MODEL STUDIES OF WIND EFFECTS – A PERSPECTIVE ON THE PROBLEMS OF EXPERIMENTAL TECHNIQUE AND INSTRUMENTATION

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ABSTRACT

Wind engineering, which comprises a large part of non–aeronautical aerodynamics, is rapidly emerging as a separate and coherent discipline. A brief historical review contrasts the more important differences in the application of aerodynamics to wind engineering, as opposed to the aerospace field. The strengths and weaknesses of the current methodology and technique of wind effects simulation are discussed, with emphasis on modelling of the natural wind, wind induced effects on buildings and structures, and diffusion problems. Instrumentation in use is reviewed and areas requiring improved capabilities are indicated.

INTRODUCTION

In the last Congress (1), a session was entitled "Broad Initiatives"; however, only one paper (2) dealt exclusively with the increasing application of aerospace facilities to problems in non–aeronautical aerodynamics. It is significant that at the Sixth International Congress on Instrumentation in Aerospace Simulation Facilities, a session has been dedicated to non–aeronautical applications. This increase in interest and activity reflects the emergence of an essentially separate and coherent discipline which has only recently been christened in North America as "Wind Engineering" and is defined by Cermak (3) as "the rational treatment of interactions between wind and man and his engineered works on the surface of the earth". This definition appears to be gaining wide acceptance in North America. In contrast, the term "Industrial Aerodynamics" has been widely accepted in Europe, with the additional connotation of including aspects of aerodynamics associated with neither the wind, nor aerospace applications, such as internal flows in pipes, for example. This paper shall essentially be limited to the area of wind engineering.

Even within the more limited terms of wind engineering, the field is wide. To continue Cermak's definition: "Applications (of wind engineering) are not for the most part aeronautical in nature, but are related to wind effects on buildings, structures, and pedestrians; short range transport of air pollutants and local wind modifications by buildings, urban geometry and topography." The field is typified by the complexity of the problems and of their interdisciplinary nature. For instance, it currently involves architects, engineers of many disciplines, meteorologists, fluid dynamicists, applied mathematicians, physiologists, and behavioural psychologists. This breadth makes it virtually impossible to cover all areas of wind engineering, let alone other non-aeronautical applications. Many useful reviews of the subject area can be found in the literature (4–8).

The perspective presented here attempts to be balanced; however, it is admittedly highlighted by the authors' experiences with particular aspects of wind engineering – specifically the interaction between wind and structures, and the dispersion of plumes. Furthermore, in this paper, applications are stressed, i.e. engineering tests, rather than more basic experiments whose techniques tend to merge with those of other disciplines.

WIND ENGINEERING – ITS EMERGENCE AS A COHERENT DISCIPLINE

It is neither the aim nor a possibility to detail here the history of wind engineering and the related disciplines from which it emerged, although some fascinating historical treatments are available (8–13). Rather, a brief summary of some of the high points drawn largely from these sources is presented below to add to the modern perspective.

Although aeronautical aerodynamics became the more sophisticated field early in the 20th century, wind engineering can lay some claim to being the older subject. Obviously wind has always influenced man, and his structures have shown a growing recognition of the problems induced by it – first in terms of shelter and later in terms of the loads which structures must withstand. Naturally, simple empirical rules formed the first body of knowledge and the beginnings of the second; in fact, it has been suggested recently (14) that some structures such as Gothic cathedrals of the twelfth to fourteenth centuries, embody designs which recognise and deliberately account for wind loads.

The 17th and 18th centuries heralded the beginning of the rational approach to wind loads – albiet not always correctly. Newton's three proportionalities between the force on a body in a fluid and its area, the square of the speed, and the fluid density, were perfectly valid as far as they went. During the same era quantitative experiments to measure forces on bodies were also beginning by such people as Mariotte, Cayley and Newton himself, using methods involving devices not specifically designed for simulation (such as observing speeds of falling objects). The earliest specialized simulation method seems to have been the introduction of the whirling arm by Rouse and Robins around 1746. The first simulation in the sense of "the first avowed model experiments" (9) is generally credited to the English engineer John Smeaton who, in 1759, reported on tests of windmill designs using the rotating arm apparatus of Fig. 1. This initial test was of a structure now classified in wind engineeering but having a highly aeronautical flavour. Smeaton also introduced a formula proposed by Rouse (13) for calculating the pressure load in air (in psf), for which a structure should be designed, as being .005 V^2 (V in mph), where the prime uncertainty then - and perhaps now - is the quantity which should be used for the velocity V. This formula corresponds to a value of $C_d \approx 2$.

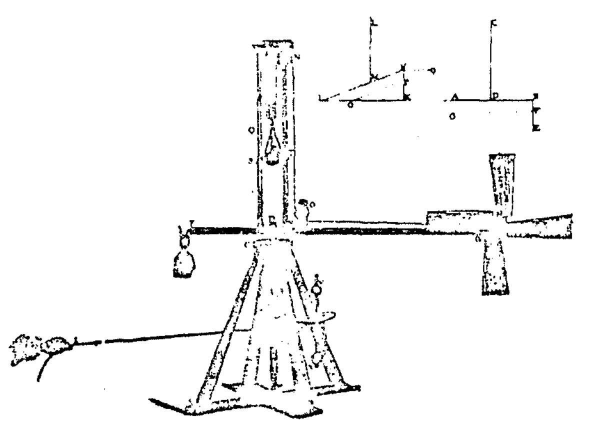


Fig. 1 Smeaton's Adaptation of the Rotating Arm for Windmill Tests (after reference 9)

In the 18th and 19th centuries, apart from the rapid rise of the scientific method with its own motivations, the primary interests fueling the development of aerodynamics were the desire to fly and the design of wind sensitive structures. The latter consisted primarily of windmills; however, the advent of large bridges and some equally large failures - in particular the Firth of Tay Bridge collapse in 1879 - gave wind engineering a strong impetus at about the same time that the wind tunnel as as a simulation facility came into being. The first wind tunnel is credited to Francis Herbert Wenham in the period 1867–1871 (10, 13). The steam injector driven wind tunnel reproduced in Fig. 2 was used by Phillips (9) shortly afterwards

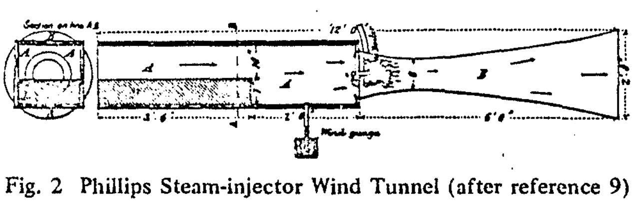


Fig. 2 Phillips Steam-injector Wind Tunnel (after reference 9)

during 1884 and 1885 to test wing sections, including effects of camber. With the concurrent interest in aerodynamics of both structures and aircraft, it is not surprising to find wind tunnel tests of both areas being carried out by Irminger in Denmark in 1893, using a small tunnel driven by the suction of a 100 ft. factory chimney (12). Figure 3 shows Irminger's early models of a wing and a house as reported by Jensen (12).

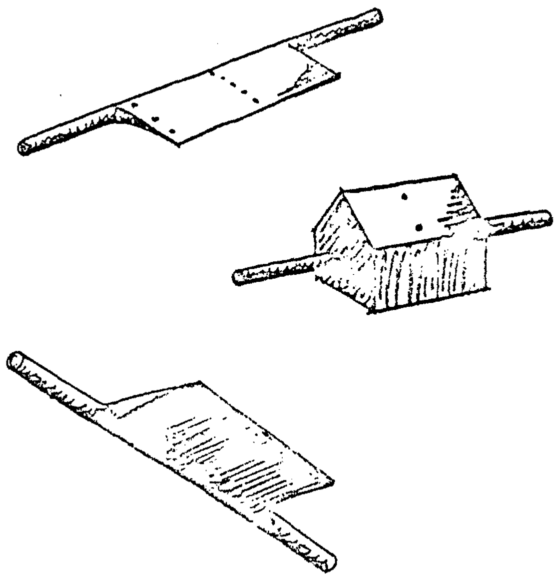


Fig. 3 Early Wind Tunnel Models Used by Irminger (after reference 12)

Instrumentation consisted of a simple water manometer. From this point on, the development of the aeronautical side of aerodynamics is well documented and rapidly led to sophisticated facilities to simulate flight. As such, the design of wind tunnels concentrated on developing smooth uniform flow to represent the flight of aircraft through a still atmosphere.

Meanwhile, the Tay Bridge collapse had initiated serious re-examinations of structural design for high wind loads and had prompted experiments to produce more rational formulas for load calculations, particularly for new bridges. It is worthwhile to mention that, at about the same time (in 1889), Eiffel built his tower using quite conservative but reasonable assumptions, including an allowance for wind increasing in speed with height. He later tried to improve on his empirical assumptions by measurements of wind and deflection of the tower, and by using the tower as a base for other aerodynamic measurements. His data haverecently been re-examined and discussed in detail by Davenport (11).

