15th Australasian Wind Engineering Society Workshop
Sydney, Australia
23-24 February 2012

# A Dual-Axis Tall Building Motion Simulator to Investigate Effects of Wind-Induced Building Motions on Human

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## Introduction

The use of high strength material and advanced structural systems produces lighter and stiffer buildings, enabling modern tall buildings to attain great heights approaching 1,000 m and adopt striking and slender shapes. These increasingly wind-sensitive buildings also possess low natural frequencies of vibration, which positions the buildings within an operating range susceptible to enhanced wind excitations such as alongwind turbulence buffeting and crosswind vortex-induced excitation, particularly for buildings in regions of high wind speeds. These enhanced wind excitations, coupled with the inherently low structural damping values, make these buildings prone to wind-induced vibrations which can heighten occupant perception of motion and cause fear and alarm. Prolonged exposure to these vibrations can cause discomfort, affect task concentration, degrade cognitive performance, and even trigger dizziness, migraine and nausea.

In the design of modern tall buildings, wind tunnel model tests are now routinely employed to determine the wind-induced loads and building top floor accelerations with which occupant comfort can be assessed against international building vibration acceptability and occupant comfort criteria such as ISO 6897: 1984 and ISO/FDIS 10137:2007(E). When the wind tunnel test results suggested that the wind-induced building vibration does not satisfy occupant comfort criteria, mitigation measures, such as modifications to the structural system and/or the building aerodynamic shape and installation of vibration control devices, may be necessary to minimize occupant perception of and discomfort due to building vibration and avoid potential complaints. However, these vibration mitigation measures are invariably costly and often attract undesirable negative impressions and publicity which may affect the building's prestige and marketability.

A versatile and transportable dual-axis tall building motion simulator was designed and built as part of an international collaborative study on occupant comfort, cognitive performance and task performance in wind-excited tall buildings. This paper describes the features and capability of the motion simulator and the calibrations of the motion simulator based on sinusoidal displacement signals.

## Motion simulator design and specifications

A dual-axis tall building motion simulator was designed at Hong Kong University of Science and Technology (HKUST) to enhance the test capability to investigate human response to wind-induced building vibration. The design of the motion simulator, as shown in Figure 1, follows the principal requirements for motion simulation described by Denoon *et al.* (2001). The design specifications of the motion simulator include:

- Bi-directional motion with both orthogonal axes independently controlled;
- Vibration frequencies in the range from 0.05 Hz to 1 Hz;
- Reproduction of sinusoidal to random vibration free from high frequency vibration/noise;
- A test platform/test room with minimum dimensions of 3 m × 3 m; and
- Demountable for transportation.

The design of the motion simulator supports the test platform on two pairs of custom-built sliding bearings riding on precision machined and levelled rails, which allow maximum vibration amplitudes of ±800 mm in one direction and ±400 mm in the orthogonal direction. This maximum amplitude generates a maximum acceleration of around 30 milli-g at a frequency of 0.1 Hz, as shown in Figure 2. This test motion condition represents an acceleration level which can cause discomfort to a significant number of people at a natural frequency of vibration in translation expected for buildings of up to 700 m in height. At a frequency of 0.05 Hz, representing a building of 1,000 m or more in height, a maximum acceleration of 8 milli-g, which is expected to be perceptible to most people, can be achieved. The motion simulator also provides the flexibility to simulate realistic building vibration along either one or two orthogonal axes at various combinations of frequency and amplitude of vibration.

A control centre controls the vibration of the motion simulator by inputting prescribed test signals to the drive mechanism of the two axes independently. The drive mechanism is based on DC motors driving the test platform through high-precision ball screws. The planar motion of the test platform is guided by an anti-yaw device.

