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CN Tower, Toronto: Model and Full Scale Response to Wind

Essais sur modèle et comportement réel au vent de la Tour CN, Toronto

CN Tower, Toronto: Berechnungsmodell und gemessenes Verhalten unter Windbelastung

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SUMMARY
The design of the 555 m high free standing CN Tower in Toronto for the action of wind was based on the findings of a comprehensive wind tunnel model study. This paper presents an overview of that study and provides comparisons with actual observations. The program of full-scale measurements, started in 1976, has provided information on properties of the wind and the response of the tower. The comparisons, although limited, are favourable and lend confidence to wind tunnel modelling techniques.

RESUME
Le projet de la tour CN à Toronto, de 555 m de hauteur, a été réalisé sur la base d'une étude approfondie et d'essais aérodynamiques sur modèle. Les résultats de l'étude sont présentés et comparés avec les mesures effectuées sur la tour. Le programme de mesures en vraie grandeur, commencé en 1976, donne des informations sur les caractéristiques du vent et le comportement de la tour. Les comparaisons, bien que limitées, sont positives et favorables aux techniques utilisées pour les essais en soufflerie.

ZUSAMMENFASSUNG
Die Berechnung des 555 m hohen, frei stehenden CN Tower in Toronto für Windbelastungen basiert auf den Erkenntnissen aus umfassenden Modellversuchen im Windtunnel. Dieser Beitrag gibt eine Übersicht über die Resultate dieser Versuche und enthält Vergleiche mit Messungen am Bauwerk. Das umfassende Messprogramm, gestartet 1976, lieferte Informationen über die Windeigenschaften und über das Verhalten des Turmes. Die Vergleiche, wenn auch begrenzt im Umfang, sind vielversprechend und stärken das Vertrauen in Modellversuche im Windtunnel.

1. INTRODUCTION

The approximately 555-m high CN Communications Tower in Toronto has now been operational for nearly a decade. The action of wind on this unique tower, which remains the world's tallest free standing structure, was extensively studied in a wind tunnel model study, carried out at the Boundary Layer Wind Tunnel Laboratory during the design of the tower. This study provided information on the overall wind loads and responses of the structure, the action of wind on various components, and its effects on the tower performance including transmission quality. A program of monitoring and recording the wind induced response of the tower and some meteorological data was started in 1977. Participants in this co-operative study included the Department of Civil Engineering at the University of Toronto, the Atmospheric Environment Service of Environment Canada, the Division of Building Research of the National Research Council and the Boundary Layer Wind Tunnel Laboratory (BLWTL).

This paper describes the wind tunnel model studies carried out for this tower with emphasis on the aeroelastic simulation. An overview is provided of the program of monitoring and recording of the wind induced response of the full scale tower and some properties of the wind. Finally, this paper presents some results of the full scale program along with comparisons obtained from the wind tunnel model study. The analysis of the full scale data is continuing and the presented information is of an initial rather than a comprehensive nature.

2. WIND TUNNEL MODEL STUDIES

A comprehensive program of wind tunnel model studies was carried out to provide information on various wind related questions affecting the design of the structure. This program continued over a period of some 6 years and included the following main parts:

i) Aeroelastic and section model wind tunnel tests were carried out to evaluate an earlier version of the tower. It was subsequently replaced by the present tower configuration which was found to be aerodynamically and economically more effective.

ii) An aeroelastic model simulation of the tower was carried out at a geometric scale of 1:450 in turbulent boundary layer flow conditions representative of wind at the project site from various compass directions. This part of the study defined the wind loads on the concrete shaft and the steel antenna and provided information on the wind induced response of the tower. This included data on the displacements and rotations of the antenna mast and the accelerations of the tower at the restaurant and other levels.

iii) A static pressure model was tested at a geometric scale of 1:450 to provide information on the local peak pressures and suctions on the elevator shaft glazing, at the restaurant and upper observation levels and at the lower accommodation levels, including the pool lobby and other lower buildings at the tower base. It is noteworthy that some of the highest local exterior suctions found in the entire study occurred on the pool lobby.

iv) A limited study of pedestrian level winds at the base of the tower was made using the pressure model of the tower and lower accommodation levels. These measurements indicated relatively high wind speeds, particularly near the three tapered legs of the shaft.

