Investigation of traffic-induced floor vibrations in a building

Bo Li, Tuo Zou, Piotr Omenzetter

Department of Civil and Environmental Engineering, The University of Auckland, Auckland, New Zealand.

ABSTRACT: In recent years, there have been an increasing number of issues associated with traffic-induced building vibrations, concerning discomfort to occupants or damage to buildings and vibration-sensitive equipment. Due to rapid development of metropolitan cities, the vibrations and noise caused by traffic moving on the adjacent roads or highways will create more serviceability problems in modern lightweight structures. This project focused on this issue and investigated a building on the University of Auckland City Campus. A series of in-situ tests were carried out with several accelerometers and a synchronized web camera to collect the experimental data of the floor and ground responses to explore the correlation between the floor vibrations and the passing of heavy vehicles. System identification analysis was performed to estimate the modal parameters of the floor system, i.e. natural frequencies and damping ratios. Transfer functions, which describe the relations between the inputs and outputs of a system, were formulated to establish a frequency-domain model between traffic excitation and floor response. An FEM model of the structure was built and calibrated for an optimal match between analytical and experimental results. Sensitivity analysis and model updating process were performed to improve the accuracy of the model by adjusting uncertain structural parameters. Vibration levels were compared to standard guidelines and found acceptable. The study helped to better understand the problem of traffic-induced vibrations in lightweight floors and buildings.

1. INTRODUCTION

Recent statistics from around the world (Hao et al, 2001) show an increasing number of reports on vibration from heavy moving vehicles felt by occupants in the buildings as well as increasing concerns about satisfying serviceability criteria applicable to modern building floors (Pavic et al, 2007). Frequent vibrations have been experienced by some occupants of the Kate Edger Information Commons (IC) building located on the University of Auckland City Campus and adjacent to Symonds Street (Figure 1). The building consists of five levels with a total gross floor area of 12,370 square meters. The main structure of the building was constructed using 2400 mm wide Double-T precast and pre-cambered reinforced concrete floor slabs with a 65 mm reinforced concrete topping over 610 mm deep UB steel beams spanning between concrete-filled 600 mm diameter steel columns, which are the main structural elements for carrying the vertical forces (Couchman, 2004).
This research project was initiated to determine whether the traffic on Symonds Street is the reason for disturbing vibrations to the IC building and to investigate the dynamics of the building’s floor system using system identification procedures and computer modelling. MATLAB was used to perform system identification from three approaches, i.e. Stochastic Subspace Identification (SSI), Power Spectral Density (PSD) method and Transfer Function (TF) method. The natural frequencies and damping ratios from system identification were then used for fine tuning, or updating, of an FEM model built in SAP2000. Vibration levels were also compared to standard guidelines.

2. FLOOR VIBRATION TEST

The objective of this test was to detect any floor vibrations that could be caused by the passing of heavy vehicles. The test was performed during the shutdown of the building to eliminate the interference from occupants and their activities. Two vertical and seven horizontal accelerometers were used in total. Figure 2 indicates the locations of the accelerometers on Level 4 and the bottom floor. “H” indicates a horizontal accelerometer while “V” represents a vertical accelerometer. (Note the accelerometers are not numbered consecutively). In order to obtain the maximum response, the vertical accelerometer on the fourth floor was located at the centre of the floor panel, aligning with the mid-point between two columns and the horizontal accelerometers were placed on edges of the floor. To ensure that the significant responses can be traced for reasons, a web-camera was installed to record the traffic flow and started rolling synchronously with the vibration test. The total continuous duration of measurement was approximately 36 hours with sampling rate of 100 Hz.

![Figure 1: The location of the tested building](image1)

![Figure 2: Locations of the accelerometers for floor test (dimensions in meters)](image2)
3. TEST RESULTS

From the time series plots, only the vertical accelerometers recorded some noticeable vibrations while the horizontal ones just captured noise. Having installed a web-camera to capture all the traffic flow during the test, any peak found in the time series plot can be traced back to its source due to the synchronisation of the web-camera and the data acquisition system. An example of recorded acceleration time-series was shown in Figure 3 with pairs of vertical red lines representing the arrivals of the heavy vehicles as recorded by the camera. The acceleration threshold which is regarded as a significant peak above the ambient noise level is ±0.0066 m/s² (green lines), and that was selected using a trial-and-error method to provide an optimal correlation between acceleration peaks and vehicle passages.

