Paper 7

THE APPLICATION OF THE BOUNDARY LAYER WIND TUNNEL TO THE PREDICTION OF WIND LOADING

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Abstract

The use of a long boundary layer wind tunnel to produce a more realistic model of natural wind than that obtained in conventional aeronautical wind tunnels is discussed with specific reference to the new boundary layer wind tunnel at the University of Western Ontario. The flow structure obtained in that tunnel is compared with models of natural wind used by other investigators, as well as, full scale results. Measurements of the mean velocity and turbulence characteristics of boundary layer flows suggest that simulation of natural wind, adequate for investigations of structural response, is achieved.

Aeroelastic model response in a turbulent boundary layer flow is found to markedly differ from that in smooth uniform velocity. A reduction or elimination of the vortex shedding peak in the lateral response and a monotonically increasing response in the direction of the wind are observed. Reference is made to recent theoretical treatments of structural response to gusty wind using statistical concepts and the main parameters influencing the dynamic behaviour of a structure are discussed.

Wind tunnel techniques for evaluating the dynamic response of a structure and integrating wind tunnel results into the design process are presented. Emphasis is placed on defining the total responsiveness of the structure as a whole, as well as obtaining information on magnitudes of maximum local pressures required in the design of the exterior shell.

Résumé

L'emploi d'une longue soufflerie d'étude de la couche de surface permet une simulation plus réaliste des vents naturels que ne le fait une soufflerie aéronautique ordinaire. Les auteurs étudient ce sujet en prenant pour exemple précis la nouvelle soufflerie d'étude de la couche de surface de L'Université Western Ontario. Ils comparent la structure des écoulements obtenus dans cette soufflerie aux reproductions de vents naturels, utilisées par d'autres chercheurs, ainsi qu'aux résultats d'expériences effectuées en grandeur nature. Les mesures de la vitesse moyenne des vents de surface et des composantes des turbulences indiquent qu'on obtient une simulation des vents naturels dans cette soufflerie, convenant à l'étude de la réponse des ouvrages.

Les auteurs ont trouvé que la réponse aéroélastique d'un modèle soumis à un écoulement turbulent de couche de surface est très différente de celle du même modèle soumis à un écoulement régulier et uniforme.

Ils ont observé l'aplatissement ou l'élimination des pointes de résonance de la courbe d'essaimage des tourbillons de réponse latérale ainsi qu'un accroissement au sens large de la réponse dans la direction due vent. Les auteurs se réfèrent à des études théoriques récentes employant l'analyse statistique du comportement structural d'ouvrages soumis à des rafales. Ils étudient également les paramètres principaux influençant le comportement dynamique d'un ouvrage, et décrivent les techniques d'évaluation de la réponse dynamique des ouvrages en soufflerie ainsi que l'utilisation du résultat de ces essais au bureau d'études. L'accent est mis sur le calcul de la réponse totale de l'ensemble de la construction, et sur l'obtention de l'échelle de grandeur des pressions locales maximales, dont la connaissance est nécessaire au calcul de l'enveloppe extérieure.

1 Introduction

This paper describes work on wind excitation of structures carried out in the Boundary Layer Wind Tunnel at the University of Western Ontario since its inauguration late in 1965. In this field, the laboratory has concerned itself with the following three areas: first, the establishment of principles of modelling natural wind in a wind tunnel; second, the development of experimental techniques for efficiently obtaining significant structural design information; and third, the establishment of principles for integrating wind tunnel results into the design process. While considerable further work is still required, some measure of progress has been achieved in each of these areas.

2 Modelling Natural Wind

Research on both natural wind and wind tunnel techniques during the past years have indicated the need for means of determining more realistic evaluations of both static and dynamic response of structures to natural wind. In particular, research notably by Jensen (1958, 1965) has indicated the necessity of obtaining a more representative model of natural wind in the wind tunnel than that found in conventional aeronautical wind tunnels. The simulation of natural wind requires the achievement of flow similarity in the wind tunnel. The following quotation from Jensen's paper "The Model-Law for Phenomena in Natural Wind", well describes the necessary similarity conditions:

> "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."

Simulation of turbulence characteristics of the flow should include the intensities, probability distributions and spectra (both shape and scale) of the individual components of turbulence and their higher order correlations (Reynolds stresses).

A complete simulation of the above wind characteristics is difficult and partial models of wind, as a result, have commonly been used to obtain information on structural behaviour. To date, four approaches have been taken:

1) Curved screens (Baines 1963) and grids of horizontal rods placed at a varying spacing (Owen and Zinkiewicz - 1957, O'Neill - 1956) have been used to model the structure of the mean wind and obtain information on time-average flow characteristics, as well as mean structural response.

2) Coarse grids have been used by a number of researchers, in particular, Baines and Peterson (1950), Vickery (1965), Surry (1967) and others, to produce large scale turbulence superimposed on a uniform wind stream.

3) Grids of flat plates with added turbulence generators (Lloyd - 1967) and vortex generators (Armitt - 1966), have been used to model both the mean and turbulence characteristics.

4) Turbulent boundary layer tunnels have been used to model wind, in particular by Bailey and Vincent (1943), by Jensen (1958), at Colorado State University and more recently at the University of Western Ontario.

3 U.W.O. Boundary Layer Wind Tunnel

The U.W.O. Boundary Layer Wind Tunnel has a working section of approximately 80 ft. long, 8 ft. wide and an adjustable height, variable from 5½ ft. at the entrance to 7½ ft. at the end. This adjustment of the roof height allows control over pressure gradients along the tunnel length. The tunnel velocity is continuously adjustable to a maximum of approximately 50 ft./sec. The unusually long working section allows the development of thick turbulent boundary layers above the artificially roughened tunnel floor. The tunnel is provided with two test areas, the first at 12 ft. from the entrance to the working section, permitting the testing in relatively uniform velocity flow, and the second at the downstream end of the working section.

The working section of the tunnel covered with surface roughness representative of a rough terrain is shown in Fig. 1. A number of such surfaces with different degrees of roughness are available to permit the simulation of natural wind over terrains ranging from built-up urban areas to open country.

The natural growth of the boundary layers over two typical roughness surfaces is shown in Fig. 2. Values of the boundary layer thickness δ at the second test area, positioned 68 ft. from the bell-mouth, are seen to be about 3 and 1¼ ft. for the two surfaces. Values of δ, permitting the use of a reasonable geometric scale, 1:400 for example, should be in the order of 4 and 2 feet for meaningful simulations of natural wind over built-up urban areas and open country respectively. Despite the long working section, therefore, some additional artificial thickening of the boundary layer becomes necessary.

