Journal of Wind Engineering and Industrial Aerodynamics, 11 (1983) 273–284
Elsevier Science Publishers B.V., Amsterdam — Printed in The Netherlands

MITIGATION OF WIND INDUCED MOTION OF TALL BUILDINGS

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1. INTRODUCTION

The current design trend of buildings with ever increasing height, use of high strength materials, use of welded connections and light facades that serve as an exterior wall without contributing to the structural strength have led to the construction of flexible structures with reduced damping. The resulting sensitivity of these buildings to dynamic excitation by wind has increased. Besides various failure possibilities, cladding and partition damage, serviceability of a building is an important design criteria. Serviceability of a building is affected by excessive acceleration experienced at the top floors in wind storms that may cause discomfort to the building occupants. Therefore, to ensure functional performance of tall buildings it is important to keep the frequency of objectionable motion levels below the discomfort threshold. Serviceability of buildings and various means of limiting the objectionable levels of motion are discussed in this paper. The pertinent problem parameters of human biodynamic sensitivity to building motion are identified and related to the existing guidelines for acceptability of the frequency and the level of building motion.

2. HUMAN SENSITIVITY TO MOTION

The human biodynamical response to motion in buildings is a complex blend of phychological, physiological, kinesiological, and ergonomical syndromes. Vibration of the whole or a part of the human body is one of the oldest and chronic environmental stresses to which we are subjected from early riders of chariots in 60 A.D., to the present day concern of swaying motion of tall buildings during windstorms.

The human body is a close, integrated network of interacting subsystems; structural, hydraulic, electrical, chemical and thermodynamic. The human brain is the central control unit over all these subsystems and it is supplemented by optical and acoustic systems. Overall biodynamical response of the human body varies in a random fashion from person to person. Therefore, the external manifestations of human response to swaying motion are varied and will differ from person to person. Concern, anxiety, fear, and even symptoms of vertigo express human psychological response to the observed motion; whereas, dizziness, headaches, and nausea are the common symptoms of motion sickness. The mechanisms for perceiving and responding to motion can be classified as tactile, vestibular, proprioception, kinesthesis, visual and audio cues, and visual-vestibular interaction. These mechanisms cause the sensing, transmitting, and integrating of the motion cues. The torsional motion of a building can often be perceived by a visual-vestibular mechanism at an order of magnitude smaller than that for perception of lateral translatory motion.

0304-3908/83/$03.00

In the theory of structural dynamics a linear transfer function relates the response of a structure to the loading function. Similarly, in the case of biodynamical response of the human body to motion, the stimulus is related to perception by a nonlinear transfer function which is an nth power law;

$$R = KS^n \tag{1}$$

where S is the stimulus, R is the sensory greatness, K is a constant. The physical parameters of stimulus are products of an amplitude and a power of frequency. Therefore, the stimulus parameters must be controlled to improve the human comfort in tall buildings.

Experimental evaluation of human perception threshold of motion stems from the investigations conducted by Reiher and Meister (1). Their experimental work was conducted in frequency ranges which are far above a typical tall building frequency. Later studies taken up by Chen and Robertson (2), Khan and Parmalee (3), Hansen et al. (4) were conducted in the normal frequency range of tall buildings. Most of these studies suggest the acceptable levels of acceleration in tall buildings. However, they differ in their details regarding the guidelines for acceptability. They also lack in the measure of acceleration, should it be the hourly peak acceleration or the rms (root mean square) value of acceleration. For human comfort, the duration and expected number of cycles of motion above a threshold value of acceleration are more significant than an occasional high peak value. The rate of change of acceleration, jerk, is a very important stimulus parameter, since it is directly proportional to the changes in the force acting on a body. A relationship between Dieckmann's sensitivity coefficient and the jerk for simple harmonic motion is available in reference 5. Studies conducted by Chen and Robertson (2) can be used to express human sensory greatness or an occupant sensitivity quotient in terms of stimulus parameters.

