Frequency Dependence of Human Response to Uni-Axial Sinusoidal Motion

Melissa Burton[a], *Kenny C.S. Kwok*[a], *Peter A. Hitchcock*[b], *Roy O. Denoon*[c]

[a]*Dept. of Civil Engineering, Hong Kong University of Science and Technology (HKUST), Hong Kong*
[b]*CLP Wind and Wave Tunnel Facility, HKUST, Hong Kong*
[c]*Ove Arup & Partners Hong Kong Ltd., Hong Kong*

Introduction

There has long been debate about the necessity of considering motion frequency in the assessment of occupant comfort during wind-induced tall building motion. Although buildings where occupant comfort governs design can range from less than 100 m to greater than 500 m in height, many designers use the same frequency independent criteria for all. Although frequency dependent criteria have been published, very little information has been gathered to clearly demonstrate the physiological response and frequency dependence at the low natural frequencies typical of modern tall buildings.

Many experiments have been conducted using motion simulators to investigate the effects of motion on individuals. The majority of these tests have focused on the psychological perception and tolerance of motion (e.g. Chen & Robertson, 1973, Denoon et al., 2000). However, human response to motion is a complex mix of a range of psychological and physiological factors. It is the vestibular system that is the primary organ of equilibrium and the otolith organs of the inner ear that are heavily involved in the detection of linear accelerations. This suggests that not only the global building acceleration, but also the local body accelerations experienced by the human subject are of utmost importance in determining motion perception. Experimental results are reported herein on the frequency dependence of physiological magnification of acceleration of human test subjects exposed to constant amplitude horizontal sinusoidal motion at frequencies ranging from 0.15 Hz to 1.00 Hz.

Methodology

Under carefully controlled laboratory conditions, utilizing the motion simulator in the CLP Wind and Wave Tunnel Facility (WWTF) at Hong Kong University of Science and Technology (HKUST), a population sample of ten human test subjects was subjected to a range of low-frequency horizontal sinusoidal motion at a constant amplitude acceleration of 13.5 milli-g (0.132 ms^{-2}). Each subject was exposed to eight motion conditions and one control condition, each of 200 second duration, presented in a random sequence, while watching a video. The experiment consisted of four frequencies, 0.15 Hz, 0.25 Hz, 0.50 Hz, and 1.00 Hz, with the motions aligned in one of two directions: fore-aft or lateral. Body and head acceleration and head displacement measurements were acquired using tri-axial accelerometers and digital video recorders respectively.

Dual-Axis Motion Simulator

The motion simulator at HKUST is designed to reproduce dual-axis, narrow-band random motion. The motion simulator underwent a series of calibrations using both sinusoidal input signals. LVDTs measured the actual simulator displacements, which were then compared with the input displacements. The sinusoidal test input drive signals were made up of one-third preferred octave center frequencies ranging from 0.1 Hz to 1.00 Hz with accelerations of 6 milli-g and 30 milli-g. The actual motion simulator displacements were found to match the input drive signals to within 5 % with no frequency distortion.

Acceleration Results and Discussion

Four high sensitivity lightweight tri-axial accelerometers, with a range of +/-2 g, were used on human test subjects to measure body accelerations in the fore-aft (x), lateral (y), and vertical (z) directions. One accelerometer was mounted in the center of the top of the subject's head. This accelerometer was bonded to a headband, which was adjusted to fit each subject. One accelerometer was positioned between the shoulder blades over the mid-thoracic region of the spinal column. The subject sat on a 4-legged hard surface stool with a height of 445 mm and a diameter of 340 mm. Acceleration measurements in the fore-aft and lateral directions, aligned with the simulator axes, were acquired at this interface using one accelerometer bonded to the bottom face of the stool. The fourth accelerometer was bonded to the frame of the motion simulator, again aligned with the simulator axes.

A total of ten channels of acceleration (fore-aft, lateral, and vertical directions on the head and back, and fore-aft and lateral on the stool and frame) were recorded. It was assumed that the vertical acceleration of the stool and frame were minimal, a fact that was demonstrated in previous calibration of the simulator. The acceleration was sampled at 20 Hz with a low-pass filter cutoff of 5 Hz. A digital band-pass filter, with a two octave bandwidth, was further applied to the recorded acceleration data to remove the low-frequency signal drift and the high-frequency 'twitches' of each subject.

The power spectral density functions for the back and head accelerations were computed from the eight motion conditions and a peak was consistently found at the frequency and direction coincident with the frequency and direction of the input motion.

The resultant standard deviation accelerations were derived from the square root of the sum of squares of the standard deviations of the individual components. The data for the ten human test subjects was compiled and trimmed means were determined by eliminating the largest and smallest subject acceleration extreme values from each motion condition to enhance the statistical reliability of the results.

