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SOMMAIRE

Ce rapport présente des mesures représentatives des mouvements causés par le vent dans le cas de l'édifice de la Banque de commerce de Toronto, Canada, et fait partie d'un projet à long terme visant à évaluer la validité des techniques courantes des essais en soufflerie dans la conception de bâtiments. Les procédés courants de conception étant fondés principalement sur les résultats des expériences en soufflerie, une certaine vérification dans les conditions d'utilisation s'avère essentielle. Le rapport se termine par une évaluation préliminaire des corrélations qui existent entre les mouvements mesurés pour le bâtiment, ceux qui sont prévus d'après les essais en soufflerie effectués en rapport avec la conception du bâtiment et les déplacements enregistrés par le procédé détaillé contenu dans le Supplément n° 4 du Code national du bâtiment du Canada 1977.

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W.A. Dalgliesh* and J.H. Rainer*

SUMMARY

This report presents typical measurements of wind-induced movements in the Bank of Commerce Building in Toronto, Canada, part of a long-term project to assess the validity of current wind tunnel techniques in building design. Since current design procedures are based mainly on results from wind tunnel experiments, some full-scale verification is deemed essential. The report concludes with a preliminary assessment of the correlations between measured building movements, those predicted from wind tunnel tests performed for the building design, and displacements computed by the detailed procedure contained in Supplement No. 4 to the National Building Code of Canada, 1977 Edition.

DESCRIPTION OF BUILDING AND INSTRUMENTATION

Commerce Court West, a 57-storey office structure, is 239 m high, and 36 m × 70 m in plan. Wind loads are resisted by frame action through moment connections and spandrels in the long direction (N-S) and by a combination of framing and core bracing in the short direction (E-W).

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Since early 1973, wind pressures have been monitored on four levels, 102 m, 138 m, 166 m and 202 m, as well as strains on selected spandrels and columns at the 51 m level, where a section change would optimize the sensitivity of strain measurements. The locations of eight pressure transducers at each level and the strain gauges are shown in Fig. 1.

In March 1975, three accelerometers were placed at 202 m, and in July 1977 two more were installed at the 234 m level along with an apparatus to measure displacements relative to a laser beam projected from the bottom of the elevator shaft at the -15 m level. Figure 2 shows the displacement sensor consisting of two pairs of photocells that are "locked" to the stationary laser beam by means of servomotors while the rest of the instrument moves with the building.

A total of 48 channels, representing wind pressures, strains, accelerations, displacements, and wind speed and direction are sampled 20 times per second to record, on magnetic tape, sums, sums of squares and extremes for five-minute periods, at hourly intervals. In addition to these hourly summary records, any mean wind speed exceeding 18.5 m/s triggers continuous records 35 min long, with each channel sampled two times per second.

TYPICAL TIME HISTORIES

Figures 3 and 4 are time histories taken during a wind from E-N-E at 18.4 m/s. A weighted average of the net pressure differences in the E-W direction at the 202 m level is given in Fig. 3a. The resulting E-W displacement at the 234 m level (machine room) is shown in Fig. 3b; the same record, low-pass filtered at 0.05 Hz (the quasi-static portion), is presented in Fig. 3c and corresponds to the major pressure variations in Fig. 3a. The filtered time histories were obtained by computing the discrete Fourier Transform of the signals, rejecting all frequency components outside the desired frequency band, and inverting back to the time domain. The final one fifth of the calculation record length was tapered off to zero with a cosine weighting function to provide an inversed filtered signal with no discernible leakage.

The associated plots of pressure, displacement and filtered quasi-static displacement for the N-S direction are presented in Figs. 4a, b and c, respectively. Again there is over-all agreement between pressure and quasi-static displacements.

Figure 4d shows the mean difference of strains at locations 815 and 818 on the spandrel beams (Fig. 1). This trace agrees very closely with the N-S displacement in Fig. 4b. Similar close agreements were found between the E-W displacement and the mean of strains at locations 809 and 814 on the interior flanges of the columns (Fig. 1). The N-S acceleration on the 50th floor is presented in Fig. 4e.

