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Standen, N. M.; Dalgliesh, W. A.; Templin, R. J.

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A WIND TUNNEL AND FULL-SCALE STUDY OF TURBULENT WIND PRESSURES ON A TALL BUILDING

BY

N. M. STANDEN, W. A. DALGLIESH AND R. J. TEMPLIN

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ETUDE EN SOUFFLERIE ET A GRANDE ECHELLE DES PRESSIONS DE VENTS TURBULENTS SUR UN EDIFICE ELEVE

SOMMAIRE

La présente étude décrit une méthode qui reproduit la couche limite naturelle du vent dans une soufflerie à section courte. Des tours à l'entrée de la section produisent des couches limites pouvant atteindre la moitié de la hauteur de la section. Le procédé a été utilisé en vue d'évaluer les pressions moyennes du vent et les gammes de pressions exercées sur le modèle d'un édifice situé dans le centre-ville de Montréal. On a répété les mêmes mesures en se servant de la technique du repérage de la rugosité longue appliquée à la production des couches limites. Enfin, on compare les résultats des deux méthodes.

On a terminé un vaste programme de mesure à grande échelle des pressions du vent sur l'édifice montréalais. Les auteurs examinent les données obtenues et comparent les valeurs, à grande échelle et en soufflerie, des pressions moyennes du vent et des gammes de pressions.

A WIND TUNNEL AND FULL-SCALE STUDY OF TURBULENT WIND PRESSURES ON A TALL BUILDING

ANALYZED

ETUDE EN SOUFFLERIE ET A GRANDE ECHELLE DES PRESSIONS DE VENTS TURBULENTS SUR UN EDIFICE ELEVE

by

N. M. STANDEN*, W. A. DALGLIESH** and R. J. TEMPLIN***

SUMMARY

This paper describes a method for simulating the natural wind boundary layer in a conventional, short working section, aeronautical wind tunnel. The boundary layers, which may be as thick as one-half of the working section height, are generated by spires at the working section inlet.

This approach has been used to measure mean wind pressures and pressure spectra on a model of a tall building in downtown Montreal. The same measurements have been repeated using the long roughness fetch technique for boundary layer generation and the results from the two methods are compared.

An extensive program of full-scale measurements of wind pressures has been completed on the Montreal building. These data are reviewed and a comparison is made between full-scale and model values of mean wind pressures and pressure spectra.

GLOSSARY

Pressure Measurement Stations on CIBC Building

TWC	Top level, West wall, Center position
TWNC	Top level, West wall, North of Center position
TWSC	Top level, West wall, South of Center position
BWC	Bottom level, West wall, Center position
BWNC	Bottom level, West wall, North of Center position
BWSC	Bottom level, West wall, South of Center position
TNC	Top level, North wall, Center position
BNC	Bottom level, North wall, Center position
TEC	Top level, East wall, Center position

Top level	Z = 545 feet (16.5 inches, model)
Bottom level	Z = 195 feet (6 inches, model)

1.0 INTRODUCTION

The study of wind effects on structures in the urban environment, the patterns of winds around buildings and at street level, and the ventilation of cities by winds are of increasing importance in the practice of a number of professions. Such a study would be greatly aided by the simulation of urban winds in wind tunnels. The criteria which must be observed in modelling the neutrally-stable atmosphere, or high-wind speed case, have been discussed in considerable detail recently by Ludwig and Sundaram (1) and Cermak (9). Criteria for modelling the non-neutral atmosphere have not been widely examined, and techniques for achieving appropriate temperature gradients in

* Assistant Research Officer, National Aeronautical Establishment, N.R.C.
** Associate Research Officer, Division of Building Research, N.R.C.
*** Senior Research Officer, National Aeronautical Establishment, N.R.C.

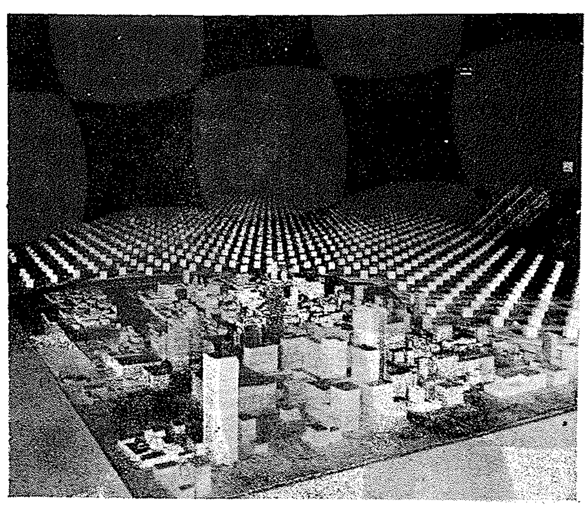
wind tunnels are in an early stage of development (9). However, for some problems, such as wind loads on tall buildings, and the dynamic response of buildings to winds, the high wind speed case is usually most critical. Therefore, good modelling of the neutrally-stable atmosphere is sufficient to allow wind tunnel investigations into such problems.

