

# CHAPTER I

## INTRODUCTION AND LITERATURE REVIEW

### 1.1 Introduction

Building designs are increasingly becoming more efficient. To increase design efficiency, light-weight floor systems utilize components such as joists and composite construction to increase both strength and span lengths. While strength is not a limiting factor in these floor systems, serviceability may be compromised. Due to decreased floor mass and longer span lengths, floor vibrations have become an area of concern.

Design criteria (Allen and Rainer 1975, Allen 1990b, Murray 1991) are available to help designers minimize annoying vibrations in floor systems. In general, floors that comply with the criteria and are used for their original purpose are found to be acceptable to the occupants. Office and residential settings require different criteria than gymnasias or assembly halls. Typically, vibrations are induced primarily by walking in office or residential environments, and partitions and furniture provide damping to the floor system. Gymnasium and dance hall environments necessitate different criteria due to vibrations induced by rhythmic activities, in addition to walking, and because of relatively little damping.

Floor vibration problems often arise when floors designed for office environments become retrofitted for health clubs. Aerobics induced vibrations may not be annoying to the participants; however, occupants of adjacent parts of the building which may be used for quieter activities often experience unacceptable levels of vibration.

Modifying existing floor systems to reduce vibrations due to walking may be as simple as adding partition walls to increase damping. However, preventing the transmission of aerobics induced steady-state vibrations to adjoining parts of the building is a difficult and expensive process (Allen 1990b). An economical solution to prevent the transmission of aerobics induced vibrations to the supporting floor system is a "floating" concrete floor system. An evaluation of a "floating" concrete floor concept is the purpose of this research.

### 1.2 Literature Review

#### 1.2.1 Floor Vibration Terminology

To better understand the terms used throughout this paper, a brief overview is presented of some of the terms not frequently used in the area of structural engineering.

Floor vibrations are primarily induced by human activity and mechanical equipment. *Transient vibrations* dissipate with time and are caused by an impact force, such as walking. *Steady-state vibrations* are continuous over time and are caused by rotating machinery or people jumping to the beat of music, for instance.

Based on the stiffness, mass, and damping of a floor, a floor system vibrates at certain *frequencies*. The *amplitude* of the motion of a floor system is the maximum response of a specified point on the floor from a position of static equilibrium. Amplitude may describe the displacement, velocity, or acceleration of a floor system and is often plotted with respect to time. However, *acceleration* is commonly used interchangeably with the term amplitude and is described in the units of  $\text{in./s}^2$  or % g, where g = acceleration due to gravity.

The *period*,  $T$ , of the vibration is a measure of the time it takes the floor system to complete one cycle of oscillation. Figure 1.1 shows a graphical representation of amplitude and period.

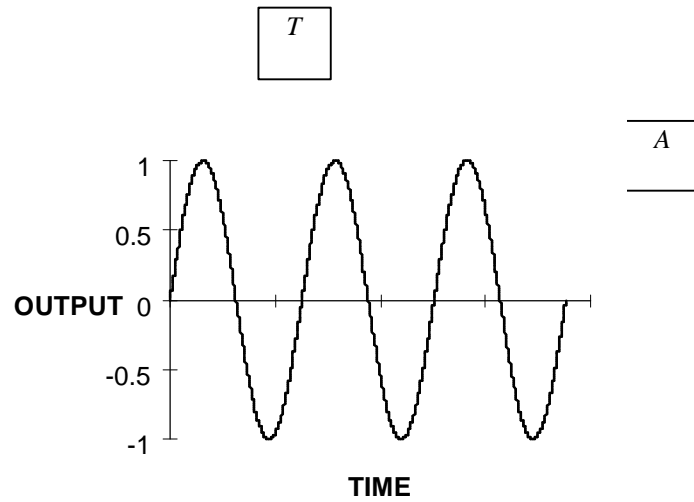
Inversely related to the period, the natural frequency,  $f$ , of the system is the number of cycles completed in one second, with the units of cycles per second or hertz (hz). A floor system may have several natural frequencies at different modes of vibration. A mode of vibration is a pattern assumed by the system where every particle is in simple harmonic motion with the same frequency. More than one mode of vibration may exist in a multiple degree-of-freedom system, with each mode having a different natural frequency. The lowest natural frequency of a floor system is the fundamental frequency of the system. The corresponding mode of vibration is known as the fundamental mode of vibration (Harris 1996).

