THE DETERMINATION OF STRUCTURAL DYNAMIC PROPERTIES OF TWO BUILDINGS IN VANCOUVER, B.C. FROM AMBIENT VIBRATION SURVEYS

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ABSTRACT

The dynamic properties, namely the natural frequencies, mode shapes and damping values of two steel frame structures in downtown Vancouver have been obtained by means of ambient vibration surveys. Fourier spectra analyses of the recorded data were used to identify the natural frequencies and associated mode shapes of the test structures. Modal damping estimates were obtained by means of the autocorrelation and partial spectral moment methods. The results of the investigation are presented in graphical and tabulated form.

INTRODUCTION

The Canadian National Committee for Earthquake Engineering (CANCEE), which is a National Research Council (NRC) Advisory Committee dealing with the earthquake provisions of the National Building Code, has proposed the use of "benchmark or reference" structures for monitoring the effect of proposed changes in these provisions on the seismic design of future structures. The benchmark structures are to be chosen from existing buildings, which are characterized by different lateral load resisting systems, construction materials and seismic risk locations. These buildings are to be tested experimentally to ascertain their dynamic characteristics - their natural frequencies, mode shapes and damping values. These properties play an important role in determining the response of a structure to earthquake excitation.

Some of the buildings chosen to be benchmark structures are located in Vancouver. The experimental study described in this paper was undertaken in order to measure the ambient vibrations (1) of two of these buildings, and from this data to determine their dynamic properties. This report describes the procedure by which this was done and presents the results obtained.

The measured quantities ultimately are to be compared with the values determined from theoretical analyses of mathematical models of the structures, in order to validate the assumptions made in defining the models, or to suggest ways of revising these assumptions. Only the experimental phase of this total program is reported herein.

MEASUREMENT PROGRAM

Two main instrumentation systems were used in this investigation, herein referred to as the Earthquake Engineering Laboratory System (EEL-system) and the Geophysics System (GEO-system). The EEL-system consists of four Ranger SD-217 seismometers, a Teledyne SC 201 signal conditioner fitted with displacement, velocity and acceleration filter cards all having a cut-off frequency of 100 Hz, a Philips ANA-LOG 7 FM/AM tape recorder and a Tektronix oscilliscope and chart recorder for visual display. The velocity filter cards were found to produce the best results in the field and were therefore used throughout the measurement program. As explained subsequently, the frequencies of the tested structures were determined from measurements taken at or near their roof levels. At these heights the ambient vibration motions have reasonable amplitudes for all modes of interest. The EEL-system was used to record this 'frequency' data and, as well, the data to define the mode shape amplitudes at various locations along the heights of the buildings.

The GEO-system contains two Willmore Mark II seismometers, amplifiers with low pass filters having cut-off frequencies of 12.5 Hz, an H.P. 3960 Instrumentation tape recorder and a Brush 222 chart recorder for visual display. It was used primarily to obtain long time history records of the building vibrations. These long recordings serve to provide stable Fourier spectra for damping estimates and at the same time offer an independent check of the natural frequencies measured with the EEL-system. The recorded data for evaluating modal damping values were also secured at the upper levels of the buildings.

Ambient Vibration Survey of the Toronto Dominion Bank Tower

The Toronto Dominion Bank Tower (T/D) is located on the south side of Georgia Street at Granville. It is a 33-storey steel structure with a 3 bay x 5 bay moment resisting ductile space frame capable of withstanding all of the design horizontal loads. The building's plan dimensions are 150' x 110' and it rises to a height of about 445'. There is a machine room on the roof, and a mechanical room on the 15 and 16 floor levels.

The four Ranger seismometers of the EEL-system were first placed side by side and in the same direction on the 26th floor for the purpose of performing a "collocation calibration". This calibration is necessary to verify the relative magnitude and phase of the seismometer outputs (with all instruments measuring the same input). A similar calibration was also performed after the completion of each ambient survey.

