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SCALING OF A NOVEL SLOSHING ABSORBER TO CONTROL STRUCTURAL VIBRATIONS

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ABSTRACT

Scaling of a novel sloshing absorber is presented for the control of structural vibrations. The sloshing absorber is coupled to a single degree of freedom structure. Numerical predictions, confirmed with experimental results for a model absorber-structure show the effectiveness of a standing wave sloshing absorber. Scaling has been used to determine the governing parameters of practical size prototype absorbers and structures. A prototype system has been simulated numerically showing identical response, non-dimensionally, with predictions for the model.

INTRODUCTION

Liquid sloshing refers to low frequency oscillations of a liquid in a container. Some common engineering applications where liquid sloshing needs to be suppressed include transportation of liquid cargo, fuel tanks of aircraft and aerospace vehicles and earthquake induced sloshing in storage tanks. In these applications, the dynamic behaviour of liquid sloshing affects the stability of the container or the manoeuvrability of the transportation vehicle. Muto et al. (1988), Sharma et al. (1992) and Anderson et al. (1997) used different techniques to suppress sloshing and reported effective control for particular geometries.

In contrast to the suppression of sloshing, the objective here is to intentionally induce sloshing in a container for the purpose of controlling structural vibrations. The control action is implemented through the pressure forces generated by the liquid as it sloshes. The advantage of such a technique is its simplicity, particularly when the suggested control can be accomplished with already existing storage containers in structures. The sloshing absorber attached to the structure to be controlled, is shown in Figure 1. The structure consists of a single degree of freedom spring, mass and damper.

For storage containers in structures, the depth of the liquid is generally comparable to the length of the container. For such cases, the fundamental sloshing mode is expected to be of standing wave type as opposed to the travelling waves obtained for shallow depths. A standing type sloshing wave has virtually no energy dissipation capability (Anderson et al. 1998a). Therefore, without additional measures, the suppression effect of sloshing may be limited. Anderson et al. (1998a) has shown that structural baffle plates cantilevered from both sides of the vertical walls of a container improve the control effect of the sloshing absorber. These plates are also shown in Figure 1.

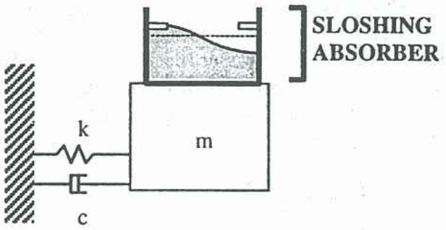

Figure 1. The proposed sloshing absorber attached to the structure to be controlled

In cases where full-scale experiments are expensive or dangerous, it can be an advantage to use scaled experiments and numerical predictions to determine promising solutions. Like many other phenomena involving liquid free surfaces, liquid sloshing can be scaled using Froude, Reynolds, Euler, and Strouhal numbers. Bass et al. (1985) used Froude and Euler scaling to conduct experiments for liquid sloshing of 1/30th to 1/50th size of prototype tanks containing liquefied natural gas. Muto et al. (1988) also used Froude scaling to represent liquid sloshing in a prototype tank with a 1/30th scale model using water as the working fluid.

Standing wave sloshing absorbers have been suggested before [Anderson et al. (1998b)], with demonstrated effectiveness comparable to a classic tuned mass damper. This earlier study used a small size container for ease of experimental observation and numerical simulations. Here, Froude, Reynolds, Euler and Strouhal numbers of liquid sloshing are used to scale a small sloshing absorber and structure to much larger practical prototype sizes. The difference between the present work and usual application of these parameters is that the system container has significant fluid structure interaction here. The container of the absorber has baffle plates to interrupt and enhance its control effect.

EXPERIMENTAL PROCEDURE

In this investigation, the model sloshing absorber consisted of a rectangular container of 210mm × 130mm filled with water to a depth of 100mm. The liquid mass was approximately 2.8kg and the structure consisted of a mass of 27.9kg supported on four mild steel columns of 3.5mm × 22mm × 390mm. The mass ratio of the water in the container to the mass of the structure was approximately 10%. The structure exhibited light damping (0.004 critical) with a natural frequency of $f_s = 2.3 \pm 0.2$Hz. The fundamental sloshing frequency of the liquid in the container, when it was tested without the structure, was observed to be $f_w = 2.3 \pm 0.2$ Hz.

For each test case, the structure was displaced by 1.3±0.05mm before being released to oscillate freely. The displacement of the structure was tracked with a laser displacement transducer and then recorded. A schematic diagram of the experimental set-up is shown in Figure 2.

