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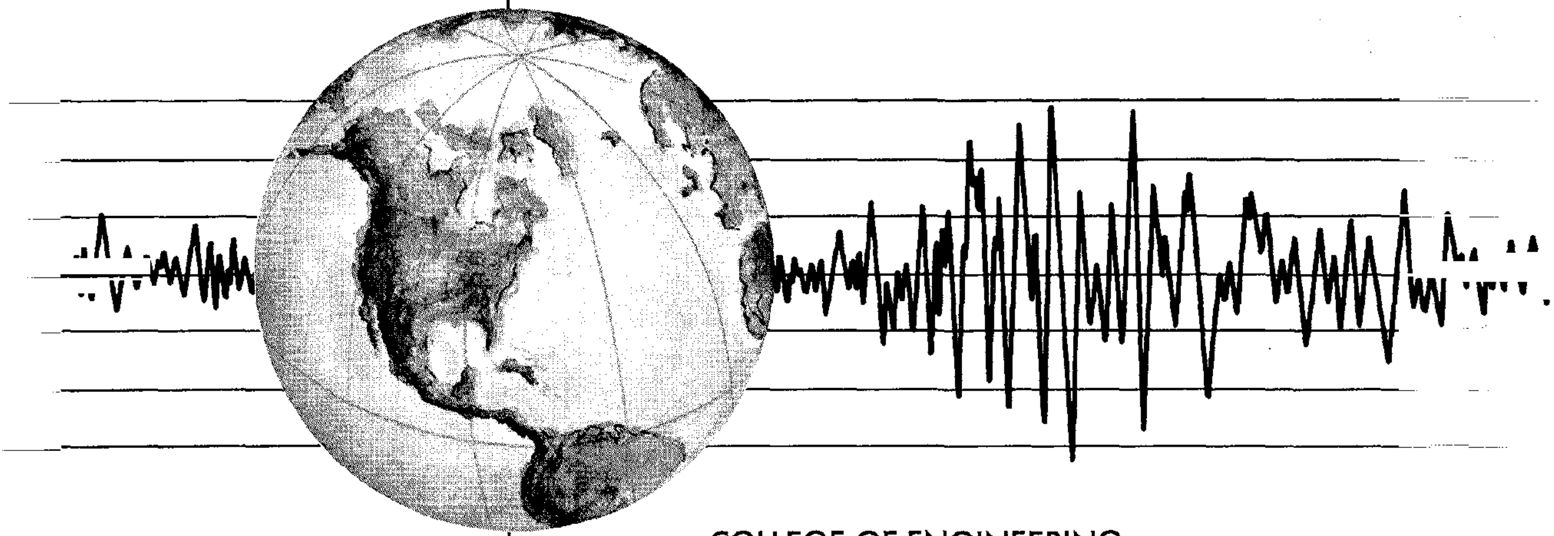
STUDIES ON HIGH-FREQUENCY VIBRATIONS OF BUILDINGS

1: THE COLUMN EFFECT

by

J. LUBLINER



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STUDIES ON HIGH-FREQUENCY VIBRATIONS OF BUILDINGS

I: THE COLUMN EFFECT

by

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Report No. UCB/EERC-79/21
Earthquake Engineering Research Center
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August 1979

ABSTRACT

It is shown that, when column mass is taken into account in the vibration of buildings, the system acquires additional degrees of freedom. If column mass is small compared to floor mass, then the modes obtained from conventional analysis persist virtually unchanged; the additional modes involve almost exclusively column motion, the characteristic frequencies being in the low audio range. The nature of the modes, as well as the transmission of ground motion, depend on whether the columns in adjacent stories are tuned to each other.

ACKNOWLEDGMENT

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INTRODUCTION

The conventional dynamic analysis of framed buildings is largely concerned with those modes of vibration in which the floors are assumed to move horizontally as rigid masses, while the columns (and shear walls, if any) act as massless shear springs. The angular frequencies corresponding to these modes are of order $\sqrt{k/M}$, where k is a typical value of the total column shear stiffness of a story, and M is a typical floor mass. That these modes (which will here be called the "primary modes") are studied to the virtual exclusion of any others is due to several factors. First: these are normally the modes with the lowest natural frequencies, and will consequently respond to a random energy input with the greatest amplitudes, thus being the likeliest contributors to structural damage. Second: these frequencies are of the order of 1 to 10 Hz, which is precisely the range which predominates in the spectra of seismic shocks. Third: the viscous damping model--almost universally used in structural dynamics--predicts an attenuation rate that is directly proportional to frequency, leading to the conclusion that high-frequency modes will be rapidly damped out and are therefore negligible.

Now let us list some reasons why it may be necessary to derive a model that takes high-frequency vibration into account.