The initial approach for thickening the boundary layer was to install a solid 1 ft. tripping board at the entrance to the working section. The disturbance initially introduced to the flow produced the required thickening of the boundary layer without appreciably affecting the mean velocity profiles over existing surface roughnesses, however, it excessively increased the turbulence level in both the boundary layer, as well as the free stream portions of the flow. Second, a 1 ft. high grid of horizontal graded round bars, designed to introduce a power law mean velocity variation with an exponent of α = .25 was used. This produced a thickening of the boundary layer of the same order as the height of the grid without appreciably increasing the free stream turbulence level. This 1 ft. grid has been necessary for most experiments to date and its use is implied in referring to standard boundary layer wind tunnel flows throughout this paper. It could be added that the use of vortex generators appears to be a promising method of "tripping" the boundary layer; the longitudinal roll vortices generated may have a structure most consistent with the large eddies in the boundary layer.

A comparison is made in Fig. 3 of the vertical variation of the longitudinal turbulence component in the boundary layer wind tunnel and those obtained by different techniques, already referred to in Section 2. The significant features of the boundary layer wind tunnel results are the approximately correct levels of turbulence and the relative constancy of the fluctuating velocity component throughout most of the boundary layer thickness. A deficiency of energy in the outer part of the boundary layer is noticeable in the model of wind used by Armitt (1966), suggesting that there is inadequate production of turbulent energy along the tunnel floor in order to maintain the entire boundary layer.

Mean velocity profiles for two practical roughness extremes are given in Fig. 4. The mean velocity measurements are seen to be in good agreement with power law velocity variation given in Equation (1).

$$\overline{U}_Z = \overline{U}_g \left(\frac{Z}{Z_g}\right)^{\alpha} \quad (1)$$

where $\overline{U}_Z$ = mean velocity at height Z

$\overline{U}_g$ = mean velocity at gradient height

Z = height above ground

Z_g = gradient height

α = exponent

The exponents of α = .36 and .16 for flows representative of built-up urban areas and open country are in agreement with those suggested by Davenport (1963). The lower portions of the mean velocity profiles are also in agreement with a logarithmic velocity variation. Longitudinal turbulence intensities for the same surfaces measured with a constant temperature hot-wire anemometer are given in Fig. 5. An approximate comparison is made with results in natural wind using observations taken at Sale, Victoria, Australia, reported by Davenport (1961) and published results for Brookhaven, Singer (1960). A geometric scale of 1:400, used in most tall building investigations at U.W.O. so far, is assumed for this comparison. The exponent of α = 0.15 is probably very close to that at Sale; Brookhaven appears to be less rough than the corresponding wind tunnel surface.

Spectra of longitudinal velocity for the tunnel flows used in Fig. 4 and 5, are presented in Fig. 6. These spectra were obtained by calculating the Fourier transform of the autocorrelation function of velocity. The latter was measured with a Technical Measurement Corporation correlation computer from the output of a constant temperature hot-wire anemometer. The spectra were each measured at a height of 1 ft. and at a distance of 66 ft. from the entrance to the tunnel working section. The shapes of the spectra are in good agreement over most of the frequency range with the strong wind spectrum proposed by Davenport (1961) and given in Equation (2).

$$\frac{n\,S_{u_z}(n)}{\sigma^2_{u_z}} = \frac{2}{3}\,\frac{\left(\frac{L\,n}{\overline{U}_{10}}\right)^2}{\left(1+\left(\frac{L\,n}{\overline{U}_{10}}\right)^2\right)^{4/3}} \tag{2}$$

where $S_{u_z}(n)$ = power spectral density at height Z

n = frequency

$\overline{U}_{10}$ = mean velocity at height of 10m

L = 1200m

$\sigma^2_{u_z}$ = variance at height $Z = 6.0\ K\ \overline{U}^2_{10}$

K = surface drag coefficient

In both cases, the full scale spectrum given in Equation (2) was fitted to the experimental results to give best agreement over most of the frequency range used. The corresponding calculated geometric scales are based on keeping $\frac{L_1 n}{\overline{U}}$ constant, where $L_1 = \frac{1}{2\pi\left(\frac{n}{\overline{U}_1}\right)_p}$, $\overline{U}_1$ is the mean at $Z_1 = 1\ ft.$ in the tunnel, and $\left(\frac{n}{\overline{U}_1}\right)_p$ the wave number corresponding to spectral peak and assuming the mean velocity profiles given in Fig. 4.

The vertical variation of local scale, defined by $L_z = \frac{1}{2\pi\left(\frac{n}{\overline{U}_z}\right)_p}$ for these two tunnel surfaces is given in Table 1.

TABLE 1

VARIATION OF L_z IN BOUNDARY LAYER WIND TUNNEL

Z ft.	Flow representative of built-up urban terrain	Flow representative of open country
0.5	1.1	0.97
1.0	1.4	1.0
1.5	1.5	0.97
2.0	1.6	

The variation of L_z with height for flow over built-up urban terrain, as seen from Table 1, is approximately exponential. The exponent is just under 0.3 and thus in the same range as 0.36 obtained for the mean velocity profile. The change of frequency content with height for the flow representing "open country", as indicated by the relatively constant value of L_z in Table 1, requires further investigation.

From the results presented, the agreement between natural wind and the flow properties measured so far in the wind tunnel appears to be reasonably good; however, comparisons of higher order correlations of velocity are required in order to determine whether the flow structures are in fact similar.

4 Response of Structures

Two aspects of structural response to wind are of particular interest; first, the mean deflection and sway of a structure as a whole; and second, the magnitudes of induced local pressures. The former is related to the design of the structural framing and the latter to the design of the cladding and glass. Information on parameters required for the evaluation of both can be obtained by studies of aeroelastic and pressure models of structures in a representative flow.

Theoretical determinations of structural response to turbulent flow and comparisons with experimental results are presented in a joint paper by Vickery and Davenport at this symposium.

4.1 Aeroelastic Models

The principles of aeroelastic modelling of structures are well established and criteria for similarity have been presented in a number of papers during the 1963 Seminar at Teddington, for example, Whitbread (1963) or Scruton (1963). It is often possible to use simplifications in the design of aeroelastic models and only investigate the dominant characteristics of the prototype structure. For example, semi-rigid models, spring mounted at the base, are commonly used in studies of tall buildings where the fundamental mode of vibration is basically linear.

The response of a structure to wind can be treated as a stationary Gaussian process and defined by the values of mean and RMS response. To define the dynamic response of a model, it thus becomes necessary to map mean and RMS values of deflection over a full range of wind speeds and directions and a representative variation of such structural parameters as mass and mechanical damping. Measurements of extreme response are in good agreement with theoretical predictions by Davenport (1964). A typical aeroelastic model, spring mounted on an inertia turn-table in the wind tunnel, and some of the instrumentation used are shown in Fig. 7. The deflections of the model are translated into electrical signals by strain gauging the spring mounting. Mean values of response are then measured by integrating the signal, using digital integrating voltmeters. True random signal RMS voltmeters, the output of which can also be integrated, are used to measure RMS values of response. Output of data can be punched directly onto cards to improve accuracy and speed up analysis. Auto- and cross-correlation functions and probability densities of model response can be computed either in real time or from magnetic tape records.

Estimates of response spectra are readily calculated from punched card data of measured correlation functions, or can be directly obtained by using a narrow band-width spectral density analyser.