*Resonance* occurs when the forcing frequency of the input activity, such as jumping, corresponds to a natural frequency of the floor system. The *harmonics of the forcing frequency* are multiples of the forcing frequency and may also cause a resonance condition if they correspond to a natural frequency of the floor.

When an object impacts a floor, energy is absorbed into the floor system and the vibration dissipates. *Damping* is a measure of how quickly a transient vibration dissipates, and is often expressed as the viscous damping factor or damping ratio (Meriam and Kraige 1992). The damping forces can come from various sources, such as fluid or air resistance, known as *viscous damping*, internal friction within the floor system, known as *structural damping*, and external friction between sliding surfaces, known as *Coulomb damping* (Avallone and Baumeister 1987).

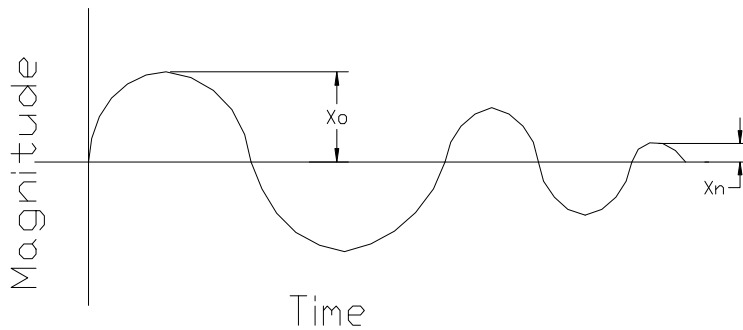
Essentially, damping is related to the slope of a line connecting adjacent maximum values of a time record of amplitude of a vibration. The maximum amplitude values of a steady-state vibration, as in Figure 1.1, would basically be equal, resulting in a horizontal line with zero slope, representing no damping. An impact force on a floor system with a high degree of damping would result in a steeply sloped line representing a high damping coefficient, as shown in Figure 1.2 where the peak magnitudes gradually decrease.

A system is critically damped when there is sufficient damping to prevent oscillatory motion. Typically, damping is measured as a ratio of the damping present in the system to the critical damping. The system is underdamped if the damping ratio is less than unity. Most floor systems are underdamped.



$T = \text{Period}; A = \text{Amplitude}$

**Figure 1.1 Representation of Amplitude and Period**



**Figure 1.2 Representation of Damping**

### 1.2.2 Floor Vibration Background Information

In any given situation involving excessive noise or annoying vibrations, there are always three factors involved:

