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by D.E. Allen and G. Pernica

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A simple absorber for walking vibrations¹

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One of the most effective ways of improving walking vibration in an existing long-span floor structure is to increase damping by adding one or more vibration absorbers to the floor structure. This note describes the principles involved and how to apply a simple plank absorber, based on experience with a test floor structure at the Division of Building Research, National Research Council of Canada.

Un des moyens les plus efficaces pour diminuer, dans les poutres de grande portée, les oscillations dues à la marche, consiste à augmenter l'amortissement en ajoutant un ou plusieurs amortisseurs à la structure du plancher. Cet article décrit les principes impliqués et, à l'aide d'un essai réalisé à la Division des recherches en bâtiment, le Conseil national de recherches Canada, montre l'utilisation d'un amortisseur simple constitué de madriers.

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Introduction

Recent use of floor systems with longer spans and less damping has resulted in annoying vibration from walking. The single most important parameter affecting the acceptability of long-span floors has been shown to be damping (Lenzen 1966; Canadian Standards Association 1978). If it is very low (damping ratio 1%), annoying vibration begins to occur at accelerations of about $\frac{1}{2}\%$ gravity. If it is large (damping ratio 6%), it takes peak floor accelerations of about five times as much, or about 2.5% gravity, for it to become annoying.

Damping is provided by a number of sources, among the most common the human body and nonstructural components such as partitions. The human body acts as a very effective shock absorber for light residential floors, and this is why the vibration comfort of such floors is governed mainly by the motion due to static deflection of the floor as a person walks across it (a criterion of 1 mm static deflection under 1 kN force usually provides satisfactory performance). Long-span floors with concrete decks are much heavier, and therefore less effective damping is provided by the occupants. As a result, the natural vibration from footstep impact can be annoying. An effective and economical way to correct the problem in an existing long-span floor is to incorporate one or more vibration absorbers into the floor system. This note describes a simple vibration absorber and how to apply it to an existing floor. It may be useful, however, first to review the principles

FIG. 1. Idealization of floor structure with vibration absorber.

that make the vibration absorber work for footstep vibration.

How the vibration absorber works for footstep vibration

A vibration absorber is an oscillator of much smaller mass (m) than that of the floor structure (M), but with the same natural frequency. The resulting floor system is idealized in Fig. 1. How the vibration absorber works is illustrated in Fig. 2, which shows the resulting natural vibration of the idealized floor system following a single footstep impulse. Figure 2a shows the natural vibration for the idealized floor system without a vibration absorber.

When a vibration absorber is attached to the floor, the energy of natural vibration produced by a footstep is

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FIG. 2. Effect of vibration absorber on natural vibration from footstep.

transferred back and forth between floor and absorber. Figure 3 shows this transfer of energy for an undamped, tuned system. The law of conservation of energy for an undamped system requires that the maximum velocity of the absorber reach $\sqrt{M/m}$ times the initial velocity of the floor before energy is transferred back into the floor. The number of cycles required to transfer this energy from the floor into the absorber is proportional to the required motion in the damper and is equal to $\frac{1}{2}\sqrt{M/m}$. This expression can be verified from the equations of motion of an undamped, tuned system with a small mass ratio, m/M .

The addition of an undamped absorber tuned to the troublesome floor frequency changes a smooth vibration into a "beating" vibration, an improvement but not a major one. If the damping in the absorber is the same as the damping in the floor, no more energy is dissipated than would be without the absorber and the maximum vibration amplitudes during beating are not decreased, as shown in Figs. 2b and 3. If damping in the absorber is greater than that in the floor, more energy is dissipated between beats and the absorber becomes much more effective in damping the vibration of the floor, as shown in Fig. 2c. If damping in the absorber is very large, however, it resists displacement of

FIG. 3. Transfer of vibration energy in an undamped tuned system.

the absorber mass and therefore prevents the transfer of vibration energy into the absorber, i.e., the absorber again becomes ineffective, as shown in Fig. 2d. To be fully effective the absorber should have an optimum damping ratio.

