

Analysis of the Effect of Vibration from Footfalls on Office Building

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Abstract Human footfalls are the main source of vibration in office building and it could affect the structure of the building as well as causing discomfort and annoyance to the occupants of the building when the vibration level inside the building exceeds the recommended level. The objectives of the study are to determine the level of vibration on each floor of a multi-storey building due to footfalls and to perform structural response on the multi-storey building due to footfalls input. The selected building for this study is Registrar Office building located in Universiti Tun Hussein Onn Malaysia (UTHM). The scope of study is focused on the effect of vibration induced by footfalls on multi-storey building and analyzing the data using MATLAB and ANSYSv14. The real inputs of vibration induced by footfalls were measured and obtained using Laser Doppler Vibrometer (LDV). The vibration level induced by footfalls on the multi-storey office building can be determined using Vibration Criteria (VC) guidelines. Finally, from the study, the vibration level achieved for this Registrar Office building is in ISO level range which is still under the acceptable limit for office building.

Keywords Vibration · Footfalls · Multi-storey · Dynamic analysis

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1 Introduction

Vibration in buildings is a common problem and concern especially in big cities because of the daily activities such as road traffic, construction work and even from internal vibration, such as from machinery and human itself. In 1831, in Manchester, England, the Broughton Suspension Bridge had collapsed due to vibration when soldier were marching over it [1].

Vibration in building could reach a level that may not be acceptable to the building occupants and may have an effect such as annoying physical sensations, interference with activities such as work, annoying noise caused by rattling of window panes, walls and loose objects and also interference with proper operation of sensitive instruments.

Vibration can also effect sensitive equipment due to transmission of vibration which will cause interference with its proper operation. Computers and scanners are examples of sensitive equipment normally located in the office building. The Registrar Office building is selected because it is a multi-storey building with occupants and computers on each floor level. The effect of vibration induced by footfalls will be investigated in this study.

There are two objectives in this study, the first one is to perform structural response on the Registrar Office building under vibration due to footfalls input and secondly is to determine the level of vibration due to footfalls on Registrar Office.

2 Internal Vibration Induced by Footfalls

Internal sources are a set of vibration sources acting inside a building, such as from mechanical excitation like washing machine or human activity itself by proving either continuous or transitory types of vibration. However, the possibility of internal vibration can be felt by residents in a building depends on the frequency source and resonance frequency and damping of the structural elements that propagate the vibration through the building. Thus, this problem is more common in high rise building [2].

Davenny [3] concluded that internal vibration from footfall is often the major source of floor vibration compare to machinery. In a word, building floor will vibrate at its natural frequency in response to a footstep impulse and is most severe at the middle of the floor and least severe near the columns.

Vibration from footfall is induced from the movement phases of legs and feet during walking. Hence, the body weight is transferred to the floor. Figure 1 shows the movement phases of legs and feet during walking.

Fig. 1 Phases of legs and feet during walking [4]

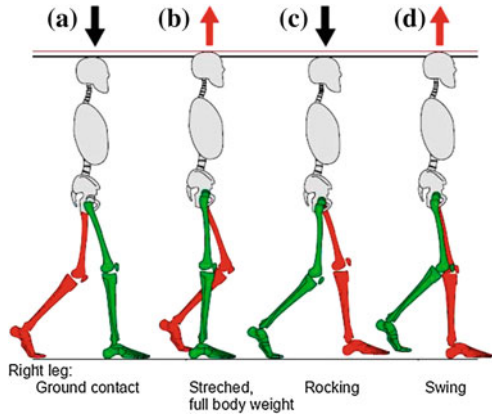


Table 1 Footfalls rate [5]

Frequency (Hz)	Designation
1.5–1.8	“Normal walking” for cellular areas
1.8–2.0	“Someone who is in hurry”
2.0–2.4	“A very brisk pace” considered likely in corridors

When the right foot touches the ground with the heel, this is the starting point of the contact forces and when the right leg is stretched, the full body weight is transmitted to the floor. Next, the right foot will rock while the left leg swings forward. This is called “Rocking”. And finally, the left foot touches the ground while the right leg swings forward.

