SLOSHING IN TANKS IN A MAGNETIC FIELD

Jannette B. Frandsen
School of Civil Engineering, The University of Sydney, NSW 2006, Australia

ABSTRACT

In this contribution, the energy from steep waves is extracted from liquid sloshing in tanks. The aim is to develop a damping device to control structural vibrations in for example free standing towers, offshore platforms and other engineering structures. The focus of the work is to add further energy to the liquid sloshing motions through a magnetic field. Without the magnetic field, the damping device may be too heavy and thus impractical. We seek to develop light weight environmental friendly dampers.

Liquid sloshing in tanks exhibit complicated free surface behavior, especially when the waves becomes steep and break. As a result, mode interactions occur which make it difficult for practitioners to know the performance of the tuned liquid dampers. It is also known that wave breaking in tanks is the source which provide maximum energy. It is this situation, we wish to exploit further in a magnetic field.

Herein, small scale physical tests are undertaken in a square tank. The parametric study includes a variation of liquid, liquid depth, magnetic strength, forcing frequency and forcing direction. The preliminary results show that a magnetic field can suppress the free surface significantly, and thus provide additional energy, potentially resulting in smaller damping devices.

1. INTRODUCTION

In this contribution, we are exploring options to develop efficient damping devices, that is, environmental friendly lightweight dampers. We are proposing to develop liquid sloshing dampers that are exposed to a magnetic field. While there has been research undertaken in the behavior Tuned Liquid Damper (TLD), mainly through physical experiments, little work has been undertaken for Tuned Magnetic Liquid damper (TMLD).

The laws of magnetism and fluid first got attention from the physicist (Faraday, 1832) in the nineteenth century. The development of MagnetoHydroDynamics (MHD) in engineering was slower and did not really get started until the 1960s. However, some early work of Hartmann did take place around the 1930s who undertook a systematic theoretical and experimental investigation of the flow of mercury in a homogeneous magnetic field.

Herein, we shall investigate the effect of a magnetic field on the free surface physics when liquid is sloshing in tanks excited by harmonic loading. These type of studies are sensitive to liquid depth, tank size and external forcing frequency. Our studies are limited to square tanks.

Liquid Motion in Tanks

Sloshing in tanks is a topic which has been studied extensively Ibrahim (2005). It is important to a wide variety of applications. For example, ship stability; liquid storage tanks; vibration concerns of structures and structural elements, etc. It is the latter which will be our focus. We seek to utilize the energy from free surface motions generated in tanks to suppress structural vibrations.

Generally, a TLD is a passive device which takes advantage of liquid sloshing motion to dissipate energy and suppress unwanted structural vibrations. An example is presented by Fujino et al. (1992) who explored the use of shallow water in a TLD to suppress horizontal motion of a structure. They conducted experiments in a rectangular tank and compared their results with numerical solutions. Good agreement was found for non-overturning waves. They showed that shallow water sloshing provides an effective means for damping unwanted structural motions.

An important point to stress is that free surface water waves exhibit solutions with hysteresis when the wave steepness become relatively large. This effect occurs both in deep and shallow depth. For example, in shallow water, the maximum elevation is expected to occur at a higher frequency compared to the linear solution. Some discussion on this matter is undertaken by for example Ikeda and Nakagawa (1997) and Frandsen (2005). Although steep to breaking waves generate maximum energy compared to its linear counterpart, nonlinear waves are not necessarily a desirable TLD characteristic. However, because nonlinear waves easily occur, and thus mode interactions, and thus add complexities to the understanding of TLD behavior, it is believed that this is the reason why TLD is less used than tuned mass dampers.

Liquid Motion in a Magnetic Field

We investigate the possibility of providing energy dissipation by applying a magnetic field to a sloshing conducting fluid. When a conductor moves in a direction perpendicular to a steady magnetic field currents are induced within the conductor which in turn setup a magnetic field opposing the applied field. This causes the conductor to experience a breaking force which will slow the motion of the conductor. A conducting fluid flowing in the presence of a steady magnetic field should therefore be slowed down by magnetic breaking. However, the efficiency of magnetic breaking is largely dependent on both the conductivity of the conductor and its relative velocity through the field. Some preliminary experiments have shown that an aqueous solution of sodium chloride does not have large enough conductivity to have a measurable effect on sloshing. Liquid metals like mercury or sodium may have large enough conductivity to cause some breaking of the fluid, however, the use of these kinds of fluids is unsafe and unfriendly to the environment and impractical.