Significant differences in model response are obtained for tests conducted in smooth uniform velocity and turbulent boundary layer flows. A comparison is presented in Fig. 8 of the dynamic response of a lightly damped square, prismatic building shape *(L/d - 7)* in uniform velocity flow and in a turbulent boundary layer representative of wind over a built-up urban area. The influence of the turbulent boundary layer flow is to completely reduce or eliminate the vortex shedding peak, found in the lateral response in smooth uniform flows. The resulting lateral response is seen to be monotonically increasing, with amplitudes proportional to a power of velocity slightly greater than 2. Some interesting preliminary results (not shown) suggest that vortex shedding response in a low turbulence type of shear flow may be greater than in uniform flow.

The dynamic response in the longitudinal direction, normally quiescent in smooth uniform flow, is also found to increase monotonically with velocity in turbulent boundary layer flow.

A general expression indicating the influence of various structural parameters on the fluctuating response in the drag direction, put forward by Davenport (1966a) and given in Equation (3), seems to be qualitatively supported.

$$x_{RMS} \propto \frac{\rho}{\gamma} \frac{1}{\sqrt{\zeta_{mech} + \zeta_{aero}}} \left(\frac{U}{n_o D}\right)^2 \psi \left(\frac{U}{n_o D}\right) \qquad (3)$$

where ρ = air density

γ = effective inertial density of building

ζ_{mech} = mechanical damping

ζ_{aero} = aerodynamic damping

$\frac{U}{n_o D}$ = reduced velocity term

$\psi \left(\frac{U}{n_o D}\right)$ = function of reduced velocity

Measurements of response correlations for models with frequency rations not approaching unity suggest that the X and Y responses are not well correlated.

The influence of structural shape on the dynamic response, for a number of common building shapes is compared in Fig. 9. In this particular case, all shapes had the same cross-sectional area, height, stiffness, density and a mechanical damping ($\zeta_{mech} = 0.01$). Values of peak response given in the comparison represent the resultant deflections calculated from Equation (4), and normalized by the response of a similar circular building.

$$\text{Resultant Deflection} = \sqrt{(\overline{X} + a\ x_{RMS})^2 + (\overline{Y} + a\ y_{RMS})^2} \qquad (4)$$

where $\overline{X}$ and $\overline{Y}$ are the mean deflections and x_{RMS} and y_{RMS} the corresponding RMS deflections, "a" was taken as 3.5 as the average extreme value of fluctuating response, is generally in the order of 3.5 RMS values in excess of the mean.

It is interesting to note that with equal stiffness, the peak response, with the exception of the triangular shapes, does not vary greatly with shape. If, as in usual practice, the stiffness is made proportional to the face width, a considerable increase in peak response is obtained for a rectangular shape, making it aerodynamically less desirable. It is also interesting to note that in all cases, the RMS deflections are of the same order as the means.

4.2 Measurement of Pressure

Significant differences in mean pressures obtained in uniform and boundary layer flows have already been reported by Jensen and Frank (1963). The most marked features of pressures obtained in turbulent boundary layer flows are the general reductions of the positive pressure due to the gradient in velocity with height, and the reductions in suctions along the roof and the back of a building. Some general features of fluctuating pressure distributions on the exterior of a model of a tall building, situated in a scaled replica environment of a large city, are presented in Fig. 10. The oscillograph records of pressures, presented as functions of reduced time $\frac{TV}{L}$, are similar to full scale measurements on tall buildings.

The complexity of fluctuating pressures, which in this case is further aggravated by the presence of surrounding buildings, emphasizes the difficulties associated in arriving at loads from a knowledge of velocity and stresses the advantages gained from obtaining the required structural response parameters from aeroelastic models. Fluctuating pressures normally constant in magnitude with height along the front face, measurements presented by Davenport (1966a), are markedly lower on the lower portion of this building, due to the presence of a somewhat smaller upstream building. Pressures along the edge of the building are seen to contain a strong component at the vortex shedding frequency. Measurements of pressure fluctuations are, as a result, most useful in the design of cladding and glass areas rather than that of the overall structure. For such purposes, it is usually sufficient to restrict measurements to a few selected points.

5 Applications to Structural Design

The current approach to structural design uses the wind tunnel as an integral tool to ascertain a complete picture of structural response and provide the designer not only with information on extreme loadings, necessary in the evaluation of structural collapse, but data required for dealing with problems of structural fatigue and comfort of occupants. Such an approach, presented by Davenport (1966a, 1966b), has been applied to a number of major buildings and embodies the following phases.

Topographical Modelling - The purpose of this phase is to determine the influence of local topography on the mean velocity profiles and turbulence structure and to establish a relationship between the properties of wind at the building site and those the nearest anemometer station. With a knowledge of the probability distribution of wind velocity at the anemometer station the probability distribution of wind velocity at the building site may be estimated and values of extreme wind velocities evaluated. Another important result of such a study is the estimation of the extremes of exposure which are used in subsequent studies of aeroelastic response and evaluation of pressure distributions.

Aeroelastic Tests - Aeroelastic models are tested in flow regimes representative of the two extremes of exposure, determined by topographical modelling, mapping both the mean and RMS response amplitudes over a range of wind velocities and directions. Separate tests are conducted for a range of mechanical damping and building density varying the frequency ratio of the structure. Typical results of response for a 50 story rectangular building, for one value of damping, mass and frequency ratio, are shown in Fig. 11.

Using such results and the probability distribution of wind speed, the probability distribution of response amplitudes can be mapped using the relationship:

$$P(A) = \int\int_{R(U,\alpha)} p(U,\alpha)\, dU\, d\alpha \qquad (5)$$

where $P(A)$ is the probability of a response amplitude $>A$, $p(U,\alpha)$ is the probability density of wind velocity U and wind direction α at the building site and $R(U,\alpha)$ represents the region in the U,α plane in which the amplitude exceeds A.

Measurements of Pressure - Measurements of mean and RMS pressures are made at points on the building for a range of wind directions in order to provide estimates of maximum pressures on window areas and cladding. Integration of mean pressures enables the calculation of aerodynamic force, shear and moment coefficients which define the mean wind loading and provide a useful basis for checking aeroelastic model results.

6 Final Remarks

- Measurements of boundary layer flow characteristics, taken to date, suggest that simulation of natural wind, adequate for structural investigations, has been obtained. Complete similarity of the flow structure cannot be ascertained, however, until information on the two other components of velocity and the higher order velocity correlations becomes available.

- Although techniques of modelling structural behaviour appear reasonable, confidence in predictions of structural response from wind tunnel data can only be gained by comparisons with full scale structures. Comparisons made to date are encouraging.

