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A FINITE ELEMENT BASED PREDICTION MODEL TO CONTROL LIQUID SLOSHING WITH CONTAINER FLEXIBILITY

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ABSTRACT

Sloshing is the low frequency oscillation of the free surface of a liquid in a partially filled container. If not controlled effectively, sloshing may cause excessive dynamic loads which may lead to structural failure (in case of storage containers) or loss of dynamic stability (in case of transport vehicles). Hence, study and control of liquid sloshing is a well justified topic in engineering and science.

Container flexibility causes moving boundaries which further complicate the treatment of this already challenging problem. On the other hand, container flexibility may be treated as a design parameter to gain benefit in controlling the free surface oscillations.

This paper details numerical predictions using standard finite elements software (ANSYS) for the simulation of liquid sloshing in a flexible container. The objective of the present work is to provide design alternatives while maintaining effective control.

INTRODUCTION

The study of sloshing is critical both industrially and environmentally, thus attracting research and academic literature which explores sloshing and attempts to control its impact. Study of sloshing generally proves challenging due to the presence of strong flow interaction with its container. These interactions become even more challenging if the container is flexible. The primary cause of these greater complexities is the moving boundaries of the fluid as the flexible container deforms under the effect of dynamic sloshing loads. As a result, the dynamic responses of a flexible container may be significantly different than that with rigid walls.

A study (Pal et al., 2003) was conducted on non-linear free surface oscillation of a liquid inside an elastic container using the finite element technique. The finite element method based on two-dimensional fluid and structural elements is used for the numerical simulations. (Bauer et al., 2004) employ an elastic membrane in a rigid container, resulting in considerable reduction of liquid sloshing. Mitra and Sinhamahapatra (2005) present a new pressure-based Galerkin finite element that takes into account the impact of walls, but the cases are restricted to linear problems with small amplitude waves. Gradinscak et al. (2004 and 2006) report the design potential of flexible containers for significant reduction of sloshing. Although tuning a flexible container can be quite successful for sloshing control, certain practical problems were observed in the earlier work.

Tuning was achieved by designating highly flexible walls which led to relatively large deflections. The container was essentially an open box, free to deflect as the liquid in the container sloshed. Next modification introduced rigid straps at the open top of the container, to limit large deflections. However, since tuning required lowering the structural critical frequencies close to the fundamental sloshing frequency, masses were added to the container. Hence, solving the original large deflection problem was simply shifted to large added masses with the straps, although impressive suppression of the liquid sloshing was possible. This case is included in the present study, as a comparison base of effectiveness.

The primary objective of the current work is to suggest design alternatives to address the practical design issues, namely to reduce (or to eliminate) the requirement to add mass, to achieve tuning. As the basic finite element model was verified with simple experiments earlier (Gradinscak, 2009), only numerical predictions are presented to support the suggested design changes.

The numerical model is briefly introduced next, for completeness. Full details are reported in Gradinscak (2009). Then a brief account of the numerical observations are presented, before concluding the current state of research. Hence, this paper is a progress report on our continuing efforts to implement the “designed” container flexibility as a practical means to suppress liquid sloshing.

NUMERICAL MODEL

The flexible container used for the numerical model is an aluminium, open-topped, rectangular prism of 1.6 m length, 0.4 m in width and 0.4 m in height. The wall thickness is 1 mm. To overcome the excessive wall deflection, three equally spaced springs were added at the top of the container, as shown in Figure 1. The container was filled with water to a depth of 0.3 m. The total weight of the container alone is 6 kg. The Young’s modulus, Poisson ratio and mass density of aluminium are taken to be of 70 GPa, 0.3 and 2700 kg/m^3, respectively.

Structural damping corresponds to 1% critical damping in the fundamental mode of the empty container.

The dynamic response of both the liquid and the flexible container are influenced by strong interactions between them. The strong interaction between liquid and container occur only when the fundamental frequency of the container is close to the fundamental frequency of the liquid. The natural frequency of the container in Figure 1 is significantly higher (in the order of 6Hz to 7 Hz with different masses) than the theoretical fundamental sloshing frequency of 1.34 Hz, (Milne-Thomson, 1968). Point masses are used to lower the container's natural frequency close to sloshing frequency, to achieve tuning.