The damping ratio of a floor structure is determined from the decay of natural vibration, as follows:

$$[1] \quad \xi = (\frac{1}{2}\pi n) \log_e (a_0/a_n)$$

where a_0 is the amplitude of an initial cycle of vibration and a_n is the amplitude n cycles later. When damping in the absorber is optimum, the effective damping ratio of the floor structure, ξ_0 , is essentially determined by the number of cycles required to transfer vibration energy from the floor into the absorber ($n \approx \frac{1}{2}\sqrt{M/m}$). Figure 2c indicates that a_0/a_n is approximately 5; from [1], therefore,

$$[2] \quad \xi_0 \approx \frac{\log_e 5}{\pi\sqrt{M/m}} \approx \frac{1}{2}\sqrt{m/M}$$

In order to dissipate vibration energy between beats yet allow transfer of energy in the first half-beat, the optimum damping ratio for the absorber should be of the same order of magnitude, i.e., $\frac{1}{2}\sqrt{m/M}$. This is the expression used by Luft (1979) to design vibration absorbers for controlling wind vibrations in tall buildings.

Figure 4 shows results of heel impact tests carried out

FIG. 4. Measurement of natural vibration from heel impact for various vibration absorbers.

on a test floor structure incorporating various vibration absorbers at the Division of Building Research, National Research Council of Canada (DBR/NRCC). They confirm the principles described above.

Application of plank vibration absorbers to existing floors

A simple wooden plank or layered system of planks with weights on top can be used as a vibration absorber to improve walking vibration in an existing floor. The planks are supported by the bottom chords of steel joists or by the bottom flanges of steel beams (Fig. 5). Weights (sand bags, concrete blocks, etc.) are added to the planks. A safety device such as a curb or net should be incorporated.

Frequency range

The range of application of vibration absorbers for walking vibration is 3–12 Hz. For fundamental frequencies greater than this, natural vibration from footsteps is generally not annoying because it decays very rapidly, even for low floor damping. Vibration from static deflection can be a problem, however, but vibration absorbers are not effective against this. Neither

are they effective for frequencies below 3 Hz because they cannot control the gradual buildup of vibration due to resonance between footstep frequency (approximately 2 Hz) and natural frequency.

Estimation of floor properties

If the troublesome natural frequency (f) of the floor structure is less than 6 Hz, it can be estimated by heel impact on the floor (up on the toes, down on the heels), counting pulsations and using a stop watch. If it is greater, an accelerometer and recording device may be needed.

The mass of the floor (M) per unit span length vibrating in the troublesome mode can be estimated as follows: for a one-way, steel-joist, concrete deck floor system the effective width is approximately 40 times the thickness of the concrete deck (Canadian Standards Association 1978—see the new edition to appear in 1984); for a girder system, the effective width is determined from the tributary area supported by a girder.

Estimation of absorber weight (mass ratio)

The mass ratio (m/M), and hence the weight of the absorber, is determined according to [2] by the effective

FIG. 5. Simple plank absorber.

floor damping required to provide satisfactory performance ($m/M \approx 2\xi_0^2$). Experiments carried out on the DBR/NRCC test floor indicate that the effective floor damping required decreases with increase in natural frequency. This is due primarily to the fact that, for the same damping ratio, vibration dies out more quickly as the natural frequency increases. An effective damping ratio ranging from $2\frac{1}{2}\%$ in the upper frequency range (8–12 Hz) to 7% in the lower frequency range (3–5 Hz) generally provides satisfactory performance. This corresponds to a range in mass ratio of $\frac{1}{4}$ –2%. Knowing the troublesome frequency, one can estimate the approximate mass ratio and hence absorber weight required for satisfactory performance. Such an estimate is needed in designing the planks, as will be described later.

