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AN IMPROVED STANDING-WAVE-TYPE SLOSHING ABSORBER

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1. INTRODUCTION

The oscillatory motion of a liquid in a container is referred as liquid sloshing. In many practical applications, it is important to control liquid sloshing. Alternatively, liquid sloshing has been exploited for the purpose of passively controlling structural vibrations. This concept was suggested earlier by Fujii *et al.* [1], Abe *et al.* [2], Kaneko and Yoshida [3] and Seto and Modi [4]. These works dealt with shallow liquid levels in the sloshing absorbers. At shallow depths, a travelling sloshing wave occurs, and travelling waves are preferable to standing waves because of their energy dissipation characteristics. The poor energy dissipation characteristics of standing sloshing waves have been reported earlier [3]. On the other hand, a sloshing absorber has recently been investigated by the present authors [5], using deep liquid levels to intentionally create standing waves.

As an extension of the previous work, the sloshing absorber is re-examined here for two reasons. Firstly, an explanation is offered for the effectiveness of the baffled sloshing-wave absorber which was introduced in reference [5]. Secondly, based on this explanation, a modification of the earlier sloshing absorber is described.

At the fundamental mode the standing sloshing wave in the absorber is tuned to the natural frequency of the structure to be controlled [5]. In the current investigation, baffle plates which are cantilevered from the vertical sides of the container, have been used to change a standing sloshing wave to an "apparent" travelling wave in the region near the baffles. In doing so, the energy dissipation characteristics of the sloshing absorber have been improved, while the tuning effect of standing waves has been maintained. Numerical simulations are given in this paper to demonstrate the performance of the improved sloshing absorber in controlling the excessive transient vibrations of a resonant structure. The response of a structure for transient disturbance is a good indication of that for random excitation such as an earthquake. The reason for this behaviour, of course, is that random excitation may be envisaged as being made up of a series of transient disturbances in time.

2. NUMERICAL PROCEDURE

The problem of concern in this paper is schematically illustrated in Figure 1(a). The structure to be controlled is represented by a single-degree-of-freedom mechanical oscillator with a mass of m, viscous damping coefficient of c, and stiffness of k. This oscillator is given

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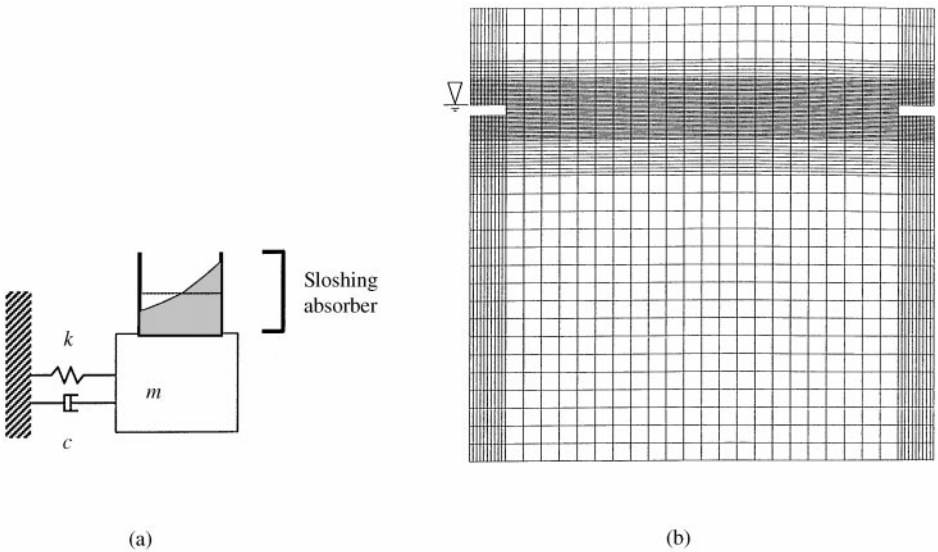

Figure 1. The proposed sloshing absorber (a) attached on the structure to be controlled and (b) the numerical grid of the container showing 10 mm long cantilevered baffles located on the static liquid surface.

an initial displacement and allowed to vibrate freely. Effectiveness of a control is measured by how quickly these free vibrations are stopped by the controller. Sloshing absorbers are used for control which are simply rigid containers half-full of liquid. Sloshing of the liquid is used to give a fluctuating control force as a result of the dynamic pressures created on the vertical walls of the container due to liquid motion.

