Experimental Implementation of Active Control to Reduce Annoying Floor Vibrations

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ABSTRACT

When excessive levels of floor vibration disturb the occupants or impair the function of a facility, repair measures are often sought. This paper discusses the role of damping and the application of active control in reducing unacceptable floor motion. The practical implementation of active control, using an electro-magnetic force actuator in a computer controlled velocity feedback loop, is also described. Finally, experimental results for two temporary installations, an office floor and a chemistry laboratory floor, are presented to illustrate the effectiveness of the active control scheme.

INTRODUCTION

Many lightweight floor systems experience excessive levels of vibration caused by normal occupant activities. In most cases, these vibrations cause no concern with respect to safety; however, when the vibration levels are such that the function of the structure is disrupted, a serviceability failure has occurred. Disruption of the function of the facility can take many forms. Consider the impact of a vibrating floor in a hospital operating room or any other facility designed for tasks where precision is required. A less direct disruption of the building function happens when a perfectly safe structure is perceived to be unsafe. In a shopping mall, for example, a vibrating floor can alarm the patrons to the point of making them shop elsewhere. Designing for serviceability limit states can be a complex task because of the vagueness of the criteria involved. Serviceability limit states, as they relate to floor systems, primarily address excessive displacements and vibrations. The descriptive term "excessive" is the source of the vagueness and depends on many variables. These variables include the perceptions and expectations of building owners and users as well as their relationship with cost. Because of the subjective nature of the requirements and the fact that life safety is not an issue, the serviceability limit states are not as rigid as those related to strength. Design criteria related to serviceability, when they exist, are considered guidelines which require careful judgment on the part of the engineer. The reader is directed to Reference 1 for an extensive discussion of commonly accepted guidelines.

Serviceability limit states are often neglected or are a source of uncertainty in the design of a floor system. The result is often an unacceptable floor in need of repair. The factors affecting the perception of floor vibration must be carefully considered when repairing a problem floor. Traditional methods for improving floor vibration characteristics vary widely in cost of implementation, obtrusiveness, and effectiveness. Full height partitions are very effective because they provide both support and damping to the floor system. They can, however, transmit annoying vibrations to other parts of the building and interfere with the building space. Adding concrete thickness to the structure is effective in reducing both the amplitude of the vibration and the natural frequency, two desirable effects with respect to human perception. The drawbacks of adding concrete thickness include inadequate strength to support the additional weight, disruption in an occupied building, and the need to modify interior walls, doors and plumbing. Structural stiffening of the framing members is effective in reducing walking vibrations provided the alterations do in fact substantially stiffen the floor structure. Effective stiffening of framing members, however, generally requires ceiling space below the floor structure that may not be available. Tuned mass dampers have also been utilized to add damping to floor systems, thus reducing resonant vibration amplitudes and duration of transient vibrations without a considerable change in the natural frequency. The effectiveness of tuned mass dampers is limited by the amount of additional mass which can be safely supported by the structure. Additionally, the mechanisms that provide the damping are often ineffective for very small amplitudes, thus rendering the device ineffective for all but the worst problem floors. The drawbacks to the traditional methods illustrate the need for an alternative to controlling excessive floor vibration.

Active control technology is used in many disciplines to improve the response of dynamic systems. In the case of a

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floor system, it is effective to use active control to add damping. Active control, in this application, is implemented using an electro-magnetic proof-mass actuator, a velocity sensor, and a computer controlled feedback loop to generate the control forces that add damping. The following section illustrates, using a simple analytical model, the importance of damping in improving a problem floor. This model is then extended in the next section to describe the application of active control to reduce floor motion. The practical aspects of implementing this concept are also discussed. Finally, case studies describing two temporary installations are presented to illustrate the effectiveness of an active control scheme.

THE ROLE OF DAMPING

The basic element in structural dynamics is the single-degree-of-freedom system. Many of the available vibration criteria utilize a strategy to simplify a complex floor system into this basic element. The role of damping in improving problem floor systems excited by resonant loads is most easily explained using the same basic element. The single-degree-of-freedom system is represented by a single mass (m), spring (k), and damper (c), as shown in Figure 1. The governing differential equation of motion for this system follows.

$$m\ddot{y}(t) + c\dot{y}(t) + ky(t) = F(t) \tag{1}$$

When the mass, m, is subjected to a time dependent input force, $F(t)$, the result is a vibration response which can be described by the displacement, $y(t)$, the velocity, $\dot{y}(t)$, and the acceleration, $\ddot{y}(t)$. The equation of motion for a single-degree-of-freedom system can also be formulated in terms of the natural frequency of the free vibration and ratio of critical damping.