v) A partial model of the upper accommodation levels and adjacent parts of the shaft was studied at a geometric scale of 1:60 to examine the action of wind on the air-supported radome enclosing the microwave transmission equipment just below restaurant level. The radome was modelled aeroelastically and information was provided on the internal pressurizaton required to limit deformations and assure its performance at high wind speeds.

vi) Analytical estimates were made to evaluate the effectiveness of two tuned mass dampers attached to the antenna mast. These two auxiliary mass absorbers were designed to ensure a minimum level of damping in the second, fourth and fifth modes of vibration of the tower. While the aeroelastic model study did not indicate excessive movements of the antenna mast, these dynamic absorbers were added to increase the reliability of performance.

vii) Some initial observations of the full-scale response were made during the construction of the tower. These measurements provided important validations of assumed tower properties. The most significant of these were made after the completion of the concrete shaft. These confirmed the structural damping used in the aeroelastic model study and the anticipated mass and stiffness properties.

viii) Meteorological data for the Toronto area were analysed to arrive at a statistical model of the probability distribution of gradient wind speed and wind direction for the area. This model provided an estimate of the probability of exceeding particular levels of wind speed from different azimuth directions and was used in the synthesis of the wind tunnel model findings to provide predictions of various wind induced full scale effects.

Only the aeroelastic model simulation is discussed in further detail at this time. A photograph of the 1:450 scale aeroelastic model mounted in the wind tunnel is shown in Fig. 1. The aeroelastic model was designed to simulate the exterior geometry of the tower and its stiffness, mass and damping properties. Details of aeroelastic similarity requirements are described elsewhere (1,2,3). Aeroelastic similarity was achieved by maintaining the equality of the following non-dimensional ratios in model and in full scale:

mass scaling:
$$\frac{\rho_s}{\rho} = \frac{\textit{inertia forces of tower}}{\textit{inertia forces of flow}} \tag{1}$$

stiffness properties:
$$\frac{EI}{\rho\, V^2\, L^4} = \frac{\textit{elastic forces of tower}}{\textit{inertia forces of flow}} \tag{2}$$

damping:
$$\zeta_s = \frac{\textit{dissipated forces in tower}}{\textit{inertia forces of tower}} \tag{3}$$

where ρ_s, ρ, E, I, V, L and ζ_s are representatively the bulk density of the tower, the air density, the elastic modulus or equivalent, the second moment of area the wind speed, a characteristic length and the structural damping expressed as a proportion of critical damping. Gravity forces were not modelled as the stiffness of the tower is dominated by elastic forces. The velocity scale, determined by the maximum speed of the wind tunnel and practical considerations of satisfying equation (2), was 1:5. This established the time scale at 1:90. The aerodynamics of the tower are largely determined by its sharp edged geometry and Reynolds number scaling was not a major consideration.

The model was constructed using a metalized epoxy commercially available under the trade name Devcon A. This material has a low modulus of elasticity and values of a density and damping comparable to those of concrete. The model tower was con-