A plot of the displacement components in the horizontal plane for a 1 min portion of record HW 861 is shown in Fig. 5. This method of presenting the results demonstrates the spatial variation in the building movement which is not readily apparent in the display of the separated axial components shown in Figs. 3b and 4b.

The power spectrum in Fig. 6 was formed by averaging four successive spectra of N-S acceleration and shows a number of closely spaced frequency components that are attributed to an amplitude dependence of the modal frequency. This is further supported by the data in Table 1, which gives dominant frequencies and corresponding wind speed. A decrease in frequencies for all three lowest modes is evident for increasing wind speeds.

The variability of natural frequencies caused problems in estimating modal damping values. The widening of resonance peaks as a result of frequency changes would increase the computed damping values unjustifiably. Closely spaced resonance peaks produced a typical "beating" of the envelope of peak amplitudes in the autocorrelation function. The only satisfactory damping calculation so far has yielded a value of one per cent of critical, but further investigation is under way.

TABLE 1

Variations of Modal Frequencies with Wind Speed

Record No.	Wind Speed, m/s (averaged over 35 min)	Direction	Frequency of Lowest Mode, Hz		
			N-S	E-W	Torsion
HW 875	8.2	S-W	0.139	0.139	0.180
HW 861	18.4	E-N-E	0.125	0.125	0.174
HW 845	18.3	S-W	0.125	0.127	0.173
HW 883	30.9	S-W	0.117	0.118	0.165

DISCUSSION OF PROTOTYPE MEASUREMENTS

A comparison of the displacement results with the pressures shows a qualitative agreement with major building motion in both the E-W and N-S axes. Some differences can be expected, however, since the pressures displayed are the net resultant of the weighted average from transducers at the 202 m level only. As the pressures are not fully correlated across the width and the height of the building, some errors are introduced by the averaging scheme.

The displacement measurements are themselves subject to some errors; among them are base rotation and thermal interference of the laser beam. The amount of base rotation is thought to be very small since the building is founded on a competent shale. The filtered signals also show that the resolution of the displacement measuring device is better than 2 mm, which includes deviations of the laser beam caused by thermal air currents.

The major excursions and the standard deviations of the filtered first mode displacements and accelerations were compared to check the consistency of the measurements and were found to agree within 6 per cent. Unfortunately, in addition to registering accelerations, the accelerometers responded to a small but as yet undetermined local rotation about a horizontal axis.

FULL-SCALE AND MODEL DISPLACEMENTS COMPARED TO BUILDING CODE PREDICTIONS

It is expected that continuous monitoring of the building will eventually provide enough records of strong winds from each of several directions to permit a thorough assessment of the accuracy of displacements predicted from wind tunnel tests and the analytical procedures referred to in building codes. For example, data logged from late September 1977 to the end of January 1978 included 68 segments of five-minute duration for which the mean reference pressure at the anemometer (286 m above ground) exceeded 50 N/m^2 with the wind directed approximately perpendicular to the east face of the building. This set of 68 segments was supplemented by 16 two-minute segments taken from a single windstorm from the east when the mean reference pressure ranged from 250 to 450 N/m^2, to form the basis for a first comparison with wind tunnel data and with calculations of the detailed procedure of Supplement No. 4 to the National Building Code of Canada.[1]

The wind tunnel tests for the building design provided mean and fluctuating displacements for 23 wind directions, at four different wind speeds.[2] The lowest speed, when converted to a mean reference pressure at 286 m for the fundamental frequencies of the actual building, represented 360 N/m^2 for along-wind and 460 N/m^2 for across-wind motion. The difference arises because the ratios of E-W to N-S frequencies were not the same in model and prototype. No correction was made for either damping or building density.

