ANALYSIS OF VIBRATION CRITERIA ON REINFORCED CONCRETE FLOOR DUE TO FOOTFALLS AND PASSING VEHICLES

SHURL YABI

A thesis submitted in fulfillment of the requirement for the award of the Degree of Master of Civil Engineering

Faculty of Civil and Environmental Engineering Universiti Tun Hussein Onn Malaysia

JANUARY 2016 (JKPS DECEMBER)
For my beloved parents, siblings and friends
ACKNOWLEDGEMENT

I would like to acknowledge Universiti Tun Hussein Onn Malaysia for the opportunity to further my study in this university, also to thank God, for all the blessings that I have received in wisdom, health and strength that enables me to finish this research study despite all the difficulties and challenges in my personal life. I would also like to express my sincere appreciation to my supervisor, Dr Nor Azizi Bin Yusoff and my co-supervisor Puan Tuan Norhayati Binti Tuan Chik for the support and guidance given throughout the duration of this research and thesis writing.

The help and support from all my friends who have helped me especially to Rachel Binti Alexius Asiew for the amazing support and encouragement given during the ups and downs that I experienced in completing my thesis writing. Appreciation also goes to everyone involved directly and indirectly towards the completion of this thesis. Last but not least, I would also to express my gratitude to my family for giving me the support that I need.

Thank You.
ABSTRACT

Vibration in buildings is a disturbance caused by activities from the surrounding area. It comes both from external and internal sources. This phenomenon can affect electronic equipment such as computers, and the comfort of building occupants especially in offices and residential buildings. The purpose of this study was to determine the vibration criteria of multi-storey building floor due to vibration from footfalls and passing vehicles. The first objective of this study is to determine the vibration response level on the office building due to ground vibration from vehicles and footfalls. Second is to model the Registrar Office building structure and investigate fundamental frequency and mode shape. Third is to analyse and compare the vibration criteria of the building from both vehicles and footfalls. Registrar office building in UTHM was chosen in this study as it is multi-storey building that serves as an administration building and is exposed to internal and external vibration. Laser Doppler Vibrometer was used in field measurement to obtain the vibration response from loaded passenger and footfalls. For footfalls, one people, three people and five people induced vibration were measured to observe the difference in vibration response. Ansys was used to model the building based on the parameters obtained from the original structural plan. ModalV and VSATs programs in Matlab were used to obtain the floor vibration criteria due to the vibration response. The floor response caused by vibration generated by passenger bus is in VC-E range. For human footfalls, the response is in VC-C, VC-A and ISO range for the three different cases. In conclusion, the vibration response from passing vehicles and footfalls does not exceed the recommended criteria. However, there is a risk that footfalls may have an effect when more people walk on the same floor panel as shown in the result, where there is a significant increase in response due to increase number of human footfalls.
ABSTRAK


"Laser Doppler Vibrometer" digunakan dalam pengukuran lapangan untuk mendapatkan tindak balas getaran dari kenderaan dan pejalan kaki. Untuk pejalan kaki, getaran disebabkan oleh satu, tiga dan lima orang diukur untuk melihat perbezaan pada tindak balas getaran. Ansys digunakan untuk memodelkan bangunan berdasarkan parameter yang diperolehi daripada pelan struktur asal. Program ModalV dan VSATs daripada Matlab digunakan untuk mendapatkan kriteria getaran lantai disebabkan getaran. Kriteria getaran disebabkan oleh bas penumpang adalah dalam julat VC-E. Untuk pejalan kaki, tindak balas adalah dalam VC-C, VC-A dan ISO. Kesimpulannya, getaran dari kenderaan dan pejalan kaki adalah tidak melebihi kriteria yang disyorkan. Walau bagaimanapun, apabila lebih ramai orang berjalan di atas panel lantai yang sama ianya mungkin akan memberi kesan, dimana keputusan menunjukkan terdapat peningkatan yang ketara dalam tindak balas disebabkan oleh peningkatan bilangan pejalan kaki.
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<td>$f$</td>
<td>frequency</td>
</tr>
<tr>
<td>$T$</td>
<td>time</td>
</tr>
<tr>
<td>$H$</td>
<td>height</td>
</tr>
<tr>
<td>$C_t$</td>
<td>moment-resist in structures</td>
</tr>
<tr>
<td>$I_{\text{eff}}$</td>
<td>effective impulse</td>
</tr>
<tr>
<td>$f_a$</td>
<td>floor Natural Frequency</td>
</tr>
<tr>
<td>Nm</td>
<td>number of modes</td>
</tr>
<tr>
<td>$\mu$</td>
<td>mode shape where the impulse(footfall) is applied</td>
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<tr>
<td>Mn</td>
<td>modal mass</td>
</tr>
<tr>
<td>$[M]$</td>
<td>mass matrix</td>
</tr>
<tr>
<td>$[C]$</td>
<td>damping matrix</td>
</tr>
<tr>
<td>$[K]$</td>
<td>stiffness matrix</td>
</tr>
<tr>
<td>${\dddot{u}}$</td>
<td>nodal acceleration vector</td>
</tr>
<tr>
<td>${\dot{u}}$</td>
<td>nodal velocity vector</td>
</tr>
<tr>
<td>${u}$</td>
<td>nodal displacement vector</td>
</tr>
<tr>
<td>${F(t)}$</td>
<td>load vector</td>
</tr>
<tr>
<td>$\omega$</td>
<td>frequency</td>
</tr>
<tr>
<td>$\xi$</td>
<td>damping</td>
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<tr>
<td>${\phi}$</td>
<td>mode shape</td>
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<td>Description</td>
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<td>Root-Mean-Square</td>
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CHAPTER 1