![Figure 3: Matching of the peaks of the 4th floor vertical acceleration with heavy vehicle passing](image)

Figure 3 shows that for this particular time period, all the peaks in acceleration corresponded to the passing of some heavy vehicles. This observation demonstrates that the passing of heavy vehicles is able to cause increased vertical vibrations in the IC building floors. From all 36 hours of vibration record, the majority of the buses and trucks passages could be directly related to peaks in the time series plots, the overall correlation coefficient being 83%. This is a high enough correlation to prove that heavy vehicles do cause floor vibrations. However, the magnitudes of the vibration accelerations were always of a similar order to those shown in Figure 3 and thus not significant enough to be considered a problem to the occupiers of the building since all the peak accelerations were far below the conservative threshold of 0.03 m/s² above which the vibration may cause discomfort according to BS6841:1987 (British Standards, 1999).

4. EXPERIMENTAL INVESTIGATION VS. ANALYTICAL COMPUTER MODELLING

It is common to compare the natural frequencies obtained from the experimental data via system identification with the natural frequencies obtained from the computer model. The natural frequency obtained from the experimental data is considered as the true natural frequency. The goal of the computer modelling and model updating was to formulate an accurate model of the structure which gives the similar natural frequencies. The process of modelling and updating is summarized in Figure 4 and subsequent sections provide detailed explanations and discussions.
4.1 System identification

System identification is a process of formulating a mathematical description of the dynamic behaviour of a system in either the time or frequency domain. By performing system identification, using SSI and PSD methods, the modal parameters such as natural frequencies and damping ratios of the floor system were determined. The natural frequencies above 25 Hz are of less interest; therefore a low-pass filter was applied to the raw data to trim the frequencies larger than 25 Hz.

4.1.1 Stochastic Subspace Identification

For system identification of the floor, firstly the SSI algorithm (Overschee and Moor, 1996) was performed due to its advantage of allowing input to be unknown for ambient dynamic testing as in the present traffic-induced building vibration experiment. SSI algorithm allows for a quick, simple and accurate determination of linear multivariable models. A stochastic subspace model can be written as

\[
\begin{align*}
\mathbf{x}_{k+1} &= \mathbf{A}\mathbf{x}_k + \mathbf{K}\mathbf{e}_k \\
\mathbf{y}_k &= \mathbf{C}\mathbf{x}_k + \mathbf{e}_k
\end{align*}
\]

where \( \mathbf{x}_k \) is the state vector of the process, \( \mathbf{y}_k \) is the output and \( \mathbf{e}_k \) is the noise vector at a discrete time instant \( k \). \( \mathbf{A}, \mathbf{C} \) and \( \mathbf{K} \) are dynamical system matrices. The SSI identifies the state space matrices by implementing QR-factorization and singular value decomposition. Once the state space matrices are found, natural frequencies, damping ratios and mode shapes can be determined from eigenvalue decomposition. The core idea is to produce the projection of the row space of the future outputs into the row space of the past outputs.

4.1.2 Power Spectral Density method

PSD method, also called peak-picking method, is a frequency-domain based algorithm. The spectral density describes how the power of a time series is distributed with frequency (Kay and Marple, 1981). For reducing the noise due to imperfect and finite data, the Welch method (Proakis and Manolakis, 1996) was used in this project. The Welch method, based on periodogram and the Bartlett method, estimates the power of the signal and thus converts a signal from the time domain into the frequency domain. It reduces noise by splitting the signal into overlapping segments, windowing them and averaging PSD estimates from the signal segments. Figure 5 shows a PSD of a piece of the vertical signal recorded in this research obtained using the Welch method.
The experimental natural frequencies of the floor from the two methods were compared and the results are shown in Table 1. From the table, the frequencies estimated using two methods are close, providing confidence in the experimental results. The fundamental natural frequency of the IC building floor is about 6.68 Hz.

4.1.3 Transfer function of acceleration between the ground floor and the 4th floor

TF is a mathematical description of the relation between the input and output of a linear time-invariant system. The IC building can be regarded as a linear system by assuming no cracks in concrete structural elements or yielding of steel, which is justifiable for small amplitude vibrations. Also by assuming constant stiffness of the structural elements, the IC building can fulfil the time-invariance requirement. Therefore it is valid to model the dynamics of the IC building using the TF method.

Mathematically, the TF of a system, denoted as $H(s)$, is the ratio of the Laplace transform of the output $Y(s)$ to the Laplace transform of the input $X(s)$:

$$H(s) = \frac{Y(s)}{X(s)}$$  \hspace{1cm} (2)

The TF between the ground floor and the 4th floor vertical accelerations for twenty random selected data sets were estimated using the Welch method. The mean absolute values of TF are shown in Figure 6. The peaks in Figure 6 occur at the frequencies very close to the corresponding peaks visible
in Figure 5 and listed in Table 1. In addition, Figure 6 has also a few new, smaller peaks. However, there are also marked differences in the level of TF and PSD values of the corresponding peaks. From Figure 5, most of the floor vibration energy corresponds to the modes at approximately 6.68 and 9.65 Hz. However, the particular TF considered demonstrates the levels of vibrations between the ground and 4th level floors are strongly magnified for the modes at approximately 15.1 and 21.6 Hz (note the former was identified above 16 Hz by SSI and PSD methods).