Generation of thick shear layers in wind tunnels has been accomplished by two techniques. The first method utilizes a specially constructed wind tunnel with a working section which is much longer in relation to its cross-sectional dimension than in conventional aeronautical wind tunnels. The model under test is placed at the downstream end of the working section, and is preceded by some type of roughness on the tunnel floor. The thick shear layer is thus generated by a long, aerodynamically rough surface. Tunnels of this type are currently in use by Cermak at Colorado State University and Davenport at the University of Western Ontario. Shear layers about three feet thick are obtained in these tunnels.

The second technique is not yet as well developed as the first. Conventional, aeronautical tunnels are used with the shear layer created over a short distance by some wake-producing device at the working section entrance. The thickness of the resulting shear layer is thus nearly equal to the height of the device. In the attempt to utilize the low-speed aeronautical tunnels of N.R.C. laboratories in the study of wind effects in cities, the N.A.E. investigated the suitability of various types of wake-producing devices as shear layer generators. After a series of tunnel experiments (2) a row of two-dimensional, tapered spires across the working section entrance was selected as the most effective shear layer generator.

Recently, a test in the N.R.C. 30 foot V/STOL wind tunnel compared the properties of shear layers generated by the long roughness fetch technique and by the tapered spires. In addition, measurements of mean and fluctuating pressures on a 1/400 scale model of the Canadian Imperial Bank of Commerce Building were taken in both shear layers. The test was suggested by the

Fig. 1: CIBC Building, Montreal; East Wall



1 Fig. 2: City Model in 30 ft. Tunnel; Long Roughness Fetch Installed

Division of Building Research as a comparison with the measurements which the Division had previously made on the actual CIBC Building (3).

This paper discusses the results of the pressure measurements on the CIBC Building model in some detail, and compares them with the full-scale measurements. Some properties of the wind-tunnel shear layers are also reported and compared with the available full-scale data.

2.0 WIND TUNNEL TEST PROCEDURE

The model of the CIBC Building (Fig. 1) and surrounding section of Montreal was installed in the 30 ft. V/STOL tunnel. The long roughness fetch technique was investigated first, so the model was located at the downstream end of the tunnel working section, a distance of 64 feet from the entrance (Fig. 2). The floor surface between the model location and the working section entrance was covered with alternately staggered rows of uniform 3 inch cubes. The arrangement and size of this block roughness was arbitrary; the uniform pattern was chosen in order to be easily repeatable.

The CIBC Building model was replaced with a vertical traverse rig carrying an X-hot wire probe (Fig. 3). With the tunnel wind speed held at 50 feet per second and the wind direction at 30° north of the normal to the westerly face of the CIBC Building, the probe was traversed from a height of 4 feet through the shear layer to 1.5 inches above the floor. Quantities measured included mean and rms (root mean square about the mean) turbulent velocity components.

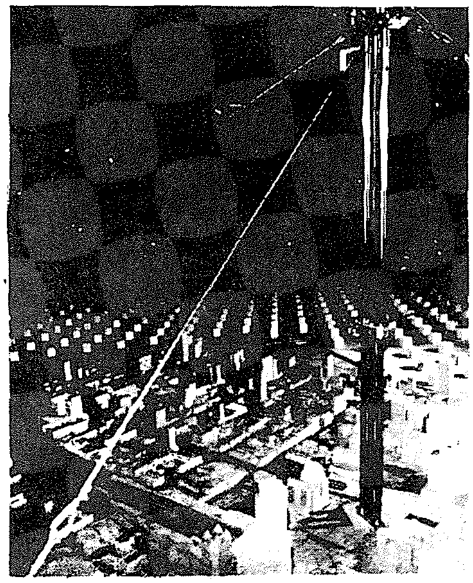


Fig. 3: Hot-Wire Traverse Rig

The traverse rig was then removed and the CIBC Building model installed. Using a microphone pressure transducer, the mean and fluctuating pressures at two points on the westerly face of the building were measured. The measurement locations were on the vertical centerline of the westerly face, one at a height of about 6 inches, and the other at about 16.5 inches (Fig. 4). These positions correspond to two full-scale measuring stations. The reference port of the transducer was connected to a tap measuring tunnel static pressure.