Of particular interest are the experiments of Baker, also discussed by Davenport (11), who initially measured loads on boards of various sizes in the natural wind in the early 1880's (15) in connection with the design of the Firth of Forth Bridge. It is noteworthy that there was no lack of perception that the wind and its gustiness presented a loading problem not fully simulated in the wind tunnel. Baker explained the smaller loads on the bigger boards by the lack of simultaneity of the gusts. Stanton (16) compared these results to wind tunnel experiments around 1903 and continued full scale investigations in more detail, including some measurement on the Tower Bridge around 1913, using instrumentation which is not only interesting in its own right, but is relevant to a later section of the paper. The apparatus, shown in Fig. 4, consisted of an ingenious mechanical system for averaging and recording pressure loads across the bridge or from other separated locations. The wire over the pulleys was connected via the rods to pressure sensitive diaphragms and also to a pen recorder. Stanton correlated his time varying loads with winds

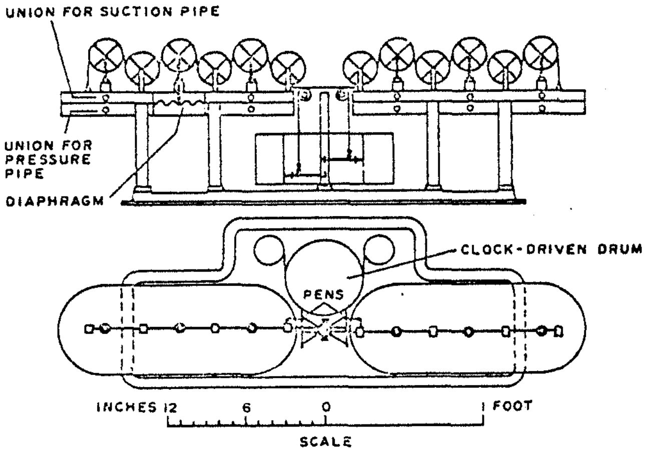


Fig. 4 Stanton's Apparatus for Averaging Wind Pressures (after reference 16)

recorded at a nearby observatory – again with considerable physical insight into the gusty structure of the wind. These experiments, however, were primarily aimed at determining the load on elements of bridge structures and hence were not affected so much by overall flow pattern changes due to the variation of speed with height.

The lack of adequate simulation of the 1000 to 2000 foot deep turbulent shear flow in model studies of complete structures was evident, and to some extent recognised, in a number of studies in the early 1930's, such as the comparison of model and full scale measurements on a railway shed by Bailey (17), shown in Fig. 5, for one wind direction. The model experiments had been carefully carried out using a base plate to minimize boundary layer effects and showed poor agreement with

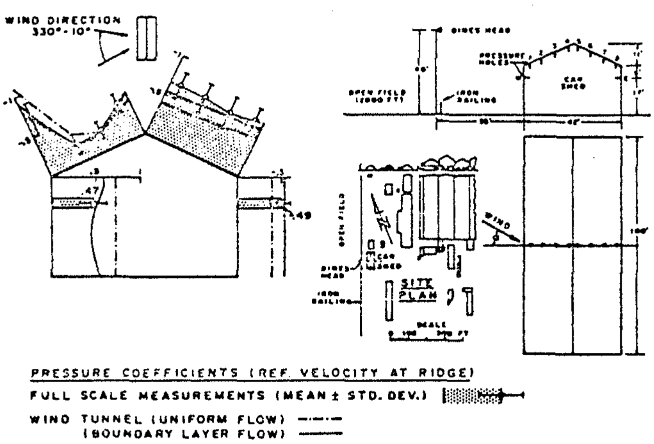


Fig. 5 Wind Pressures on a Railway Car Shed by Bailey (after reference 11)

full scale. Considerably later, Bailey and Vincent (18) used models on the floor of a long tunnel where the boundary layer to height ratio was seven and found much better agreement, as is also shown. This was one of the first experiments to attempt simulation of the earth's shear layer. Similar work was concurrently in progress by Irminger and Nokkentved (19) in Copenhagen who realized the importance of the boundary layer, but used depths considerably less than required (12). Nevertheless, it was not until 1958 that the model law was formally stated by Jensen (20) as

> "The correct model test for phenomena in the wind must be carried out in a turbulent boundary layer and the model law requires that this boundary layer be to scale as regards the velocity profile".

Jensen's definitive results, shown in Fig. 6 indicate that correct simulation of the atmospheric boundary layer characteristics are vital in many problems of wind engineering.

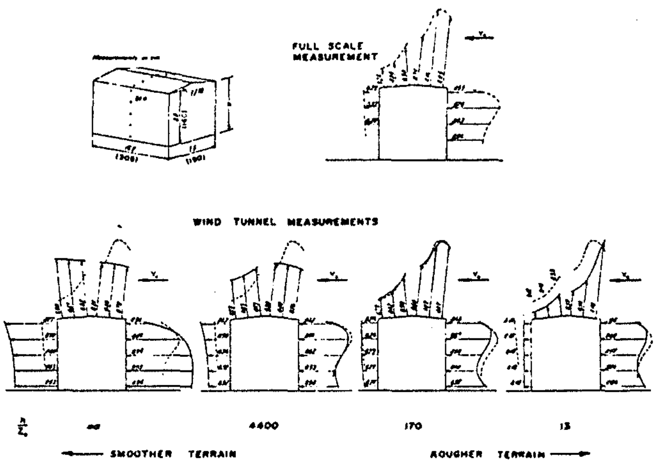


Fig. 6 Comparison of Full-scale and Wind Tunnel Measurements of Wind Pressure: The influence of ground roughness and boundary layer profile (after reference 20)

These examples illustrate the slow realization of the first major difference between the requirements for most aeronautical and wind engineering applications – the former requiring smooth steady flow over a large range of speeds and the latter requiring incompressible turbulent shear flow. Naturally this division is not always the case – in fact many aeronautical engineers are currently looking at problems where wind engineering can in turn make contributions. In particular, the flying and landing of STOL aircraft through the atmospheric boundary layer, problems of wind shear, problems of ground obstructions affecting flight paths, and the behaviour of trailing vortices near the ground are all areas in which atmospheric shear layer simulation may be important.

A second major difference between the two fields has been the degree of contribution of aerodynamics to design. In aeronautics, the aerodynamics of an aircraft always played a major role in its design but the aerodynamics of a structure usually played a less important role and was justifiably treated with empiricism. Consider, for example, that in the era of the skyscraper in New York in the 1930's, the prescribed building code wind load (21) was only 20 psf. above 200 ft. (nothing below this), which only corresponds to a wind speed of 72 mph. for a drag coefficient of 1.5. In practice, for the more significant structures, the design wind load was often increased; however, the general success of codes was due largely to conservative safety factors and to the neglect of the substantial contribution from components considered non-structural, such as exterior masonry walls.

The increasing attention paid to structural aerodynamics or "wind engineering" arose from a number of factors. First, as pointed out by Pocock (6), the rapid development of wind engineering in the late 1950's had much to do with the "economics of scale". Even small infrequent effects of wind repeated in a multiplicity of structures became economically significant. Secondly, in recent years, improved tools of analysis and new construction methods, in particular the use of welding, high strength steels and light facades serving as exterior walls without contributing to structural strength, have lead to more flexible, lighter structures with reduced damping. The resulting sensitivity of these modern structures to dynamic excitation by wind action has led to the increased significance of design against wind.

Certainly in the past wind sensitive structures have highlighted the aerodynamic problems; however, generally these were more the exception than the rule. Again, bridges were the early focal point for dynamic effects. The dramatic collapse of the Tacoma Narrows Bridge in 1940 prompted renewed interest in aerodynamics of structures – this time because collapse due to dynamic forces occurred during moderate wind speeds. Significantly, the primary role in the interpretation of the disaster was carried out by aeronatutical aerodynamicists who had experience with dynamic problems such as flutter; but who tended to interpret the phenomena in terms of experiments carried out under aeronautical, and hence non-representative, conditions. Davenport (11) maintains that the nature of the collapse is still not fully understood. This doubt is reflected in current controversies regarding the validity of sectional model tests on bridges tested essentially in non-representative flows, as against tests of complete models in atmospheric simulations. A modern example of the importance of modelling the shear flow characteristics for unsteady response is illustrated by Novak's (22) experiments with galloping of a 1 x 2 cross section whose behaviour in smooth flow – galloping when the narrow side is facing the wind and being stable when the broad side is exposed – is completely reversed when turbulent shear flow is introduced.

Nevertheless, the essentially secondary nature of the aerodynamics of structures and the primacy of aeronautical aerodynamics led to the unfortunate situation for the first half of this century that many non-aeronautical applications were handled on an ad-hoc basis by aerodynamicists, without full appreciation of the simulation problems – and this continues to some extent today.

