Floor serviceability under dynamic loading

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Abstract

Some structures such as floors and tall buildings that meet the code design criteria exhibit unacceptable vibrations relative to the human user. In particular, occupants of long-span floors constructed with open-web joists and light-weight concrete are likely to experience perceptible or annoying vibrations due to normal human activity that is characterized by impact, such as walking, dancing, running, and jumping. Thus, it is important that a serviceability criterion based on human response be used at the design stage to avoid costly problems after the floor is constructed and put into service. Note that human response to vibration is a function of the human body characteristics, the intensity and type of the loading, and the characteristics of the structure such as its frequency, stiffness, mass, and damping. In this paper, a serviceability criterion based on the human-load-structure system is presented. This criterion is the value of the absorbed power (rate of energy dissipation) through the human body as represented by a biomechanical model. The absorbed power levels for the thresholds of perception and annoyance were determined and compared with available human comfort curves. The close agreement demonstrates that absorbed power is a good measure of human response to vibration. To demonstrate the usefulness of absorbed power, floor serviceability was assessed due to walking, heel impact, and dancing. Also, the serviceability of forty-one floors was evaluated using absorbed power and compared to the reported subjective assessments. Absorbed power values correctly predicted the serviceability of thirty-nine of the floors. Furthermore, design curves were produced to assist the engineer in designing serviceable floors.

Keywords: floor serviceability, absorbed power, biomechanical models, human response to vibration, vibrations, walking, dancing.
1 Introduction

Long-span structures such as floors, built with materials possessing low damping, are likely to exhibit perceptible or annoying vibrations under dynamic loading although the relevant building code requirements for strength and deflection are met. The loads that cause disagreeable vibrations are usually different in type and intensity from the design live load, and often are only a small fraction of it. The serviceability of a structure to vibration is dependent upon the imposed excitation and the characteristics of the structure such as frequency, stiffness, mass and damping. Additionally, since the human user is the recipient of the vibrations, then any objective criterion for assessing structural serviceability should incorporate the characteristics of the human user. Several criteria such as amplitude, velocity and acceleration have been used by investigators, Goldman and Von Gierke [1], Janeway [2], Lenzen and Murray [3] and Allen [4] to evaluate human response to vibration. Such criteria, coupled with frequency, specify the maximum allowable response of the structure that avoids disagreeable vibrations relative to the human user. To avoid the use of several criteria that sometimes are in conflict with each other, an objective criterion based on absorbed power (rate of energy dissipation) through the human body as represented by a biomechanical model has been developed by Farah [5]. This criterion is evaluated based on the human interaction with the vibrating floor. Floors can experience steady-state or transient vibration due to human activity. The available human response data are mainly for steady-state vibrations, Coermann et al [6] and Zeigenruecker and Magid [7]. However, since humans are more tolerant to transient motion, Lenzen and Murray [3] recommends that the steady-state vibration limits be scaled by a factor of ten to enable the assessment of serviceability to transient vibrations. A typical standard load used for the evaluation of floor serviceability to transient vibrations, is an impulse obtain from the heel drop test proposed by Yolles et al [8]. This is used in this work to develop design curves that provide serviceable floors under transient loading.

2 Floor serviceability

Floors in residential, office, and recreational buildings are usually subjected to human activity such as walking, running, jumping, and dancing. The resulting floor vibrations could be periodic, transient, random or a combination thereof. A serviceable floor is one where the occupants do not experience vibrations that are strongly perceptible or annoying. In order to assess the serviceability of a floor, human response to vibration must be estimated. This requires modelling of the human-floor-load system and the use of human comfort curves to establish the response levels that are consistent with a serviceable floor. In such a system, the human body is modelled as a multi-degree-of-freedom system. While generally the degree of complexity of the biomechanical model depends on the application for which the model is to be deployed, it is considered adequate for floor vibration to estimate whole body vibration rather than the response of individual
body parts. A simple model that achieves this objective is a two-degree-of-freedom model.

