AD 253

Design Considerations for the Vibration of Floors

Introduction

Designers are more frequently facing the need to consider, in detail, the vibration response of floors. This Advisory Desk article is the first of a collection of articles which are being written as summaries of the key issues.

A structure that is composed of any material will vibrate if subjected to cyclic or sudden loading. In most cases, the vibrations are imperceptible, and so can be neglected in building design. However, in some circumstances, the response of the structure to a common cyclic load (e.g. walking activities, etc.) is sufficient to produce a response that is perceptible to the occupants of the building. The most common example of such small, but perceptible, vibrations occurs in floor structures. This is not a new phenomenon, but it is more noticeable within the working environment of modern offices.

What disturbs building occupants?

For structures that are subjected to static loading, it is normal for the engineer to calculate the vertical deflection of the floor. This is to avoid undesirable deflections and to limit the possibility of damage to brittle finishes that will occur in serviceability conditions. However, for floors that are subject to cyclic or sudden loading, human perception of motion is usually related to *acceleration* levels rather than displacement. In most practical building structures, if the magnitude of these acceleration levels is not limited, the typical reaction of the building occupants varies between irritation and a feeling of insecurity. This is based on the instinctive human perception that motion in a 'solid' building structure indicates structural inadequacy or failure.

The working environment also affects the perception of motion. For busy floors, where the occupant is surrounded by the activity that is producing the vibrations, the perception of motion is reduced. In contrast, for quiet environments (such as laboratories and residential dwellings), where the source of the vibration is unseen, the perception of motion is significantly heightened.

A simple model of a vibrating system

A simple model that illustrates the vibration behaviour of a structure is shown in Figure 1 (a). The bending stiffness is modelled as a spring of stiffness *k*, and the floor mass is modelled by a point of mass *m*. All practical structures will have some damping, conveniently modelled as a viscous (or oil-pot) damper. Damping refers to the loss in mechanical energy within a mechanical system. Practical floor structures possess a low level of natural damping (normally in the order of 1%), which does not affect the natural frequency of the system. However, the magnitude of the damping is very important, as this determines the maximum possible magnification to the acceleration response of the floor (see below). Higher damping depends on the energy dissipation through non-

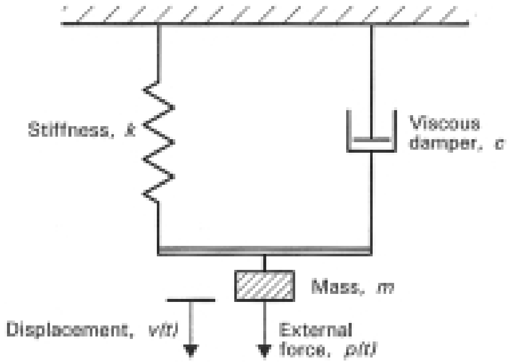


Fig. 1(a). Idealised single-degree-of-freedom system, basic components.

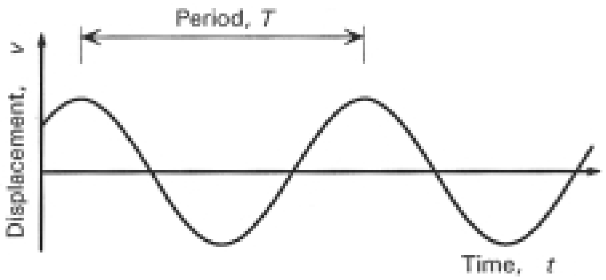


Fig. 1(b). Idealised single-degree-of-freedom system, undamped free vibration response.

structural components such as partitions, which are largely dependant on frictional forces. Intuitively, it might be expected that the presence of the false flooring would have an effect on the damping. However, experimental studies have shown that this is not the case. The reason is that deflections of modern false floors do not produce sufficient movement to develop significant friction forces.

A disturbance to the floor by a suddenly applied load will cause the system to vibrate as shown in Figure 1 (b). If no other external forces are applied to the system, the damping will cause the displacements to die away with time.

Walking activities

Walking produces a cyclic loading that is repeated at regular intervals called *periods*, which are inversely proportional to the pace frequency. A typical example of a load-time function that is produced by walking activities is shown in Figure 2 (a).