The detailed procedure in Supplement No. 4 for calculating along-wind and across-wind accelerations includes an expression for displacement in terms of lateral loading, fundamental frequency in bending, building dimensions and density; moreover, the ratio of standard deviation of along-wind displacement to mean displacement forms part of the computation of the gust effect factor. This permitted a three-fold comparison between observations and computed displacements as shown in Figs. 7a, b, c: along-wind mean, along-wind standard deviation and across-wind standard deviation of displacement.

The wind tunnel mean and standard deviation of along-wind displacements lie slightly above the full-scale measurements (Figs. 7a and 7b), whereas the standard deviation of across-wind displacement for the wind tunnel result is close to the central tendency of the full-scale measurements (Fig. 7c). The displacements computed according to Supplement No. 4, on the other hand, agree well with the along-wind measurements and are somewhat high in the across-wind case.

CONCLUSION

The consistency of time histories recorded by various types of sensors gives confidence in the methods employed and points to the possible use of less complicated equipment for monitoring building displacements after calibration by direct measurement. At Commerce Court, where for practical purposes moderate to strong winds excite only the fundamental modes, the strain gauges at the 52 m level might be calibrated to give an adequate representation of displacement at the 234 m level, provided the strong correlation between strain and displacement demonstrated so far is maintained for a wide range of wind speeds and directions.

Good agreement was found between observed displacements and those calculated according to Supplement No. 4 of the National Building Code of Canada, provided that the observed natural frequencies of the building were used in the calculations. Wind tunnel data, which had been adjusted for building frequency, correlated well with the observed motion.

Accurate estimates of frequency are essential for the success of any procedure for predicting building response, and it is important that the values used be applicable to the wind speed of interest. In view of the observed dependence of building frequency on wind speed, it is concluded that buildings must be monitored for as wide a range of wind conditions as possible.

ACKNOWLEDGEMENTS

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FIGURE CAPTIONS

Fig. 1 Plan View of Instrumentation Layout

Fig. 2 Laser Tracking Device for Displacement Measurements

Fig. 3 Time Histories of E-W Building Response

a) Pressure at 202 m level

b) Displacement at 234 m level

c) Filtered displacement at 234 m level

Fig. 4 Time Histories of N-S Building Response

a) Pressure at 202 m level

b) Displacement at 234 m level

c) Filtered displacement at 234 m level

d) Strain on spandrel beams at 51 m level

e) Acceleration at 202 m level

Fig. 5 One-minute Path Followed by Centre of Building (squares at 0.5 s intervals)

