic approach of Owen and Zienkiewicz[8] provides a useful method for calculating an arrangement for a grid of rods to produce a uniform shear flow whilst Elder[9] has calculated the effect of using gauzes of non-uniform resistance to produce various velocity profiles. Both these approaches show good agreement between theory and experiment and it seems likely that one or both of these methods will form a suitable basis for representing natural wind gradients in the wind tunnel.

4.3 *Atmospheric Gusting*

The gust spectrum present in the natural wind arises from the diverse eddy systems produced by the viscous interaction between the atmosphere and the ground surface. Until recently the effects of gusting winds have been taken into account by specifying a design wind speed equal to that of the gust speed and computing the wind loading as for a steady wind of this speed. The gust speed referred to here is a maximum mean speed over a short period of time and, of course, varies with the duration chosen. The gust duration and hence the design wind speed is usually related to the time taken for the gust to develop over the whole structure and to the response characteristics of the structure itself.

Davenport[10] had adopted a more rigorous approach and using the concept of a stationary time series has determined the response of a simple structure to a turbulent gusty wind in terms of the resultant stresses and deflections.

4.4 *Possibilities of Producing Gust Effects in Wind-Tunnel Testing*

To make use of the turbulence levels available in existing wind tunnels, models would have to be impracticably small. The methods described in the previous section for the production of a velocity gradient by means of grids or screens do not in general reproduce the right scale of turbulence. On the other hand the method of roughening the surface of the wind-tunnel floor in the manner suggested by Jensen[6] would appear to reproduce both the gradient and gust effects at the same time. In fact the 'Model Law' approach appears to be the only method of reproducing a gust spectrum representative of the natural wind although in some cases the use of wire screens or perforated plates may be useful in producing turbulence of a particular intensity.

5. THE EFFECTS OF WIND-TUNNEL-WALL INTERFERENCE ON MODEL RESULTS

5.1 *The Interference Effect*

Full-scale wind loads based directly on uncorrected wind-tunnel measurements on a model situated within an enclosed working section will tend to be overestimated because extraneous suction effects are introduced into the wake (termed "Wake blockage") due to the proximity of the tunnel walls. The extent to which this overestimation occurs is directly related to the proportion of the tunnel cross-sectional area occupied by the model. It is further dependent on whether the flow over the model is attached or separated. In order to limit the errors introduced into wind-tunnel force and pressure measurements to an acceptable amount therefore, it is desirable to limit the size of model so that less than 5 per cent of the area of the working section of the wind tunnel is occupied by the model. In cases where the use of larger models is unavoidable, it is essential to apply corrections for the effect of wake blockage. Investigation of this effect has shown that simple empirical corrections may be applied to force and pressure measurements although these would not be expected to provide sufficient accuracy for models occupying more than 10 per cent of the tunnel working section area.

The interference effect is associated with the flow downstream of the model, where the reduced value of the stream-wise velocity in the wake region requires an increase in speed of the air outside the wake region to maintain continuity of mass flow across the section of the tunnel. This increase in speed is balanced by a decrease in static pressure of the air outside the wake since the stagnation pressure* of this air is unaffected by the presence of the model. Consequently, since the static pressure within the wake is governed by that of the steady airstream immediately adjacent to the boundary of the wake, the static pressure in the lee of the model (termed the base pressure) tends to be less than it would be if the airstream were unconfined as in the full-scale case. For this reason wind forces on models, in particular the drag, tend to be overestimated in wind-tunnel tests.

The magnitude of the change in base pressure is dependent on the flow conditions prevailing on the model. For a stream-lined shape where the flow remains attached over the entire model surface the wake is very narrow and the correction required is much smaller than that for a model of similar cross-sectional area where the flow is completely separated and the wake is as wide if not wider than the model itself. The wake blockage correction developed for stream-lined shapes has proved inadequate for tests on bluff building shapes where flows are mainly of the completely separated type. In the following section the correction equation used in NPL tests on bluff building shapes is presented and details of its application are discussed.

5.2 *The Correction for Wake Blockage*

A complete expression for wake blockage suggested by Maskell[11] is quoted below. In the quoted form it is applicable to a model on which separation of the flow occurs towards the rear of the model so that both components for attached and separated flows are included in the equation:-

$$\frac{C_{D_m}}{C_{D_F}} = 1 + 0.5\left[C_{D_o}\frac{S_m}{C} + C_{D_g}\frac{S_g}{C}\right] - \frac{1}{C_p}\left[C_{D_m} - C_{D_o} - C_{D_I}\right]\frac{S_m}{C} \qquad \ldots(5.1)$$

where C_{D_m} is the measured value of C_D based on an area S_m

C_{D_F} is the true value of C_D for the free-stream condition

C_{D_o} is the minimum value C_D for which $C_L = C_C = 0$ for completely attached flow

C_{D_I} is the lift and cross wind force contribution to C_D

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* The pressure developed by an airstream when it is brought to rest.

C_{D_g} is the value of C_D, based on an area S_g, for any obstruction in the airstream which is not directly included in the model measurements

C_p is the base pressure coefficient in the separated wake behind a bluff body. For a flat plate normal to the airstream $C_p = -0.4$ in the aspect ratio range 1 to 5 so that for a general case $-\frac{1}{C_p} = 2.5$.