In general, a repeated force can be represented by a combination of sinusoidal forces, whose frequencies are multiples (or *harmonics*) of the pace frequency as shown in Figure 2 (b). The magnitude of the force for each of these harmonic components is taken as a proportion of the static weight of the person multiplied by a Fourier coefficient α_n.

The values of the Fourier coefficients have been established experimentally for different activities and different activity frequencies. For walking activities Figure 3 shows how the magnitude of the first three harmonic components varies with frequency.

The trend exhibited by Figure 3 is that the magnitude of the Fourier coefficient is lower for higher harmonics. For example, the average Fourier coefficient for the first three harmonics of walking is typically taken as $\alpha_1 = 0.4$, $\alpha_2 = 0.1$ and $\alpha_3 = 0.1$. In buildings, it is considered that a walking frequency of between 1.7 and 2.4Hz can realistically occur. (However, a higher frequency range may be found for other activities e.g., dancing, aerobics, etc.).

Floor response

When cyclic forces (such as those from walking activities) are applied to a structure, it will begin to vibrate. If the cyclic forces are applied continuously to the simple model in Figure 1(a), the motion of the structure will reach a steady-state i.e., vibration of a constant amplitude and frequency will be achieved (see Figure 1 (b)). The magnitude of the peak acceleration response for a long continued excitation is given by:

$$a_{peak} = \left(\frac{applied\ force}{mass}\right) \times Dynamic\ magnification\ factor$$

As can be seen from the above expression, the peak acceleration response decreases as the mass of the floor increases and increases as the dynamic magnification factor increases.

Mathematically, the dynamic magnification factor is given by the following identity:

$$D = \frac{1}{\sqrt{\left(1-\beta^2\right)^2 \left(2\zeta\beta\right)^2}}$$

Fig. 2(a). Loading caused by an individual walking at 2.0 Hz, load-time function.

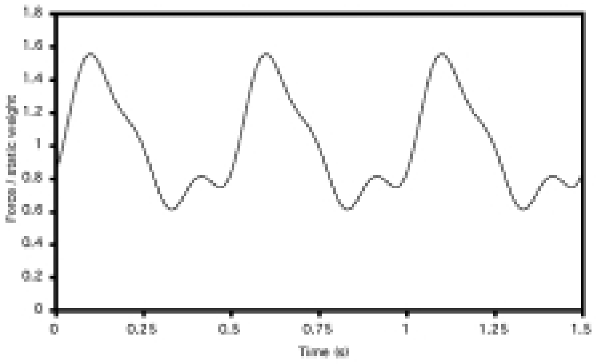
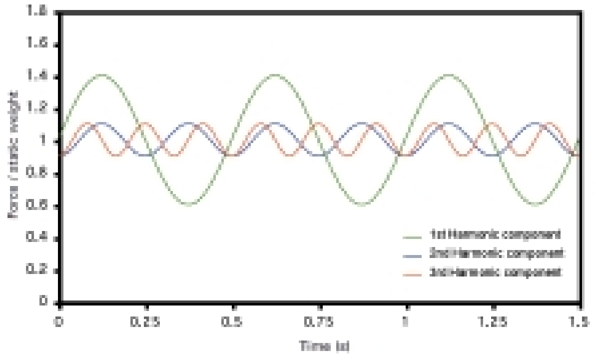


Fig. 2(b). Loading caused by an individual walking at 2.0 Hz, decomposition of the load-time function into the first three harmonic load components.



where β is the ratio of the activity frequency to the natural frequency of the structure and ζ is the damping ratio.

As can be seen from the second equation, the dynamic magnification factor is related to the level of damping that the floor possesses, and the ratio β (e.g., from walking, etc.) This variation is shown graphically in Figure 4 below.

Figure 4 shows different types of response depending on the frequency ratio β. When the cyclic force from the activity is applied at a frequency much lower than the natural frequency of the system ($\beta << 1$), the response is quasi-static. In these circumstances, the steady-state response is governed by the stiffness of the structure, resulting in an amplitude close to the static deflection. Conversely, when the dynamic force is applied at a frequency much higher than the natural frequency of the system ($\beta >> 1$), the steady-state response is governed by the mass (inertia) of the structure. In this case, the amplitude is less than the static deflection. Neither of these ranges of β are of great practical importance.

