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Dynamics of Stiff Floors for Advanced Technology Facilities

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ABSTRACT

Vibration control in vibration-sensitive advanced technology facilities generally involves design of a stiff floor for the vibration-sensitive area. The authors have found that the range of floor stiffness required for semiconductor facilities and laboratories falls on a continuum between "soft" and "stiff" floors. A significant variation in properties can be observed along this continuum. This paper will review the dynamic properties of floors, addressing the effects of column-slab interaction on their point stiffness and resonance frequency.

INTRODUCTION

Advanced technology facilities with stringent vibration requirements call for close attention to floor vibrations, particularly when the floor is suspended by columns. For example, a typical semiconductor production facility with a basement might have for its 5,000 m^2 cleanroom a 1m deep concrete grillage floor supported on columns spaced at 4m x 4m. A generic laboratory floor, which might have vibration requirements an order of magnitude less stringent, might be designed with a flat plate or with conventional slab/deck/steel-framing schemes similar to—but significantly stiffer than—conventional office building framing.

In general, the basic configuration of a floor system must be established very early in the design process—usually the Schematic Design phase—long before the building is defined in enough detail to justify a rigorous analysis. Hence, simplified analytical tools are quite desirable. Issues such as floor-to-floor height, building height, piping and ducting interference, and the requirements for accurate costing all dictate the need for an early—but accurate—structural sizing. In a semiconductor facility (called a "fab") the designers must resolve such issues as slab type and depth, along with column length and spacing. In a laboratory facility, which has much less stringent requirements, the designers usually must establish bay sizes, beam layout and member sizes. This paper discusses some of the simple relationships that can be used for both early-stage analysis and evaluation later in the design process.

GORDON'S MODELS FOR FLOOR VIBRATION

Mechanical Excitation: Gordon (1987) developed simple models that could be used to predict vertical floor vibrations throughout all stages of the design process, particularly at earliest stages when most of the conceptual design is carried out. He examined actual vibration performance of a collection of fab floors in terms of the maximum one-third octave band frequency component of rms velocity. A comprehensive regression analysis suggested that the variation of maximum amplitude was inversely proportional to mid-bay point stiffness, k. He proposed a predictive model, given in Equation (1), in which V_m is the maximum rms velocity due to mechanical excitation, C_m is an empirical constant, and k is the minimum point stiffness of the floor. The measured data and statistical "fits" are illustrated in Figure 1.[1]

$$V_m = \frac{C_m}{k} \qquad (1)$$

The above equation predicts the vertical floor response due to random vibration generated from mainly facility sources such as mechanical systems and machinery, fluid turbulence in ducting and piping, process equipment, etc. The equation is limited in application to facilities in which the energy consumption and volumetric fluid flow are comparable to that of a fab.[2] There may also be some amplification of ambient site vibrations by the structure, but Gordon has concluded from comparison of fab floor measurements before and after mechanical systems are turned on that site effects are less significant than the excitation due to turbulent flow. The data scatter in Figure 1 can be attributed to variables too complex to quantify for inclusion in a simple model, including variations in soil conditions, structural paths for dynamic loads, and vibration isolation hardware.

Walker Excitation: Gordon extended the derivations of Ungar and White (1979) to obtain the relationship in Equation (2), which relates the walker-induced maximum one-third octave band rms velocity amplitude to kf, the product of point stiffness k and the fundamental resonance frequency f of the floor / column assemblage.

$$V_w = \frac{C_w}{kf} \qquad (2)$$

The semi-empirical coefficient C_w is based upon measured data obtained for a different persons walking on a variety of floors at 100 paces per minute. Corrections between the weight of the walker and a "standard" walker was made. This correction, and another correction for walker speed (which can be derived from Ungar and White) can be used to adjust for other weights and speeds in application of the model. This model is applicable to the full range of floor stiffness. However, experience has shown that V_m will exceed V_w when f exceeds about 20 Hz—often the case in a modern fab.

INTERACTION BETWEEN SLAB AND COLUMNS

We have seen in the preceding section that one must be able to develop estimates for k and f fairly early in the design process if we are to obtain V_m and V_w with any degree of accuracy. There are closed-form solutions for k and f for simple cases with various boundary conditions, but it is very important that the correct support conditions be assumed. We can compare the stiffness at the center of the floor (assuming rigid supports) with the actual support stiffness. If the actual column stiffness is considerably greater than the centerpoint stiffness of the floor (assuming rigid supports), one may assume with relatively small error that the floor can be modeled with rigid supports. However, in the case where the centerpoint floor stiffness (again assuming rigid supports) approaches or exceeds half of the column stiffness, a considerable error will arise from assuming rigid support conditions.

