

CHAPTER II

PROCEDURE USED TO EVALUATE A "FLOATING" AEROBICS FLOOR

2.1 Determination of Floor Components

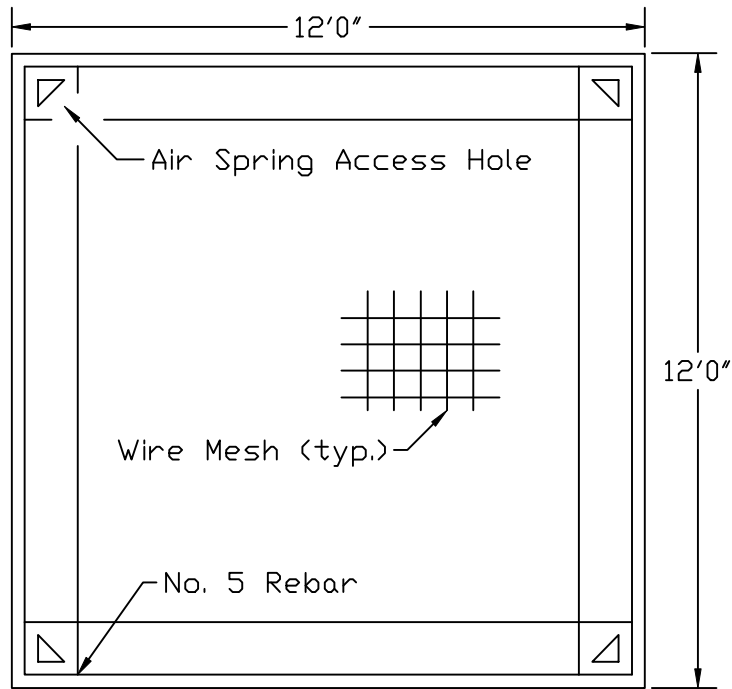
2.1.1 Determination of Concrete Slab Dimensions

The concept of a "floating" floor necessitates a floor that is easily installed as well as providing sufficient mass to meet vibration acceptability criteria for the participants. A wooden floor on springs is easy to install but the mass of a wooden floor does not provide sufficient inertial resistance to the aerobics forces to control the floor vibrations. A relatively light weight wooden floor acts as a trampoline and the motion of the floor could possibly cause a "seasick" feeling. A concrete floor made of pre-cast panels is also easy to install but, in contrast to a wooden floor, has sufficient mass to limit vibrations of the floating floor.

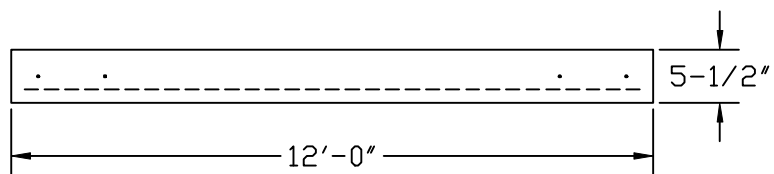
The characteristics of the laboratory test floor used in this investigation are similar to a floor that would be installed in an existing building. The dimensions of the test floor (Figure 2.1) were determined primarily by ease of assembly and total mass of the slab. Using a slab thickness of 5.5 in., the test slab was framed easily with conventional 2 in. x 6 in. lumber and provided sufficient depth for reinforcement. The 12 ft x 12 ft dimensions allow sufficient space for several participants to jump simultaneously on the floor. Additionally, using these dimensions, the total mass of the floor is less than the laboratory crane capacity of 5 tons. The dimensions also represent the size of three 4 ft x 12 ft precast panels joined along the edges, a configuration which may be used in an actual floor. Additional details of the laboratory floor are shown in Figures 2.2 and 2.3.

Reinforcement for the floor consisted of two 5/8 in. diameter No. 5 bars, placed along the bottom edges of the slab. The bars provided bending resistance to the slab edges as well as the corners where triangular holes were framed to provide access to the air spring mounting plate (Figure 2.2). Wire reinforcing mesh was placed across the bottom of the slab with a 1-1/2 in. cover, based on ACI 318-95 code requirements. The reinforcement provided sufficient strength to prevent corner cracking throughout the testing process.