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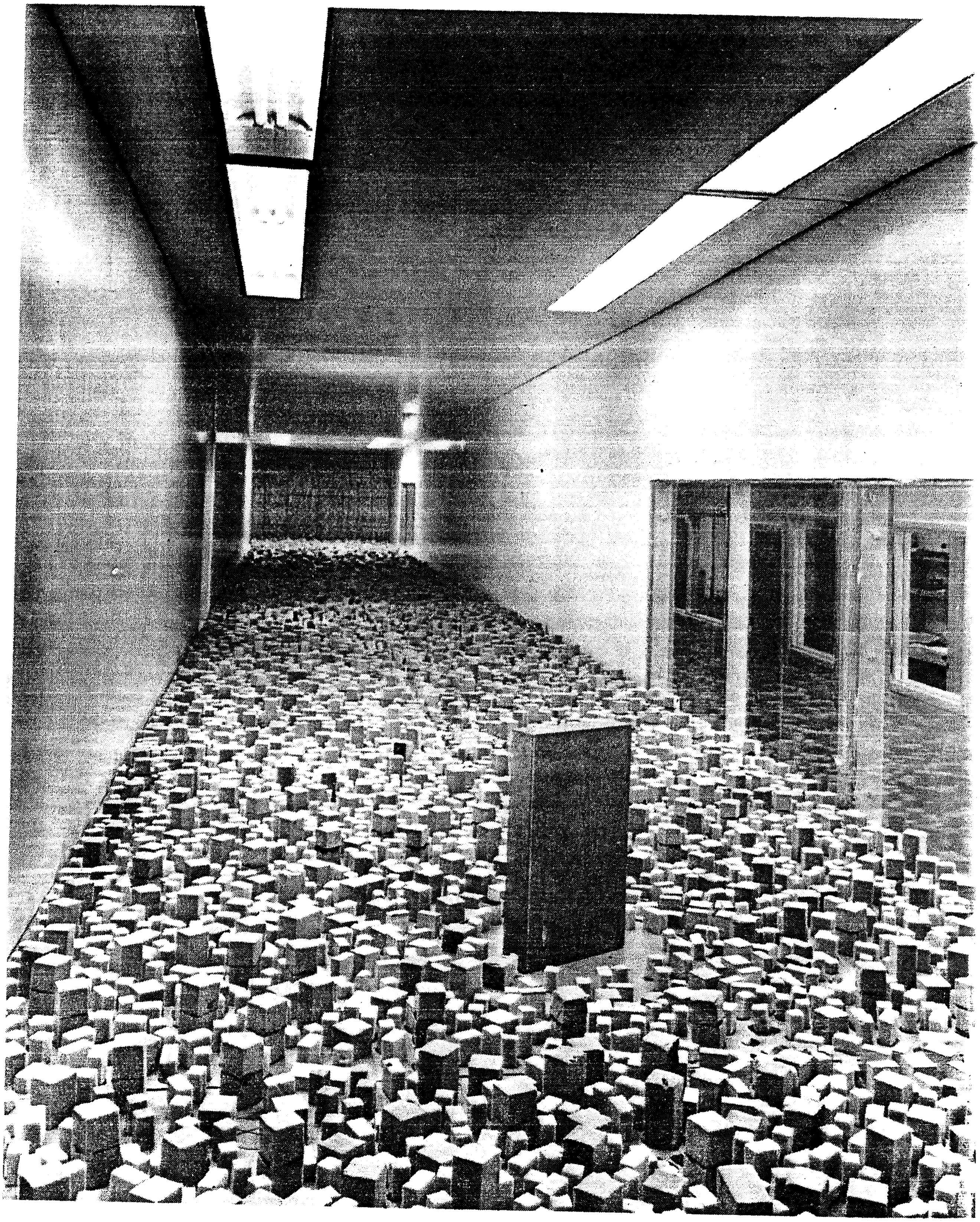
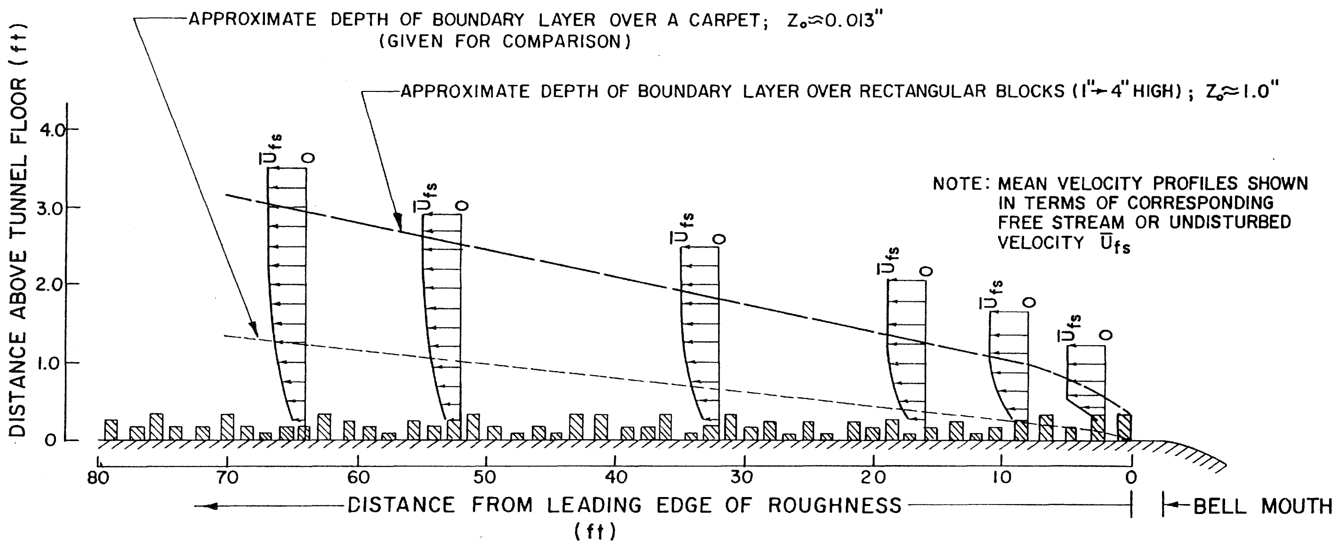