After determining the behavior of the free vibrations of the structure alone, a rectangular container was secured to the structure. A series of tests was performed where the liquid motion was controlled by cantilevered baffles attached to the vertical sides of the container. The baffles were constructed from 3mm thick plywood, and their surfaces were sealed to reduce water absorption. The performance of the damper has been evaluated for a baffle size of 10mm located at different heights of 5mm above the liquid surface, on the liquid surface and 5mm below the liquid surface.

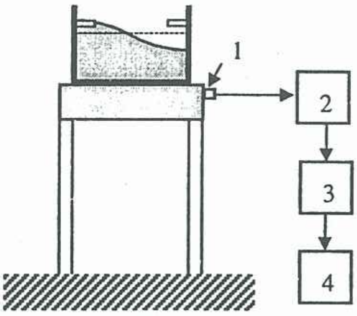

Figure 2. Experimental setup.

1: Keyence, LB-12 laser displacement transducer;
2 :Keyence LB-72 amplifier and DC power supply;
3: DataAcq A/D conversion board;
4: Total Peripherals Group, Pentium 200MHz, Personal Computer

NUMERICAL PROCEDURE

The solution of the flow field was obtained using CFX-F3D Version 4.1. A two dimensional model of the rectangular container was created. For liquid sloshing, a viscous, multiphase simulation was adopted with a surface sharpening algorithm. Grid independence was achieved after evaluating a series of mesh refinements. A non-uniform grid of 64 × 70 cells was chosen with a finer grid in the region near the baffles. A time-step of 0.001s was determined to be sufficiently small for the model system. The equation of motion for the structure was solved at each time step in a FORTRAN routine developed within the CFX environment. The force of liquid sloshing on the structure was determined by calculating the resultant pressure force on the walls of the container (Anderson et al. 1998a).

Numerical trials were conducted for a series of different baffle sizes and positions. Of the promising cases, 10mm baffles submerged at 5mm below the liquid surface exhibited the best performance of the absorber for structural control. The performance of these baffles was verified experimentally. The numerical model was then scaled up to represent an absorber and structure system of a larger practical size. The scaling parameters are discussed next.

SCALING PARAMETERS

In this section, the scaling parameters developed for a sloshing absorber coupled with a single degree of freedom structure are given. These parameters are adapted from those of free surface flows. An outline of the tank used for the sloshing absorber is shown in Figure 3, where h_b is the height of the baffles, L_1 is the length of the container in the direction of sloshing L_2 is the length of the container sufficient to ensure two dimensional sloshing, and L_b is the length of the baffles to suppress sloshing.

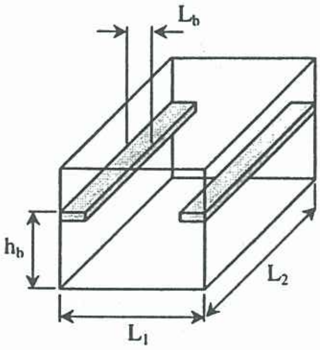

Figure 3. The sloshing absorber with baffle plates.

The small model tank and the larger prototype tank must be scaled geometrically ensuring that all dimensions have the same linear-scale ratio, defined as $\alpha = L_m/L_p$ where L_m and L_p are the model and prototype lengths, respectively.

Froude Number

Froude number is the ratio of inertial to gravity forces for flows with free surfaces. Two frictionless waves are kinematically similar if the Froude numbers are identical (White 1994). For a model wave (m) scaled to a prototype wave (p) the Froude number is defined as;

$$Fr_m = \frac{V_m}{gX_m} = \frac{V_p}{gX_p} = Fr_p$$

where V is the wave propagation velocity and g is acceleration due to gravity. When applying Froude number to the sloshing absorber, V is used as the velocity of the tank, and X as the displacement of the coupled absorber-structure system.

Therefore, scaling of velocity and displacement becomes,

$$V_m = V_p\sqrt{\alpha}$$
$$X_m = X_p\alpha$$

Since velocity is the relationship of distance and time, Froude number can be used to scale time:

$$T_m = T_p\sqrt{\alpha}$$

Here, T is also the period of sloshing in the absorber as well as the period of structural oscillations. This relationship can be shown using Strouhal number, too.

Reynolds Number

Reynolds number is the ratio of inertial to viscous forces. Scaling of viscous effects is done by keeping Reynolds number constant for model and prototype absorbers. Bass et al. (1985) reported that for liquid sloshing, viscous effects were insignificant if Reynolds number was larger than 10^3, and for such cases, viscous scaling need not be considered. This conclusion is in close agreement with observations given by Popov et al. (1992) where viscosity had no effect for Re in the range 10^5–10^7, and the effect was small for Re in the range $10^3 - 10^5$.