INTRODUCTION

1.1 Research background

Vibration in buildings is a common problem and a major concern, especially in urban areas because of daily activities from both internal and external sources. This is mainly caused by vehicles passing on roads with uneven surfaces, construction work such as piling, service machineries in buildings and from human footfalls. In most major cities, complaints are usually made by annoyed owners of residential homes and occupants of office buildings.

The effects of vibrations include movement of building floors that can be felt by the occupants, rattling of windows, shaking of items on walls and shelves as well as perceptible rumbling noise. In a few extreme cases, the vibration can cause damages to the building structures. Vibration serviceability control has become one of the requirements in designing structures and post-construction stage due to many failures in structures under dynamic loading.

In Bloor West, Canada, vibrations from a subway has caused major problems in an apartment, due to the constant rattling and shaking in the building. The constant shaking has caused annoyance towards the residents of the building [1]. One of the most extreme cases involving structural failure occurred in 1831, United Kingdom.
Where, Broughton Suspension Bridge had collapsed due to vibration when soldiers were marching over it [2].

1.2 Problem statement

According to Hao and Cheng [3], there has been increased number of reports on vibration from heavy moving vehicles felt by occupants in the buildings and also concern about satisfying serviceability criteria applicable to modern building floors. Vibration induced from internal source which is mainly caused by human footfalls and external sources from road traffic and construction work is a major concern on the long-term effect on old buildings in weak condition, nuisance to occupants and on sensitive equipment housed inside sensitive facilities such as hospitals.

However, according to BRE Press (1995), although ground-borne vibration can be felt by humans, it rarely causes damage to building. In a building that houses sensitive equipment, even a low level of vibration can cause serious effects during experiments, for example in high-precision labs equipped with microscopes [4]. According to Pridham [5],

"Sensitive instrumentation is located on slab-on-grade to avoid vibration problems. However, for urban centres, sensitive instruments may be located on elevated floor due to limited spacing. Most research and healthcare facilities contain vibration sensitive spaces such as imaging suites and laser-based surgical suites”

For buildings such as office and residential home, where no sensitive equipment is housed inside, vibration that reach unacceptable level can cause annoying physical sensations, interference with activities, annoying noise caused by rattling of window panes, walls and loose objects, and interference of electronic equipment (e.g. computer) [6]. In addition to that, high vibration level above the recommended criteria in building can cause headaches, dizziness, irritability and stress to the occupants. These illnesses are also known as Sick Building Syndrome [7].
As stated in Traffic Advisory Leaflet [8], vibration levels from ground-borne vibration generated by heavy vehicles such as buses is high. However, for building which is far from places with large levels of external vibration, the effect of internal vibration, especially from human footfalls may cause more serious problem compare to vibration induced by external vibration [9]. Johansson concluded that in residential and office building, the most important source of annoying vibration is from human footfalls [10].

Despite of all these problems, study on small scale vibration has never been done before in Malaysia as consultants do not consider it as something that will affect the performance of the building structure itself. Human comfort and the performance of sensitive equipment inside buildings are often overlooked as something negligible. Hopefully, this study can be a stepping stone in the study of structural dynamic in building vibration for many interested researchers and consultants in our country.