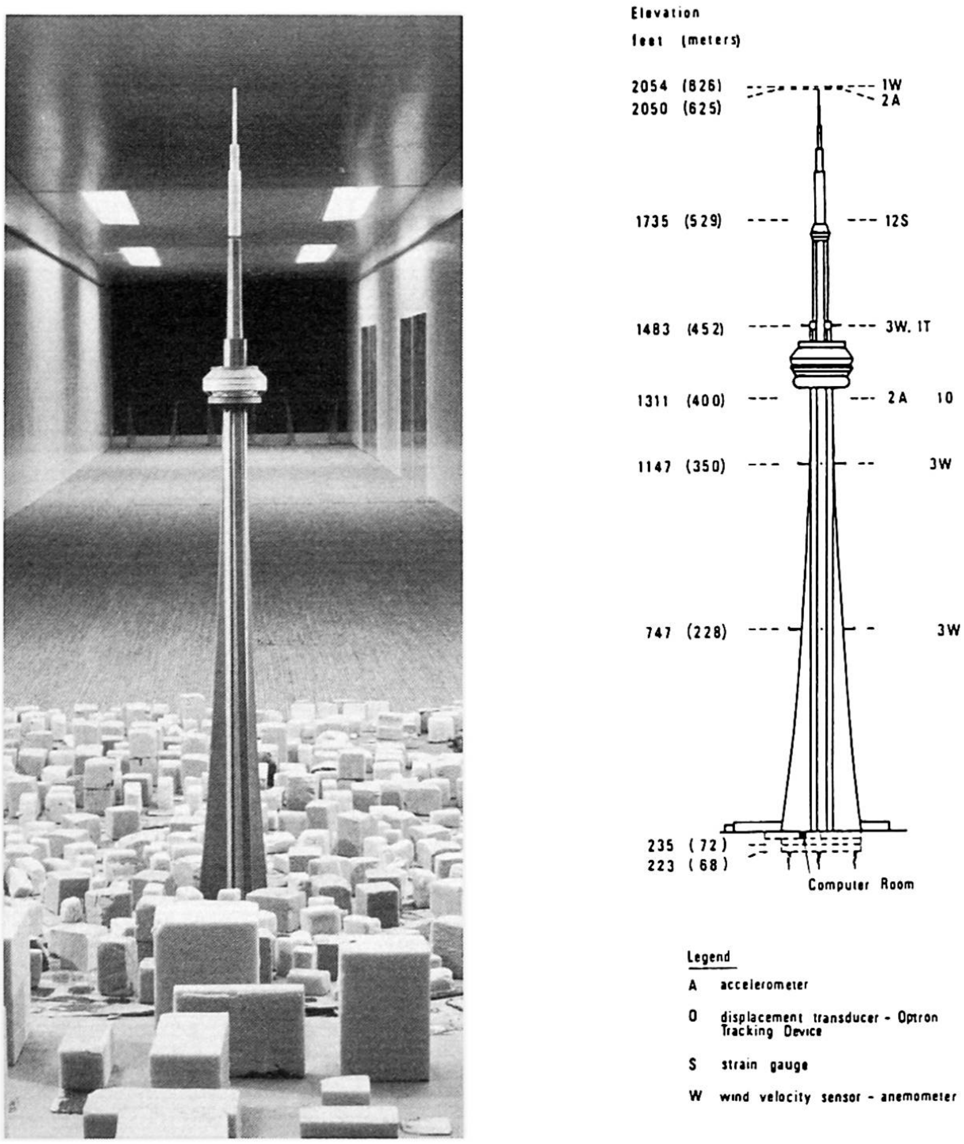

Fig. 1 **View of Aeroelastic Model of Tower in Wind Tunnel and Summary of Full Scale Wind and Response Sensing Instrumentation of Full Scale Tower**

structed using sheets of Devcon A precast to the correct thickness. These sheets, with a thickness as low as 0.25 mm in some cases, were cut and glued to form the shape of the tower shaft. The structural properties of the antenna mast were simulated by a specially fabricated spline using aluminum and hypodermic tubing. This spline was enclosed by non-structural radomes made of styrofoam to the correct exterior dimensions.

The instrumentation of the aeroelastic model included a strain-gauged balance capable of measuring the static and dynamic overturning and torsional moments at the base of the tower; accelerometers at the restaurant level; and strain-gauges on the antenna spline which measured the overturning moments at the base of the antenna mast in two orthogonal directions. The model was tested in turbulent boundary layer flow conditions representative of natural wind at the project site for a full range of wind directions and a range of wind speeds. In most of the tests model wind speeds simulated full scale values up to about 55 m/s (125 mph). Higher wind speeds were examined in selected cases.

3. OVERVIEW OF FULL SCALE MONITORING PROGRAM

The instrumentation used to measure the properties of the wind and the tower response is summarized in Fig. 1. Bendix-Friez anemometers and directional vanes are located at elevations of 228, 350, 452 and 626 metres. The top level has a single anemometer. The other levels have three anemometers each located on a boom extending 9.1 m (30 ft) beyond the end wall of each of the three tapered legs. Other instrumentation shown in Figure 1 include accelerometers at elevations of 400 and 625 m, an Optron tracking device at an elevation of 400 m and strain-gauges on the antenna mast at an elevation of 529 m. Details of other instrumentation, including other strain-gauges, gas analyzers and temperature probes, can be found elsewhere (4,5,6). The data acquisition and recording system was capable of sampling 80 channels of data continuously at a rate of 5 Hz. In the normal operating mode, the sampled data are analyzed in real time and only 10 minute average data are logged on magnetic tape. During strong winds all data are recorded on magnetic tape. These two data bases are respectively referred to as "average" and "high speed" data. Details of procedures used and assessments of data reliability and quality can be found elsewhere (4,5,6,7). Not all of the instrumentation functioned reliably and the assessment of data quality has become an important aspect of data analysis.