(1) It is a simple matter to conceive of a damping model that predicts relatively undamped high-frequency modes: for example, the Maxwell model [1], or a model with essentially frequency-independent attenuation [2]. It is the latter model that most closely describes the actual behavior of structures [3].

(2) In a building that does not collapse in an earthquake, the principal danger to occupants comes from loose wall or ceiling material or other objects that may be dislodged, and typically it is the high-frequency vibration that creates this danger.

(3) Audible noise is a troublesome by-product of civilization, and it is important to study the role of buildings in transmitting such noise, both from within and from without. There exists some literature on structure-bourne sound [4,5] but not, to my knowledge, in relation to framed buildings.

The principal model of dynamic analysis of framed buildings of moderate height (to about 25 stories) is the well-known "shear building," in which the floors move as rigid masses, while the massless columns transmit shear passively from floor to floor. It is this model, with one degree of freedom per story, that is responsible for the aforementioned low-frequency modes. Additional degrees of freedom appear when the columns are allowed to deflect in modes other than the shear mode shown in Figure 1a--particularly in the so-called "fixed-fixed" mode shown in Figure 1b.

By giving the building two degrees of freedom per story, we are modeling it somewhat as an array of alternately heavy and light masses connected by springs. Such a model recalls the "NaCl" structure of solid-state physics [6]. It will be remembered that the characteristic frequencies of this structure fall into two disjoint bands: a lower band, known as the "acoustic branch," in which the frequencies range from zero (at infinite wave length) to a cut-off frequency $\omega_1 = \sqrt{k/M}$, corresponding to a mode in which the light masses remain still while the heavy masses move with equal amplitude in alternately opposed directions (Figure 2a) and whose wave length is twice the spatial period; and a narrow band (the so-called "optical branch") in which the frequencies range from $\omega_2 = \sqrt{k/m}$ corresponding to a mode similar to that just described, but with light and heavy masses reversed (Figure 2b) to $\omega_3 = \sqrt{k(1/m + 1/M)}$ corresponding to the infinite-wave-length mode in which all the heavy masses move together in one direction and all the light masses move together in the opposite direction (Figure 2c). The addition of further degrees of freedom per period introduces additional frequency bands.

In what follows we shall attempt to determine to what extent a building with two degrees of freedom per story resembles the periodic structure just described.

ANALYSIS

Let $w(y, t)$, $-\frac{h}{2} \leq y \leq \frac{h}{2}$ denote the transverse displacement at time t of a section of the column whose height above the midpoint is y . In the absence of transverse forces, w is a solution of the partial differential equation

$$EI \frac{\partial^4 w}{\partial y^4} + \frac{m}{h} \frac{\partial^2 w}{\partial t^2} = 0 \qquad (1)$$

where EI is the flexural stiffness and m the total mass of the column. The general solution is a superposition of solutions of the type

$$(A \cosh \beta y + B \cos \beta y + C \sinh \beta y + D \sin \beta y) e^{\pm i\omega t} \tag{2}$$

where ω is an angular frequency and $\beta = (m\omega^2 h^3/EI)^{1/4}/h$.

All solutions of (1) must satisfy the rigid attachment condition

$$\left.\frac{\partial w}{\partial y}\right|_{y=\pm h/2} = 0 \tag{3}$$

Thus, for each partial solution of the form (2), two of the coefficients are eliminated. However, the condition that the displacement of the column at the joint equal that of the floor is a time-dependent, nonhomogeneous boundary condition which does not furnish a discrete frequency spectrum. Nonetheless, we know that the characteric frequencies of motion of the floors are much smaller than the natural frequencies of vibration of the columns. Consequently the deflection of the column will be close to the static one, which we know to be a cubic parabola, and which we can quite well approximate by

$$\begin{aligned} w(y\,,t) \;=\; & \frac{1}{2}[u_o(t) + u_1(t)] \\ & + \frac{1}{2}[u_1(t) - u_o(t)] \sin \frac{\pi y}{h} \end{aligned} \tag{4}$$

where u_o and u_1 describe the translation of the lower and upper floors, respectively. This deflection mode is illustrated in Figure 1a.

In addition to the deflection induced by floor displacements, however, the column may also undergo a deflection w which, besides condition (3), satisfies

$$w(\pm\frac{h}{2}\,, t) \;=\; 0 \quad , \tag{5}$$

as illustrated in Figure 1b. Equations (3) and (5) applied to the solution (2) produce an eigenvalue problem, the characteristic problem for the so-called "fixed-fixed" column. The first fixed-fixed mode corresponds to $\beta h = 4.73$ and the mode shape is given by

$$W(y) \;=\; 0.1127 \cosh 4.73\frac{y}{h} + 0.8873 \cos 4.73\frac{y}{h} \quad , \tag{6}$$

so that $W(0) = 1$, while $W(\pm\frac{h}{2}) = W'(\pm\frac{h}{2}) = 0$. An adequate approximation to this is

$$W(y) \;=\; \frac{1}{2}(1 + \cos \frac{2\pi y}{h}) \quad ; \tag{6}$$

with this function, Rayleigh's method leads to the value 4.77 as an approximation to βh, an error of less than 1%.

