Ocean Systems Engineering, Vol. 1, No. 2 (2011) 131-155 131
DOI: http://dx.doi.org/10.12989/ose.2011.1.2.131

Sloshing of liquids in partially filled tanks – a review of experimental investigations

M. Eswaran and Ujjwal K. Saha*

Department of Mechanical Engineering, Indian Institute of Technology Guwahati, Guwahati-781 039, India.

(Received December 5, 2010, Accepted June 5, 2011)

Abstract. Liquid sloshing constitutes a broad class of problems of great practical importance with regard to the safety of liquid transportation systems, such as tank trucks on highways, liquid tank carriages on rail roads, ocean going vessels and propellant tanks in liquid rocket engines. The present work attempts to give a review of some selected experimental investigations carried out during the last couple of decades. This paper highlights the various parameters attributed to the cause of sloshing followed by effects of baffles, tank inclination, magnetic field, tuned liquid dampers, electric field etc. Further, recent developments in the study of sloshing in micro and zero gravity fields have also been reported. In view of this, fifteen research articles have been carefully chosen, and the work reported therein has been addressed and discussed. The key issues and findings have been compared, tabulated and summarized.

Keywords: sloshing; experimental review; ER fluid; MR fluid; micro gravity.

1. Introduction

Sloshing can be described as back and forth motions of the liquid in a partially filled tank. Slosh is a phenomenon where liquid in a container moves irregularly with a splashing sound. Elevated water towers and industrial storage tanks under excited ground motion, sloshing effects on large dams, liquefied natural gas (LNG) ship containers and moving oil tanks are studied by civil engineers and seismologists. Moreover, aerospace and nuclear scientists, designers of road and ship tank builders, applied mathematicians and physicists are having the great concern on liquid sloshing. The large liquid movement during sloshing creates highly localized impact pressure on tank walls which may in turn cause structural damage and may even create sufficient moment to affect the stability of the vehicle that carries the container. Sometimes, the dynamic motion of the liquid in tanks influences the wave induced motions on ships.

The effect of sloshing in a moving liquid container causes safety and comfort issues such as undesirable forces on brake systems in liquid carrying tankers like LNG (Graczyk *et al.* 2003, Lee 2007), high impact loads upon the containment system and structural parts. Further, under earthquake conditions, it creates fatigue, safety problems in nuclear reactors and power generating plants (Kimura *et al.* 1995). Sloshing also produces unnecessary noises referred to as "clinking

*Corresponding author, Associate Professor, E-mail: saha@iitg.ernet.in

noises" in automobile fuel tanks (Wiesche 2006) and safety issues in propellant tanks in the spacecrafts under micro-gravity conditions (Snyder 1999). As compared to rigid loads, the number of road accidents related to liquid loads is significantly higher. This is due to the fact that the dynamic behavior of a liquid in a transporting container significantly affects the stability and controllability of the vehicle (Popov *et al.* 1992). Liquid sloshing occurs in several marine engineering applications including vessels transporting liquids in hold tanks (Veldman 2007). Water waves in the tank sloshing have similarities with green water on deck. Violent free surface motion can be expected in these two cases and a similar resonance phenomenon will occur in both problems. Hence, the problem of sloshing gains more attention and practical importance in the engineering community (Valentine 2005).

In conventional studies, the linear approximation was applied to the formulation of the liquid motion, and thus, influences of the nonlinearity of sloshing on the magnitude of stresses in an elastic floating roof have not been investigated (Utsumi and Ishida 2008). However, the linear theory of liquid sloshing is adequate for determining the natural frequencies and wave height of the free surface. This theory is also useful for finding the liquid velocity, hydrodynamic pressure, forces and moments as long as the free surface maintains a planar shape with a nodal displacement that remains perpendicular to the line of excitation. The amplitude of slosh, in general, depends upon the amplitude and frequency of the tank motion, liquid-fill depth, liquid properties and tank geometry. Numerical simulations are used to verify the validity of analytical results if experimental results are not available.