3.1 Wind Structure

The anemometers at elevations 228, 350 and 452 m despite the 9.1 m booms, are within the aerodynamic influence of the tower and the measured wind speeds and directions must be corrected. Correction factors, which relate the recorded wind speeds and directions to ambient values were obtained from wind tunnel model tests at the BLWTL (8). While the top anemometer at elevation 626 m, has functioned throughout most of the program, the operation of the other anemometers has been intermittent. There are few "high speed" records for which all anemometer levels were operational. While "averaged data" have been used to examine the structure of the mean and turbulent wind (7), more high speed data are necessary before any conclusions can be drawn. Generally, the wind speed at the top anemometer is significantly higher than that at the 452 m and other levels. The intensity of turbulence at the top anemometer is significant. Typical values for winds over land and off-the-lake are about 10 and 5 percent respectively. A typical time history of the wind speed at the top anemometer is given in Fig. 2. A spectrum of the longitudinal component of turbulence, measured at the top anemometer, is presented in Fig. 3. The overall shape is seen to approximately follow the Davenport spectrum (9). The peak wave length in this case has been adjusted to give best fit to the measured data.

Trends to date suggest that the boundary layer at the tower location is significantly deeper than conventionally assumed. Unfortunately more detailed assessments must await further data. For example, there are suggestions that the top anemometer, assumed to require no corrections, may in fact for some wind directions be within the aerodynamic influence of the antenna top.

3.2 Overall Tower Response

Time histories of some of the tower responses during June 20th, 1980 are shown in Fig. 2. These records, taken over approximately 1 hour, are typical of the "high speed" tower data. The wind speed at the top anemometer and the east-west displacement of the tower, measured by the Optron system at the 400 m level, are shown for the full duration of the record. Five minute portions of the wind speed and displacement records are shown at an expanded time scale. Also shown, are the east-west and north-south accelerations at the 400 m level.