Fig. 6 Power Spectrum of N-S Acceleration at 202 m level

Fig. 7 Comparison of Prototype and Wind Tunnel Model with Code Calculation

a) Mean of along-wind displacements

b) Standard deviation of along-wind displacements

c) Standard deviation of across-wind displacements

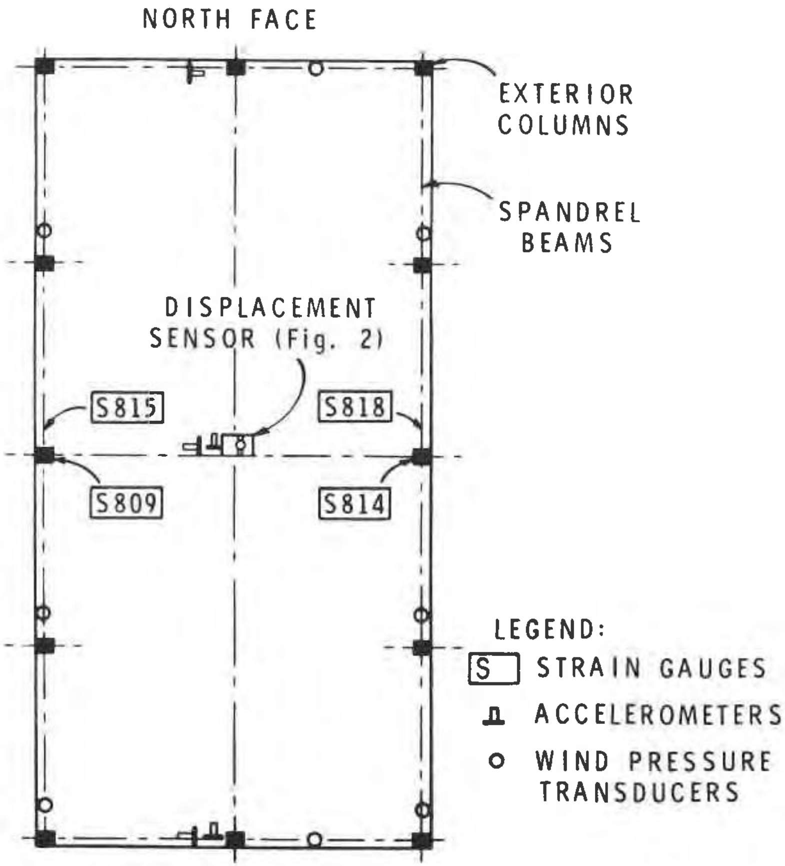


FIG. 1: PLAN VIEW OF INSTRUMENTATION LAYOUT

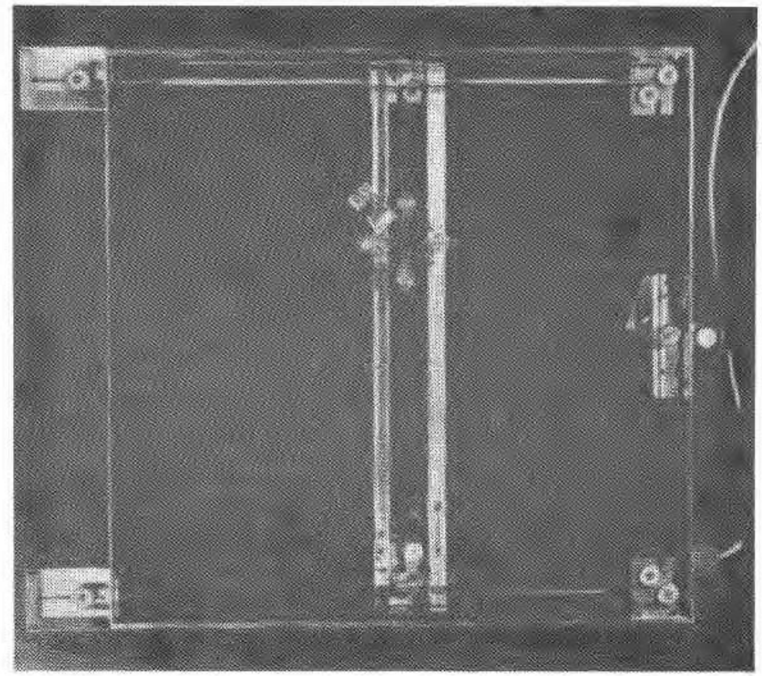
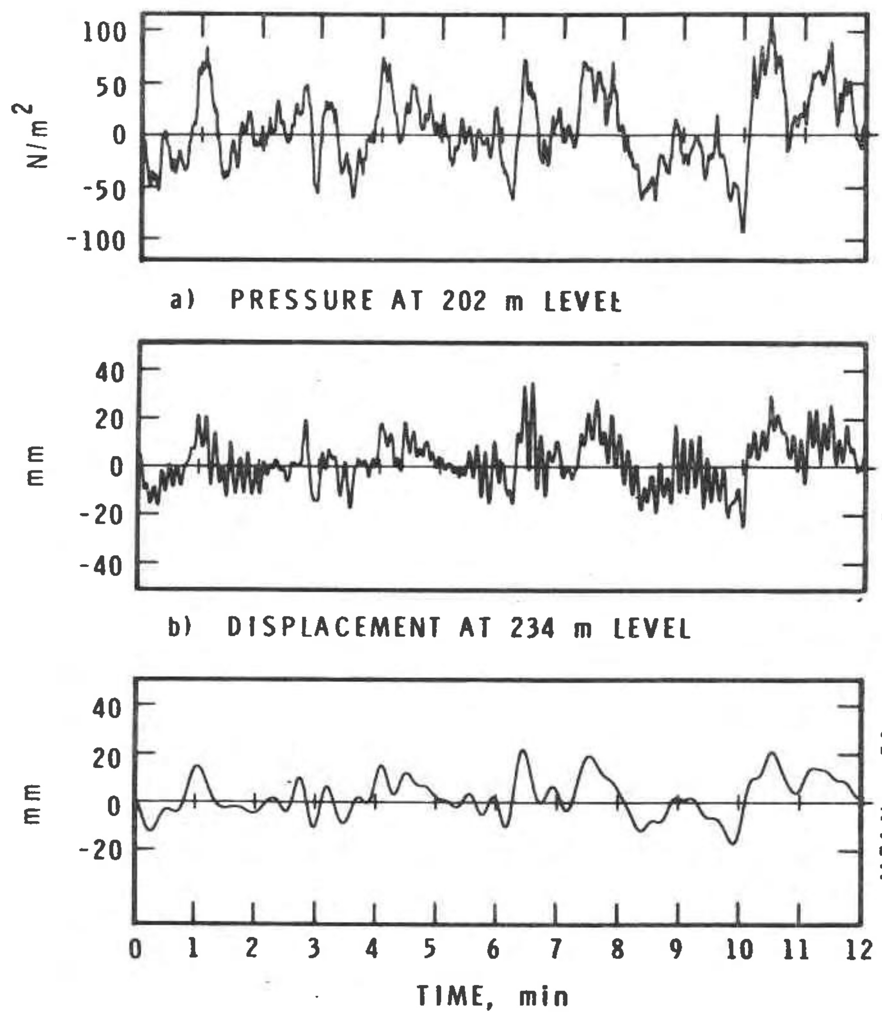