After the pressure measurements had been completed, the city model was replaced with additional rows of the 3-inch cube roughness. The hot wire traverse rig was then installed and the shear layer properties mentioned above were measured and recorded. These data were intended to indicate the properties of a fully-rough boundary layer, generated by a uniform roughness.

The city model was then moved to a position such that the CIBC Building model was 24 feet from the working section entrance. Again, the tunnel floor between the CIBC model location and the working section entrance was covered with the uniform block roughess. A row of tapered "spires" 4 ft. in height, was then placed at two foot intervals across the entrance, as shown in Fig. 5. The wind speed was set at 50 feet per second and the wind direction was 30°. The shear layer was then surveyed with the X hot-wire, the same properties being measured and recorded as in the other hot wire traverses.

With the CIBC Building model installed, more extensive transducer measurements of pressure were made. Six stations on the westerly face, two on the northerly wall and one on the easterly wall were instrumented with the pressure transducer.

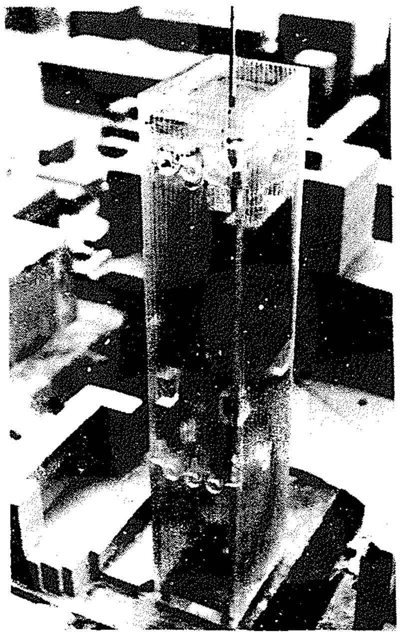


Fig. 4: West Wall, CIBC Model Transducer Locations

3.0 FULL-SCALE TEST PROCEDURE

The 600-foot CIBC Building in Montreal was instrumented in September 1968 with 6 pressure transducers on the 16th floor and 6 more on the 43rd floor (the two mechanical floors). The transducers were connected by 18-inch long plastic tubes to 1/8-in. diameter holes through the walls to the outside air. The reference ports of all twelve transducers were connected by tubing to the space above the 40th floor ceiling near the core of the building.

The pressure differences measured by the transducers were transmitted as analog voltages to a multi-channel data acquisition system which sampled each channel at 2, 4 or 8 times per second as desired, and recorded digitally on magnetic tape. In addition to the twelve pressure differentials, wind speed and direction were recorded from a three-cup anemometer and vane on a mast on the roof of the building (800 feet above street level).

Half-hour records were begun automatically whenever the wind speed exceeded a pre-set value, and after 10 months more than 30 hours of records with mean speeds from 30 to 80 fps were collected.

3.1 Treatment of Pressure Measurements From Field Data

Field measurements present more problems for data reduction than similar measurements in a controlled wind tunnel experiment. The mean speed is not generally steady for more than 10 or 15 minutes at a time and mean wind direction may vary by as much as 5 degrees over a difference in elevation of 500 feet. Unfortunately, in the present test, it was not practical to install a sufficient number of anemometers and vanes to determine the variation of speed and direction of the wind approaching the CIBC Building.

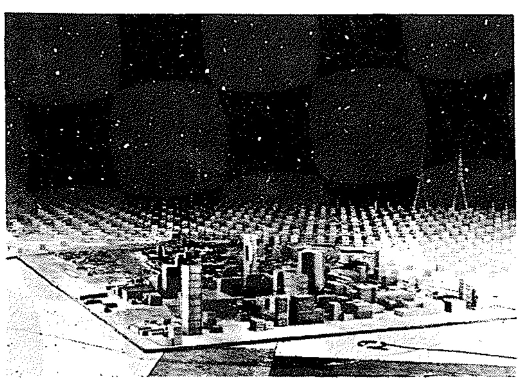


Fig. 5: City Model, Spires and Roughness

A "least-squares" linear regression analysis was employed to minimize the effects of poor correlation between the reference dynamic pressure calculated from the wind speed measured at 800 feet on the one hand, and, on the other, the surface pressures on on the building at 545 foot and 195 foot levels. Individual determinations of mean pressure coefficients were based on 30 to 60 separate 200-second averages after all the averages had been sorted into 5-degree direction intervals. Rms pressure coefficients, on the other hand, were based on 10-minute samples sorted into 10-degree direction intervals.