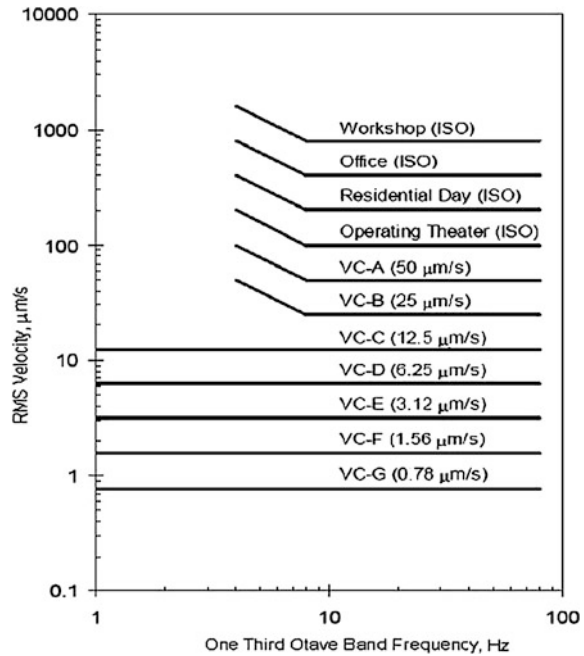
However, the vibrations due to footfalls also depend on the speed of walking. A more general footfall rate classification prepared by Arup [5] is presented in Table 1.

3 Vibration Criteria (VC) Curve

In this study, a specific vibration criteria guideline was used in order to investigate and obtain the performance of the structures. The curves and descriptions were intended to meet the needs of all tools within each category as the previous researchers could judge based on experience mingled with tool-specific specifications [6].

Vibration criteria curves is important as a guideline in designing facilities such as buildings and instruments that are sensitive to vibrations [4]. Each curve of the criteria are associated with line width or size detail which is a representation of the device capabilities [7] as shown in Fig. 2. The form of the criteria is taken through a

Fig. 2 Generic vibration criteria (VC) curves for vibration sensitive equipment [7]



set of one-third octave band velocity where the generic vibration criteria ranges from ISO for the effects of vibration on human occupants in building to VC-G for evaluation only [4].

Table 2 shows the application and range of the vibration criteria limits including ISO criteria for human taking into account through experience on past and present projects [7].

4 Field Measurement at Site

Field measurement was conducted to obtain the signal data for this study by using the Vibrometer equipment. The amplitude of the vibration produced by footfalls is measured during office hour on working days. Figure 3a shows the Vibrometer equipment used in this study, Laser Doppler Vibrometer (LDV 100) and Fig. 3b shows the location of the measurement in the office building, while Fig. 4 shows the side view of the Registrar office building.

The footfall vibration measurement conducted inside the building produced the vibration waves as shown in Fig. 5. Next, this raw data must be processed and analyzed using specific algorithm in Mathematics Laboratory (MATLAB) to obtain

Table 2 Application and range of the vibration criteria curve [7]

Vibration curve	Amplitude (µm/s)	Detail size (µm/s)	Application and experience
<i>a</i>			
Workshop (ISO)	800	N/A	Distinctly perceptible vibration. Appropriate to workshops and no sensitive areas
Office (ISO)	400	N/A	Perceptible vibration. Appropriate to offices and no sensitive areas
Residential day (ISO)	200	75	Barely perceptible vibration. Appropriate to sleep areas in most instances. Usually adequate for computer equipment, hospital recovery rooms, semiconductor probe test equipment and microscopes less than 40×
Operating theatre (ISO)	100	25	Vibration not perceptible. Suitable in most instances for surgical suites microscopes to 100× and other equipment of low sensitivity
<i>b</i>			
VC-A	50	8	Adequate in most instances for optical microscope to 400×, microbalances, optical balances, proximity and projection aligners, etc.
VC-B	25	3	Appropriate for inspection and lithography equipment (including steppers) to 3 µm line widths
VC-C	12.5	1–3	Appropriate standard for optical microscopes to 1,000×, lithography and inspection equipment (including moderately sensitive electron microscopes) to 1 µm line widths. TFT-LCD stepper/scanner processes
VC-D	6.25	0.1–0.3	Suitable in most instances for demanding equipment, including electron microscopes (TEMs and SEMs) and E-beam systems
VC-E	3.12	<0.1	A difficult criterion to achieve in most instances. Assumed to be adequate for the most demanding of sensitive systems including long path, laser-based, small target systems. E-beam lithography systems working at nanometer scales and other systems requiring extraordinary dynamic stability
VC-F	1.56	N/A	Not recommended for use as a design criterion, only for evaluation
VC-G	0.78	N/A	Not recommended for use as a design criterion, only for evaluation

N/A not available

a signal input which can be used to further analyzed in finite element modeling using ANSYS software to obtain the natural frequency, mode shapes and time history of the building.



