Vibration Criteria Analysis on Floor due to Human Walking

T N T Chik, P C Xian and N A Yusoff

1 Faculty of Civil and Environmental Engineering, Universiti Tun Hussein Onn Malaysia, 86400, Parit Raja, Batu Pahat, Johor, Malaysia
2 Research Center for Soft Soil, Universiti Tun Hussein Onn Malaysia, 86400, Parit Raja, Batu Pahat, Johor, Malaysia
Corresponding author: thayati@uthm.edu.my

Abstract. The development of concrete material technology and modern structural design pattern in Malaysia may not consider the effect of vibration from seismic and other sources. Floor vibration may affect the serviceability of the structural and also provide uncomfortable environment to occupants. The main purpose of this study is to investigate the dynamic analysis on floor at the first floor of Faculty of Technology Management and Business (FPTP) building. The analyses are compared with the vibration criteria guidelines by Gordon (1991) to identify the vibration sensitivity of the floor. The investigation on floor vibration due to people walking is using Finite Element Modelling (FEM) in ANSYS software in order to perform modal analysis and transient analysis. Modal analysis shows the result of the natural frequency of the floor and different mode shapes react with subjected various frequency. The time history of the vibration signal will be performed by transient analysis. Furthermore, the results are transferred to MATLAB software (e.g. VSATs) to assess the vibration criteria curve. The result of the vibration plot show the middle of floor panel and laboratory room are categorized under ISO level. Therefore, it can be concluded that this room is not suitable to accommodate the sensitive equipment particularly at the middle of the floor.

1. Introduction

Floor vibration generally makes people anxious and creates panic of structural collapse, even though there is only small displacements and stresses that are actually produced [1]. FPTP building is located in Universiti Tun Hussein Onn Malaysia (UTHM) campus received a complaint regarding the floor vibration in survey and construction laboratory. Therefore, the purpose of conducting this study is to analyse the amplitude of the vibration and sensitive area due to human walking vibration. Dynamic analysis is used to find the physical structures behaviour dynamically subjected to the forces. Modal analysis is the investigation of the dynamic testing of the structures under vibration excitation. Modal analysis can verify the parameter of natural frequency, natural mode, damping factor, modal scaling and etc. [2]. Two major parameters concerned in this study which are natural frequencies and mode shapes in designing a structure for dynamic loading condition. While, transient analysis is used to verify the dynamic response of the structure under the action of any general time-dependent loads. It can produce the time-varying displacement, strains, stresses and forces in a structure as it response to any combination of static, transient and harmonic motion [3].

First floor of FPTP building are investigated due to the dynamic response in serviceability condition by using ANSYS software. This software is used to run modal and transient analysis. The results are transferred to MATLAB software to perform the vibration curve and vibration plot of the floor. Moreover, the vibration curve and vibration plot results are compared with the vibration criteria curve.
by Gordon [4] in order to determine the vibration sensitivity of floor. Vibration criterion curves were enhanced in the 1980’s, it is a design standard to assist a wide range of tools and instruments used by microelectronics, medical and biopharmaceutical industries [4]. Vibration is produced when subjected to the significant of dynamic, it might cause the building structure damage and human comfort when the amplitude is high. This study can be a reference sources due to vibration sensitivity on low consideration of vibration safety factor in the design building guidelines.

2. Literature review

The development of the concrete material technology and modern structural design may focus on cost, material and beautiful. Modern structures adopt high strength and lightweight construction materials resulting in decreased structural mass and damping properties. Vibration system involve the transfer of potential energy to kinetic energy and kinetic energy to potential energy. Energy in a cycle of vibration dissipated should replace with external sources to maintain the state of steady vibration [5].

2.1 Types of vibration

2.1.1 Free vibration
Free vibration is the natural response of a structure to some influence or displacement to produce oscillation where the total energy stays the same over the time. This is theoretical idea because in reality the energy will be dissipated to the surrounding over the time amplitude decays away to zero, this dissipation of energy is called damping. The damping effect will depend on the characteristics of the materials and also the condition of vibration.