4.0 MEASUREMENT RESULTS AND DISCUSSION

The emphasis in this paper is on reporting and discussing the pressure measurements on the CIBC Building model. The tunnel shear layer properties are mentioned only to compare the two generating techniques. Detailed discussion of the shear layer characteristics is contained in Ref. 4.

Full-scale measurements in the City of Montreal did not include profiles of mean wind velocity gradient or turbulence intensities. Consequently, while a comparison of the wind profile characteristics in full scale and model scale is not possible, wind data from the full-scale test at 800 feet can be compared to the tunnel data at the corresponding point.

4.1 Mean Velocity Profiles

The mean velocity profiles of the shear layers were fitted with non-dimensional power laws of the form $\frac{U}{U_o} = \left[\frac{Z}{\delta}\right]^{\alpha}$ where δ is the effective outer edge of the shear layer, Z is the height above the floor, and U_o and U are the mean velocities at δ and Z respectively. The value of δ is chosen by inspection of the data at the point at which $U/U_o = 1.0$. The numerical values of α are obtained by a curve fit to the data. For urban winds, a value of $\alpha = 0.35$ to 0.40 is usually considered appropriate (5).

In Fig. 6 the velocity profiles obtained from the two techniques are shown, and the corresponding values of α and δ are indicated. The effective shear layer thickness over the city behind the spires scales to about 1600 feet, while the long roughness fetch and city together generated a shear layer equivalent in height to 1100 feet.

The power law fit to the long roughness profiles is the closest of the two techniques to the accepted value of 0.35 to 0.40 for urban winds. The spires seem to generate a shear layer with two distinct regions, and therefore two power law fits. In the lower 20 inches, the best power law exponent is 0.60, whereas above this height a much smaller exponent of 0.23 appears to fit the data. This two-region characteristic of the spire-produced boundary layer is apparent in other properties of the layer, as will be seen in the following sections.

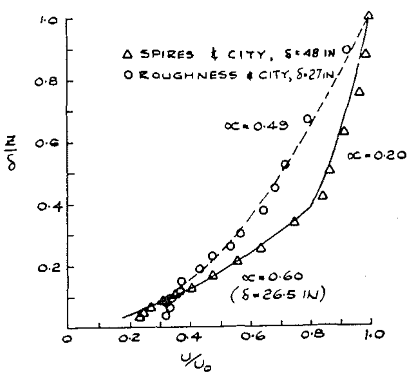


Fig. 6: Mean Velocity Profiles

4.2 Turbulence Intensities

The root mean square values of the longitudinal (u) and vertical (v) turbulence components are shown in Fig. 7 and Fig. 8. In both shear layers, the maximum turbulence intensity, both for the longitudinal and vertical component, occurs at about 0.25δ. The peak longitudinal turbulence intensity in the roughness-generated shear layer is about 17 percent, whereas the spire-generated layer has a maximum longitudinal intensity of about 14 percent. In Fig. 7 three additional data points are shown. These indicate the longitudinal turbulence intensity based on the mean velocity at the 800 foot level (or model equivalent), for both the model and full-scale tests.

The secondary maximum in the longitudinal intensity in the spire-generated layer, at a height of about 35 inches, is probably related to the existence of two regions in the velocity profile. It should be noted that this "hump" in the intensity profile begins at a height of 20 inches, the same height as that at which the break in the velocity profile occurs.

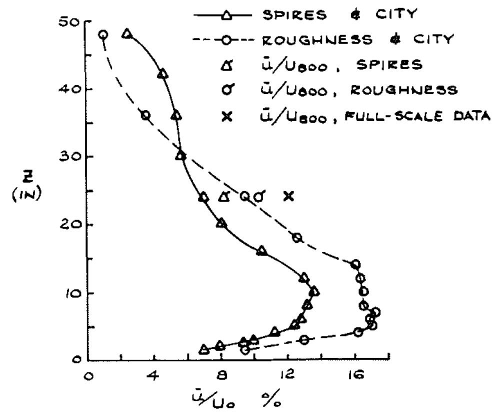


Fig. 7: Longitudinal Turbulence Intensity

The intensity of the vertical component of turbulence (Fig. 8) shows much the same form of distribution as the longitudinal turbulence intensity. The peak intensities occur at about the same heights as the peaks in the longitudinal component. The magnitude of the vertical component peak intensity is about 60 percent of the longitudinal intensity. Again, the hump in the spire-generated profile is apparent, and begins at a height of 20 inches.