The four instruments were then assembled in pairs in positions 1 and 2, Figure 1, to pick up torsional and flexural movements. To isolate the torsional and flexural frequencies (as well as to ascertain the phase relationship of vibration motion on different floors) simultaneous recordings, after digitization, were added and subtracted in turn before being transformed into the frequency domain. Torsional or out-of-phase signals will be enhanced after subtraction is performed; flexural or in-phase signals will be enhanced after addition is performed. Enhancement (or lack of it) is detected from the resulting change in amplitude of the Fourier spectra spikes defining the frequencies isolated.

After the frequency data had been secured the four Ranger seismometers were placed on various floors to record data used to define the mode shapes. These ambient vibration measurements were taken relative to a reference seismometer located on the 28th floor. The remaining three instruments were placed at various levels and in the same direction as this reference meter to record storey movements at the same time. The phase relationships of the storey movements relative to the reference point were found by a process of addition and subtraction of simultaneous digitized signals. The relative displacement amplitudes of the building were found by comparing the spectral amplitudes at the natural frequencies identified on the Fourier spectra, which were determined from Fourier Transforms of simultaneous recordings at various floors, with the corresponding amplitudes of the reference floor. The phase and relative displacements define the mode shapes. In Figure 1 the positions 4, 5 represent the locations of seismometers in two perpendicular directions on a particular floor.

The GEO-system was deployed on the 28th floor. The seismometers were located in positions similar to 1 and 2 for the purpose of determining the damping values, and as a backup to the EEL-system for evaluating the torsional and flexural frequencies.

Ambient Vibration Survey of the IBM Building

The IBM Tower is situated on the north side of Georgia Street at Granville. It is also a steel structure with a moment resisting ductile space frame. The building layout consists of 3 bays by 4 bays having plan dimensions of 110' and 120' respectively. It has 21 storeys and is about 320 feet tall.

Collocation calibration of the EEL-system was performed on the 18 floor and then recordings for frequency evaluation were taken with instruments on the 18th floor in positions similar to 1 and 2, Figure 1. The mode shape recording positions on a typical floor are approximately indicated by 4 and 5 in Figure 1.

In this test, the GEO-system was placed on the 18 floor and the transducers were positioned in locations resembling 1 and 2, Figure 1, to secure data for determining the damping and the natural frequencies of the structure in two perpendicular directions.

ANALYSIS OF MEASURED DATA

The recorded analog data were played back through an analog filter (low pass corner frequency at 15 Hz - there were no significant frequencies visible in the respective building signals above these limits) and digitized using an AN5800 A-D converter system modified for simultaneous sample and hold, a Kennedy 8108 9-track digital tape transport with Kennedy B203 buffered formatter. The sampling rate was 39.075 Hz with a Nyquist frequency in excess of 19.5 Hz. The digitized data had equal time intervals of .0256 seconds and were recorded on tapes compatible with UBC Computer facilities. The record lengths used in the analysis for frequency and damping estimates were between 25-40 mins.

Two steps were involved in the analysis of the digitized data.

Frequency and Mode Shape Determination

Building frequencies were determined from a frequency domain analysis of the measured motions. The bandwidth selected for the data analysis was 0.02 Hz. The predominant frequencies in a vibration record were identified from the spikes in its Fourier spectrum. The associated mode shape ratios were obtained by dividing the Fourier coefficients at each storey level by the Fourier coefficient of a selected reference level. The phase between any two levels was established by forming the sum and the difference of the digitized records for these levels. If both are in phase, they must show a higher spectral value for the sum than for the difference. Conversely, if the difference yields a greater value, then they are 180° out of phase. Similarly, to identify torsional modes, the difference of the records of two parallel seismometers at a floor level were taken to eliminate the translational modes and, as a check, the sum was used to subtract out the torsional modes. By comparing the two Fourier spectra thus obtained, the torsional frequencies were readily identified.