There is another important ramification of the second order nature of the aerodynamics of structures as compared to the aerodynamics of aerospace vehicles. The lesser sensitivity of economics to the overall strength and safety of a common civil engineering structure, the complexity of the flow field, the uncertainties of transfer functions relating wind induced effects to the flow, and the inherent difficulties – even statistically – of determining design speeds have implications upon the levels of accuracy acceptable for solutions to many wind engineering problems. This generally lower degree of acceptable precision should be borne in mind when instrumentation specifications are defined for many wind engineering test areas.

The most recent factors affecting the role of wind engineering in modern society is the increasing awareness of what have long been considered lesser effects – namely, the diffusion of pollutants, and the comfort of people around and within structures. Such factors are now becoming, in many cases, primary requirements leading to investigations in the wind engineering field.

Finally, it is perhaps most significant in the development of wind engineering as a coherent discipline that the leading roles have not developed directly from aeronautical engineering, but rather under the drive of individuals who are, in many cases, primarily civil engineers. As a result, the field has developed somewhat differently to conventional aerodynamics although it has naturally drawn a great deal of the initial basic techniques of instrumentation from aerodynamics and basic fluid mechanics.

METHODOLOGY FOR STUDIES OF WIND ENGINEERING PROBLEMS

Model studies of wind engineering problems in the past have concentrated on defining worst case response parameters. This approach is justifiable for trouble shooting or for situations where the need is mainly to determine whether an unacceptable instability exists. However, this approach does not take full advantage of the potential of wind tunnel methods as general design tools. In many aeronautical problems, wind tunnel derived aerodynamic properties can be combined with an analytical model to investigate performance (in the general sense). For most wind engineering problems, suitable analytical descriptions simply do not exist. Although the structural dynamics can be described, the forces produced, even by a well defined wind, cannot in general be determined. Add to this the complexities of a city environment, and it is clear that the role of the wind tunnel becomes that of an analogue simulator of the entire system behaviour. Inherently, problems in wind engineering require, in the final analysis, estimates of meteorological conditions, whether these be wind speeds and directions likely to occur at a particular site, or other climatic conditions affecting dispersion of pollutants or human comfort. Hence, at The Boundary Layer Wind Tunnel Laboratory, application of wind tunnel methods for design purposes has, as its basis, the combination of simulated aerodynamic response and full scale wind statistics. This involves three basic steps:

1) Wind tunnel measurement of the detailed aerodynamic behaviour of the response variables of interest for a complete range of relevant parameters on a suitable model of the structure. The response variables may be local surface pressures relevant to the design of the glass and cladding, overall forces and bending moments relevant to the strength of the structure; acceleration of the structure and the ground level wind environment relevant to human comfort; or concentrations of pollutant – relevant to human safety and comfort and to the plant environment. The test matrix of parameters might include several mean wind speeds, all wind directions and a variety of model configurations.

2) The development of a statistical description of the full scale wind at the project site at gradient height.

3) The combination of the above information to provide predictions of the response expected for certain levels of probability – usually couched as return periods for certain response levels.

These steps are shown in more detail in flow chart form in Fig. 7, taken from Isyumov (23).

The approach is detailed elsewhere (24,25) and has been applied in design studies for a number of significant structures (26,27,28,29,30). An example of the simple form of the resulting information is illustrated in Fig. 8, showing contours of peak suctions predicted to occur with a 50 year return period. Note this presentation is independent of wind direction. This description of the load in probabilistic terms can be used to determine design loads associated with various levels of risk. The accuracy of the results depends on the quality of the individual steps outlined above. Because of the mathematical procedure used in arriving at the predicted loads

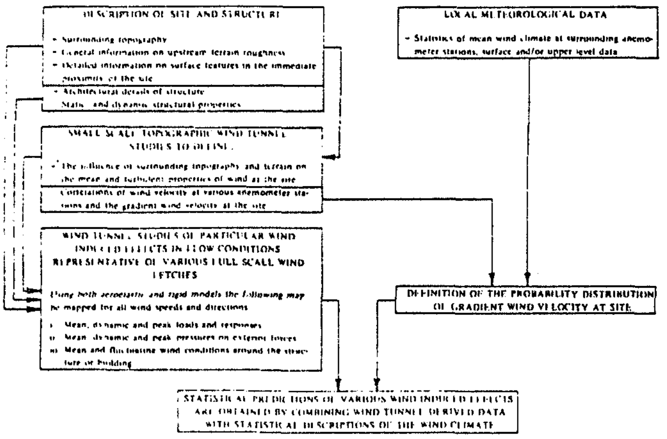


Fig. 7 Outline of a Typical Wind Tunnel Design Study (after reference 23)

Fig. 8 Contours of Exterior Peak Suctions for a Tall Building Predicted for a 50 Year Return Period

(especially the integrations incorporated) and the use of statistical as opposed to deterministic methods, the effects of small random errors in the modelling, and in the description of the wind climate, tend to be smoothed out. Insofar as the modelling and atmospheric simulation is concerned, experience and full scale comparisons (31,32) suggest that the use of the wind tunnel analogue for deriving aerodynamic characteristics is fairly reliable. However, a reliable description of the real wind climate is more difficult due to the practical limitations of the meteorological data. Thus, the overall accuracy of the prediction of wind effects depends largely on the accuracy of available statistics of the wind climate. Further discussion of this point can be found elsewhere (33).

MODELLING REQUIREMENTS

Natural Wind and its Simulation

The need for representative flow simulation for phenomena in natural wind has already been stressed. Before discussing the relevant similarity requirements, it is useful to briefly review the more important aspects of natural wind. Pressure gradients caused by unequal heating of the earth's surface by the sun are the driving forces for atmospheric motion. The resulting flow is influenced by numerous effects such as: the rotation of the earth, the topography and roughness of the earth's surface, the diurnal and seasonal cycles, the reflective and thermal properties of the earth's surface, and the presence of water vapour with the resulting changes of cloud cover, precipitation and latent heat fluxes. The resulting complex and variable flows have scales ranging from global dimensions to those of micrometeorology. If all flow speed variations are viewed in terms of their distribution of energy with frequency, a distinct gap exists in the power spectrum at periods of about an hour. This conveniently divides atmospheric motion into "atmospheric turbulence", and quasi-steady mean speeds associated with slowly varying synoptic or climatological time scales. Thus, the working hypothesis in simulating wind at a particular location is that the micrometeorological time scales of the order of 1 hour and less can be represented by turbulent boundary layer flow in a wind tunnel with locally stationary mean and turbulent properties. Long term variations in the wind are then determined independently from full scale synoptic data.

For slowly moving pressure systems, the motion of air at heights above the frictional and thermal influence of the earth's surface is essentially parallel to the isobars and governed by the pressure gradient, the coriolis acceleration and the centrifugal acceleration due to isobar curvature. Wind at this height is referred to as the gradient wind, or geostrophic wind if the isobars are essentially parallel. During periods of neutral atmospheric stability, which normally prevails during strong wind conditions, the gradient height or the depth of the atmospheric boundary layer is determined by the terrain roughness and typically varies from about 900 feet over open country to about 1700 feet over built-up urban areas (34). Within the atmospheric boundary layer, the flow becomes increasingly more dependent on shear stresses of mechanical and buoyant origin. Even though the mean velocity vector rotates slightly with height due to coriolis effects, the flow within this atmospheric boundary layer can still be reasonably described as a turbulent boundary layer over a rough surface.

Although wind tunnel modelling attempts to date have almost exclusively been confined to the simulation of locally stationary boundary layer type winds, a number of atmospheric wind conditions fall outside this category. Important exceptions are winds with very strong vertical vorticity of various scales such as hurricanes, tornadoes, water spouts and dust devils (8). Other special winds of importance to wind engineering are downslope winds called by such names as mistral, bora, foehn etc. and strong local thunderstorms and squall lines. Neither the detailed physical mechanisms nor the structure of these various winds is currently well understood. The physical modelling of such winds has been attempted in some instances but mostly remains an experimental challenge.

Similitude requirements for wind tunnel models of boundary layer type winds can be obtained directly from dimensional arguments or from non-dimensionalization of the governing equations. Detailed derivations of the various similarity requirements can be found elsewhere (8,35,36,37). In summary, exact modelling of the atmospheric boundary layer entails the following:

i. The simulation of conditions at the solid boundary (i.e. terrain roughness, topographic relief and surface temperature)
ii. Similarity of the approaching flow (i.e. the unsteady velocity and temperature fields), and

iii. Equality of the Rossby, Richardson, Reynolds, Prandtl and Eckert numbers.

Exact similarity at a reduced geometric scale is not possible. Fortunately, providing requirements (i) and (ii) are satisfied, the exact equality of all of the above non-dimensional parameters is not necessary for representative model studies of most wind induced effects. Critical discussions of the practical consequence of relaxing the above similarity requirements can be found in the literature (8,36,37). These consequence differ according to the problem.

Equality of Rossby number, which relates shear forces to forces resulting from the Coriolis acceleration, cannot be achieved in available wind tunnels. The significance of an infinite model Rossby number and consequently no rotation of the mean velocity vector over the boundary layer height (compared to actual rotation of the order of 10 degress or so) s not considered significant for most wind engineering problems (8). One exception is the additional cross-wind diffusion of pollutants for large downstream distances. Pasquill's observations (38), for example, indicated that the enhancement of lateral plume spread by the rotation of the mean speed vector becomes significant for downstream distance in excess of 5 km.