4.3 Reynolds Shear Stress (uv Correlation Coefficient)

The data of Fig. 9 indicate some scatter in the measurement of the Reynolds shear correlation for the roughness-generated boundary layer. However the mean curve faired through this data is in good agreement with a similar representation given by Reichardt for a fully-rough channel flow (see Ref. 6). In the lower 20 inches of the spire-generated shear layer, the variation of the correlation coefficient is also in agreement with the Reichardt curve. However, above 20 inches height, the uv correlation coefficient increases, rather than continuing to decrease. Taken together with the peculiarities in the distributions of turbulence intensities and mean velocity, this behaviour of the correlation coefficient suggests some well-established eddy motion in the upper levels of the spire-generated shear layer. Unfortunately, no power spectral density studies were made in this shear layer above 20 inches in height, so this important additional evidence is lacking at present. If such a motion does exist, it may be due to vortex shedding from the thin upper portion of the spires.

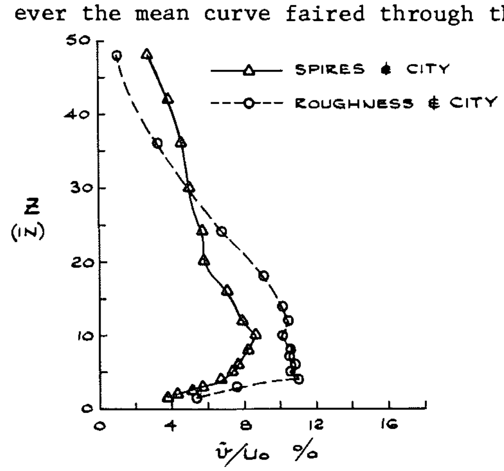


Fig. 8: Vert. Turb. Intensity

The Reynolds stress coefficient $-\overline{uv}/U_0^{2}$ may be obtained from the above figures by multiplying the correlation coefficient by both turbulence intensities $\tilde{u}/U_0$ and $\tilde{v}/U_0$ at the corresponding height. As shown in Fig. 10 neither boundary layer presents a region of effectively constant shear near the floor, a condition suggested for atmospheric modelling (1). As Cermak (9) points out, however, this requirement may be relaxed in a city environment where the effective roughness height is large compared to the shear layer thickness. Fig. 10 also shows the measured shear distribution for the boundary layer

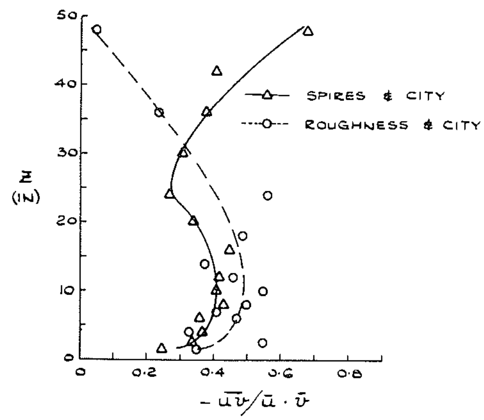


Fig. 9: Reynolds Stress Correlation Coefficient

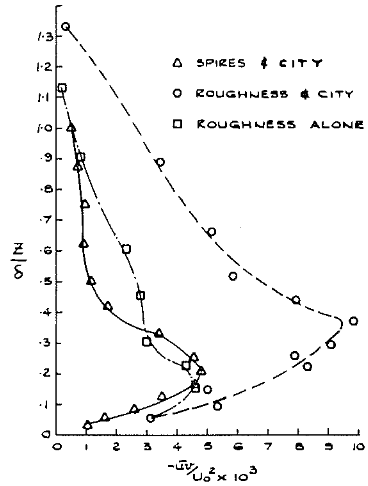


Fig. 10: Reynolds Stress

generated by the block roughness alone, without the city model in place. Again, no region of constant shear stress can be distinguished, although the variation in the stress values in the lower 30 percent of the boundary layer is less than the variation in the two other layers.