2.1.2 Forced vibration
Forced vibration is the reaction of a structure with forces that cause the structure vibrate at the frequency of the excitation. When present the external force in the system correspond with one of the natural frequency of the system will produce resonance amplitude in the system. Therefore, the amplitude of the force is corresponding to the vibration level.

2.2 Sources of vibration
Floor vibration is produced by dynamic loads applied either directly or indirectly to the floor system producing motion sufficient to be perceptible by the occupants. The temperature and humidity effect will affect the frequency occur from sources [6]. When the temperature increase will deteriorate the modulus of elasticity of concrete significantly causing the natural frequency decrease. Natural frequency also decrease with humidity increase because the specific absorbs more water in high humidity environment and increase mass.

2.2.1 External forces
Floor vibration that caused by the external sources includes ambient vibration at the site, nearby road and rail traffic, construction activities and machinery running nearby buildings. For a tall building, wind load also consider as sources to contribute vibration to floor structure. With rapid urbanization, high-density development with housing, industrial and commercial areas are organised caused the building being constructed close to the road and highways. Traffic induced ground vibration could be examined as continuous in nature and concluded that can damage the structure if peak particle velocity exceeds 5mm/s and structural damage may take place if exceed 10 mm/s [7].

2.2.2 Internal forces
The source of internal force may include human activities, elevator and conveyance system and service machines. This research will only consider the floor vibration due to people walking. According to research done by Murray, Allen and Ungar concluded a repeated force can be represented by a combination of sinusoidal force whose frequencies, $f$ are multiples or harmonics of the basic frequency of the force repetition [8]. Walking vibration action on long-span floor has shown that the higher modes of vibration need not be appraised because they die out quickly and do not cause discomfort [9].
2.3 Arup prediction method

According to Arup, a floor with fundamental frequencies above 10Hz can use an empirical formula, \( L_{eff} = 42 f^{0.43} / f_n^{1.3} \) (where \( f \) is pacing rate and \( f_n \) is floor frequency). Figure 1 shows the damping is largely irrelevant when the maximum velocity occurs the instant the impulse is applied and the decay is redundant [10].

![Figure 1. Response using Arup formula [10]](image)

2.4 Dynamic analysis

Dynamic analysis is a simple extension of static analysis by adding the inertia force from the loads or displacement applied. In real structures, computer model is used to simulate the behaviour of the structure because structures potentially have an infinite number of node (joint) displacement [11]. There is various structural dynamic analysis can perform by using modal analysis and transient analysis to analyse the floor vibration.

2.4.1 Modal analysis

Modal analysis is used to verify the vibration characteristics of a structure or machine component to perform the natural frequencies and mode shapes. Design a structure for dynamic loading condition, natural frequencies and mode shapes are the parameters. The parameter depends on the material properties (mass, damping and stiffness) and boundary conditions of the structure [12]. Silva et al. (2003) have evaluated the dynamic performance of composite slab with various load frequencies induced by humans which are slow walk, standard walk, fast walk, standard run and fast run [13].

The reciprocal of the period is the natural frequency of an object that oscillation of the mass continuously. The period is a time interval to complete a cycle of oscillation and it can be derived as,

\[
f_n = \frac{1}{2\pi} \sqrt{\frac{k}{m}}
\]

where the relation of natural frequency to static deflection is shown by diagonal-dashed line with substitute the stiffness, \( k = mg/\delta_n \) [14].

2.4.2 Transient analysis

Transient analysis is used to calculate the dynamic response of a structure under the forces of any general time-dependent loads. Transient analysis can find out the time-varying displacements, strains, stresses and forces in a structure as it responds to any combination of static, transient and harmonic loads [15]. Pavic et al. [16] has investigated the time-domain analysis established on the application of a single or several pulse representing footfall impact. It analyse with applied a single impulse and a series of impulses loads at either antinodes of the modes or test point. Time history is a linear or nonlinear evaluation of dynamic structural response under loading which may vary according to specified time
function. The basic elements equation of the dynamic system is \( F(t) = ma + cv + kx \), where \( m \), \( c \) and \( k \) refer to mass, viscous damping coefficient and stiffness [17].