Damping in absorber

The optimum damping ratio of the vibration absorber can be determined by [2] and ranges from $2\frac{1}{2}\%$ for a mass ratio of $\frac{1}{4}$ to 7% for a mass ratio of 2%. The damping ratio of a wooden plank with a weight on top is about 2%, which is less than optimum. Experiments carried out on the DBR/NRCC test floor indicate that a single wooden plank is often effective when the troublesome frequency is in the upper range, 6–12 Hz. For troublesome frequencies in the lower range, 3–6 Hz, experiments on the DBR/NRCC test floor indicate that more damping is required to eliminate the beating effect shown in Fig. 4c. Friction between planks can be used to increase damping in the absorber (see Fig. 4d), but it must be low enough for sliding to be initiated during noticeable walking vibrations, i.e., where peak accelerations are as low as 1% gravity.

Friction between wood surfaces is too high to achieve this, however. Mechanisms to reduce it include placing polyethylene sheets between planks (Fig. 5) and locating the absorber weight near midspan, where sliding does not occur.

Design of planks

Once the absorber weight has been estimated, the chosen plank stiffness should ensure that the natural frequency of the absorber is approximately equal to the troublesome floor frequency. A useful formula for design is

$$[3] \quad \delta_{\text{stat}} \text{ (in mm)} = (17.6/f)^2$$

where δ_{stat} is the deflection of the absorber due to estimated absorber weight. This formula is obtained from the relation between fundamental frequency of a simply supported beam and deflection under its own uniformly distributed weight (Timoshenko *et al.* 1974). For a single plank the deflection can be determined from the usual beam formula. For a layered friction system, which acts noncompositely during sliding, the load is shared among layers according to relative stiffness. The strength of the planks should be checked under a load of $m(g + a\sqrt{M/m})$, where mg is the weight of the absorber and a is the estimated maximum floor acceleration. If the acceleration is not known, the load can be approximated by $2mg$.

Tuning of vibration absorber

The vibration absorber can be coarsely tuned to the troublesome frequency, f , by adding weights until the deflection of the absorber due to its total weight is equal to $(17.6/f)^2$ mm. Fine tuning can be carried out by

FIG. 6. Effect of inaccurate tuning on natural vibration from footstep.

adjusting weights and checking the absorber frequency in one of two ways. The first is to shake the absorber at a rate corresponding to its natural frequency; if it is properly tuned, resonance vibrations will be observed in the floor structure. The second method is to observe how the absorber responds to a heel impact applied to the floor; if it is in tune, the absorber will vibrate vigorously in accordance with the amplification factor $\sqrt{M/m}$. If the troublesome frequency is high, it is possible that neither method will work very well and an accelerometer with a recording or display device may be required. Figure 6 shows the effect of inaccurate tuning on footstep vibration for the idealized floor system of Fig. 1. Evidently a mass within 10% of the correct one is still quite effective.

Summary

A simple wooden plank or layered system of planks with weights on top can be used as a vibration absorber to improve walking vibration in an existing floor. The

planks are supported by the floor structure and weights are added until the frequency of the plank absorber is equal to the troublesome frequency of the floor structure. If the troublesome frequency is in the upper range, 6–12 Hz, a simple plank absorber with a mass ratio of $\frac{1}{4}$ – $\frac{1}{2}$ can be used. If the troublesome frequency is in the lower frequency range, 3–6 Hz, a layered plank system with a mass ratio of $\frac{1}{2}$ –1 can be used. Because floors can vibrate with more than one frequency (owing to multiple modes), more than one absorber might be required. Start with one and add others as necessary.

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- f frequency of natural vibration
- g acceleration due to gravity
- m mass of vibration absorber
- M mass of floor structure
- n number of cycles of vibration decay
- ξ_a damping ratio of absorber
- ξ_0 optimum damping ratio of floor structure and absorber, eq. [2]
- ξ damping ratio of floor structure

List of symbols

a acceleration