FIG. 2: LASER TRACKING DEVICE FOR DISPLACEMENT MEASUREMENTS



a) PRESSURE AT 202 m LEVEL

b) DISPLACEMENT AT 234 m LEVEL

c) FILTERED DISPLACEMENT AT 234 m LEVEL

FIG. 3: E-W BUILDING RESPONSE FOR WIND FROM E-N-E AT 18.4 m/s

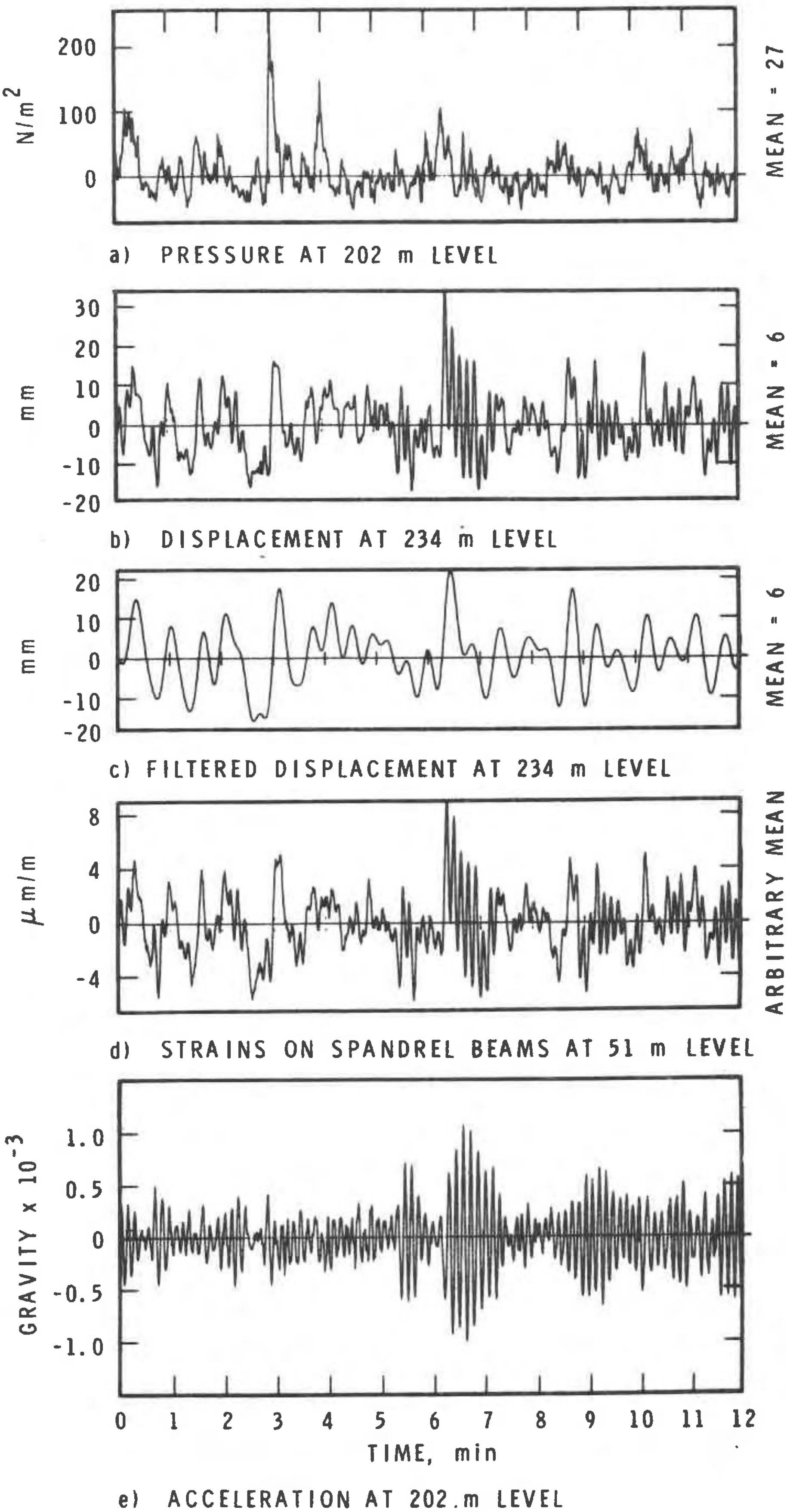


FIG. 4: N-S BUILDING RESPONSE FOR WIND FROM E-N-E AT 18.4 m/s

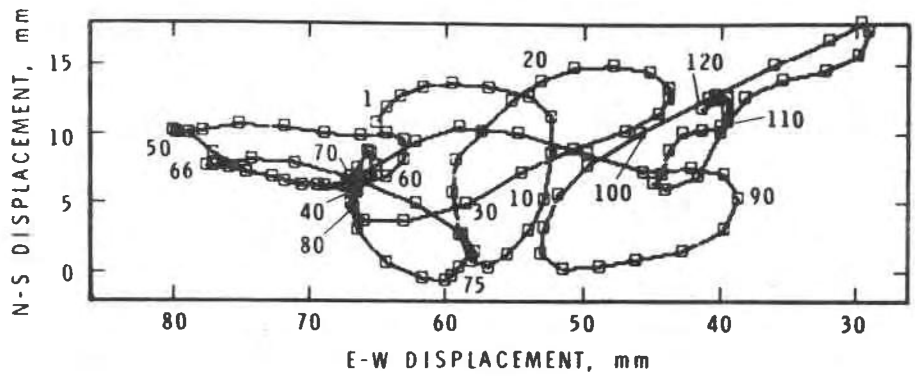


FIG. 5: ONE MINUTE PATH OF BUILDING CENTRE (SQUARES AT 0.5 s INTERVALS)