The triangular access holes at each corner were recessed 4 in. from the slab edge and were 7 in. x 7 in. right triangles. A 14 in. x 14 in. x 3/8 in. steel plate was set in the bottom of the slab at each corner and the triangular access hole was framed on top of the plate. Within the triangular access hole, two 1/2 in. and one 1-1/4 in. diameter holes were drilled for the air spring mounting bolts and air inlet assembly, respectively. Two anchor studs were placed on opposite sides of the triangular access holes to provide additional strength to the corner of the slab.



a) Plan View



b) Cross Sectional View

Figure 2.1 Laboratory Floor Dimensions

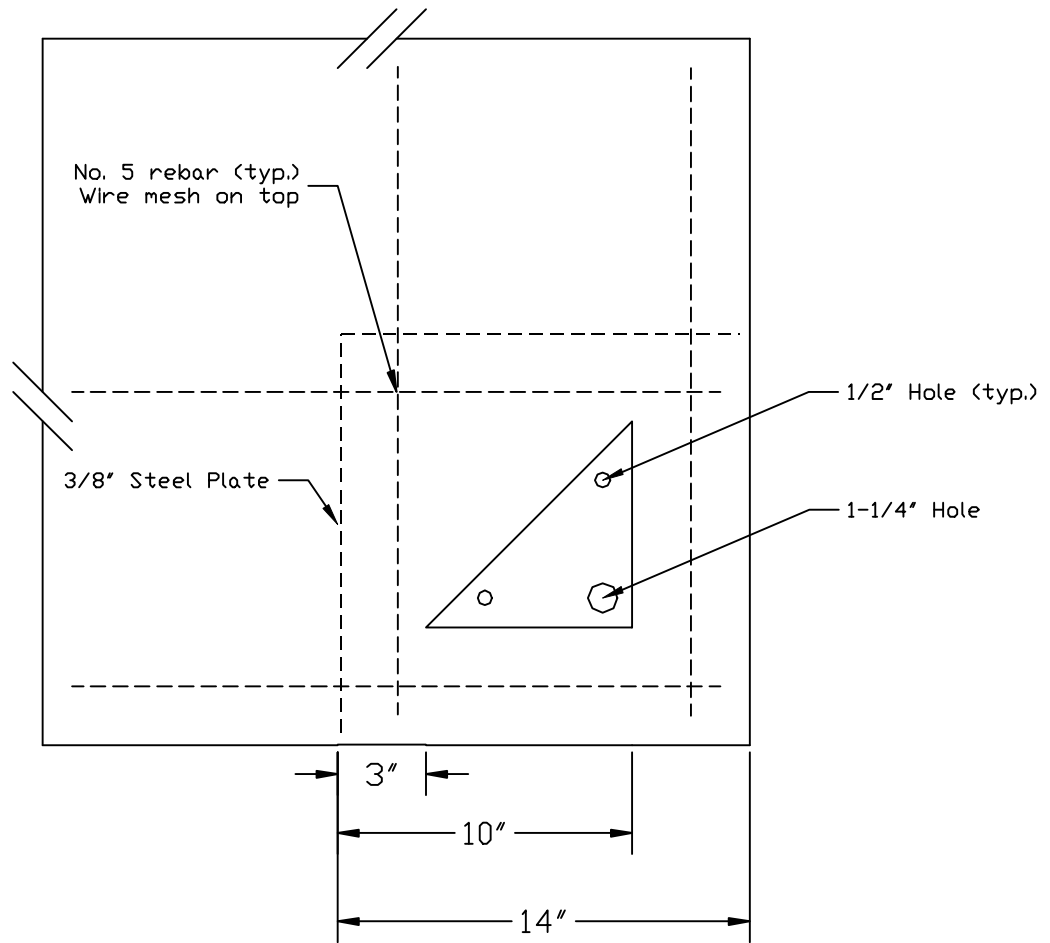


Figure 2.2 Floor Corner Details

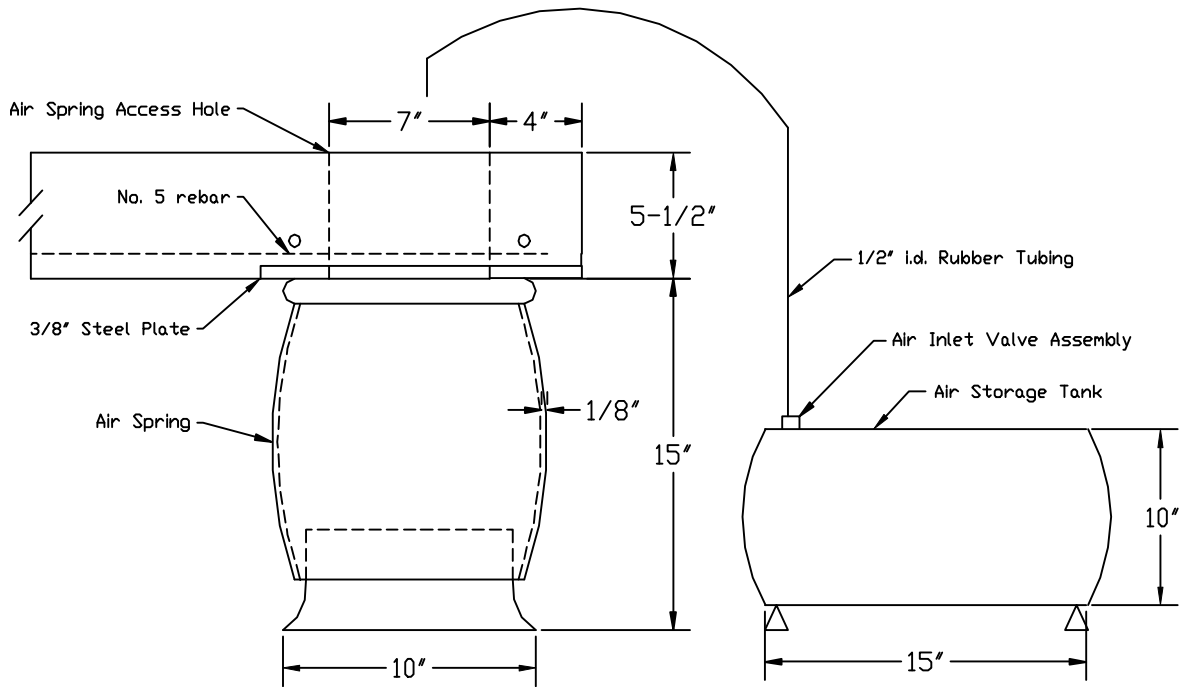


Figure 2.3 Air Spring Support Details

2.1.2 Selection and Sizing of Air Springs

To prevent resonance of the floor system due to aerobics-induced vibrations typically ranging in frequency from 1.5 to 3.0 hz (Allen 1990a), the selected isolator requires a natural frequency below 1.5 hz. A certain amount of softness is required in the isolator to achieve a natural frequency of 1.5 hz as well as sufficient damping to prevent the "sea sickness" effect. Pneumatic air springs typically used in truck suspensions were selected to provide the required softness, as well as damping, by utilizing an auxiliary air storage tank.

Firestone Model 1T15M-6 Air Mount manufactured by Firestone Industrial Products was the isolator selected for the floor system (Firestone 1996). The selected isolator was a rolling lobe type pneumatic air spring in which the base acts as a piston and the flexible outer membrane "rolls" along the surface of the base (Figure 2.3).

Based on the Firestone Design Guide, the 1T15M-6 dynamic characteristics at a 15.0 in. design height, 40 psi internal air pressure, and supporting a 2,720 lb load were a spring rate of 395 lb/in. and natural frequency of 1.19 hz. Utilizing the design guide, a required spring pressure of 36 psi and an initial height of 14.5 in. were determined, based on the slab weight of 2400 lb per spring.