1.3 Objectives

It is becoming increasingly important to understand the vibration serviceability performance of floors in office building since excessive level of vibration can cause discomfort to the occupants and affecting their work performances. The work presented in this thesis has the following objectives:

i. To determine the vibration response level on the office building due to ground vibration from vehicles and footfalls

ii. To model the Registrar Office building structure and investigate fundamental frequency and mode shape

iii. To analyse and compare the vibration criteria of the building from both vehicles and footfalls
1.4 Scope of study

In this study, vibration effect from both footfalls and vehicles on the multi-storey Registrar Office building in Universiti Tun Hussein Onn Malaysia (UTHM) was studied. The vibration from these two sources were analysed and compared to vibration criteria guideline by Gordon and Amick to determine the response and the effect on the office building.

Registrar Office building in UTHM was chosen in this study. The building is a multi-storey building that serves as an administration building and is exposed to vibration from both internal and external sources. The building consists of four levels including the ground floor. The first three levels are used as the office areas and also houses computers and photocopy machine, while the fourth level is mainly used for meeting and banquet area. To accomplish the foregoing objectives, the study is defined to include the following two scopes. The first scope is to obtain the vibration level of the Registrar Office through field measurement and the second scope is to identify the level of vibration criteria of the office building through numerical modelling.

Field measurement was taken from 1.00 pm - 2.00 pm, where it coincided with the peak hour for the bus inside UTHM. This duration was the most suitable time to record the vibration response in the building produced by passing bus in front of the Registrar Office building. Measurement for vibration induced by human footfalls was conducted using five handpicked test subjects with the average weight of 65 kg. Three different cases were considered for human footfalls vibration response; taken from one person walking, three people walking and five people walking.

Two software were used in this study; Ansys and Matlab. The structural response on the building floor generated from both footfall and passing vehicles were obtained by applying input from field measurement on the building model in Ansys, this technique of applying vibration input into the modelling is known as transient analysis. From transient analysis, compatible files for further analysis using Matlab analysis were created.

These files were then transferred to Matlab for criteria analysis due to vibration response from footfalls and passing vehicles using ModalV and VSATs
programs in Matlab. These two programmes were developed based on Amick and Gordon vibration criteria guideline. Due to limited resources from published case studies and papers done on multi-storey office building, especially using VSATs, most of the studies had to rely on few published papers and thesis. Thus, there are limited opportunities to study from past experiences either in such way of success or failures.

1.5 Thesis outline

This thesis consists of five chapters. Chapter 1 provides a brief introduction to the research problem, objectives and scope of work.

Chapter 2 presents a literature review of previous work relating to ground borne vibration from traffic and human footfalls. Vibration sources, path and the effect of vibration on floor of office building are described. In addition, standard and guideline used in this study is presented.

Chapter 3 describes the methodology of the whole study. Describes the equipment used for field measurement and numerical modelling using Ansys and Matlab.

Chapter 4 presents the result of the building natural frequency from both modelling and theoretical calculations, as well as the vibration criteria of building floor obtained using ModalV and VSATs programs in Matlab due to vibration response from footfalls and passing vehicles.

Finally, Chapter 5 presents conclusion founded during the development of this study suggestions and recommendations for future work.
CHAPTER 2

LITERATURE REVIEW

2.1 Basic concept of vibration

Vibration is a repeating motion that may or may not perpetuate and does not have to be a literal duplication while some vibration can repeat in a statistical sense. He and Fu [12] emphasized,

"The vital elements for vibration are not the presence of inertial and elastic components such as mass and spring. Since vibration can be regarded as the transfer between the kinetic energy and potential energy, a vibratory system has to include means of storing (and releasing) both energies."

Generally, vibration is a repeated motion of the system over a period of time, and an extensive movement in a given period of time is called cycle. The number of cycles per unit time is called frequency. Acceleration, velocity and displacement are related matters to vibration.
2.2 Vibration theory

Vibration is an oscillatory rapidly fluctuating motion of a medium such as floor and
ground [13]. The oscillatory motion causes particles to move in a retrograde ellipse
as shown in Figure 2.1. There is no net movement of the vibratory element because
of the oscillatory motion.

![Diagram of particle motion](image)

Figure 2.1: Vibratory Motion [13]

Hajek et al. [13] stated that six variables corresponding to three directional
components and three rotational components are required for a complete description
of the vibratory motion at a point. The three important components that are taken into
accounts are amplitude (maximum displacement), velocity (instantaneous speed of
the movement) and acceleration (the rate at which the speed changes).