UPSTREAM VIEW OF BOUNDARY LAYER WIND TUNNEL WITH MODEL OF A RECTANGULAR BUILDING IN FOREGROUND

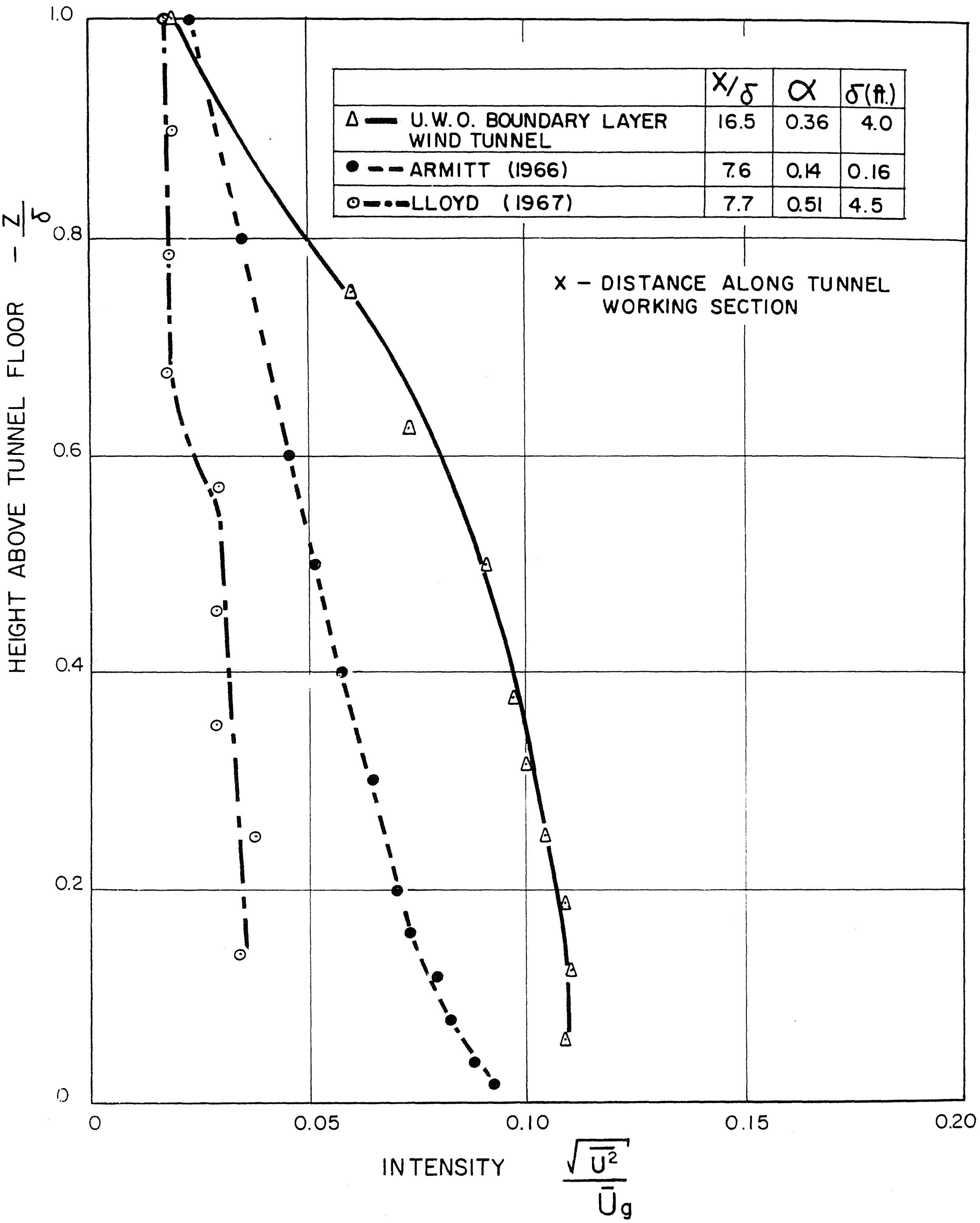
FIGURE I



DEVELOPMENT OF BOUNDARY LAYER

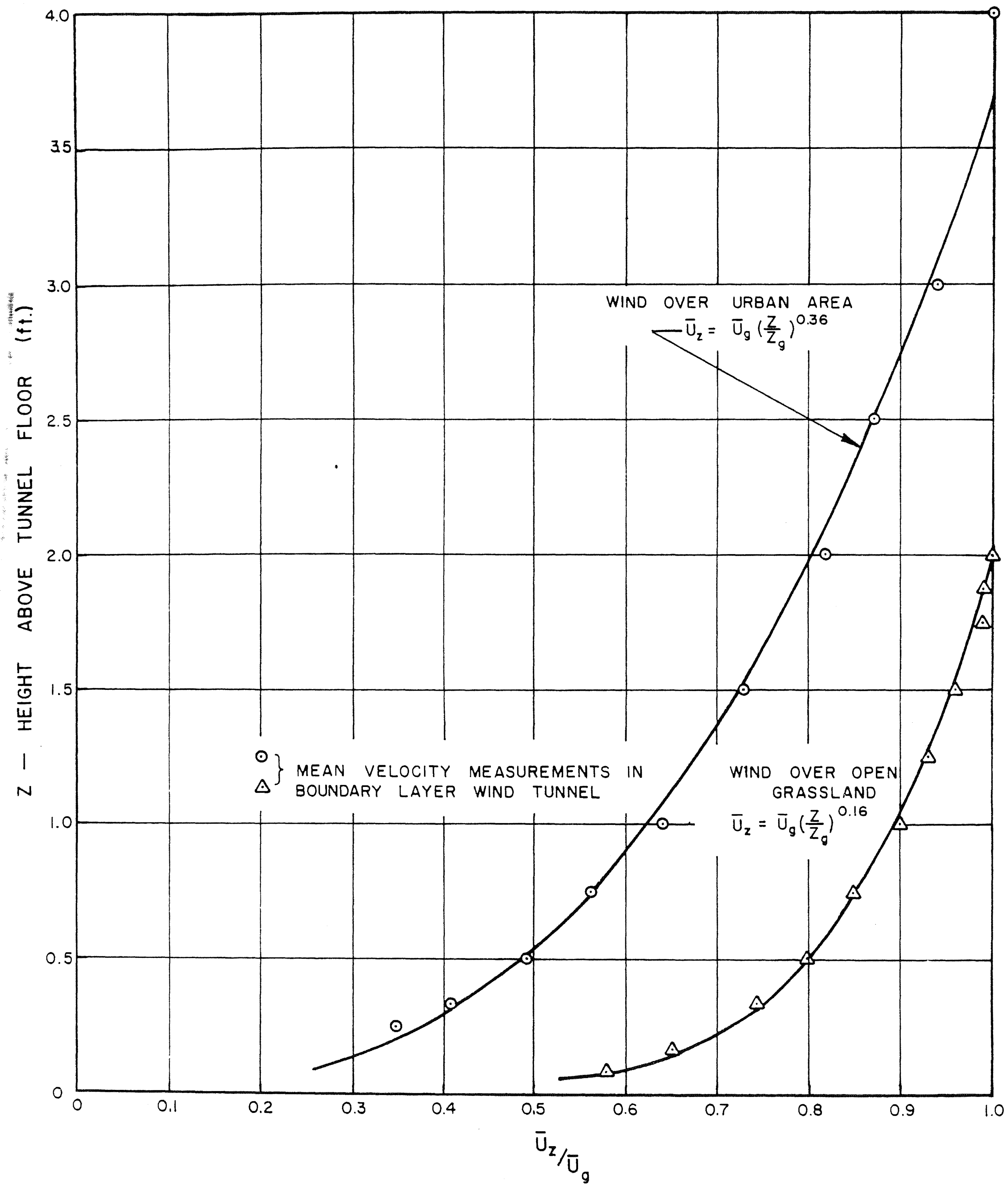
OVER TYPICAL TUNNEL SURFACES

FIGURE 2



COMPARISON OF LONGITUDINAL TURBULENCE INTENSITY MEASURED IN DIFFERENT SHEAR FLOW MODELS OF NATURAL WIND.