2.1.3 Selection of Air Storage Tanks

Air storage tanks were required to increase the damping of the floor system by allowing air to flow in and out of the air springs during compression and expansion. Initially, one 5 gallon air storage tank was connected with 3/8 in. diameter rubber tubing in series with the four air springs. After preliminary testing, the desired natural frequency was not achieved with this configuration.

After consulting the Firestone design engineers, a 5 gallon air storage tank was connected to each of the air springs with 1/2 in. rubber tubing to provide the necessary dynamic characteristics. The air storage tanks were equipped with a flow control valve which could be used to adjust the amount of damping in the system.

The 5 gallon air storage tanks were selected due to the low cost and availability for the feasibility testing.

2.2 Determination of Floor Vibration and Force Transmission Characteristics

2.2.1 Measurement Equipment

Excitation of the floor system was necessary to determine the dynamic characteristics. A human impact, known as a heel drop, was used to excite the floor system. The standard heel drop force is the impact force resulting from a 170 lb person initially raised

on the balls of his feet with heels approximately 2-1/2 in. above the floor. The person suddenly relaxes from the raised position and allows the heels to impact the floor (Murray 1979).

The heel drop loading function is approximated by a linearly decreasing 600 lb ramp function over a 50 ms time period. To achieve consistent impact data, a mechanical impactor was used throughout this research. The impactor, known as a Heel Drop Simulator (HDS), simulates the heel drop impact of a 170 lb person (Figure 2.4).