We introduce the MHD equation of motion for an element of conducting fluid,

$$\frac{\partial \mathbf{v}}{\partial t}+(\mathbf{v}\cdot\nabla)\mathbf{v} = -\nabla\,\mathbf{P}/\rho+\mathbf{g}+\nu\nabla^{\mathbf{2}}\mathbf{v}+\sigma\,B^{\mathbf{2}}\,\mathbf{v}/\rho\,, \tag{1}$$

where it is assumed that the velocity is perpendicular to the magnetic field, and that no electric field is applied. The terms on the left hand side of (1) describes the inertia and convection force contributions acting on a fluid element of unit volume moving at the local flow velocity. The first term on the Right-Hand-Side (RHS) of (1) represents the pressure gradient across the element, the second represents any body forces acting on it (where g is gravity due to acceleration), and the third term represents viscous forces. The last term on the RHS represents a magnetic drag on the fluid element, where B is the magnitude of the magnetic field, σ is the conductivity, and $\mathbf{v}$ is the velocity of the fluid, and ν is the kinematic viscosity. Further, we shall introduce the Hartmann number, M,

$$M = B\,L\,\sqrt{\sigma/\rho\,\nu}\,, \tag{2}$$

which expresses the ratio of the magnetic drag forces to the normal viscous forces. In the case of a saturated aqueous solution of sodium chloride, with a magnetic field $B = 0.025$ Tesla, and a scale length $L = 0.28$ m (tank base dimension). M is less than 0.002. Therefore, for this particular case, the magnetic forces are very small compared to viscous forces. Fluids with larger conductivities and stronger magnetic fields are required if any damping is to be provided by magnetohydrodynamic forces. The use of sloshing magnetic fluids in an intelligent device may prove to be more promising. Ni et al. (2004) developed a tuned liquid column damper containing magnetorheolgical (MR) fluid which can be semi-actively controlled by the application of a magnetic field. This particular device takes advantage of the ability of MR fluid to quickly and reversibly change its viscosity. It allow for control of structural vibrations over a much wider range of loading conditions than a traditional tuned liquid column damper using water. Not all magnetic fluids show this type of rheology. For example, Bossis et al. (2002) explain the difference in behavior of MR fluids and magnetic fluids (ferrofluids). The behavior of different types of magnetic fluids in the presence of a magnetic field is strongly dependent on the size of the magnetic particles dispersed in the fluid. In order to achieve the viscosity changing effects, MR fluids must have particle sizes around 1μm. For ferrofluids, which have even smaller magnetic particles, thermodynamic particle motions dominate the magnetic forces and the viscosity of these fluids does not vary significantly in a magnetic field. In the vicinity of a magnetic field these ferrofluids will flow to the areas where there is the most magnetic flux with little change in fluid viscosity. Sawada et al. (1999) studied sloshing of a magnetic fluid with particle sizes of 5 to 15 nm in a laterally excited rectangular container with base dimension of 0.02×0.08 m^2 and fluid depth of 0.04 m. Sawada et al. showed that the maximum free surface elevation occurred at higher forcing frequencies when a magnetic field was applied. This finding agreed well with their solution obtained from nonlinear potential flow theory with third order accuracy. It should be noted that Sawada et al. replaced the acceleration due to gravity in the dynamic free surface boundary condition with an effective g (acceleration due to gravity) to account for the effect of the magnetic field on