Fig. 3 a Laser Doppler vibrometer (LDV 100). b Measurement at site



Fig. 4 Registrar office building (side view)

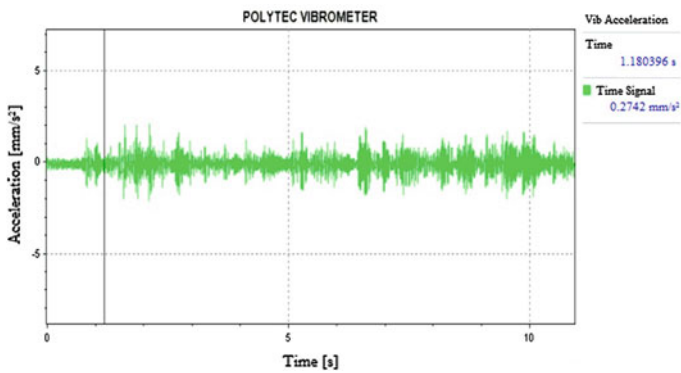


Fig. 5 Vehicles vibration waves measured by LDV 100

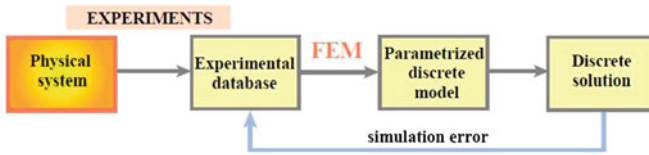


Fig. 6 Finite element method process [8]

5 Finite Element Method (FEM)

The process of FEM is shown in Fig. 6, and it is applied using the ANSYS and MATLAB software. In this study, the numerical simulation of vibration response on the Registrar office building was carried out by using ANSYS, finite element package software and a tool developed using MATLAB interface and algorithm known as Vibration Serviceability Assessment Tools (VSATs).

All relevant outputs from ANSYS were processed in MATLAB programs, where it will analyze the data from ANSYS and the output produced will be used to determine the level of vibration subjected by the building. Next, the data will then be compared to the vibration criteria curves which are used as a guideline in this study.

6 Results and Discussions

6.1 Mode Shape Analysis

Mode shape analysis was performed to determine the condition of the floor structure of the Registrar office building when subjected to different frequency modes. The first tenth modes are shown in Fig. 7. The fundamental mode of the building has a natural frequency of 1.02 Hz and shows no obvious deformation for the rest of the modes. Changes in the horizontal direction are not taken into account as the displacement at the column is not considered in this study. Only the vertical direction which shows changes on floor behaviour is taken into consideration.

The highest peak displacement for both directions is represented by the red area while the minimum displacement is represented by the blue area. For areas with the highest deflection, it is not recommended for sensitive equipment. The occupants in that area may also be affected.

A detailed description for each mode as shown in Fig. 7 is described in Table 3 for both horizontal and vertical directions. The model was analyzed under 100 modes to obtain the peak response of natural frequency and vertical behavior of the building floor structure.

Mode shape analysis is used to determine the condition of the floor structure of the building when subjected to different frequency modes. Highest peak displacement is