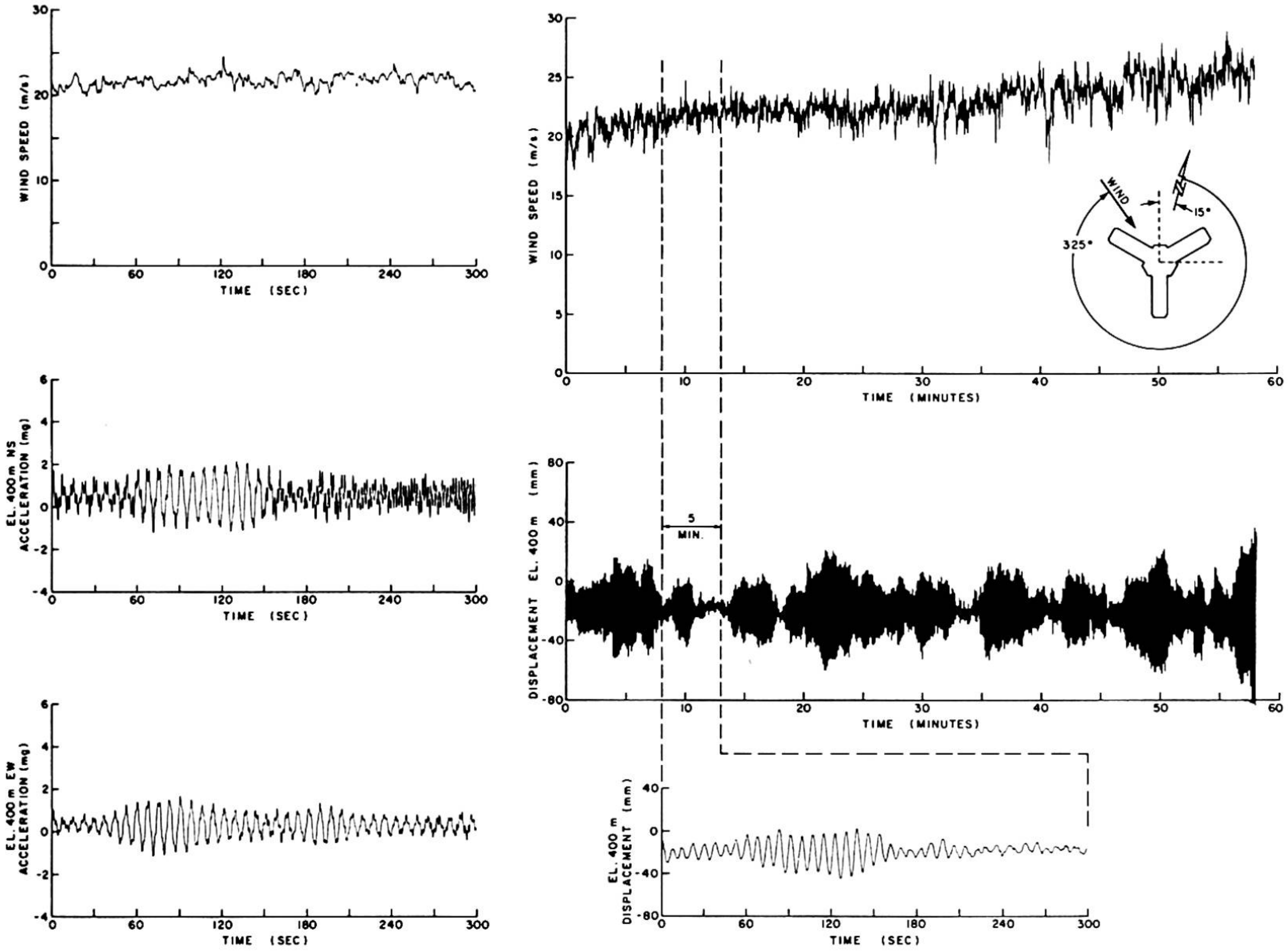

Fig. 2 Time Histories of the Wind Speed at Top Anemometer and Some Tower Responses During June 20, 1980

The wind speed is seen to increase somewhat over the length of the record. Loss of stationarity becomes a concern for longer records. This poses difficulties for spectral analysis as longer records are required to achieve a proper resolution and to reduce statistical variability. Of the various measures of the tower response, the accelerometers at the 400 m and the 626 m levels are found to provide the most reliable measures of the wind induced response. The Optron record, shown in Fig. 2, had to be adjusted in order to correct for instrument drift. The measured displacement is also sensitive to temperature variations. For example, on sunny days there is a pronounced diurnal movement of the tower which follows the sun.

Examining the expanded time history of the tower displacement, the dynamic response is seen to be predominantly in the fundamental mode of vibration. This is consistent with the findings of the aeroelastic wind tunnel study which showed that the wind induced dynamic response of the concrete shaft primarily comprised oscillations in the fundamental mode of vibration. Higher modes of vibration, however become significant for the movements of the antenna mast. Spectra of a number of wind tunnel model and full scale responses are shown in Fig. 4. As seen from the spectra of the base bending moments, both the along wind and across wind dynamic responses of the tower shaft are principally in the fundamental mode of vibration. Spectra of the antenna base moment measured in the aeroelastic study, however indicate significant contributions from higher modes of vibration. The overall behaviour of the tower, predicted by the aeroelastic model, is generally confirmed by the full scale tower data. Spectra of the acceleration at the 400 m level and strain gauges near the antenna are in