It will be assumed that the deflection of the i-th story columns, $w_i(y, t)$, is given by a superposition of the quasi-static deflection induced by the floor displacements u_{i-1} and u_i, as approximated in equation (4), and of the lowest fixed-fixed mode as approximated by expression (6), with amplitude $v_i(t)$. Consequently,

$$w_i(y, \cdot) = \frac{1}{2}(u_i + u_{i-1} + v_i) + \frac{1}{2}(u_i - u_{i-1})\sin\frac{\pi y}{h} + \frac{1}{2}v_i\cos\frac{2\pi y}{h} \tag{7}$$

The potential energy is

$$U_i = \frac{EI}{2}\int_{-h/2}^{h/2}\left(\frac{\partial^2 u}{\partial y^2}\right)^2 dy = \frac{1}{2}\frac{EI\pi^4}{8h^3}\left[(u_i - u_{i-1})^2 + 16v_i^2\right] .$$

We can identify $\pi^4 EI/8h^3$ with the i-th column shear stiffness k_i (the difference between this and the static stiffness $12EI/h^3$ is 1.5%). Thus, the potential energy of an n-story building can be expressed as:

$$U = \frac{1}{2}\sum_{i=1}^{n} k_i \left[(u_i - u_{i-1})^2 + 16v_i^2\right]$$

with $u_o \equiv 0$.

Similarly, we obtain the kinetic energy of the i-th column:

$$\begin{aligned} T_{c_i} &= \frac{1}{2}\frac{m_i}{h}\int_{-h/2}^{h/2}\left(\frac{\partial w}{\partial t}\right)^2 dy \\ &= \frac{1}{2}m_i\left[\frac{3}{8}(\dot{u}_i^2 + \dot{u}_{i-1}^2) + \frac{\dot{u}_i\dot{u}_{i-1}}{4} + \frac{1}{2}(\dot{u}_i + \dot{u}_{i-1})\dot{v}_i + \frac{3}{8}\dot{v}_i^2\right] . \end{aligned}$$

If the mass of the i-th floor is M_i, then the total kinetic energy is

$$T = \sum_{i=1}^{n}\left(\frac{1}{2}M_i\dot{u}_i^2 + T_{c_i}\right)$$

The building is now modeled as an elastic system with 2n degrees of freedom, the generalized coordinates being u_i, v_i $(i=1, \ldots, n)$. It is convenient to define a set of generalized coordinates q_i $(i=1, \ldots, 2n)$ by $q_{2i-1} = v_i$, $q_{2i} = u_i$ $(i=1, \ldots, n)$. With respect to these generalized coordinates, both the stiffness and mass matrices are banded, with bandwidth 5, and are given, respectively, as follows:

$$k_{2i,2j} = \begin{cases} k_i + k_{i+1} , & j = i < n \\ k_n , & j = i = n \\ -k_{i+1} & j = i+1 < n \\ -k_i , & j = i-1 \geq 1 \end{cases}$$

$$k_{2i-1,2i-1} = 16\,k_i$$

$$m_{2i,2j} = \begin{cases} M_i + \frac{3}{8}(m_i + m_{i+1}) , & j = i < n \\ M_n + \frac{3}{8}\, m_n , & j = i = n \\ \frac{1}{8}\, m_{i+1} , & j = i+1 < n \\ \frac{1}{8}\, m_i , & j = i-1 \geq n \end{cases}$$

$$m_{2i,2i-1} = m_{2i-1,2i} = \frac{1}{4}\, m_i$$

$$m_{2i,2i+1} = m_{2i+1,2i} = \frac{1}{4}\, m_{i+1}$$

$$m_{2i-1,2i-1} = \frac{3}{8}\, m_i$$

All other elements are zero.