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[1] It should be noted that the axes of Figure 1 are deliberately not labeled, as the measured data and derived coefficients are proprietary.

[2] Fabs are somewhat unique in that they have a power consumption density (e.g., watts/m^2) about 100 times that of a conventional building.

A finite element parametric study was carried out using a 3-bay x 3-bay plate supported on springs, this representing a flat plate, grillage or waffle floor supported on columns. The study was limited to square bays. The model was used to obtain point stiffness and mobility spectra[3]; the peaks on the mobility spectra correspond to the resonance frequencies which can be excited at the loading point. The model demonstrated that the point stiffness and dynamic response of a plate on multiple elastic point supports vary according to the relative stiffnesses of the plate and supports.

Frequency Interaction: One must calculate the floor's fundamental frequency for use in Equation (2). Figure 2 tracks three resonances (column, C1, and two plate modes, P1 and P2) of a multi-span slab floor as thickness is increased and column stiffness is held constant. When the plate fundamental resonance frequency is less than the calculated column resonance frequency, the column resonance peak does not appear in the mobility curves and the plate resonance P1 is the system fundamental. The slope of the P1 curve is $t^{1.5}$. When the frequency of the plate fundamental P1 begins to exceed that of the column resonance C1, a peak corresponding to C1 begins to appear on the mobility curve and, in effect, becomes the system fundamental.

From an examination of the changes in modeshapes associated with P1 and P2 we find two ways in which the columns participate in the plate modeshapes. When the resonance frequency of P1 is less than that of the columns, the tops of the columns remain static and—in effect—act as rigid supports. The P1 "nodal line" forms a diamond containing the loaded bay; the midpoints of each side fall at a column. When the resonance frequency of the column is exceeded, the four columns around the load point begin to participate in the P1 and P2 modeshapes, thus acting as flexible supports, rather than rigid ones. The "nodal lines" of the P1 modeshape move outward toward the next square of columns. As thickness increases, the P1 and P2 lines become asymptotic to a slope of $t^{1.5}$.

Stiffness Interaction: Column stiffness, k_c can be calculated using Equation (3), in which A is area, E is Young's Modulus, and L is length. Column stiffness combines in series with the footing stiffness, which is much less straightforward to define analytically.

$$k_c = \frac{AE}{L} \tag{3}$$

The interaction of column and plate stiffness may be defined in terms of α, the ratio between k_p the midbay stiffness of the plate (assuming rigid support at the column locations) and k_c the stiffness of a column. The relevant equations follow:

$$\alpha = \frac{k_p}{k_c}\text{, where} \tag{4}$$

$$k_p = 64.3\frac{Et^3}{12(1-\nu^2)L^2} = 64.3\frac{D_x}{L^2}, \tag{5}$$

$k_c =$ stiffness of one column,
$L =$ span between columns,
$t =$ effective thickness of slab, and

[3] A *mobility spectrum* is a velocity spectrum for a unit load of swept frequency.

$E, n =$ Young's modulus and Poisson's ratio of slab.

Both k_p and k_c can be considered "inherent properties" of a given floor configuration. (It should be noted that k_c should include both the column and footing stiffness.) The point stiffness at any location on the floor varies between a maximum value above the columns to a minimum value at the middle of a bay. In a floor with an extremely "soft" slab, α will be small, the midbay stiffness will be approximately k_p and the stiffness at a column will be approximately k_c. As the relative stiffness of the slab increases, α increases and the observed stiffness at both column and mid-bay locations increases. The midbay stiffness becomes more and more a function of column stiffness, and the stiffness above one column increases due to carryover from neighboring columns.

When the ratio α is less than 0.5, the error in slab point stiffness introduced by assuming rigid supports is slight; when it exceeds 0.5, support stiffness must be considered. When $\alpha = 1$ the error of assuming rigid supports is a factor of 1.4.

