VIBRATION CHARACTERISTICS OF AN APS LAB FACILITY IN BUILDING 401

by

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ABSTRACT

The vibratory behavior of a lab facility located in Building 401 of the Advanced Photon Source site at Argonne National Laboratory is summarized. Measurements of ambient vibration indicate that acceptable displacement levels are usually maintained (rms value below 0.1 microns) for the measured frequency range, above 0.2 Hz. An exception occurs when strong wind conditions excite a horizontal building resonance near 1.85 Hz to rms levels as high as 0.3 microns. Measurements of the laboratory floor's dynamic response to directly applied force excitation agree with theoretical predictions. The primary component of the floor construction is a reinforced concrete slab. The slab has a transverse fundamental resonant frequency of 18.5 Hz and an associated damping level of roughly 8.5 % of critical. It is also shown via experimental measurements that the linoleum surface adhered to the concrete slab is far more compliant than the slab itself and can significantly influence the floor's dynamic response to local excitations.

1. INTRODUCTION

The Advanced Photon Source (APS) Experimental Facilities Division (XFD) has set up a vibrations laboratory, Rm. 1108 in Bldg. 401, to support the continued development of beamline positioning devices for use in the APS. Low level vibratory response of these systems, on the order of 0.1 microns, is critical, and, consequently, the vibration characteristics of the laboratory facility are of interest. Ambient levels of vibration due to background sources, such as building dynamics, and ventilation equipment, are of concern. Also of interest is the dynamic response of the lab floor, which will support vibration testing of beamline positioning components. In this report, ambient measurements of horizontal and vertical floor motion are summarized for different cases. Also summarized are theoretical models and supporting measurements of the floor dynamic properties. While this study focuses specifically on Rm. 1108, results and techniques reported will have applicability to other rooms in Bldg. 401, as well as to other buildings of similar construction.

2. OBJECTIVES

The objectives of this study are as follows:

- Measure the response of the APS XFD Vibrations Laboratory to ambient vibration sources. Identify sources and observe any variations due to weather, ventilation equipment operation, and location in room.

- Determine the dynamic characteristics of the laboratory floor based on theoretical calculations and supporting measurements of its response to transient impulse excitations and wide-band continuous excitations.

- Summarize the capabilities of the facility, in terms of the level of sensitivity and frequency ranges for which reliable vibration measurements can be made and in terms of the influence of floor dynamics on vibratory measurements.

3. AMBIENT VIBRATION LEVELS

3.1 Experimental Methods

In these tests, two high sensitivity, low frequency piezo-based accelerometers (VibraMetrics Model 1030) and a 2-channel dynamic FFT signal analyzer (HP 35665a) were used to measure vertical and horizontal acceleration in the frequency domain. Initial calibration studies verified that both accelerometers and analyzer channels gave identical responses for the same excitation given that components were left undisturbed for 15 to 20 minutes, allowing instrumentation and transducers time to reach an equilibrium condition. Recorded acceleration data were converted to rms displacement and plotted using *MATLAB* software. Tests were repeated under different ambient conditions and for different frequency ranges. Also recorded was the electrical noise of the instrumentation with the accelerometer detached. Different ambient conditions were considered to assess the contribution of vibration sources, including the ventilation fan located in the lab and day-to-day changes in weather conditions that may affect building motion. During these measurements, no foot traffic took place in the lab itself. Whether or not the room wall has an effect on response to the different sources was also investigated based on the comparison of measurements at different points. Different frequency ranges were used to focus on low frequency motion, which is expected, in general, to have greater amplitude.

3.2 Results and Discussion

High Frequency Ambient Levels. Results of ambient measurements up to 50 Hz are shown in Figures 1 and 2. Beginning with Figure 1, room response under normal, quiet conditions is shown. Clearly, above 7 Hz, vertical motion becomes more significant than horizontal motion with numerous resonant peaks throughout the spectrum. Also shown is the broadband electrical noise level, which, for this frequency range, is insignificant. In Figure 2, measurements of room vibration taken with and without the ventilation fan turned on are shown. The large peak present at 27 Hz corresponds to the ventilation fan rotational frequency. It is notably absent when the fan is turned off. A comparison of the data in Figure 2 shows other differences in the power spectrum. Numerous measurements taken over the course of several months indicated that this is to be expected, even from minute to minute. There are many activities occurring in the APS building at any time. Some of these will excite various building resonances. They may also affect the level of electrical noise measured at 30 Hz and 60 Hz, which did fluctuate to some degree. Specific tests with and without the fan on in the laboratory on the ground floor below this laboratory showed no noticeable difference in responses. A comparison of the responses measured in the center of the room with those measured within 1 meter of the wall showed no significant differences. With respect to high-precision vibration studies of APS equipment (as small as 0.1 micron), based on these measurements, ambient levels of vibratory motion above 5 Hz are insignificant. However, the lower frequency range needs further analysis.

Lower Frequency Ambient Levels. Careful studies focusing on low frequency motion were made. The lower limit of 0.2 Hz was, according to specifications, dictated by the accelerometer limitations but perhaps more significantly was limited by electrical noise, which is amplified at lower frequencies. Acceleration is dependent on motion multiplied by the square of the frequency. As frequency decreases, the same level of motion results in a significantly reduced acceleration level. Because the transducers measure acceleration, the signal-to-noise ratio becomes poorer.

Vertical and horizontal ambient motion up to 6.25 Hz are shown in Figures 3 and 4. Whereas at higher frequencies, vertical motion was dominant; at lower frequencies, horizontal motion is more prevalent. Several distinct peaks are present to varying degrees primarily in both horizontal directions. They are associated with overall building resonances. Their consistent presence with relatively the same characteristic shapes suggest that they are not dependent on changing activities occurring in the building itself. Aside from these peaks, the response spectrum is flat and is believed to represent the noise level of the transducer and electrical circuitry combination. Note that it follows the trend of the electrical noise level very closely.