3 Biomechanical model

In order to determine the parameters of a biomechanical model, use is made of available data from tests on human subjects. The data is in the form of a frequency response or impedance of the subject being tested. The frequency response curve is developed by subjecting the human to one frequency at a time over a wide range of frequencies. On the other hand, the impedance is obtained through the application of a transient excitation such as a drop test where the force $f(t)$ and the velocity $v(t)$ at the point of contact between the human and the platform are recorded. The impedance $Z(\omega)$ is given by:

\[ Z(\omega) = \frac{F(\omega)}{V(\omega)} \]

(1)

Where $F(\omega)$ and $V(\omega)$ are the Fourier transforms of $f(t)$ and $v(t)$ respectively. The parameters of the biomechanical model are obtained by fitting, in a least squares sense, the theoretical impedance of the model to the measured impedance. Fig. 1 shows a good fit between the impedance, and the parameters of the biomechanical model. Also note that the first two resonant frequencies of whole body vibration of a standing man are approximately 5.6 Hz and 10 Hz.

![Figure 1: Experimental impedance (Coermann) and corresponding two-degree model of standing man.](image-url)
4 Modelling of floors

Depending on the type of construction, floors can be approximated by simple models to enable the assessment of serviceability. Thus, for one-way construction, the floor system can be approximated by an equivalent beam, while for two-way construction, an approximation of the floor as a slab with stiffened ribs in two directions would be adequate. This results in an orthotropic plate. However, modelling the floor by an equivalent one-degree-of-freedom system simplifies the analysis and produces adequate results for serviceability assessment. The modelling process makes use of transformation factors for mass, stiffness and load as indicated by Vannoy and Harris [9]. This is achieved by equating the kinetic and strain energies to the work done by the external loads for the equivalent and actual systems.

5 Modelling of loads

Floor serviceability problems arise from human activity such as walking, dancing. Other causes include traffic and machinery induced vibrations. The loads can be steady state, transient or random.

5.1 Steady state vibrations

The most severe loads are those that are periodic and whose frequency is approximately equal to the fundamental frequency of the floor. In such situations, resonance takes place that can cause damage to the floor and annoy the human occupants. Due to the low threshold of psychological response of humans to vibration, even low-intensity vibrations trigger concern and may lead to lack of confidence in the safety and adequacy of the floor. Synchronized walking and dancing may cause resonance if the frequency of the floor is equal to the frequency or a multiple thereof of the frequency of the activity. Additionally, if the load frequency is equal to one of the whole body resonant frequencies, then the human discomfort is further amplified. Thus, the intensity and frequency of the load are both important in assessing floor serviceability.

5.1.1 Walking

The force due to normal walking can be represented by the force of interaction between the human and the floor. Although the force of interaction varies among individuals, the variation is substantially reduced when the force is expressed in terms of the weight, and the time in terms of the step time. Additionally, during brisk walking, the force due to heel impact becomes significant and must be accounted for.

5.1.2 Dancing

During vigorous dancing such as that of the rock and roll type, the imposed frequency may excite floor resonance. This could result in damage to the floor,
discomfort to the users of the floor itself and to occupants in adjacent units of the building. The loading due to dancing can be approximated by a series of equally spaced impulses. The synchronization of the period of the impulses with that of the floor produces resonance.

### 5.2 Transient vibrations

Floors are normally subjected to transient vibrations due to human activity. The human body is considered to be less sensitive to transient as compared with steady state vibrations. To simulate floor response to transient vibrations, the heel drop test is used. The test consists of a 77-kg man, wearing street shoes with hard rubber heels, supports himself on the ball of his feet with heels raised 63.5mm, suddenly transfers the load to the floor. The resulting impact produces the force curve shown in fig. 2. Due to the short duration (45ms) of the resulting force, it is convenient to approximate the load by an equivalent impulse of 67 N·s. The serviceability of the floor is then related to the human response to this loading.

![Force vs. time for Heel Drop Test](image)

**Figure 2:** Force vs. time for Heel Drop Test (after Lenzen and Murray [3]), modified by Author.
Absorbed power is the rate of energy dissipation through the human body. It is also a good measure of the human comfort level to vibration. The higher the level of absorbed power, the higher the discomfort level will be. Based on human comfort curves, the thresholds of perception, annoyance, and tolerance are 0.0002 watt, 0.2 watt, and 200 watt respectively. The absorbed power level of 0.2 watt and the boundaries of the threshold of vibration, based on subjective assessments, are shown in fig. 3. The agreement is quite good.