$$\ddot{y}(t) + 2\zeta\omega_o\dot{y}(t) + \omega_o^2 y(t) = \frac{F(t)}{m} \tag{2}$$

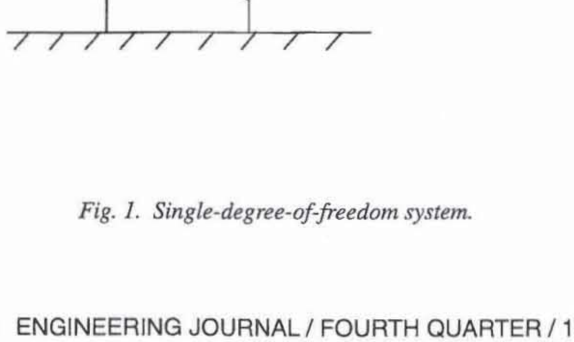

Fig. 1. Single-degree-of-freedom system.

where

ω_o = circular natural frequency, radians/s
$= \sqrt{k/m} = 2\pi f_o$
f_o = natural frequency, Hz
ζ = ratio of critical damping
$= c/c_{cr}$
c_{cr} = critical damping, the value of damping for which the roots of the characteristic equation are equal
$=2\sqrt{km}$

The time-dependent input force can take any form. For the purpose of studying floor vibration, it has been shown that the dynamic component of the forces due to walking can be represented by the following series:[2]

$$F(t) = P \cdot \sum_{n=1}^{N} \alpha_n \sin(n2\pi ft + \phi_n) \tag{3}$$

where

P = static weight of person,
α_n = amplitude coefficient,
n = order of harmonic of footstep rate, $n = 1, 2, 3, \ldots$,
f = footstep rate in steps per second,
t = time,
ϕ_n = relative phase angle,
N = total number of harmonics to adequately represent the walking force.

In this form, a solution for the dynamic displacement response can be obtained by superimposing the response of the system for each individual sinusoidal force input. For each term in the series of Equation 3, Equation 2 can be expressed in the general form (neglecting the relative phase angle):

$$\ddot{y}(t) + 2\zeta\omega_o\dot{y}(t) + \omega_o^2 y(t) = \frac{A_o}{m}\sin(\omega_f t) \tag{4}$$

where

A_o = peak amplitude of the sinusoidal input force,
ω_f = circular natural frequency for the harmonic being investigated.

The solution to this differential equation can be found in most structural dynamics textbooks. For the underdamped case (i.e. $\zeta < 1.0$), the solution is as follows:

Complementary Solution

$$y(t) = e^{-\zeta\omega_o t}[C_1\cos(\omega_d t + C_2\sin(\omega_d t)]$$

Particular Solution

$$+\frac{A_o}{k}\left[\frac{1-r^2}{(1-r^2)^2+4\zeta^2r^2}\sin(\omega_f t) - \frac{2\zeta r}{(1-r^2)^2+4\zeta^2r^2}\cos(\omega_f t)\right] \tag{5}$$

where

ω_d = damped frequency,
$= \omega_o(1 - \zeta^2)$,
$r = \dfrac{\omega_f}{\omega_o}$

As noted, the solution has two parts. The complementary solution, also known as the transient response, disappears with time, leaving the particular solution or the steady-state response. Through an investigation of this steady-state response, the concept of resonance and the important role of damping in a resonance response can be clearly understood. Rearranging, the particular solution takes the following form.

$$y_{ss}(t) = \frac{A_o}{k} \frac{\sin(\omega_f t - \theta)}{\sqrt{(1 - r^2)^2 + (2\zeta r)^2}} \tag{6}$$

where

$y_{ss}(t)$ = steady-state response,

$\theta = \tan^{-1}\left(\dfrac{2\zeta r}{1 - r^2}\right)$

Resonance occurs when the frequency ratio, r, is equal to 1.0 and Equation 6 reduces to:

$$y_{ss}(t) = \frac{A_o}{k} \frac{\sin(\omega_f t - \theta)}{2\zeta} \tag{7}$$

From this expression, the important role of damping in reducing resonant vibration levels is obvious.

Typical lightweight floor systems have damping ratios, ζ, between 0.03 and 0.05 (3 - 5 percent). The repair of a problem floor being subjected to resonant excitations, such as walking, dancing, and jumping, can be accomplished by increasing the damping in the system. The next section describes a new strategy to do this.

