Journal of Wind Engineering and Industrial Aerodynamics, 36 (1990) 725-737
Elsevier Science Publishers B.V., Amsterdam — Printed in The Netherlands

Reduction of Wind Induced Motion Utilizing a Tuned Sloshing Damper

Ahsan Kareem*

ABSTRACT

Serviceability of buildings is affected by excessive acceleration experienced at the top floors in wind storms that may cause discomfort to the occupants. To ensure functional performance of tall buildings it is important to keep the frequency of objectionable motion levels below the discomfort threshold. This paper addresses a new approach that facilitates mitigation of wind induced motion of buildings utilizing tuned sloshing dampers. First, a theoretical background of the fluid sloshing system is given, which is followed by modeling of sloshing fluid and structural systems. An example of a tall building equipped with a tuned sloshing damper is presented to illustrate the effectiveness of such devices in mitigating structural motion. Finally, a brief discussion of the potential for practical applications is presented.

INTRODUCTION

The current trend of buildings with ever increasing heights and lights facades has led to the construction of relatively flexible structures possessing quite low 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. The 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. Various possibilities exist to achieve this goal, the global design modifications presented in Table 1 range from considering alternative structural systems to aerodynamic modification. Further details on the effectiveness of each alternative are discussed in Kareem (1983).

The use of tuned mass dampers and viscoelastic dampers is gaining wide acceptance in building industry as evidenced by recent implementation of these devices in tall buildings and other flexible structures (e.g., McNamara, 1977, Wiesner, 1986, Keel, 1987 and Kitamura, et al. 1988). Recent studies have demonstrated that sloshing fluid in a container if properly tuned acts like a tuned mass damper in reducing structural response (Sun & Kareem, 1986; Kareem & Sun, 1987; Modi & Welt, 1987; Fujino, et al., 1988; Tamura et al., 1988). Earlier studies, though not particularly focussed on their application to engineering structures, also concluded that for a proper selection of design parameters, containers partially filled with fluids serve as good vibration dampers (Sayar & Baumgarten, 1982). Dampers utilizing liquid motions have been utilized successfully in satellites and on ocean vessels (Bhuta & Kovak, 1966, Harris & Crede, 1987). Most of

* Professor and Director, Structural Aerodynamics and Ocean System Modeling Laboratory, University of Houston, Houston, TX 77204-4791.

0167-6105/90/$03.50

these investigations considered simplified modeling of the primary and the secondary systems. Kareem & Sun (1987) reported stochastic response of structures (Multi-degree-of-freedom systems) with fluid-containing appendages (also modeled as multiple-degree-of-freedom system). A building with a water tank situated at any floor, excited by an earthquake, was used to illustrate the methodology. An important feature of the combined system is that the response of the primary system is suppressed when one of the sloshing modes of the secondary fluid appendage is tuned to the fundamental mode of the primary system. In the following section a brief discussion concerning the behavior of the combined system is presented.

Tuned Sloshing Dampers (TSD) can be broadly classified into two categories, shallow-water and deep-water dampers. This classification is based on the ratio of the water surface elevation in the direction of motion to the water depth. Like a TMD, the TSD when installed in a structural system indirectly imparts additional damping to the system by modifying the frequency response function of the structure, thereby reducing the response. In the shallow water case the TSD damping originates primarily from energy dissipation through the action of the internal fluid viscous forces and from wave breaking. The provision of the surface contamination, such as PVC beads or a lip along the wall parameter can add to the dissipation of sloshing energy. For the deep-water damper, in addition to viscous damping, the presence of baffles or screens may further increase the damping. The damping mechanism is, therefore, dependent on the amplitude of the fluid motion and wave-breaking patterns. To correctly model the contribution of a TSD to the dynamical behavior of the combined system, the transfer function of the TSD must account for the resultant changes in damping values for different motion amplitudes and directions.