Housner (1957, 1963) developed an analytical method for the determination of hydrodynamic wall pressures under the assumption that the tank is rigid structure fixed at the base and only the fundamental sloshing mode is important. Applications in the aerospace industry has been reviewed and discussed by Abramson (1966) both analytically and experimentally. Feng (1973) used a three-dimensional version of the marker and cell method (MAC) in a rectangular tank. This method consumes large amount of computer memory and CPU time and the results reported indicate the presence of instability. A nonlinear analytic method for simulating sloshing, which satisfies the nonlinear boundary condition at the free surface was suggested by Faltinsen (1974). The coupling effect between liquid sloshing and structural vibration is usually neglected in practice. The preliminary study of these coupling effects in cylindrical tanks was carried out by Haroun (1980, 1983). Partom (1987) presented the most popular volume of fluid (VOF) method developed by Hirt and Nichols (1981) for tracking the free surface boundary for cylindrical container. From 1980 much attention has been paid to modeling transient free-surface potential flows by means of the Boundary-Element Technique (BET), Finite Volume Method (FVM), Finite Difference Method (FDM) and Finite Element Method (FEM) after booming of the new numerical techniques and invention of high speed computers.

Research work, during last fifty years revolved around experiments as well as numerical simulation. However, review work reported here is limited to experimental investigations only. First of all, it identifies and discusses the various important terms and parameters associated with sloshing. This is followed by detailed literature review some of which also have been summarized in tabular forms. Section 2 presents some important notable facts in the history of liquid sloshing, milestone research articles, and accidents. Section 3 identifies and discusses the various important terms and parameters associated with sloshing. Fifteen research articles have been chosen, and the investigations reported therein have been compared effectively based on the important parameters of sloshing such as container shape, type of excitation, flow impediment objects, fluids used, container wall, and the field. Brief review of published work has been summarized in tabular forms.

2. Some notable facts

The earlier study on sloshing was performed by Jacobson and Ayre (1951), and Graham and Rodriguez (1952). In 1957, the research and development agency, USAF/ABMA, launched a Jupiter IRBM AM-1B vehicle, which terminated at 93 seconds because of propellant slosh when the missile achieved an altitude of 60,000 feet. Again in 1964, when the test vehicle F1 was launched by ELDO satellite launcher vehicle Europe I, a catastrophic instability occurred, resulting in premature engine cut and an oscillation in both pitch and yaw plane were commenced at about 130 seconds. Loss of control of the vehicle near the end of the flight aroused due to fuel sloshing.

The 1964 Alaska earthquake and the extensive damage inflicted on various kinds of liquid storage tanks seems to have initiated an intense and uninterrupted, since then, interest on the seismic behavior of modern structures used for the storage of liquids or liquid like materials, e.g., water, fuel, oil products, chemicals, wastes, and liquefied natural gas (Lamb 1932, Drosos 2008). As cited by Matsui (2007), in the past major earthquakes, many tanks have been subjected to serious damages, which may be attributed to liquid sloshing. Especially, during the 2003 Tokachi-oki earthquake, seven oil-storage tanks of floating roof type located at Tomakomai, Hokkaido, Japan were seriously damaged (Hatayama *et al.* 2005). In addition, the failure of the floating roof and the fire of oil-storage tanks have been observed frequently, e.g., during the 1964 Niigata earthquake and the 1983 Nihonkai-chubu earthquake, the sinking of the floating roof caused by sloshing has never been experienced so far in Japan (Matsui 2009).

Recently, Space Exploration Technologies (SpaceX) launched Demo Flight 2, Falcon 1 launch vehicle on March 20, 2007. Initially, instability grew in pitch and yaw axes, and after about 30 seconds a noticeable roll torque was also induced. This roll torque eventually overcame the 2nd stage's roll control thrusters and centrifuged the propellants, causing flame-out of the Kestrel engine. There is high confidence that LOX slosh was the primary contributor to this instability.