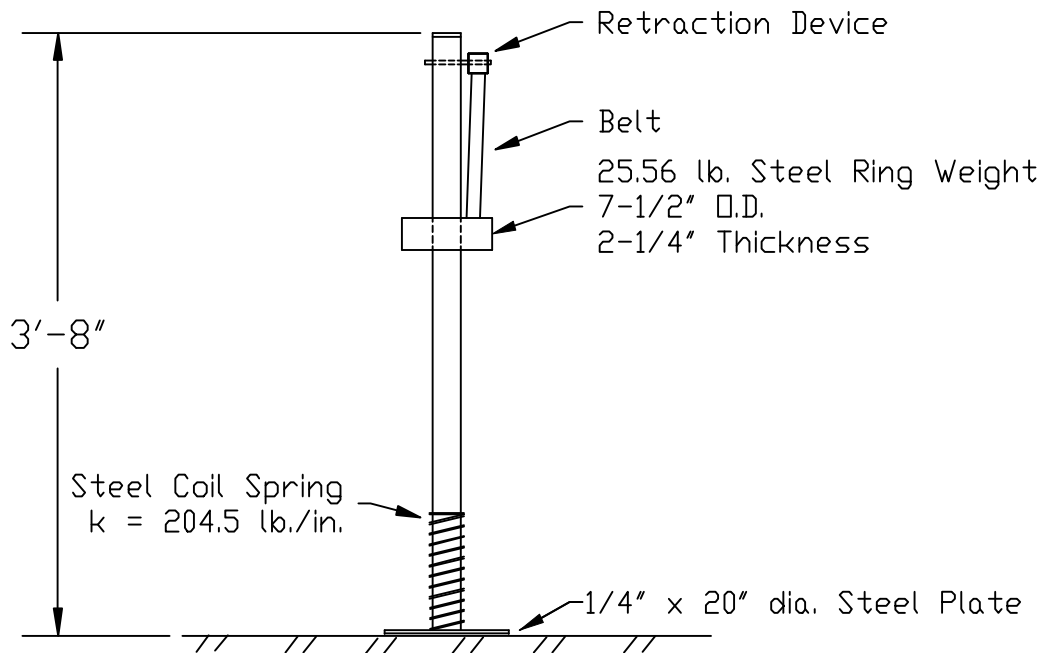
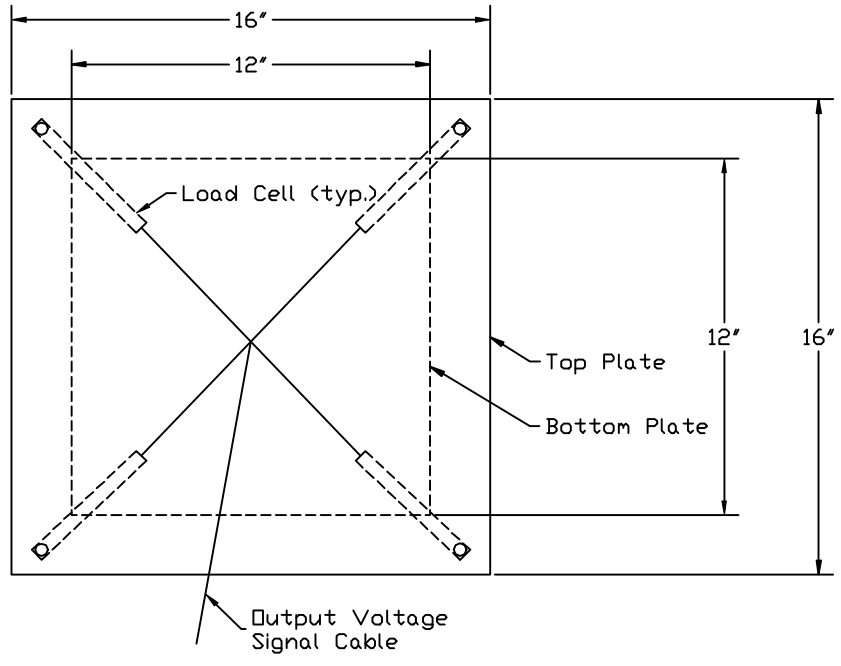
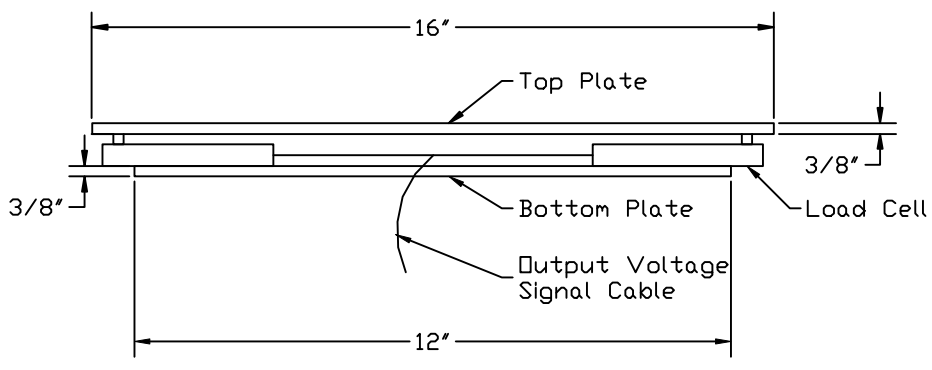