In numerical simulations, the solution of the equation of motion of the oscillator is approximated by the standard fourth order Runge–Kutta scheme in response to the dynamic fluid forces. Fluid forces were calculated at every time-step from the finite-difference approximation of the Navier–Stokes equations using a commercially available package, CFX Version 4.2. These fluid forces were then assumed to remain constant for one time-step to compute the oscillator's response which was then used as the moving boundary of the container for the fluid solution. Details of the numerical procedure are given in reference [5] along with detailed experimental validation of the numerical model.

The two-dimensional, uneven grid of the numerical model in CFX Version 4.2, with finer increments close to the free surface, is shown in Figure 1(b). The indentations on the sides of the container in Figure 1(b) indicate the position of the rigid baffles. A multiphase solution was carried out taking into account the air and liquid in the sloshing absorber. Grid independence was determined through a trial-and-error procedure. A time-step of 0·001 s was determined to be the largest possible for numerical accuracy.

Same as in reference [5], the mass of the oscillator was 30·8 kg, and the mass of the water was 2·8 kg. The container length in the direction of motion was 0·13 m, its width was 0·21 m and the water depth was 0·1 m. The stiffness constant of the spring was 6374 N/m, and structural damping was set to zero. Initially, the system was given a displacement of 1·3 mm before being allowed to respond freely. As demonstrated earlier [5, 6], these system parameters can be scaled to fit applications of different size, such as in liquid storage structures.

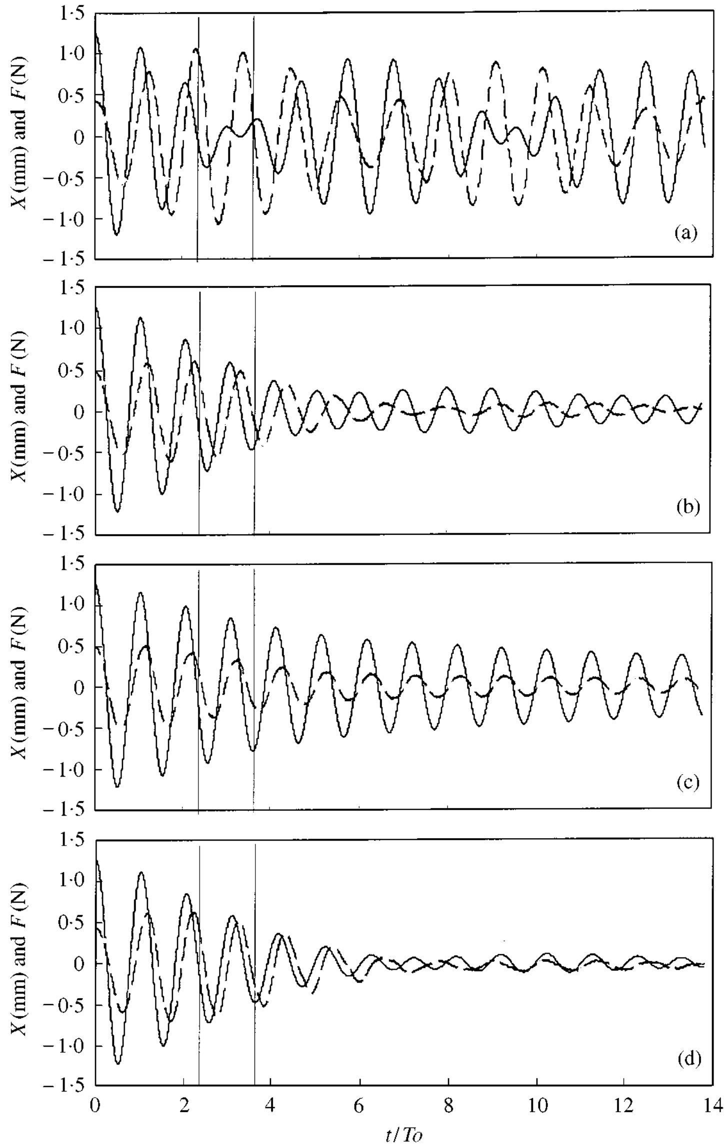

Figure 2. Displacement and force histories of the sloshing absorber, (a) without baffles, (b) with two baffles 10 mm long submerged 5 mm below the static liquid surface, (c) with two baffles 15 mm long submerged 10 mm below the static liquid surface and (d) with one baffle 15 mm long submerged 10 mm below the static liquid surface.