3. MITIGATION OF WIND INDUCED MOTION

3.1 Aerodynamic Modifications

The wind induced motion of a tall building can be controlled either by reduction at the source or by reducing the response. An appropriate choice of building shape and architectural modifications can result in the reduction of motion by altering the flow pattern around a building. Open passages in the building would allow the air to bleed into the wake and separated regions thereby increasing the base pressure and consequently reducing aerodynamic forces. Another potential source for reducing aerodynamic excitation involves the discharge of air from the side and leeward faces of a building into the wake region. This concept is popular in aviation technology but its acceptance in building design is impeded by the mandatory routine maintenance required for satisfactory performance of this system. Buildings with tapered and nonuniform cross sections along the height would inhibit any formation of coherent wake fluctuations resulting in a reduction of transverse periodic loading. Small vanes fitted to the corners of a prismatic building with a gap between the vanes and the corner can help to alleviate negative pressures under the separated shear layers on the side faces. However, the added drag introduced by these vanes and the associated increase in structural stiffness, and additional structural strength requirements for the vane subsystem may preclude this alternative. All these aerodynamic modifications are of passive nature. Alternative active aerodynamic devices can be used to function in an optimal fashion to reduce aerodynamic forces on buildings (6). However, such measures require regular inspection and maintenance which makes them less attractive at present.

3.2 Reduction of Response

Parametric adjustments in the structural properties, i.e., mass, stiffness, and damping can be made to achieve more desireable response levels. An increase in the stiffness, damping, and mass of a building will result in a concomitant decrease in the structural response. The rms response of a system, subjected to random excitation, is inversely proportional to the product of mass and square root of the damping ratio. Influence of increasing the stiffness, by keeping other properties unchanged, can be shown by assuming that the rms acceleration at the building top is proportional to $\sqrt{\frac{f_n S(f_n)}{m_n^2 \xi_n}}$; in which f_n = nth frequency, ξ_n = structural damping ratio, and $S(f_n)$ = power spectral density of wind loading evaluated at the nth frequency, and m_n = generalized building mass in the nth mode. The power spectrum of wind loading is proportional to $(f_n)^{-\gamma}$, in which γ is a constant. The value of γ depends on the approach wind characteristics, building geometry and the direction of loding (7). For a square cross-section building the value of γ for the crosswind loading is approximately equal to 5.5. The ratio between the rms acceleration response of structures having the same mass, and damping, but different stiffnesses can be expressed as:

$$\frac{\sigma_2}{\sigma_1} = \left(\frac{f_1}{f_2}\right)^{\gamma-1} \tag{2}$$

in which f_1 = original frequency and f_2 = new frequency. By doubling the stiffness of a structure the natural frequency is increased by a factor of 2. Using Eq. 2 there is a reduction of 55% in the rms response, which does not apear to be a promising alternative. Increasing the structural stiffness reduces the amplitude of motion, but it increases the natural frequency of motion which influences occupants sensitivity to motion. Generally people are more susceptible to the higher frequency motion than the lower frequency motion.

Addition of damping would result in a reduction in the rms response of a building by a factor which is the square root of the fraction of the original and the new damping values. By keeping all the parameters constant except the damping value, the ratio of rms responses is given by

$$\frac{\sigma_2}{\sigma_1} = \left(\frac{\xi_1}{\xi_2}\right)^{1/2} \tag{3}$$

The addition of damping appears to be a very attractive alternative. In steel buildings additional damping can be introduced through passive visco-elastic systems, e.g., frictional pads, viscoelastic layers, and viscoelastic dampers (8). The composite steel-concrete buildings have considerably higher values of damping as compared to those of steel buildings. Furthermore, the use of stone as the fascade of these buildings adds to the overall damping value of the structure. Besides, the high damping characteristics the composite construction has higher mass which directly contributes to limiting the building motion.

