Vibration testing for dynamic properties of building floors

Tuan H A Nguyen
University of Architecture Ho Chi Minh City (196 Pasteur St., Dist. 3, HCMC, Vietnam)
E-mail: tuan.nguyenhuanh@uah.edu.vn

Abstract. The paper presents a comparison of testing methods and post processing techniques for modal properties of a fully furnished chipboard floor and an unfurnished prestressed concrete floor. A thorough modal testing required relocation of transducers among test setups to acquire multiple synchronous measurements of floor response due to heel drop excitation or shaker excitation. The comprehensive experimental data was processed by a specialised operational modal analysis software. On the other hand, a simple testing approach only required records of floor response at a single point due to heel drop. The measured response can be easily analyzed using simple procedures of structural dynamics. Whilst valuable information about the floor modal properties including the mode shapes was obtained using the sophisticated approach, the uncomplicated single-point heel drop test was found to provide reasonably accurate evaluation of natural frequencies and damping ratios for both of the test floors, which verifies the attractiveness of the simple technique. Based on experimental results, both of the floors would be considered as low-frequency floors by commonly used guidelines on human-induced floor vibrations. Furthermore, the effect of fit-out conditions and construction materials on the huge discrepancy between damping values of the two floors was also observed.

1. Introduction

The vibration levels of building floors due to human activities should be controlled within acceptable limits recommended by international standards and design guides in order to ensure occupant comfort and safety of sensitive equipment [1-3]. Considering any potential vibration problems during the design stage is preferable to fixing an as-built floor, which would be more expensive and awkward. The main factors affecting the dynamic behaviour of a floor system are the mass, stiffness and damping of the floor. It is common practice to convert all types of damping from different sources, structural and non-structural, to an overall equivalent viscous damping ratio which is a fraction of critical damping. Current floor vibration guidelines have proposed analytical procedures ranging from simple manual methods to finite element models to predict the modal properties and human-induced dynamic response of floor systems [2,3]. Whilst these analytical methods rather than costly experimental methods are commonly used by design engineers, dynamic testing of floors enables validation and enhancement of prediction methods and assessment of floor performance. Typically, a measurement system requires a set of transducers suitable for recording vibration response, an excitation source, a data acquisition system and suitable signal analysis techniques to extract modal properties.
This paper investigates experimental methods for the determination of the dynamic characteristics of two real building floors with different structural materials and fit-out conditions. The results obtained from a simple single-point heel drop test and data analysis will be compared with those acquired from a sophisticated multi-point modal testing and specialised data post-processing software.

2. Literature review

In-depth discussions on theory and application of vibration testing and experimental modal analysis can be found in comprehensive documents such as [4]. This section just provides a brief overview of testing procedures and post processing techniques for measurement of floor dynamic properties.

Heel drop impact is a simple test commonly used to measure the floor natural frequencies and damping. The test is performed by a person rising onto his toes with his heels about 63 mm off the floor and suddenly dropping his heels to the floor. In unreferenced drop tests, only the floor response is measured. On the other hand, an instrumented heel drop test would be more robust when allowing measurement of the heel impact force using load cells together with the floor response [5]. Testing using an impact hammer can help determine the floor stiffness as the load is measured via a load transducer fixed to the hammer head [6]. However, Hanagan et al. [7] compared the heel drop force measured by a force plate with the force generated by an instrumented hammer hitting the floor and found that the peak force generated by the hammer was about 3 times less than that produced by a heel drop. It was suggested that the hammer force would not be large enough for use on real floors and hence employing heel drop tests would be more suitable. Forced vibration testing utilising a vibration generator such as a shaker is a much more comprehensive method by which the floor stiffness and mode shape can be reasonably measured [8]. The force applied by a shaker can be directly measured using a force transducer (force plate) or indirectly measured using an accelerometer attached to the moving shaker armature [9]. A fixed-input roving-response setup is commonly used by which a shaker excites the floor at a single point whilst accelerometers are relocated across the floor area of interest. Recently, multi-input multi-output (MIMO) modal testing of floors using several electrodynamic shakers has been explored. The MIMO technique employs multiple electrodynamic shakers and uncorrelated random drive signals. This modern technique, however, has not been commonly used for civil engineering structures due to its high cost and practical difficulties [10,11].