2.5 ANSYS software

ANSYS software is based on finite element algorithmic the powerful numerical value simulation software, it is exploited by the Swanson Analysis System Inc. The characteristic of ANSYS software is convenience, comprehensiveness, facility, supernal performance and agility plot function, meshing grid function, multi-selective iterative solution function and powerful postprocessor function. Pavic et al [16] have used ANSYS software to analysis the walking induced vibration at three storey blocks which have both office and laboratory space on each of the floors. Figure 2 shows the entire floor surface was performed in 3D finite element model.

![3D pre-test finite element model](image)

**Figure 2.** 3D pre-test finite element model [16]

2.6 MATLAB software

Vibration Serviceability Assessment Tools (VSATs) is a MATLAB based GUI-driven software developed in Vibration Engineering Section with the aim to analyse and assess the vibration serviceability limit state of large slender civil engineering structure. Moreover, ModalV function is used to perform root-mean-square velocity spectra by input the result of transient analysis from ANSYS in one-third octave band generic vibration criteria [18].

2.7 Generic vibration criteria

The vibration criterion (VC) curves were developed by Gordon and his colleague in 1980, but due to time passed the curves were extended to reflect the needs of technology and tool developments, primarily in the microelectronics industry. There were five types of VC curve, which are curve VC-A to VC-E that shows particular equipment category the measured one-third octave band velocity spectrum shown in Figure 3 [4].

3. Materials and methods

The structural plan of FPTP building was analysed to obtain the required information such as parameter and geometry by using ANSYS structural analysis software. It is essential to solve dynamic analysis with using batch mode. In modal analysis, the first step is build the model with the information from structural plan and apply load by using data from previous researcher. Then, the analysis was ran and produced the natural frequency and mode shapes of the structure. Next, transient analysis was performed with mode superposition method. It sums factored mode shapes (eigenvectors) from a modal analysis to calculate the building response.
The next stage is ModalV analysis which is in house developed in MATLAB software was ran to perform vibration curve from ANSYS result. The results obtained is one-third octave RMS velocity spectra will compare to the vibration criteria curve to determine the vibration sensitivity level of floor. Then, Vibration Serviceability Tools (VSATs) analysis with import and specify analysis was performed to produce the floor vibration response using loaded modal parameters. The vibration response was generated by plotting the response due to vibration criteria guidelines.

![Figure 3. Generic VC curve for vibration-sensitive equipment [4].](image)

**Table 1.** Application and interpretation of the generic vibration criterion (VC) curves [4].

| Criterion curve        | Amplitude $^1$ $\mu$m/s ($\mu$m/s) | Details size $^2$ $\mu$m | Description of use                                                                 |
|------------------------|-------------------------------------|---------------------------|-----------------------------------------------------------------------------------|
| Workshop (ISO)         | 800 (32 000)                        | N/A                       | Distinctly perceptible vibration. Perceptible vibration. Appropriate to workshops and nonsensitive areas. |
| Office (ISO)           | 400 (8 000)                         | N/A                       | Barely perceptible vibration. Perceptible vibration. Appropriate to offices and nonsensitive areas. |
| Residential day (ISO)  | 200 (8 000)                         | 75                        | Vibration not perceptible. Suitable in most instances for surgical suites, |
| Operating theatre (ISO)| 100 (4 000)                         | 25                        |                                                                                   |
The 2nd Global Congress on Construction, Material and Structural Engineering
IOP Conf. Series: Materials Science and Engineering 713 (2020) 012046 doi:10.1088/1757-899X/713/1/012046