The motion of liquids in rigid containers has been a subject of many studies in the past few decades, due to its frequent application in several engineering disciplines. Although the phenomenon of liquid sloshing in spherical and cylindrical shaped containers has been extensively studied, liquid sloshing in prismatic rectangular tanks has received limited attention. A large number of the present and previous studies have been based on linear and/or nonlinear potential flow theory (e.g., Lamb, 1947; Cooper, 1960; Abramson, 1966; Cokelet, 1977; and Holyer, 1979). Unfortunately, due to the underlying potential flow assumptions, these studies cannot take into account the effect of fluid viscosity which is central to the TSD concept. Chester (1968) and Verhagen and Wijngaarden (1978) utilizing a perturbation approach solved the shallow-water wave equation, but viscous effects were neglected. More recently, Faltinson (1978) introduced a fictitious term in the Euler equations to artificially include the effect of viscous dissipation. However, the form of this damping term caused considerable numerical difficulty in the solution of the equations of motion.

The subject of viscous dissipation in progressive waves has been addressed in a number of classical papers (e.g., Boussinesq, 1868; Hough, 1897; and Lamb, 1945). More recently, Keulegan (1959) investigated the decay modulus of finite-amplitude waves in a rectangular basin. In this analysis, it was assumed that the energy dissipation was entirely due to the boundary layers near the basin walls. Under certain conditions, a boundary layer type solution provided satisfactory agreement with the experimental studies. Prosperetti (1976) investigated the transient behavior of small-amplitude standing waves on the plane surface of an infinitely deep viscous liquid. The results exhibited some departure from the existing studies for all but small values of viscosity. The hydrodynamic aspects of the motion of a viscous fluid having a free surface in a rolling tank has been investigated by Demirbilek (1983) utilizing both simplified analytical methods and numerical techniques. Modi et al. (1988) investigated energy dissipation due to a sloshing liquid in torus shaped dampers both analytically and experimentally, their analysis accounts for both nonlinear and viscous effects. More recently, Lepelletier and Raichlen (1988) reported a nonlinear, dispersive, dissipative model to describe the fluid motion in a rectangular basin excited by an oscillatory, transient, unidirectional translational motion. It was noted that for a continuously excited basin and for shallow water waves the linear theory becomes inadequate near resonance. Their model showed a good agreement with the experiments for all cases investigated.

MODELING OF SLOSHING FLUID AND STRUCTURAL SYSTEMS

The fluid sloshing system can be represented by an equivalent mechanical model in which the fluid is replaced by lumped fluid masses, springs and dashpots [Fig. 1]. The mechanical characteristics of the equivalent system are established by following the dynamic similitude of the sloshing fluid (potential flow theory) or by experimental methods (Abramson, 1966). The energy transferred to the fluid may be dissipated by the viscous action of the fluid, damping devices or the wave breaking action. A theoretical estimation of the damping available in sloshing may include consideration of the nonlinear wave surface profile and the computation of the energy dissipated in a viscous fluid [Lamb, 1945]. A finite-element model is being developed to investigate the dynamics of a liquid sloshing in a partially-filled rigid tank, including the effects of free-surface nonlinearity, viscosity and energy dissipation, and to validate the numerical results by means of a series of controlled laboratory experiments. The liquid sloshing model is based on the nonlinear shallow-water wave theory in two horizontal directions.

The mechanical parameters of a typical TSD based on potential flow theory for rectangular tanks are summarized here. The equivalent sloshing mass m_ℓ where $\ell = 1, --- J$ is given by

$$m_\ell = \{8 \tanh [2\ell - 1)\pi r]/\pi^3 r(2\ell - 1)\} M_L \tag{1}$$

in which r = h/a, h = depth of fluid, a = length of tank in the direction of motion and M_L = total fluid mass, m_o is equal to the fluid mass which oscillates with the structure in a rigid body mode and is equal to $M_L - \sum_{\ell=1}^{J} m_\ell$ and $k_\ell = m_\ell \omega_\ell^2$ for $\ell = 1,2,----J$.