The Richardson number, which is the inverse of the densimetric Froude number, can be modelled providing that facilities for introducing thermal stratification are available (8,39). Producing thermally stratified flows in large wind tunnels is expensive and consequently most wind tunnel facilities are limited to modelling wind during conditions of neutral atmospheric stability (Ri = 0). Fortunately, neutral conditions prevail during most strong winds and, as a result the simulation of non-neutral stability (Ri ≠ 0) becomes significant only in studies of atmospheric diffusion.

Similarity of the Prandtl number, or the ratio of momentum diffusivity to thermal diffusivity, is satisfied as long as air remains the working fluid. Eckert number, which is equivalent to the square of the Mach number, is not important for incompressible flows.

Equality of Reynolds number is not practicable here, as in most other wind tunnel modelling. Fortunately, natural surfaces are aerodynamically rough at all but near calm conditions and Reynolds rather than viscous shear stresses govern. Thus Re equality becomes a secondary consideration in simulating the wind, providing that a fully developed turbulent shear flow is used. Neverthless, incomplete Re scaling affects the detailed flow structure around particular shapes and leads to dissimilarities of spectral shape at high frequencies, as the onset of the dissipation range is governed by viscosity – a fluid rather than flow property. The ratio of the peak wavelength to the microscale depends on $Re^{3/4}$ and leads to significant narrowing of the inertial subrange at very small Re (36,37,40,41). The almost complete absence of the inertial subrange in small scale diffusion studies where the velocity scale is governed by the densimetric Froude number is illustrated in Fig. 9 after Isyumov, Jandali and Davenport (41). The practical consequences of such severe spectral dissimilarity require further study.

The influence of Re on flow over rounded bodies is well known and adjustments of experimental results in conversion to full scale are possible in certain cases. Although flow separation for sharp-edged bodies is primarily governed by the geometry, some Re dependence of growth of local boundary layers and locations of low reattachment remains. This has been commented on by Wardlaw and others at the National Research Council of Canada (42). An approach currently taken is to roughen surfaces as much as practical, in order to stimulate turbulent boundary layers which hopefully simulate the characteristics of full scale; however, this is on a very empirical basis, and no firm guidelines exist as to when such effects are of importance. Such roughening of surfaces has also been used to simulate high Reynolds number flow characteristics on circular cross-section bodies, such as cooling towers by Armitt (43) with apparent success – although a certain degree of debate remains as to how representative the results are of high Re conditions.

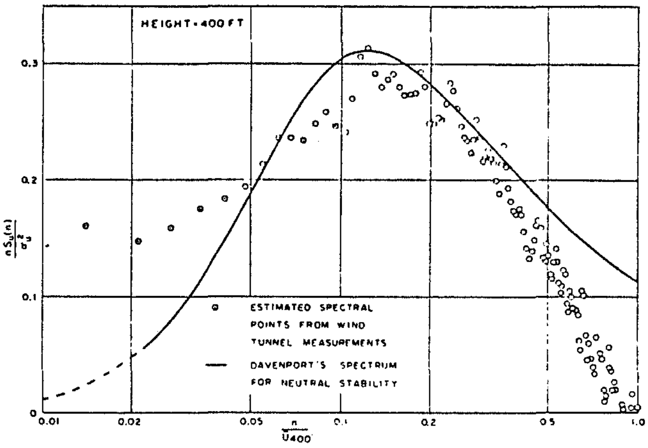


Fig. 9 Power Spectrum of the Longitudinal Component of Velocity at Small Model Reynolds Number (after reference 41)

Practical Models of Wind

Practical models of the atmospheric boundary layer for strong wind conditions consist of the simulation of the solid boundaries (both topographic relief and terrain roughness) and the modelling of natural wind by a turbulent shear flow with zero longitudinal pressure gradient and mean and turbulent flow characteristics matched to known full scale values. It is usually possible, with various degrees of success, to representatively match the mean velocity profile (no rotation with height) and the intensities, power spectra and scales of turbulence. Thermal stratification is added in studies where non-neutral conditions of atmospheric stability are significant. In all such simulations, the atmospheric boundary layer is taken to be locally stationary, and wind effects are determined for particular values of some reference mean hourly wind speed. Mesoscale and long term variations of the mean wind speed are taken into consideration, analytically based on statistical models of the full scale mean wind speed developed from meteorological records.

Early modelling attempts of wind induced effects were based on partial models of the atmospheric boundary layer. These ranged from the use of curved screens (44) and grids of graduated rods (45) to models with turbulent flows but uniform mean velocities, as obtained behind coarse grids (46, 47). The latter is still a commonly used technique for more fundamental aerodynamic studies in turbulent flow. Presently most serious simulations of natural wind achieve some degree of similarity of both the mean and turbulent flow fields. An extensive review of current simulation techniques can be found in a report on Euromech 50 by Hunt and Fernholz (48).

Currently accepted methods of simulation can be grouped into two major categories. The first is to simulate natural wind with a turbulent boundary layer developed naturally over a long fetch of appropriate tunnel floor roughness. Both randomly and evenly spaced surface roughness elements of various shapes are currently used to develop turbulent boundary layer flows. Although the selection of the surface roughness has so far been largely based on ad hoc empirical methods, attempts to rationalize relationships between the flow properties and the characteristics of roughness elements are underway (49). The suitability of boundary layer wind tunnels for modelling various phenomena associated with natural wind has been discussed in the literature (8,24,50,51). The main advantage of this technique is that the flow remains in equilibrium with the local surface shear stress; and mean velocity profiles and turbulence intensities, spectra and scales are essentially invariant over a significant portion of the working section. Furthermore, this approach leads to more consistent scaling of the various inherent lengths, such as the roughness length, the boundary layer depth and the scales of turbulence. The similarity of the flow regime over relatively long fetches makes this approach particularly suitable for model diffusion studies. Also, the fundamental dependence of the properties of the flow field on the terrain roughness lends greater confidence to model flows developed over terrains for which there is no previous full scale experience.

The Boundary Layer Wind Tunnel at the University of Western Ontario has a working section about 80 feet long, 8 feet wide and about 7 feet high. A view upstream with a model mounted on the turntable is shown in Fig. 10.

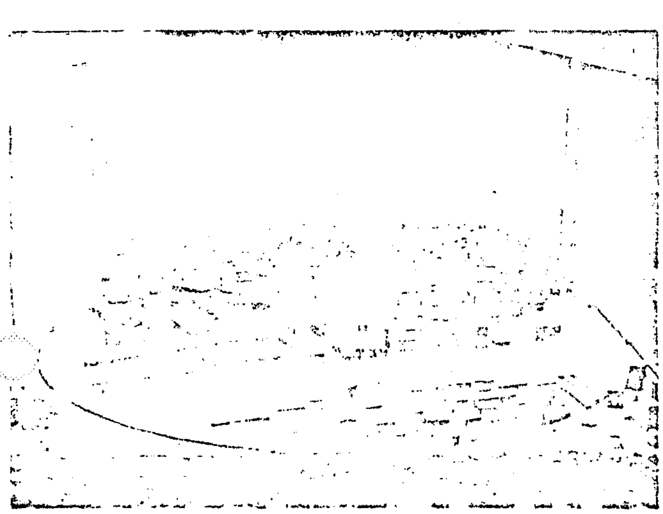


Fig. 10 Upstream View of the University of Western Ontario Boundary Layer Wind Tunnel with a Model of a Tall Building and its "Proximity" in the foreground.

Boundary layer depths ranging from 2 to 4 feet are obtained at the test section with different surface roughnesses. As a result, geometric scales of about 1:400 to 1:500 are possible for studies of wind effects on buildings and structures. Somewhat smaller scales have been used for topographic flow investigations and diffusion studies. Despite the capital cost disadvantages of such a facility due to the very long test section, several other large boundary layer wind tunnels have become operational.

The second major technique for simulating atmospheric flows uses various active and passive devices at the entrance to the test section to artificially create thick turbulent shear flows within a few tunnel diameters. Having removed the need for a long working section, considerable savings in capital cost can be realized. Furthermore, this technique allows utilization of existing aeronautical wind tunnels for atmospheric simulation. Passive devices in use range from solid trips, rods and screens to combinations of trips and spires or vortex generators (40,52,53). Some of the active devices include co-flowing jets (54), counterflowing jets (55), normal jets (56) and horizontal cross jets of variable strength (57). An approach used in France (48) consists of using floor jets and the addition of low frequency energy by slowly oscillating the fan speed. In all of these artificial methods some tunnel floor roughness is used in the test section. Many of these methods are capable of matching known full scale mean and turbulent properties of natural wind. Unlike boundary layer wind tunnel techniques, artificial methods are not suitable for generating wind over complex terrains for which there are no full scale data. Furthermore, if used in converted aeronautical tunnels, the usually short working sections limit their use for diffusion studies.