The lowest resonant peak, at 1.8 Hz, has an rms displacement on the order of 0.1 micron. Hence, it may significantly affect high precision measurements in the lab. In Figure 4, identical measurements of horizontal (east-west) motion are shown for several different days. The first day corresponded with light storm conditions and wind. On the other two days, conditions were calm. It appears that the resonance at 1.8 Hz may be significantly affected by the weather conditions to the point where it may interfere with experiments in the laboratory.

4. ROOM FLOOR DYNAMICS

In ambient studies it was seen that very low frequencies were dominated by gross horizontal building motion. The laboratory floor itself did not experience flexural motion but tended to move as a whole with the building. At higher frequencies, vertical (out of plane) floor motion becomes more dominant. It was expected that there may be significant flexural motion, which will influence vibratory experiments conducted on the floor in the lab. Consequently, floor vertical response to vertical excitations was investigated. Another issue is the impact of heavy equipment in the room on floor motion.

Numerous articles have been published that cover theoretical and experimental methods for the calculation of the vibratory response of floors in buildings [1-4]. Typically, these have focused on determining the resonant frequencies and associated damping levels of gross modes of vibration excited by such things as human activity or equipment operation. Some of the methods used are employed here. In addition, a brief investigation of the localized dynamic properties of the surface of the floor is presented. The room under study is located on the first floor above a ground level. The floor is constructed of a reinforced concrete slab 8.5 inches thick. A 1/4”-thick linoleum tile is adhered to the concrete slab. The floor is supported by reinforced concrete columns that are 20 inches by 20 inches square and 188 inches in height. They are spaced at 20 and 34 foot intervals in the two horizontal directions [5]. The transverse (vertical) dynamic response of the floor is considered here.

4.1 Theory

Due to the complex network of steel tendons that reinforce the concrete slab and the support columns, a simple, precise analytical model for floor dynamics is not possible. However, with some simplifying assumptions, approximate analyses are feasible.

Referring to Figure 5, in order to calculate the resonant frequencies for transverse (vertical) vibrations of the floor, a rectangular section of it bounded by four columns may be viewed as a plate-like structure with boundary conditions that behave as a cross between simply supported and clamped [4]. Wall partitions constructed on the floor should have minimal impact on the natural frequencies. The exact solution using thin plate theory for the mn^{th} natural frequency f_{mn} (Hz), which corresponds to the mn^{th} mode for the simply supported case, is given by the following [6],

$$f_{mn} = \omega_{mn}/2\pi = \frac{\pi}{2}\sqrt{\frac{D}{\rho h}\left[\left(\frac{m}{L_x}\right)^2 + \left(\frac{n}{L_y}\right)^2\right]}, \qquad D = \frac{Eh^3}{12\left(1-\upsilon^2\right)}, \tag{1}$$

where E, ρ, υ, h, L_x, and L_y refer to the plate modulus of elasticity, density, Poisson’s ratio, and thickness and length between columns in the x and y directions, respectively. An approximation for the fundamental frequency f_{11} of the clamped plate based on Rayleigh’s method is given by [6],

$$f_{11} = \omega_{11}/2\pi = \frac{\pi}{2}\sqrt{\frac{D}{\rho h}}\left(\frac{1}{L_x}\right)^2 \sqrt{\frac{12 + 8\left(L_x/L_y\right)^2 + 12\left(L_x/L_y\right)^4}{2.25}}.. \quad (2)$$

Here, $L_x > L_y$. Typical material properties used for a reinforced concrete slab are E = 28 x 10^9 N/m^2, ρ = 3200 kg/m^3, and υ = 0.2 [4,7]. It should be noted that the modulus of elasticity E varies from 24 to 32 x 10^9 N/m^2 depending on the concrete grade as denoted by its characteristic cube strength at 28 days [7]. For the parameter values listed above, the fundamental natural frequencies for the simply supported and clamped models are 10.7 Hz and 21.3 Hz, respectively.

The above calculations have neglected the effect of any mass loading on the floor, which may alter its response. We may approximate a test object on the floor as a point mass m_p at location $\{x_p, y_p\}$. Using the simply supported boundary condition, the equation for transverse motion of the point mass and floor system is [8]:

$$\rho h\ddot{z}(x,y,t) + D\nabla^4 z(x,y,t) = -m_t \ddot{z}(x,y,t)\delta\left(x - x_p\right)\delta\left(y - y_p\right), \quad (3)$$

where

$$\ddot{} \equiv \partial^2/\partial t^2 \,,\ \nabla^2 \equiv \partial^2/\partial x^2 + \partial^2/\partial y^2 \ \text{ and }\ \delta\left(x - x_p\right) \equiv \begin{cases} 1 & x = x_p \\ 0 & x \neq x_p \end{cases}. \quad (4a\text{-}b)$$

In order to determine the loading effect that m_p has on the fundamental resonant frequency, we substitute the fundamental mode shape $Z_{11}(x,y)$ for floor vibrations where

$$z(x,y,t) = z_{11} Z_{11}(x,y) e^{i\omega t}, \qquad Z_{11}(x,y) = \sin\left(\frac{\pi x}{L_x}\right)\sin\left(\frac{\pi y}{L_y}\right) \quad (5a\text{-}b)$$

into Equation (3), multiply by $Z_{11}(x,y)$, and integrate over x and y from 0 to L_x and 0 to L_y, respectively. Here z_{11} is the modal amplitude and $i = \sqrt{-1}$. This leads to the following expression, where M_{11} is the modal mass of the floor associated with ω_{11}:

$$M_{11}\left[\omega_{11}^2 - \omega^2\right] = m_p \omega^2 Z_{11}^2\left(x_c, y_c\right). \quad (6)$$