In order to study the transmission of ground motion, we can define the u_i as floor displacements relative to the ground floor; the absolute displacements are then $u_i + u_g$, where u_g is the ground displacement, and we can simply add $\dot{u}_g$ to each $\dot{u}_i$ in the expression for the total kinetic energy. If we define

$$\mu_i = \frac{\partial^2 T}{\partial \dot{q}_i \partial \dot{u}_g} \qquad (i=1, \ldots, 2n)$$

then a generalized force $-\mu_i \ddot{u}_g$ acts on the i-th degree of freedom. In particular,

$$\mu_{2i-1} = \frac{1}{2}\, m_i \qquad , \quad i=1, \ldots, n$$

$$\mu_{2i} = \begin{cases} M_i + \frac{1}{2}(m_i + m_{i+1}) , & i < n \\ M_n + \frac{1}{2}\, m_n , & i = n \end{cases}$$

The characteristic angular frequencies and the corresponding mode shapes of free vibration are given by the solution of the eigenvalue problem

$$(\underset{\sim}{K} - \omega^2 \underset{\sim}{M}) \underset{\sim}{r} = 0 \quad .$$

Let $\underset{\sim}{r}^{(k)}$ denote the modal vector (normalized so that the largest component is ±1) corresponding to the angular frequency ω_k . The motion of the structure, as given by the vector function $\underset{\sim}{q}$ whose components are the generalized coordinates q_i $(i=1, . . . , 2n)$, is then

$$\underset{\sim}{q}(t) = \sum_{k=1}^{2n} \underset{\sim}{r}^{(k)} p_k(t) \quad ,$$

where p_k is the function describing the time history of the k-th mode. Under a given ground motion u_g , p_k is governed by

$$\ddot{p}_k + \omega_k^2 p_k = - \phi_k \ddot{u}_g \quad ,$$

where

$$\phi_k = \frac{1}{\underset{\sim}{r}^{(k)^T} \underset{\sim\sim}{Mr}^{(k)}} \underset{\sim}{r}^{(k)^T} \underset{\sim}{\mu}$$

is the ground-motion participation factor for the k-th mode.

DISCUSSION

The eigenvalue problem for two-banded, symmetric, positive definite matrices is an easy task for computer solution. Nevertheless, it is worthwhile to make qualitative predictions on the nature of the solution.

We begin by studying a one-story building. Since this is a two-degree-of-freedom system, it can be dealt with analytically. The characteristic equation with $n = 1$ is

$$(\frac{3}{8} m M + \frac{5}{64} m^2) \omega^4 - (16 M + \frac{51}{8} m) k \omega^2 + 16 k^2 = 0 \quad ,$$

where m is the total column mass and M is the upper floor (roof) mass. Typically, the former is small compared to the latter. The roots of the equation can therefore be written as

$$\omega_1 = \omega_s (1 - \frac{3}{16} \frac{m}{M} + o(\frac{m}{M})) \quad ,$$

$$\omega_2 = \omega_c (1 + \frac{1}{6} \frac{m}{M} + o(\frac{m}{M})) \quad ,$$

where $\omega_s = \sqrt{k/M}$, the angular frequency obtained by neglecting column mass ("shear-mode frequency"), while $\omega_c = \sqrt{128k/3m}$ is the angular frequency corresponding to an infinite floor mass ("column-mode frequency"). It is seen that the actual frequencies differ only slightly from these limiting frequencies. Furthermore, the modal vectors are given, again to within $o(\frac{m}{M})$, by

$$\underset{\sim}{r}^{(1)} = < \frac{1}{64}\frac{m}{M}, 1 > ,$$

$$\underset{\sim}{r}^{(2)} = < 1 , -\frac{1}{4}\frac{m}{M} > .$$

Thus, the first mode is virtually indistinguishable from the shear mode, and the second mode from the column mode. We can therefore say that, with m/M small, the shear and column modes are practically uncoupled.

We can furthermore surmise that a similar lack of coupling occurs in multistory buildings provided that column masses are small compared to beam masses. The 2n modes of vibration in an n-story building are thus grouped into two families: a low-frequency family which is virtually the same as that derived from the elementary shear-building model, with the columns undergoing essentially static deflection; and a high-frequency family in which the floors are practically still while the columns vibrate in the fixed-fixed mode.

This grouping into families is analogous to the "acoustic" and "optical" branches of the frequency spectrum that describes atomic vibrations in crystals [6]: the shear modes correspond to the acoustic and the column modes to the optical branch (see Figure 2 for illustrations of some of the modes). It would be misleading, however, to use the nomenclature of physics in the present case because in fact it is the high-frequency family that is contained in the audible range: the fixed-fixed column frequency is given by

$$f_c = \frac{\omega_c}{2\pi} = \frac{1}{2\pi}\sqrt{\frac{128}{3}\,\frac{\pi^4 EI}{8h^3}\,\frac{1}{\rho A h}} ,$$

or

$$f_c = \frac{2\pi}{\sqrt{3}}\,\frac{cr}{h^2} , \qquad (8)$$

where $c = \sqrt{E/\rho}$ is the longitudinal wave speed in a rod of Young's modulus E and mass density ρ, and $r = \sqrt{I/A}$ is the column radius of gyration.