For each simulation, a 20 s period is allowed for the flexible container walls to deflect to a static equilibrium (in response to the weight of the water). No sloshing takes place during this period. The flexible walls oscillate in perfect unison, causing the free surface of the liquid to bob up-and-down. After 20 s, sloshing is induced by imposing a transient 5 mm-sinusoidal displacement of one cycle to the base of the container. After one cycle, base is kept stationary. Frequency of excitation is 1.34 Hz, same as the fundamental sloshing frequency of a rigid container. A transient solution is obtained with a time step of 0.01 s and a 50 mm square grid for the container, and 50 mm cube for the fluid element using ANSYS (2009). Fluid-structure interaction is achieved by coupling the liquid and container displacements normal to the walls, (Gradinscak, 2009).

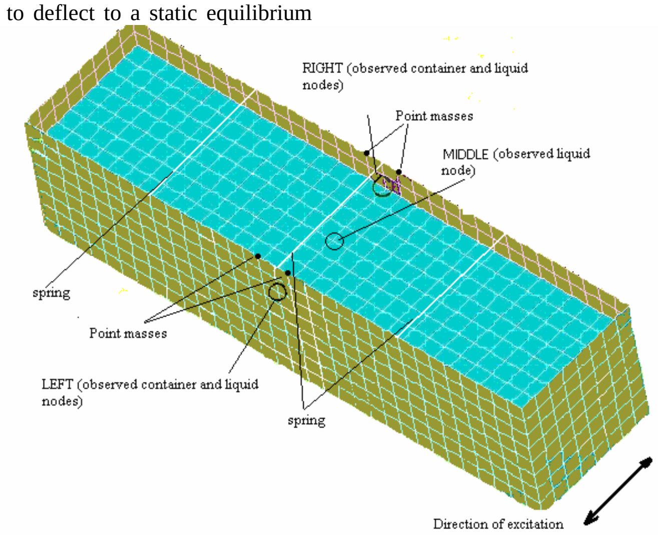

Figure 1: The numerical model, showing the direction of excitation, springs, point masses and observation nodes (circled).

NUMERICAL OBSERVATIONS

In Figure 2(a) the predicted vertical displacement histories of the free surface of the liquid are given at the nodes indicated as RIGHT and LEFT in Figure 1, for the rigid-walled container. These two histories are almost perfectly out of phase. When the liquid climbs approximately 20 mm on one wall, it simultaneously drops 20 mm at the other one. Hence, a 40 mm peak-to-peak stroke is experienced at the container walls, for each cycle of sloshing. As there is no viscous dissipation, liquid sloshing continues indefinitely without decay. The first 20 s waiting period, has no response due to having rigid walls. It is included here for completeness, and to indicate the difference for cases with flexible container walls.

In Figure 2(b) where the corresponding frequency spectrum of the sloshing history is given, the fundamental sloshing frequency is suggested to be around 1.35 Hz, quite close to the theoretical value of 1.34 Hz. Another small spectral peak is around 2.3 Hz, possibly corresponding to the second mode. The rigid container case serves as the comparison base here, for the performance of the container with flexible walls.

Currently, the most effective flexible container to suppress sloshing is shown in Figure 3. This case has 9 kg masses to achieve tuning. Rigid straps are used, in place of the three springs in Figure 1, to limit excessive wall deflections. Figure 3(a) has the history of the free surface displacements at the same nodes as those in Figure 2(a), (blue on the left, cyan on the right side). Figure 3(b) has the corresponding frequency spectra. Figures 3(c) and 3(d) have the history and the frequency spectrum of the displacement of the left container wall.

The surface motion is perfectly in phase, during the first 20 s. The liquid level drops approximately 12 mm, due to container deflection. Sloshing occurs in response to the transient base disturbance after 20 s. The peak-to-peak displacement occasionally reaches 20 mm, as opposed to the persistent 40 mm of the rigid container case in Figure 2(a). The root-mean-square (rms) average of the left, middle and right surface nodes are 4.5 mm, 4 mm and 4.9 mm, respectively (whereas the rigid container has approximately 14 mm on the two sides, and less than 0.5 mm in the middle – representing the fundamental mode shape of the free surface). These rms values represent a suppression in the order of 65% as compared to the rigid container.