6

microscopes to 100x and for the other equipment of low sensitivity.
Adequate in most instances for optical microscopes to 40x, microbalances, optical balances, proximity and projection aligners, etc.
Appropriate for inspection and lithography equipment (including steppers) to 3 µm line widths.
Appropriate standard for optical microscopes to 100x, lithography and inspection equipment (including moderately sensitive electron microscopes) to 1 µm details size, TFT-LCD stepper/scanner processes.
Suitable in most instances for demanding equipment, including many electron microscopes (SEMs and TEMs) and E-Beam systems.
A challenging criterion to achieve. 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 nonometer scales, and other systems requiring extraordinary dynamic stability.
Appropriate for extremely quite research spaces; generally difficult to achieve in most instances, especially cleanrooms. Not recommended for use as a design criterion, only for evaluation.

4. Results and discussions
The model of the FPTP Building by Floor, Room and Panel have been modelled by ANSYS software. ANSYS software is used to carry out modal analysis to perform the natural frequency and mode shape of building. In addition, transient analysis perform the time history (acceleration versus time graph) of the response from the results of previous researcher due to human walking vibration. Furthermore, all of the data will transfer to MATLAB perform the vibration curve and vibration plot with compared to the generic vibration criteria.

4.1 Modal analysis
The first tenth mode shape for the first floor, laboratory room and corner panel is shown in Figure 4. The column of the modelling is consider fixed for single floor, room and panel, therefore the displacement of the column is not consider to the horizontal direction and only consider the vertical direction of the beam and slab displacement. The maximum vertical displacement of the slab for first

| VC-A | 50 (2 000) | 8 |
|------|------------|---|
| VC-B | 25 (1 000) | 3 |
| VC-C | 12.5 (500) | 1-3 |
| VC-D | 6.25 (250) | 0.1-0.3 |
| VC-E | 3.12 (125) | < 0.1 |
| VC-F | 1.56 (62.5) | N/A |
| VC-G | 0.78 (31.3) | N/A |
floor, laboratory room and panel were mode 7 with 8.8 mm displacement, mode 4 with 13.7 mm and mode 8 with 13.6 mm respectively. The result shows an increment trend of natural frequency while the mode is increased.

| Mode Shapes          | First floor | Laboratory room | Corner panel |
|----------------------|-------------|-----------------|--------------|
|                      | Mode 1, 5.62Hz | Mode 1, 11.83Hz | Mode 1, 13.09Hz |
|                      | Mode 2, 7.50Hz | Mode 2, 13.53Hz | Mode 2, 22.91Hz |
|                      | Mode 3, 8.42Hz | Mode 3, 19.52Hz | Mode 3, 25.74Hz |
|                      | Mode 4, 8.43Hz | Mode 4, 22.21Hz | Mode 4, 33.36Hz |
|                      | Mode 5, 9.69Hz | Mode 5, 24.68Hz | Mode 5, 39.91Hz |

**Figure 4.** Mode shapes of FPTP building structure
4.2 Transient analysis

Transient analysis was ran as the input for the problem laboratory room and the panel. The result will transfer to MATLAB to run ModalIV function to generate the vibration curve. Moreover, the vibration curve is not perform due to the result input from ANSYS. This is because the acceleration reaction of the floor in laboratory room and panel was very small, therefore the vibration curve is not perform or near to zero. Figure 5 shows the results of transient analysis by using MATLAB. It illustrated the acceleration time graph for Floor, Room and Panel structure. The acceleration wave became more stringent due to smallest structure modelled.
4.3 Vibration criteria analysis

VSATs is used to calculate the response of the floor vibration by using the data input by ANSYS and also Arup equation to determine the vibration criteria. The highest VC level was ISO that suitable to workshops and non-sensitive areas while the lowest level was VC-E that provide to sensitive systems required extraordinary dynamic stability. Figure 6 shows the two method of VC respond at the middle of slab in laboratory room and panel was in the range over the ISO level when referred to generic vibration criteria. It is proven that the slab is prone to vibration and not suitable to place sensitive equipment on that particular location as described in Table 1.