2.3 Frequency

Frequency is the number of a repeating event per unit time. It is a period of duration
of one cycle in a repeating event. Frequency is measured in the unit hertz (Hz).

\[ f = \frac{1}{T} \quad (2.1) \]

where;
\( f \) = frequency (Hz)
\( T \) = time (second)
Wavelength ($\lambda$) is the distance between waves, where the short wavelength indicates a high frequency and long frequency indicates a low frequency. Amplitude is the size of the wave, also known as the value of maximum displacement from an average value or position. Figure 2.2 shows the relationship between frequency, amplitude and wavelength.

![Figure 2.2: Frequency, amplitude and wavelength](image)

There are two main impacts for vibration in buildings. The first one is perceptible vibration which comes from vibration of floors and walls inside buildings that can be perceived by human or audible motion such as rattling of windows. Second one is low frequency noise also known as noise, for example sound waves radiated by the vibrating surfaces inside buildings that are perceived by the human ear as noise [15]. Wang concluded that multiplication of the vibration or noise transfer functions contributes to the forced vibration or absolute response [16].

### 2.4 Natural frequency

Natural frequency is the frequency where a system naturally vibrates when it is set in motion. In short, natural frequency is the number of times a system will oscillate between its original and displaced position and with no outside interference.
However, when two natural frequencies coincide with each other, resonance will occur and vibrations will be amplified [17].

Each structure has its natural frequency and associated mode shapes as degrees of freedom and is commonly sorted by the amount of energy that is activated by oscillation. The first natural frequency has the lowest energy level and it is the most likely to be activated in building structure. Feldman stated that the first natural frequency is also known as fundamental frequency [18].

Klein and Rainer [19] recommended the natural frequency of concrete slabs and walls to be between 10Hz and 30Hz while the horizontal frequency of the entire structure is between 5 Hz to 10 Hz. However, for a whole building structure, it has its own natural frequency as the height is the main determinant of the natural frequency of building [20]. Period height formulas for displacement-based design are proposed by Ghopra and Goel [21]. And in 2004, Crowley and Pinho [22], added one standard deviation to the best-fit curve derived by Goel and Ghopra, thus providing:

\[ T = 0.067 \cdot H^{0.9} \]  \hspace{1cm} (2.2)

where;

\( T \) = Fundamental natural period (sec)

\( H \) = Height of the building (meters)

Other than the proposed formula by Crowley and Pinho, the natural frequency of building can also be derived from the formula of natural period in Eurocode 8 [23]. Menziane et al. supports the usage of these two formulas to calculate the natural frequency of a building; as the frequencies obtained using these formulas are almost similar with the result obtained through experimental measurements [24].

\[ T1 = CtH^{0.75} \]  \hspace{1cm} (2.3)

where;

\( Ct = 0.085 \) for steel moment-resisting frames, \( 0.075 \) for concrete moment-resisting frames or steel eccentrically braced frames, \( 0.05 \) for other types of frame
2.5 Damping

Damping is the energy loss of an oscillating system. In general, the loss is either internal (material damping) or to another system (radiated damping). Damping ratio is employed in characterizing the damping level of building structure and seismic design of a building. Furthermore, the ability of structure to dissipate vibration energy can be calculated as damping ratio. The total damping consists of material and structural damping, damping by furniture and finishing, and geometrical radiation, which is the propagation of energy to the building structure [25]. Damping is expressed as percentage of critical damping, also known as damping ratio, $\zeta$ (%). Table 2.1 shows the recommended values of damping based on the types of structure by Smith.

<table>
<thead>
<tr>
<th>Types of structure</th>
<th>Damping ratio, $\zeta (100 %)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material damping:</td>
<td></td>
</tr>
<tr>
<td>Steel</td>
<td>0.003 – 0.15</td>
</tr>
<tr>
<td>Concrete</td>
<td>0.15 – 1.0</td>
</tr>
<tr>
<td>Wire rope</td>
<td>0.4 – 2.0</td>
</tr>
<tr>
<td>Bridges: All steel</td>
<td></td>
</tr>
<tr>
<td>Composite construction</td>
<td>0.2 – 1.0</td>
</tr>
<tr>
<td>Reinforced concrete or pre-stressed concrete</td>
<td>0.3 – 1.6</td>
</tr>
<tr>
<td>Chimney: Steel</td>
<td></td>
</tr>
<tr>
<td>Concrete</td>
<td>0.3 – 0.8</td>
</tr>
<tr>
<td>Steel masts and towers</td>
<td>0.3 – 2.9</td>
</tr>
<tr>
<td>Multi-storey buildings</td>
<td>0.7 – 2.9</td>
</tr>
<tr>
<td>One or two storey houses</td>
<td>1.0 – 5.0</td>
</tr>
</tbody>
</table>

2.6 Response

Vibration response calculation of a floor is a combination of mass, stiffness and damping properties of the structure and by applying a suitable excitation function [27]. Ungar argued that the steady state response and transient response need to be checked in low frequency floor because when the frequencies of the floor become lower, it may result in transient response being greater [25].