Here,

$$M_{11} = \rho h \int_0^{L_x}\int_0^{L_y} Z_{11}^2(x,y)\,\partial y\,\partial x \quad (7)$$

and ω_{11} is given by equation (1). From this, the fundamental resonant frequency of the mass-loaded floor, ω_{p11}, can be expressed as a function of the unloaded floor resonant frequency ω_{11}:

$$\omega_{p11} = \omega_{11}\Big/\sqrt{1 + m_p Z_{11}^2\left(x_c, y_c\right)/M_{11}}\ . \quad (8)$$

Clamped boundary conditions will lead to a very similar relationship between ω_{p11} and ω_{11} of Equation (2). For the parameter values given above, $M_{11} = \rho h L_x L_y/4 = 43.8 \times 10^3$ kg. For a test object mass of $m_p = 1 \times 10^3$ kg located in the center of the concrete slab, f_{p11} = 0.99 x f_{11}. If m_p = 10 x 10^3 kg, then f_{p11} = 0.9 x f_{11}. The types of objects to be tested in the laboratory are not expected to weigh any more than a few thousand kilograms and consequently should not significantly alter the natural frequencies of floor vibrations.

The level of damping in reinforced concrete floors must be estimated based on experiment. Unlike the natural frequency, it can be very dependent on what is constructed on the floor, including wall partitions. According to references, the damping level associated with the fundamental resonant frequency typically ranges from between $\zeta = 2$ % of critical damping for bare concrete floors to $\zeta = 10$ % for finished floors with wall partitions installed. With 10 % damping, at resonance the input excitation is amplified by a factor of 5. The damping level usually increases for higher system resonances.

Higher natural frequencies are often ignored in simple floor analyses. In other words, a single degree-of-freedom (SDOF) model for the floor is assumed. This is because the response of the floor to impulse excitations, such as footfalls, is typically dominated by the response at the fundamental natural frequency. In equation (7), the equivalent mass of the SDOF model is given. From this and the natural frequency ω_{11}, the equivalent spring stiffness K_{11} may be calculated, $K_{11} = \omega_{11}^2 M_{11}$. Ignoring the multi-degree of freedom nature of the floor however may lead to serious errors in modeling its response to excitations well above f_{11} [9].

In the laboratory, a common activity will be the vibratory analysis of structures used in the APS over a wide frequency range, up to a few hundred Hz. Some of these structures will be studied while resting on the floor. An alternative descriptor for the floor dynamics over a wide frequency range is needed. A good candidate is the driving point mobility, the ratio of the velocity of floor motion at a particular point, $\dot{z}$, to the force input at that point, F_z, as a function of driving frequency, ω. For an infinite plate, the translational driving point mobility is given by the following [10]:

$$\frac{\dot{z}}{F} = \frac{1}{8\sqrt{D\rho h}}. \tag{9}$$

Note that it is independent of frequency. (A frequency-dependent expression for rotational mobility, out of plane floor rotation due to out of plane moment excitations, is given in the same reference.) The floor may be approximated as infinite for frequencies above f_c where

$$f_c = \frac{4}{\pi\eta L_x L_y}\sqrt{\frac{D}{\rho h}}\ . \tag{10}$$

Here, η is the structural loss factor, which may be approximated as $\eta = 2\zeta$. For the assumed system parameter values and taking $\zeta = 0.085$, we have $f_c = 22.3$ Hz. The predicted floor mobility is shown in Figure 6 for the single degree-of-freedom model and the infinite-plate model.

4.2 Experiment

For experimental verification of theory, floor response to transient excitation from jumping was used to estimate certain dynamic properties. Then, floor-surface dynamic behavior was studied using measurements of drive point mobility and wave propagation speed.

Response to Jumping. Floor response to jumping is shown in Figure 7 for two different cases. Both cases show the vertical acceleration from a 90 kg person jumping from a height of 0.3 meters landing 0.3 meters from the accelerometer. For Case A, an open area of the laboratory was selected relatively near to a wall spanning two columns, as indicated in Figure 5. For Case B, also marked in Figure 5, the point was closer to the center of the slab and in the middle of several heavy pieces of equipment mounted on the floor and weighing, in entirety, approximately 2000 to 3000 kgs. For Case A, there is an initial sharp impulse response, which quickly decays. For Case B, the initial impulse is much attenuated, apparently by the presence of the mass load. However, because this location is further from any of the columns, the impact more capably couples into the fundamental mode shape and excites the first natural frequency of the floor. From this response curve, the natural frequency and damping value associated with the first mode can be roughly calculated. The period of motion is estimated as shown in Figure 7. The logarithmic decrement δ, the ratio of amplitudes of successive peaks of the oscillating response, is estimated as 0.542. From these, f_{11} and ζ_{11} are calculated using the following formulas.

$$f_{11} = 1/T_p = 18.5 \text{ Hz, and } \varsigma_{11} = \delta \Big/ \sqrt{4\pi^2 + \delta^2} = 0.085 \qquad \text{(11a-b)}$$

The value for f_{11} falls within the range of values predicted by simple plate theory. The estimate of ζ_{11} is in agreement with typical values reported in the literature.

Localized Floor Surface Response. Transient excitation from jumping introduced enough energy into the floor to cause gross motion at its first flexural plate natural frequency. Some experimental activities in the laboratory may be very localized and not impart this much energy into the floor. They may be affected by the local dynamic properties of the linoleum covering adhered to the reinforced concrete slab. No theoretical treatment of this behavior is discussed here; however, relevant experimental measurements of it are provided.