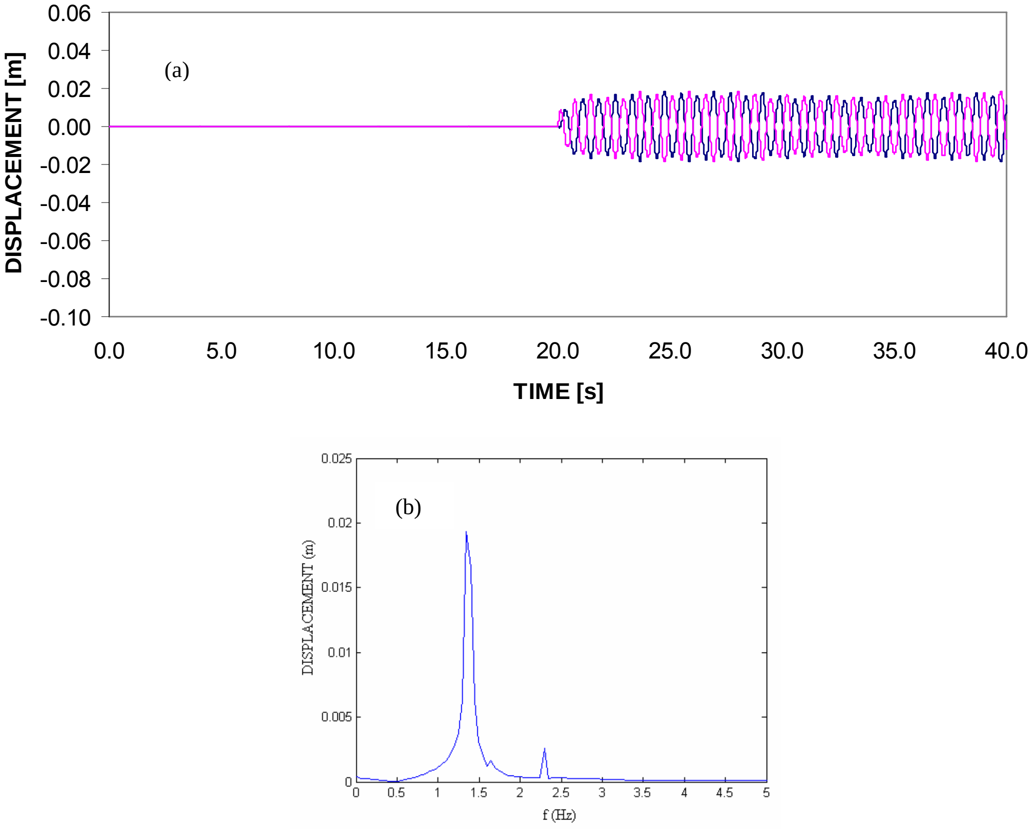

Figure 2: Predicted (a) displacement histories of the left (—) and right sides (—) the liquid free surface and (b) corresponding frequency spectrum in a rigid container.

It is interesting to note that the container motion practically seizes around 5 s in Figure 3(c), with an outward deflection of approximately 13 mm to accommodate the weight of the liquid. However, the free surface continues its in-phase motion in Figure 3(a), without any noticeable decay until the end of 20 s. Imposition of the external disturbance at 20 s, makes little difference in the displacement magnitudes in absolute sense, except that the two sides now start to move out-of-phase from each other.

After 20 s, flexible walls start to oscillate again (only left wall is shown here, but right wall behaves in a similar manner), but at frequencies significantly lower than the initial 4 Hz during the first 5 s. This drop in frequency is due to the added mass effect of the sloshing liquid.

In Figure 3(b), free surface nodes include peaks at 0.6 Hz, 0.8 Hz, 1.35 Hz, 1.4 Hz, 1. 6 Hz, 2 Hz, 2.6 Hz and 3Hz. The container has spectral peaks only at 0.6 Hz, 0.8 Hz and 1.35 Hz, as shown in Figure 3(d). It should be mentioned here that all spectral distributions are obtained for the period after the base excitation, after 20 s.

At 0.6 Hz, the spectral peak magnitude of the container is significantly larger than those of the liquid, possibly indicating that the container drives the liquid. At 0.8 Hz, the opposite is observed, the liquid being very energetic and container responding with a rather small, forced magnitude. 1.35 Hz is the fundamental frequency corresponding to the rigid container. This frequency is persistently "remembered" in all cases.

In Figure 3(b), the rich distribution of spectral peaks higher than 1.4 Hz are due to moving boundaries of the flexible container. They contribute quite significantly to the overall response of the free surface, and their presence is detrimental to the suppression efforts. Hence, elimination of these higher modes is clearly recognised to be another design objective to further enhance the benefits of container flexibility.

As mentioned earlier, the case presented in Figure 3, is the most effective container design to date (Gradinscak 2009). The mass of the container in Figure 1 is about 6 kg, whereas 18 kg of point masses (two 9 kg on each side) are required to obtain the suppression. The present objective is to address a point of practical interest, namely the amount of point mass required to tune the dynamics of the flexible container to that of the sloshing liquid.