FIG. 3



MEAN VELOCITY PROFILES OVER TUNNEL SURFACES REPRESENTATIVE OF URBAN AND OPEN GRASSLAND TERRAINS

FIGURE 4

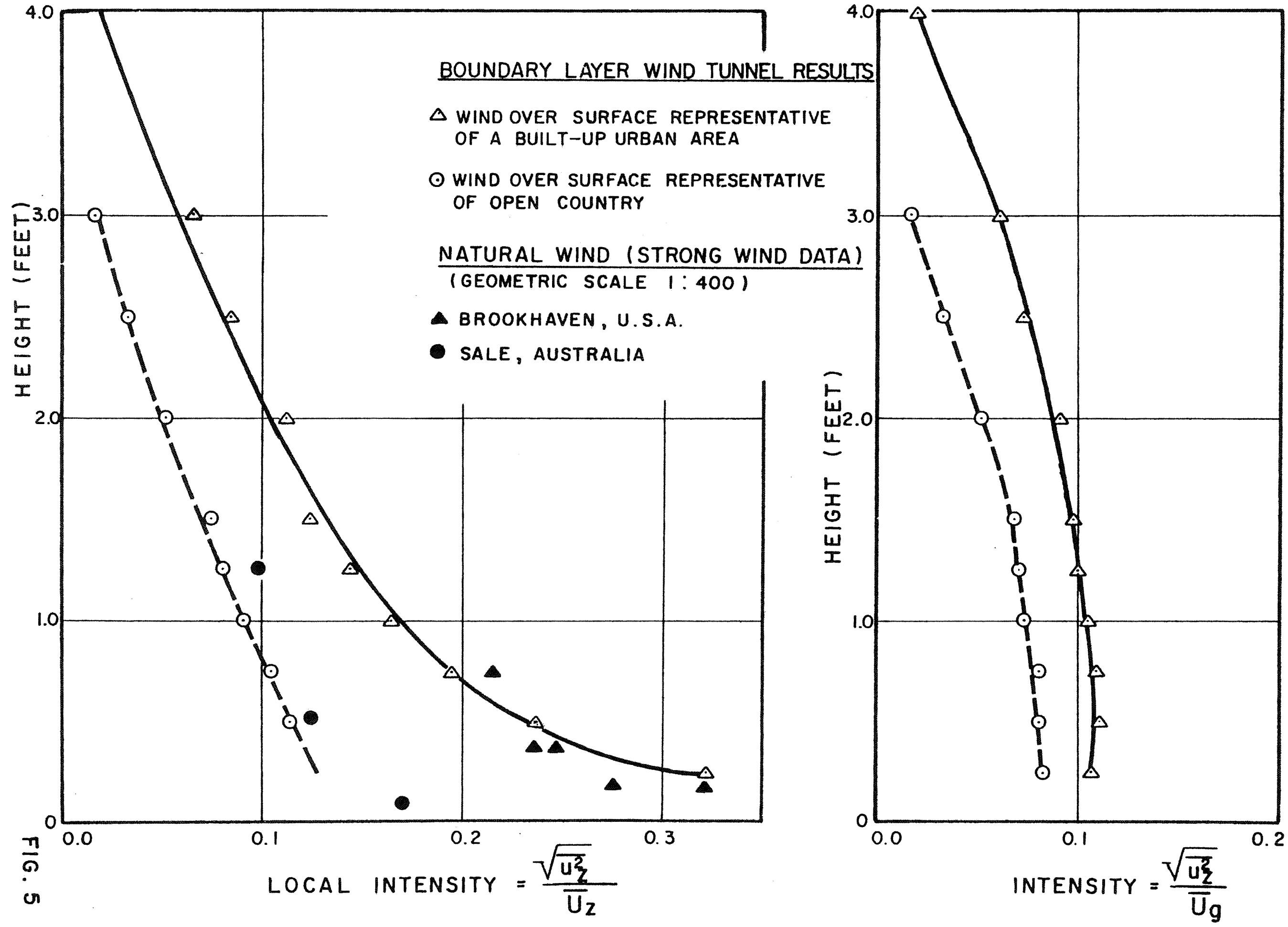


FIG. 5

Measured intensity of longitudinal turbulence in U.W.O. boundary layer wind tunnel (X = 66 ft.)