The primary structural system may be conveniently modeled by a lumped mass system consisting of n-lumped masses. The combined sloshing fluid and structural system can be represented by the model shown in Fig. 2. The equations of motion for the combined primary and secondary systems are

$$\underline{M}^S \ddot{\underset{\sim}{X}}^S + \underline{C}^S \dot{\underset{\sim}{X}}^S + K^S \underset{\sim}{X}^S = \underset{\sim}{f}(t) \tag{2}$$

in which

$$\underline{M}^S = \begin{bmatrix} \underline{M} & 0 \\ 0 & \underline{m} \end{bmatrix}; \qquad \underline{C}^S = \begin{bmatrix} \underline{C} & \underline{C}_a^T \\ \underline{C}_a & \underline{c} \end{bmatrix}$$

$$\underline{K}^S = \begin{bmatrix} \underline{K} & \underline{k}_a^T \\ \underline{k}_a & \underline{k} \end{bmatrix} ; \qquad \underset{\sim}{X}^S = \begin{Bmatrix} \underset{\sim}{X} \\ \underset{\sim}{x} \end{Bmatrix} .$$

In the preceding equation $\underset{\sim}{X}$ and $\underset{\sim}{x}$ are displacements corresponding to the structural and sloshing fluid degrees of freedom

$$\underset{\sim}{X} = [X_1, X_2 \cdots X_N]^T \; ; \qquad \underset{\sim}{x} = [x_1, x_2 \cdots x_j]^T . \tag{3}$$

The submatrices in the system mass and stiffness matrices are given by

$$\underline{M} = \begin{bmatrix} M_1 & & & \\ & M_2 & & \\ & & \ddots & \\ & & & (M_N + M_\ell - \sum_{m=1}^{J} m_m) \end{bmatrix}$$

$$\underline{m} = \begin{bmatrix} m_1 & & & \\ & m_2 & & \\ & & \ddots & \\ & & & m_J \end{bmatrix}$$

$$\underline{K} = \begin{bmatrix} K_1+K_2 & -K_2 & & \\ -K_2 & K_2+K_3 & & \\ & & \ddots & \\ & & & (K_N + \sum_{m=1}^{J} K_m) \end{bmatrix}$$

$$\underline{k}_a = \begin{bmatrix} 0 & - & - & - & - & - & -k_1 \\ 0 & - & - & - & - & - & -k_2 \\ \vdots & & & & & & \\ 0 & - & - & - & - & - & -k_j \end{bmatrix}_{J \times N}$$

$$\underline{k} = \begin{bmatrix} k_1 & & & & 0 \\ & k_2 & & & \\ & & \ddots & & \\ & & & \ddots & \\ 0 & & & & k_J \end{bmatrix} \tag{4}$$

The damping submatrices follow the form of stiffness matrices. The combined system represents N + J degrees of freedom. The associated frequency and the mode shapes of the combined system are obtained from the following equations

$$[\underline{K}^S - \underline{M}^S \omega_i^S]\phi_i^S = 0 \tag{5}$$

Alternatively, a perturbation approach may be utilized which permits the evaluation of the eigen properties of the combined system in terms of the dynamic properties of the structural (primary) and sloshing fluid (secondary) system [Kareem & Sun, 1987]. This formulation helps to avoid computation difficulties in the numerical solution of the eigenvalues that may arise as a result of the difference in the magnitudes of various elements in the mass and the stiffness matrices. The response of the combined system to aerodynamic loading may be evaluated employing a modal superposition technique. It is also important to note that in general, the combined systems are not modally damped even if it is assumed that each of the two subsystems are proportionally damped. For special cases, one may invoke the assumption of classical damping for the combined system without introducing a sizeable error. However, for nonclassically damped systems, the equations of motion may be expressed in terms of a state-vector which provides a convenient solution [e.g., Meirovitch, 1980 and Kareem, 1987]. The response statistics may also be obtained, without resorting to the normal mode approach, by utilizing direct frequency domain approach involving system transfer function [Kareem, 1987].