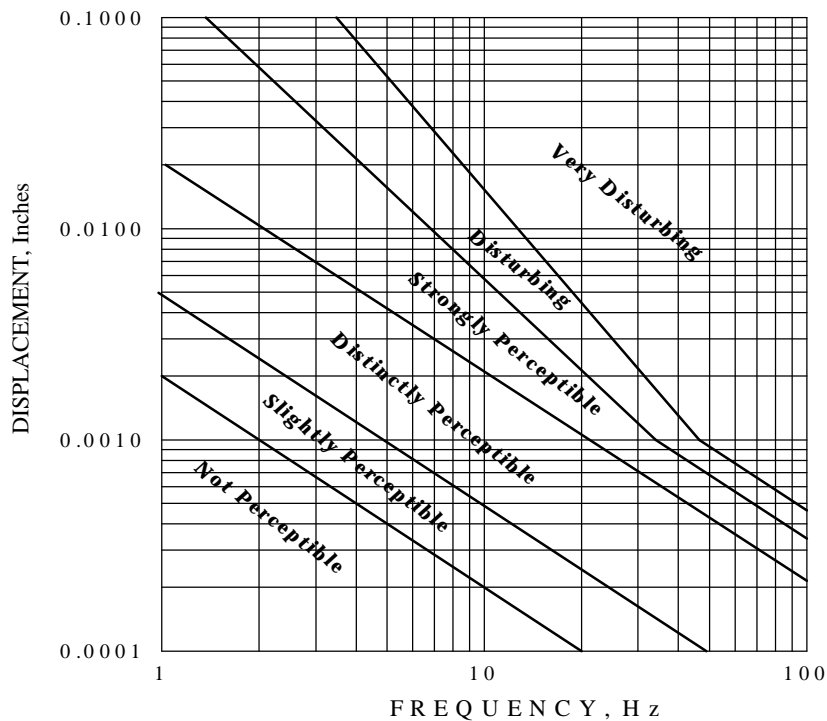
- Source - where the dynamic forces are generated,
- Path - how the energy is transmitted, and
- Receiver - how much noise/vibration can be tolerated (Dossing 1988).

For floor vibrations, the source is typically human induced vibration due to normal usage, such as walking or jumping. Lenzen (1966) stated that "a normal floor is not subjected to a steady-state vibration induced by machinery" because "the machinery can be easily isolated from the floor system and, thus, the vibrations eliminated." Therefore, most research concerning floor vibrations is focused on limiting the effect of transient and steady-state human-induced vibrations.

The path is how the vibrations are transmitted to the receiver. In this case, the building structure is the path. The receivers of the transmitted vibrations are other humans occupying the same floor system as the source.

Based on the type of activity they are performing, humans have a certain threshold of tolerance to vibration. People in office or residential settings will tolerate much lower vibration levels than those participating in an activity (Allen 1990b). Additionally, Hanes (1970) reported that based on automobile and aircraft passenger comfort studies, the natural frequency of human internal organs is between 5-8 hz. Therefore, floor systems with natural frequencies in that range will possibly cause human discomfort. Murray (1991) investigated over 100 problematic floors and in a majority of the cases, the first natural frequency of the floors was between 5-8 hz.

Scales rating human acceptability to floor vibrations exist for both transient and steady-state vibrations. In the early 1930's, Reiher and Meister developed a scale for human response to steady-state vibrations (Figure 1.3) based on the frequency and amplitude of the vibrations (Murray 1979).



**Figure 1.3 Reiher-Meister Scale**

Lenzen (1966) researched human response to transient vibrations and discovered that damping is a critical factor in controlling vibrations. The transient vibrations were not problematic if there was sufficient damping to reduce the vibration to a negligible amount within five cycles.

Murray (1979) reviewed four floor system vibration acceptability criteria and found them to be inconsistent and to underestimate the strong influence of damping on acceptability. A new criterion for steel beam- or steel joist-concrete slab floor systems was proposed based on normal human activity in office or residential environments and the results of 90 in-situ tests of floor systems. The criterion states that the motion of the floor system due to normal human activity will not be objectionable to the occupants if the following equation is satisfied:

$$D > 35A_0f + 2.5 \quad (1.1)$$

where  $D$  = damping in percent of critical,  $A_0$  = maximum initial amplitude of the floor system due to a heel-drop excitation (in.); and  $f$  = first natural frequency of the floor system (hz).

Allen, Rainer, and Pernica (1985), developed a minimum satisfactory natural frequency formula for dancing which produces a nearly sinusoidal dynamic load. The formula is as follows:

$$f_o \geq f \sqrt{1 + \frac{1.3 \mathbf{a} w_p}{\left(\frac{a_o}{g}\right) w_t}} \quad (1.2)$$

where  $f_o$  = forcing frequency, hz;  $\alpha$  = dynamic load factor coefficient;  $a_o/g$  = acceleration limit;  $w_p$  = equivalent uniformly distributed load for the participants;  $w_t$  = total floor weight (including participants).

