A motion simulator to investigate physiological and psychological effects of tall building motion in wind

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Introduction

As the demand for taller, lighter and more slender structures continues to increase, so does the importance of designing for wind-induced building motion. Dynamic response of tall buildings needs to be considered not only in terms of loading and deflection during extreme storms, but also in terms of the effects of motion on the building occupants during more frequent storms. These effects range from perceptibility of the motion to interference of daily activities caused by the motion. Recent field experiments (Denoon et al., 2000a) demonstrated that occupant perception of wind-induced motion of flexible structures is dependent both on peak accelerations and on the natural frequency of vibration at which these accelerations occur. However, the majority of the research conducted to determine the perceptibility of motion has been completed inside motion simulators using a sinusoidal signal input. There has been much debate over the validity of the use of a sinusoidal wave because wind-induced tall building motion is generally narrow-band random motion in nature. The difference between the two motions is related by the peak factor; a sinusoidal wave has a peak factor of $\sqrt{2}$, whereas narrow band random motion has a peak factor of approximately 3.5 (Denoon et al., 2000b). It has been shown that subjects are much more sensitive to random multi-frequency vibration than other types of motion (Denoon et al., 1999).

Although many experiments have been conducted using motion simulators to investigate perception thresholds, no experiments have been conducted using the two degree-of-freedom narrow band random motion typical of tall building motion in wind. In particular, very little information has been gathered on frequency dependence of motion perception at the very low natural frequencies typical of modern super-tall buildings. In general, a building moves in three directions when subjected to wind: along-wind, crosswind, and torsion. These three directions translate to a fore-aft, transverse, and yaw motion experienced by building occupants. However, the yaw motion, away from the center of stiffness, is felt by the occupants as either fore-aft or transverse motion.

Previous simulator tests (Denoon et al., 2000b) showed that single degree-of-freedom narrow band random motion did not have significant effects on cognitive performance for a range of tasks investigated. However, more subtle effects are possible, and the effects of motion on additional more complex cognitive processes have not been investigated. Extensive surveys of occupant reaction to wind-induced motion in a control tower (Denoon et al., 2000a) indicated a strong link between personality types and tolerance of

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wind-induced motion, while other research has shown the potential for physiological and psychological pre-determination of motion sickness susceptibility (Golding, 1998). These factors require further investigation in the context of tall building design.

This paper describes the design of a motion simulator at the Hong Kong University of Science and Technology (HKUST) and the development of test batteries and testing protocols.

Motion Simulator Design

The advantage of conducting investigations in a motion simulator is the controllability of motion conditions. In the field it is very difficult to foresee when testing conditions will be at an optimum and it is also difficult to have subjects immediately available when the appropriate conditions do emerge. Denoon et al. (2001) described the principal requirements for motion simulation, and these principles have been adhered to in the design of the HKUST simulator.

The simulator has been designed to reproduce two degree-of-freedom tall building random motion with dominant natural frequencies between 0.1 and 1.2 Hz. The orthogonal axes can be controlled independently and, thus, different natural frequencies can be used in each direction. This independent control gives a more realistic simulation of actual building motion. Two of the primary goals in the design were the avoidance of any high-frequency vibration from the drive system that could contaminate the quality of motion, and extraneous noise that could act as a motion cue. Even slight mis-alignment of the driving gears could transmit a kinesthetically perceptible amount of chattering to the platform.

The simulator has a 3 m by 3 m platform, as shown in Fig. 1. Aluminum plates are installed on the platform with an access panel at the center, above the drive mechanism, to allow for future modifications and maintenance. The size was selected, as it is a suitable for a test room capable of housing six subjects at a time, and was the maximum size that could be accommodated in the laboratory. A smaller test room would require much greater lengths of time in testing and would be likely to induce feelings of claustrophobia in some subjects. The platform has also been designed to accommodate the testing of passive damper devices.

The test room will be fitted with six workstations, each workstation comprising of a computer, a desk and a stool. An air conditioner will be installed in the test room to maintain a comfortable working environment for the subjects, and in addition, will mask any transmitted noise from the outside laboratory. This noise masking is important because it must be ensured that the subject's perception of motion is not triggered by noise generated from the moving platform.

The platform is supported on four custom-built hydrostatic bearings, which allow maximum amplitude of motion of ±160 mm. This allows accelerations of 30 milli-g to be achieved at frequencies as low as 0.22 Hz. At 0.1 Hz, a maximum acceleration of 6.5 milli-g can be achieved. This is sufficient to determine perception thresholds. The motion of the simulator will be controlled from a control center. The input drive signals are generated from both wind tunnel and modified full-scale displacement data. There are two accelerometers orthogonally mounted on the simulator to verify correlation between the input and output signals and to collect motion data during the investigations. The drive mechanism is based on DC motors driving the platform through high-precision ball screws and backlash is controlled through pre-loaded pneumatic cylinders. A constant pressure of 4 bar is required to ensure a smooth transition when the platform is undergoing a direction change. The plane of the motion is controlled by an anti-yaw mechanism.