In structural metals the value of c is about 5×10^3 m/sec; with a column height of 4 m, we have a value for f_c (in Hz) of about $5 \times 10^3/(h/r)$. With a slenderness ratio of about 100, the column frequency is about 50 Hz, that is, in the low audio range.

There remains the question of the transmission of vibration from story to story. In the shear modes, the columns of course act as passive transmitters. In the column modes, however, transmission can only take place through resonance between columns in neighboring stories. Consequently, if the column frequencies of neighboring stories are sufficiently far apart (so that the stories are "untuned" relative to each other), vibration will not be transmitted. Similarly, audio-frequency ground motion will not be transmitted to the upper floors if the second story is untuned relative to the first.

Numerical results confirm all these surmises. With column masses of the order of 10% of beam masses, there is virtually no coupling between shear and column modes. As to the effect of tuning, if f_c is the same in every story, then (1) every column mode involves significant participation by most, if not all, stories, (2) all the characteristic frequencies of the column modes are clustered around f_c, and (3) every column mode has a ground-motion participation factor that differs significantly from zero.

If, at the other extreme, all the values of k_i/m_i $(i=1, \ldots, n)$ differ, then each column mode has a characteristic frequency that is very close to one particular value of f_c and the vibration is largely confined to the corresponding story. For example, if in a six-story building the values of f_c vary from story to story by as little as 5%, then, compared with the principal vibrating story, the vibration of a neighboring story will be attenuated to some 15%. With variations of 10% and 15%, the respective attenuations are 7.5% and 5%. In a ten-story building, frequency variations of 5%, 10%, and 15% produce attenuations of some 25%, 13%, and 8.5%, respectively. Illustrations of typical results appear in Figures 3 through 5.

Similar results apply to the transmission of ground motion. In a building in which the upper stories are "tuned" but the ground floor is "untuned" by 10% to 15%, the participation factor for the mode that is

centered in the ground story is around 0.65, while for the other modes it does not exceed 0.02. If the "untuning" is only around 4% to 6%, then the participation factors for the upper-story modes are still no more than 0.05. If the whole building is untuned, then the participation factor decreases with the number of the story in which the mode is centered, while in a tuned building all the participation factors are approximately equal in magnitude.

From extensive computations on sample buildings, it appears that an approximate empirical relationship among the degree of untuning u (percentage variation in f_c from story to story), the attenuation a (in per cent), and the number of stories can be expressed in the form

$$\frac{ua}{n} = C \qquad , \qquad (9)$$

where C is a constant equal to about 12.5.

Equation (9) is proposed as a design formula for situations in which the spread of audio-frequency vibration (such as that from machinery) from the story in which it is produced through the walls to neighboring stories is to be prevented. Let us recall that f_c is given by equation (8) for columns of a single material, such as steel. With all stories having equal height, then, untuning is produced entirely by varying the column radius of gyration r .

In the case of reinforced concrete columns, on the other hand, the cross section (and hence the mass) is customarily constant from story to story; thus, it is the variation in reinforcement that produces untuning.