When liquid sloshing is used in a sloshing absorber, the control force on the structure is the resultant pressure force on the walls of the tank. If compressibility effects are negligible for a rigid wall container, then the free surface shape, wave velocity and density of the liquid govern the impact pressure (Bass et al. 1985). Here, the density of the liquid in the model absorber is kept identical to the density of the liquid in the prototype absorber. Reynolds number is kept constant by selecting an appropriate liquid viscosity. For liquid sloshing Reynolds number is defined as,

$$\mathrm{Re}_m = \frac{\rho_m L_m \sqrt{g L_{1m}}}{\mu_m} = \frac{\rho_p L_p \sqrt{g L_{1p}}}{\mu_p} = \mathrm{Re}_p$$

where μ is the absolute viscosity and L_1 is the length of the container in the direction of liquid sloshing.

Euler Number

Euler number is the ratio of pressure to inertia forces, and it is used here to scale sloshing impact pressures on the walls of the absorber. Euler number is defined as,

$$Eu_m = \frac{P_m}{\rho_m V_m^2} = \frac{P_p}{\rho_p V_p^2} = Eu_p$$

where P, V and ρ are the fluid pressure (at the tank walls), velocity and density, respectively.
Furthermore,

$$\frac{P_m}{Pp} = \alpha \frac{\rho_m}{\rho_p}$$

and therefore,

$$\frac{F_m}{Fp} = \alpha^3 \qquad \text{for } \rho_m = \rho_p.$$

where F is the pressure force.

Strouhal Number

The final scaling parameter is Strouhal number which concerns the frequency and velocity of oscillating flows. Here, Strouhal number is used to scale the period of oscillation of the sloshing wave in the absorber. The scaling of the period is also shown earlier with Froude number (and hence, these two parameters are not independent of each other for this particular problem). The same relationship can be obtained using Strouhal number defined by,

$$St_m = \frac{\omega_m L_{1m}}{V_m} = \frac{\omega_p L_{1p}}{V_p} = St_p$$

where, ω is frequency of sloshing. Therefore,

$$T_m = T_p \sqrt{\alpha}$$

The structural natural frequency of the model and prototype scale similarly.

$$\omega_m = \frac{\omega_p}{\sqrt{\alpha}}$$

DISCUSSION OF RESULTS

The model sloshing absorber of 0.13m length, 0.21m width containing 2.8kg of water was scaled up, using α=0.026, to a prototype absorber of L_1=5m and L_2=8.1m, containing 158,427kg of water. The model and prototype structures were scaled based on the scaling parameters defined in the previous section. The resulting system parameters, are presented in Table 1. The ratio of liquid mass in the absorber to the mass of the structure was 10% for both model and prototype systems.

Having determined the dimensions of the absorber, and characteristics of the structure, the viscosity of the fluid in the prototype absorber was calculated. Reynolds number for the model tank was Re_m=150000. Therefore, viscous effects were expected to be insignificant (Popov et al. 1992). Although this point was verified numerically, the Reynolds number was kept identical for both systems. The density of liquid was kept constant in the model and prototype simulations at 1020 Kg/m^3 for water.

Table 1. System parameters of model (m) and prototype (p) absorber-structure systems.

	Numerical Model	Numerical Prototype
L_1 (m)	0.13	5.0
L_2 (m)	0.21	8.1
H_b (m)	0.095	3.7
L_b (m)	0.005	0.19
Liquid Depth	0.10	3.8
Initial Displacement (m)	0.0013	0.05
Reynolds Number	150000	150000
Liquid Viscosity (Ns/m^2)	0.001	0.24
Liquid Density (kg/ m^3)	1020	1020
Fundamental Sloshing Frequency (Hz)	2.2	0.35
Liquid Mass (kg)	2.8	158427
Structural Mass (kg)	28	1584270
Spring Stiffness (N/m)	6374	9376283
Structural natural frequency (Hz)	2.3	0.37
Time Step (sec)	0.001	0.006

Since the natural frequency of sloshing was 0.35 Hz, instead of the small model's 2.3 Hz, the time-step in the simulation was increased for the large prototype using Froude number scaling. The computational results obtained for the model system were verified experimentally. In Figure 4, the numerically predicted and the experimentally observed displacements are shown for the small model system. The non-dimensional time scale is the ratio of time (T) and the natural period of the structure (T_s) without the absorber. The agreement between the two displacement histories was found acceptably close. Differences arise due to energy dissipation mechanisms not fully represented in the numerical model.

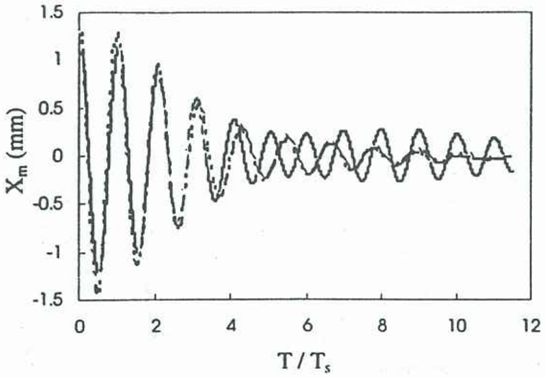

Figure 4. Comparison of the computational and experimental results for the model system.——, predicted displacement;--- experimental displacement.