The preceding analysis can be simplified if the contribution of structural higher modes can be ignored. Although studies have shown that for the wind induced acceleration response the higher modes do have sizeable contribution [Kareem, 1981]. In this case the structural system is represented by a mode-generalized system with respect to the fundamental mode [Fig.3]. The transfer function of the combined system is given by

$$H_x(i\omega) = \frac{1}{\left(1 - (\frac{\omega}{\omega_b})^2 + i2\zeta_b(\frac{\omega}{\omega_b})\right) - (\frac{\omega}{\omega_b})^2 \sum_{n=1}^{J} \frac{m_n}{M_b} \dfrac{1 + i2\zeta_n(\frac{\omega}{\omega_n})}{\left(1 - (\frac{\omega}{\omega_n})^2 + i2\zeta_n(\frac{\omega}{\omega_n})\right)}} \tag{6}$$

in which the symbols have been defined in Fig. 3. As noted earlier, contrary to a typical TMD (tuned mass damper) the parameters, in particular, the damping available in the sloshing fluid is a function of wave surface topology and wave breaking which depends on the amplitude of motion of the TSD container. As stated earlier that the estimation of damping can be best made by experimental method. In light of this the transfer function of the sloshing fluid in a TSD container can be determined by exciting the TSD with a known base acceleration on a shake table or a similar facility and measuring the force between the container and the shake table. By means of a dummy container without any fluid, the inertia force introduced by the container mass can be substracted. Normalizing the force due to the sloshing fluid by the input force given by the fluid mass and the shake table acceleration, a convenient transfer function can be established. Equation 6 can be recast in this case to the following form

$$H_x(i\omega) = \frac{1}{\left(1 - \left(\frac{\omega}{\omega_b}\right)^2 + i2\zeta_b\left(\frac{\omega}{\omega_b}\right)\right) - \left(\frac{\omega}{\omega_b}\right)^2 \sum_{n=1}^{J} \frac{m_n}{M_b} H_a(i\omega)} \tag{7}$$

in which $H_a(i\omega)$ is the transfer function of the sloshing system.

The number of sloshing damper modes to be incorporated in the analysis is generally small and for maximum effectiveness the fundamental sloshing mode is tuned with the fundamental mode of the building. In this case the natural frequency of the fundamental sloshing mode is very close to the first natural frequency of the building. Furthermore, for small displacement of the building top, the TSD transfer function is likely to be very close to that of TMD. However, at larger top floor displacement, the sloshing system will have higher damping which alters the transfer function characteristics of the sloshing fluid. This is essentially a small reduction in the natural frequency and an associated decrease in the amplitude of the transfer function. This may in turn influence the optimal tuning of the combined system which in addition to other parameters depends on the damping contributed by the sloshing fluid.

EXAMPLE

A building 100 ft square in plan, and 600 ft tall was modeled as a five degree-of-freedom system. The salient characteristics of the building are presented in Table II. A sloshing damper was attached to the top level and the fundamental period of sloshing was tuned to the first natural period of the tall building. The container dimensions in plan were 20 ft x 20 ft and water height equal to 2.06 ft. The building response to the alongwind loading with and without the TSD was computed. The alongwind loading was modeled following a covariance synthesis scheme by invoking strip and quasi-steady theories [e.g., Kareem, 1985]. Details may be found in Kareem [1985]. The mode-generalized loads were evaluated based on the mode shapes computed for each configuration.

In Fig. 4, the transfer function of a typical building - TSD system is plotted. The estimated damping for liquid sloshing is taken to be equal to 4 percent. It is noted that the addition of the TSD significantly modifies the transfer function which thereby facilitates the reduction of building response. The modification in the transfer function resulting from different masses sloshing liquid is demonstrated in Fig. 5. It is obvious that an increase in the liquid mass ratio to the building mass in the first mode results in a concomitant decrease in the transfer function amplitude as well as the location of the peaks. An optimal value of the mass ratio can be derived to maximize the benefits derived and to minimize premium for the additional mass. The building acceleration response and the building - TSD acceleration response are given in Fig. 6. The results demonstrate the effectiveness of the damper.