Modelling Wind Induced Effects

Similarity requirements for modelling the atmospheric boundary layer and actually practicable wind tunnel models of natural wind have been discussed above. Providing that the approaching wind has been representatively modelled, local flow similarity at a particular point of interest requires the reproduction of the aerodynamic characteristics of the immediate surroundings. Since Reynolds number scaling is generally unattainable, this reduces to the scaling the geometry and the surface roughness (sometimes to an exaggerated degree) of the surroundings. In the case of a city environment, this entails a scaled block outline reproduction of all major buildings in the immediate proximity. The degree of detail usually considered necessary for these "proximity" models can be seen from Fig. 10. Having discussed the requirements for flow similarity, the remainder of this section deals with the additional similarity consideration required for model studies of exterior pressure, overall forces and responses of buildings and structures and the dispersion of pollutants.

Modelling of Pressures For incompressible flow the additional similitude requirements for exterior pressures are geometric similarity at the same length scale as used for modelling the flow and Reynolds number equality. Except in very specialized facilities either the assumption is made that Reynolds number similarity can be relaxed or extrapolation techniques are utilized. In many wind engineering problems the former appears to be a valid assumption because of the predominance of structures with sharp corners and hence well defined separation points. However, full scale structures do have sections with strong Reynolds number dependence. Even with sharp edged structures, however, Re number differences, as already discussed, lead to some differences in the local flow field and consequently pressures. Also dissimilarities of the high frequency part of the pressure spectrum result. This effect is usually negligible because the high frequency range is of limited interest due to other considerations. Specifically the higher the frequency of pressure fluctuations, the smaller the area over which they are fully correlated. When this area becomes smaller than a cladding element – say a window – the effective loads are sharply reduced. Furthermore, the contribution to the total fluctuating energy appears small at high frequencies. Nevertheless, recent work at the Boundary Layer Wind Tunnel has introduced some uncertainty into the problem. It appears that there do exist intermittent pressure peaks which contribute very little to the total energy but may be of a very high amplitude and of sufficient size to affect a typical panel.

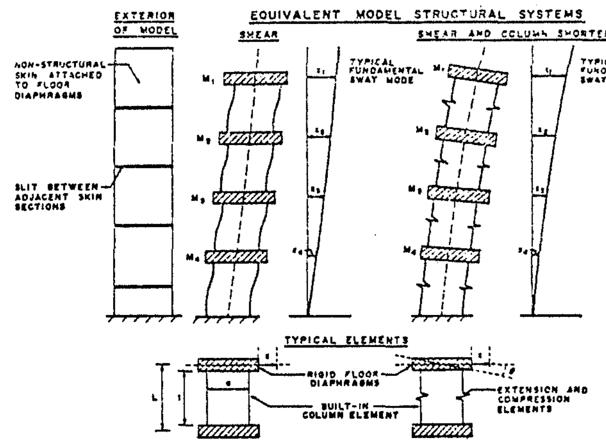
Aeroelastic Modelling In addition to the similarity of the atmospheric boundary layer and the aerodynamic characteristics of shape, wind tunnel modelling of wind induced forces and responses requires aeroelastic similarity: namely, similarity of wind induced forces and the inertia, stiffness and damping forces of the structure. In addition to geometric similarity at a scale providing consistent scaling of all lengths including the characteristic lengths of the flow, aeroelastic similarity requires equality of the following non-dimensional quantities:

- Reynolds number (based on building dimensions)
- Froude number (ratio of gravity to inertia forces)
- Cauchy number (ratio of elastic to inertia forces)
- density ratio (ratio of inertia forces of the structure to those of the flow)
- critical damping ratio.

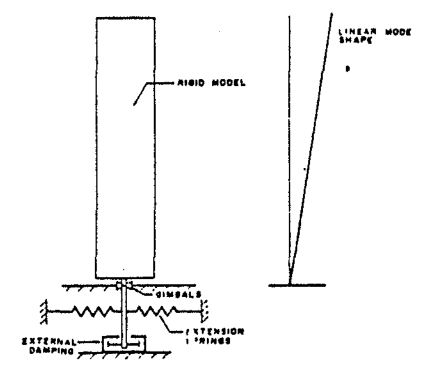
Detailed discussions of aeroelastic modelling approaches for studies of wind effects can be found elsewhere (8,23,58,59). Equality of the ratio of structural dimensions to such characteristic flow lengths as the boundary layer depth and the peak wavelength of the turbulence spectra, maintains similarity of the mean velocity variation over the height of the structure and spectral similarity of aerodynamic forces. The latter requirement is particularly important for relatively stiff structures for which the quasi-steady dynamic response may be comparable or greater than the resonant component. Reynolds number equality as already discussed is not practicable and aeroelastic models tests are usually carried out at Re values typically 3 orders of magnitude smaller than corresponding full scale values. For certain shapes, circular cylinders for example, corrections for Re dissimilarity based on quasi-steady assumptions are attempted. For sharp-edged bodies, although some differences occur in the local pressure field, the Re influence on overall forces and responses due to buffeting by turbulence are small. The influences of Re on such forcing mechanisms as vortex shedding and galloping, however, remain continuing research topics. Even here, however, representative scaling of atmospheric turbulence appears to be the more dominant requirement. Nevertheless, it is important to maintain high enough Reynolds numbers in order to ensure similarity of velocity spectra at least up to frequencies of structural interest.

Carrying out aeroelastic simulation in a wind tunnel implies that for correct scaling of inertia forces the bulk densities of the structure are the same in model and full scale. Maintaining a constant value of ρ_S, although usually a formidable modelling challenge, is an attainable requirement. The velocity scaling in aeroelastic modelling is obtained from similarity requirements for gravity forces and elastic forces. The extent of modelling the Froude and Cauchy numbers depends primarily on the stiffness properties of the structure under consideration. The modelling of the Froude number is important in cases where an appreciable proportion of the stiffness is derived from the action of gravity. Suspension bridges, suspended roofs and guyed towers are examples of such structures. For such structures, the velocity scale is determined by the Froude number and becomes the square root of the length scale. Froude number scaling is of little consequence for structures where the stiffness depends primarily on elastic forces. This is usually the case for buildings; free standing towers, masts and chimneys, and truss, girder, arch and cable stayed bridges. Froude number scaling for such structures can be neglected and the velocity scale is selected to maintain Cauchy number equality. In most cases this reduces to the equality of the reduced velocity or, V/n D, namely the ratio of a characteristic velocity to the product of a characteristic frequency and length of the structure. Maintaining equality of the damping ratio presents practical difficulties and additional damping elements often have to be added to achieve model damping consistent with expected full scale values.

Practicable aeroelastic models range from replica models used for stacks, cooling towers, tubular structures, roof membrances, etc. to a variety of equivalent models or mechanical analogues designed only to simulate certain modes of vibration (23,58, 59). Aeroelastic models of buildings as seen from Fig. 11 taken from Isyumov (23) for example, range from rigid models, spring mounted at the base and fitted with dash pots or an eddy current damper to simulate the two fundamental sway modes, to more complex lumped parameter analogues designed to simulate several of the lower sway and torsional modes of vibration. Experience at the Boundary



A) SCHEMATIC OF LUMPED MASS EQUIVALENT AEROELASTIC MODELS OF A TALL BUILDING



B) SCHEMATIC OF SPRING MOUNTED RIGID AEROELASTIC MODEL

Fig. 11 Aeroelastic Modelling Approaches used for Tall Buildings (after reference 23)

Layer Wind Tunnel Laboratory indicates that the dynamic wind induced response of most tall buildings is predominantly in the two fundamental sway modes of vibration. As a result, rigid aeroelastic models spring mounted at the base in most cases provide adequate information on wind induced dynamic effects. A comparison of the dynamic drag and lift response obtained with a rigid spring mounted model and a corresponding seven lumped mass model is indicated in Fig. 12 taken from Isyumov (23). The indicated structural damping of $\zeta_{STRUC} = 1\%$ is a nominal value and the differences in the lift response around the vortex shedding peak are attributed mainly to differences in the actual damping present. The relatively good agreement indicated by Fig. 12 also suggests that the provision of horizontal cuts or slits between adjacent segments of the exterior skin in multi-degree of freedom models does not significantly influence the overall aerodynamic forces on sharp-edged bodies. There are some suggestions in the literature that this is not the case for rounded bodies, for which the separation points are not fixed by the exterior geometry.

