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BY

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

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

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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.

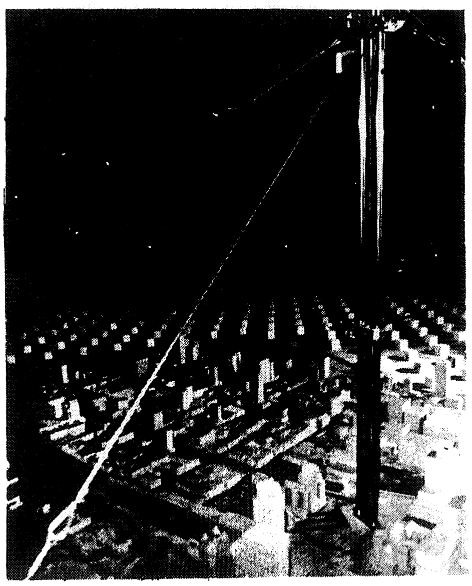

Fig. 3: Hot-Wire Traverse Rig

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.

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 $\frac{U}{U_0} = \left[\frac{Z}{\delta}\right]^{\alpha}$ where δ is the effective outer edge of the shear layer, Z is the height above the floor, and U_0 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 $U/U_0 = 1.0$. 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.

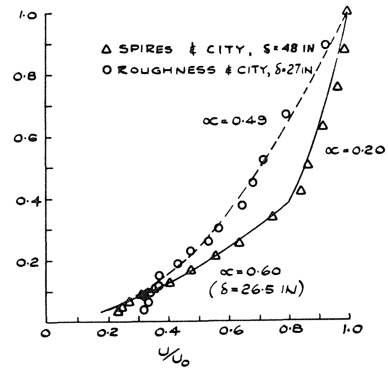

Fig. 6: Mean Velocity Profiles

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 effective roughness height is large compared to the shear layer thickness. Fig. 10 also shows the measured shear distribution for the boundary layer 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.

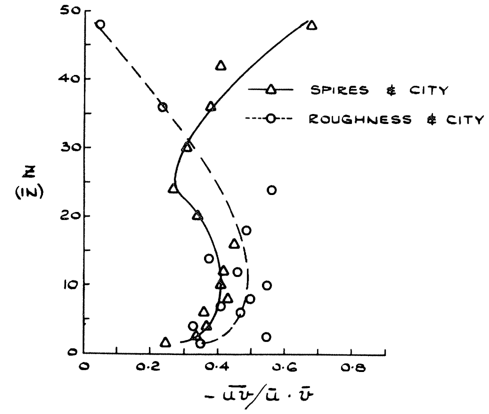

Fig. 9: Reynolds Stress Correlation Coefficient

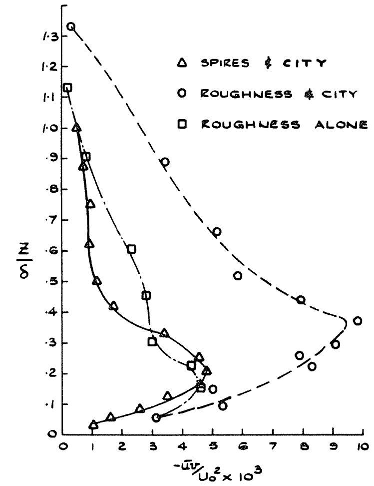

Fig. 10: Reynolds Stress

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.