![Figure 6: TF of accelerations between the ground and 4th floor](image)

4.2 **Computer modelling and model updating**

To build an accurate FEM model in order to simulate the real structure, the as-built structural drawings were used. A model of the whole building was constructed using SAP2000 and is shown in Figure 7. Using this whole building model, the fundamental vertical frequency was found to be 6.29 Hz using concrete Young’s modulus of 25 GPa. This value is close to the experimental one but could be improved via model updating.

![Figure 7: 3-D model of the whole building](image)

In order to improve the accuracy of the model, simple model updating was performed to reduce the initial difference between the analytical model frequency and experimental frequency of the fundamental vertical mode of the floor. Model updating is a process of systematic adjustment of model...
parameters, usually mass and stiffness, in order to match target parameters such as natural frequencies and mode shapes.

The updating used the sensitivity method. The definition of sensitivity is that it represents the ratio of an infinitesimal change in a given target value to an infinitesimal change in model parameter, or mathematically

\[ S_{ij} = \frac{\partial R_{ai}}{\partial P_j} \]  

(3)

where \( R_{ai} \) is the i-th model output, and \( P_j \) is the j-th model parameter. The larger the sensitivity ratio, the larger the parameter’s influence on the target value. In this research, sensitivity was calculated by replacing derivative with finite differences \( S_{ij} = \frac{\Delta R_{ai}}{\Delta P_j} \). This approximation works well for reasonably small changes of the model parameters. Sensitivity method for model updating is based on the following Taylor expansion:

\[ \mathbf{R}_{ai}(\mathbf{P} + \Delta \mathbf{P}) = \mathbf{R}_{ai}(\mathbf{P}) + \frac{\partial \mathbf{R}_{ai}(\mathbf{P})}{\partial \mathbf{P}} \Delta \mathbf{P} = \mathbf{R}_{ai}(\mathbf{P}) + \mathbf{S}(\mathbf{P}) \Delta \mathbf{P} \]  

(4)

where \( \mathbf{R} \) is the vector of analytical model outputs, \( \mathbf{P} \) is the vector of the model parameters, and \( \mathbf{S} \) is the sensitivity matrix. In order for the analytical model outputs to become equal to their experimental counterparts the required change of model parameters can be found as

\[ \Delta \mathbf{P} = \mathbf{S}^+ (\mathbf{P}) \left[ \mathbf{R}_{ai}(\mathbf{P} + \Delta \mathbf{P}) - \mathbf{R}_{ai}(\mathbf{P}) \right] \]  

(5)

where \( \mathbf{S}^+ \) is the pseudoinverse of \( \mathbf{S} \). Because the Taylor expansion on Equation 4 ignores higher order terms, iterative application of Equation 5 is normally required to obtain satisfactory results.

The natural frequencies of the building depend on mass and stiffness. Usually, the mass of a building is more certain and is consequently not chosen as a variable updating parameter. In terms of stiffness, there are three main aspects that need to be considered. They are Young’s modulus, element cross-section dimensions and boundary conditions. The sizes of the elements (beams, slabs and columns) were assumed certain in this case. Boundary condition involve member connectivity and support conditions. The type of support of the building columns on foundations will have negligible effect in the case of vertical modes of floor vibration. However, the boundary conditions for the support of the floor beams are more important. These connections were assumed to be hinged. Young’s modulus of concrete was considered to be the most uncertain parameter and was selected for updating.

The value of concrete Young’s modulus was updated from 25 GPa to 29.6 GPa in four iterative steps. This was considered to be accurate enough, yielding the natural frequency value of 6.68 Hz.

5. **CONCLUSIONS**

By performing system identification using the ambient test results of the IC building and formulating a computer model of the structure, the findings of this project are as follows:

1. Heavy vehicles are able to cause floor vibrations in the IC building.
2. The traffic-induced vibrations are mainly in the vertical direction and affect floors.
3. The traffic-induced floor vibration level is hardly able to cause discomfort of building occupants as its intensity is well below a conservative threshold adopted after BS6841:1987 (British Standards, 1999).
4. The fundamental frequency of the 4th level floor system is approximately 6.68 Hz.
5. The natural frequency obtained from the computer model is 6.68 Hz after model updating process. This indicates that model updating led to an accurate structural model. Although the ambient traffic is not able to cause significant floor vibrations, the occupants of the IC building are still observing annoying vibrations. Therefore further research should focus on human-induced vibrations in the building.

6. REFERENCES