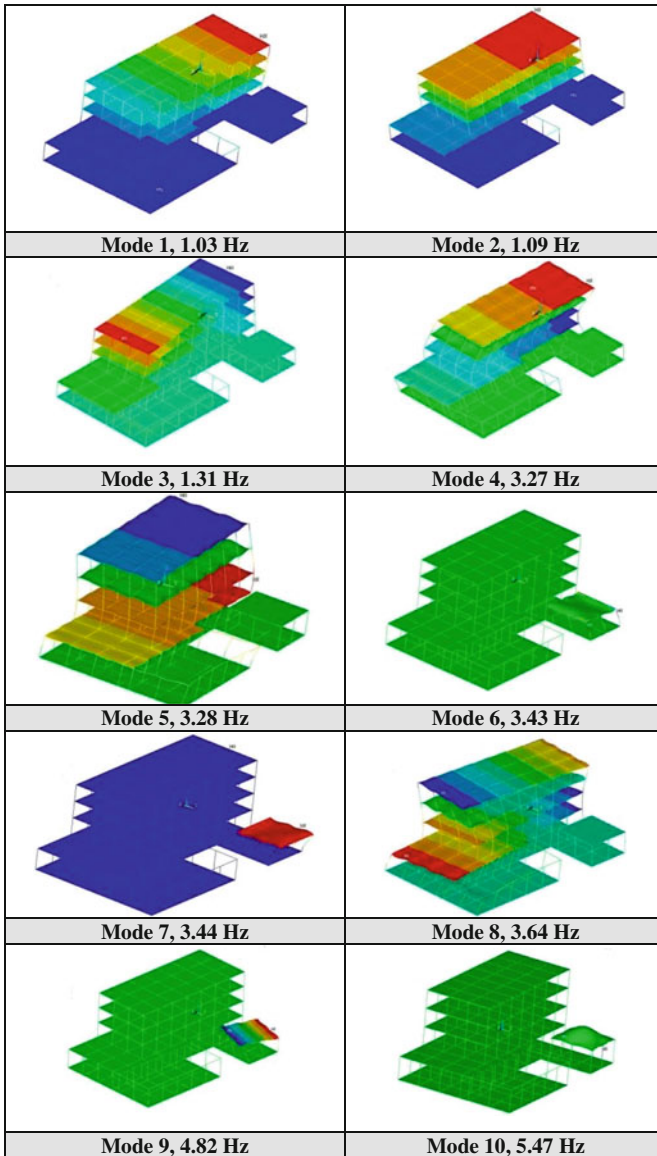


Fig. 7 First ten mode shapes of the Registrar office building

represented by the red area while the minimum displacement is represented by the blue area. Green areas shows a little displacement and not so obvious. For areas with the maximum deflection, that area is not suitable for sensitive equipment and people in this area may also be affected.

Table 3 Mode description for first ten modes

Mode/frequency (Hz)	Mode description	Displacement value (mm)
<i>a</i>		
Mode 1/1.03	Horizontal: small displacement	0.429
	Vertical: small displacement	1.543
Mode 2/1.09	Horizontal: small displacement	1.067
	Vertical: very small displacement	0.269
Mode 3/1.31	Horizontal: very small displacement	0.631
	Vertical: medium displacement	2.056
Mode 4/3.27	Horizontal: small displacement	0.856
	Vertical: small displacement	0.802
Mode 5/3.28	Horizontal: very small displacement	0.661
	Vertical: small displacement	0.931
<i>b</i>		
Mode 6/3.43	Horizontal: medium displacement	3.747
	Vertical: very small displacement	0.0159
Mode 7/3.44	Horizontal: very small displacement	0.0175
	Vertical: medium displacement	3.753
Mode 8/3.65	Horizontal: very small displacement	0.55
	Vertical: medium displacement	1.719
Mode 9/4.82	Horizontal: small displacement	4.064
	Vertical: small displacement	8.089
Mode 10/5.47	Horizontal: very small displacement	0.579
	Vertical: very small displacement	0.584

6.2 Vibration Serviceability Assessment Tools (VSATs)

VSATs is a MATLAB based GUI driven software developed to analyze and assess the vibration serviceability state of large structures such as footbridges. The software enables results from different models to be compared and can also be used for assessing vibration serviceability of structures where the model properties and serviceability is known [9].

Figure 8 shows the mode shapes of the first tenth modes obtained using VSATs analysis. Results obtained from VSATs in Fig. 8 shows the mode shape of each floor be identical or almost identical with the mode shape obtained in Fig. 7.

6.3 Vibration Criteria (VC) Analysis

Vibration serviceability analysis was carried out on each floor using VSATs. Figure 9a shows the vibration input and Fig. 9b shows the response after applying the input from field measurement on the third floor of the Registrar Office building.

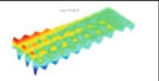
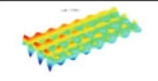
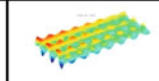
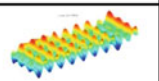
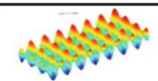
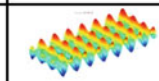
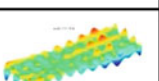
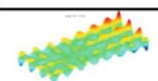
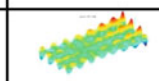
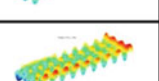
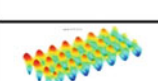
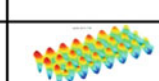
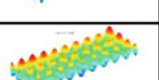
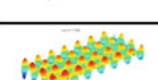
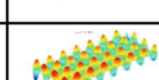
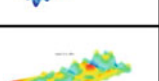
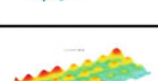
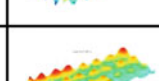
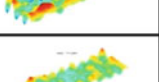
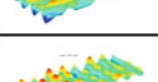
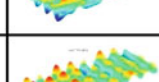
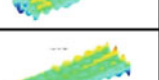
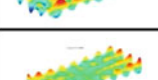
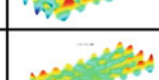
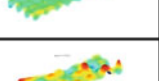
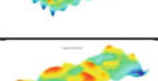
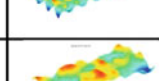
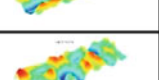
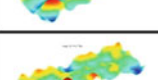
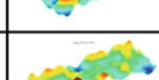
Mode/ Frequency (Hz)	First Floor	Second Floor	Third Floor
1/ 1.03			
2/ 1.09			
3/ 1.31			
4/3.27			
5/ 3.28			
6/ 3.43			
7/ 3.44			
8/ 3.64			
9/ 4.82			
10/ 5.47			

Fig. 8 Deform shape in VSATs, **a** first floor, **b** second floor, and **c** third floor

The dark blue areas represent the highest VC level which is above ISO standard, unsuitable for area with sensitive equipment while the light blue areas represent the ISO standard VC level, appropriate for office and no sensitive areas. The brown area represents VC-E, the lowest VC level.