3. RESULTS

In Figure 2, histories of the numerically predicted displacement of the oscillator (—) and sloshing force (– –) are given for four different sloshing absorbers. In Figure 2, the horizontal axis represents non-dimensional time, t/T_0, and T_0 is the natural period of the structure to be controlled without the sloshing absorber attached. In Figures 3–6, vector plots of velocity for the same four sloshing absorbers as in Figure 2 are given. These velocity vector plots show a series of instantaneous images of the flow field in the sloshing absorber from

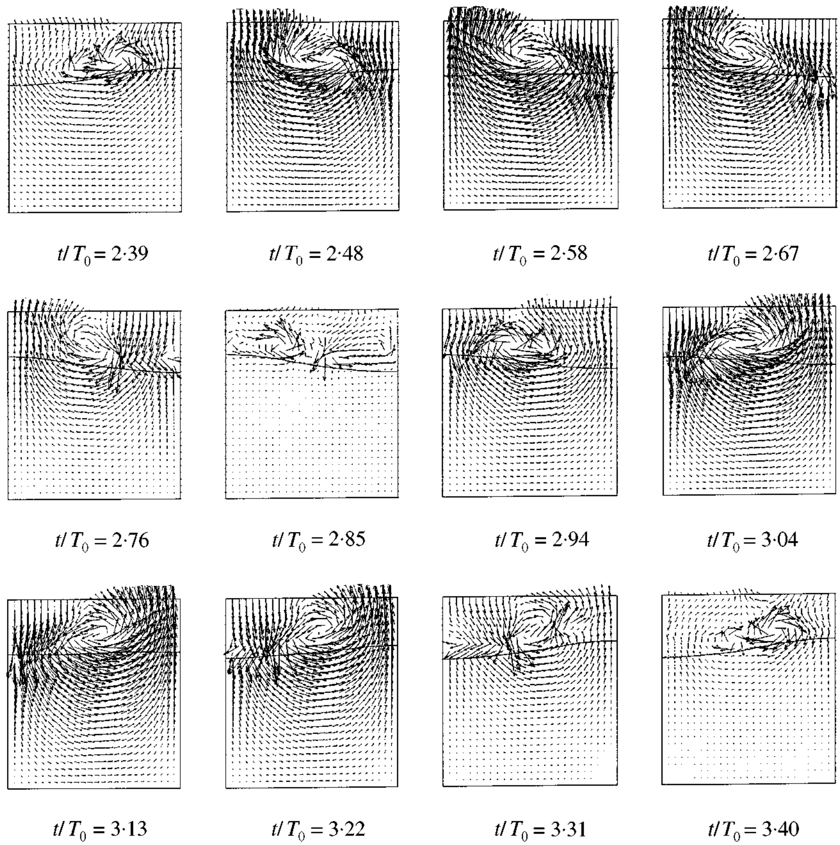

Figure 3. Velocity vector plots for a sloshing absorber with no baffles.

2·39 units to 3·40 units of non-dimensional time. This period of time is marked in Figure 2 with two vertical lines. The performance of each sloshing absorber is discussed next with reference to these figures.

In Figure 2(a), the sloshing absorber has no baffles. The poor control effect is characterized by a beat in the displacement of the structure. The initial displacement of 1·3 mm decays significantly between 2·39 and 3·40 units of non-dimensional time. However, there is little energy dissipation in the sloshing liquid, and the displacement amplitude returns to almost 1·3 mm at 6 units of non-dimensional time. This strong interaction between the sloshing liquid and the structure between 2·39 and 3·40 units of time can be explained in relation to the velocity vector plots in Figure 3.

In Figure 3, velocity vector plots are given for the sloshing absorber with no baffles. The liquid-free surface is shown by a solid line in each frame. Vectors above and below the free surface represent air and liquid velocities respectively. The first frame represents the velocity field in the absorber at 2·39 units of non-dimensional time, and consecutive frames show approximately one period of wave motion to 3·40 units of non-dimensional time. From 2·39 to 2·48 units of time, the sloshing wave is higher on the right side than on the left side of the container. During this time, the resultant force on the container is to the right. This is also indicated by the positive value of force in Figure 2(a). The displacement history shown in Figure 2(a) shows that the structure is moving to the left. Therefore, the sloshing force is opposing the motion of the structure.