The present tuning efforts, require lowering the structural critical frequencies. Lowering structural frequencies could be achieved by either increasing the mass and/or decreasing the effective stiffness. Decreasing structural stiffness is attempted by replacing the rigid straps of the case in Figure 3, with springs of finite stiffness. The most promising configuration to date, has been obtained with 3kg added mass, instead of 9kg. This decrease by a factor of three, is assumed to be significant enough to search for useful values of strap stiffness.

The case presented next corresponds to a stiffness distribution of k_1 – 100 k_1 – 10 k_1, corresponding to the spring on the left, middle and right in Figure 1. k_1 is the unit stiffness used as the design parameter. Figure 4 has the identical format to that in Figure 3, but for k_1 of 10^4 N/m.

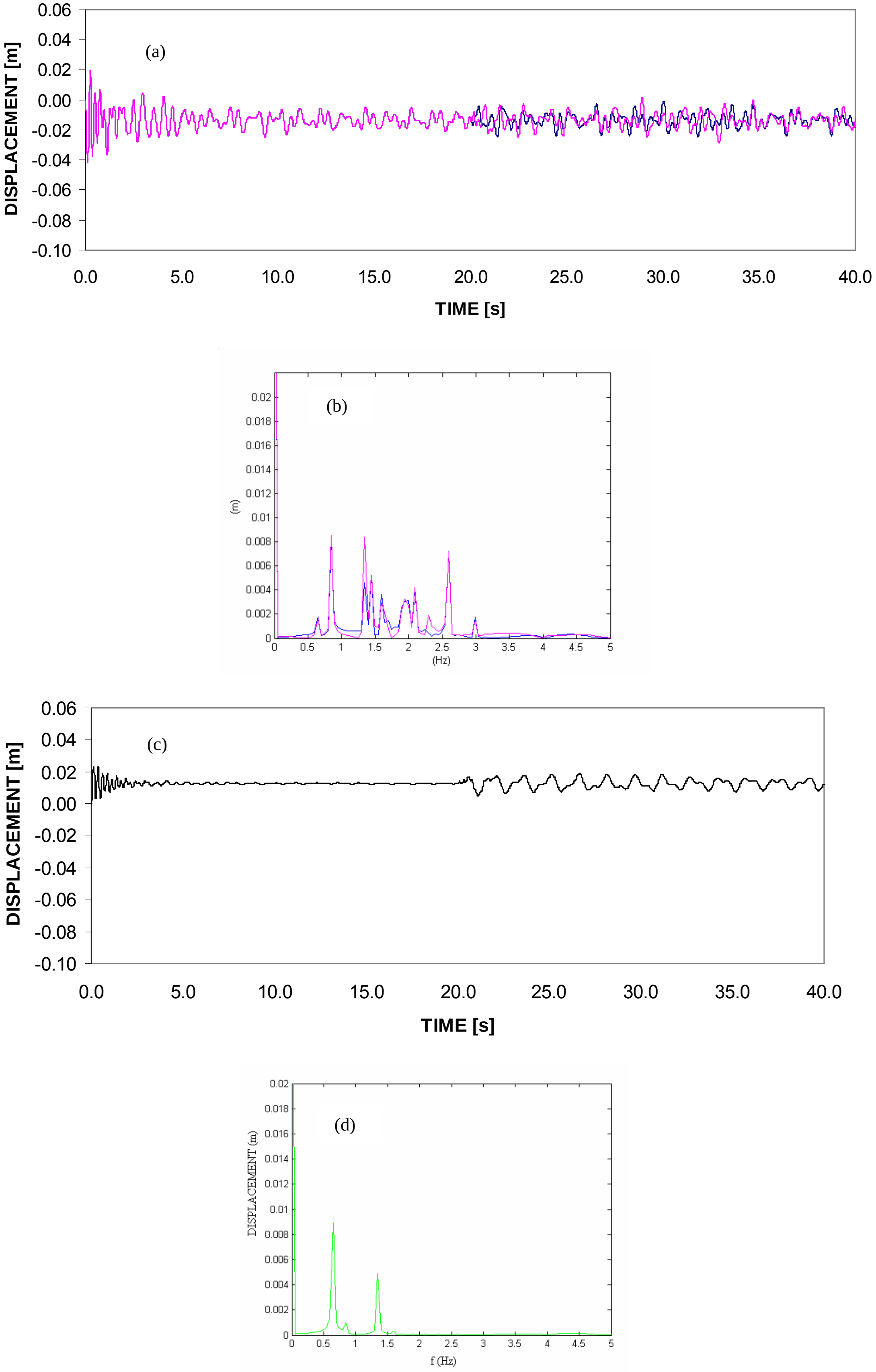

Figure 3: Free surface vertical displacement (a) histories and (b) frequency spectra of the two sides, and container horizontal displacement (c) history and (d) its frequency spectrum.