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

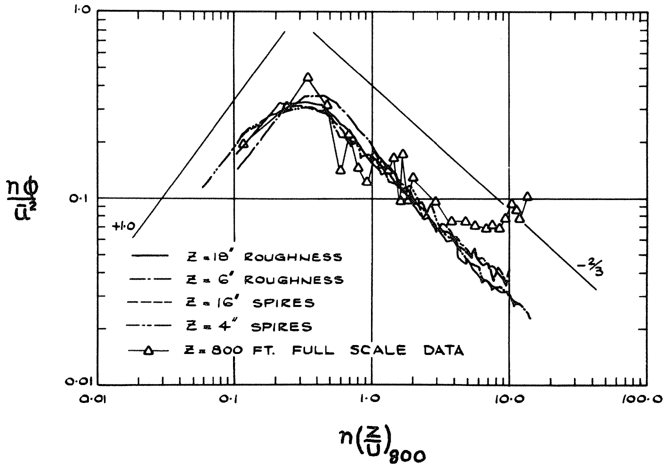

Fig. 11: Velocity Power Spectra

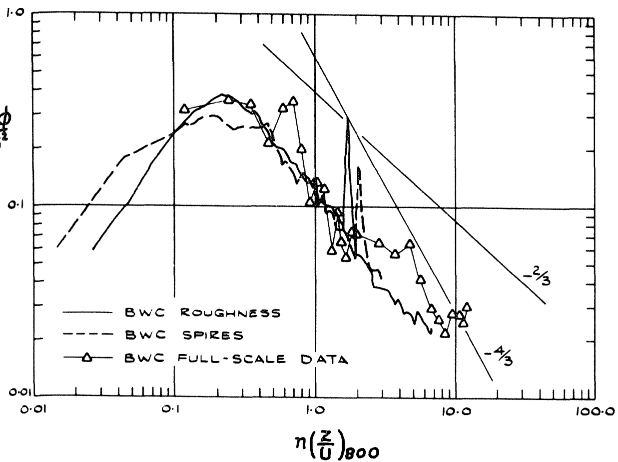

Fig. 14: Pressure Spectra, BWC

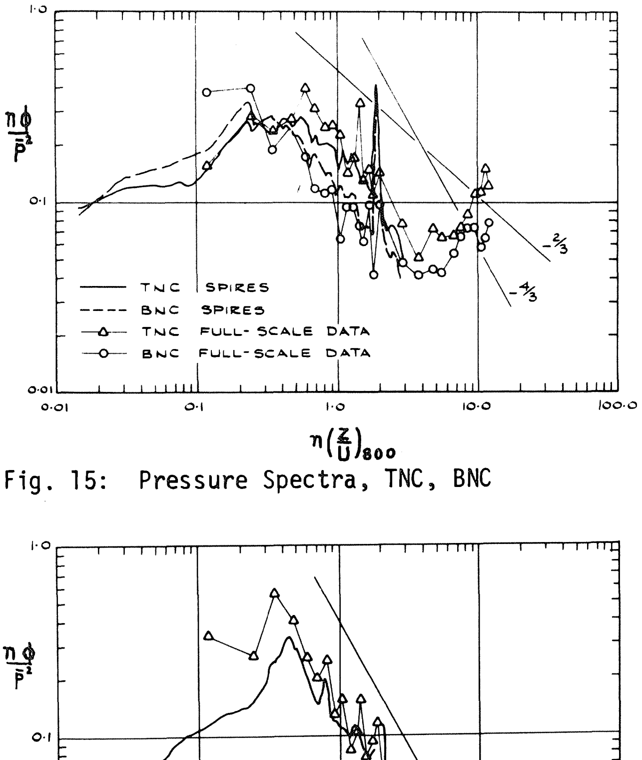

Fig. 15: Pressure Spectra, TNC, BNC

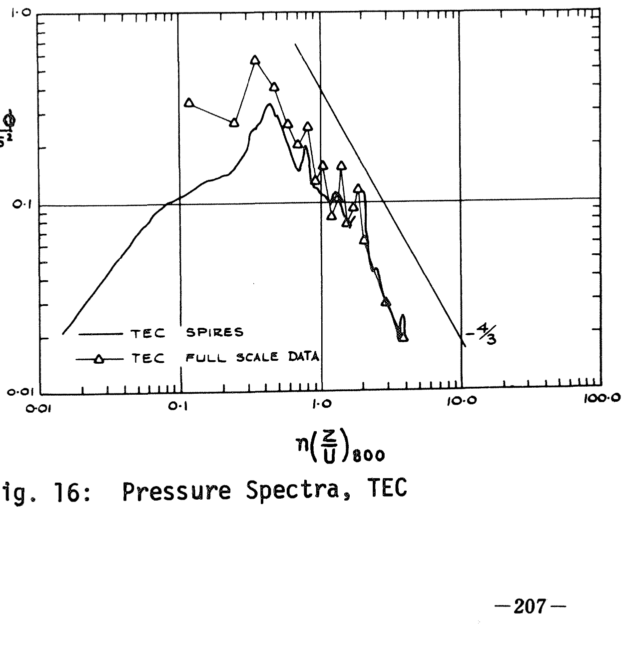

Fig. 16: Pressure Spectra, TEC

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

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