4. DYNAMIC VIBRATION ABSORBER

Another promising approach to augment the inherent built-in damping of a building is the introduction of a dynamic vibration absorber in the structural system (7, 10, 11, 12, 13, 14, 15). The dynamic vibration absorber is commonly known as a tuned mass damper (TMD). This energy dissipative device has been installed in a few tall buildings recently to mitigate objectionable levels of building motion. For incorporation in the structural system, the dynamic vibration absorber in its simplest form can be visualized as a block of concrete on rubber springs or viscoelastic material, located at the top of the building. This can be accomplished by levitating the damper mass on a nearly frictionless film of oil (14). A dynamic vibration absorber when installed in a structural system of a building imparts indirectly extra damping to the system by modifying the mechanical admittance function of the building and thereby reducing the response. Estimates for the modified system damping can be made using random vibration analysis. Generally the building system is represented by a single degree of freedom system with generalized mass, stiffness and damping associated with the fundamental mode. The transfer function for response of a building system represented by an equivalent single-degree-of-freedom system is given by

$$\left| H_b^2(f) \right| = \frac{1}{(2\pi f_1)^4 \, M_1^2 \left\{ \left(1 - (f/f_1)^2\right)^2 + \left(2\xi_1 f/f_1\right)^2 \right\}} \qquad (4)$$

in which f_1 = fundamental frequency, ξ_1 = damping ratio in fundamental mode, M_1 = generalized building mass in the fundamental mode. The transfer function of an absorber-building system (Fig. 1) is given by

$$\left| H_{ba}^2(f) \right| = \frac{(A^2 - B^2)}{\left\{ (2\pi f)^4 M_1^2 (C^2 - D^2) \right\}}, \quad A = h^2 - g^2$$

$$B = 2hg\,\xi_a \; ; \; C = A(1-g^2) - \mu h^2 g^2 - 4hg^2 \xi_1 \xi_a \; ; \; h = f_a/f_1 \qquad (5)$$

$$D = 2g\left(\xi_1 A + h\xi_a (1 - g^2 - \mu g^2)\right) ; \; g = f/f_1 \; ; \; \mu = M_a/M_1$$

in which f_a = absorber frequency, and M_a = absorber mass. For harmonic excitation the dynamic vibration absorber is optimally tuned (16), i.e., the absorber is designed effectively to minimize the primary response, when

$$h = \frac{1}{1+\mu} \; ; \quad \xi_a = \sqrt{\frac{3\mu}{8(1+\mu)}} \qquad (6)$$

In the case of random external excitation the optimal damper parameters are

$$h = \frac{(1+0.5\mu)^{1/2}}{(1+\mu)} \; ; \quad \xi_a = \left\{ \frac{\mu(1+0.5\mu)}{4(1+\mu)(1+0.5\mu)} \right\}^{1/2} \qquad (7)$$

Equation 7 was derived in reference 17 by optimizing the mean square value of response, assuming that the primary system damping was negligible. An analytical solution is not possible since some of the characteristics of the classical system (existance of invariant points) do not exist when damping is introduced in the primary system. Depending on the values of absorber parameters the transfer function described in Eq. 5 exhibits one or two peaks, but in case of near optimum choice of parameters there are always two peaks. One of the peaks is slightly lower and the other is greater than the original natural frequency of the system. The spread between the two frequencies depends on the size of the secondary mass attached to the primary system. For a given secondary-to-primary mass ratio there exists an absorber-to-structure frequency ratio and an absorber damping that will optimize the reduction in response. A search for the optimum values of h, and ξ_a can be based on the min-max definition of the optimum system, in which the peak or rms primary amplitude is minimized. Randal et al. (18) have presented computational graphs for determining the optimal vibration absorber for linear damped primary system. As the primary system damping increases, there is a small decrease in the optimum value of h, and this change is more marked when the mass ratio, μ, is large. The absorber damping ratio increases slightly as the primary system damping ratio increases. Thus the allowance for damping in the primary system, which has been assumed to be relatively small, to obtain Eq. 7 has only a small effect on the values of h and ξ_a. Equation 7 results in a higher value of h for a given mass ratio μ than the one obtained using Eq. 6 in which the value of h is obtained from classical solution of parameter optimization. The optimum value of damping for the absorber, ξ_a, is lower using Eq. 7 than for the harmonic excitation case (Eq. 6). Generally, the exact value of the structural damping available in a building structure cannot be estimated accurately, therefore, the expression obtained in Eq. 7 should suffice the design requirements of wind excited structures. If the absorber damping is represented by hysteretic damping instead of viscous damping the transfer function is slightly modified. Kareem (10) has presented a detailed treatment of hysteretically damped absorbers.