USING ACTIVE CONTROL

Active structural control, by its most general definition, is where the motion of the structure is controlled or modified by the action of a control system through some external energy supply.[3] This control system can take the form of an externally generated force which modifies the dynamic response of the system. Such a modification can be illustrated using the single-degree-of-freedom system described in the previous section. The modification to the equation of motion is as follows:

$$m\ddot{y}(t) + c\dot{y}(t) + ky(t) = F(t) - F_c(t) \tag{8}$$

where $F_c(t)$ is the control force. In the case of a problem floor system, the desired effect of the control force, F_c, would be to add damping. This would yield a control force of the form:

$$F_c = g \cdot \dot{y}(t) \tag{9}$$

where g is a constant called the control gain. A control force of this form is a special subset of active control called feedback control because the measured response of the system is used in generating a control force to produce a desired effect, much like a thermostat is used to control room temperature.

Substituting Equation 9 into Equation 8 and rearranging illustrates that supplying a control force which is proportional to the velocity response of the system has the desired effect of adding damping to the system when the control gain, g, is positive.

$$m\ddot{y}(t) + (c + g)\dot{y}(t) + ky(t) = F(t) \tag{10}$$

Equation 10 mathematically illustrates the use of feedback control to add damping to a floor system; however, the real challenge is implementing this concept physically.

In this experimental application, the control force is generated by an electro-magnetic shaker also known as a reaction mass actuator. An illustration and theoretical model of the shaker is shown in Figure 2. This device, which is smaller in size than a two drawer file cabinet, can either sit on top of the floor or it can be installed in the ceiling cavity below the floor slab. It should be noted that the control force, F_c, is generated between the reaction mass, m_a, and the support frame of the device which transmits the load to the floor structure. The reaction mass is supported by elastic bands which are represented by a spring with stiffness k_a in the theoretical model. The damping in the shaker, c_a, is generated by friction and internal motor properties. With such a configuration, the mathematical representation of the controlled system is altered slightly from that in Equation 10; however, the basic concept remains the same.

The velocity of the floor system is measured using a piezoelectric velocity sensor. This type of sensor produces a voltage signal, proportional to the velocity, which is monitored by a computer controlled data acquisition system. In the control loop of the computer program, the velocity voltage signal is multiplied by a pre-selected gain as described by Equation 9 and sent back out as a voltage signal to the shaker. The force generated in the electro-magnetic coil of the shaker

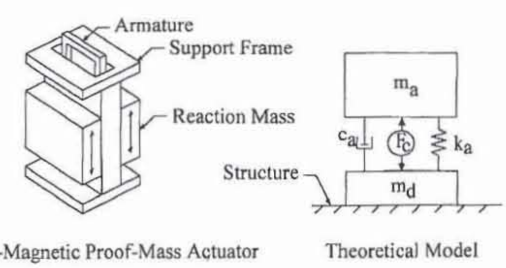

Fig. 2. Illustration and theoretical model of shaker.

is proportional to the input voltage. The result is a control force, F_c, which adds damping to the floor system.

Although outside of the scope of this paper, equations which mathematically describe the behavior of a controlled floor system when subjected to a specified excitation have been developed by Hanagan and Murray.[4] These equations allow for the study of a more complex floor system model than that represented by the single-degree-of-freedom system in Equation 1. The equations developed in Reference 3 also include dynamic properties introduced by both the sensor and the actuator.

IMPROVING A PROBLEM OFFICE FLOOR

An office floor in a light manufacturing facility was reported to have annoying levels of occupant induced floor vibrations. A plan of this floor is shown in Figure 3. The construction of this floor consists of a 2½-in. lightweight concrete slab on metal deck supported by joist framing members as indicated on the plan. The 28-ft-4-in. span was found to be the problem area. In this span, two long rows of desks are separated by an aisle near the center of the span. This open office area is used primarily for order processing with personal computers on nearly every desk. Walking in the aisle causes computer monitors to rock, thus intensifying the degree of annoyance. One particularly disturbing characteristic of this floor is that annoying levels of vibration are felt even when the occupant movement is several bays away.

An attempt was made to actively control the floor movement at a location where the problem was particularly acute. The control actuator and sensor were placed at the controller location noted in Figure 3. The floor response due to a person walking in the aisle between the desks was measured for the uncontrolled and controlled system. To provide a valid comparison, care was taken to keep the walking excitation as consistent as possible for the two measurements. A comparison of the results for the uncontrolled and controlled system is shown in Figure 4. For each vibration measurement the root-mean-square (rms) acceleration was calculated. The uncontrolled floor system had an rms acceleration level of 0.57 percent of g while the controlled system had a level of 0.17 percent of g. This represents more than a 70 percent reduction in the vibration level.