PRACTICAL APPLICATIONS

The initial success of the concept as applied to wind sensitive structures has been demonstrated in preliminary studies carried out in the U.S. and Japan.

The analysis shown in this paper demonstrates the effectiveness of tuned sloshing dampers in reducing the structural response. These dampers unlike other passive dampers such as TMDs require minimum maintenance and an existing water storage facility in the building may be utilized to help mitigate motion of tall buildings. The convenience of installation offers great potential for incorporation in existing structures and for temporary use during construction phase, especially controlling the motion of elevator shafts. The prospects for their application in offshore platforms are also promising. The potential benefits arising from the application of the TSD concept to offshore platforms range from reducing the motions of tension leg platforms and the vibration of their tethers, to improving the fatigue life of jacket-type platforms and reducing the stresses in the production risers and flare booms of both existing and new structures.

Recently a portable version of tuned sloshing dampers has been installed in airport towers in Japan to reduce wind induced motion of these flexible structures. The serviceability of such structures to ensure comfort of airport traffic controllers is an important issue [Tamura et al., 1988]. Multiple layers of liquid in circular containers were utilized in this application and full-scale response measurements showed a reduction in the response level of these towers. Other potential applications exist for flexible bridge structures, chimneys and communication towers. More analytical and experimental studies are needed to be able to better model the frequency response function of TSDs for a wide range of structural response, especially in the case of buildings which experience combined lateral-torsional motion. In the case of torsional motion, dampers located near the outer walls of the top floor would provide an optimal spacing.

CONCLUSIONS

It is demonstrated that a sloshing damper can effectively reduce the motion of buildings when the fundamental sloshing and building frequencies are synchronized. Like a tuned mass damper, the tuned sloshing damper imparts indirectly additional damping to the system by modifying the frequency response function of the structure; thereby reducing response. The sloshing fluid system absorbs structural vibration energy and dissipates by means of viscous action of the fluid, wave breaking or damping devices. The potential applications of the tuned sloshing dampers include among others tall buildings, towers, bridges and offshore platforms. More analytical and experimental studies are needed to better model the frequency response function of TSDs to ensure the effective mitigation of the motions of both existing and new land-based and offshore structures and their critical subsystems.

ACKNOWLEDGEMENTS

Financial assistance provided in part by the PYI-84 award to the author under National Science Foundation Grant ECE-8352223, matching funds by the several industrial sponsors and by the Texas Advanced Technology Program under Grant 003652200-ATP are gratefully acknowledged.

TABLE I. DESIGN MODIFICATION OF HIGH-RISE BUILDINGS

- Modify Structural System
  a. Try different structural systems
  b. Adjust stiffness & mass distribution to modify mode shape
- Change Building Material
  a. Change from steel to concrete or a composite system
- Increase Damping
  a. Direct damping, e.g., coating damping material add partition walls
  b. Indirect damping
     i. Passive control, e.g., tuned mass dampers, tuned sloshing dampers, and viscoelastic dampers
     ii. Active control, e.g., tendon control, pulse control, active dampers, aerodynamic appendages and mass impact
- Aerodynamic Modification
  a. Aerodynamically efficient shape
  b. Architectural modification, e.g., chamfering corners, spoilers, vanes and openings

Table II. Building Properties

<u>Building Stiffness Matrix</u>

$$\begin{bmatrix} 1.754 & -0.877 & 0.0 & 0.0 & 0.0 \\ -0.877 & 1.754 & -0.877 & 0.0 & 0.0 \\ 0.0 & -0.877 & 1.754 & -0.877 & 0.0 \\ 0.0 & 0.0 & -0.877 & 1.754 & -0.877 \\ 0.0 & 0.0 & 0.0 & -0.877 & 0.877 \end{bmatrix} \times 10^7$$

<u>Diagonal Mass Matrix</u>

$$\begin{bmatrix} 0.45 & 0.45 & 0.45 & 0.45 & 0.45 \end{bmatrix} \times 10^6$$

REFERENCES

Abramson, H. N., "The Dynamic Behavior of Liquid in Moving Containers," NASA SP-106, 1966.