A theoretical value for the driving point mobility of the concrete slab by itself was derived in Section 4.1. Here, the drive point mobility at a point on the surface of the linoleum is measured by using an impedance head driven by an electrodynamic shaker near the center of the room. Broadband random excitation was used, and response was recorded in the frequency domain via use of the dynamic FFT signal analyzer Real and imaginary parts of the mobility are shown in Figure 8. The values are significantly higher than the theoretical values for the concrete slab by itself, given in Figure 6. This indicates that the linoleum gives the floor much more compliance for small energy deformation at a local point. However, it appears there is some flexural excitation of the concrete slab resulting in a resonant response at 18.5 Hz. Overall, the response follows a mix of trends predicted by the single degree-of-freedom and infinite-plate models, but with a significantly higher mobility due to the linoleum compliance. How this dual behavior of the floor will react for a given experiment will depend on several factors, including the geometry of the test object, its weight, and the resulting level of vibratory excitation of the floor.

For the infinite-plate model theory as discussed in Section 4.1, vibrational waves in the structure are dispersive, i.e., their speed of propagation c_s is a function of frequency and is given by the following formula [10]:

$$c_s = \sqrt{\omega D/\rho h} \tag{12}$$

In this study, the floor was driven with sinusoidal motion of different frequencies and a linear array of accelerometers was used to measure transverse wave propagation speed across the floor. Experimental measurements and theoretical predictions based on the concrete slab model and Equation (10) are shown in Figure 9. Again, the order of magnitude difference indicates that the compliance of the floor surface is much greater than that of the concrete slab. However, there is a similar trend with respect to frequency indicative of infinite plate-like behavior.

5. SUMMARY

Experimental measurements of ambient vibration levels and floor dynamics in the laboratory facilities of the Advanced Photon Source Experimental Facilities Division in Building 401 have been conducted. Supporting theoretical analysis of the floor flexural behavior has also been undertaken. Key results discussed in this report are summarized.

- For frequencies above 0.2 Hz, ambient vibration levels remain below 0.1 microns under most circumstances. One notable exception is a resonance near 1.85 Hz, associated with horizontal building motion. Under windy weather conditions, its rms amplitude has been recorded as high as 0.3 microns.

- The laboratory floor has a transverse fundamental resonant frequency of 18.5 Hz for flexural motion of the concrete slab. This value agrees with theoretical predictions. The associated damping level is roughly 8.5 % of critical. This values agrees with values for similar situations reported in the literature.

- The localized vibratory response of the floor is affected by the linoleum covering adhered to the concrete slab. The linoleum greatly increases the floor mobility, a measure of its motion response to force excitation. Also, at higher frequencies, the floor exhibits behavior more indicative of an infinite plate than of a single degree-of-freedom spring-mass-damper system.

While all the results reported here were for measurements conducted in the Vibrations Laboratory located on the first floor of Building 401, similar values should be expected for other laboratories in this building and in similar buildings. One would expect that on higher floors, the amplitude levels of low frequency, horizontal resonances associated with gross building motion will increase. Also, it should be noted that the floor thickness is not the same throughout the building. The concrete slab is 8.5 inches thick only in the laboratory wing. It is 6.5 inches thick elsewhere in the building. This will affect transverse floor dynamics.

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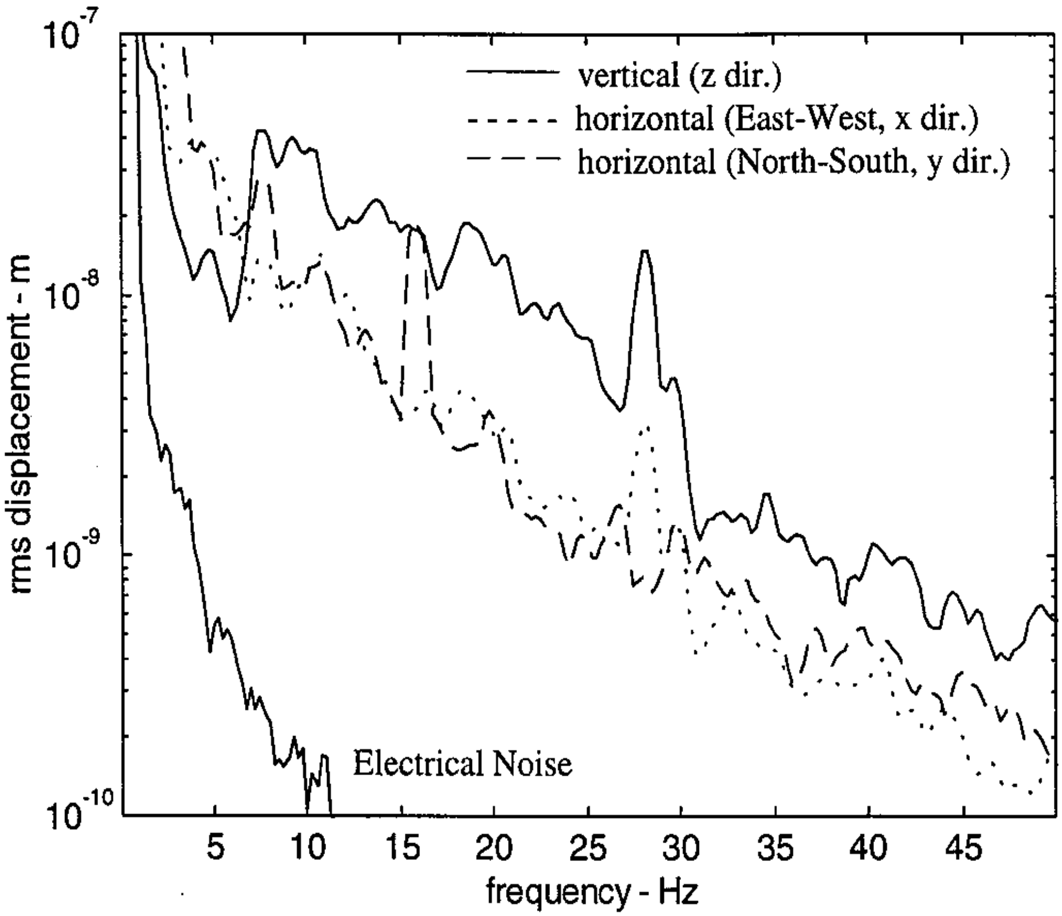

Figure 1. Ambient vibration levels. Horizontal and vertical directions.