IMPROVING A PROBLEM CHEMISTRY LABORATORY FLOOR

Excessive floor vibration due to occupant movement was reported to exist in a chemistry laboratory where sensitive microscopes were in use. A partial plan of the floor system is shown in Figure 5. The 7-ft span is a corridor with laboratory rooms on either side. The floor construction consists of a 3½-in. concrete slab on metal deck supported by joist members as shown in the plan. The problem area, in the laboratory with the 28-ft-7-in. span, contains three island type

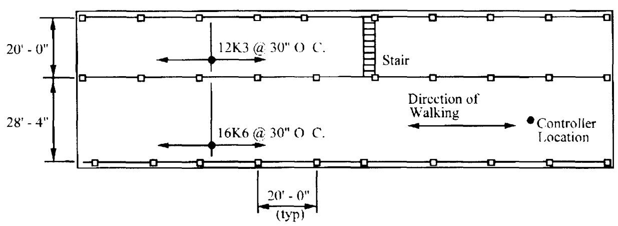

Fig. 3. Office floor plan.

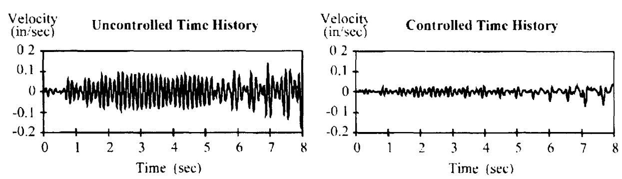

Fig. 4. Uncontrolled and actively controlled response of an office floor.

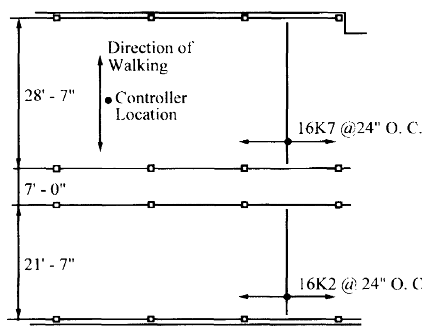

Fig. 5. Chemistry laboratory floor.

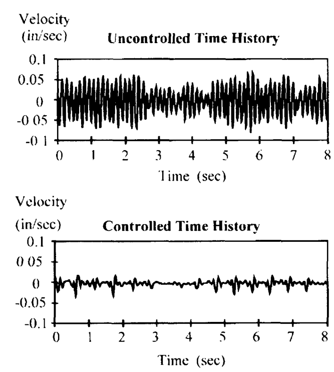

Fig. 6. Uncontrolled and actively controlled response of a chemistry laboratory floor.

workbenches where the function has been impaired due to disturbing levels of floor vibration.

The active control scheme was implemented to reduce the floor motion. Several tests were performed to assess the impact of the control. Results from the walking excitation tests are shown in Figure 6. For this test, the control actuator and sensor were placed between two of the workbenches. This location is noted in Figure 5. From the data shown in the graphs, the uncontrolled rms acceleration was computed to be 0.37 percent of g for the uncontrolled response and 0.09 percent of g for the controlled response. This represents over a 75 percent reduction in the vibration level.

SUMMARY AND CONCLUSIONS

Traditional methods for reducing objectionable levels of floor vibration are often found lacking and alternative repair measures are sought. Active control, using an electro-magnetic force actuator to add damping, is presented as another option. Results from the experimental implementation of active control to reduce floor vibration were presented for two floor systems. Reductions of 70 percent and 75 percent in floor vibration velocity amplitudes were observed for the office and the chemistry laboratory floors, respectively. This dramatic improvement was achieved with very little disruption to the building occupants while the repair was being implemented. Other advantages of this system are that it is relatively light weight and it is easy to install. The control effect was obtained with only 60 lb. of moving mass. A tuned mass damper of similar weight would have a negligible effect on improving the dynamic properties of the floor system. Active control, as implemented in this research, also has drawbacks. Cost is currently the major disadvantage to the active system. The hardware alone is approximately $16,000 for a single control circuit. One must keep in mind, however, that any new technology is expensive and often becomes more reasonable in time. Maintenance and reliability issues, although not prohibitive, also detract from the attractiveness of an active system. Permanent installations are necessary to address these long term issues. Through research and the expanded use of this new technology, the construction industry will most likely come to view active control as a viable repair measure in reducing excessive floor vibrations.

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