4.4 Power Spectral Density of the Longitudinal Turbulence Velocity

The calculated power spectral density of the u-component of turbulence is shown in Fig. 11 for both model and full-scale shear flows. The spectral densities in the model wind were calculated from data taken at heights of 18 inches and 6 inches in the roughness-generated boundary layer, and at 16 inches and 4 inches for the spire-generated layer. The spectral density of the u-component of turbulence in the full-scale wind was obtained at 800 feet altitude.

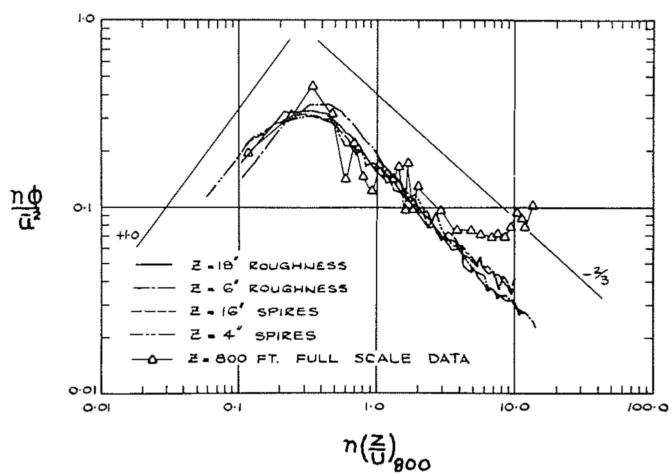


Fig. 11: Velocity Power Spectra

Using a Monin-Obukhov non-dimensional frequency (8) in which the length and velocity are independent of height in the shear layer, the peaks of the spectra at the various heights and in the different boundary layers occur at close to the same non-dimensional frequency. In Fig. 11 and all other spectral density graphs in this paper, the non-dimensional height and velocity have been the 800 foot elevation (2 foot elevation in model scale) and the velocity at this elevation. In the spectral density distributions of the velocity turbulence, Fig. 11, these values establish the peak non-dimensional frequency at a value of between 0.30 and 0.40. The von Karman theoretical curve (2) provides a peak frequency of 0.36, using a

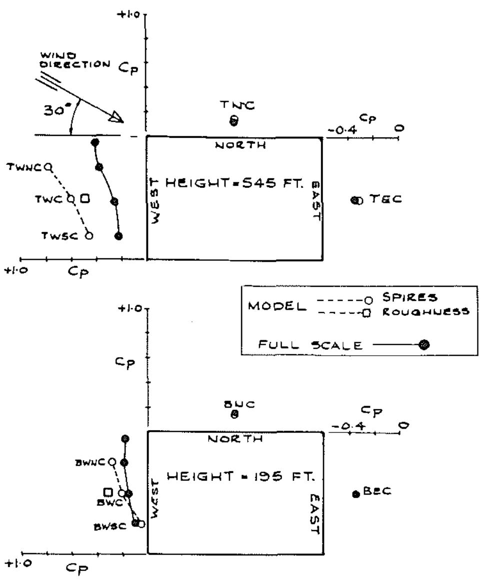


Fig. 12a: Mean Pressure Coeff.

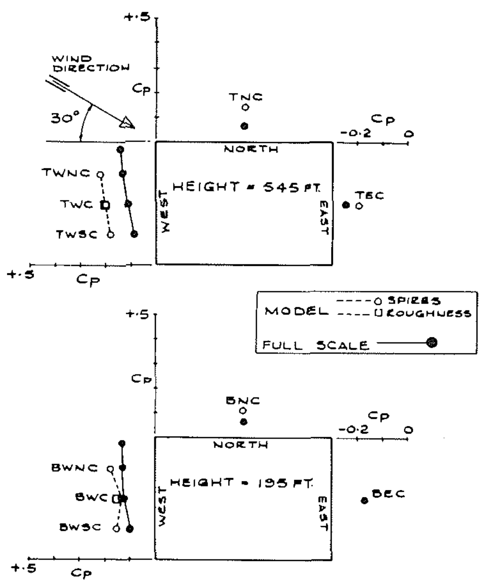


Fig. 12b: RMS Pressure Coefficients

value of 0.40 as the ratio between large eddy scale and reference height. In addition, the von Karman distribution has a slope of -2/3 at frequencies above the peak and +1.0 below the peak when expressed in Monin coordinates. The velocity spectral densities in Fig. 11 are in good agreement with these slopes. The ordinate scale has been nondimensionalized by multiplying the spectral density, $\phi(n)$, by the frequency n and dividing by the variance u^2.