The common measures of vibration amplitude are velocity, where the unit measure is in meter per second (m/s). Acceleration is also commonly used to measure vibration amplitude and the unit is in meter per second squared (m/s²). Furthermore, acceleration is also denoted in unit the unit g, which refers to
gravitational acceleration constant which is an important value in dynamic calculation and commonly equal to $9.8\text{m/s}^2$ [11].

2.7 Types of vibration

According to Australia Department of Environment and Conservation [28], vibration and its effects can be classified as:

i. Continuous vibration continues uninterrupted for a defined period of time (daytime and/or night-time). This type of vibration is assessed on the basis of weighted RMS acceleration values.

ii. Impulsive vibration is a rapid build up to a peak and then followed by a damped decay that may or may not involve several cycles depending on frequency and damping. It can also consist of sudden application of several cycles at approximately the same amplitude when the duration is short (less than 2 seconds).

iii. Intermittent vibration is an interrupted periods of continuous (e.g. drill) or repeated period of impulsive vibration (e.g. pile driver), or continuous vibration that varies significantly in magnitude. Main source from impulse sources (e.g. pile drivers) or repetitive sources (e.g. pavement breakers), or sources which operate sporadically, but produces continuous vibration if operated continuously.

2.8 Sources of vibration

Vibration is a phenomenon referred to sources that produce noise and shaking condition to its environment. There are several causes that can contribute to vibration response in the building, where it may vary both is space and in time. In general, vibration source can be categorized into three main classifications; seismic or ground vibrations, acoustic vibrations, and force that applied directly to the load on the working surface such as human footfall [29]. The typical sources of vibration that are frequently identified in buildings are shown in Figure 2.3.
A completely vibration-free environment inside of a building is impossible to achieve. Yet, it is possible to reduce the vibration level into an acceptable level. There are three major sources of vibration that can affect structures and the sensitive equipment housed inside a building structure [17]. These three major sources are:

i. External sources that include ambient vibrations at the site (micro-tremors), road and rail traffic, construction activities and machinery operating from outside or nearby building.

ii. Internal activities such as footfalls, service activities (repair works)

iii. Service machinery that includes all mechanical and electrical equipment such as an air-conditioner

Ungar reported that vibration sources from Pedestrian’s footfalls and ground-borne vibration from traffic are most common sources of vibration in sensitive facilities [25]. Similarly, Pavic also considered these two as the most critical source of excitation of vibration in Residential and office building [31].
2.9 Internal vibration

Internal sources are a set of vibration sources acting inside a building, these sources from mechanical excitation like washing machine or human activity itself are either continuous or transitory types of vibration [32].

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 [32].

Internal vibration from footfalls is often the major source of floor vibration compare to machinery. Davenny concluded that the 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 [33].

2.9.1 Internal vibration induced by footfalls

Vibration induced by person walking on the floor also known as footfalls are one of the major concerns in building design and construction. In building design process, vibration induced by footfall must be considered in the early stage, especially for building floors that support vibration sensitive equipment [34].

While floor vibration is more serious on steel and composite floor structure, it is not restricted to these two only. Although reinforced concrete floors that are used in most office and residential use are adequate, Debney and Willford recommended that vibration by footfalls must still be checked even in an area where the external vibration is not a main problem especially for more sensitive occupancies such as laboratories [35].

Pavic and Reynolds [36] defined walking as a combination of individual footfalls in time as shown in Figure 2.4. The individual footfall force impulses depend on the walking rate and very little on the weight of the individual walking, although the peak values and rise time of the impulses appear to vary significantly with walking rate and the walker’s weight [25]. The individual footfall force impulses for normal walking and fast walking are shown in Figure 2.5.
Figure 2.4: Typical forcing pattern for walking [25]

Figure 2.5(a): Single footfall forcing time history for normal walking, and (b) Single footfall forcing time history for fast walking [25]

Vibration from footfalls is induced from the movement phases of legs and feet during walking, where the body weight is then transferred to the floor. Figure 2.6 below shows movement phases of legs and feet during walking.
Figure 2.6: Phases of legs and feet during walking [18]

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 footfall also depend on the speed of walking. Figure 2.7 shows the typical velocity response time of a floor due to walking loads [18].