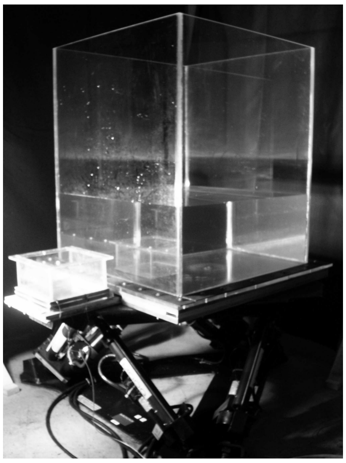

Figure 1: Sloshing tanks.

the fluid. This approach is an equivalent means of accounting for the added downward force on the fluid caused by the permanent magnets (in this case located at the bottom of the sloshing tank). The results of Sawada et al. also showed a decrease in the horizontal velocity of the fluid, and a decrease in peaks of the power spectra as the magnetic field increased. Furthermore, Ohira et al. (2001) investigated the frequency response of a TMLD through experiment and numerical simulations. They used a 0.14 m diameter cylindrical tank with 0.03 m fluid depth and four horizontally oriented electromagnets. They showed that the effectiveness of the TMLD could be increased by applying a time dependent magnetic field and through switching the magnetic field conditions at the resonance frequency. We shall also acknowledge and make the reader aware that the above is only a snapshot of the literature and not a comprehensive review. Instead we have focused on the exploratory research, as introduced in the remaining part of the proceeding paper.

2. EXPERIMENTAL INVESTIGATIONS

TLDs could be designed to take advantage of the ability to manipulate the frequency response and energy content of a sloshing magnetic fluid. More unwanted structural kinetic energy may be dissipated by the sloshing and breaking wave motion of a magnetic fluid than that dissipated by the liquid alone. Therefore smaller more manageable dampers could in principle be designed. Moreover, breaking wave motion provides a mechanism to keep magnetic particles mechanically dispersed in the fluid. Expensive colloidal magnetic fluids could be replaced with cheap simple mixtures of liquid and magnetic particles in which, when at rest, the particles can settle out. Allowing for a controllable time varying magnetic field opens up a host of possibilities of designing intelligent damping devices which respond to structural motion by varying the magnetic field and therefore the sloshing motion and energy dissipation. The sloshing problem is mathematically complicated because of the inherent nonlinear behavior especially near resonance. Furthermore, the possibility of breaking waves and magnetic forces gives rise to further complications.

Herein, preliminary experimental investigation of free surface motions in square tanks is pursued to investigate the requirements of the design of such devices. We examine the possibility of manipulating liquid motion by adding magnetic particles to water and applying a magnetic field to the tank leading to more freedom in the design of intelligent structural dampers. The present experiments are carried out in a 0.28 m square tank of plexiglas which is rigidly fixed to a motion base which is excited harmonically in the horizontal direction. The forcing amplitude is 0.003 m for all test cases presented. The tank is shown in Fig. 1 relative to a larger tank (1×1 m^2 base dimension). With regard to assessing scale effects, we undertook some comparisons between the 1×1 m^2 tank, and the present tank (about 1/3 smaller in base dimension size). Our comparison tests included sway base excitation (Froude no. scaling was applied). We forced the tank to move in sway motions with forcing frequency ω_f and extracted the maximum free surface elevation η_{max} from time series (> 50 s). For tank aspect ratio of $h_0/b = 0.2$ (where h_0 is the still water depth, and b is the tank width), the free surface elevations in the small tank were in general underestimated, as shown in Fig. 2. For $h_0/b = 0.4$, near critical depth, the resonance cases mainly resulted in over-estimated free surface peaks in the small tank. However, the smaller tank do capture the hysteresis effects known to exist in steep sloshing motions. It can also be observed that the overall flow patterns of the smaller tank follow those of the larger tank. It should be noted that these findings may not hold for other forcing directions as the extent of scale effects problem depend on type/direction of tank base excitation because of, for example, linear (sway) or exponentially (heave) resonances, respectively.

