Measurements of dynamic properties of tall buildings

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1. INTRODUCTION

Wind tunnel model testing has been an invaluable tool in the design of many tall buildings and structures, ranging from super tall signature buildings to large-scale public housing projects. The predicted design wind loads (including shear forces and base moments) and wind-induced responses (including deflections and accelerations) are very dependent on the predicted natural frequencies of vibration and particularly damping values. Despite significant advances in numerical modelling of structures using finite element methods (FEM), uncertainties remain in the prediction of the natural frequencies of vibration and particularly the damping values. These uncertainties can be critical in the prediction of the design wind load and building performance in terms of motion perception and occupant comfort assessment.

This paper describes the different test techniques employed to measure the dynamic properties of buildings and presents the results of tests on three buildings.

2. MEASUREMENTS OF DYNAMIC PROPERTIES OF TALL BUILDINGS

Test techniques involving ambient excitation, crane excitation and synchronised human excitation have been successfully employed to excite different types of structures from which the resultant vibrations are analysed to identify their dynamic characteristics (e.g., Glanville et al., 1996). Strong winds, including typhoon winds, occur frequently in Hong Kong and are a reliable source of ambient excitation for the measurement of dynamic properties of tall buildings (Campbell et al., 2004).

2.1 Crane excitation

A slab-like building over 250m in height has recently been tested in Hong Kong using crane excitation. However, the test was hampered by the relatively small excitation force exerted by the crane and energy transfer between the crane and building. Nevertheless, building vibrations were detectable from which the first mode natural frequency was determined but beating and re-excitation between the crane and the building precluded the use of free vibration decay measurement to determine the damping value.

2.2 Synchronised human excitation

With an experienced team, synchronised human excitation is a simple and quick method to excite a building to facilitate the measurement of the dynamic properties. A team of "shakers" is lined up along a long wall, such as an external wall or a lift foyer wall on the level at which the sensors are located. Synchronised "push-ups" are performed against the wall prompted by using a metronome set close to the natural frequency of the building along the direction of force application. The building vibration builds up progressively as each push-up is applied, until the vibration reaches a level that is clearly measurable by the sensors. The building vibration is then allowed to decay naturally, from which the frequency of vibration and damping value can be accurately determined. This technique has been successfully employed for measurements on light-weight structures such as light towers and lattice structures (Glanville, et al., 1996), more substantial structures such as airport control towers (Kwok, et al., 2000), and buildings up to 32 storeys high (Denoon, et al, 1998, Rooney,2002). Measurements have recently been taken on a group of crucifix cross-section high-rise residential buildings approximately 110 m in height (38 storeys) using a team of six "shakers" to determine the natural frequencies of vibration and damping values (Kwok, 2004).

2.2 Mechanical shaker

Variable-speed (frequency) mechanical shakers, such as an eccentric mass shaker, can concentrate the input energy over a range of frequencies and hence they are an ideal tool to excite a building to vibrate at the fundamental mode or any higher modes of interest. This is also a reliable method of determining the damping values and amplitude effects on damping by analysing the free vibration decay for desired amplitudes of vibration and at a desired frequency. The design and fabrication cost of a mechanical shaker is usually not prohibitively expensive and is readily justified by the quality of the measured data. A purpose-built, single-degree-of-freedom, variable-speed mechanical shaker is shown in Figure 1. The design of the shaker is based on a high precision, computer-controlled, servomotor driven ball-screw mechanism with a payload of 1 tonne, a shaking frequency ranging from less than 0.1 Hz to in excess of 4 Hz and a stroke of ± 200 mm. The load capacity and range of excitation frequencies of the shaker are designed to excite the majority of medium to tall buildings and structures to a detectable amplitude of vibration.