A current trend with some design teams is to decrease column stiffness, either by increasing column length or decreasing cross-sectional area (in order to make more space available in the subfab). Figure 3 shows an examination of the effect of varying column stiffness while slab stiffness is held constant. It normalizes the stiffnesses at midbay and above the column—dividing both by k_c—showing how stiffnesses at these two locations vary with changes in column stiffness for a constant slab configuration. For a "conventional" floor (such as an office), which would have a low α, there is a large variation in stiffness between column and midbay locations. For a "stiff" floor (such as that of a fab), which would have a high α, the variation of point stiffness over the floor is quite small, thus producing a fairly uniform distribution of vibration amplitude.

REFERENCES

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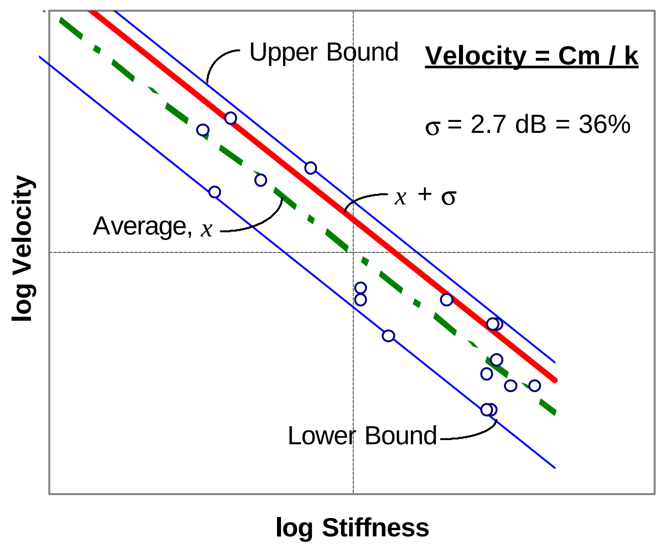

Figure 1. Measured floor vibration data and Gordon Model

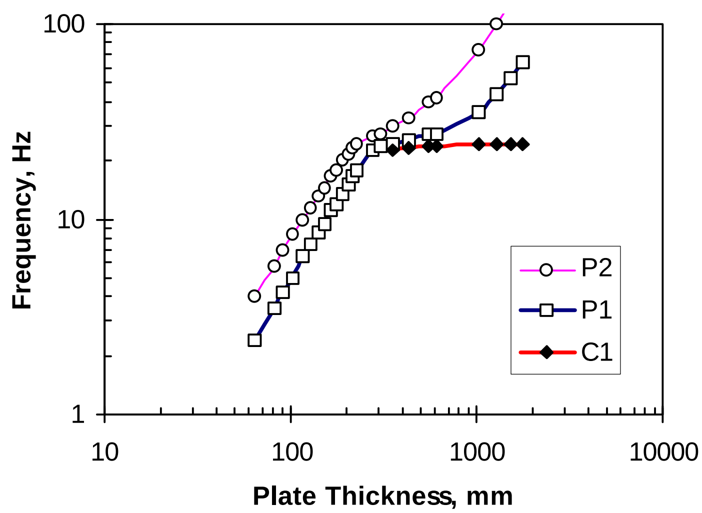

Figure 2. Resonance peaks from calculated mobility curves for 3x3 bay FE model.

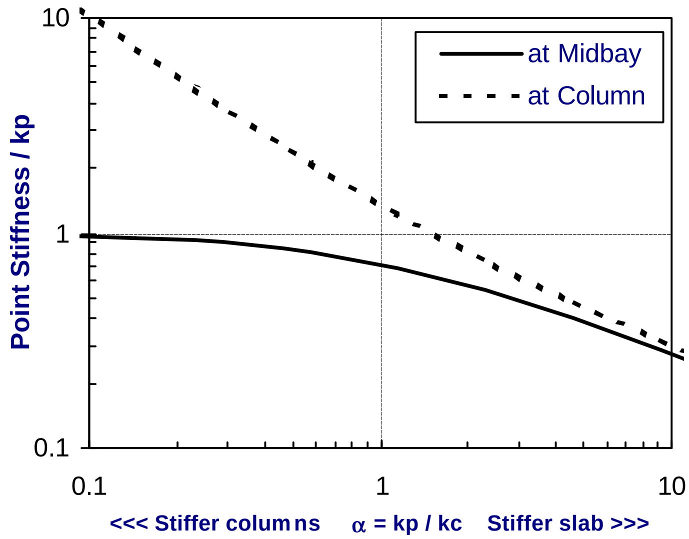

Figure 3. Relationship between point stiffness and stiffness ratio.