4.1 Response Analysis

The mean square value of the acceleration response of a building alone when subjected to stochatic wind load, is given by

$$\sigma_b^2 = \int_0^\infty \Theta |H_b^2(f)| S_F(f) df \quad ; \quad \Theta = (2\pi f)^4 \tag{8}$$

in which σ_b^2 = mean square displacement response of building alone, $|H_b^2(f)|$ = building transfer function, $S_F(f)$ = power spectral density (PSD) of wind loading. The integral in Eq. 8 is generally evaluated using numerical integration. However, if the function $SF_{(f)}$ does not vary significantly in the vicinity of structural frequency, it can be replaced by an equivalent white noise with an amplitude equal to $S_F(f)$. Subsequently, the integral in Eq. 8 can be evaluated using residue theorem and it is given by

$$\sigma_b^2 = \frac{\pi \; f_1 \, S_F(f_1)}{4 \, \xi_1 \, M_1^2} \tag{9}$$

A more general expression for the mean square value of various components of response is given by

$$\sigma_{b_r}^2 = \frac{\frac{\pi}{4} f_1 S_F(f_1)(2\pi f_1)^{2r}}{(2\pi f_1)^4 \xi_1 M_1^2} \qquad (10)$$

in which r represents various derivitives of the displacement response, e.g., r = 0, 1, 2, 3 represent displacement, velocity, acceleration and jerk, respectively. Similarly, the response of a building-absorber system is given by

$$\sigma_{ba}^2 = \int_0^\infty |H_{ba}^2(f)| \, S_F(f)\,df \qquad (11)$$

in which σ_{ba}^2 = mean square displacement response of building-absorber system. The above integral can also be evaluated assuming that S_F =(f) does not vary significantly in the range of the two peaks generally present in the transfer function of an optimal building-absorber system. Therefore, the white noise assumption can be used to evaluate analytically (13) Eq. 11 and it is given by

$$\sigma_{ba}^2 = \frac{\pi}{2} f_1 S_F(f_1) \left\{ \frac{B_0^2(A_2A_3 - A_1) + A_0A_3(B_1^2 - 2B_0B_2) + A_0A_1B_2^2}{A_0(A_1A_2A_3 - A_1^2 - A_0A_3^2)} \right\} \qquad (12)$$

in which

$$A_0 = h^2 \;;\; A_1 = 2\xi_1 h^2 + 2h\xi_2 \;;\; A_2 = \mu h^2 + 4h\xi_1\xi_2 + 1 + h^2$$

$$A_3 = 2h\xi_2 + 2\xi_1 + 2h\xi_2\mu \;;\; A_4 = 1$$

$$B_0 = h^2 \;;\; B_1 = 2h\xi_2 \;;\; B_2 = 1$$

If the power spectral density of the forcing function varies significantly in the vicinity of the transfer function peaks, it is recommended that a numerical scheme be used for evaluating Eq. 11.