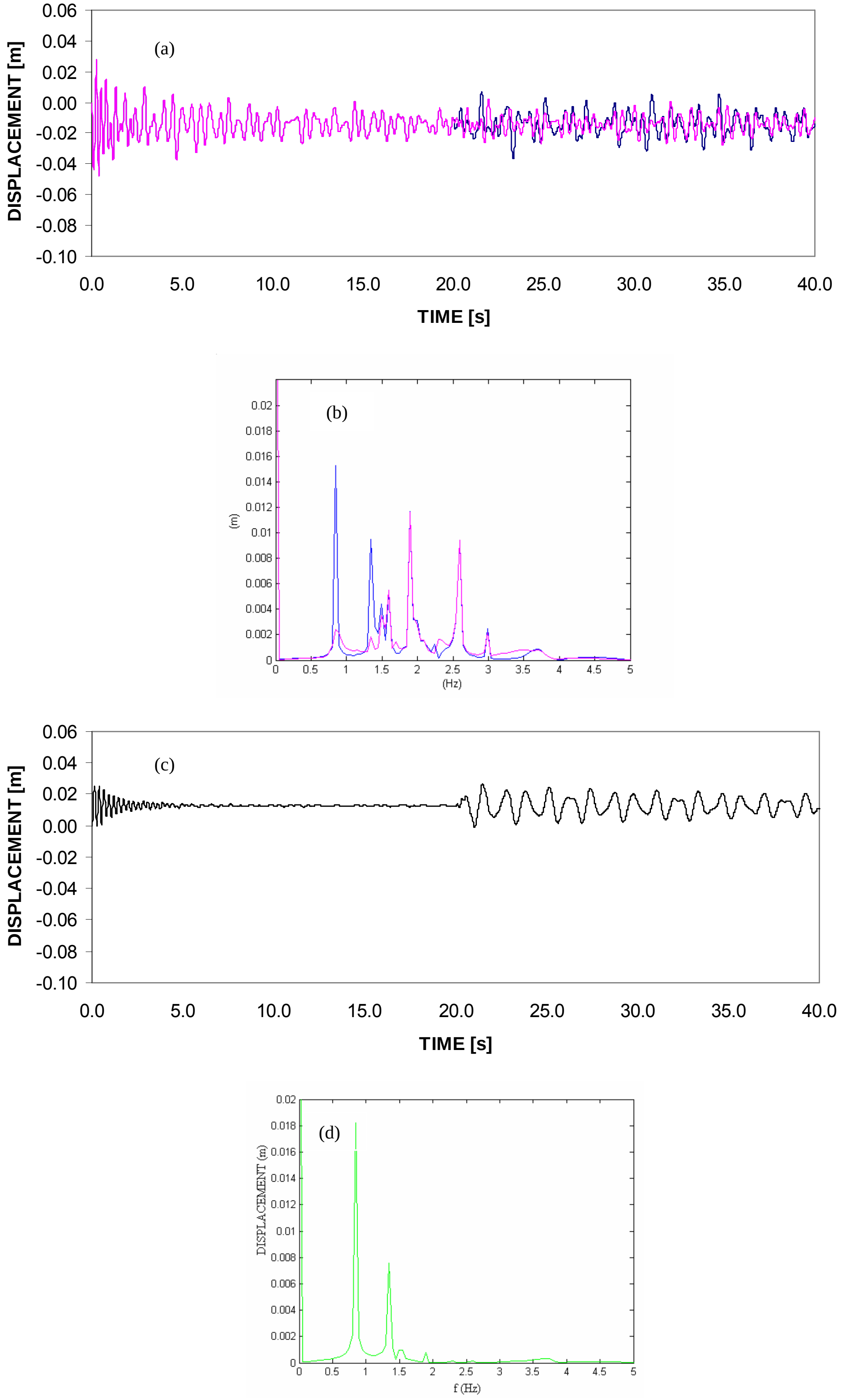

Figure 4: Same as in Figure 3, but with 3 kg added mass and with three springs, $k_1 = 10^4$ N/m.