As expected, the recorded accelerations of the frame and stool did not change with increasing frequency. In both the fore-aft and lateral directions an increase in the measured back acceleration up to 0.50 Hz was observed, after which the acceleration began to drop off slightly. The mean head acceleration values exhibited a definite upward trend with increasing frequency of oscillation. It appeared that as the frequency of oscillation increased, the accelerations of the subject's back, and particularly head, were increasingly magnified. The magnification factor of the acceleration is defined in Equation (1).

$$\text{Acceleration Magnification Factor} = \frac{\text{Subject Standard Deviation Acceleration}}{\text{Simulator Standard Deviation Acceleration}} \tag{1}$$

To calculate the acceleration magnification factors, the resultant standard deviation accelerations of the back, and head mounted accelerometers for each subject were divided by the measured resultant standard deviation acceleration of the frame mounted accelerometer. The trimmed means, which eliminate the maximum and minimum value, and standard deviations of the magnification factors were determined. These are shown in Figures 3 and 4 for the back and head, with error bars of one standard deviation and a second order polynomial curve fit.

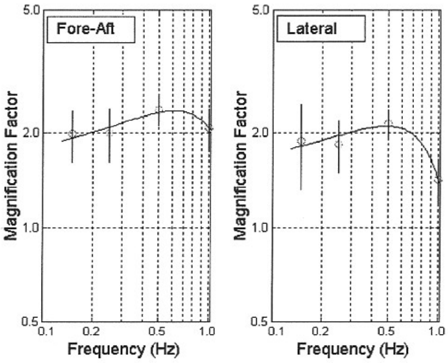

Figure 3: Magnification Factor of the Back

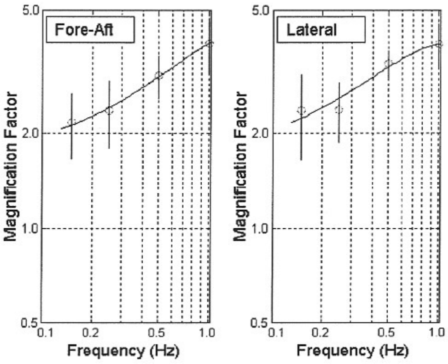

Figure 4: Magnification Factor of the Head

Figure 3 shows little variation in the magnification factor of the back in the fore-aft direction across the frequency of oscillation, with the values remaining relatively constant at a magnification factor of around 2. There is a noticeable reduction in the acceleration magnification factor of the back at 1.00 Hz in the lateral direction of motion. This is most likely due to the para-spinal muscles evoking stretch reflexes at this higher frequency, acting against the input accelerations and damping the body acceleration to limit undesirable excursion, as shown in previous research (Lin & Rymer 2000). However, the noticeable decrease in the magnification factor at higher frequencies may also be attributed to the varying deformations of the spinal vertebrae at the changing frequencies. Lee & Svensson (1993) investigated spinal deformation at loading rates of 1.00 Hz, 0.50 Hz and a "quasi-static" rate and demonstrated a significant reduction in displacement of the spinal vertebrae as the frequency was increased to 1.00 Hz.

In contrast to the observed decrease in the magnification factor of the back acceleration at 1.00 Hz, the magnification factor of the head acceleration demonstrates continuously rising values as the frequency of oscillation increases from 0.15 Hz to 1.00 Hz. The mean acceleration magnification factor increases from approximately 2 at the low-frequency of oscillation of 0.15 Hz to approximately 4 at 1.00 Hz. The acceleration magnification factor of the head is obviously dependent on the frequency of oscillation. This dependence on frequency and continual increase of the magnification factor could be potentially linked to the perception of motion, because the vestibular organs, some of the body's primary motion sensors (Walsh, 1961, Israel & Berthoz, 1989), are located in the inner ear.

Displacement Results and Discussion

Displacement information was collected using two digital video recorders, one mounted 2 m in front of the subject to detect lateral motion and the second mounted 2 m to the right of the subject to detect fore-aft motion. Grids of 5 mm squares were bonded to the wall surface behind, and to the left of the subject to provided reference distance measurements for displacement relationships. Video editing software was used to frame-grab the positive and negative peak displacement of the subject's head. Displacement of the subject's head was identified in terms of pixels and related to the reference distance. Displacement for each of the eight motion conditions was taken as the average peak-to-peak displacement of the ten cycles. The individual displacement data was then combined with the group data; maximum and minimum extreme values were determined and eliminated from each test motion condition, similar to the acceleration results, to calculate the trimmed mean value of the subject's displacement.

Figure 5 shows the group trimmed mean displacement for each frequency of oscillation and error bars, which represent one standard deviation, for the fore-aft and lateral direction of motion. Also shown is the second order polynomial curve fit to the data. This variation in the peak-to-peak displacement of the human test subject's head across the frequency range of testing is relatively small when compared with the peak-to-peak displacement of the simulator. For the four frequencies of oscillation, 0.15, 0.25, 0.50 and 1.00 Hz, the simulator peak acceleration is constant at 13.5 milli-g, resulting in peak-to-peak displacement values of 198, 108, 26, and 6.8 mm respectively, for both the fore-aft and lateral directions of motion.