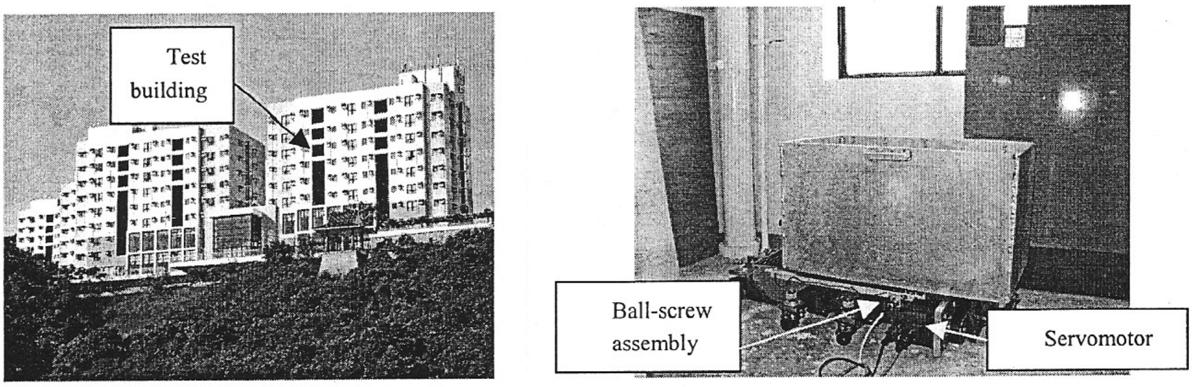

Figure 1. Eight storey residential building tested by a single-degree-of-freedom mechanical shaker

The single-degree-of-freedom mechanical shaker has been used to test three buildings: an eight storey residential building at HKUST and two high-rise residential buildings. The natural frequencies of vibrations, deflected mode shapes and damping values of up to three modes were determined accurately. Once the modal frequency (or frequencies) was identified, either through ambient wind excitation or through a frequency sweep test using the mechanical shaker, each mode was excited in turn by operating the shaker at the corresponding resonant frequency. A gradual build-up of resonant type response usually occurred, until a steady-state response was reached, after which the shaker motion was stopped and the building vibration allowed to decay naturally. Pairs of orthogonal accelerometers placed at multiple building levels near the building core and the building edges captured the relative motions from which the deflected mode shapes, including torsion and complex mode shapes, were determined. Results obtained from the tests on the eight storey residential building at HKUST, using a shaker mass of 600 kg, are shown in Figures 2 and 3. The deflected mode shape of the first mode (3.955 Hz) was found to exhibit coupling in translation and torsion. The steady build-up of resonant type response at the first mode frequency of 3.955 Hz and the free vibration decay upon cessation of shaking are clearly evident. The damping value was found from the free vibration decay curves shown in Figure 3 to be approximately 1.2 % of critical damping.

The dynamic properties of two high-rise residential buildings, the V-shaped Tower 1 (256m) and the crucifix-shaped Tower 2 (235m), excited by the mechanical shaker with a shaker mass of 1 tonne are summarized in Table 1. The measured natural frequencies for the first three modes were found to be significantly higher than the predicted values. The relatively low measured damping values reflect the small magnitude vibrations, of the order of 0.3 milli-g or less, imparted by the shaker. The normalized deflected mode shapes of two translational modes and one torsional mode for Tower 1 are shown in Figure 4. There are good agreements between the measured and predicted mode shapes, particularly for the two dominant sway modes, despite the discrepancies in the natural frequencies. The measured torsional mode shape is complex with significant contributions from all three components, while the computer model suggested a much simpler mode shape.

Table 1 A summary of dynamic properties of two high-rise residential buildings

Tower 1	Direction	Measured Freq. (Hz)	**FEM** (Hz)	Measured damping (%)
1st mode	X (translation)	0.244	0.171	0.350
2nd mode	Y (translation)	0.317	0.211	0.290
3rd mode	Z (torsion)	0.454	0.205	0.590
Tower 2	Direction	Measured Freq. (Hz)	**FEM** (Hz)	Measured damping (%)
1st mode	X (translation)	0.273	0.177	0.350
2nd mode	Y (translation)	0.293	0.172	0.340
3rd mode	Z (torsion)	0.459	0.153	0.410