4.5 Pressure Measurements on the CIBC Building - Model and Full Scale

The comparison of the measured pressures on the full-scale CIBC Building and on the model behind the spires is shown graphically in Fig. 12. The data shown are the pressure differentials as measured by the transducer, non-dimensionalized by the dynamic pressure of the wind at the 800 foot level (full scale) and 2 foot level (model). The mean pressure coefficients at the upper level locations on the east and north walls of the model compare favourably with corresponding measurements in full scale. On the upper west wall, however, the mean pressure coefficients on the model are about twice as large as those measured in the field. The rms coefficients of the pressure fluctuations at all upper level locations on the model are also about twice as great as in the full-scale case. The comparison between model and full scale at the lower level stations is better

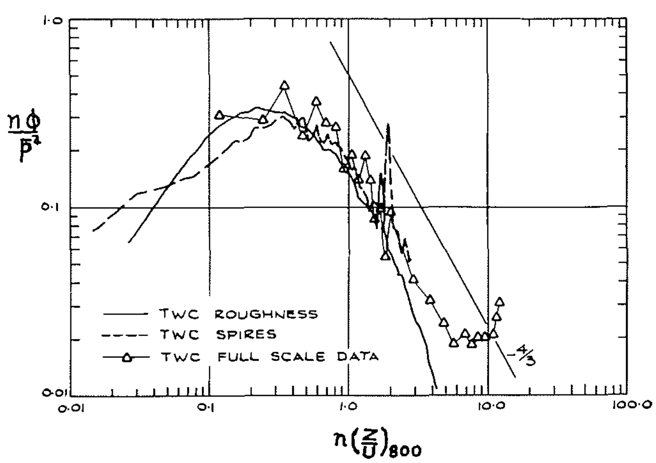


Fig. 13: Pressure Spectra, TWC

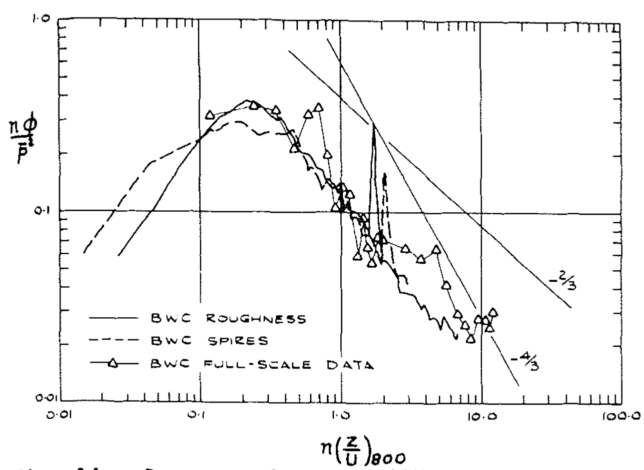


Fig. 14: Pressure Spectra, BWC

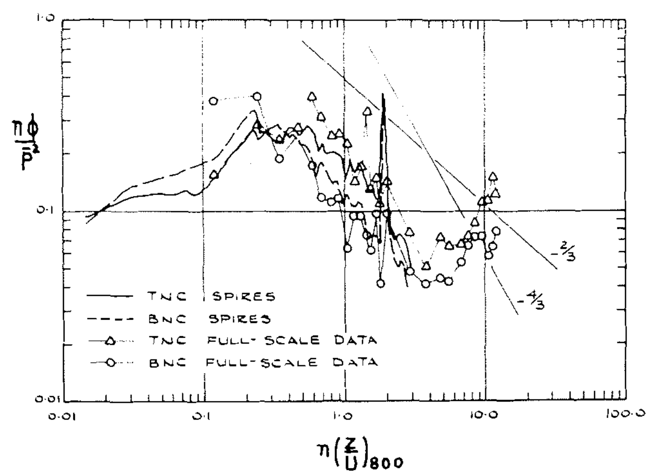


Fig. 15: Pressure Spectra, TNC, BNC

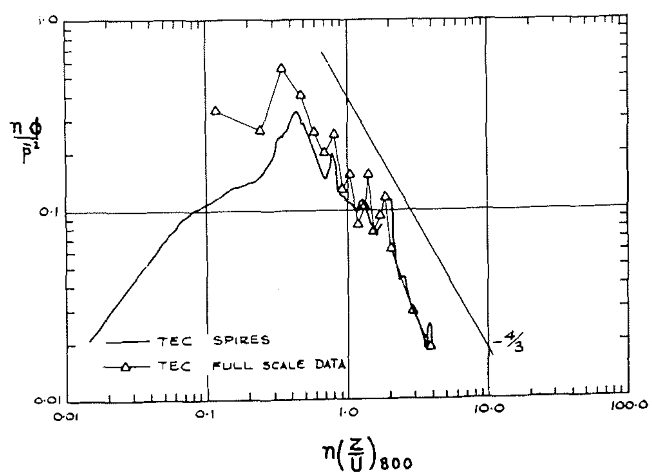


Fig. 16: Pressure Spectra, TEC

than was the case at the upper level.

4.6 Power Spectral Densities - Pressure Turbulence on the Building's Surface

The power spectral distributions of the pressure fluctuation ions on the building surfaces in the model and full-scale tests are compared for five different positions in Figures 13 through 16. When plotted in non-dimensional coordinates described in 4.4, the model and full-scale spectra are generally in close agreement.

The model results for the spire-produced turbulence tend to be more irregular than those for roughness-produced turbulence in Fig. 13 and to have a flatter peak with more energy at low frequencies in Fig. 14. These tendencies may be related to a narrower analysis bandwidth for the spire data, since wider bandwidths tend to smooth the spectral distribution and to provide less definition at low frequencies.

The spikes that occur in the model data (Fig. 13) at a non-dimensional frequency of 1.8 to 2.0 (about 42 Hz.) are unexplained to date. It was noted, however, that a Strouhal Number of 0.15, based on building model width and free stream velocity, would indicate a vortex-shedding frequency of about the same value. The large increase in the energy at higher frequencies in the full-scale data in Fig. 15 is interesting and invites further investigation. The analysis of the model data at corresponding frequencies has not yet been conducted, so no comparison is possible at this time.