A detailed discussion of this equation will not be given in this paper but will appear in a paper to be published by Maskell[11]. For the present purposes the flow around bluff building shapes is regarded as completely separated and so that only the part of Maskell's equation which deals with this type of flow* will be considered. The correction for completely separated flow may be written therefore as:-

$$\frac{C_{D_m}}{C_{D_F}} = 1 - \frac{1}{C_p}\left[C_{D_m} - C_{D_I}\right]\frac{S_m}{C} \qquad \ldots (5.2)$$

Here C_{D_o} and C_{D_g} have been omitted from equation 5.1 because C_{D_o} no longer represents a real quantity and it is assumed that the model is supported internally so that there is no obstruction to the flow other than the model itself. Although equations 5.1 and 5.2 derive a correction based primarily on drag measurement it is considered that the same percentage correction is applicable also to the other measured forces and moments.

The simplified correction equation 5.2 is considered to be adequate for most tests on building shapes so that the only information additional to the measured drag, required to apply the correction is a value for the coefficient C_{D_I}. An estimate of this so-called induced drag coefficient may be obtained by considering the induced drag equation derived for aerofoil theory:-

$$C_{D_I} = \frac{k}{\pi}\left(\frac{C_c^2}{A_1} + \frac{C_L^2}{A_2}\right) \qquad \ldots (5.3)$$

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* Particular cases, such as reflector dishes, may experience attached flow for certain attitudes of the dish, in which case the complete correction given by equation 5.1 is required.

where A_1 is the aspect ratio appropriate to forces in the cross wind force-drag plane and A_2 to those in the lift-drag plane. The value of k will, in general, be determinate only in cases of attached flow where k is the slope of the C_{D_m} versus $\frac{1}{\pi}\left(\frac{C_c^2}{A_1} + \frac{C_L^2}{A_2}\right)$ curve at the minimum value of C_{D_m}. The extent to which this method may be applied to shapes with completely separated flows is limited by the non-linearity of the C_{D_m} versus $\frac{1}{\pi}\left(\frac{C_c^2}{A_1} + \frac{C_L^2}{A_2}\right)$ curve; in general it has not been found possible to ascertain the value of k by direct measurement. However for most structural shapes C_{D_I} is small and it is considered that a correction based on k = 1 provides sufficient accuracy.

Equation 5.2 is intended to be applied to tests where the wind upstream of the model has a uniform velocity profile. Measurements made in non-uniform velocity profiles have been corrected using the same equation although the effect of a velocity profile on wake blockage is uncertain.

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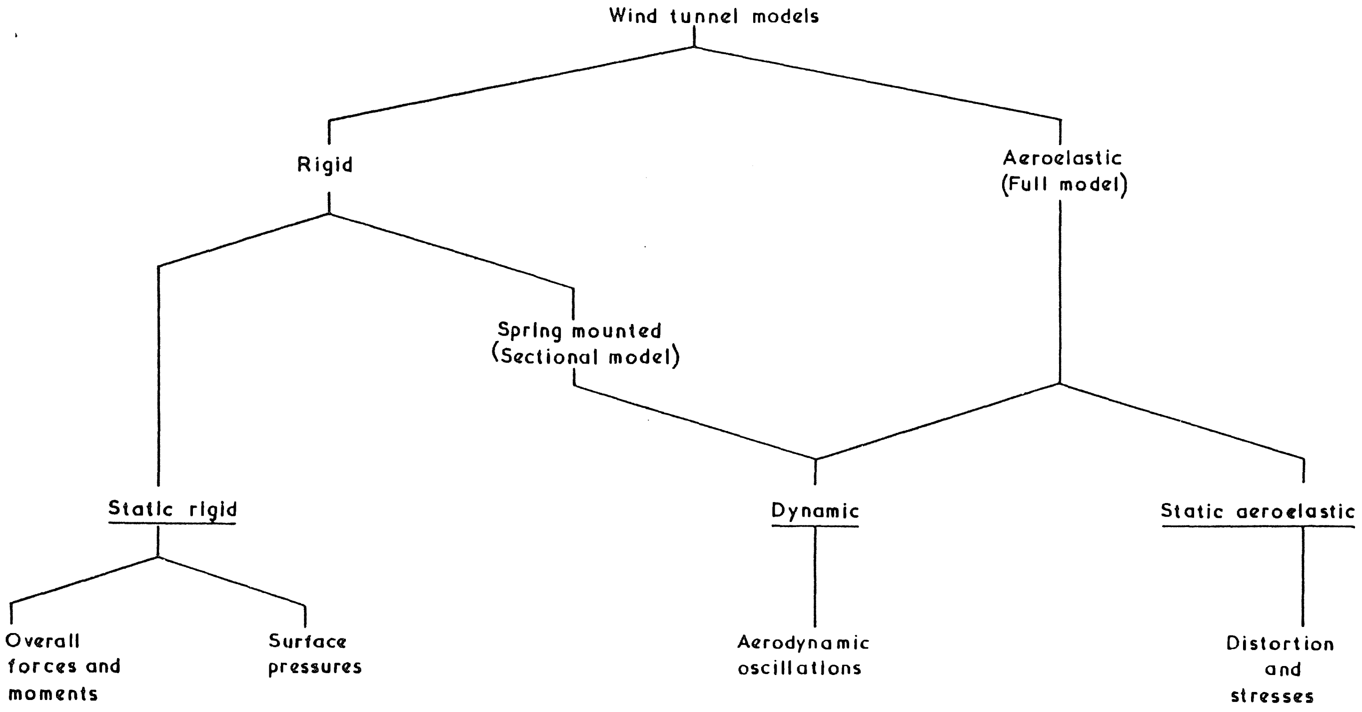

Fig.1. Wind-tunnel models and their application to wind loading problems