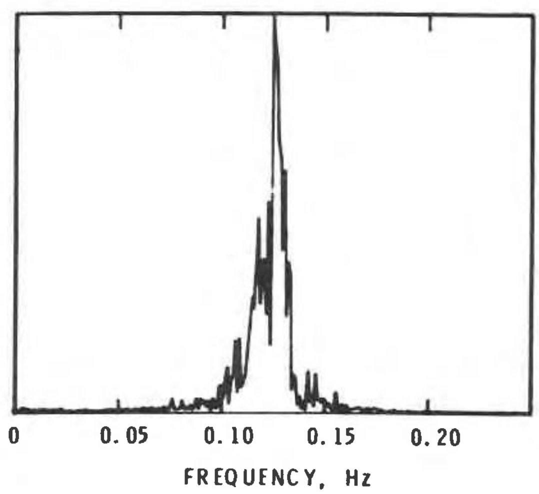


FIG. 6: POWER SPECTRUM OF N-S ACCELERATION AT 202 m LEVEL

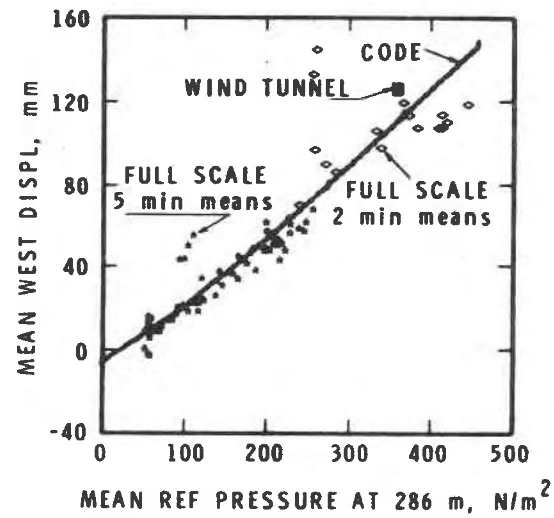


FIG. 7a) MEAN OF ALONG-WIND DISPLACEMENTS

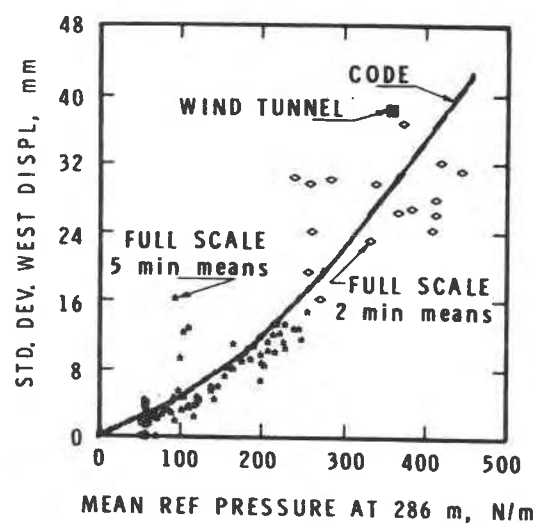


FIG. 7b) STANDARD DEVIATION OF ALONG-WIND DISPLACEMENTS

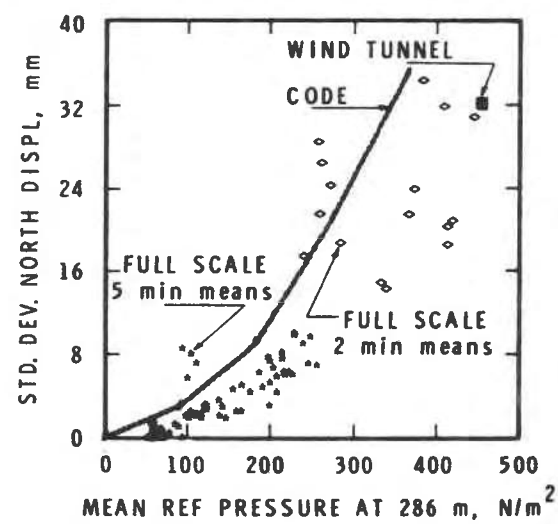


FIG. 7c) STANDARD DEVIATION OF ACROSS-WIND DISPLACEMENTS