Jumping exercises, such as high impact aerobics where both feet leave the ground, produce "sinusoidal loading components that involve not only the beat of music but also multiples or harmonics of the beat of music" (Allen 1990a). Allen (1990b) developed a guideline specifically for floors designed to support dancing or exercise activities. An acceleration limit of 2% g, or 7.75 in/s<sup>2</sup>, was proposed for facilities combining aerobics and weight lifting on the same floor level, while an upper limit of 7% g, or 27.0 in/s<sup>2</sup>, was suggested for facilities used exclusively for aerobics.

Allen (1990b) proposed a minimum recommended natural frequency formula for aerobics floors based on Equation (1.2), which is as follows:

$$f_o \geq if \sqrt{1 + \frac{2 \mathbf{a}_i w_p}{\left(\frac{a_o}{g}\right) w_t}} \quad (1.3)$$

where  $i$  = harmonic number of the forcing frequency, and the other terms are as defined in Equation (1.2).

Equation (1.3) accounts for the first three harmonics of the loading. Frequencies due to sinusoidal loading beyond the third harmonic typically are relatively small in magnitude compared to the first three harmonics and can be ignored for practical purposes.

Music for high impact aerobics typically occurs at about 150 beats per minute, or 2.5 hz, up to a maximum of 2.75 hz. The second and third harmonics of a forcing frequency of 2.5 hz are, correspondingly, 5.0 hz and 7.5 hz, which could correspond to a natural frequency of the supporting floor system, resulting in a resonance condition. In general, Equation (1.3) results in a required natural frequency greater than 9-10 hz.

Murray (1991) recommends providing structural framing so that the first natural frequency satisfies Equation (1.3), and isolating the floor system from the remaining structure using separate columns when designing an exercise facility to avoid unwanted motion of the floors. Additionally, if the exercise floor has been built and vibrations are annoying, Murray recommends separate ceilings and partitions immediately below the exercise floor by supporting the ceiling on its own framing and by not extending partitions to the floor above. Many other methods for controlling the transmission of floor vibrations are available.

### 1.2.3 Review of Methods to Control Transmitted Vibrations

Designing a floor to prevent annoying floor vibrations is easily accomplished by following the design criteria for the intended use of the floor. Difficulties arise when floors are designed and installed without regard to vibration control or are used for applications other than their original purpose, e.g., office floors used for exercise activities.

Isolating the source of vibration, such as a vibrating machine, from the floor system is the simplest and most effective method of controlling annoying floor vibrations. However, with human induced vibrations, humans are both the source of vibrations and the receiver, making it difficult to isolate the source from the floor system. Thus, the structure itself must be modified. To prevent vibrations due to walking, the most effective method of modifying the structure is by increasing the damping (Allen and Swallow 1975).

Active and passive controls exist for the limitation of floor vibrations. Hanagan (1994) used a proof mass actuator, an active control method which utilizes outside energy sources to control vibrations. Based on the measured movement of a floor system, the electromagnetic actuator receives an input signal. The actuator reaction mass counteracts the motion of the floor and reduces the vibration level.

Passive controls use the reaction of the device to the floor vibration to limit the floor vibration. Examples of passive control devices include wall partitions, damping posts, tuned mass dampers, and the installation of stiffeners to structural floor members (Rottmann 1996). These methods vary widely in implementation costs and in the amount of obstruction to the usable floor space.

Lenzen (1966) proposed that "simple loads other than humans do not increase the damping values. A floor loaded with concrete cylinders had much less damping than when unloaded. The activation of the dead load provided more energy which had to be absorbed before the vibrations would decrease." Lenzen successfully employed a test floor dashpot damper with 7.5% of critical damping. Actual installations utilizing the dashpot damper were not reported. Human beings were found to be one of the best dampers available.