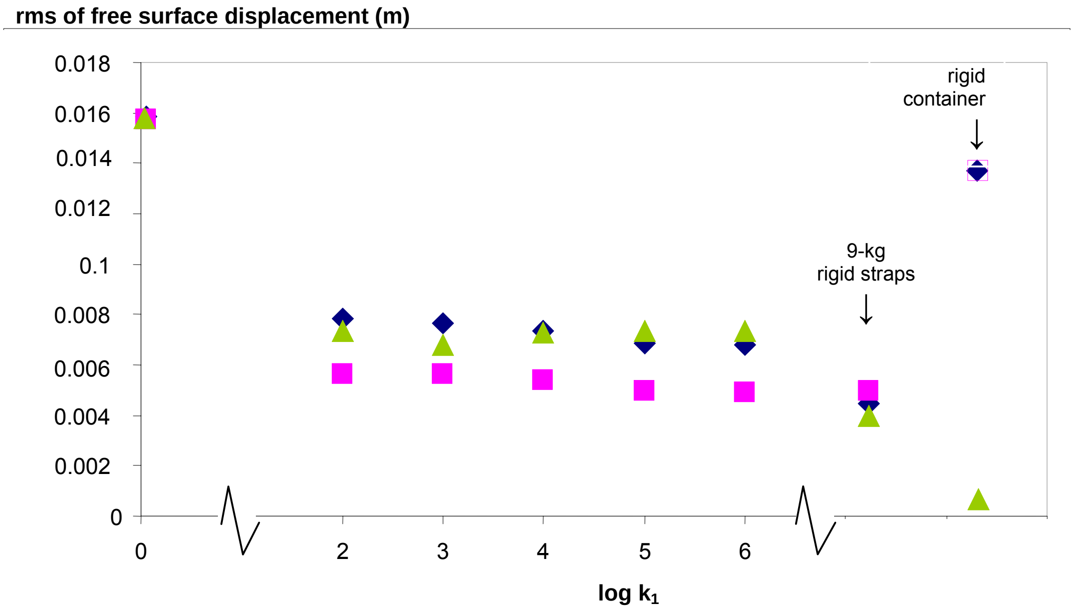

Figure 5: Variation of rms of the sloshing magnitudes with strap stiffness and 3 kg added mass.
♦: left side, ▲: middle and ■ : right side of the free surface.

Most of the comments made regarding the case in Figure 3, are valid for Figure 4, with some exceptions. The free surface drops by 14 mm due to container's flexibility. Walls deflect out by 13 mm due to the weight of the liquid. The peak-to-peak displacement reaches 40 mm once, around 32 s. The rms averages of the left, middle and right surface nodes are 7.4mm, 7.3 mm and 5.4 mm. The difference in the displacement of the left and right sides, is due to the asymmetric distribution of the strap stiffnesses. The rms averages correspond to about 50% suppression as compared to the rigid container case, a 15% loss in effectiveness as compared to the case in Figure 3.

Spectral distribution of the free surface nodes and the container have one significant difference from those in Figure 3. The 0.6 Hz container mode in Figure 3(d), has now merged with the 0.8 Hz liquid mode, resulting in a significantly large response at this frequency, possibly accounting for the loss in effectiveness.

The rms average of the free surface nodes for different k_1 is presented in Figure 5. The 3kg added mass case with no springs indicates a larger response than that of the rigid container. Then there is marginal change from a k_1 of 100 N/m to 10^6 N/m. Further increases result in drastic deterioration of performance (not shown).

CONCLUSIONS

The problem of interest in this paper is to suppress excessive liquid sloshing of the free surface of a partially full container. The implicit assumption here is that suppressing the wave height will result in suppression of the sloshing force on the walls of the container. Predictions from numerical simulations with a standard finite elements approach are presented, to suggest benefits which could be obtained with a flexible container.

The existing most effective container design requires large amount of added mass to achieve the required tuning. The numerical predictions presented here are able to suggest a reduction of the required added mass by a third, with some loss of suppression effectiveness. This loss is in the order of 15% in rms sense.

The contents of this paper should be taken as a progress report. As some rather arbitrary constraints are imposed on the present search, the reported efforts are considered encouraging. Among these constrains are the number and location of the straps used at the open end of the container to limit the excessive wall deflections. As structural asymmetry seems to be beneficial, removal of this particular constraint may prove fruitful. Currently, a search is being planned for numerical experiments in this direction. In addition, other structural design improvements are being examined for a practical implementation of new container designs for liquid bulk carriers with designed flexibility.

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