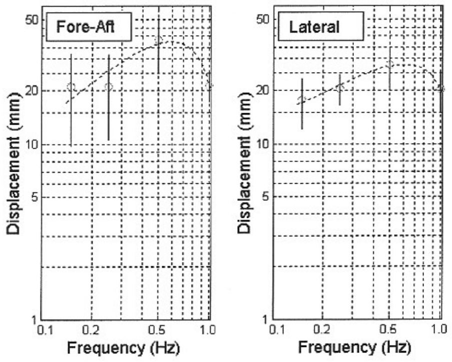

Figure 5: Head Displacement

When the head moves in translation, the image of a close object generates a more rapid movement on the retina than does the image of a distant object. These object relative cues, the projection of motion on the retina of near objects relative to far objects, are thought to be the main visual perception motion cue (Wertheim, 1994). The complexity of this stabilization increases if the environment is also in motion, because visual kinaesthesis is less efficient than vestibular processing in conveying motion information (Goldberg & Hudspath, 2000). There is a common tendency for an individual to misinterpret sensory information, especially if two modes of motion perception are in conflict, and an individual will permit one sense to dominate the other (Harris et al., 2000). When a building is subjected to wind-induced motion, individuals within the building receive cues from their vestibular apparatus, because their body is undergoing linear acceleration, yet they believe themselves to be stationary relative to the building. This sensory conflict could be potentially linked to visual parallax of relative object motion in tall-buildings.

Conclusions

The results presented in this paper demonstrate a non-monotonic human subject response to a physical vibration stimulus. The biodynamic human body vibration response occurring during exposures to this low-frequency constant amplitude acceleration motion was demonstrated. A frequency dependence of this motion was established, revealing an increasingly magnified acceleration of the head as the frequency of oscillation increased. Through the knowledge that the vestibular system is the primary indicator of motion perception, the frequency dependence of the head acceleration can be directly translated into a frequency dependence of motion perception. It was clearly demonstrated that with decreasing frequency of oscillation there was an increase in perception threshold, and vice versa. Therefore the assessment of occupant comfort criteria should include frequency dependency of motion. A comparatively constant peak-to-peak displacement of the head across the frequency range of interest for constant amplitude acceleration motion was also demonstrated, and was shown to be potentially linked to visual parallax of relative object motion in tall-buildings.

Acknowledgements

The research described in this paper has been made possible by funding provided by the Research Grants Council of Hong Kong (Project HKUST6239/00E). The experiments were approved by the Human Subject Panel of the HKUST committee on Research Practices. The authors would like to gratefully acknowledge the enthusiastic participation and contributions of HKUST and WWTF staff, without whose help this project would never be completed.

References

Chen, P.W., and Robertson, L.E., (1972), “Human Perception Threshold of Horizontal Motion", *Journal of Structural Division*, ASCE, Vol. 98, No. 8, pp. 1681-1695.

Denoon, R.O., Roberts, R.D., Letchford, C.W. and Kwok, K.C.S., (2000), “Field Experiments to Investigate Occupant Perception and Tolerance of Wind-Induced Building Motion”, *Research Report No. R803, Department of Civil Engineering*, University of Sydney, Australia.

Goldberg, M.E., Hudspath, A.J., (2000), *Chapter 40, The Vestibular System. In: Principles of Neural Science*. Kandel, Schwartz, and Jessel eds. 4th Edition, pp. 801-815.

Harris L.R., Jenkin M., Zikovitz D.C., (2000), "Visual and Non-Visual Cues in the Perception of Linear Acceleration", *Experimental Brain Research*, Vol. 135, pp. 12-21.

Israel, I., Berthoz, A., (1989), "Contribution of the Otoliths to the Calculation of Linear Displacement", *Journal of Neurophysiology*, Vol. 62, pp. 247-263.

Lee, M., Svensson, N.L., (1993), "Effect of Loading Frequency on Response of the Spine to Lumbar Posteroanterior Forces", *Journal of Manipulative Physiological Therapeutics*, Vol. 16, No. 7, pp. 439-446.

Lin, D.C., Rymer, W.Z., (2000), "Damping Actions of the Neuromuscular System with Inertial Loads: Soleus Muscle of the Decerebrate Cat", *Journal of Neurophysiology*, Vol. 83, pp.652-658.

Walsh, E.G., (1961), "Role of the Vestibular Apparatus in the Perception of Motion on a Parallel Swing", *Journal of Physiology*, Vol. 155, pp. 506-513.

Wertheim, A.H., (1994), "Motion Perception During Self-Motion: The Direct Versus Inferential Controversy Revisted", *Behavioral and Brain Sciences*, Vol. 17, No. 2, pp. 293-355.