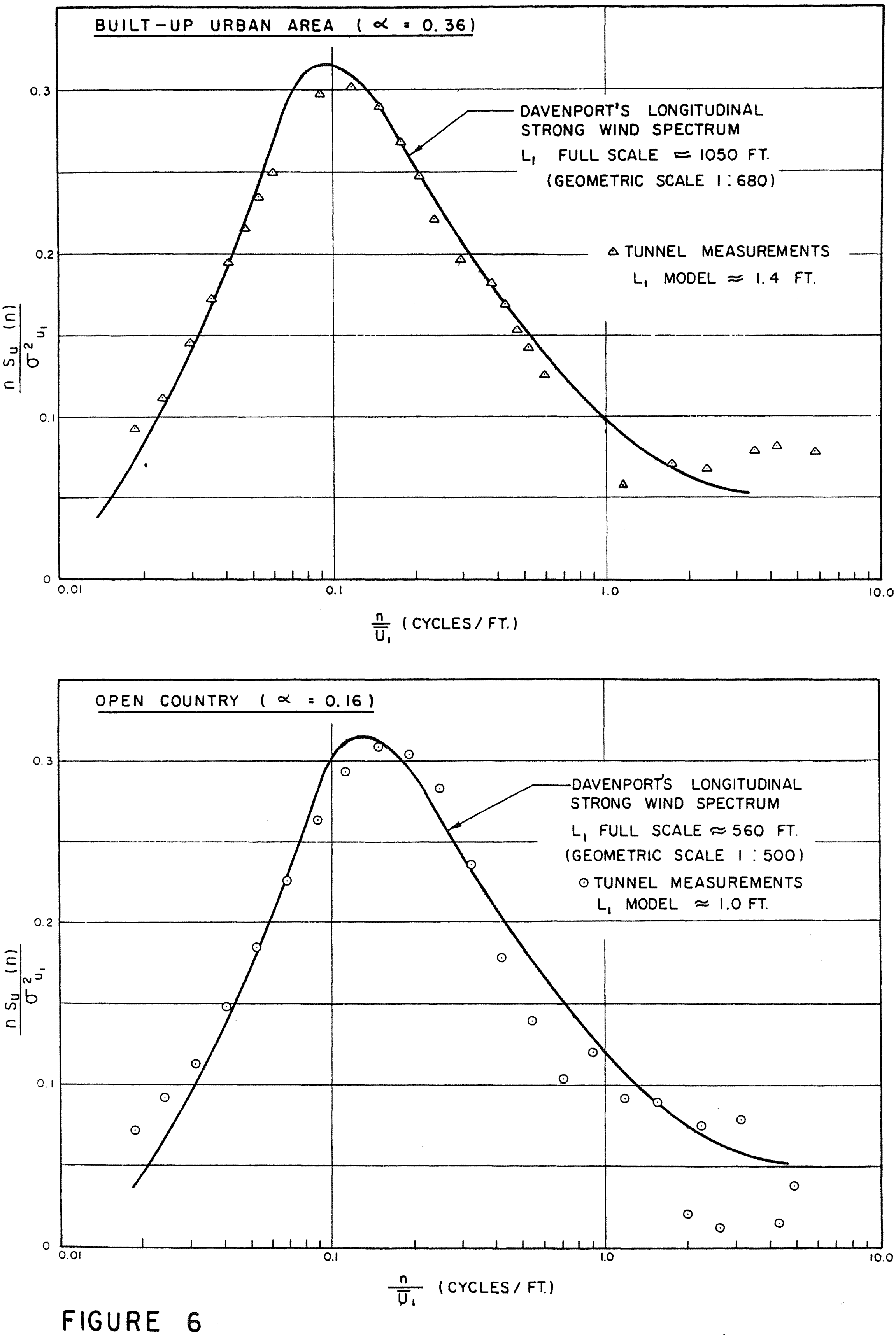


FIGURE 6

LONGITUDINAL SPECTRA MEASUREMENTS IN BOUNDARY LAYER WIND TUNNEL FOR SURFACES REPRESENTATIVE OF BUILT-UP URBAN AND OPEN COUNTRY TERRAINS (Z = 1 FT)

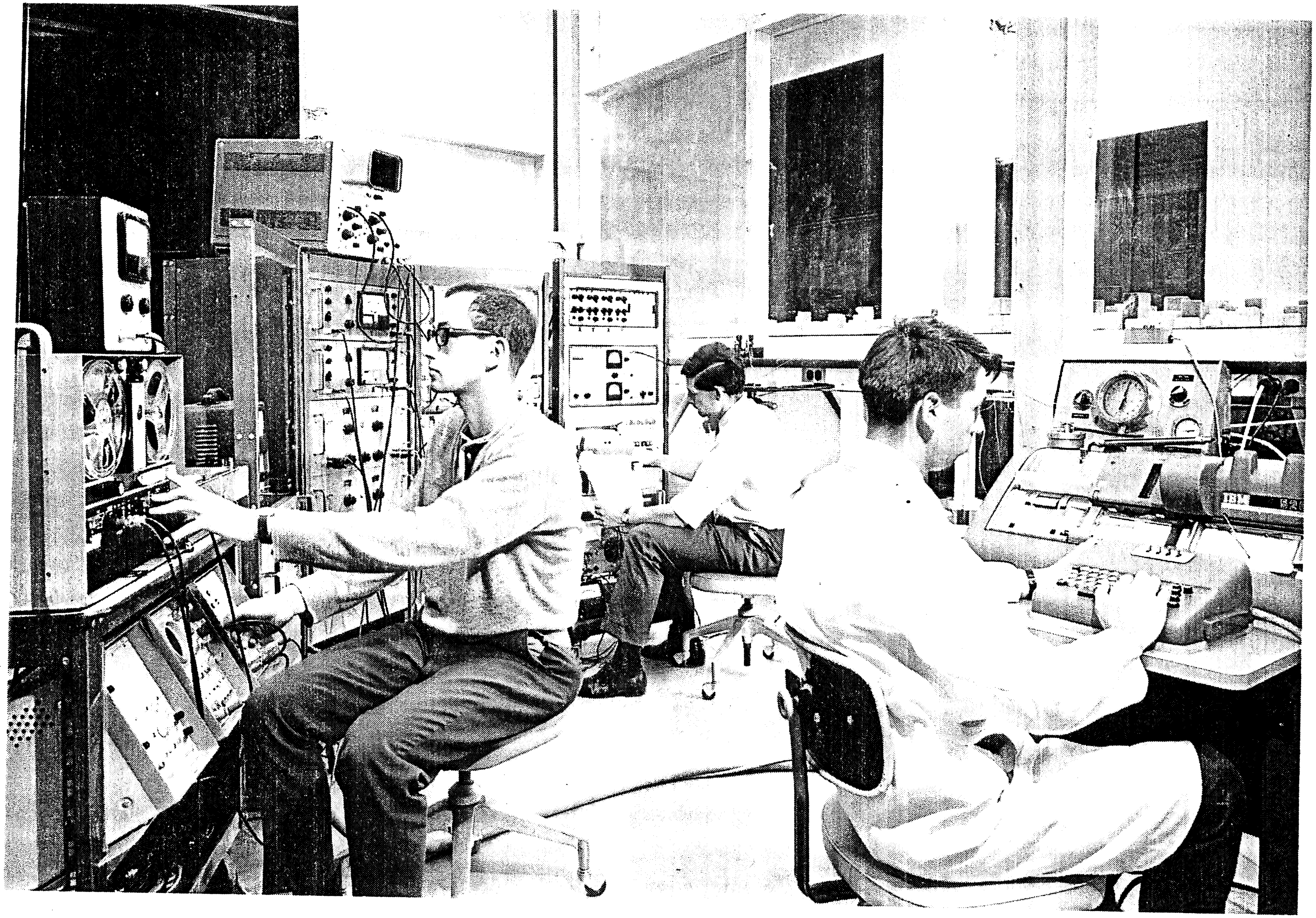
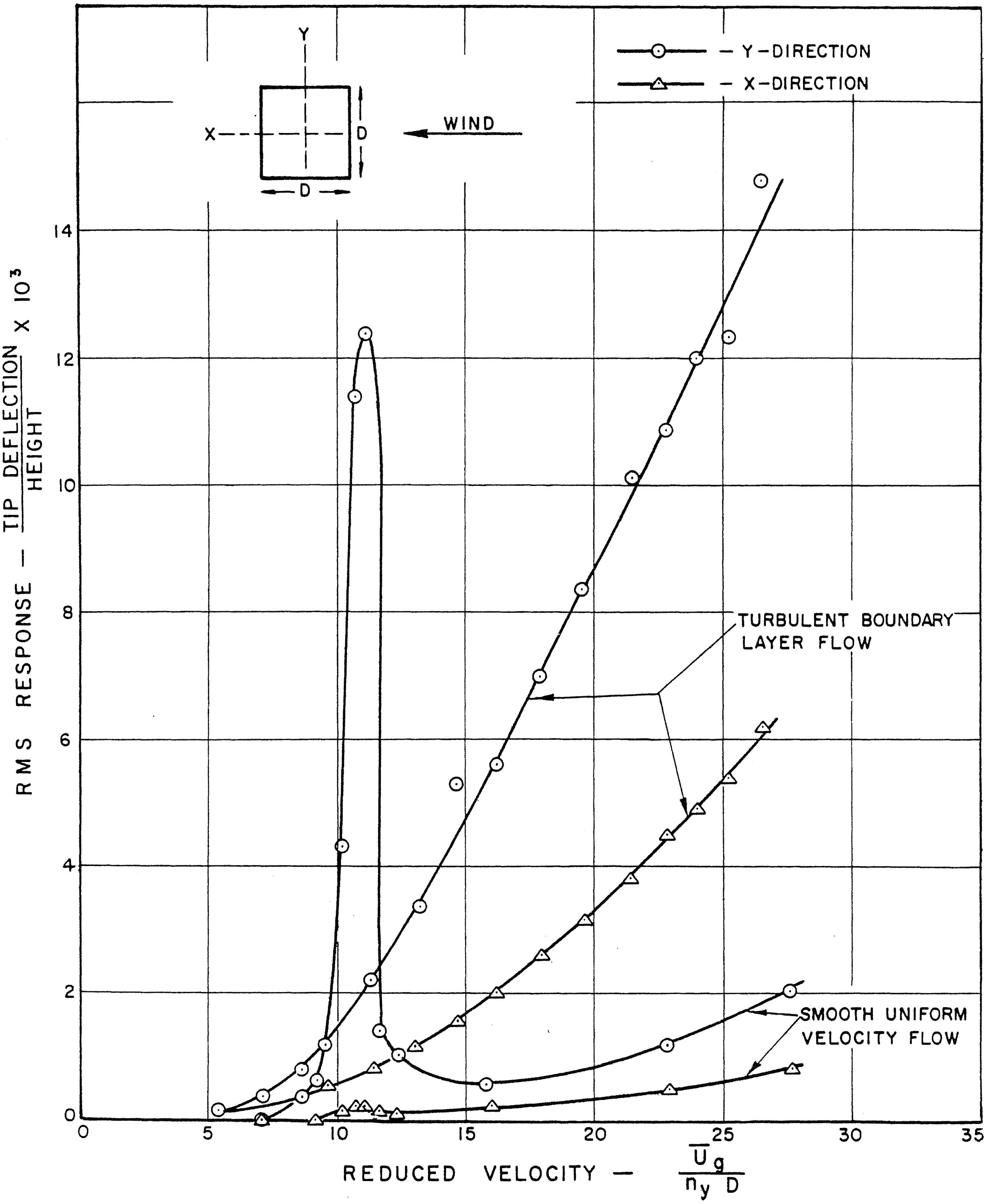