Damping Determination

Two different methods were employed to obtain estimates of the modal damping values, namely: the autocorrelation method, and the partial spectral moment method. The autocorrelation method can be applied to individual "well-defined" spectral peaks filtered out from the Fourier spectra. It yields a cosinusoidal function with exponential decay (2). The decay of the envelope of the autocorrelogram (the plot of the autocorrelation function) of the building's response to ambient vibration excitations was used to estimate the critical damping ratio of each mode by the log decrement method. In some modes the autocorrelograms may not damp in the expected manner and may oscillate irregularly (2); damping values are not reported in these circumstances. Since autocorrelation operates in the time domain, the process of transform/inverse-transform may cause some problems if no attention is paid to the limitations of the filtering process. These difficulties were minimized by incorporating a smoothing process in the computer program used for this damping estimation method.

The partial spectral moment method does not depend as much on a "well defined" spectral peak, as it involves the area and also the first and second spectral moments of the power spectral density within specified frequency limits. It is known to be more stable (3) than methods which depend on the ordinates of the spectral density; smoothing processes are not needed to refine the damping estimates obtained from "raw" spectral estimates. The partial spectral moment procedure provides, as well, an estimate of the natural frequencies. The method is sensitive to the cut-off frequency ratios; efforts were made to keep these ratios very close to unity.

PRESENTATION AND DISCUSSION OF RESULTS

The results of the data analysis are presented in graphical and tabulated form.

The Toronto Dominion Tower Test

Typical Fourier spectra from which the natural frequencies of the T/D Tower were established are shown in Figure 2. These values are summarized in Table 1.

The mode shapes associated with some of these frequencies are shown in Figures 3(a) to (c). It may be noted that the cross-over points for the second mode in both the N-S and E-W directions (Figures 3(a) and 3(b)) are located at a lower than typical building elevation. This is likely due to the existance of mechanical floors at the 15 and 16 storey elevations, resulting in a "softening" of the structure at these levels.

Theoretical natural frequencies and mode shapes of this building were available and provided by Professor Jean-Guy Beliveau (4) of Sherbrooke University. The theoretical frequencies also are given in Table 1 and the corresponding mode shapes in Figure 3. It can be seen that there is good agreement between the measured and computed fundamental flexural frequencies and that the low experimental cross-over points noted above are confirmed by analysis.

The critical damping values, ξ, for the T/D Tower, obtained by the autocorrelation and partial spectral moment methods, are reported in Table 2. An example, autocorrelogram is shown in Figure 4. The damping values evaluated by both methods are, in general, comparable as regards their order of magnitude. The values of ξ have been obtained from the records which gave the highest signal to noise ratio for the particular frequency concerned. The percentage lag is an important consideration in the autocorrelogram method (5), and sufficient lag time to produce a minimum of 5 peaks in the autocorrelogram was used. The lag time is the product of the lag number and the digitization interval (0.0256 sec.).

The partial moment method also gives (as output) a natural frequency based upon the spectral moment calculations. Frequencies determined by this method are also listed in Table 2. These frequencies can be compared with the frequencies reported in Table 1, which were detected from the Fourier spectra plots, and with which they agree. This indicates that the damping estimates obtained by this method are satisfactory (3).

The IBM Tower

The character of the ambient vibrations recorded for this structure is shown in Fig. 5. Figure 6 presents typical Fourier spectra for the IBM Tower. The natural frequencies identified from these spectra are summarized in Table 3. Corresponding mode shapes are drawn in Figure 7(a) to (c). Figure 8 shows a typical autocorrelogram obtained from the analysis. The damping values determined for this building are summarized in Table 4. The agreement between results evaluated by the various methods is again seen to be reasonable.

SUMMARY AND RECOMMENDATIONS

The principal results obtained from this investigation may be summarized as follows:

1. The objectives of this research - which was concerned with the determination of the natural frequencies, mode shapes and damping values of two buildings in Vancouver - were realized. There were no particular difficulties encountered with the tests or data analysis of the Toronto Dominion and IBM Towers.