As indicated earlier, a dynamic vibration absorber imparts indirectly additional damping to the system through the modification of the building transfer function. Therefore, the effectiveness of a dynamic vibraiation absorber can be evaluated by considering the amount of extra damping imparted to the system (12, 15). The effective system damping can be computed by equating the response of a building-absorber system to the response of a single-degree-of-freedom system with an effective damping ξ_e. Following this approach ξ_e is given by

$$\xi_e = \frac{1}{2}\left\{ \frac{A_0(A_1A_2A_3 - A_1^2 - A_0A_3^2)}{B_0^2(A_2A_3 - A_1) + A_0A_3(B_1^2 - 2B_0B_2) + A_0A_1B_2^2} \right\} \qquad (13)$$

This is the value of damping available to the building with a dynamic vibration absorber. If the estimate of ξ_e is available the response components of a building-absorber system can be computed as

$$\sigma^2_{ba_r} = \frac{\frac{\pi}{4} f_1 S_F(f_1)(2\pi f_1)^{2r}}{(2\pi f_1)^4 \xi_e M_1^2} \tag{14}$$

The analysis of response upcrossing above a threshold value, with and without the dynamic vibration absorber, can be used to evaluate the effectiveness of an absorber (10).

A building 100 ft. (31 m) square in plan, and 600 ft. (183 m) tall was modeled as an equivalent single-degree-of-freedom system. In fig. 2 the cross-wind rms and peak acceleration response of the building alone and building-absorber system with a number of values of μ are presented. It is obvious that the largest value of μ yields the best results, however, final selection of μ is based on the economic evaluation. A high μ would require the basic load bearing structure to be stiffer which directly contributes to an increased in the building cost. A simplified equation is developed in liu of Eq. 13 for evaluating effective damping available to the system to aid preliminary design procedure. The equation is given by

$$\xi_e = 0.9 \frac{\sqrt{\mu}}{4} + 0.8 \xi_1 \tag{13a}$$

4.2 Dynamic Vibration Absorber in Multi-Degree-of-Freedom Systems

Generally, the behavior of a building absorber system is studied as a two-degree-of-freedom systgem. However, it is indicated in the literature that a damper designed to restrict dynamic motion in the fundamental mode of vibration have caused structural damage when the structure vibrated in the higher modes (19). Luft (15) reports that the damper acts as a concentrated load on the top of the building and, therefore, excites several modes and it is not fully effective in the fundamental mode. The contribution of higher modes of vibration to the overall response of a building becomes more significant as the ratios of the natural frequencies in the higher modes to the fundamental frequency become closer to unity (20). This is generally not true in typical high-rise buildings. A stochastic analysis of a multi-degree-of-freedom system (Fig. 3) with a dynamic vibration absorber is presented to observe any adverse effects of vibration in higher modes on the performance of an absorber. The equations of motion of a multi-degree-of-freedom system are given by

$$[M]\{\ddot{y}\} + [C]\{\dot{y}\} + [K]\{y\} = \{P(t)\} \tag{15}$$

Introducing the normal-coordinates ($y = \Phi\alpha$) and using modal analysis the response in ℓ-th mode is given by

$$M_\ell \ddot{\alpha}_\ell + 2\xi_\ell \omega_\ell M_\ell \dot{\alpha}_\ell + M_\ell \omega_\ell^2 \alpha_\ell = P_\ell(t) = \Phi_\ell^T \{P(t)\} \tag{16}$$

The addition of a dynamic vibration absorber to the n-th mass of the original mdof system, leads to a (n+1) degree-of-freedom system. For low values of μ it can be assumed that mode shapes are not modified significantly; therefore, the equations of motion of (n+1) of system can be uncoupled. The uncoupled equation of motion in the ℓ-th mode is given by

$$M_\ell \ddot{\alpha}_\ell + 2\xi_\ell \omega_\ell M_\ell \dot{\alpha}_\ell + M_\ell \omega_\ell^2 \alpha_\ell + \Phi_{\ell n}^2 (2\xi_a \omega_a \dot{\alpha}_\ell + \omega_a^2 \alpha_\ell) - \Phi_{\ell n}(2\xi_a \omega_a \dot{y}_a + \omega_a^2 y_a) = P_\ell(t) \tag{17}$$

in which $\Phi_{\ell n}$ is the ℓ-th mode shape value at the n-th mass where the damper is attached to the building system (Fig. 3). The equation of motion of the damper mass is given by

$$M_a \ddot{y}_a + 2 M_a \omega_a \xi_a \dot{y}_a + k_a y_a - 2\xi_a \omega_a M_a \dot{y}_n - M_a \omega^2 y_n = 0 \tag{18}$$