With this in mind, we continue with the description of the experimental set-up of the present experiments. A vertically oriented mag-

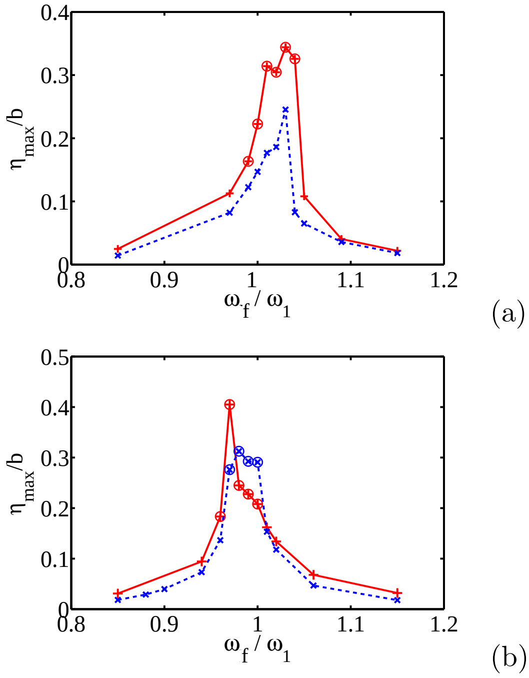

Figure 2: Illustration of scale effects of water sloshing in tanks. – –x– –, small tank (0.28×0.28m^2); —, big tank (1×1m^2). Tank aspect ratios: (a) $h_0/b = 0.2$; (b) $h_0/b = 0.4$. ∘ denotes wave breaking.

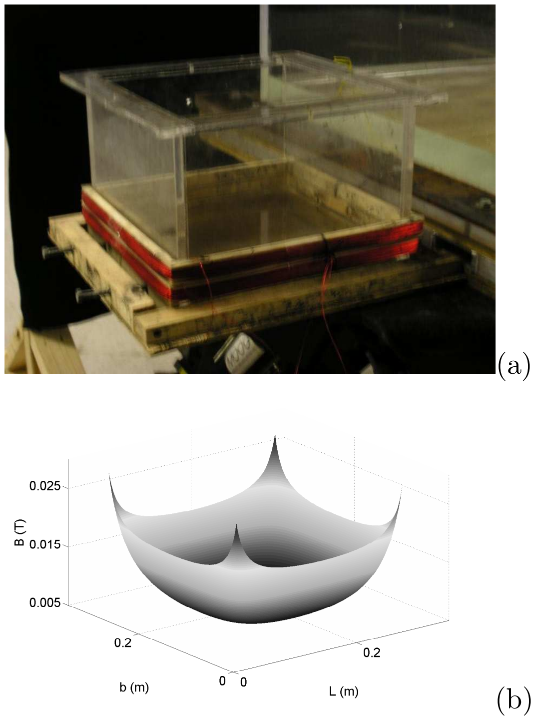

Figure 3: (a) Test set-up. (b) Magnetic field induction (Tesla) in still water.

netic field is set-up by a square coil of 350 winds of copper wire placed just outside the tank with its center at the still water level (Fig. 3a). Fig. 3b shows a sample calculation of the magnetic field induction inside the tank at the resting level of the free surface with a 5A current through the coils. Due to the square shape there is maximum magnetic flux at the corners. The frequency of the base motion is varied along with fluid depth. In all experiments water has been used the reference fluid and the depth is shallow. It should be mentioned that water has a low conductivity and thus not ideal/efficient liquid. However, sloshing motion of water are well covered in the literature (Ibrahim, 2005) and create a foundation necessary for understanding the effect of magnetic field.

The magnetic powder is obtained from burning steel wool then grinding the ash. It is important to note that the fluid we are using is not a stable dispersion. It is a simple mixture of solid magnetic particles and water. Therefore we cannot expect this mixture to behave as a homogeneous fluid. When the tank is at rest most of the particles quickly settle to the bottom of the tank. The free surface elevation is measured, at the center of one wall which is perpendicular to the forcing direction, with a capacitive wave gauge which samples at a rate of 30 Hz. Each test series are carried out with and without the magnetic field. As mentioned, the test series with plain water and no particles added are also undertaken and serve as our point of reference.