Figure 2.4 Heel Drop Simulator



a) Plan View



b) Elevation View

Figure 2.5 Force Plate Transducer

A force measuring device, known as a force plate, was used to measure the impact force (Figure 2.5). The force plate consists of four cantilever load cells supported by a 12 in. x 12 in. x 3/8 in. steel bottom plate. The load cells support the four corners of a 16 in. x 16 in. x 3/8 in. steel top plate which transfers the impact force.

A voltage proportional to the measured force was produced by each load cell and averaged in a junction box to produce a single output voltage. The output voltage was amplified and sent to a 2 channel dynamic signal analyzer (Figure 2.6). The force plate output voltage was calibrated at 68,124 lb/volt (Hanagan 1994) and the measured force was displayed on the dynamic signal analyzer. The output force was verified before each testing session.

The acceleration response of the floor system was measured with a Wilcoxon Model 731 seismic accelerometer in conjunction with a Wilcoxon Model P31 signal amplifier.

The acceleration response was recorded with a Hewlett Packard Model 35660A two channel Dynamic Signal Analyzer. The analyzer was configured throughout this research to record 1024 data points over a 16 second time record.

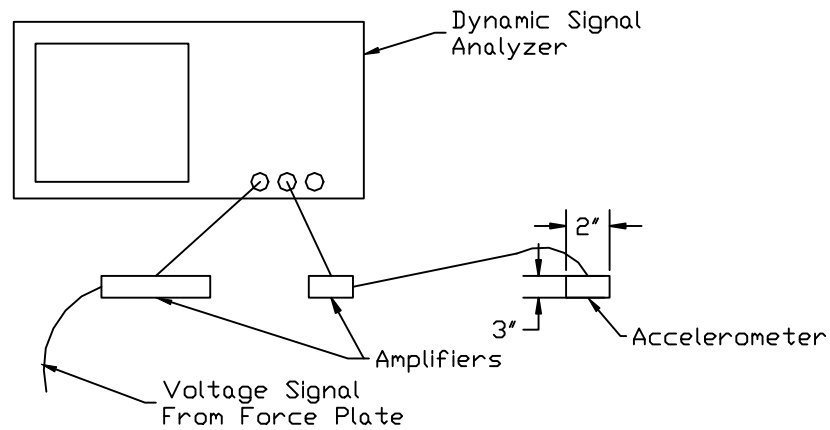


Figure 2.6 Data Acquisition System

2.2.2 Determination of Floor Natural Frequency

2.2.2.1 Frequency Due to Vertical Mode of Oscillation

The methods used to predict and measure natural frequency of the floor system acting as a Single Degree of Freedom (SDOF) system are discussed in this section. The SDOF model assumes the floor to move up and down only in a vertical mode of oscillation. To ensure only vertical motion, a lateral restraint as described in Chapter 3 was used.

The predicted natural frequency was calculated using the following equation:

$$f_n = \frac{1}{2\pi} \sqrt{k/m} \quad (2.1)$$

where f_n = natural frequency (hz), k = spring constant (lb/in.), and m = total mass supported by the spring (lb- s²/in.).

The spring constant of the air springs is non-linear due to deviations in the effective area, internal volume, and internal pressure from the design height. Utilizing the Firestone Design Catalog, a spring constant of 395 lb/in. was used to approximate the spring constant of the air springs. This constant was determined from a load of 2720 lb, design height of 15.0 in., and air spring pressure of 40 psi.