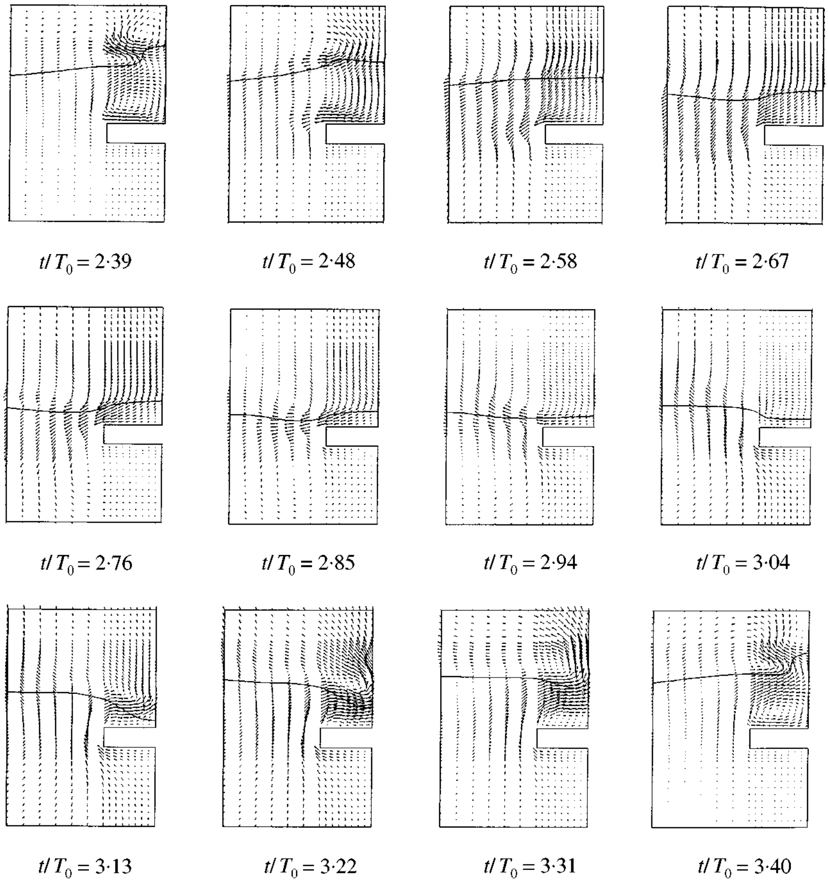

Figure 4. Velocity vector plots for a sloshing absorber with two 10 mm baffles submerged 5 mm below the static liquid surface.

At 2·58 time units, Figure 3 shows that the sloshing wave is approximately flat. At this point, the resultant sloshing force is negligible. The structure has slowed down, and it is about to change direction to start moving to the right. This is indicated by the first turning point in the displacement history in the region of interest, which is marked with the two vertical lines in Figure 2(a). In Figure 3, the wave continues to climb high on the left wall in frames for 2·67 to 2·94 units of time. The resultant sloshing force increases to a maximum to the left at time equals 2·85 units. This is shown in Figure 2(a) by the 1 N negative force at this instant. The displacement history shows that the structure is moving to the right. The sloshing force is to the left with a magnitude capable of prematurely stopping the structure and making it change direction at time equals 3·04 units. This strong interaction continues to time 3·40 units with the sloshing wave climbing on the right-side wall and creating a resultant sloshing force to the right. At this point, the structure is once again made to stop and change direction.

In Figure 3, the characteristic wave shape at the fundamental mode of sloshing in the absorber is shown. This wave shape is referred as a standing wave, and it has a clear nodal point. This nodal point is located on the liquid-free surface, and it is shown in the vector plots as an area of recirculation. This type of wave has poor energy dissipation