Figure 2.7: Typical velocity response time due to walking loads [18]

In addition, a more general footfall rate classification prepared by Arup [37] is presented in Table 2.2. The step frequencies for different activities proposed by Johansson are displayed in Table 2.3 [10].
Table 2.2: Footfalls rate [37]

<table>
<thead>
<tr>
<th>Frequency [Hz]</th>
<th>Designation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5 – 1.8</td>
<td>“Normal walking” for cellular areas</td>
</tr>
<tr>
<td>1.8 – 2.0</td>
<td>“Someone who is in hurry”</td>
</tr>
<tr>
<td>2.0 – 2.4</td>
<td>“A very brisk pace” considered likely in corridors</td>
</tr>
</tbody>
</table>

Table 2.3: Step frequencies for different activities [10]

<table>
<thead>
<tr>
<th>Activity</th>
<th>Steps/second</th>
</tr>
</thead>
<tbody>
<tr>
<td>Walking</td>
<td>1.7 – 2.3</td>
</tr>
<tr>
<td>Running</td>
<td>2.0 – 3.5</td>
</tr>
<tr>
<td>Jumping</td>
<td>1.8 – 3.0</td>
</tr>
<tr>
<td>Sports activity</td>
<td>2.0 – 3.0</td>
</tr>
<tr>
<td>Dancing</td>
<td>1.9 – 3.3</td>
</tr>
</tbody>
</table>

The formula to predict responses due to footfall induced vibration by ARUP [37] is given below

\[
I_{eff} = 54 \frac{f^{1.43}}{f_n^{1.30}}
\]  

(2.4)

where;

\( I_{eff} \) = Effective impulse (Ns)

\( f \) = Footfall pace (Hz)

\( f_n \) = Floor natural frequency

The total vibration response to each footfall is found by summing the velocity responses in each mode using the following formula:

\[
v_i(t) = \sum_{n=1}^{N_m} V_{i,n} \left( t \right) = \sum_{n=1}^{N_m} \mu_{i,n} \mu_{i,n} e^{-\zeta_n \omega_n t} \sin(\omega_n t)
\]

(2.5)

where;

\[
\omega_{nd} = 2\pi f_n \sqrt{1 - \zeta_n}
\]

(2.6)

\[
\omega_n = 2\pi f_n
\]

(2.7)
and,

\[ N_m \] the number of modes considered
\[ \mu_i \] the mode shape coordinate corresponding to the point \( i \) where the impulse (footfall) is applied
\[ \mu_j \] the mode shape coordinate corresponding to the point \( j \) where the impulse (footfall) is applied
\[ M_n \] the modal mass

2.10 Ground borne vibration

The common sources of ground-borne vibration are trains, buses on rough roads and construction activities [38]. Figure 2.8 shows the basic concepts of ground-borne vibration from the train railway. Vibration energy is created from the train wheels rolling on the rails that are transmitted through the track support system into the transit structure. However, the amount of energy transmitted is highly depending on the how smooth the wheels and rails are and also the resonance frequencies of the vehicle suspension system and the track support system [39].

![Figure 2.8: Propagation of ground-borne vibration into building [39]](image)
Vibration of the underground subway structure is generated under the ground and create vibration waves which then propagate through the various soil and rock strata to the foundation of any adjacent building, then throughout the remainder of the building structure. The maximum vibration amplitudes of the floors and walls of the building normally will be at the resonance frequencies of various components of the building [39].

Apart from that, ground-borne vibration is highly dependent on the direction, position and frequency. In analysing the response of a multi-storey building frame subjected to base acceleration such as earthquake and ground borne vibration, the dynamic equilibrium, the equations of motion for free (unforced) vibration are referred as [39]:

\[ f_i + f_D + f_s = 0 \]  \tag{2.8}

where:

\[ f_i = m\ddot{x} = m\ddot{x}(t) \quad = \text{inertia force} \] \tag{2.9}
\[ f_D = c\dot{x} = c(x_g(t) - x(t)) \quad = \text{damping force} \] \tag{2.10}
\[ f_s = kx = k(x_g(t) - x(t)) \quad = \text{elastic spring force, positive when } x_g > x \] \tag{2.11}

The relative motions of \( x \) between the masses and the base due to structural deformations produce elastic and damping force. The rigid body component of the displacement of the structures produces no internal forces.

2.10.1 Ground borne vibration from road traffic

Vehicles that come with a direct contact with the road surface will induce a dynamic load on the road pavement. The loads will propagate through the soil, where it will reach to the foundation of any nearby building. As a result, the building will vibrate and affect the equipment and occupants inside the building.