3. RESULTS

We present some free surface behavior studies with/without a magnetic field for water depths h_0/b = 0.89 and 0.13, respectively. Fig. 4 shows the non-dimensional maximum free surface elevation for forcing frequency ratios $\omega_f/\omega_1 \in$ [0.85;1.3] for a water depth of $h_0 = 0.025$ m. The results suggest that the addition of solid particles does indeed effect the sloshing behavior. For plain water the maximum free surface height occurred when the forcing frequency was $1.16\omega_1$ where ω_1 denotes the first natural sloshing frequency of the tank based on the linear dispersion relationship: $\omega_n = \sqrt{g\, k_n\, tanh(k_n\, h_0)}$, g is acceleration due to gravity, $k_n = n\,\pi/b$ is the wave number where n=1,2,.... Furthermore, a downward shift in the peak resonance frequencies can be observed when solid magnetic particles are added to the water. Also a broader range of relatively large response can be observed, resembling

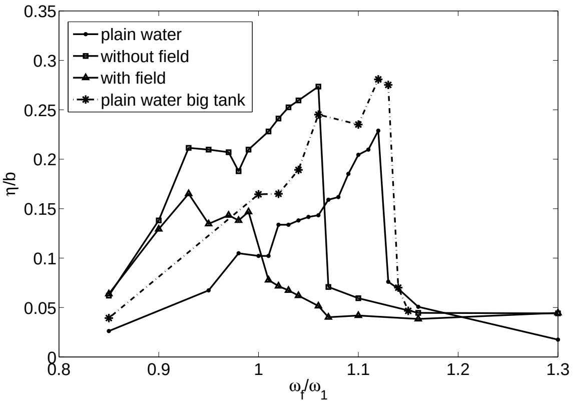

Figure 4: Maximum free surface elevation ($h_0 = 0.025$ m). –△–, with field; —, without field; —, plain water; –*–, big tank ($1{\times}1$ m^2).

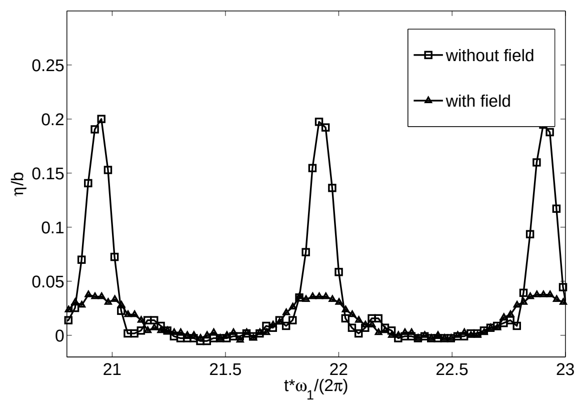

Figure 6: Free surface time elevation at the wall at $\omega_h/\omega_1 = 1.01$ ($h_0 = 0.025$ m).

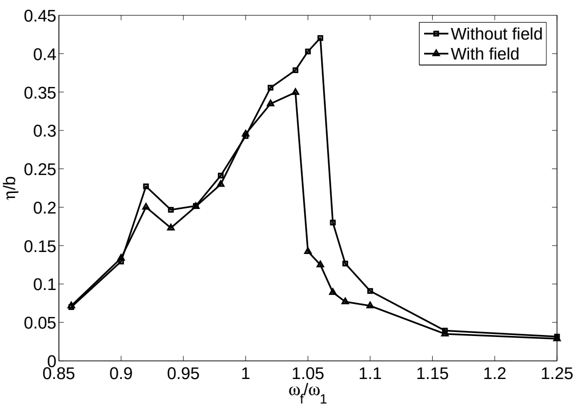

Figure 5: Maximum free surface elevation ($h_0 = 0.035$ m). –△–, with field; —, without field.