The range of β of greatest importance is where the dynamic force is applied at a frequency close to the natural frequency of a structure. In any structure which is lightly damped (as is found in most practical floor systems), very large responses will occur. The condition when the frequency ratio is unity is called *resonance* (i.e., the frequency of the applied load equals the natural frequency of the structure; $\beta = 1$). At resonance, very large dynamic magnification factors are possible and, for undamped systems (i.e. $\zeta = 0$) the steady-state response tends towards infinity. A more general result may be obtained from the second Equation, which shows that for resonance ($\beta = 1$) the dynamic magnification factor is inversely proportional to the damping ratio, and (Fig. 4.):

$$D_{\beta=1} = \frac{1}{2\zeta}$$

Since in many practical structural systems the natural damping ζ is of the order of 1%, if precautions against resonance are not made, magnification factors of up to 50 may result. Given that the force in the structure is proportional to the displacement, the dynamic magnification factor also applies to structural forces. In spite of this, for office floors, the magnifying effects to this load are normally neglected when assessing ultimate limit state criteria because the static weight of an individual walker is so small. This is certainly not the case when large groups of people (crowds) take part in synchronised activities (i.e. dancing, aerobics, etc.). In these circumstances, the magnification on the static load of the crowd may cause extreme loading to the floor, and should be considered as an additional imposed loading case for design at the ultimate limit state. In the UK, guidance is given in BS 6399-1: 1996 for structures that fall within this special category.

The above gives a basic overview of dynamics, and what considerations should be made in the design process for floors, which are to be subjected to occupant-induced vibrations. Design equations for estimating the fundamental frequency, and response of a floor, may be found in SCI publication 076. In addition, further design recommendations can be found in a recently completed SCI technical report RT 852 entitled *Design Guide for Vibrations of Long Span Composite Floors*, which also compares the performance of present design guide predictions with measured results. As well as acting in an advisory role, for the past three years, the SCI has also offered a consultancy service for designers. Our experts have produced all the necessary calculations for clients, on a variety of different types of floor. In addition to the initial design stage, we have evaluated existing floors and, where necessary, offered advice on remedial measures. We can also offer an *in situ* testing service on floors where it is perceived that there may be a potential vibration problem.

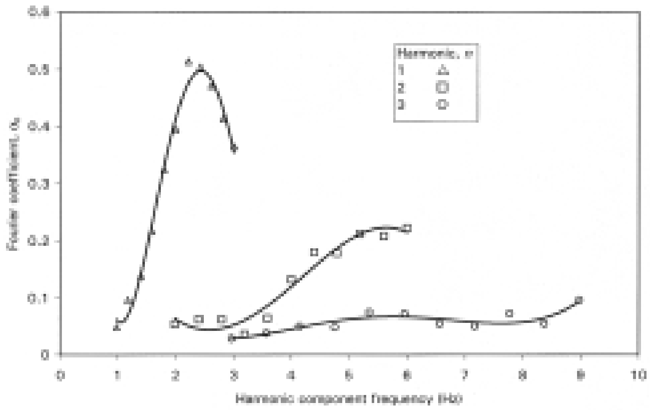


Fig. 3. Fourier coefficients for walking activities.

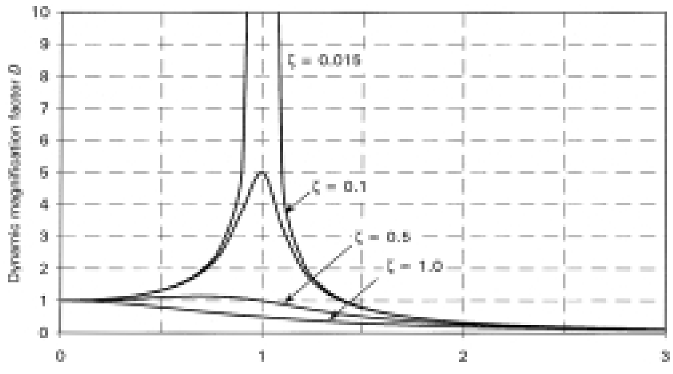


Fig. 4. Variation of dynamic magnification factor with damping and frequency.