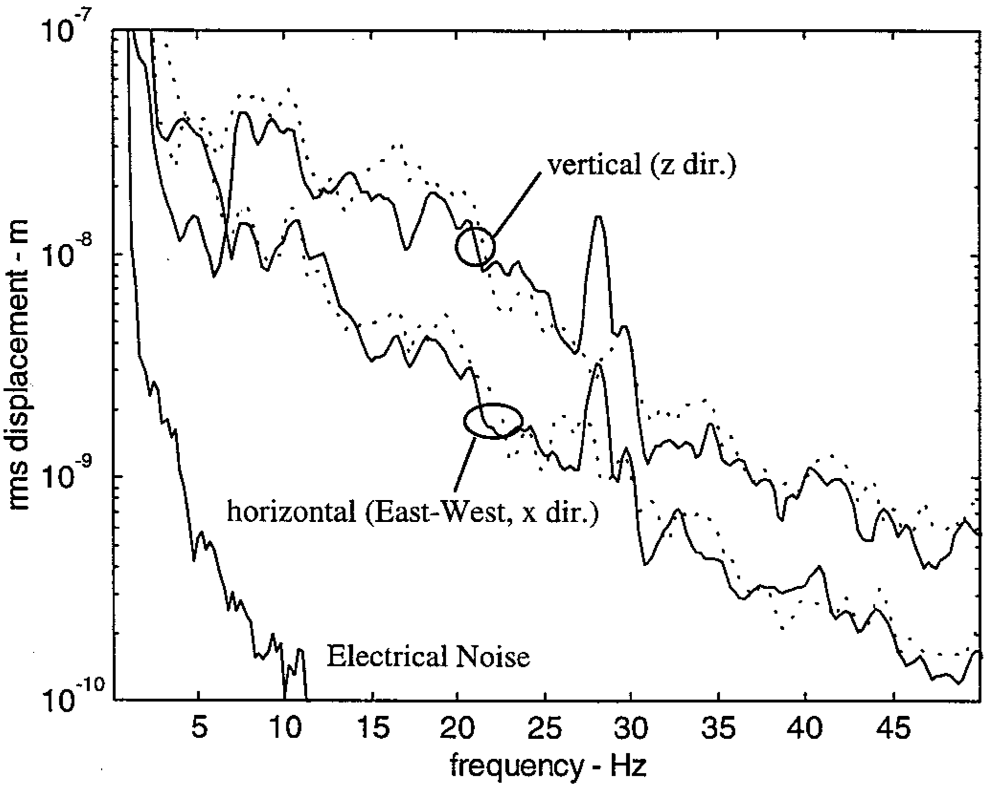

Figure 2. Ambient vibration levels. Effect of ventilation fan. Key: ______ fan on, - - - - fan off.

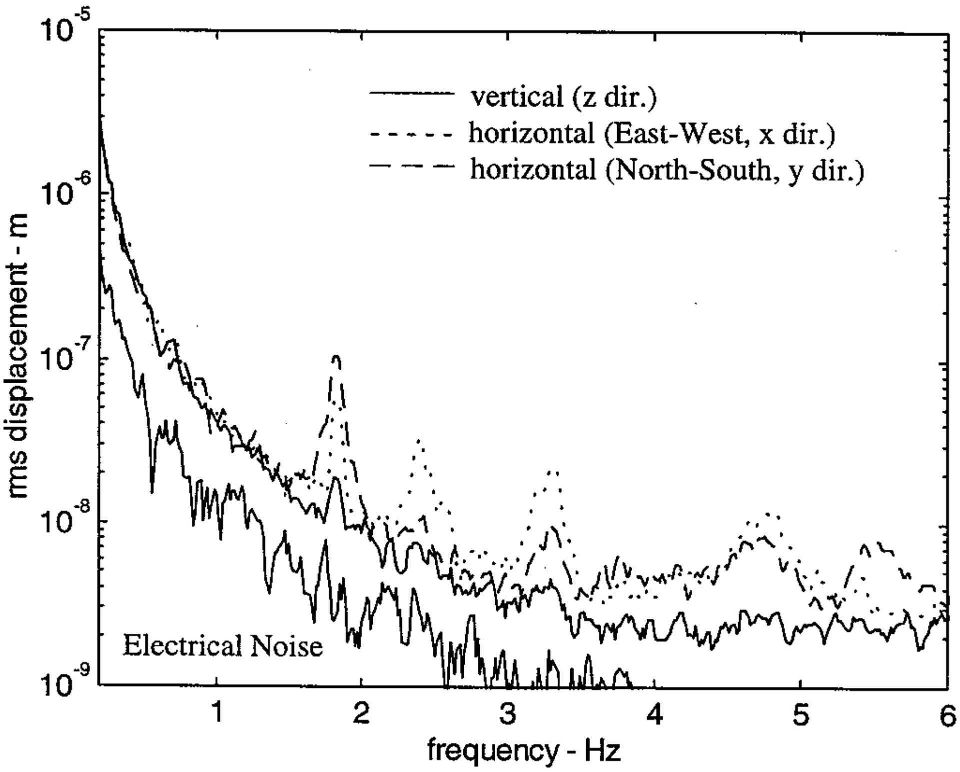

Figure 3. Ambient vibration levels. Low frequencies. Horizontal and vertical directions.