Allen and Swallow (1975) recommend partition walls and planters as a low cost method to increase damping. Additionally, damping posts connected to the bottom chord of the floor joist and the floor below increased damping from an original level of 3.75% to 4% of critical in one application. The increase in damping is relatively small but it brought the floor system to within acceptable vibration limits. The relative motion between the floors causes shearing of a rubber ring, which increases the damping of the floor system. However, the post interferes with the clear space of the floor, limiting its practicality.

Another passive damping device called a dynamic absorber consists of a steel box loaded with concrete blocks positioned between adjacent floor joists and attached to the

bottom chord of the joists at each corner of the box with a compression spring and housing. The assembly reportedly works well (Allen and Swallow 1975).

A tuned mass damper is a second mass, single degree of freedom system attached to the bottom of the floor system. A spring supports a mass in parallel with a damper. The tuned mass damper is placed at the point of largest amplitude of the floor vibration and the spring-mass-damper system counteracts the motion of the floor vibration. Tuned mass dampers can be successfully used to control floors with one or multiple modes of vibration. The level of success of the tuned mass dampers depends on the amount of damping in the floor system and its frequencies (Rottmann 1996).

Previously, Allen (1990b) reported limited success with tuned mass dampers in actual installations. Murray (1991) stated that passive control devices require some relative movement between the device and the floor system. However, very small amounts of displacement can be annoying to humans, which limits the effectiveness of the damping devices.

Machine vibrations are effectively isolated from supporting structures by mounting the machine on springs, rubber mounts, cork padding, or some other type of shock absorber (Avallone and Baumeister 1987). For example, automobile engines rest on rubber mounts to reduce the transmission and engine vibrations transmitted to the car body.

Firestone Tire and Rubber Co. adapted the pneumatic spring to the automotive industry in the 1930s to limit the transmission of vibrations from the suspension to the car body (Spring Design Manual 1994). Currently, pneumatic springs are used extensively in the trucking industry to isolate the trailer frame from the suspension. Utilizing the same principles, pneumatic air springs have been used in applications to absorb floor vibrations.

#### **1.2.4 Review of Existing Aerobics Floor Installations**

**Overview.** Aerobics floors and dance floors are similar in design and many different types are on the market. The majority of modern aerobics floors provide cushioning to the participants to prevent injuries, referred to as resilient floors (Loeffler 1988), but are not designed to prevent the transmission of vibrations to the supporting floor structure.

**Types of Aerobics Floor Construction.** The most common shock absorbing or sprung aerobics floor construction method is the "basket weave". Typically consisting of three to five crossed layers of 1 in. x 3 in. boards placed 16 in. on center, basket weave floors provide sufficient weight-bearing support as well as shock absorption of the impact of the participants (Loeffler 1988).

Other types of resilient dance floors involve the use of foam blocks, coiled springs, leaf-springs, and inflatable supports. Stagestep of Philadelphia, PA markets the Springstep

floor consisting of a 2 in. x 4 in. wood frame mounted on high density 2 in. foam blocks and covered with plywood decking (Stagestep 1996). Other companies such as Gerstung Floor Systems of Baltimore, MD and Wooden Kiwi Productions of Somerville, MA manufacture similar floor systems to the Springstep floor. Landa Enterprises of Rochester, NY produces a floor known as the Flex-Aire which mounts on inflatable air tubes (Loeffler 1988).

Kinetics Noise Control of Dublin, OH specializes in the control of noise and vibration transmission control. Kinetics manufactures dance floors similar to the wood frame on foam block construction previously described. In addition, Kinetics produces Air Supported Vibration Isolation Systems for precision measuring equipment, electron microscopes, and other isolation applications.

The Kinetics system consists of several components. The air supports are elastomeric air springs encased in steel housings to increase the damping and lateral stiffness of the springs. Up to 90% of critical damping can be achieved with the use of auxiliary tanks with adjustable damping valves which allow air to flow out of the springs when compressed. Use of the tanks lowers the natural frequency of the isolation system. Fluidic leveling sensors prevent the floor system from becoming unbalanced. The entire assembly is typically mounted on a thick, steel plate sufficiently rigid to support the system (Kinetics 1996). Figure 1.4 shows the basic layout of a Kinetics installation. Exact dimensions of the installation were not available.