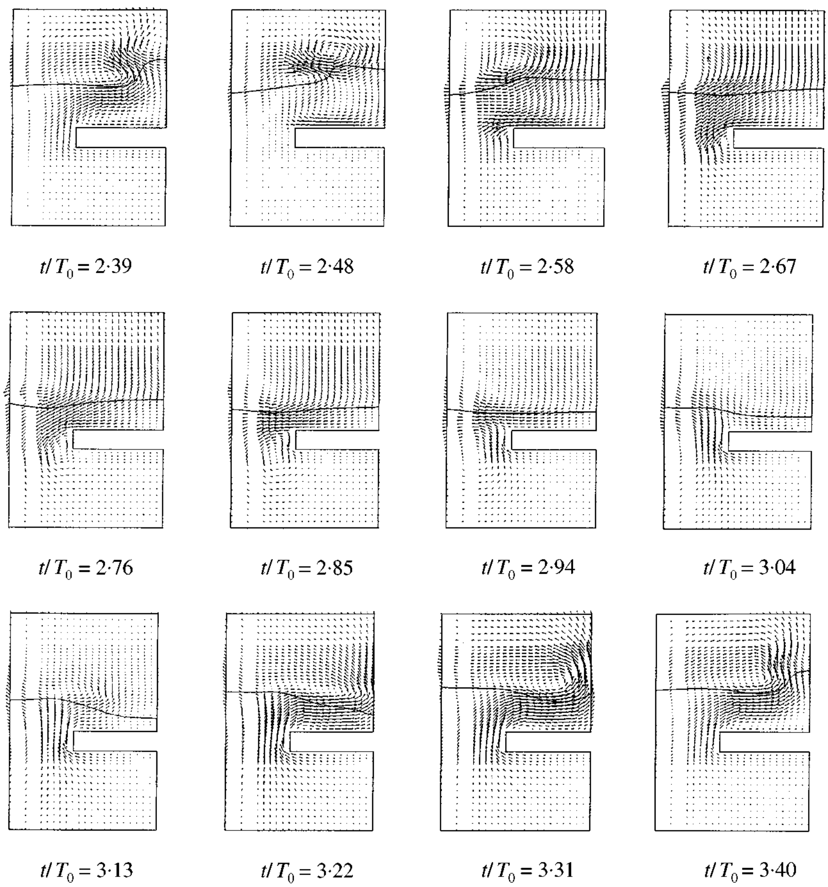

Figure 5. Velocity vector plots for a sloshing absorber with two 15 mm baffles submerged 10 mm below the static liquid surface.

characteristics. To improve the performance of the sloshing absorber, cantilever baffles have been used [5]. Sloshing absorbers with baffles are discussed next.

In Figure 2(b), the force and displacement histories are given for a sloshing absorber with 10 mm long baffles places on each side of the container submerged 5 mm below the static liquid surface. This configuration is the optimum for a sloshing absorber with two baffles as described in reference [5]. In Figure 4, the velocity vector plots as well as liquid-free surface shapes are given for this absorber. Here, the vector plots are not for the entire flow field. To achieve the desired level of resolution, the vectors have been plotted for only a small area near the right baffle. At time equal to 2·39 units the sloshing wave has climbed to a high point on the right wall. A vortex exists above the baffle at this instant. In the consecutive frames, from time equals 2·48 units to 2·94 units of time, the sloshing wave dissipates on the right side of the container, and the vortex disappears. At time equals 2·85 units another vortex has formed below the left corner of the baffle.

At 3·13 natural periods, the sloshing wave is about to start climbing up the right side of the container again. In this frame, the free surface shape of the liquid is showing a travelling wave. There is a clear wavefront that has a horizontal velocity towards the wall. This is in contrast to a standing wave that has only vertical motion near the wall. In frames for