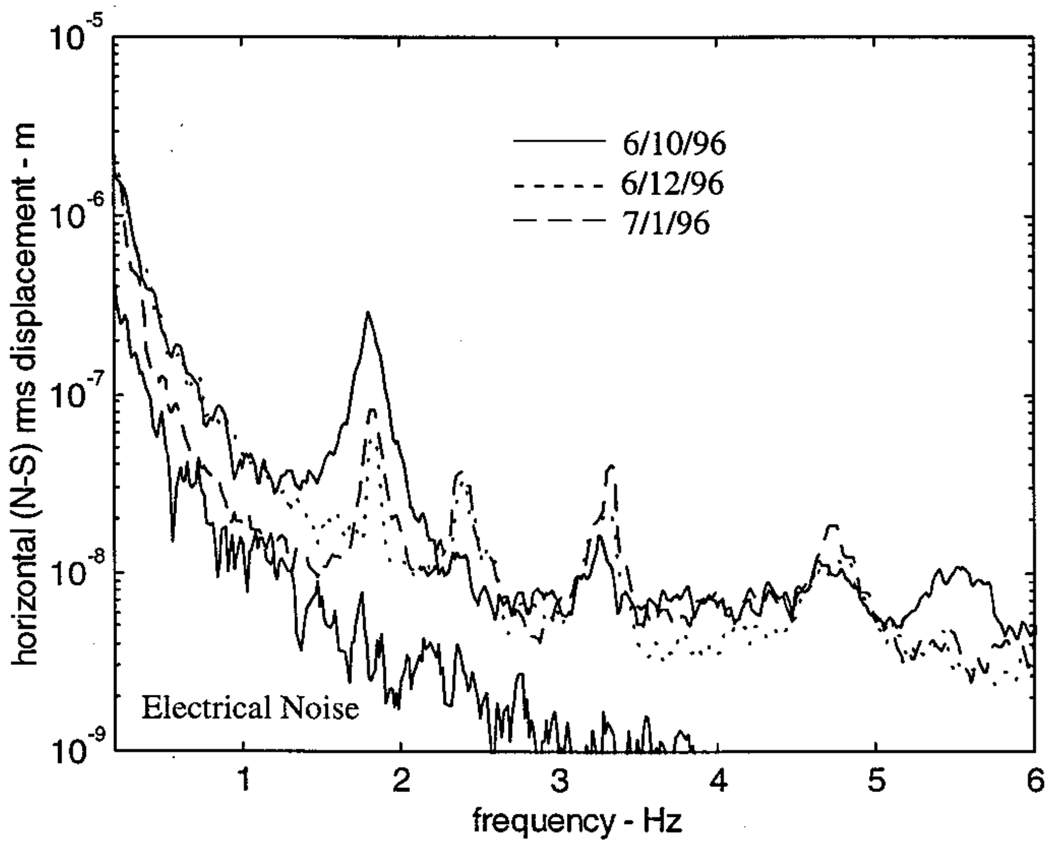

Figure 4. Ambient vibration levels. Low frequencies. Effect of weather on horizontal motion.

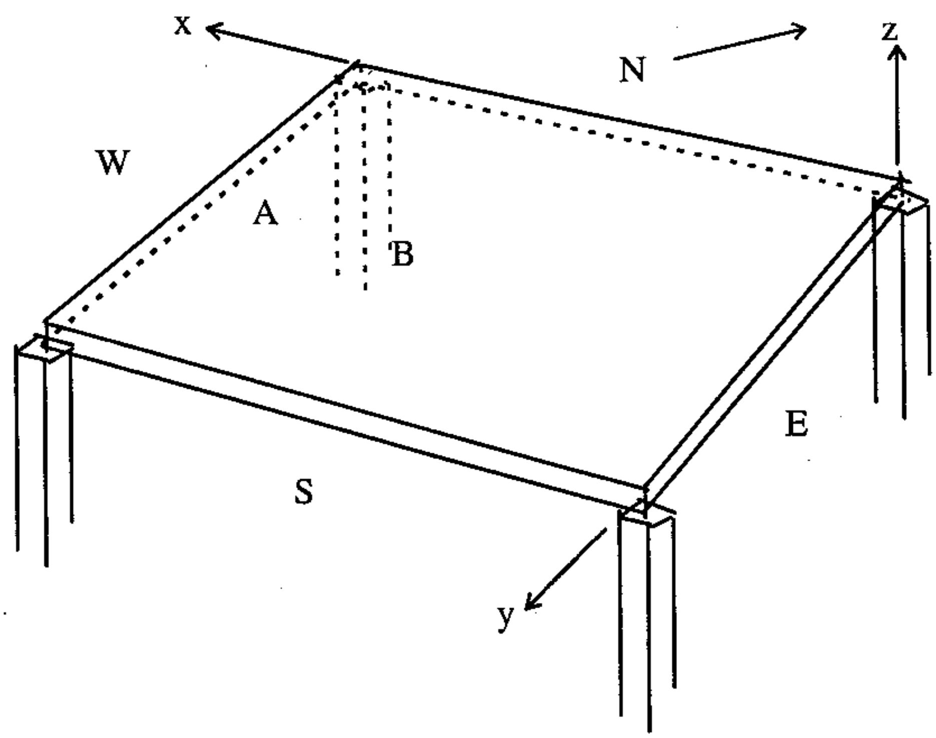

Figure 5. Theoretical model for vertical floor vibrations.