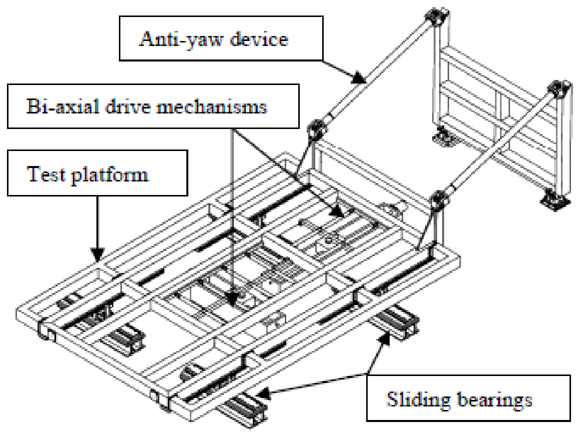


Figure 1: Features of dual-axis tall building motion simulator

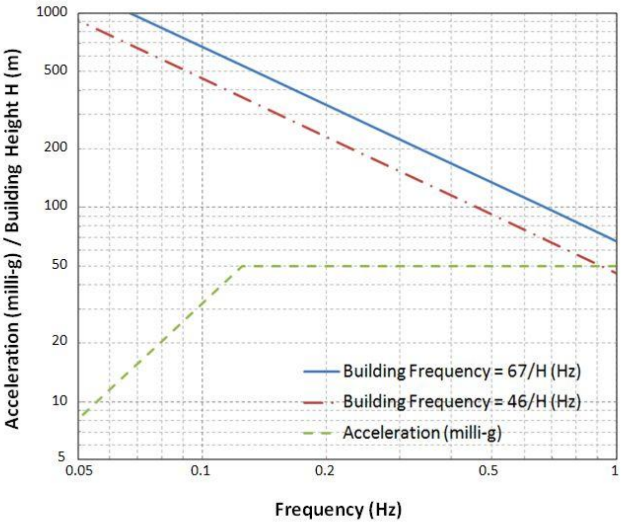


Figure 2: Capability of dual-axis tall building motion simulator

The construction of the motion simulator was completed in mid-2011. Representative external and internal views of the motion simulator are shown in Figure 3 and Figure *4* respectively. The test room can be configured and decorated to simulate a comfortable working environment or any test environment. It is able to be fitted with six workstations which will be used for occupant comfort and task performance investigations. An air conditioner was installed in the test room to maintain a suitable temperature for the participants.

Figure 3: External view of motion simulator

Figure 4: Internal view of motion simulator

## Calibration results

### Displacement measurement setup

Primarily, the physical displacements of the motion simulator were measured by using laser displacement sensors. Two laser displacement sensors were installed, as shown in Figure 5, to measure the physical displacements of the simulator along the x- and y- axes and their waveforms. In addition, a pair of orthogonally aligned accelerometers was installed on the simulator to measure the acceleration time history of each signal for cross checking with the measured displacement time histories.

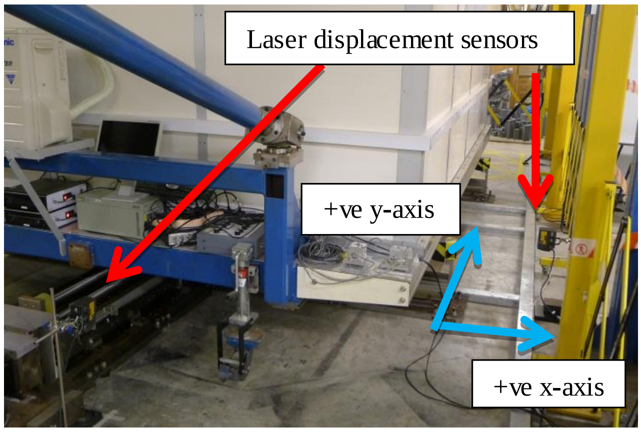


Figure 5: Experimental setup for motion simulator displacement measurements

The displacements and accelerations of the motion simulator along the x- and y- axes were recorded for durations of approximately 180 seconds for each test signal at a sampling frequency of 100 Hz.

### Input sinusoidal displacement signals

Six sinusoidal displacement signals were generated and used as input signals to verify the competence of the motion simulator to reproduce designated displacement signals. The peak displacement and frequency responses of the simulator response time histories were determined and verified against the target peak displacement and frequency responses corresponding to the designated displacement signals. The characteristics of the six sinusoidal displacement signals, including peak displacement, frequency (f) and peak acceleration, are summarised in Table 1.