2. The fundamental frequencies of the Toronto Dominion and IBM Towers were determined from ambient vibration measurements to be 0.26 Hz and 0.38 Hz respectively in the N-S direction, and 0.24 Hz and 0.42 Hz respectively in the E-W direction. The respective fundamental torsional frequencies were 0.83 Hz and 1.43 Hz. The T/D fundamental frequency agrees closely with the value reported in an existing analytical study.

3. The fraction of critical damping in the fundamental N-S mode for the Toronto Dominion and IBM buildings, as determined from the partial spectral moment method, was found to be 2.64% and 3.35% respectively. The corresponding E-W values were 2.15% and 3.12%. These low values are typical of results determined from ambient vibration tests. The damping estimates derived from the autocorrelogram process provided a confirmation of the order of magnitude of these figures.

4. Stable estimates of the Fourier spectra and autocorrelograms were achieved in this experimental program. The reported dynamic characteristics of the structures investigated by the ambient vibration survey can therefore be viewed with reasonable confidence.

5. It is recommended that theoretical analyses of mathematical models of all buildings tested in the overall CANCEE "benchmark" program should be carried out, and that the results should be compared with their measured dynamic properties. This comparison would serve to validate the assumptions made in defining the models, or to suggest ways of revising these assumptions.

ACKNOWLEDGEMENTS

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(3) E.H. Vanmarcke and R.N. Iascone, "Estimation of Dynamic Characteristics of Deep Ocean Tower Structures", MIT Sea Grant Project, June 1972.

(4) J-G. Beliveau, Private Communication.

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TABLE 1

MEASURED AND ANALYTICAL NATURAL FREQUENCIES OF T/D TOWER

DIRECTION	MODE 1 FREQ (Hz)	MODE 2 FREQ (Hz)	MODE 3 FREQ (Hz)
NORTH-SOUTH (flexural)	0.26 (0.27)*	0.75 (0.58)	1.89 (0.97)
EAST-WEST (flexural)	0.24 (0.22)	0.68 (0.48)	1.41 (0.77)
TORSIONAL	0.83	0.99	1.21

* ANALYTICAL VALUES SHOWN IN BRACKETS

TABLE 2

DAMPING VALUES FOR T/D TOWER

FREQ (Hz)	DIRECTION	ξ (% CRITICAL DAMPING)	
		AUTOCORRELOGRAM*	PARTIAL MOMENT
0.26	N - S (flexural)	——	2.64
0.75	N - S (flexural)	1.76	1.82
1.89	N - S (flexural)	——	2.92
0.24	E - W (flexural)	4.12	2.15
0.68	E - W (flexural)	1.54	2.42
0.99	Torsion	----	3.58

* PERCENTAGE LAG IS ABOUT 15%
---- Satisfactory plot not obtained.

TABLE 3

MEASURED NATURAL FREQUENCIES OF IBM TOWER

DIRECTION	MODE 1 FREQ (Hz)	MODE 2 FREQ (Hz)	MODE 3 FREQ (Hz)
NORTH-SOUTH (flexural)	0.38	1.20	2.14
EAST-WEST (flexural)	0.42	1.30	2.00
TORSIONAL	1.43	1.76	2.48

TABLE 4

DAMPING VALUES FOR IBM TOWER

FREQ (Hz)	DIRECTION	ξ (% CRITICAL DAMPING)	
		AUTOCORRELOGRAM *	PARTIAL MOMENT
0.38	N - S (flexural)	——	3.35
1.20	N - S (flexural)	2.19	0.78
2.14	N - S (flexural)	----	1.16
0.42	E - W (flexural)	3.62	3.12
1.30	E - W (flexural)	3.01	2.27
2.00	E - W (flexural)	——	1.12
1.43	TORSIONAL	2.37	2.52
1.76	TORSIONAL	3.61	3.54

* PERCENTAGE LAG IS ABOUT 15%
---- Satisfactory plot not obtained.