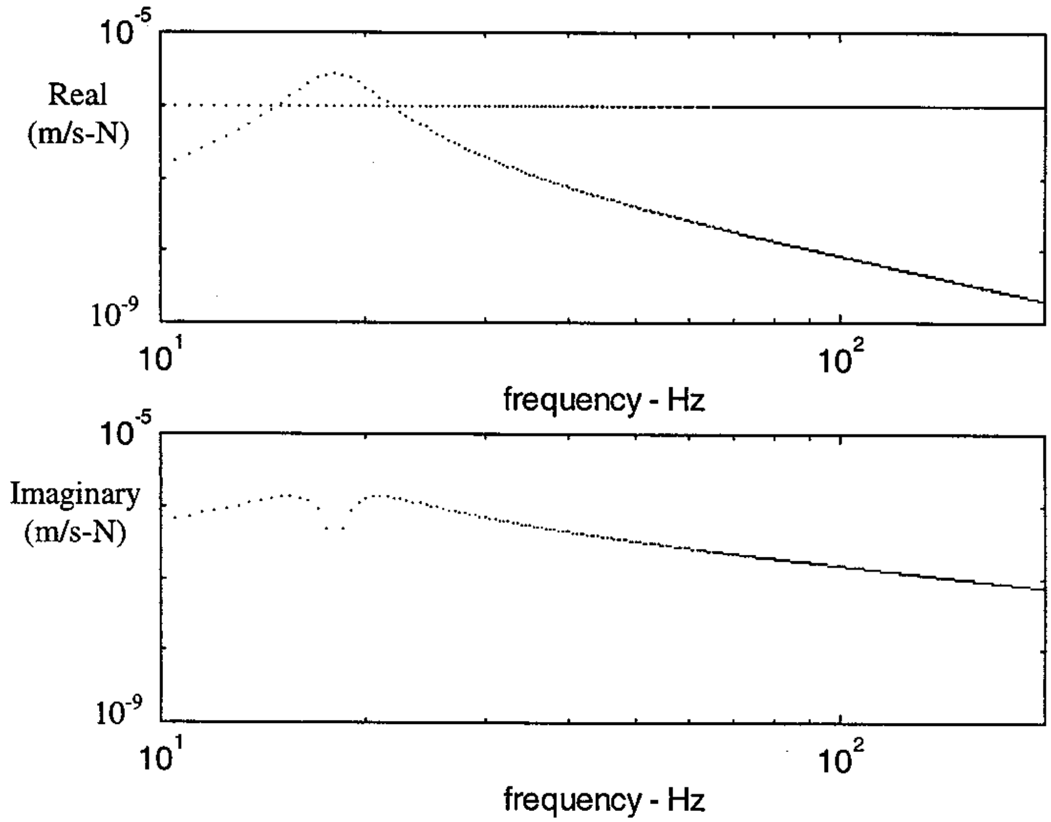

Figure 6. Theoretical floor drive point mobility. Key: ——— infinite plate model, ······ SDOF model.

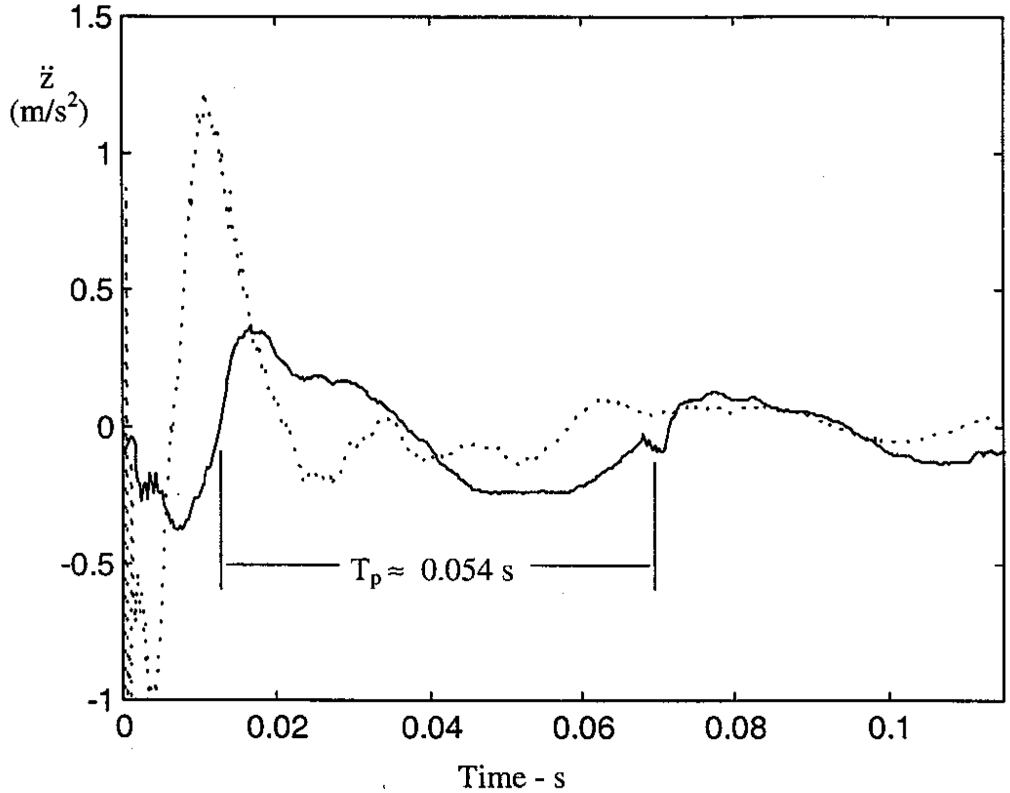

Figure 7 Floor vertical response to jumping. Key: - - - - - Location A, ——— Location B (See Figure 5).