Bhuta, P. G., and Koval, L. R., "A Viscous Rind Damper for a Freely Processing Satellite," Int'l. J. Mech. Sci., Vol. 8, 1966.

Boussinesq, J., "Memoir on the Influence of Friction in the Regular Motion of Fluids," J. of Math., Vol. 2, 1868.

Chester, W., "Resonant Oscillations of Water Waves," Proc. Royal Society, Vol. 306A, 1968.

Cokelet, E. D., "Steep Gravity Waves in Water of Arbitrary Uniform Depth," Phil. Trans. Royal Society, Vol. 286A, 1977.

Cooper, R. M., "Dynamics of Liquids in Moving Containers," J. Am. Rocket Soc., Vol. 30, 1977.

Demirbilek, Z., "Energy Dissipation in Sloshing Waves in a Rolling Rectangular Tank - I. Mathematical Theory," Ocean Engrg., Vol. 10, No. 5, 1983.

Faltinson, "A Numerical Nonlinear Method of Sloshing in Tanks with Two-Dimensional Flow," J. of Ship Research, Vol. 22, 1978.

Fujino, Y., et al., "Fundamental Study of Tuned Liquid Damper (TLD) - A New Damper for Building Vibrations," Proceedings of the Symposium/Workshop on Serviceability of Buildings, 16-18 May 1988.

Harris, C. M. and Crede, C. E. (Editors), Shock and Vibration Handbook, McGraw-Hill Book Company, 1987.

Holyer, J. Y., "Large Amplitude Progressive Interfacial Waves," Journal of Fluid Mechanics, Vol. 93, 1979.

Hough, M. A., "On the Influence of Viscosity on Waves and Currents," Proc. London Math. Society, Vol. 28k, 1897.

Kareem, A., "Lateral-Torsional Motion of Tall Buildings to Wind Loads," Journal of Structural Engineering, ASCE, Vol. 111, No. 11, 1985.

Kareem, A., "Mitigation of Wind Induced Motion of Tall Buildings," Journal of Wind Engineering and Industrial Aerodynamics, Vol. 11, 1983.

Kareem, A., "Wind Effects on Structures: A Probabilistic Viewpoint," Probabilistic Engineering Mechanics, Vol. 2, No. 4, 1987.

Kareem, A., "Wind-Excited Response of Buildings in Higher Modes," J. of the Struct. Div., ASCE, Vol. 107, No. ST4, 1981.

Kareem, A. and Sun, W.-J., "Stochastic Response of Structures with Fluid-Containing Appendages," Journal of Sound and Vibration, Vol. 119, No. 3, 1987.

Keel, C. J. and Mahmoodi, P., "Design of Viscoelastic Structural Dampers for the Columbia Center Building," Building Motion in Wind, Edited by N. Isyumov and T. Tschanz, ASCE, NY, 1986.

Keulegan, G. R. L., 1959, "Energy Dissipation in Standing Waves in Rectangular Basins," J. Fluid Mech. 6. 33.

Kitamura, H. et al., "Design and Analysis of a Tower Structure with a Tuned Mass Damper," Proceedings, 9th World Conference on Earthquake Engineering, Tokyo, Japan, 1988.

Lamb, H., Hydrodynamics, Dover Publication Inc., Dover, New York, 1945.

Lepelletier, T. G. and Raichlen, F., "Nonlinear Oscillations in Rectangular Tanks," Journal of Engineering Mechanics, ASCE, Vol. 114, No. 1, 1988.

McNamara, R. J., "Tuned Mass Dampers for Buildings," J. of the Structural Div., ASCE, Vol. 103, No. ST9, 1977.

Meirovitch, L., Computational Methods in Structural Dynamics, Sijthoff and Noordhoff, 1980.