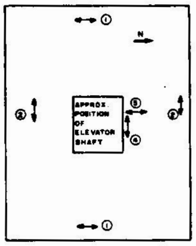

Fig. 1 TYPICAL FLOOR PLAN - T/D TOWER SHOWING SEISMOMETER LOCATIONS.

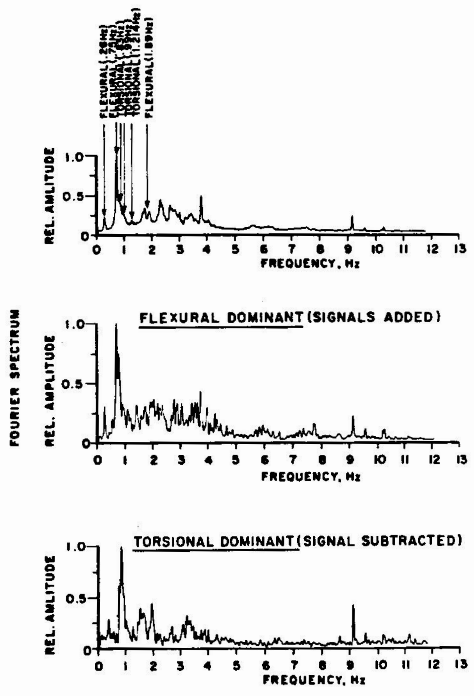

Fig. 2 FREQUENCY IDENTIFICATION: TORONTO DOMINION TOWER (N-S)