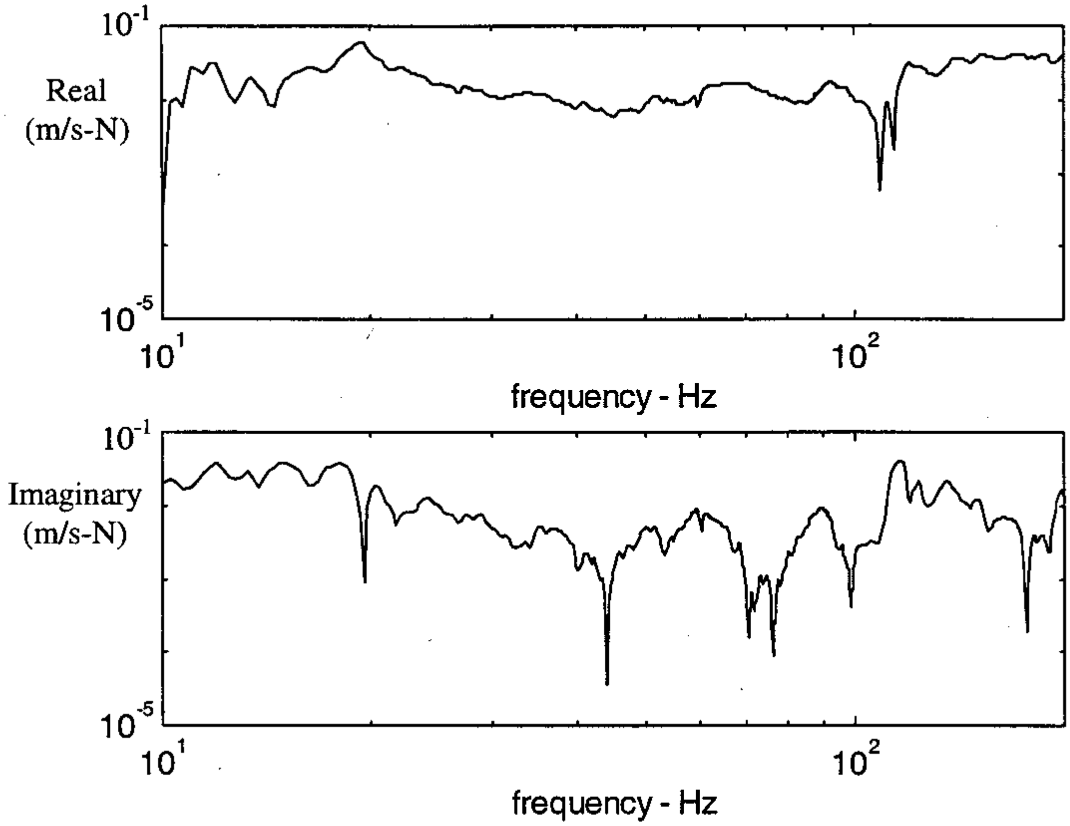

Figure 8. Experimental floor drive point mobility.

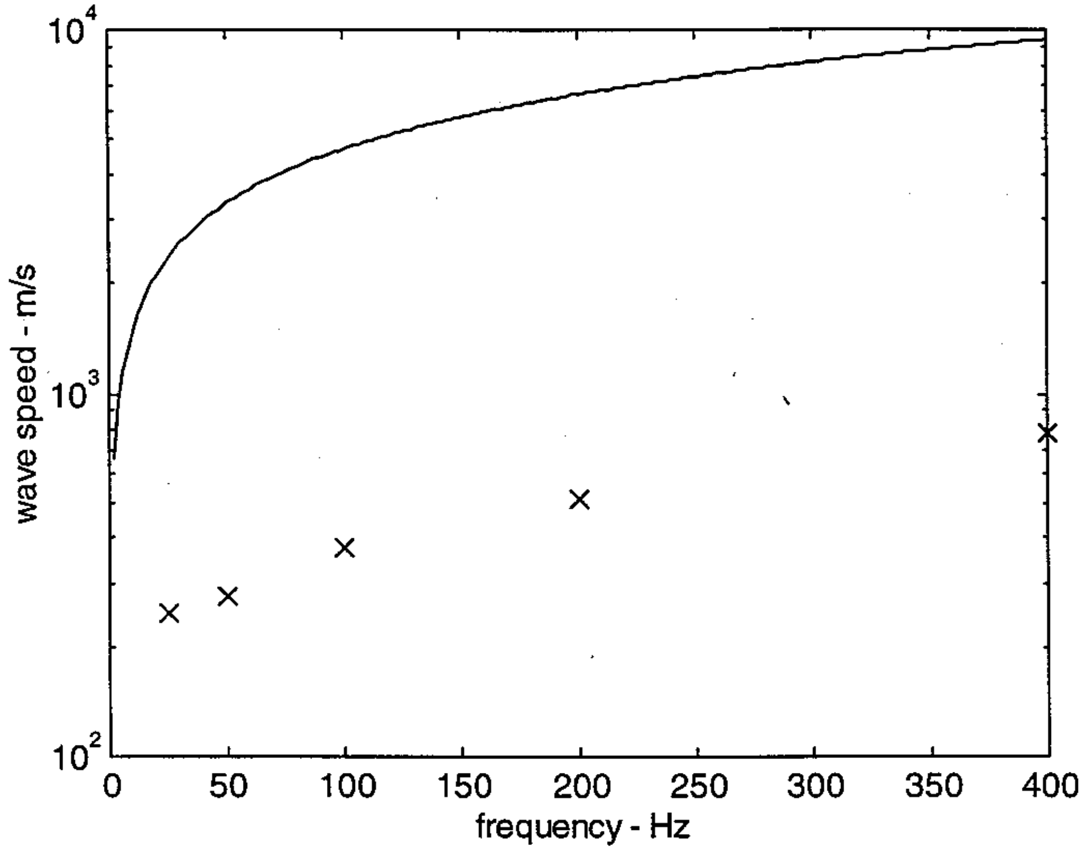

Figure 9 Speed of transverse wave propagation on floor surface. Key: X experiment, ——— theory for concrete slab.