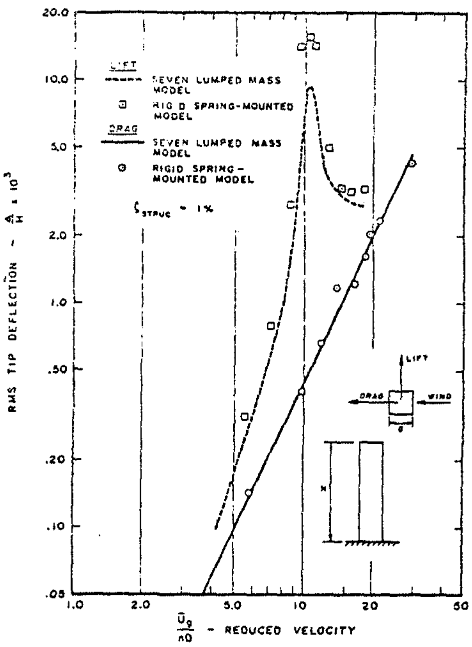


Fig. 12 Aeroelastic Sway Response Obtained with Multi-degree of Freedom and Spring Mounted Rigid Models of a Tall Building of Square Cross-Section (after reference 23).

In addition to full aeroelastic models, dynamically scaled section models of essentially two-dimensional structures such as long span bridges, cables and towers have been used to examine aerodynamic stability and to yield various aerodynamic derivatives for use with theoretical models. Unfortunately correct scaling of the turbulence structure is not practicable with such model tests. The development of a taut strip model (60,61) of long bridges which can be tested in correctly scaled turbulent shear, may provide a practicable alternative.

It should be pointed out that it is generally only practicable to obtain similarity of elastic behaviour. Ultimate load considerations have to be based on theoretical arguments using elastic wind tunnel response data.

Modelling of Stack Gas Diffusion

Flue gases exit the stack at typically some 300°F above the ambient air temperature and at velocities generally significantly higher than those of the ambient wind. As a result, the plume rises to some height well above the stack before buoyancy and momentum effects become negligible and dispersion by atmospheric turbulence dominates plume behaviour. Although analytical methods are available to provide estimates of ground level concentrations in certain idealized cases, prediction of plume behaviour in unusual terrain or atmospheric conditions or the evaluation of possible "aerodynamic downwash" (a general term used to denote the entrainment of stack gases by the wake of the stack itself, the wake of surrounding buildings and the wake formed by gross topograhpic features) largely rely on wind tunnel simulations.

In addition to the correct simulation of the atmospheric boundary layer and the geometry and aerodynamic properties of the stack and its surrounding buildings, wind tunnel modelling of stack gas dispersion also requires correct simulation of the stack gas properties. Similarity requirements for wind tunnel plume dispersion studies have been extensively discussed in the literature (8, 37,39,41,62,63,64,65,66). The additional similarity requirements for gaseous plumes can be summarized as follows:

(i) equality of the densimetric Froude number at the stack exit (ratio of buoyancy forces to the inertia forces of the ambient air)

(ii) equality of the ratio of the momentum flux of the exit stack gas to that of ambient air; and

(iii) equality of the ratio of exit stack gas density to that of ambient air.

If equality of the density ratio is maintained, the first two requirements imply conventional Froude number scaling and a constant ratio of stack gas to ambient air velocity. With geometric scales of typically between 1:400 to 1:800, conventional Froude number scaling results in very low tunnel speeds. For example, with a geometric scale of 1:800 a wind tunnel speed of about 0.5 ft./sec would be required to simulate a 10 mph full scale wind. Wind tunnel operation at such speeds entails many practical problems. It is difficult to generate fully developed turbulent boundary flows, as Reynolds number effects become significant. Also although such low speeds are attainable either directly or by using auxiliary fan drive systems, it is very difficult to maintain steady flow conditions. The stability of low speed flows is very sensitive to small disturbances and low frequency oscillations are generally unavoidable. The effect of such oscillations on the low frequency end of the turbulence spectra can be seen from Fig. 9. Spectral dissimilarities at the high frequency end at very low Reynolds numbers have already been discussed.

To reduce the above difficulties the requirement of an equal ratio of the exit stack gas density to that of ambient air is relaxed. In most model studies the density of the model gas is reduced by either accentuating the gas temperature or by using pure helium or helium air mixtures. Maintaining equality of the densimetric Froude number in such cases results in exaggerated model exit gas velocities. The effects of exaggerating the exit gas velocity on measured ground level concentrations have been examined by Barret (65) and Meroney *et al.* (66). The degree of plume dissimilarity, when equality of the density ratio is not maintained, and the consequent influence on plume behaviour of scaling efflux momentum and exaggerating the exit gas velocity or relaxing efflux momentum scaling and maintaining a constant scaling of all velocities, requires further study.

MEASUREMENTS AND INSTRUMENTATIONS

The methodology for wind tunnel studies described above has two main implications. First, the instrumentation system must be capable of handling considerable quantities of data as automatically as possible. Second, the precision required of the system is not as high as in more fundamental tests. As a result measurement systems tend to favour rugged, flexible and generally less expensive equipment. The development of specialized instrumentation common in more fundamental areas is relatively rare, and as a result experimenters in wind engineering tend to be users rather than developers of instrumentation.

These implications, and the stochastic nature of the response variables and their associated sophisticated analysis requirements led the Boundary Layer Wind Tunnel Laboratory very early to adopt digital processing with emphasis on on-line digital data acquisition and on-line preliminary data reduction. An early version of this system is described in detail in (67). The system is built around a PDP8-I processor which controls the experiment, as well as derives statistical parameters of the aerodynamic responses. Typically, the requirements are to derive the mean, root-mean-square, and extreme values of the response as well as probability and spectral distributions. It has been the norm until fairly recently to utilize separate specialized pieces of equipment for these tasks; however, the advent of cheap and powerful mini-computers with specialized plug-in boards appears to make it inevitable that a single processor can manage adequately all tasks required. Wind engineering problems in the main are aided by the fact that frequencies of interest are generally under a kilohertz and often under 100 Hz.

Although our laboratory was initially relatively unique in the application c ` this digital approach, it is rapidly being adopted elsewhere. The major current requirement in this area is the development of more sophisticated software to enable more on-line interaction. The aim is to bring the analogue realization of civil engineering problems closer to a real time interactive design process for the participating architects and engineers.

Instrumentation for Flow Measurements

The instrumentation needed must allow definition of the unsteady velocity field associated with incompressible turbulent boundary layers and their interactions with bluff bodies. Most of the techniques in use are simply adaptations of those developed previously in experimental low speed fluid mechanics. The relatively small geometric scales used in wind engineering studies add some complications.

The flow field measurements of interest can be roughly divided into three classes. The first are flows with moderate turbulence levels. Such measurements are required to monitor the speed outside of the boundary layer, i.e. the gradient speed, and to determine the mean and turbulent flow properties within the boundary layer. For these purposes, pressure probe techniques (68) and hot wire or hot film techniques are more than adequate. For instance, hot wire and hot film technology is such that sensitivities and frequency response introduce no restrictions. Furthermore, scales of turbulence are such that, for the most part, finite probe geometry is unimportant. Also fluidic anemometers (69) hold some attraction, although most available ones are too large for the geometric scales commonly used.

The second class of flow problems occur for tests where Froude numer scaling dictates extremely low speeds for testing purposes (of the order of 1 ft./sec). In this case, conventional pressure probe and hot-wire techniques are unreliable, although a specialized hot film probe (commercially available) which is linearizable through the free convections range has been of some use in defining mean and intensity characteristics within the boundary layer. The stable measurement of the free stream speed outside the boundary layer has been handled by using the highly organized vortex shedding from circular cylinders in the Reynolds number range between 50 and 200 (after Roshko (70)). Essentially, measurements of the frequency of the vortex shedding and knowledge of the cylinder diameter and the Strouhal vs. Reynolds number relation for this Reynolds number range allows the determination of the mean speed to within less than 5 per cent. The detection of the shedding frequency is accomplished using any crude hot wire to probe the shear layer. Other instrumentation has recently become available for accurate measurements of low mean speeds. The ion discharge anemometer is useful where portability is important. Both methods are unsuitable for unsteady measurements. Time of flight measurements have been used sporadically for velocities; however, such methods inherently require more complex data reduction and hence, are used only where other forms cannot be utilized.

The third category of problems is that of highly turbulent flows and, in particular, the flows which exist near the ground in street canyons. High turbulence intensities, with the possibility of instantaneous flow reversals are common near the surface in a turbulent boundary layer. The city environment not only further complicates the flow field but also make access to sensors extremely difficult. The directions of the mean flows are often not self-evident, and the flows may, in fact, be reversing.

This is an area where improvement in simple instrumentation is desirable. Current techniques at the Boundary Layer Wind Tunnel Laboratory use vertical single-ended hot film probes extended upward above ground at locations of interest. These indicate the magnitude of the total velocity parallel to the ground. The major shortcoming of these probes is that they give no indication of direction and are thus only suitable for speed measurements. A typical plaza with such sensors in place is shown in Fig. 13. In cases where flow direction is of concern small wind vanes or flags are used. Time exposure photographs of the flags from above show images of the envelopes of the flags. A typical image is in the form of a sector of a circle with the line of greatest brightness corresponding to the prevailing wind direction and the angular width of the sector providing a measure of the directional fluctuations. The interpretation of the photographs, however, is relatively coarse. It was interesting to note that in the last measurements conference somewhat similar flags were reported (71) for use in high speed flow to determine flow directions outside the boundary layer. A promising alternative for these situations is Bradbury's (72) pulsed wire probe utilizing a time of flight principle. Although soon to be marketed in automated form it may not meet the criteria of simplicity and economy as a general purpose instrument.