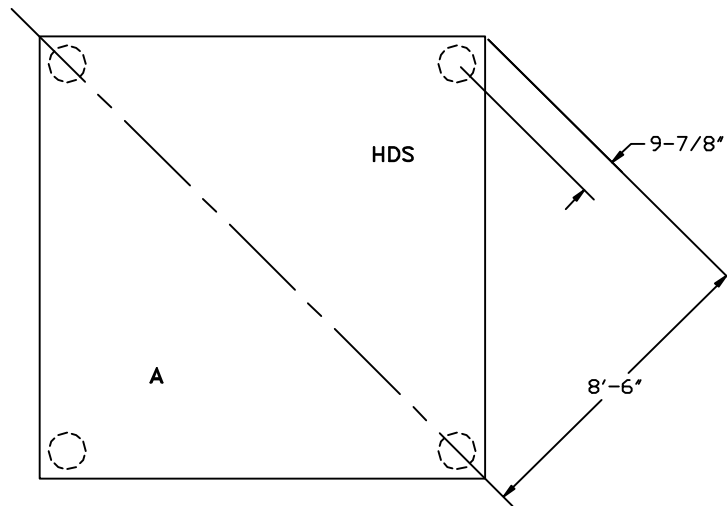
The measured natural frequency was determined by utilizing the Fast Fourier Transform (FFT) on the acceleration response. The HDS and accelerometer were placed at the center of the floor and the floor impacted. The acceleration response was measured and the FFT displayed on the signal analyzer for immediate feedback on the system response. After testing was completed, the FFT again was used in a Microsoft Excel spreadsheet to plot the frequency response of the floor system and determine relative magnitudes of the response based on the acceleration response data.

2.2.2.2 Frequency Due to Floor Corner and Side Rotating Mode of Oscillation

When the test floor was impacted at a corner 1/4 point, the floor rotated about an axis through opposite corners of the slab (Figure 2.7). To reduce the amplitude of the rotating motion, nine 60 lb solid concrete blocks were placed at each corner to increase the effective mass at each corner.

Using an approximate method, similar to Allen (1990b), the predicted natural frequency of this corner rotating mode of oscillation was determined using an effective mass of the slab acting at each spring. An exact analysis was also performed to verify the approximate solution.

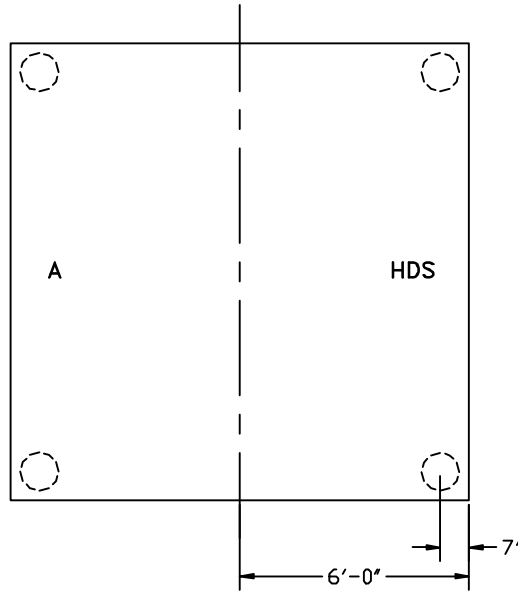
Utilizing the approximate method, the effective mass acting at the corner of the slab



was related to the total effective mass of the slab acting at one spring due to an impact at the center of the slab causing a vertical mode of oscillation.

A = Accelerometer Location; HDS = Heel Drop Simulator Location

Figure 2.7 Corner Rotation Axis



A = Accelerometer Location; HDS = Heel Drop Simulator Location

Figure 2.8 Side Rotation Axis

The following equations were used to calculate the effective vertical, corner, and side masses and natural frequencies of the slab due to rotation when impacted at the corner and side:

$$W_{eff,vert} = W_b + wL^2 \quad (2.2)$$

$$W_{eff,rotate} = W_b + wL \int_0^L y^2 dx \quad (2.3)$$

$$f_{n,rotate} = f_{n,vert} \sqrt{\frac{W_{eff,vert}}{W_{eff,rotate}}} \quad (2.4)$$

where $W_{eff,vert}$ = total effective mass weight of the slab acting at one spring due to an impact at the center of the slab (lb), W_b = total mass weight of blocks added to one corner (lb), w = weight per unit area of the slab (psf), L = length of slab from axis of rotation to corner of slab, $W_{eff,rotate}$ = effective mass weight of the slab acting at one spring due rotation of the slab about the diagonal (lb), y = modal displacement of the effective section of the floor, $f_{n,rotate}$ = predicted natural frequency of the floor rotating about an axis through opposite corners (hz), and $f_{n,vert}$ = predicted natural frequency of the floor in the vertical mode of oscillation (hz).