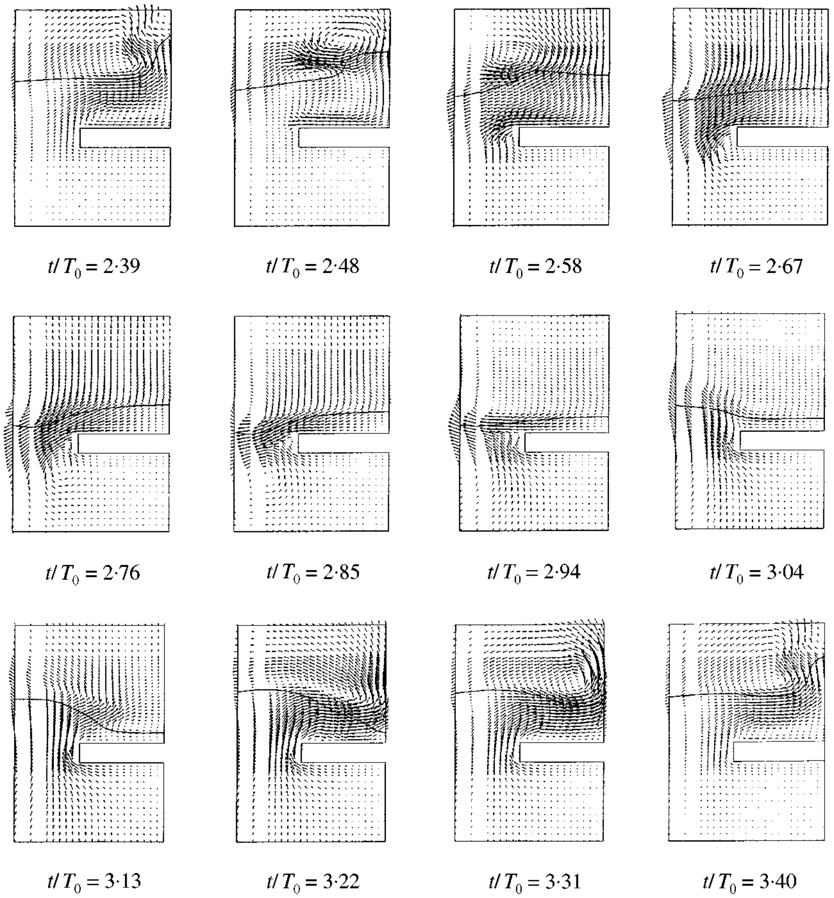

Figure 6. Velocity vector plots for a sloshing absorber with two 15 mm baffles submerged 10 mm below the static liquid surface.

3·13–3·40 units of time, the travelling wave impacts on the right wall, and the vortex above the baffle forms again. The vortex formation above each baffle is associated with energy transfer from the translational liquid motion. The vortex is forced to decay with the travelling wave, providing energy dissipation. This dissipation of energy produces a sufficient control action, and it significantly reduces the vibration of the structure after 6 units of time, as shown in Figure 2(b). A travelling wave is likely to develop when the liquid depth is shallow compared with the length of the container. As the length of each baffle is increased, a region above the baffles is created where a travelling wave is likely to form.

In Figure 2(c), force and displacement histories are given for a sloshing absorber with 15 mm long baffles placed at each side of the container at a depth of 10 mm below the liquid surface. The intention here is to induce a travelling wave in the regions near the baffles. However, Figure 2(c) shows a poor control effect. The displacement amplitude decays slowly. There is a more dramatic increase in the decay of the sloshing force, suggesting that sloshing has been suppressed excessively, and the absorber is starting to behave like an added mass. Figure 5 shows the velocity vector plots for the same region as shown in Figure 4. When time equals 2·39 units, the sloshing wave has climbed high on the right wall of the container. Similar to Figure 4, a vortex is also visible above the baffle. However, here, the vortex has been elongated to form an ellipse with its longer axis parallel to the baffle. The amplitude of sloshing is reduced compared with Figure 4, and the travelling wave at time 3·13 is less pronounced. Here, the wavefront has some vertical velocity component. The baffles suppress sloshing too severely to allow a strong interaction between the absorber and the structure. In order to reduce the control of sloshing and promote strong liquid–structure interaction, one of the baffles is removed, as discussed next.

In Figure 6, the velocity vector plots are given for the sloshing absorber with one 15 mm long baffle placed at 10 mm below the static liquid surface. At times 2·39 and 2·48, there is a vortex in the region above the baffle. At time 2·76, the wave height has dropped, and the vortex above the baffle is not present. At this time, another vortex has formed at the lower left corner of the baffle. At 3·13 units of time, a clear travelling wavefront is developing. At time 3·22, this travelling wave is characterized as having only a horizontal velocity, whereas a standing wave would have primarily a vertical velocity. Although the vector velocity field given in Figure 6 is remarkably similar to that in Figure 5, it must be noted that it is no longer symmetrical. It is speculated that with double baffles as in Figure 5, the resulting sloshing frequency may differ too much from the tuning frequency, giving poor control. In Figure 2(d) the displacement and force histories for this system are given. This absorber provides the best passive control effect amongst the cases tried here. Initially, the structure has a displacement of 1·3 mm, and the system has only potential energy. From 0 to 4 time units, some of this energy travels to the absorber where it is dissipated. This dissipation of energy produces a control action that significantly suppresses the vibrations of the structure after approximately 6 units of time.

4. CONCLUSIONS

In this investigation, numerical results are presented to show that the effectiveness of a standing-wave sloshing absorber can be improved by utilizing the energy dissipation characteristics of a travelling wave. A small travelling wave has been created in the region near a baffle plate. By creating a travelling wave in only part of the absorber, the "tuning" effect of the standing sloshing wave is mostly maintained.

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