FIG. 7

SET-UP AND INSTRUMENTATION USED FOR TESTING AN AEROELASTIC MODEL OF A TALL BUILDING IN BOUNDARY LAYER WIND TUNNEL



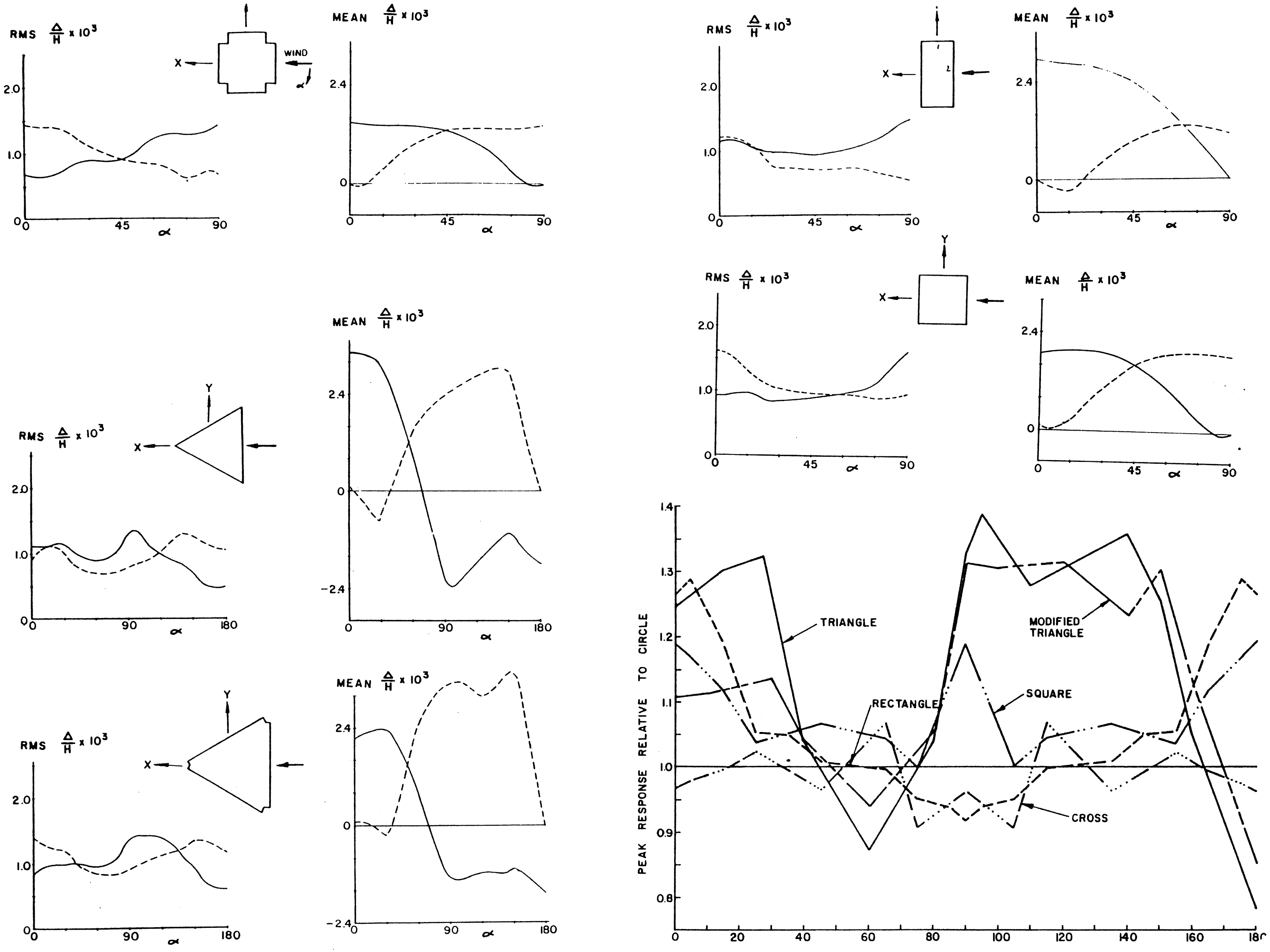
AEROELASTIC RESPONSE OF A SQUARE BUILDING (H/D = 7) IN TURBULENT BOUNDARY LAYER AND SMOOTH UNIFORM VELOCITY FLOWS (ζ = 1%)

FIG. 8

FIGURE 9

AEROELASTIC RESPONSE OF DIFFERENT BUILDING SHAPES IN TURBULENT BOUNDARY LAYER FLOW

CROSS-SECTIONAL AREA AND LENGTH CONSTANT FOR ALL SHAPES, REDUCED VELOCITY $\frac{\bar{U}_g}{n\sqrt{A}} = 7.2$



AZIMUTH ANGLE α IS TAKEN IN A CLOCKWISE DIRECTION FOR ALL SHAPES