In a similar manner, Equations (2.2) - (2.4) were used to calculate the predicted natural frequency of the floor system rotating about the slab centerline axis (Figure 2.8) when impacted at the mid-point of one side of the slab.

The exact analysis involved the motion of the rotating system. The rotational equation of motion can be expressed as follows:

$$M + I (d^2\Theta/dt^2) = 0 \quad (2.5)$$

where M = moment about rotational axis (lb-ft), I = mass moment of inertia about rotational axis (lb-ft-s²), and $d^2\Theta/dt^2$ = angular acceleration (rad/s²).

The moment equation for the corner mode of oscillation, shown in Figure 2.9, is as follows:

$$M = 2 (k) (d) (d \Theta) \quad (2.6)$$

where k = spring constant (lb/in.), d = moment arm from the rotation axis to the spring location (in.), and $d \Theta$ = rotational displacement, using small angle theory (in.).

Substitution of Equation (2.6) in Equation (2.5) results in the following equations to determine the natural frequency:

$$2 k d^2 \Theta + I (d^2\Theta/dt^2) = 0 \quad (2.7)$$

$$\mathbf{w} = \sqrt{\frac{2 k d^2}{I}} \quad (2.8)$$

$$f_{n,rotate} = \frac{1}{2\mathbf{p}} \mathbf{w} \quad (2.9)$$

where \mathbf{w} = angular natural frequency (rad/s), and the other terms are as defined in Equations (2.5) and (2.6). Sample calculations are shown in Appendix A.

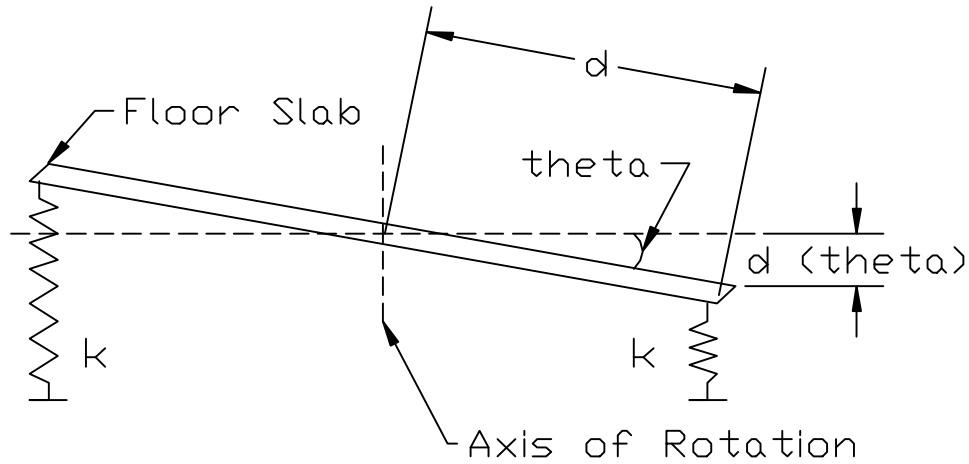


Figure 2.9 Rotational Displacement of Floor Slab

The measured natural frequencies of the corner and side rotating modes of vibration were determined using the HDS and accelerometer at opposite 1/4 points. An FFT analysis was performed on the acceleration response and the natural frequencies were determined from peaks on the frequency response.

2.2.3 Determination of Floor System Damping Ratio

The logarithmic decrement and half-power band-width methods are commonly used to calculate of the damping ratio in a vibrating floor system. The logarithmic decrement method may be used to calculate the damping ratio of a single frequency oscillation directly from the acceleration response due to an impact force. The logarithmic decrement method determines the viscous damping ratio from a measured acceleration response and is defined by the following equation:

$$d = \frac{2pz}{\sqrt{1-z^2}} = \frac{1}{n} \ln \left(\frac{x_o}{x_n} \right) \quad (2.10)$$

where d = logarithmic decrement, z = damping ratio, n = number of cycles used, x_o = cycle amplitude at time $t = t_o$, and x_n = cycle amplitude at time $t = t_n$ (McConnell 1995). The cycle amplitudes x_o and x_n are represented in Figure 1.2 in Chapter 1.