3. Detailed literature review

The nonlinear nature of sloshing is the greatest hindrance in solving such a problem analytically and even computationally. Further a number of assumptions are to be made, in which the solutions may deviate from the actual values. Experimental studies have been the most popular approach for liquid sloshing and have provided valuable insights into the physics.

3.1 General experimental procedure

In most of the studies, as shown in Fig. 1, the tank attached to a shaking table can be moved to and fro by a mechanical arrangement driven by a motor (Akyildiz and Unal 2005, Panigrahy 2006) or by a lathe machine (Pal *et al.* 2001) etc. For the pressure measurement, pressure sensors are fixed on the walls of the tank. The output of the pressure gages was fed to the channels of the data acquisition system or a data logger that was coupled to a PC. The data were decrypted using any commercial data acquisition software that displayed the output in millivolts. The free surface

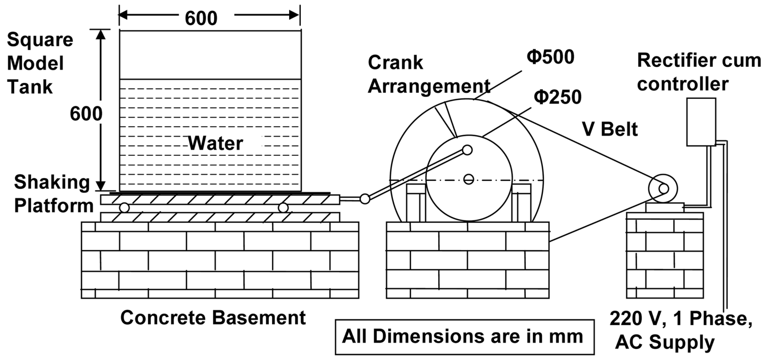


Fig. 1 A simple experimental setup for tank sloshing

displacement was captured using a motion movie camera or a laser sensor or some other capturing device. Popov *et al.* (1992) developed the sloshing setup for measuring liquid height to validate his numerical values. An electro hydraulic actuator fixed horizontally was used to generate translational motion of the tank in the horizontal plane. The displacement and acceleration of the tank as well as the force developed in the link between the tank and actuator were recorded. The liquid free-surface oscillations were also recorded with a video camera in order to compare them with those computed numerically at similar conditions.

3.2 Description of sloshing parameters

This section deals with the description of the sloshing parameters, such as container shape, excitation, flow impediment objects, fluids used, container wall, and the field in which the experiments are conducted. Fifteen research articles (Cole 1996, Dodge 1966, Bugg 1970, Sudo *et al.* 1987, Chiba 1992, Warnitchai and Pinkaew 1998, Modi and Munshi 1998, Grundelius and Bernhardsson 1999, Pal *et al.* 2001, Sakamoto *et al.* 2001, Sawada *et al.* 2002, Akyildiz and Unal 2005, Yano and Terashima 2005, Nasar *et al.* 2008, Panigrahy *et al.* 2009) have been chosen to find and analyze the effect of these parameters on sloshing. The work reported in these investigations has been compared, and summarized in Table 1.

3.2.1 Container shape

The first parameter concerns with the shape of the container which can be either symmetric or asymmetric. From Table 1, it is clear that both rectangular and cylindrical shaped containers seemed to have found equal importance. It is noticeable that no one used asymmetric container in their experiments. This is probably due to the fact that in real time applications, liquid tanks are often built symmetrically. The recent increase in demand for midsize tankers and LNG carriers entails more attention on the accurate prediction of sloshing fluid behavior inside tanks, whereby ship motions are more reactive to the external disturbances and the natural periods of sloshing are longer due to growing individual tank sizes and its shapes (Rhee 2005). In general, many researchers used basic container shapes like rectangular and cylindrical tanks for their analytical and numerical studies because of its simplicity. Other container geometries such as annular cylinder, horizontal cylinder, spherical, triangle, oblate spherical, canal shape, elliptic containers etc. have also been used in rare cases. The sloshing frequencies of a horizontally resting cylindrical tank are difficult to