A traditional Experimental Modal Analysis (EMA) requires simultaneous measurement of both the structure response and excitation force from which an output acceleration spectrum and an input force spectrum can be produced. The ratio of the output spectrum to the input spectrum defines the frequency response function (FRF) which shows how the structure will respond to input at a certain frequency. Curve fitting techniques can be used to match the measured FRF with mathematical models to estimate the floor modal parameters including frequencies, damping ratios, mode shapes, and modal masses [2,4]. In the case of output-only modal testing or operational modal analysis, the FRF cannot be obtained because the excitation force is not measured. However, the mode shapes can still be constructed using established techniques dedicated to output-only modal identification [12].

3. Methods

3.1. Description of case study floors

Vibration testing was performed on two building floors located in Melbourne, Australia. The first case study floor was a lightweight floor of a fully furnished office. The floor structure consisted of 20 mm deep chipboard flooring supported by 150 mm deep steel channels, spanning 2.7 m at 450 mm spacing. The channels B1 were in turn carried by 360 mm deep universal steel beams G1 spanning 9.5 m, as shown in figure 1. The second case study floor was a prestressed concrete floor without furnishings in a
building under construction. The post tensioned concrete slab was 200 mm thick, spanning 10.2 m between band beams which were 2400 mm wide and 350 mm deep, as depicted in figure 2. For comparative purposes, different testing methods were investigated in each of the case study floors as summarised in table 1.

**Table 1.** Testing methods.

| Floor  | Simple test                      | Full EMA                        |
|--------|----------------------------------|---------------------------------|
| Floor 1| Heel drop, single-point measurements | Heel drop, multi-point measurements |
| Floor 2| Heel drop, single-point measurements | Shaker excitation, multi-point measurements |

3.2. Experimental setup

The experimental setup consisted of relocatable Dytran seismic accelerometers of 5 V/g sensitivity and a laptop-controlled data acquisition system. The simple heel drop test would require the acceleration to be measured only at a single point (marked as point 1 in figures 1 and 2) on the test floor. The full EMA, on the other hand, would need multiple synchronous measurements of response from a grid of transducers. To cover the 8×10 m test area of floor 1, eight accelerometers were used with one reference sensor locating near the bay centre and seven free sensors moving around the floor in five test setups, creating a measurement grid of 36 points (see figure 1). For the 8.5×20.4 m test zone of floor 2, seven accelerometers were used with one reference transducer close to the centre of the Western bay and six roving transducers arranged in seven test setups, forming a measurement grid of 43 points (see figure 2). The position of the reference accelerometer was fixed in all test setups.

![Figure 1](Figure 1. Floor 1: framing details and accelerometer locations.)
Figure 2. Floor 2: framing details and accelerometer locations.

Unreferenced heel drop tests were performed on both test floors. Moreover, a signal generator controlled APS electromagnetic shaker was utilised for full modal testing of floor 2. The shaker exerted swept sine forcing in the frequency range of 5 Hz to 13 Hz on the floor. The excitation frequency range was selected based on a preliminary finite element model of the floor. The acceleration response was recorded at a sampling rate of 128 Hz. Repeat tests were performed in each setup for averaging purposes. Photos of the test setup and testing equipment are depicted in figures 3 and 4.

Figure 3. Floor 1: (a) Accelerometers on floor, (b) heel drop test in progress.
3.3. Analysis of experimental data

3.3.1. Simple heel drop with single-point measurements. The floors' natural frequencies and damping values were estimated from the heel-drop induced response measured by the accelerometer denoted "1" in figures 1 and 2. Fourier transformation to the frequency domain was employed to the response time history for acquiring the frequency response spectrum whose significant peaks indicated the natural frequencies [13].