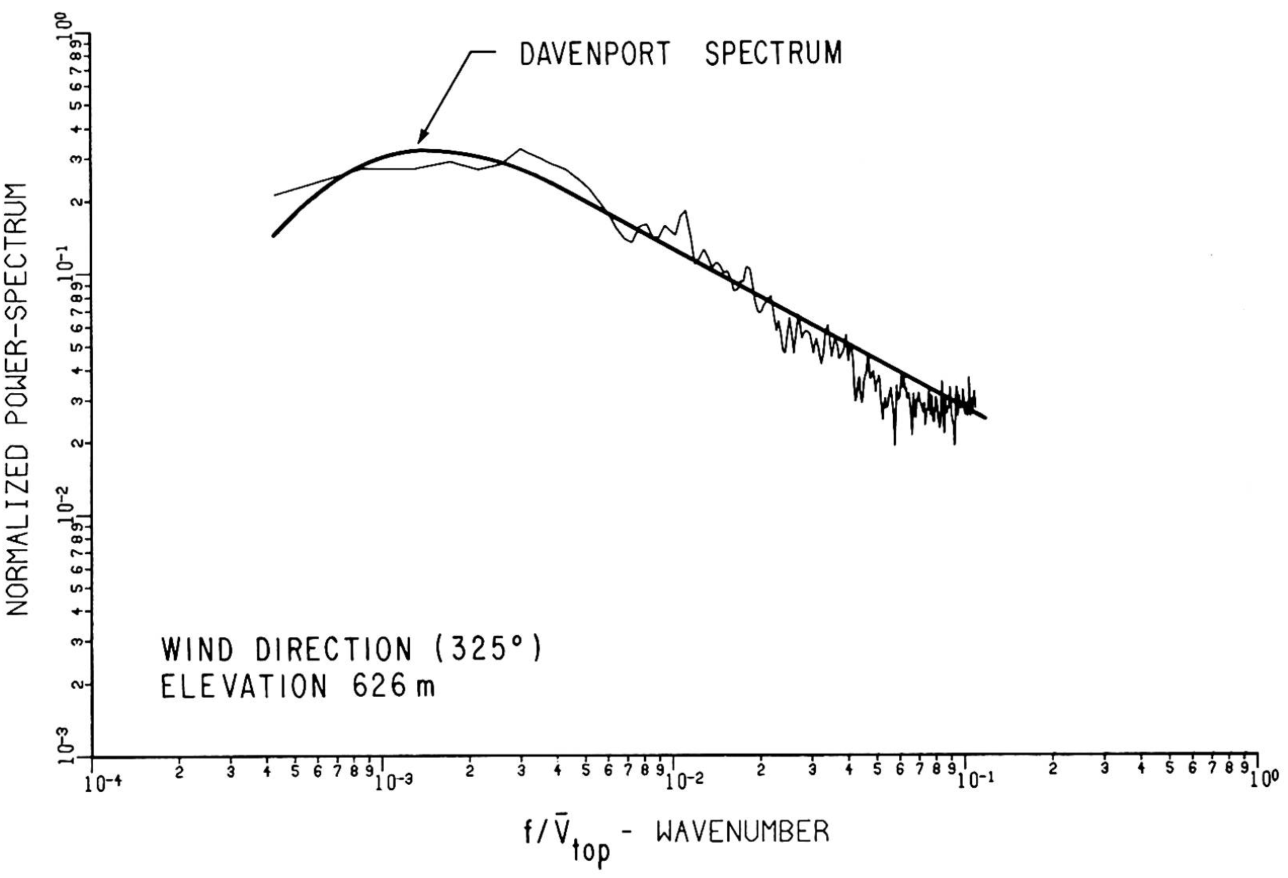

Fig. 3 Power Spectrum of Wind Speed at Top Anemometer During June 20, 1980

general agreement with the model study. As seen from the spectra of the accelerations at elevation 626 m, the higher modes of vibration become important near the top of the antenna. The dynamic response of the tower in the along-wind direction is found to be greater than that in the across-wind direction. This confirms aeroelastic model tests which indicated that the drag response dominated for wind speeds of practical interest.

Table 1 summarizes the frequencies of the tower in its first seven modes of vibration. This includes analytical estimates carried out in 1974 with the final projected tower stiffness and mass data measurements of the frequencies of vibration of the tower near its completion in November of 1976. These measurements, made near the base of the antenna, did not indicate any contributions from the 3rd, 6th and 7th mode of vibration. Current estimates are also shown in Fig. 1. Generally, the observed frequencies agree well with analytical estimates which used projected tower properties. Extensive material testing and full scale observations at the completion of the concrete shaft (10) provided improved estimates of the tower properties. Measurements of the tower frequencies to-date have not indicated significant changes with time or with wind speed.

The damping of the structure in its fundamental mode of vibration was initially estimated to be in the range of .5 to .75 per cent of critical (10). Limited estimates of the damping so-far (7) indicate that the structural damping in the fundamental mode of vibration is somewhat below 1% of critical and the total damping including contributions of aerodynamic damping is in excess of 1%.