Another Kinetics installation was completed in 1995 for Greenwich Hospital Cancer Center, Greenwich, CT. An aerobics facility was installed on the fifth floor of the hospital directly above a surgical area sensitive to vibrations. A "floating" concrete floor was installed on steel coil springs positioned 3 ft. on center throughout the room. Foam blocks were inserted to provide damping to the spring system. Vibration characteristics of the floor are unavailable but the installation is satisfactory to the building occupants (Mastriani 1997).

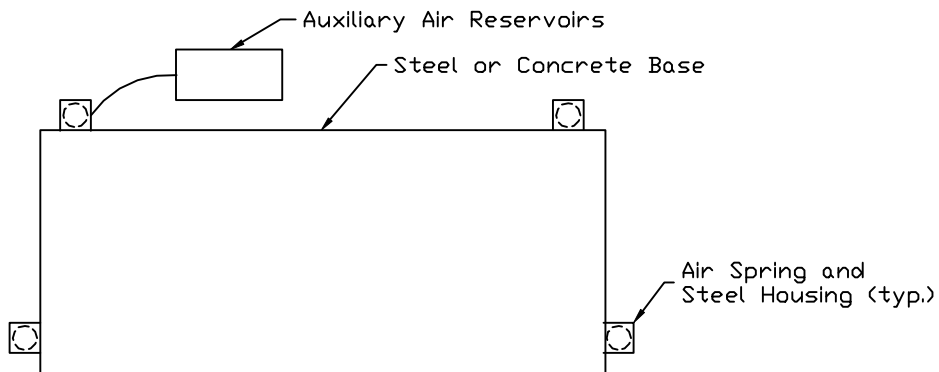
### **1.3 Research Objectives**

The purpose of this research is to evaluate a prototype "floating" concrete aerobics floor designed to be a cost efficient solution to the problem of transmitted floor vibrations due to rhythmic exercise in existing structures. The results of the evaluation are presented in Chapters 3 and 4.

Three configurations of the test floor were tested in the laboratory. The vibration properties were determined based on a heel-drop excitation, and the transmitted forces were determined from jumping tests at various frequencies for each test configuration. The acceleration and force traces were analyzed to determine the damping coefficient and natural frequencies utilizing Fast Fourier Transforms (FFTs).

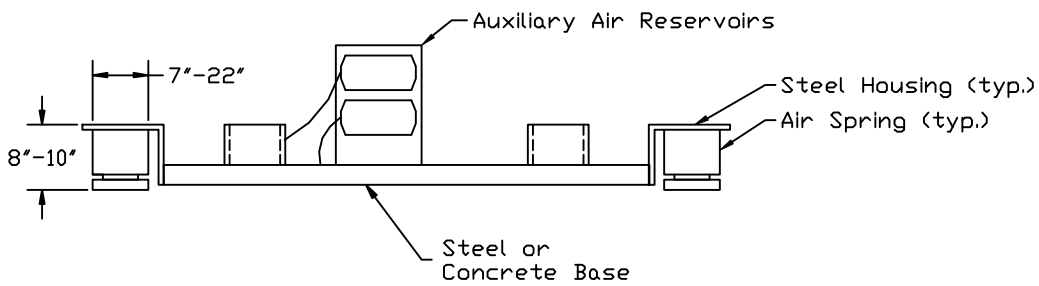
Analytical results were determined based on vibration theory for a Single Degree of Freedom (SDOF) system. In this report, the analytical and experimental results are compared

and recommendations are made concerning the acceptability of the "floating" floor concept and possible applications.



(Note: Exact spacing of air springs and size of base unknown. Figure represents an example set-up.)

**a) Plan View**



**b) Elevation View**

**Figure 1.4 Kinetics Air Supported Isolation System  
(after Kinetics 1996)**