Table 1: Characteristics of six sinusoidal displacement signals

| Test signal | Motion direction | Peak displacement (mm) | f (Hz) | Peak acceleration (milli-g) |
|---|---|---|---|---|
| 1 | x-axis | ±250 | 0.15 | 22.6 |
| 2 | y-axis | ±250 | 0.15 | 22.6 |
| 3 (in-phase) | x-axis | ±250 | 0.15 | 22.6 |
| | y-axis | ±250 | 0.15 | 22.6 |
| 4 (out-of-phase) | x-axis | ±250 | 0.15 | 22.6 |
| | y-axis | ±250 | 0.15 | 22.6 |
| 5 | x-axis | ±100 | 0.25 | 25.2 |
| 6 | x-axis | ±25 | 0.50 | 25.2 |

The six sinusoidal displacement signals comprise two acceleration levels, approximately 22.6 milli-g and 25.2 milli-g, and three frequencies: 0.15, 0.25 and 0.50 Hz, corresponding to natural frequencies of building with heights ranging from approximately 100 m to 500 m, as suggested in Figure 2.

Of the six sinusoidal displacement signals, test signals 1, 2, 5 and 6 are uni-directional motion signals and test signals 3 and 4 are bi-directional motion signals. For the bi-directional motion signals, the motions along the x-axis and y-axis are in-phase and out-of-phase for test signals 3 and 4 respectively.

## Output displacement responses

A typical output displacement time history corresponding to uni-directional test signals 1 to 4 is presented in Figure 6, showing that the motion simulator is able to simulate uni-directional motions with a sinusoidal waveform.

The output displacement of the motion simulator for test signal 4, of which the x- and y-axes motions are out-of-phase, are shown in Figure 7, illustrating the motion simulator capability to simulate orthogonal sinusoidal motions which are independently controlled.

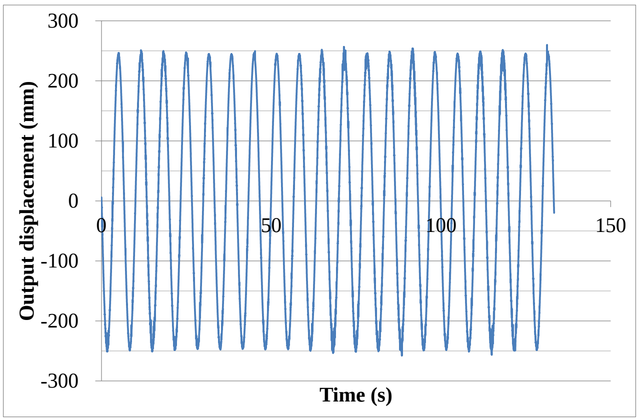


Figure 6: A typical output displacement time history of motion simulator corresponding to uni-directional test signals 1 to 4

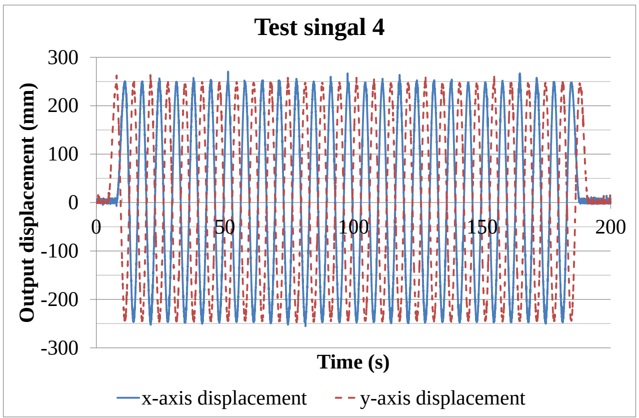


Figure 7: The output bi-directional displacements of motion simulator corresponding to Test signal 4

The peak values of the motion simulator output displacement time histories were compared with the corresponding peaks of each of the six sinusoidal displacement signals. The comparison results are presented graphically in Figure 8 and summarised in Table 2. Evidently, the percentage differences between the peak output and the corresponding input sinusoidal displacement signals are generally well within 10% for all signals within the peak displacement range from 25 mm to 250 mm.