Solving for α_ℓ from the above equations

$$\begin{aligned} \alpha_\ell &= \bar{P}_\ell \left(\omega_a^2 M_a + 2i\xi_a \omega \omega_a M_a - M_a \omega^2\right) / Den \\ Den &= \left[M_\ell(\omega_\ell^2 - \omega^2) + (\omega^2 M_a + 2i\omega\xi_a M_a \omega_a)\Phi_{\ell n}^2\right] \times \\ &\quad \left[\omega^2 M_a + 2i\omega\xi_a M_a \omega_a - M_a \omega^2\right] - (\omega^2 M_a + 2i\omega\xi_a M_a \omega_a)^2 \Phi_{\ell n}^2 \end{aligned} \tag{19}$$

Rearranging terms in the above equation

$$\begin{aligned} |H_{\alpha_\ell}^2(f)| &= \frac{\alpha_\ell}{\bar{P}_\ell} = \frac{\Delta_n}{\Delta_D}; \quad \Delta_n = (\omega^2 M_a + 2i\omega\xi_a \omega_a M_a - M_a \omega^2) \\ \Delta_D &= \omega_\ell^4 \Phi_{\ell n}^2 \Big\{\left[M_\ell^*(1 - \omega^2/\omega_\ell^2) + (M_a + 2i\xi_a M_a \omega_a \omega/\omega_\ell^2)\right] \times \\ &\quad \left(\frac{\omega^2}{\omega_\ell^2} M_a + 2i\xi_a M_a \frac{\omega\omega_a}{\omega_\ell^2} - M_a \omega^2/\omega_\ell^2\right) - \\ &\quad \left(\frac{M_a \omega^2}{\omega_\ell^2} + 2i\xi_a M_a \omega\omega_a/\omega_\ell^2\right)^2\Big\}; \quad M_\ell^* = M_\ell/\Phi_{\ell n}^2 \end{aligned} \tag{20}$$

The transfer function in the ℓ-th mode is given by

$$|H_{\alpha_\ell}^2(f)| = \frac{1}{(2\pi f_\ell)^4 M^{*2} \Phi_{\ell n}^4} \left[\frac{A^2 - B^2}{C^2 - D^2}\right]$$

$$A = h_\ell^2 - g_\ell^2 \; ; \; B = 2 h_\ell g_\ell \xi_a \; ; \; C = A(1 - g_\ell^2) - \mu_\ell h_\ell^2 g_\ell^2 - \tag{21}$$
$$-4 h_\ell g_\ell^2 \xi_\ell \xi_a \; ; \; D = 2 g_\ell \left(\xi_\ell A + h_\ell \xi_a (1 - g_\ell^2 - \mu_\ell g_\ell^2) \right)$$
$$h_\ell = f_a / f_\ell \; ; \; g_\ell = f / f_\ell \; ; \; \mu_\ell = M_a / M_\ell^* \; ; \; M_\ell^* = M_\ell / \Phi_{\ell n}^2$$

Equations 5 and 21 are very similar. For the fundamental mode analysis $\ell = 1$ which gives exactly the same results as Eq. 5. The mean square value of response in the ℓ-th mode due to stochastic wind loads can be evaluated by

$$\sigma_{\ell n}^2 = \left[\int_0^\infty \left[\{\Phi_\ell\}^T [G_F(f)] \{\Phi_\ell\} \left[H_{\alpha \ell}^2(f) \right] df \right] \Phi_{\ell n}^2 \tag{22}$$

in which $G_F(f)$ = cross-power spectral density of wind load, $|H_{\alpha\ell}^2(f)|$ = system transfer function in ℓ-th mode.