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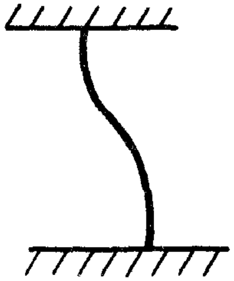
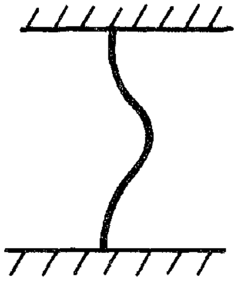
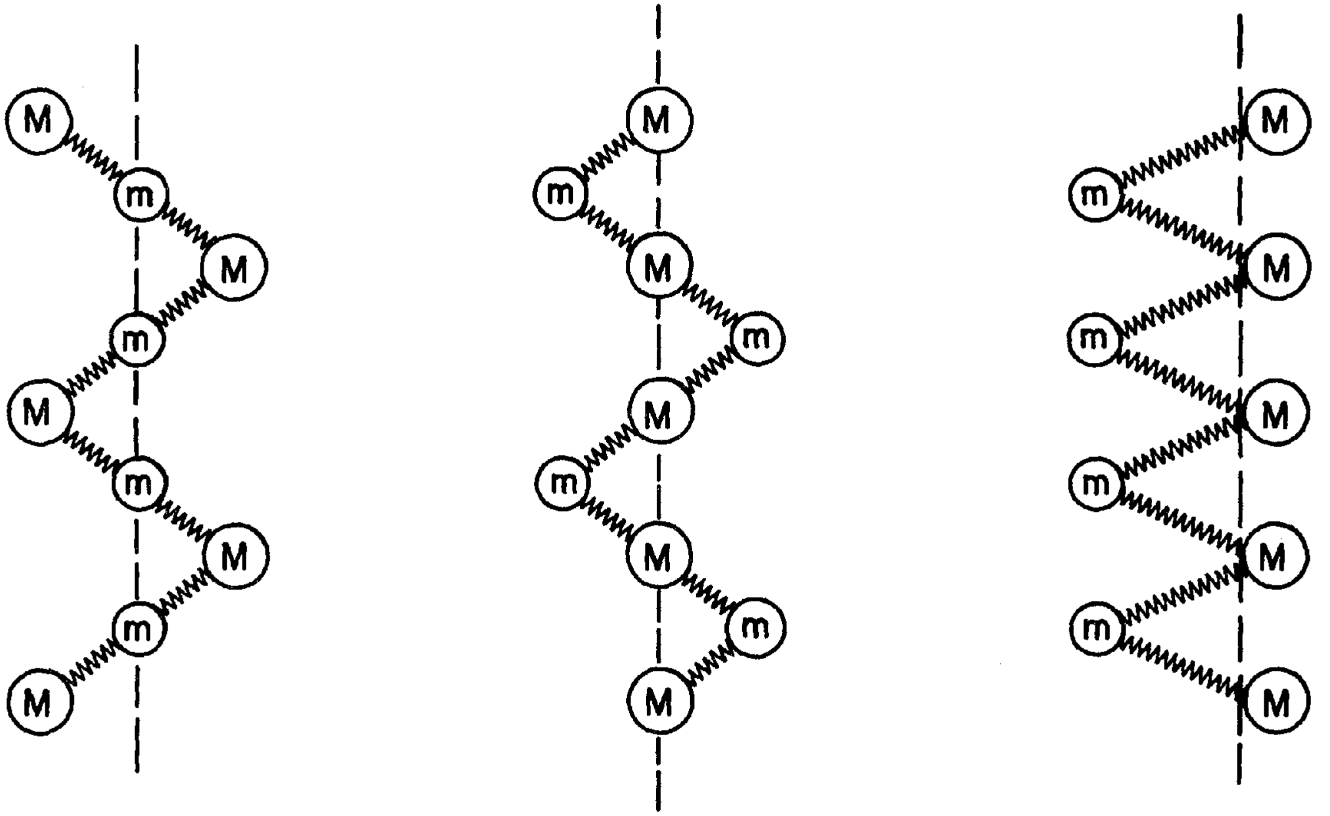


(a) SHEAR MODE



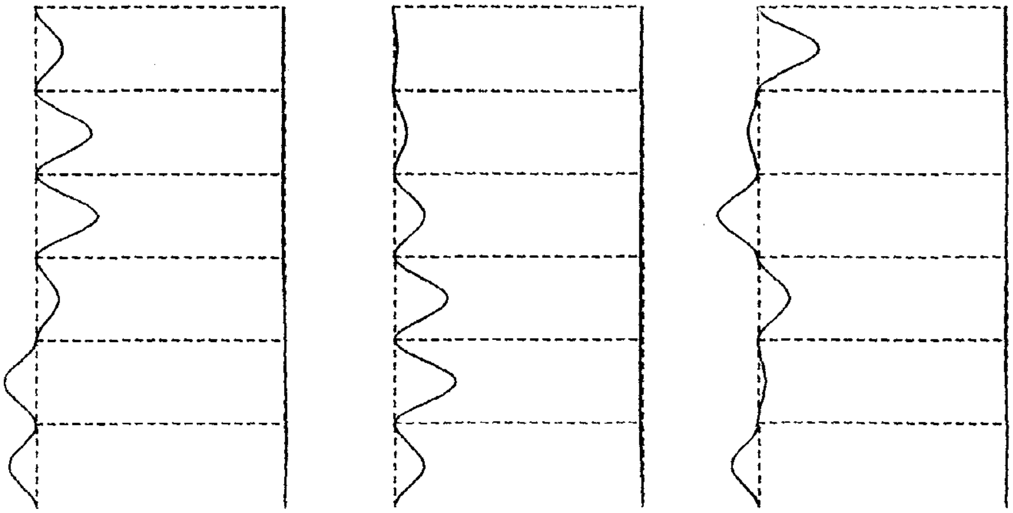
(b) LOWEST FIXED-FIXED MODE

FIGURE 1 COLUMN DEFLECTION MODES



(a) $\omega = \sqrt{k/M}$ (b) $\omega = \sqrt{k/m}$ (c) $\omega = \sqrt{k(1/m+1/M)}$