3.3 Comparisons of Wind Induced Accelerations

Comparisons of wind tunnel and full scale horizontal accelerations for selected

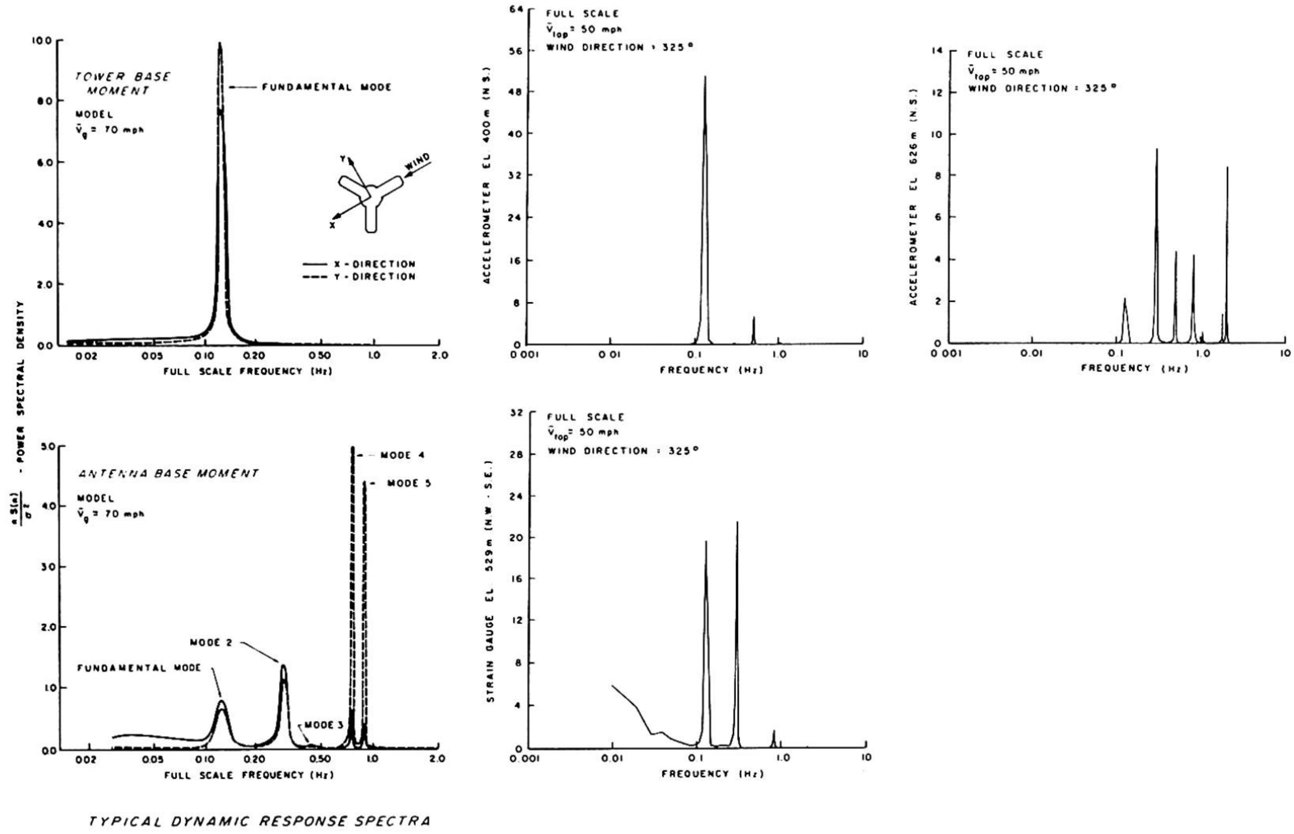

Fig. 4 **Some Response Spectra From Wind Model Study and Full Scale Observations**

TABLE 1

FREQUENCIES OF MODES OF VIBRATION OF TOWER

Mode of Vibration	Analytical Estimate (1)	Measurements Near Completion(2)	From Current Tower Data
1	.124	.129	.127
2	.266	.305	.298
3	.486	-	.483
4	.815	.838	.815
5	1.03	1.07	1.02
6	1.83	-	1.78
7	2.02	-	2.03

(1) Based on final projected tower properties in 1974.
(2) Taken on November 25, 1976 near base of antennna.

wind directions during the period of June 16 to June 22, 1980 are shown in Fig. 5. The comparison is based on the resultant RMS acceleration in both full scale and model. While there is considerable scatter in the full scale observations, the accelerations of the tower at both 400 and 626 m levels tend to approach the wind tunnel data at higher wind speeds. The lowest wind speed examined in the wind tunnel study corresponded to about 25 m/s at gradient height.