In his conclusion, Humaidi [17] points that if the natural frequencies of the soil coincide with any of the natural frequencies of the building structure or any of its
components, resonance will occur and vibrations will be amplified. Traffic vibration is characterized by a source-path receiver scenario as shown in Figure 2.9.

Figure 2.9: Traffic vibration source-path receiver scenario [17]

When vehicles strike on an uneven surface, it will generate an impact load and an oscillating load due to the “axle hop” of the vehicle. As a result of the impact ground vibrations are generated and it is predominant at the natural vibration frequencies of the soil. Likewise, the axle hop generates vibrations at the hop frequency [38].

Passenger cars and light trucks generate vibrations that are not perceptible in buildings. Road traffic vibration nuisance in buildings is mainly caused by heavy vehicles that pass at relatively high speed on a road with an uneven surface profile as shown in the Figure 2.10.

Figure 2.10: Passage of a bus on a transition between an asphalt surface and paved surface [38]
The interaction between the wheels and the road surface causes a dynamic excitation which will generate waves that propagate in the soil and into the foundations of adjacent buildings. It then transfers the vertical vibration components to be amplified at such resonance frequencies on the flexible floors and transfers the horizontal components to be amplified over the height of the building [38]. However, vibration level will decrease with distance from the road and the building structure itself. As a result of “geometrical spreading” of the vibration energy and its dissipation by soil viscosity and friction [38].

2.10.2 Factors influencing ground borne vibration level and frequency

Road traffic will likely produce vibrations with frequencies in the range from 5 to 25 Hz (oscillations per second). Whereas the amplitude of the vibrations ranges between 0.005 and 2 m/s² (0.0005 and 0.2 g) measured as acceleration, or 0.05 and 25 mm/s measured as velocity. The frequencies and amplitude of the vibration are influenced by factors such as the condition of the road, soil type and stratification, vehicle weight, speed and suspension system, weather and type of building [17].

Figure 2.11 shows the comparison between vibration levels by a transit bus and a truck. The figure is correlated to the Table 2.4 which presents vibration levels by transit bus and a truck of the same weight category travelling on a rough road. The vibration levels induced were almost similar with at 25 km/h. However, at 50 km/h, the vibration levels induced by the bus were twice higher than the vibration levels induced by the truck.
Figure 2.11: Comparison between vibration levels induced by bus and a truck. Vibration levels are significantly different due to the differences in suspension systems [17].

Table 2.4: Comparison of vibration levels (mm/sec$^2$, RMS) induced by a bus and a truck, showing the effect of different suspension systems at different speeds [17].

<table>
<thead>
<tr>
<th>Location</th>
<th>25 km/h</th>
<th>50 km/h</th>
<th>25 km/h</th>
<th>50 km/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground in front of house</td>
<td>20.5</td>
<td>19.9</td>
<td>64.5</td>
<td>33.2</td>
</tr>
<tr>
<td>External foundation wall</td>
<td>11.2</td>
<td>10.1</td>
<td>30.9</td>
<td>15.7</td>
</tr>
<tr>
<td>Mid-point of floor in 1$^{st}$ storey</td>
<td>20.3</td>
<td>20.8</td>
<td>62.9</td>
<td>30.1</td>
</tr>
<tr>
<td>Mid-point of floor in 2$^{nd}$ storey</td>
<td>35.0</td>
<td>37.3</td>
<td>96.2</td>
<td>46.7</td>
</tr>
</tbody>
</table>

*Bus had air-bag suspension system; truck had multi-leaf steel spring suspension system

Vibration amplitudes and the predominant frequencies are influenced greatly by soil type and stratification. Higher vibration will occur when the stiffness and damping of the soil is low. As a result, traffic vibrations are worst in areas underlain by soft clay soil layer. Table 2.5 summarized some of the many factors influencing the level of ground-borne vibration.
Table 2.5: Summary of factors influencing ground-borne vibration level [39].