Absorbed power for steady state vibrations is defined as:

$$P = \lim_{T \to \infty} \frac{1}{T} \int_{0}^{T} f(t)v(t)dt$$

(2)

Where \( f(t) \) and \( v(t) \) refer to the force and velocity respectively, at the point of contact between the human and the floor, and \( T \) is the period of time. Note that for transient vibrations, the power should be averaged over a finite period of time. A three second period would be adequate for the human to react to the
vibration. The expression for absorbed power in the frequency domain is obtained by using Fourier transforms:

\[ P = -\frac{1}{\pi} \int_{0}^{\infty} \omega y(\omega) \text{Im} G(\omega) d\omega \]  

(3)

Where \( \omega \) is the circular frequency, \( P_y(\omega) \) is the power spectrum of the displacement and \( G(\omega) \) is the transfer function between the force and displacement at the point of contact, and \( \text{Im} \) refers to the imaginary component.

7 Examples of floor serviceability assessment

In order to illustrate the usefulness of absorbed power, examples of serviceability assessment of floors under various loading conditions are presented.

7.1 Serviceability of a floor under a dancing load

The floor under consideration had a serious vibration problem during rock dances as reported by Vannoy and Heins [9]. The frequency of the induced vibration was measured in the range of 2.5-4.0Hz which is of the same magnitude as that of the fundamental frequency of the floor. The problem arose despite the fact that the floor met the code requirements for strength and deflection. The floor is supported by large girders spaced at 6.1m. The slab is 63.5mm thick made of light-weight concrete on a thin composite metal deck. The test program consisted of monitoring the induced dynamic deformations and strains at critical points on the floor girder and slab, at various times during the dance period. For example, when the imposed frequency was 4.0Hz and the amplitude was 0.56mm, absorbed power was 0.058 Watt and the vibrations were assessed as being strongly perceptible. However, ninety minutes later, the imposed frequency was 4.0Hz but the amplitude was 1.56mm with an absorbed power of 0.45 Watt, placing the vibrations in the strongly annoying range. The remedy was to modify the floor system by introducing columns. As a result, the deflection dropped to 0.02mm and the corresponding absorbed power was reduced to \( 2.9\times10^{-6} \) Watt, placing the vibrations in the imperceptible range. Note that in all of these assessments, the absorbed power conclusions were consistent with the reported subjective assessments.

7.2 Transient vibrations

A floor has a joist construction with a span of 18.6m, a slab thickness of 63.5mm, a fundamental frequency of 5.0Hz, a critical damping ratio of 3\%, and an equivalent mass of 5,800kg. The absorbed power by the two-degree biomechanical model, located at mid-span and due to a 67N.s impulse loading, is 0.027 Watt for a period of 3 seconds. This places the vibrations in the strongly perceptible category and thus the floor is classified as unacceptable since it exceeds the 0.0035 Watt level which is considered to be the boundary between
satisfactory and unsatisfactory. The classification of this floor is in agreement with the reported subjective assessment. As a further check, based on the appropriate curve of fig. 4 that was developed by Farah [10], the required equivalent mass for a serviceable floor must be at least 9800kg. This is much higher than the actual mass of 5800kg. Also, absorbed power was used to evaluate the serviceability of forty-one floors reported by Allen and Rainer [11]. The assessments correctly predicted the serviceability of thirty-nine of the floors.

Figure 4: Variation of equivalent mass and damping for a serviceable floor design for various floor frequencies.

7.3 Walking and heel impact

A floor, modelled as a beam, has a span of 16.67m, an equivalent mass of 1074kg/m, and a fundamental frequency of 6.0Hz. The floor was subjected to a load of a walking man with and without heel impact. The absorbed power by a biomechanical model placed at mid-span is shown in fig. 5 for various damping ratios. It is seen that as damping increases, absorbed power decreases, and that the rate of decrease is higher in the low damping range. Also, note that the heel impact contributes significantly to the absorbed power level.
8 Conclusions

The representation of the human user by a biomechanical model, and the incorporation of this model in the human-floor-load system, has enabled the calculation of absorbed power that has been shown to be a good measure of the serviceability of floors subjected to human activity such as walking, heel impact, and dancing. Additionally, curves relating damping, mass, and frequency of floors have been presented to assist in the design of serviceable floors.

Figure 5: Effect of floor damping on absorbed power for walking and heel impact, (2 step/sec, step length = 0.76m).
References