Modi, V. J. and Welt, F., "Damping of Wind Induced Oscillations Through Liquid Sloshing," Preprint Vol. 5, Seventh International Conference on Wind Engineering, Aachen, W. Germany, July 6-10, 1987.

Prosperetti, A., 1976, "Viscous Effects on Small Amplitude Surface Waves," Physics Fluids 19. 195.

Sun, Wei-Joe and Kareem, A., "Stochastic Response of Structures with Appendages Containing Fluids," Dynamic Response of Structures, Edited by G.C. Hart and R.B. Nelson, ASCE, NY, 1980.

Tamura, Y., et al., "Wind-Induced Vibration of Tall Towers and Practical Applications of Tuned Sloshing Damper," Proceedings of the Symposium/Workshop on Serviceability of Buildings, 16-18 May 1988.

Verhagen, J. H. G., and Wijngaarden, V. L., "Nonlinear Oscillations of Fluid in a Container," Journal of Fluid Mechanics, Vol. 22, 1965.

Wiesner, K. B., "Taming Lively Buildings," Civil Engineering, ASCE, June 1986.

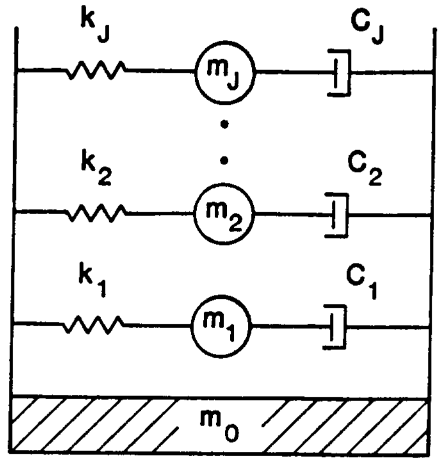

Fig. 1. Mechanical Model of Sloshing Fluid

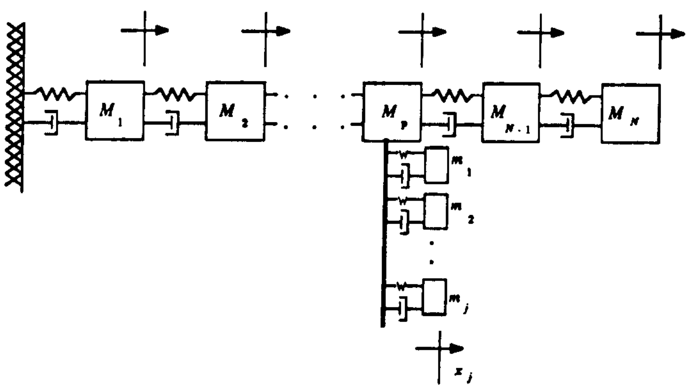

Fig. 2. Model of Fluid and Structural Systems

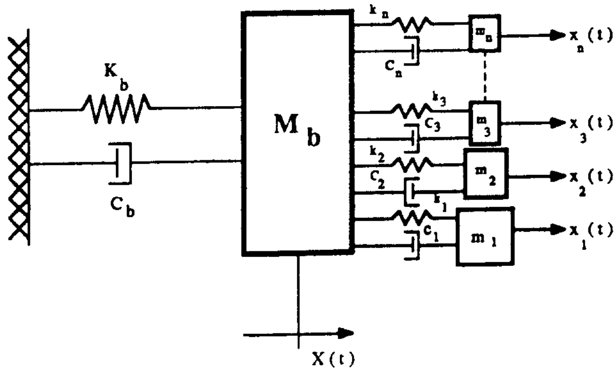

Fig. 3. Equivalent Model of the Building and the Fluid System

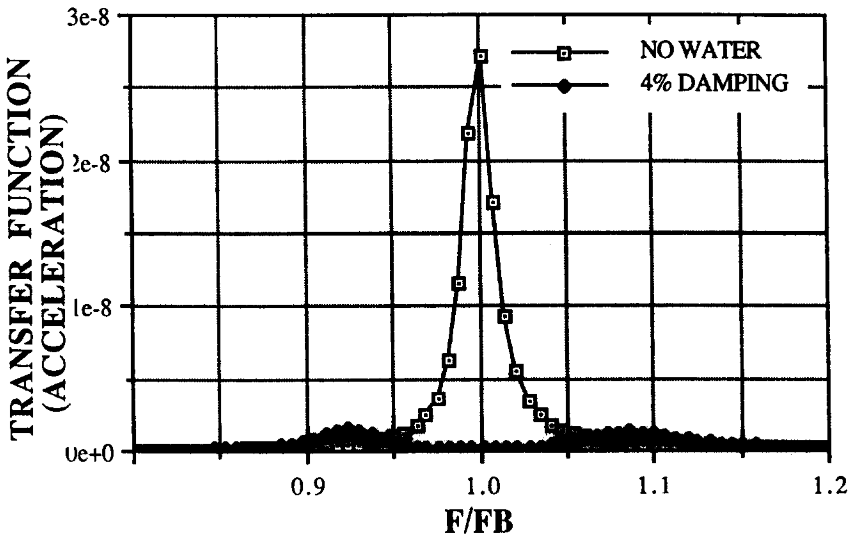

Fig. 4. Transfer Function of Building - TSD System

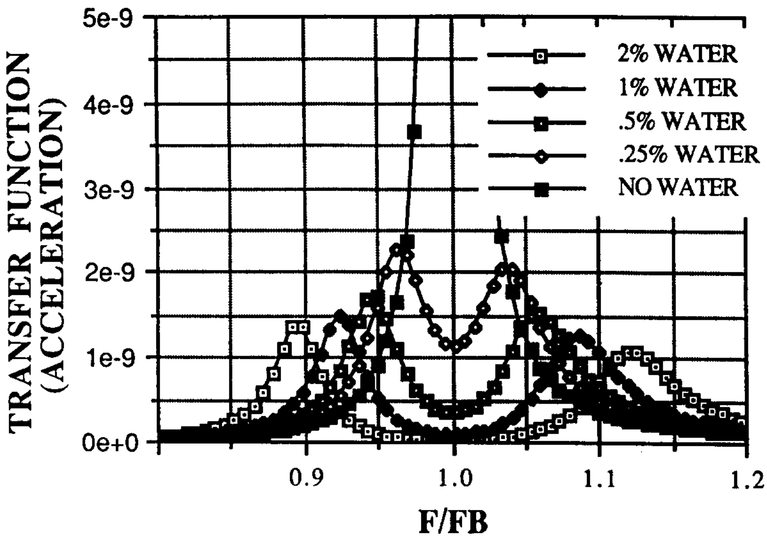

Fig. 5. Building - TSD Transfer Functions for Different Liquid Masses

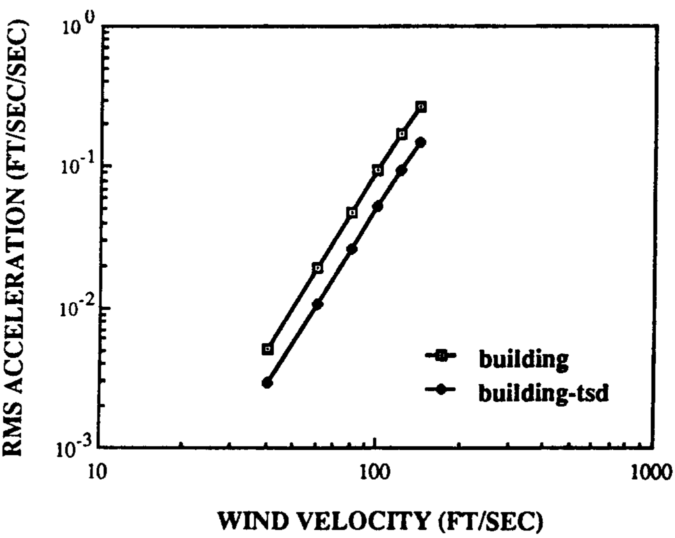

Fig. 6. Acceleration at the Building Top