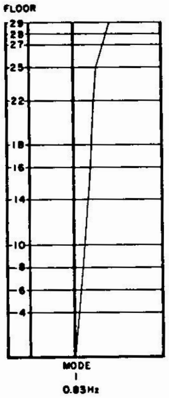

Fig. 3(C) TORONTO DOMINION BANK TOWER MODE SHAPE TORSIONAL

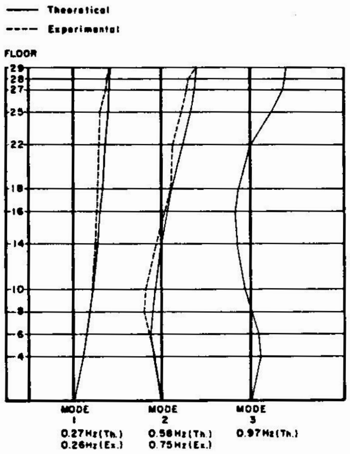

Fig. 3(A) TORONTO DOMINION BANK TOWER MODE SHAPES (NORTH-SOUTH) - FLEXURAL

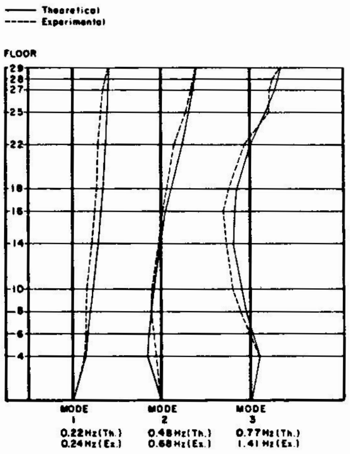

Fig. 3(B) TORONTO DOMINION BANK TOWER MODE SHAPES (EAST-WEST) - FLEXURAL

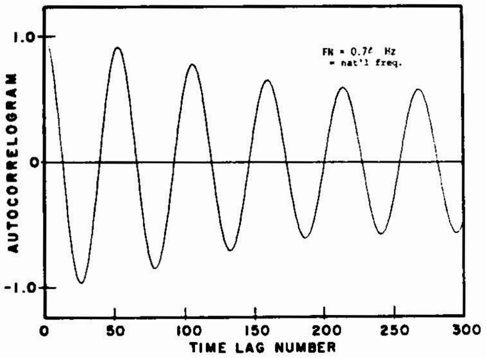

FIG. 4 TORONTO DOMINION TOWER (N-S)
AUTOCORRELOGRAM

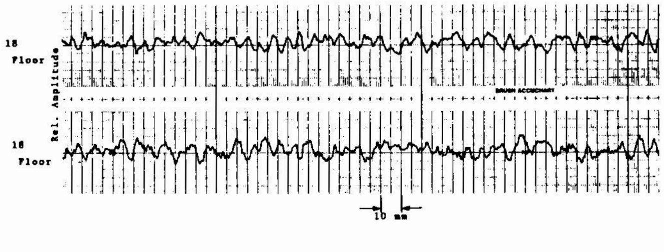

Chart Rate: 25 mm/s

FIG. 5 TYPICAL AMBIENT VIBRATION TRACES
IBM TOWER

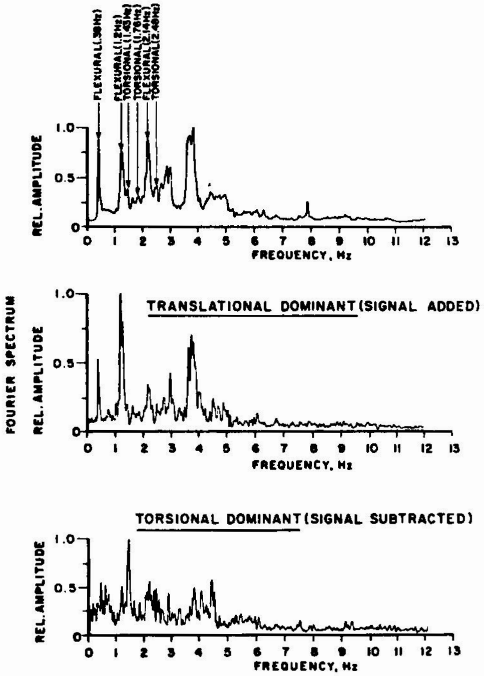

FIG. 6 FREQUENCY IDENTIFICATION: IBM TOWER (N-S)

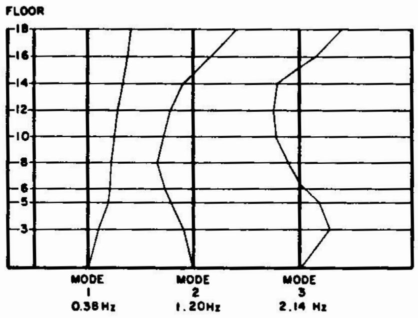

Fig. 7(A) IBM TOWER SHAPES (N-S) FLEXURAL

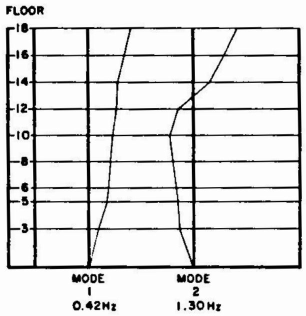

Fig. 7(B) IBM TOWER MODE SHAPES (E-W) FLEXURAL

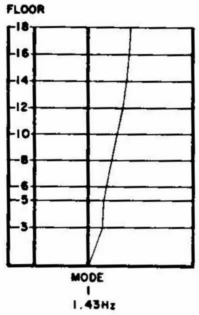

Fig. 7(C) IBM TOWER MODE SHAPE TORSIONAL

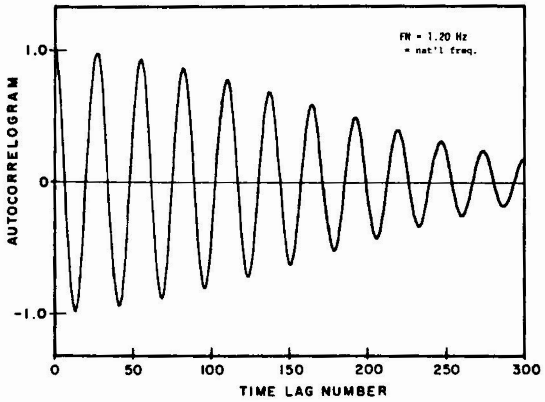

Fig. 8 IBM TOWER (N-S) AUTOCORRELOGRAM