Furthermore, the Random decrement (RANDEC) technique was employed to eliminate the random part of the response time history in order to extract the free vibration response from which the damping ratio can be calculated [14]. The basic concept of the RANDEC method is illustrated via figure 5 which shows a certain response time history $X(t)$. Firstly, a triggering level or response amplitude $X_0$ was selected, and a number of $N$ successive response segments with the same duration $\tau$ and initial amplitude $X_0$ were taken from the response history. Let $X_0(t_r + \tau)$ be a typical segment starting with amplitude $X_0$ at time $t_r$. Averaging $N$ segments $X_0(t_r + \tau)$ yields a response history $\delta(\tau)$ as given by equation (1):

$$\delta(\tau) = \frac{1}{N} \sum_{r=1}^{N} X_0(t_r + \tau)$$

![Figure 5. Taking response segments for RANDEC analysis.](image-url)
When the number of segment $N$ is reasonably large, the averaging procedure would effectively cancel out the random response component. The resultant response history $\delta(\tau)$ can hence be considered as the free-decay response due to an initial displacement only. Figure 6 shows a typical free-decay response where the damping ratio $\zeta$ can be computed using the classical logarithmic decrement method:

$$\zeta = \frac{1}{2\pi k} \ln \left( \frac{X_i}{X_{i+k}} \right)$$

where $X_i$ and $X_{i+k}$ are two peaks with $k$ vibration cycles apart [13].

3.3.2. Full EMA with multi-point measurements. The extraction of the floor modal parameters was carried out by using ARTeMIS, an operational modal analysis software developed by Structural Vibration Solutions A/S. The locations of the transducers and the measured response time histories from all test setups were inputted into the ARTeMIS software whose output-only modal analysis techniques can separate noise from the outputs and return the unbiased modal information. Not only can the natural frequencies and damping ratios of the test floors be evaluated but also the corresponding mode shapes can be found using the patented Enhanced Frequency Domain Decomposition technique [15].

4. Results and discussion

4.1. Case study floor 1

To compare with the ARTeMIS results, simple analysis as described in subsection 3.3.1 was performed on the single-point response data. Figure 7 shows a typical acceleration time trace of the floor due to a series of heel drop excitation, measured at the location of the reference accelerometer. Figure 8(a) illustrates the corresponding frequency response spectrum whose significant peaks revealed the dominate natural frequencies of 5.50 Hz and 15.25 Hz for the first and second modes, respectively. In determining the floor damping, a manipulated acceleration time trace was obtained using the RANDEC method, as shown in figure 8(b). The popular logarithmic decay method was then conducted on this response history from which the damping can be estimated at 10.2% for the fundamental mode.

For the sophisticated EMA using the acceleration data measured from all 36 channels, the ARTeMIS program provided the floor mode shapes as displayed in figure 9. A natural frequency of 5.64 Hz and damping ratio of 10.90% were estimated for the first mode. The second mode was found to have a natural frequency of 15.26 Hz and damping ratio of 5.90%.
Figure 7. Floor 1: Response to a series of heel drop.

Figure 8. Floor 1: (a) Response to heel drop in frequency domain, (b) decay curve from RANDEC.

Figure 9. Floor 1: ARTeMIS-identified mode shapes.

4.2. Case study floor 2
Figure 10(a) shows the averaged frequency response spectrum due to heel drop excitations, measured at the location of the reference accelerometer. The fundamental frequency was estimated at 7.62 Hz,
followed by the second natural frequency of 9.12 Hz. In estimating the floor damping associated with the fundamental mode, the RANDEC technique was performed on the filtered acceleration record to acquire an averaged acceleration history shown in figure 10(b). Applying the logarithmic decrement method to the RANDEC decay curve yielded a damping ratio of just 1.12%.

Regarding the full EMA, figure 11 shows a typical acceleration time history along with its Fourier transformation due to shaker excitation. The frequency spectrum reveals a sharp peak at 7.64 Hz followed by a lower peak at 9.14 Hz. An extensive analysis of the data from all 43 measurement channels was performed using the ARTeMIS software. Figure 12 depicts the mode shapes revealed by ARTeMIS. The damping ratios were found to be 1.16% and 1.06% for the first and second modes respectively.

Figure 10. Floor 2: (a) Response to heel drop in frequency domain, (b) Decay curve from RANDEC.