| Structure | Vibration testing data | Arup method |
|-----------|------------------------|-------------|
| Room      | ![Vibration testing data](image1) | ![Arup method](image2) |
| Panel     | ![Vibration testing data](image3) | ![Arup method](image4) |

Figure 6. Vibration plot for the laboratory room and panel.
5. Conclusions
As a conclusion, the first floor of the FPTP building was modelled by floor, room and panel to perform the natural frequency and mode shapes of the model by using ANSYS software. The sensitivity of the floor was identified after the process of transient analysis and transfer to MATLAB for further analysis to compare with the generic vibration criteria. From the result obtained, it shows the laboratory is not suitable to allocate sensitive equipment particularly at the middle of floor. It is because the ISO level is achieved at that location which is perceptible to any vibrations. The suitable location is on top of beam which showing at the VC-A to VC-E level based on Arup method. It shows the certain location is at VC-E level which is around the column area. Therefore, this is the most suitable place if the owner of the room planned to accommodate the sensitive equipment.

6. References

[1] Allen D E and Pernica G 1998 Control of Floor Vibration (Ottawa: Institute for Research in Construction) pp 1-4.
[2] Qu Z Q 2004 Model order reduction techniques Model Order Reduction Techniques: With Applications in Finite Element Analysis (London: Springer London) pp 31-46
[3] ANSYS 1 1998 Structural Analysis Guide Retrieved on Mac 15, 2018 from http://www.ansys.stuba.sk/html/guide_55/g-str/GSTRToC.htm
[4] Gordon C G 1991 Generic vibration criteria for vibration sensitive equipment Proc. Int. Society for Optical Engineering 1619 71-85
[5] Struik D J 1948 Fundamentals of Vibration In History of Mathematics (Dover Publications)
[6] Xia Y Hao H Zanardo G and Deeks A 2006 Long term vibration monitoring of an RC slab : Temperature and humidity effect Engineering Structures 28 441-452
[7] Whiffen A and Leonard D 1971 A Survey of Traffic Induced Vibrations (Berkshire: Road Research Laboratory)
[8] Murray T M Allen D E and Ungar E E 2003 Floor Vibrations Floor Vibrations Due to Human Activity (Chicago: American Institute of Steel Construction)
[9] Allen D E and Rainer J H 1976 Vibration criteria for long-span floor Canadian J. of Civil Engineering 3(2): 165-173
[10] Brownjohn J M W 2006 Dynamic performance of high frequency floors Proc. of IMACXXIV St. Louis pp 1-8
[11] Wilson E L 2002 Three-Dimensional Static and Dynamic Analysis of Structures (Berkeley: Computer and Structures)
[12] Guillaume P 2006 Modal analysis Vrije Universiteit Brussel 117(10) 2585-2588
[13] Silva J G S D, Vellassco P C G D S, Andrade S A L, De Soeiro F J D C P and Werneck R N 2003 An evaluation of the dynamical performance of composite slabs Computers and Structures 81 1905-1913
[14] Blake R E 2002 Basic Vibration Theory Harris’ Shock and Vibration Handbook (New York: McGraw-Hill) pp 1-32
[15] Wang E and Nelson T 2002 Structural Dynamic Capabilities of ANSYS (Int. ANSYS Conf.)
[16] Pavic A, Reynolds P, Prichard S and Lovell M 2002 Evaluation of mathematical models for predicting walking-induced vibrations of high-frequency floors Int. J. of Structural Stability and Dynamics 3(1) 107-130
[17] Wright C 2012 Introduction to Structural Impact (Fairfax: PDH Center) pp 12
[18] Pan T, You X and Lim C L 2008 Evaluation of floor vibration in a biotechnology laboratory caused by human walking J. of Performance of Constructed Facilities June 122-130

Acknowledgements
This research work is supported by the TIER 1 Grant code H259 at Universiti Tun Hussien Onn Malaysia (UTHM), Batu Pahat, Johor.