FIGURE 2 "NaCl" STRUCTURE MODES



MODE 1

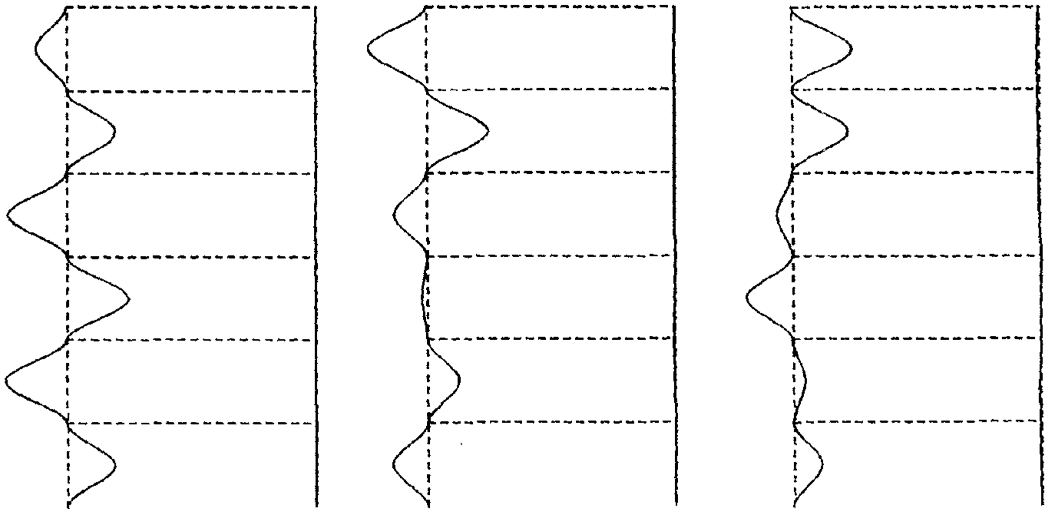
ANGULAR
FREQUENCY 6.650

MODE 2

ANGULAR
FREQUENCY 6.692

MODE 3

ANGULAR
FREQUENCY 6.581



MODE 4

ANGULAR
FREQUENCY 6.535

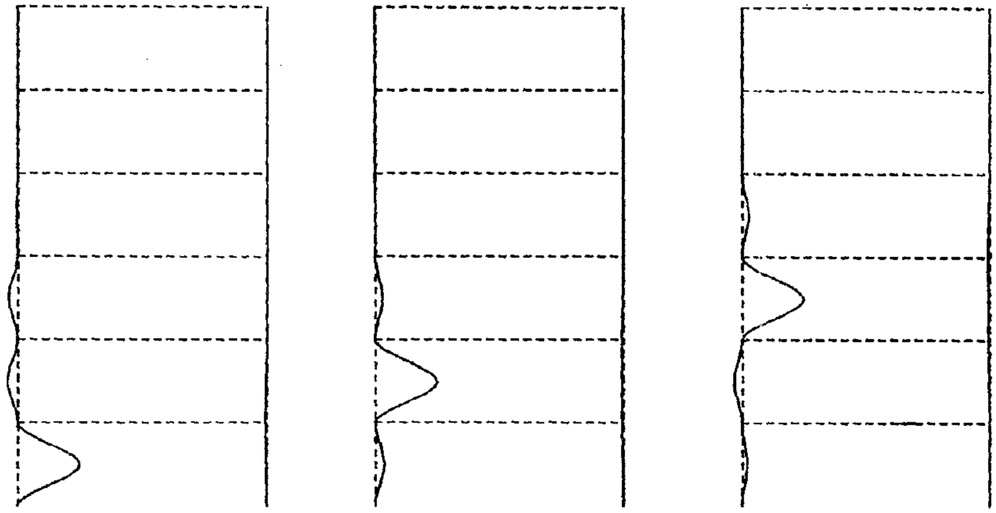
MODE 5

ANGULAR
FREQUENCY 6.551

MODE 6

ANGULAR
FREQUENCY 6.615

FIGURE 3 COLUMN MODES AND CHARACTERISTIC ANGULAR FREQUENCIES (IN ARBITRARY UNITS) FOR A TUNED SIX-STORY BUILDING



MODE 1

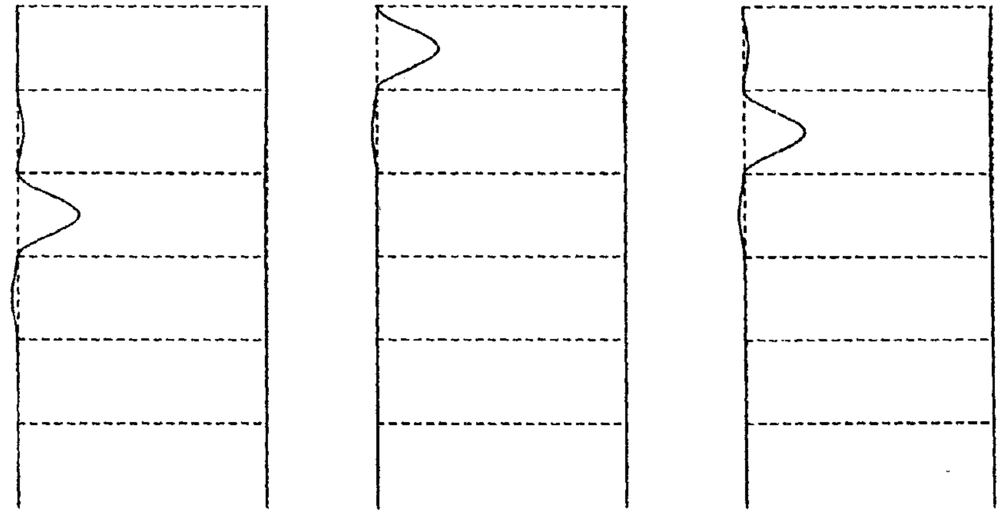
ANGULAR
FREQUENCY 6.306

MODE 2

ANGULAR
FREQUENCY 6.639

MODE 3

ANGULAR
FREQUENCY 6.245



MODE 4

ANGULAR
FREQUENCY 5.843

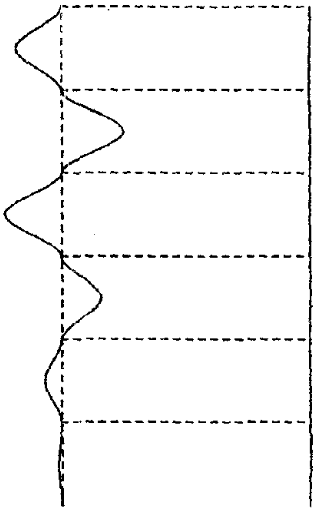