<table>
<thead>
<tr>
<th>Factors Related to Vibration Source</th>
<th>Influence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle Suspension</td>
<td>If the suspension is stiff in the vertical direction, the effective forces will be higher. On transit cars, only the primary suspension affects the vibration levels, the secondary suspension that supports the car body has no apparent effects.</td>
</tr>
<tr>
<td>Wheel Type and Condition</td>
<td>Normal resilient wheels on rail transit system are usually too stiff to provide significant vibration reduction. Wheel flats and general wheel roughness are the major cause of vibration from steel wheel/steel rail system.</td>
</tr>
<tr>
<td>Track/Roadway Surface</td>
<td>Rough track are often the cause of vibration problems. Maintaining a smooth surface will reduce vibration levels.</td>
</tr>
<tr>
<td>Track Support System</td>
<td>On rail systems, the track support system is one of the major components in determining the levels of ground – borne vibration. The highest vibration levels are created by track that is rigidly attached to a concrete tracked. The vibration levels are much lower when special vibration control track system such as resilient fasteners; ballast mats and floating slabs are used.</td>
</tr>
<tr>
<td>Speed</td>
<td>As intuitively expected, higher speeds result in higher vibration levels.</td>
</tr>
<tr>
<td>Transit Structure</td>
<td>The general rule – of – thumb is that the heavier the transit structure, the lower the vibration levels. The vibration levels from a lightweight bored tunnel will usually be higher than from a poured concrete box subway.</td>
</tr>
<tr>
<td>Depth of Vibration Source</td>
<td>There are significant differences in the vibration characteristics when the source is underground compared to at the ground surface.</td>
</tr>
<tr>
<td>Soil Type</td>
<td>It is generally expected that vibration levels will be higher in stiff clay type soils than loose soils.</td>
</tr>
<tr>
<td>Rock Layers</td>
<td>Vibration levels often seem to be high near the track when the depth to bedrock is 10 m or less. Subways founded in rock will result in lower vibration amplitudes close to the subway. Because of efficient propagation, the vibration level does not attenuate as rapidly in rock as it does in soil.</td>
</tr>
<tr>
<td>Soil Layering</td>
<td>Soil layering will have a substantial, but unpredictable, effect on the vibration levels since each stratum can have significantly different dynamic characteristics.</td>
</tr>
<tr>
<td>Depth of Water Table</td>
<td>The presence of the water table is often expected to have significant effect on ground – borne vibration, but evidence to date can’t be expressed with definite relationship.</td>
</tr>
<tr>
<td>Frost Depth</td>
<td>There is some indication that vibration propagation is more efficient when the ground is frozen.</td>
</tr>
<tr>
<td>Foundation Type</td>
<td>The general rule – of – thumb is that the heavier the building foundation, the greater the coupling loss as the vibration propagates from the ground into the building.</td>
</tr>
<tr>
<td>Building Construction</td>
<td>Since ground – borne vibration is almost always evaluated in terms of indoor receivers, the propagation of the vibration through the building must be considered. Each building has different characteristics relative to structure borne vibration. The general rule for this, is that the more massive a building is the lower the levels of ground – borne vibration will be.</td>
</tr>
<tr>
<td>Acoustical Absorption</td>
<td>The amount of acoustical absorption in the receiver room affects the levels of ground – borne vibration.</td>
</tr>
</tbody>
</table>
2.11 Vibration path

Vibration path is a medium where excitation from the vibration source is transmitted to the receiver and the structural elements such as building foundations, floors, walls, beams and columns. It includes the non-structural elements such as removable partitions. For forces applied directly to the structure such as footfalls, it involves the simulation of the response of the structure of these forces [40].

There is a significant problem to predict how the vibration ground-borne vibration propagates and attenuates from the source to the receiver [41]. Figure 2.12 displays the block diagram for ground-borne vibration model of railway track. The propagation of waves plays an important role in vibration control, particularly when planning for minimal vibration effects for housing and other sensitive installations.

![Block diagram for ground-borne vibration model from railway track](image)

Figure 2.12: Block diagram for ground-borne vibration model from railway track [42]
2.12 Vibration receivers

Vibrations generated from sources such as construction and traffic will propagate through the ground can be transmitted to the building foundation and then to other parts of the building. Internal vibration inside the building itself can also propagate and be transmitted to the whole building structures. Subsequently, vibration can affect the building occupants and the equipment inside if the vibration level exceeds the vibration criteria (VC). Thus, the building can be classified as a “vibration receiver”.

2.12.1 Building

Based on a study by Hajek et al. [13], it is known that the amount of vibration experienced by occupants of a building depends on the parameters and location of the building where the vibration of floors or walls above ground is larger than the basement floors. According to a study done by Rudder [43],

"The vibration of floors is higher than the corresponding vertical vibration at foundations. Measurements carried out on one and two story buildings indicate that vibrations increase with height above ground. The increase of vibrations with building height may not apply above a certain building height above the ground”

The vibration level in building also depends on the mass and stiffness material used. Concrete floors would meet the vibration criteria, whereas steel and composite materials would require additional material to provide mass and stiffness to achieve the same vibration criteria as concrete [37].
REFERENCES


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