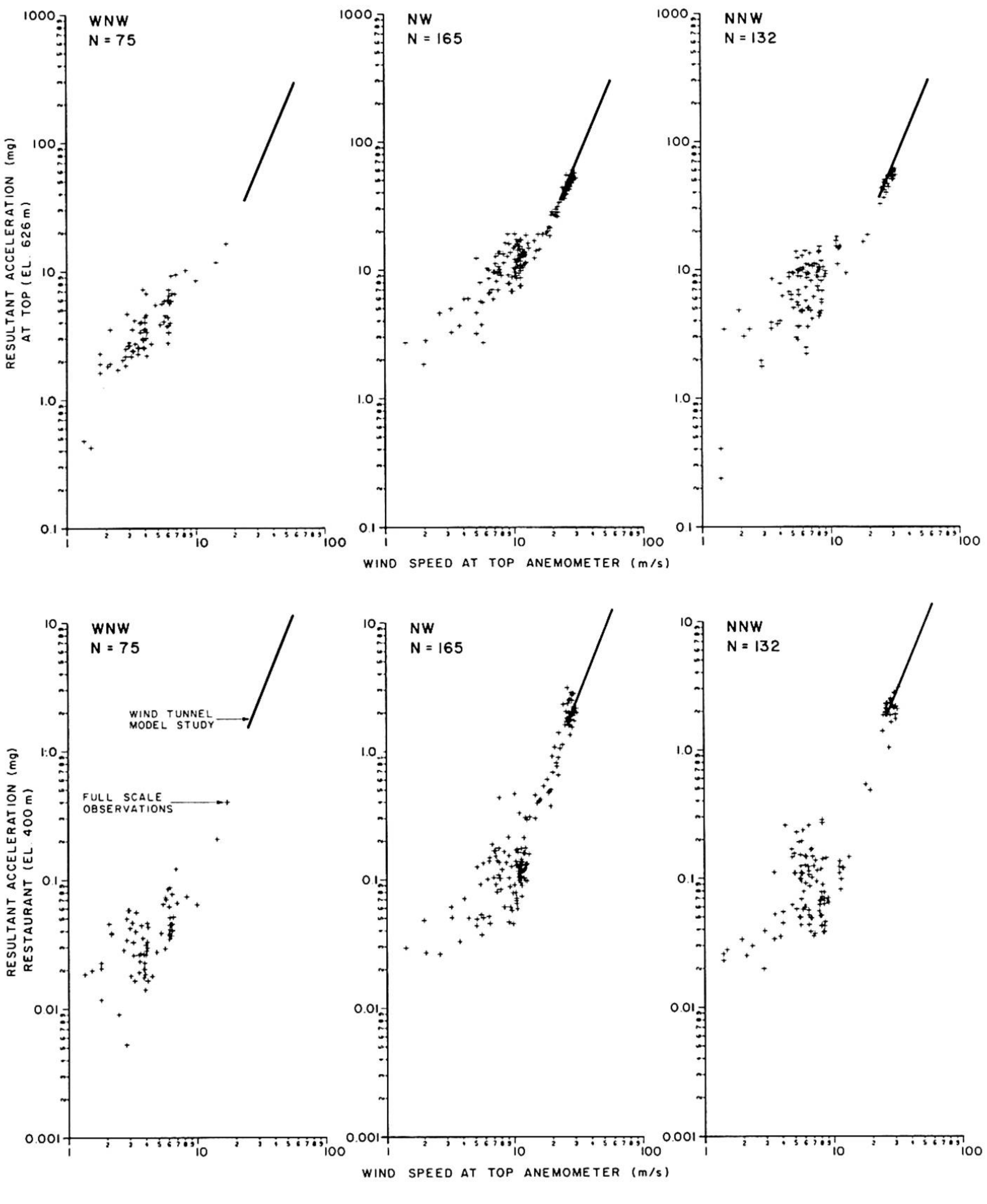

Fig. 5 **Comparisons of Observed Resultant RMS Accelerations With Wind Tunnel Data**

Examining the individual components of the resultant acceleration, the drag accelerations are found to be dominant in both full scale and in the aeroelastic study. While the agreement with the aeroelastic study is good for the data shown in Fig. 5, other directions in particular from the south, showed less favourable agreement. This relates to the overall question of full scale data quality and must wait the analysis of further data before more complete comparisons with the aeroelastic study can be made.

4. CONCLUDING REMARKS

Although the full scale monitoring program has been operational for a number of years, data comparable to the findings of the wind tunnel model study are just now becoming available. Generally there appear to be no surprises in the observed response of the tower. Its dynamic properties tend to be consistent with its design values and indications so far suggest that the wind tunnel model study provided representative estimates of the wind induced response of the tower. Somewhat more unexpected are the properties of the wind. The boundary layer appears to be deeper and the turbulence intensity higher than conventionally anticipated.

Evaluations of the full scale tower response are complicated by difficulties with data quality. Work is currently in progress to improve corrections to the anemometer data to allow for aerodynamic influence of the tower and to generally assure the quality of the data.

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