The building used earlier in the example was modeled as a five degree-of-freedom system (20). In reference 20 the wind excited response of this building in higher modes was computed. In this example the response in each mode was evaluated using the dynamic vibration absorber tuned to the fundamental mode. In Table 1 the results are reported, for acceleration at the top of the building, which indicate that the higher modes do not have any adverse effects on the performance of the damper and in fact the response is considerable reduced in the higher modes as well as the fundamental mode.

In reference 21, Warburton has reported an analytical study which evaluated the effect on optimum absorber parameters of the contributions to the response from the higher modes, using a two degree-of-freedom main system with a parameter which allowed the variation of frequency ratio between the fundamental and second mode (f_2/f_1). He concluded that an equivalent one degree-of-freedom system can be used to predict optimized response with acceptable accuracy, provided $f_2/f_1 \gg 2$ for small values of μ and $f_2/f_1 \gg 3$ for larger values of μ. In case of high-rise buildings the translational frequencies are generally well separated. Therefore, an equivalent one-degree-of-freedom system can be used for the absorber analysis. However, in exceptional cases when the above stated inequalities are not satisfied, the optimum absorber parameters will deviate from the values given by Eqs. 6 and 7. A more detailed error analysis can be performed using the procedure presented in reference 22. The results shown in this paper and those of reference 21 indicate that an equivalent one degree-of-freedom system can be effectively used to represent a multi-degree-of-freedom system in designing a dynamic vibration absorber for tall buildings.

5. CONCLUSIONS

The parameters of human biodynamic sensitivity to building motion are identified. Various means of controlling the motion of high-rise buildings are discussed. A detailed analysis of a dynamic vibration absorber (TMD), for mitigating objectionable levels of motion of tall buildings, is presented. The effectiveness of an absorber is quantified by evaluating the effective damping available to the system, and an approximate expression is developed to aid the preliminary design procedures. An example building is used to illustrate the analysis presented in the paper. It is also shown that a building with well separated natural frequencies can be adequately represented by an equivalent single-degree-of-freedom main system for the analysis of a dynamic vibration absorber.

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Table 1

Mode	RMS ACCEERATION (Percent g) Building	Building-Absorber
1	1.093	0.615
2	0.143	0.023
3	0.019	0.004
4	0.006	0.003
5	0.003	0.0006

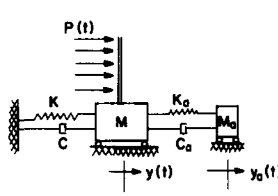

Fig. 1 Building-absorber model

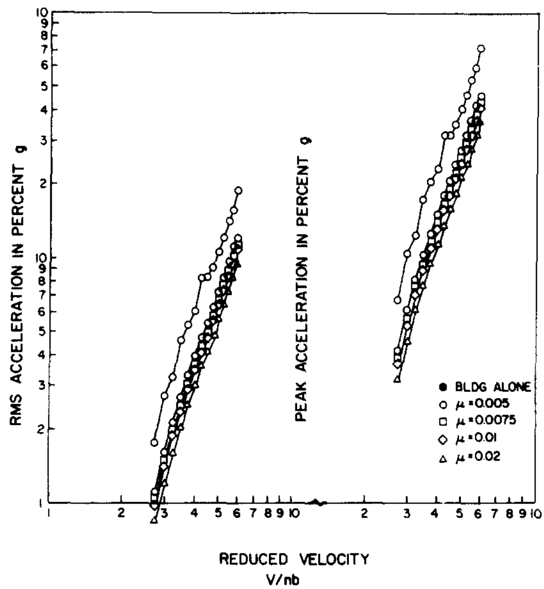

Fig. 2 Response of building-absorber system

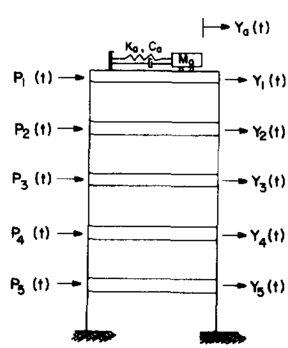

Fig. 3 Multi-degree-of-freedom building-absorber model.