All three floors show almost the same vibration response where the response obtained for each respective floor is in ISO standard range when referred to the

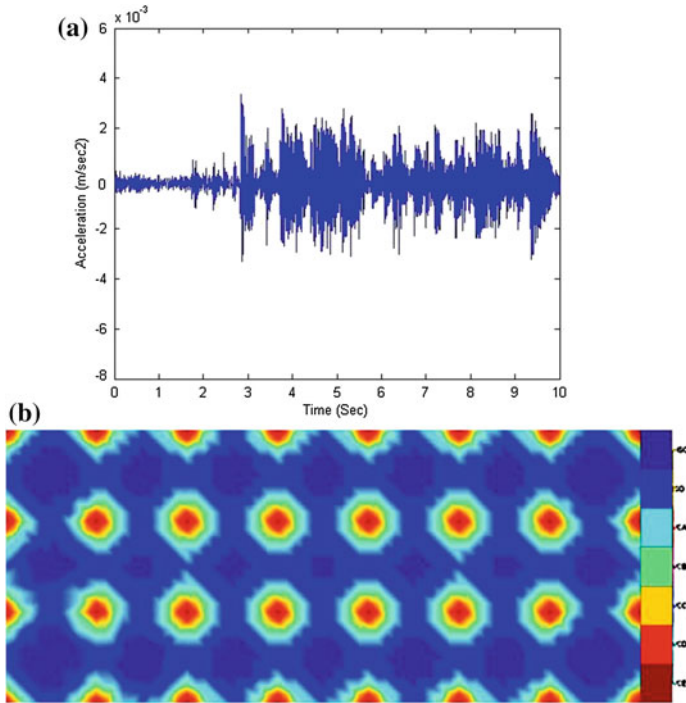


Fig. 9 a Vibration input and b response on the third floor of the Registrar office building

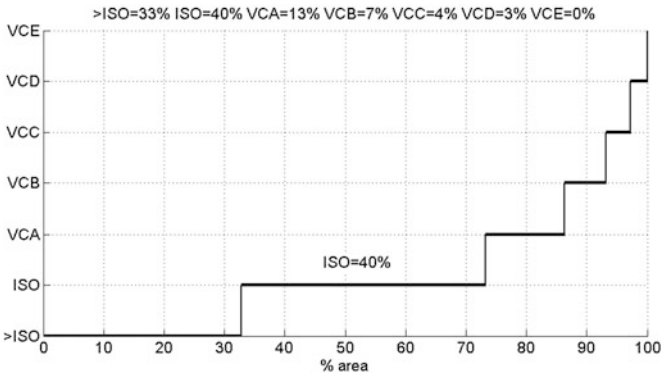


Fig. 10 The vibration criteria value on the third floor of Registrar office building

generic criteria guideline [4], 38 % ISO for first floor, 39 % ISO for second floor and 40 % ISO for the third floor. The vibration response for third floor is shown in Fig. 10.

7 Conclusion

The average value for the vibration criteria of the Registrar office floors are ISO level with the percentage of 38 % for the first floor, 39 % for the second floor and 40 % for the third floor. For the above ISO level, the percentage for first floor is 34 and 33 % for both the second and third floor. Referring to Table 2, the maximum value of amplitude for ISO level is 400 $\mu\text{m/s}$, which is appropriate for office building with no sensitive equipment. Whereas, the maximum value of amplitude for above ISO level is 800 $\mu\text{m/s}$, which is appropriate for workshop. Therefore, the maximum response value obtained from footfall is acceptable as the response obtained is mainly at the range of ISO and below. Thus, the vibration level would not affect the building structure, occupants and any electronic office equipment in this office.

It is really important to ensure that vibration level in building does not exceed the recommended standard to avoid costly repair of structure damage, replacement of electronic equipment and annoyance to the occupants in building. The objectives were achieved where the structural response on the UTHM's Registrar office building subjected to the footfalls vibration input was obtained and it was within the acceptable limit based on the generic vibration criteria.

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