Comparisons were also conducted between the peak accelerations determined from the acceleration time histories measured by using the installed accelerometers and the target peak acceleration of the corresponding designated signals. The comparisons indicate that the deviations between the peak accelerations of each measured time history and designated signal are generally less than 10%, further validating the accuracy of the reproduced displacement time histories.

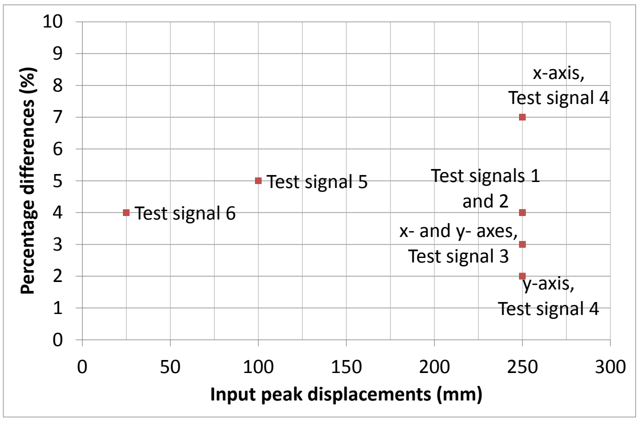


Figure 8: Percentage differences of peak displacements between input and output

Table 2: Output displacements of motion simulator measured for six sinusoidal displacement signals

| Test signal | Motion directions | f (Hz) | Peak acceleration (milli-g) | Peak displacement (mm) | | Displacement distortion (%) |
|---|---|---|---|---|---|---|
| | | | | Input | Output | |
| 1 | x-axis | 0.15 | *22.6* | 250 | 260 | 4 |
| 2 | y-axis | 0.15 | *22.6* | 250 | 260 | 4 |
| 3 (in-phase) | x-axis | 0.15 | *22.6* | 250 | 258 | 3 |
| | y-axis | 0.15 | *22.6* | 250 | 258 | 3 |
| 4 (out-of-phase) | x-axis | 0.15 | *22.6* | 250 | 270 | 7 |
| | y-axis | 0.15 | *22.6* | 250 | 255 | 2 |
| 5 | x-axis | 0.25 | *25.2* | 100 | 112 | 5 |
| 6 | x-axis | 0.5 | *25.2* | 25 | 26 | 4 |

## Output frequency responses

Burton *et al.* (2004, 2006) investigated the human biodynamic responses, through a series of motion simulator tests, subjected to uni-axial horizontal (both fore-aft and lateral) sinusoidal vibrations at a range of low frequency (0.15 Hz, 0.25 Hz, 0.5 Hz and 1.0 Hz) and a constant peak acceleration of 13.5 milli-g. The investigation results suggest that human perception of vibration is dependent on vibration frequency, highlighting the crucial importance of the motion simulator to accurately reproduce designated signals at correct frequency for occupant comfort investigations.

The spectra of the six output displacement time histories were computed. Typical spectra of uni-directional input test signals 1 to 4 and corresponding output displacement signal are shown in Figure 9. Evidently the energy peaks of the spectra are centred at a frequency of 0.15 Hz, which is the motion frequency of test signals 1 to 4. Furthermore, the magnitudes of the spectra are similar for both the input and output sinusoidal displacement signals.