Figure 11. Floor 2: Response to shaker excitation.

Figure 12. Floor 2: ARTeMIS-identified mode shapes.
4.3. Discussion

As both of the test floors possessed fundamental frequencies of less than 10 Hz, they could be classified as low-frequency floors with possibility of resonant built-up response when human-induced vibrations were of concern [2,3]. The damping of the fully furnished chipboard floor was found to be significantly higher than that of the prestressed concrete floor in bare condition. The natural frequencies and damping ratios acquired from the simple heel drop test with single-point measurement compared well with those resulted from the sophisticated ARTeMIS analysis utilising multi-point measurements. The mode shapes found by the ARTeMIS analysis clearly showed the location of sensitive floor areas with large modal displacement.

5. Conclusions

Comprehensive information about the floor modal properties including the mode shapes was obtained using a thorough modal testing which required sophisticated software and hardware. Several test setups and relocation of accelerometers were needed when the number of measurement points for EMA exceeded the number of available transducers or the number of input channels of the data acquisition device. On the other hand, the much simpler heel drop test utilising single-point measurement data analysed by the RANDEC technique was found to provide a reasonably accurate evaluation of natural frequencies and damping ratios for both of the case study floors. The simple testing approach is hence really useful, particularly in the event of only limited resource being accessible.

The type of construction materials and fit-out conditions would account for the huge discrepancy between the damping values of the two test floors. The concrete floor exhibited a quite low damping ratio of about 1.1% probably because it was prestressed and in an as-built unfurnished condition when tested. It is predicted that both of the floors may be forced into resonance vibrations by people walking normally at a pacing rate of 1.8-1.9 Hz whose third and fourth harmonics closely match the fundamental frequencies of 5.64 Hz and 7.62 Hz for the chipboard floor and concrete floor respectively.

References

[1] International Organisation for Standardization. ISO 10137:2007 Bases for design of structures - Serviceability of buildings and walkways against vibrations (Geneva: ISO)
[2] Smith A, Hicks S and Devine P 2009 SCI P354 Design of Floors for Vibration: A New Approach (Ascot: The Steel Construction Institute)
[3] Murray T M, Allen D E, Ungar E E and Davis D B 2016 Steel Design Guide 11: Vibration of Steel-Frame Structural Systems Due to Human Activities (Chicago: American Institute of Steel Construction)
[4] Ewins D J 2009 Modal Testing: Theory, Practice, and Application (Philadelphia: Research Studies Press)
[5] Blakeborough A and Williams M S 2003 Measurement of floor vibrations using a heel drop test Structures and Buildings 156 367-371
[6] Ellis B R 2001 Dynamic monitoring Monitoring and Assessment of Structures ed G Armer (London: CRC Press) chapter 2
[7] Hanagan L, Raebel C and Trethewey M 2003 Dynamic measurements of in-place steel floors to assess vibration performance J. Perform. Constr. Fac. 17 126-135
[8] Reynolds P and Pavic A 2000 Impulse hammer versus shaker excitation for the modal testing of building floors Exp. Tech. 24 39-44.
[9] Davis B, Barrett A and Murray T 2011 Use of a force plate versus armature accelerometer for measuring frequency response functions Exp. Tech. 35 73-79.
[10] Reynolds P 2008 Dynamic testing and monitoring of civil engineering structures Exp. Tech. 32 54–57
[11] Hameed A F and Pavic A 2016 Multi-shaker modal testing and modal identification of hollow-core floor system *Dynamics of Civil Structures, Vol 2: Proc. of the 34th IMAC (Orlando)* ed S Pakzad and C Juan (New York: Springer) pp 331-340

[12] Cunha A and Caetano E 2006 Experimental modal analysis of civil engineering structures *Sound and vibration* 6 12-20

[13] Inman D J 2013 *Engineering vibration* (New Jersey: Pearson Prentice Hall)

[14] He J and Fu Z F 2001 *Modal analysis* (Oxford: Butterworth-Heinemann)

[15] ARTeMIS Extractor Pro. 2010 software. Aalborg East: *Structural Vibration Solutions A/S*