To prevent the transmission of high-frequency vibration 25 ft. long hoses were used between the hydraulic pumps and the hydrostatic bearings, and to reduce system chattering, from the damping pneumatic cylinders, which was detected after extended usage, a lubricator was installed in the compressed air input.

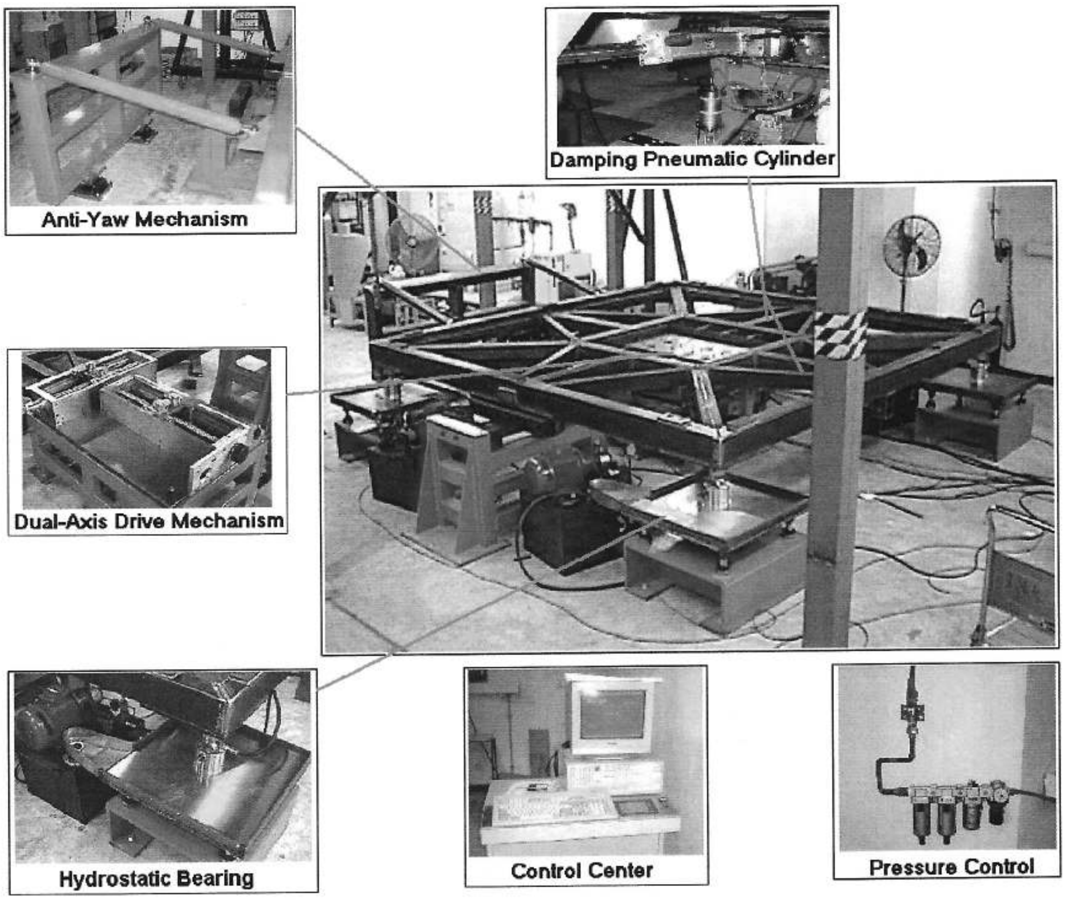

Fig. 1: Motion Simulator Shaker Table at HKUST

Development of Test Batteries and Protocols

As motion perception plays such a critical role in occupant tolerance of wind-induced motion, one of the primary aims is to extend knowledge of frequency dependence of sinusoidal motion to two degree-of-freedom narrow band random motion. In previously conducted studies, the sensing of motion has been the main focus of the investigations. Because this was the only task in which the subjects were involved, the perception of motion curve was potentially lowered to an unrealistic level. To perceive motion in a real building environment, occupants have to be distracted from their principal activity. This distraction threshold (Denoon et al., 1998) is the most useful for application to building design. Therefore, in order to investigate thresholds, subjects must be given a principal task (or tasks) other than motion detection.

Previous experiments on the effects of motion on cognitive performance investigated some major psychological constructs but this was not done in terms of a specific macro-theory. For this study, tasks are being developed according to a Cognitive Abilities Measurement framework. The three main tasks will focus on tactical kina esthetics, visualisation, and cognitive studies. The subjects will be tested over a range of frequencies and varying amplitude. Firstly, the testing will begin with one-degree of freedom motion and test for dependence between a changing frequency and amplitude. Secondly, a two-degree of freedom motion will be simulated, again testing for dependence between frequency and amplitude. Following each round of testing, subjects will be asked to complete a questionnaire, answering general questions regarding whether they perceived any motion during the test and whether they have any previous experience with building motion.

Motion sickness susceptibility will be examined in terms of field-dependence, personality and postural control, with the potential of allowing pre-screening of potential tenants for lively buildings and structures. These test batteries are currently under development. This research will offer insight into occupant comfort and motion tolerance with the aim of increasing the reliability of serviceability design of tall slender structures.

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