Two points emerge from the power spectra studies. First, the frequency at the main peaks in the longitudinal turbulence velocity spectra is independent of height in the shear layer, as is shown by agreement between top and bottom levels when scaled by the wind speed and height at the 800 foot level. Second, in spite of significant discrepancies in mean and rms pressure coefficients, there is substantial agreement between model and full-scale non-dimensionalized pressure spectra at corresponding positions on the building.

5.0 CONCLUSIONS

Both the long roughness fetch and the spires with roughness produced acceptable models of the urban wind. In particular, modelling of wind velocity spectra and building surface pressure spectra was noteworthy.

With some modifications to improve the mean velocity profile of the resulting shear layer, the spires can be enlarged to provide thicker boundary layers in the N.R.C. 30 foot V/STOL tunnel. This would permit the testing of larger-scale building models.

In this connection, the writers think that the question of scale effect with regard to the boundary layers originating and growing on building surfaces should be investigated. Ideally, the Reynolds Numbers of both tunnel and full-scale flows should be identical. Cermak (9) has suggested, however, that this requirement can be relaxed for city winds, and can be replaced with a requirement that the flow patterns around structures in the city must be accurately modelled. He suggests that such a flow pattern invariance can be achieved by maintaining a minimum Reynolds Number in the test. The following hypothesis accepts for the present that the Reynolds Number need not be correct for the tunnel model. It does, however, suggest a more stringent requirement for pursuing invariant flow patterns around structures, determined by the relation between the size of building surface features and surface boundary layer thickness.

As a first approximation, the building surface boundary layer may be considered to be turbulent, with a mean velocity profile following the 1/7th power law, developing under a uniform pressure field. The boundary layer thickness at a given point would then be proportional (6) to the 4/5 power of the Reynolds Number based on distance over which the boundary layer has developed.

The mullions on the CIBC Building protrude sufficiently to have a significant effect on both the magnitude and direction of surface boundary layer growth. Consequently, they should be scaled according to boundary layer depth rather than the geometric scaling factor for the building as a whole. As the full-scale wind speed and tunnel wind speed were the same, this would mean a scaling ratio of $(1/400)^{4/5}$, or about 1/120. In the CIBC Building model, the mullions should thus protrude at least 3 times as far from the building as they did in the present test. Whether such scaling of surface features would significantly affect the building surface pressure distributions has not yet been demonstrated, but since the boundary layer interacts with and modifies the main flow, this would seem to be a strong possibility.

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