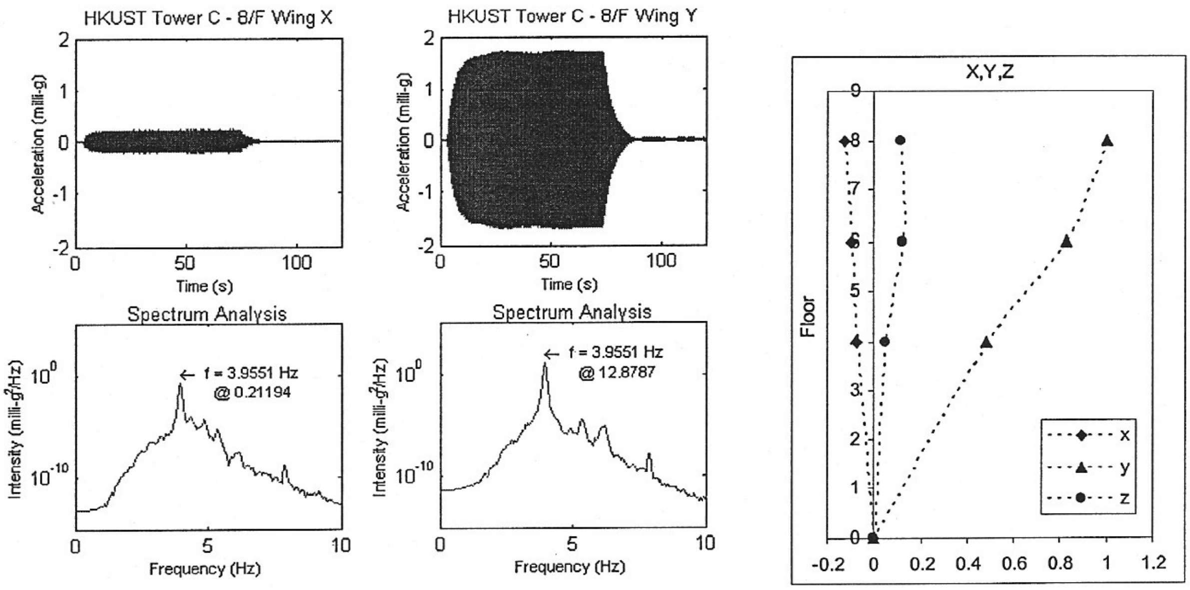

Figure 2. . Building vibration build-up and decay curves and spectra and measured mode shape

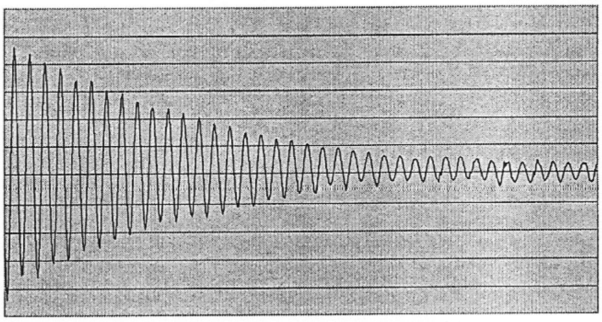

Figure 3. Free vibration decay curve obtained by using a mechanical shaker

3. CONCLUSIONS

Different test techniques, including ambient wind excitation, crane excitation, synchronized human excitation and mechanical shaking, have been used to excite a number of buildings to identify their dynamic properties. Synchronized human excitation using a team of six "shakers" was employed to test a 38 storey, 110 m high residential building to extract the natural frequencies and damping values of one torsional and two sway modes. A compact variable-speed mechanical shaker, with a shaker mass of up to 1 tonne, was used to excite an eight storey residential building and two residential high-rise buildings up to 256m in height, from which the natural frequencies, deflected mode shapes and damping value (for low deflection amplitude) of two sway and one torsional modes were accurately measured. There are good agreements between the measured and predicted mode shapes, particularly for the two dominant sway modes, despite the discrepancies in the natural frequencies.