MODE 5

ANGULAR
FREQUENCY 4.937

MODE 6

ANGULAR
FREQUENCY 5.409

FIGURE 4 COLUMN MODES AND CHARACTERISTIC ANGULAR FREQUENCIES (IN ARBITRARY UNITS) FOR AN UNTUNED SIX-STORY BUILDING



MODE 1

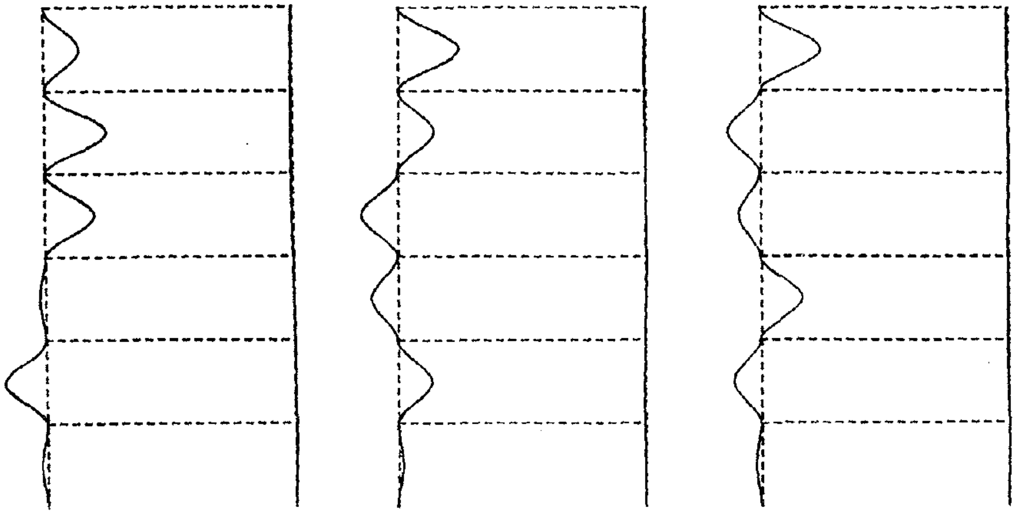
ANGULAR
FREQUENCY 6.682

MODE 2

ANGULAR
FREQUENCY 6.305

MODE 3

ANGULAR
FREQUENCY 6.542



MODE 4

ANGULAR
FREQUENCY 6.640

MODE 5

ANGULAR
FREQUENCY 6.604

MODE 6

ANGULAR
FREQUENCY 6.569

FIGURE 5 COLUMN MODES AND CHARACTERISTIC ANGULAR FREQUENCIES (IN ARBITRARY UNITS) FOR A SIX-STORY BUILDING WITH THE FIRST STORY UNTUNED

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