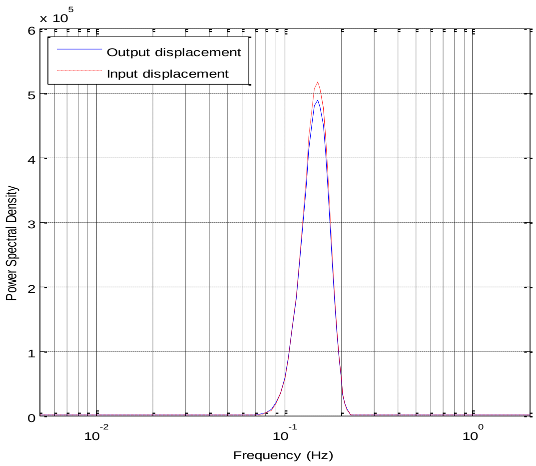


Figure 9: Typical spectra of test signals 1 to 4

Similarly, the spectra for the measured displacement time histories and the corresponding designated signals of test signals 5 and 6 are nearly identical, as shown in Figure 10 and 11 respectively. The energy peaks registered at frequencies of 0.25 Hz in Figure 10 and 0.50 Hz in Figure 11 also match the motion frequencies of test signals 5 and 6. Furthermore, the magnitudes of the spectra of the measured displacement time histories and the designated signals are very similar.

Overall, there is negligible frequency distortion of the output displacements of the motion simulator in either x-axis or y-axis motions for all test signals.

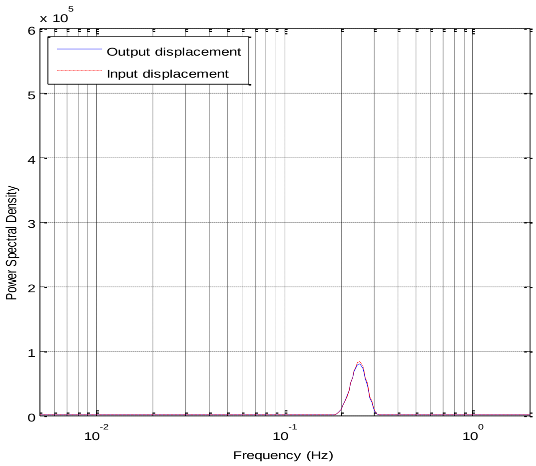


Figure 10: Spectra of x-axis motion of test signal 5

## Conclusion

A versatile and transportable dual-axis tall building motion simulator was designed and built as part of an international collaborative study on occupant comfort, cognitive performance and task performance in wind-excited tall buildings. The motion simulator was calibrated with six sinusoidal displacement signals. The calibration results indicated that the motion simulator is able to reproduce the six input sinusoidal displacement signals with negligible frequency distortion. The output peak displacements of the motion simulator were found to be generally within 10% of the input sinusoidal displacement signals for frequencies within the range of 0.15 to 0.5 Hz and peak displacements ranging from 25 mm to 250 mm.

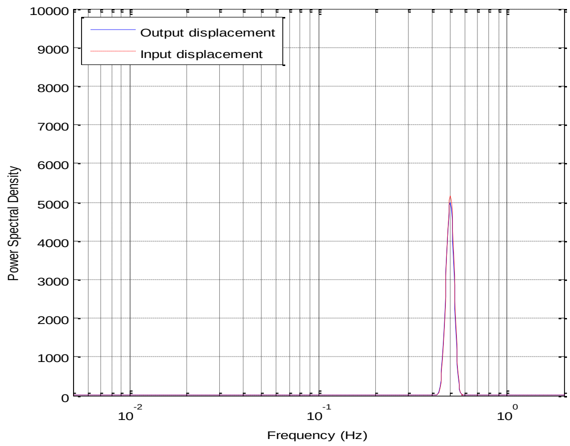


Figure 11: Spectra of x-axis motion of test signal 6

## Acknowledgments

The authors gratefully acknowledge HKUST's Design and Manufacturing Services Facility who designed and built the dual-axis tall building motion simulators, with the funding support of a HKUST Research Equipment Fund awarded in 2007. This research is supported by Australian Research Council Discovery Project Scheme (Project DP1096179). The authors also acknowledge the contributions to the calibration of the motion simulator by the staff of the CLP Power Wind/Wave Tunnel Facility at HKUST, particularly Mr David Leung, Mr Harry Fung and Mr Andrew Wong.

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