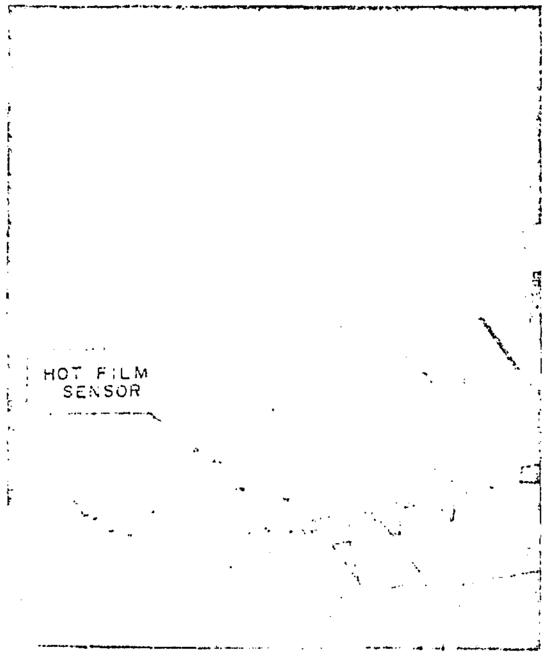


Fig. 13 Typical Plaza Wind Speed Measuring Instrumentation

In the above we have omitted two areas which deserve some comment. These are laser velocimetry and flow visualization. Laser velocimetry is certainly a subject which we are attempting to keep in touch with: however, we have not developed any practical experience ourselves. The reasons for this are as follows: first, it appears that in regimes where laser velocimetry is directly competing with hot-wire techniques, the latter are still by far the simplest and cheapest way of extracting the necessary information. Secondly the application of laser velocimetry to the problem of measurement of plaza winds in street canyons, although attractive, is complicated by the difficulty of access and the requirement for rapid measurement of simple flow quantities. Flow visualization has been widely used as a basic wind tunnel tool (73,74) and has been applied to some extent in wind engineering experiments. For instance, smoke studies have been widely made. Also shadowgraphs of the plumes using helium have been found useful. The visualization of flow within a complex city environment, however, is hampered by the highly unsteady nature of the flow. Experience with neutral helium bubbles and smoke indicate that little of value can be obtained from these techniques except where highly organized flow patterns exist. For instance, some unpublished work at Colorado State University using surface flow visualization around isolated structures in an atmospheric boundary layer simulation have been very successful in contributing to an understanding of the flow field.

Instrumentation for Pressure Measurements

The practical problem of pressure measurements is to find transducers and transducer tube systems which will (a) adequately measure relatively low pressures (the University of Western Ontario wind tunnel free stream dynamic pressure is about 2.4 psf.), (b) provide sufficient dynamic response, and (c) be able to measure many surface points in as short a period of time as possible. The last two requirement have led to the widespread utilization of some form of pressure switch which can be automatically controlled. Typically eight standard scanivalves in parallel – each capable of handling 48 different pressure inputs – are used at the Boundary Layer Wind Tunnel Laboratory. Such systems introduce compromises, especially in attaining the maximum frequency response. The frequency response generally goes down with increasing tubing length; however, a minimum tubing length is required by a system which handles around 350 pressure taps on a single model and where the total number of measurements on that model may exceed 14,000 tap/aximuth combinations. Since the model size is dictated by the scaling of the atmospheric boundary layer it is rarely possible to include the pressure switch within the model . Typical lengths of tubes joining the surface pressure taps to the pressure switch are around two feet. Introducing a restriction to damp the resonance in the tube transducer scanivalve system results in frequency responses effectively flat to about 80 to 100 Hz, as shown in Fig. 14.

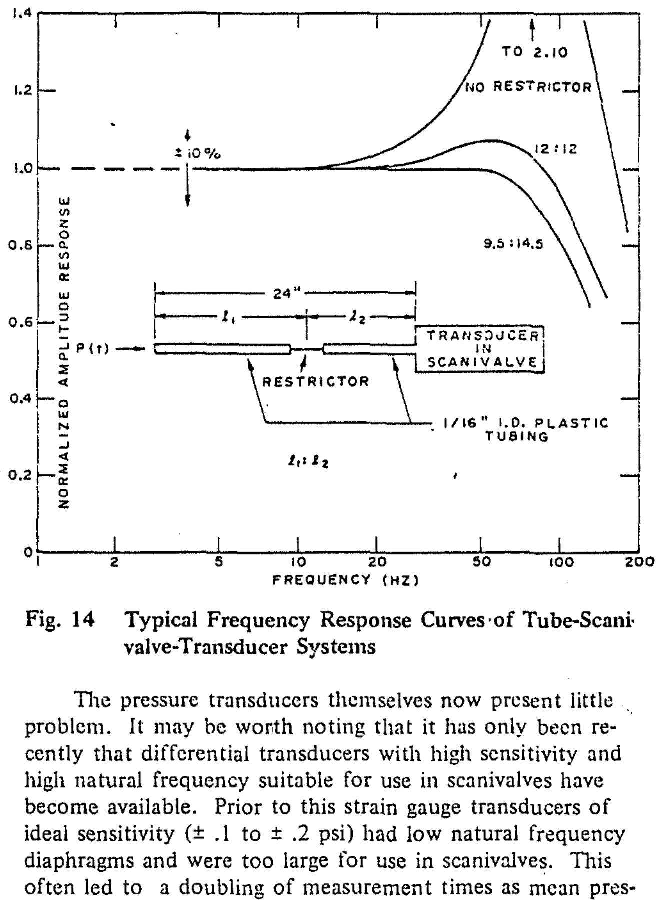


Fig. 14 Typical Frequency Response Curves of Tube-Scanivalve-Transducer Systems

The pressure transducers themselves now present little problem. It may be worth noting that it has only been recently that differential transducers with high sensitivity and high natural frequency suitable for use in scanivalves have become available. Prior to this strain gauge transducers of ideal sensitivity (± .1 to ± .2 psi) had low natural frequency diaphragms and were too large for use in scanivalves. This often led to a doubling of measurement times as mean pressures were measured using a sensitive transducer external to the scanivalve with subsequent measurements of the fluctuating pressures using a miniature variable reluctance transducer within the scanivalve which provided adequate sensitivity but was not sufficiently stable for measurements of the mean response. Current experience indicates that use of much higher range tranducers is also feasible. For most engineering tests, ± 2.5 psi range strain gauge transducers, the most sensitive of this type which can still fit in the scanivalves, are used at the Boundary Layer Wind Tunnel Laboratory. Although only a small part of the range is used, errors due to linearity and hysteresis are negligible. The only significant problem introduced is that of temperature drift. Under our experimental conditions, simple corrections can be applied to give final accuracies of the order of ± 5%. This is not to say that sensitive, miniature differential pressure transducers suitable for flush diaphragm applications and of small cost size would not be useful in some of the more fundamental applications.

The above systems are designed to measure pressures over a a small area corresponding to perhaps a window pane or less. Quite often, applications occur where the fluctuating load on a somewhat larger area is required. Typically, this could be a section of roofing or a section of cladding on the exterior surface of the building associated with the basic framing of the structure. A total instantaneous load on such a complete section is difficult to determine. A force element transducer could be specially made; however, the problems of sealing to the surrounding surface and specialized design essentially obviates this choice. Similarly the use of numerous pressure transducers whose outputs could be electronically averaged is economically impractical. This has led to experiments with pneumatic averaging systems. The idea here is simply to manifold several pressure taps together as is often done to obtain an approximate average for static pressures in the test section of wind tunnels. This approach can be shown to be valid for mean pressures if the tubes are long enough to ensure that losses at the ends are small compared to flow losses within the tubes and if flow in the tubes remains laminar under all possible applied pressures. A recent literature search has indicated that the dynamic properties of such parallel pressure tube systems have not been examined completely, although some relevant work has been reported (75,76). It is interesting to note the similarity between this idea and the ancient mechanical pressure averager of Stanton (Fig. 4). Efforts are underway at the Boundary Layer Wind Tunnel Laboratory to produce an experimental device following guidelines indicated by studies of the response of simpler pressure tube systems. The frequency response of an eight tube manifold where each tube consisted of the optimum geometry shown is presented in Fig. 15. This curve was derived by comparing the spectrum obtained using the manifold to the spectrum obtained using eight independent tube transducer systems with electronic averaging. Studies on simpler two tube manifolds have been done in more detail including simultaneous cross spectral

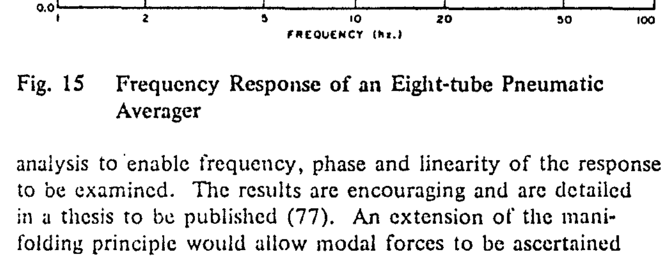


Fig. 15 Frequency Response of an Eight-tube Pneumatic Averager

analysis to enable frequency, phase and linearity of the response to be examined. The results are encouraging and are detailed in a thesis to be published (77). An extension of the manifolding principle would allow modal forces to be ascertained perhaps with pneumatically applied weighting factors. A similar averaging principle has been advanced independently by Vickery (78) which involves using a porous surface as a means for averaging surface pressure over a region. This appears to be a suitable method for obtaining average pressures but its frequency response has yet to be examined. The use of electrets may also provide a suitable alternative.