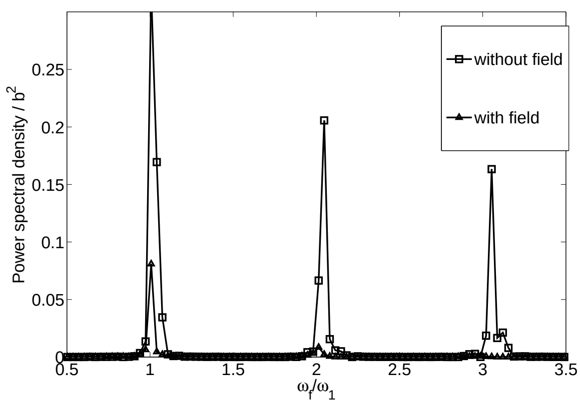

Figure 7: Spectrum of free surface time elevation at the wall $\omega_h/\omega_1 = 1.01$ ($h_0 = 0.025$ m).

a plateau rather than a peak. The test series with plain water at this depth shows a hardening oscillator effect, as resonance occurs at a frequency higher than the predicted first natural sloshing frequency. This is typical behavior in shallow water, and demonstrate that the addition of solid particles to the water has some positive effect in terms of energy dissipation. The addition of the magnetic field causes a further downward shift in the resonance frequency and an over all decrease in the maximum surface elevations of the waves in the tank. In the range of frequencies from $1.01\omega_1$ to $1.06\omega_1$, the effect is notable. Regarding scale effects, we also observed the smaller tank tends to underestimate the free surface elevations relative to the bigger tank with base dimensions ($1{\times}1$m^2). Furthermore, we carried out a similar study but with an increase in still water depth to $h_0 = 0.035$ m. Fig. 5 shows for fluid depth of 0.035 m shows similar effects compared to $h_0 = 0.025$ m. Again the effect of the magnetic field is to cause a downward shift in the resonance frequency, however, the size of the shift is only about half of what is observed at the shallower water depth of 0.025 m. Fig. 6 shows an approximately two period snapshot of the time histories of the surface elevation for depth 0.025 m and forcing frequency $1.01\omega_1$. At this frequency the effect of the magnetic field is readily apparent. In this case we observed the free surface oscillation to be almost completely suppressed by the application of the field. Frequencies $1.05\omega_1$ and $1.06\omega_1$ with fluid depth 0.035 m showed a similar effect. In addition to drastically reducing the amplitude of the free surface, the magnetic resulted in a near linear wave field which is not typical for this water depth. In cases with plain water and cases without the magnetic field the waveform usually observed can be characterized as a traveling wave with wavelength shorter than twice the tank width (which reflects back and forth in the tank at a frequency near to the forcing frequency). At frequencies outside resonance a second or even third traveling wave was observed to follow the first wave. At $1.06\omega_1$ only a single wave was observed. This wave form was not as often observed in the cases with the applied magnetic field. In cases without the applied magnetic field, the majority of the magnetic particles settle to the bottom of the tank and participate relatively little in the motion. However, they do have some participation contribution which must be considered when comparing to plain water. In cases where the magnetic field is applied, we observed that the magnetic particles form into lines parallel to the magnetic field lines. As the water moves in the tank it pushes these structures back and forth. This is how the magnetic particles participate in the sloshing motion and are able to effectively suppress the motion of the water. Fig. 7 shows the power spectrum for the same case discussed above. It is clear from this figure that the applied magnetic field and subsequent resistance to motion of the magnetic particles provides a means to dissipate energy from the motion of the water. There is also possibility that by adjusting the strength of the magnet, the amount of energy dissipated, and maybe even the frequency response may be effected. It may be found that by using these means a smaller, controllable, more manageable type of tuned liquid damper may be designed. We should also note that the present test series data contain no breaking waves. More experiments need to be done with larger forcing amplitudes in order to study the effect of breaking waves, the added mixing of particles it causes, and the effect of the magnetic field.

In support of the experiments and with regard to advancing the progress of knowledge on TMLD development further, we have also initiated numerical model development. We plan to elaborate on the approach at the conference.

4. CONCLUSION

The preliminary experiments demonstrated that a magnetic field can have a significant influence on the free surface behavior in tanks. In the context of damper device development, it means that this may result in a reduction in the size, and thus reductions in additional mass of a damper to structural mass, due to the extra energy generated by the interaction between the wave motion and the magnetic field.

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