The half-power band-width method uses the frequency response of a floor system due to an impact excitation and the fact that a higher degree of damping in a system is associated

with a broader peak in the frequency response (Harris 1996). This method may be used to determine the damping ratio of systems with more than one mode of oscillation. The mode of oscillation is determined and the peak magnitude of the corresponding frequency is determined. The peak magnitude is divided by an amplification factor, $\sqrt{2}$, and the two frequencies corresponding to this magnitude are used in Equation (2.6) to determine the damping ratio, as follows:

$$z = \frac{f_b - f_a}{2f_n} \quad (2.11)$$

where f_n = peak or natural frequency, f_a and f_b = frequencies corresponding to peak magnitude divided by $\sqrt{2}$.

The damping ratio values obtained by different methods of calculation, e.g., logarithmic decrement and half-power band-width, are not related and cannot be directly compared. Guidelines for estimating damping of a floor system have varied by over 100 percent due to the use of different damping calculation methods (Murray 1996). The logarithmic decrement method was used throughout this report in the calculation of damping ratio values. This method was selected because it can be easily calculated from the acceleration response.

2.2.4 Determination of Impact Force

The force plate was the measurement device used to measure the impact force. To determine the impact force due to the HDS, the HDS was placed directly on the force plate at the center of the floor slab. A 160 lb man jumping to the beat of a metronome on the force plate at the center of the floor slab was used to determine the impact force transmitted to the floor system at the first harmonic of various jumping frequencies.

The weight of the HDS or man was measured and recorded for each test and then subtracted from the reported values to give the true impact forces. For example, the HDS assembly weighs approximately 150 lb which was subtracted from the impact forces recorded to give the true impact forces.

The measured impact force at the second harmonic of the jumping frequencies was determined by multiplying the measured impact force at the first harmonic by the ratio of the magnitudes of the frequency response spectrum of the first and second harmonics. In a similar manner, the measured impact force at the third harmonic was obtained.

2.2.5 Determination of Transmitted Output Force

The transmitted output force is the force initiated by an impact of the floor slab and transmitted through the air springs to the supporting floor. The value of this force was measured by the force plate which was placed directly under one of the air springs before the

system was inflated. The measured output force is the force transmitted by one air spring. All input forces were initiated at the center of the floor slab. It was assumed that the output force was uniformly distributed to each of the four air springs. The output force measured by the force plate was multiplied by four to represent the force transmitted by all four air springs acting in unison. The measured percent force transmission of the system is the ratio of the measured output force to the measured input force, multiplied by 100.

For steady-state excitation, such as jumping, the predicted output force was expressed as a percentage of the input force, known as the transmissibility of the system (Maltbaek 1988). This transmissibility is given by the following equation:

$$t_r = \frac{\sqrt{1 + \left[2z\left(\frac{f}{f_n}\right)\right]^2}}{\sqrt{\left[1 - \left(\frac{f}{f_n}\right)^2\right]^2 + \left[2z\left(\frac{f}{f_n}\right)\right]^2}} \times 100 \% \quad (2.12)$$

where t_r = transmissibility (%), z = damping ratio, f = excitation frequency of the input force (hz), and f_n = vertical natural frequency of the floating floor system (hz).

The transmissibility equation is used to determine the force transmitted at the first, second, and third harmonics of the input forcing frequency. For example, for an input jumping frequency of 1.5 hz, the second and third harmonics are 3.0 hz and 4.5 hz, respectively. The value of f is varied in the transmissibility equation to obtain a predicted output force at the higher harmonics.

2.2.6 Determination of Peak Acceleration

Jumping tests were performed by one person jumping at specified frequencies at the center of the floor slab. The resulting acceleration of the floor slab was recorded by an accelerometer and peak acceleration values were determined for each harmonic of the jumping frequency from the acceleration response and corresponding FFT.

To obtain a prediction of how the "floating" floor concept will perform in an actual installation, the peak acceleration values were multiplied by four to obtain an estimate of the acceleration levels induced by an aerobics class spaced evenly across the floor slab. A reasonable weight of aerobics participants per square foot is 4.2 psf or 0.2 kPa, which allows sufficient space for aerobics motions without interfering with another participant or hitting a wall (Allen 1990b). The weight of the person who performed the jumping tests was 160 lb and the surface area of the floor slab is 144 ft², resulting in a weight per square foot of 1.11 psf. It was assumed that four participants in an aerobics class could exercise within the 144 ft² floor slab area with a weight per square foot of 4.44 psf. This value corresponds to the original assumption of 4.2 psf.

2.3 Acceptability Evaluations By Experienced Aerobicists

Subjective evaluations were performed by two experienced aerobicists. The evaluations involved two aerobicists performing three typical low impact aerobics steps on the floor at various frequencies, while one person stood on the floor. Additionally, one person stood on the floor while two others stepped onto the floor and walked across it several times.