In summary, pressure measurements can be made adequately for most applications in wind engineering simulation. However, a more thorough understanding of the frequency response of complex tube tranducer systems is required. Further miniaturization may help to extend the available frequency response. It is also possible that application of semiconductor and other technologies may lead to selected applications of flush diaphragm transducers.

Instrumentation for Aeroelastic Response Measurements

Unlike pressure and flow measurements it is rarely possible, with the exception of accelerometers, to utilize standard or shelf item transducers for aeroelastic models. The aeroelastic response characteristics of such structures as bridges, towers, stacks, large telescopes, hanging roofs etc. are usually unique and hence demand specifically tailored response sensing instrumentation. Somewhat greater standardization is possible in the case of tall buildings for which instrumentation needs are relatively similar. Instrumentation for aeroelastic studies can be grouped into three main areas. These are: instrumentation for measurements of mean and dynamic forces and moments; mean and dynamic deflections and rotations; and accelerations. In some cases of course it is possible to ascertain information on all three of the above parameters with a single transducer.

Conventional wind tunnel balances are not suitable for dynamic force and moment measurements with most aeroelastic models used to study wind engineering problems. As a result custom made transducers, usually instrumented with electrical resistance strain gauges, are used to measure overall forces and moments. The design of such tranducers invariably entails a trade-off between the conflicting requirements of high sensitivity and a high natural frequency of the transducer itself. For the design of strain gauged mounts to measure base forces and moments, the matching of the transducer flexibility to the scaled flexibility of the full scale foundations in some cases adds a further constraint. There are usually no difficulties with the availability of suitable commercial strain gauges. Also commercially available carrier amplifiers with continuous output terminals are more than adequate for most aeroelastic studies.

In the case of rigid spring mounted aeroelastic models (Fig. 11) a base transducer provides complete information on forces, deflections and accelerations. The variation of dynamic forces and responses with height is obtained theoretically knowing the mode shape, frequency, and mass distribution. The vertical variation of mean forces is obtained from the integration of mean exterior pressures measured with a separate pressure model. Even in the case of multi-degree of freedom models of tall buildings, force and moment measurements at the base provide sufficient information for the definition of wind induced forces required for design. Separate measurements of acceleration are made near the top of the building, however, to more accurately account for the effect of higher modes of vibration.

In the case of continuous or replica aeroelastic models it is usually necessary to strain gauge the model structure directly. The number of strain bridges may vary upward from

6 or 9 depending on the structure. In any event sufficient data are required to permit a complete definition of wind induced static and dynamic wind loads providing that the dynamic properties are known. Calibrations of the individual strain bridges on statically indeterminate structures usually present some difficulties.

In the case of rigid aeroelastic models, spring mounted and instrumented at the base, both deflections and accelerations are obtained directly from base bending moment measurements. For more complicated models, it is usually also possible to compute the dynamic deflection and the accelerations providing that accruate estimates of the participations of the various modes of vibration can be made from measured bending moment or strain spectra. Computed estimates of mean deflections of course require additional information on the mean force distribution. Nevertheless direct measurements of deflections and/or accelerations are often made in order to improve estimates possible from measured moments and/or forces or in order to avoid the extensive computational task otherwise required. Acceleration measurements currently do not present any difficulties as inexpensive miniaturized acclerometers, weighing around 0.3 grams with a high natural frequency and flat low frequency response down to D.C. are commercially available. The measurement of deflections presents greater practical problems, as suitable commercially available sensors tend to be expensive. As a result in house development of suitable displacement and rotation sensors is common.

A displacement sensor must not significantly distort the dynamic and aerodynamic characteristics of the model. This usually necessitates a non-contacting mode of operation. Other design requirements are: linearity over a significant range (± 0.1" or better) to permit flexibility of use; good resolution (± 0.001" or better); simplicity of operation (continuous electric output a necessity); and a flat frequency response from D.C. up to a few hundred Hz. Of the various possible modes of operation, optical methods and devices based on changes of capacitance between a stationary plate and the model provide the most suitable alternatives. Detailed reviews of various principles of operation can be found in the literature (79,80). A number of capacitance type proximity sensors are commercially available. Their suitability as general displacement sensors, however, is limited by their relatively small linear range of operation. Some of the optical methods used are: cathode ray tube displacement followers; interferometer techniques based on the interference between incident and reflected beams, as well as, edge diffraction; change in transmissivity using optical wedges; devices measuring the location of the reflected beam, for example the commercially available Fotonic proximity sensor; and incident beam position indicators. The last category uses various types of photodiodes attached to the model to indicate its movement from a reference position. Some of the more common sensor types are: the quadrant cell, consisting of four separate photodiodes; the Wallmark diode; one and two directional Schottky barrier photodiodes; and solid state image sensors which comprise a large matrix of small individual photosensitive elements on a single silicon clip.

Devices which have been used at the Boundary Layer Wind Tunnel Laboratory with varying degrees of success are capacitance transducers, optical wedges, Fotoric sensors and a custom developed modified miniature Schottky barrier photodiode (80) with a linear range of about ± 0.15". The latter has been found very useful due to its light weight and good linearity and stability. Background illumination nevertheless still presents some practical difficulties. An interesting development reported in the literature (81) is a passive device called a "Photentiomatic" which works essentially as a potentiometer. Solid state image sensing matrices are seen as the displacement sensors of the future once sufficient miniaturization of the individual diodes becomes possible to provide a good resolution low weight device.

Instrumentation for Plume Dispersion Studies

Early plume dispersion studies relied mainly on visual and/or photographic observations of smoke or some tracer material added to the plume For example, non-buoyant helium filled soap bubbles have been used at the Boundary Layer Wind Tunnel Laboratory in studies of plumes from stacks and cooling towers. Although useful for establishing the occurrence of plume entrainment or the location of plume touchdown such methods only provide semi-quantitative data. Furthermore, plume visualization methods are not useful in high turbulence flows, accept for short diffusion times.

Quantitative measurements of downwind concentration are usually made by measuring the concentrations of a tracer material added to the model stack gas. Tracer gases used include helium, freon, ammonia, ammonia propane, carbon dioxide and others (41,65,82,83). Either finite or continuous samples of air are aspirated at points of interest and measurements of the tracer gas concentration are made using gas analysers, mass spectrometers, thermal conductivity cells or photocoloric meters. Other techniques comprise the use of aerosol generators and particle counters; the use of radioactive tracer materials, for example Krypton-85 gas (8,39,66,84), and subsequent measurements of the radioactivity levels of finite aspirated samples; and the use of temperature sensors (thermistors) to detect concentrations of heated model stack gas.

The procedure developed at the Boundary Layer Wind Tunnel Laboratory uses a misture of air and helium to model the stack effluent. Resulting downwind concentrations are quantitatively determined by measuring the helium concentration with a thermal conductivity cell. Consequently helium is used both to simulate plume buoyancy, as well as, a tracer gas. In order to remove the effects of increased ambient He concentration during continuous operation, the system actually only detects the differential in He concentration with respect to the ambient. The system sensitivity is 0.45 p.p.m. of helium per millivolt.

All of the currently used common methods are only capable of measuring time-average concentrations. Although this is sufficient for most wind engineering diffusion problems, instrumentation is required to conveniently measure the fluctuating components of concentration. Such measurements are required for more fundamental studies of mass transfer by turbulent diffusion.

CONCLUDING REMARKS

The authors have attempted to outline, including a historical review, the emergence of wind engineering as a separate and coherent discipline. The role of aerodynamics, wind tunnel methods, and design methodologies in this new field have been pointed out and differences with aerospace problems stressed. Current understanding of the fundamental underlying physical and aerodynamic phenomena of most wind engineering problems are largely still incomplete. As a result physical wind tunnel modelling for some years to come will continue to provide the only practicable means for defining the transfer functions which relate various wind induced effects to the properties of the atmospheric boundary layer.

This dependence on physical modelling makes the importance of representative modelling of natural wind paramount. Similarity requirements, as well as, practical simulations of wind engineering problems, with emphasis on wind induced effects on buildings and structures and atmospheric diffusion, have been presented. Lastly the authors, based on their experience, have reviewed current measuring and instrumentation systems and have indicated areas requiring further development.

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