4. ACKNOWLEDGEMENTS

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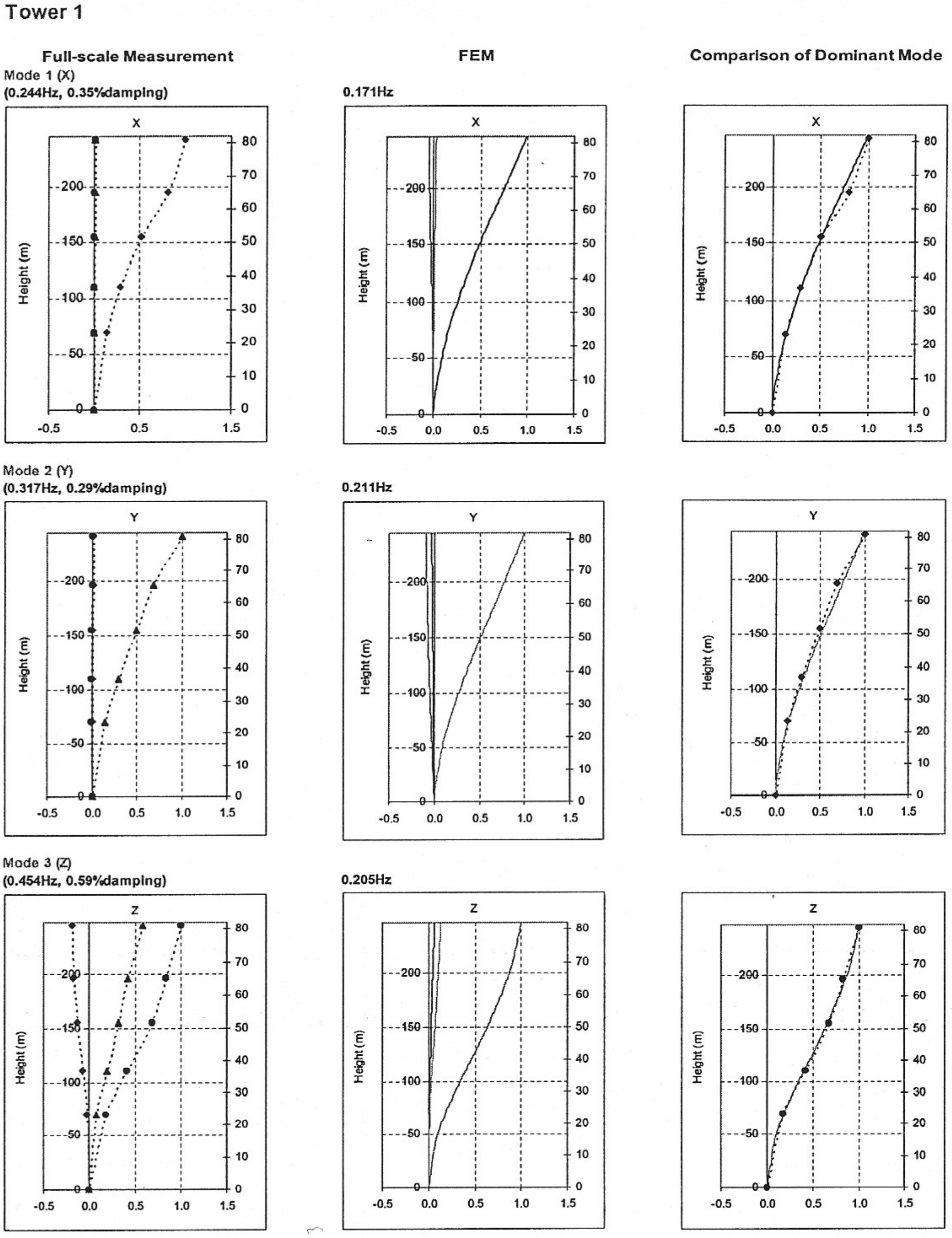

Figure 4. Normalized deflected mode shapes of two translational and one torsional modes for Tower 1

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