The force and displacement histories of (a) the model simulation and (b) the prototype simulation are shown in Figure 5. The displacement and force histories for the prototype structure have been plotted on modified scales.

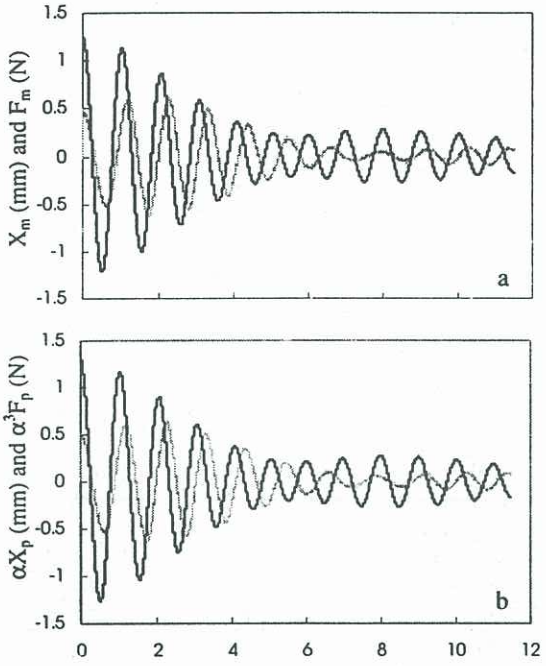

Figure 5. Computationally obtained displacement and force histories for (a) the model system and (b) the prototype system.——, predicted displacement; ......, predicted force.

The prototype displacement is multiplied by α, and the corresponding force is multiplied by α^3. As a result, Figure 5 shows no detectable differences between the model simulation and the prototype simulation plotted for non-dimensional time. Hence, the suggested scaling procedure successfully applies to this highly non-linear system with strong fluid structure interaction.

CONCLUSION

The scaling of liquid sloshing is an advantage when scaled down experiments can be conducted for applications where full-scale testing is expensive, impractical or even dangerous. In this investigation, scaling parameters for liquid sloshing have been applied to a sloshing absorber coupled to a structure. Froude, Reynolds, Euler and Strouhal numbers are used for this purpose. After confirming the computational results for the small model sloshing absorber experimentally, an identical match was obtained between simulations of the model and prototype systems.

REFERENCES

ANDERSON, J. G., TURAN, Ö. F. and SEMERCIGIL, S. E., "Control of Sloshing in Rigid wall Containers; Part I - An Experimental Evaluation with Cylindrical Geometries", *ASME Fluids Engineering Division Summer Meeting*, Paper No FEDSM97-3133, 1997.

ANDERSON, J. G., SEMERCIGIL, S. E. and TURAN, Ö. F., "A Modified Sloshing Absorber to Control Structural Oscillations" *to be presented during ASME Fluids Engineering Division Summer Meeting*, Paper No. FEDSM98-5096, 1998a.

ANDERSON, J. G., SEMERCIGIL, S. E., and TURAN, Ö. F., "Comparison of Sloshing Absorber and Tuned Absorber for Optimal Vibration Control", *Proceedings of The Australasian Conference on Structural Optimisation*, pp. 199-206, 1998b.

BASS, R.L, BOWLES, E.B., TRUDELL, R.W., NAVICKAS, J., PECK, J.C., YOSHIMURA, N., ENDO, S., and POTS, B.F.M., "Modelling Criteria for Scaled LNG Sloshing Experiments", Transactions of the ASME. *Journal of Fluids Engineering*, vol. 107, pp. 272-280, 1985.

MUTO, K., KASAI, Y. and NAKAHARA, M., "Experimental Tests for Suppression Effects of Water Restraint Plates on Sloshing of a Water Pool", Transactions of the ASME, *Journal of Pressure and Vessel Technology*, vol. 110, pp. 240-246. 1988.

POPOV, G., SANKAR, S., SANKAR, T.S. and VATISTAS, G.H., "Liquid Sloshing in Rectangular Road Containers", Computers in Fluids, Vol. 21, No. 4, pp. 551-569, 1992.

SHARMA, R., SEMERCIGIL, S. E., and TURAN, Ö.F., "Floating and Immersed Plates to Control Sloshing in a Cylindrical Container at the Fundamental Mode", *Journal of Sound and Vibration*, vol. 155, pp. 365-370, 1992.

WHITE, F. M., "Fluid Mechanics", *3rd Edition McGraw-Hill*, pp. 268-279, 1994.