Table 1 Comparative data of major sloshing parameters

Sl. No	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Research articles [See Footnote]	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[8]	[10]	[11]	[12]	[13]	[14]	[15]
(a) Container Shape								-							
Symmetric															
Rectangular	x			x		x	x			x		x		x	x
Cylindrical	x	x	x	x	x				x		x		x		
Asymmetric															
(b) Excitation															
Free Oscillation			x												
Forced Translation															
Linear								x							
Harmonic	x	x	x	x	x	x	x		x	x		x		x	x
Forced Rotation															
Random / Combination											x		x		
(c) Damping Devices															
No baffles		x	x	x	x			x	x	x	x	x	x	x	x
Horizontal Baffle	x											x			x
Vertical Baffle												x			x
Ring baffle	x								x						x
Semi-circular solid							x								
Others															
TSD/TLD						x	x								
(d) Fluids Used															
Inviscid fluid															
Water	x	x			x	x	x		x			x	x	x	x
Viscous fluid															
ER/MR Fluid				x						x	x				
Others		x	x					x							
(e) Tank Wall															
Rigid wall	x	x	x	x		x	x		x	x	x	x	x	x	x
Flexible Wall					x			x							
(f) Field															
Gravity Field	x		x	x	x	x	x	x	x	x	x	x	x	x	x
High bond number (Low / Micro gravity)		x													

x - the possibility was mentioned to exist; blank - the possibility was mentioned not to exist or was not mentioned.

[1] Cole (1966), [2] Dodge (1966), [3] Bugg (1970), [4] Sudo *et al*. (1987), [5] Chiba (1992), [6] Warnitchai and Pinkaew (1998), [7] Modi and Munshi (1998), [8] Grundelius and Bernhardsson (1999), [9] Pal *et al*. (2001), [10] Sakamoto *et al*. (2001), [11] Sawada *et al*. (2002) , [12] Akyildiz and Unal (2005), [13] Yano and Terashima (2001), [14] Nasar *et al*. (2008) and [15] Panigrahy *et al*. (2009).

obtain, even for an ideal frictionless liquid (Wiesche 2008). Study of the LNG container shapes and optimizing of container shapes are still interested topic. During the filling process in LNG ship container, the LNG exercises unsteady forces on the tank walls and makes the vessel react to these forces by ship motion. Baeten (2009) predicted the hydrodynamic wall pressure from LNG sloshing on different tank shapes and specific test cases have been validated against experimental data for launch vehicle tank fuel sloshing carried out at NASA test facilities.

Romero *et al.* (2005) conducted experiments to determine the magnitudes of lateral sloshing forces within tanks of three container shapes like oval, circular and modified oval (that are commonly used in commercial applications) under high fill volumes (about 90% to 98%). The results showed that the sloshing forces depends on the angle between the fluid free surface and the tank wall, the outage's length and average height of the tanks. For the 90% of fill level, highest sloshing forces first occurred on the circular tank followed by the oval and the modified oval shapes, respectively. However, for 98% of fill level, this order just got reversed. Moreover, the sloshing pressure was investigated for two different sized containers by Hwang *et al.* (2008). The container shape mainly defines the liquid free surface profile.

3.2.1.1 Effect of inclination of tank in sloshing

Bugg (1970) performed experiments to determine the effect on liquid oscillation frequency of changes in the angle (Fig. 2) between the tank axis and force body vector. Tank was tilted from 0° to 60° to the local vertical, and the liquid depth to tank radius (d/r) was also varied. Two modes of oscillation were studied, one with its nodal line along the minor axis of the liquid free surface, and the other with its nodal line along the major axis of the surface. The frequency of each of this modes was decreased by increasing the tank tilt, with the frequency of the former being decreased much more than the frequency of the latter. He concluded that the tank angle made only a small effect on shuttle propellant dynamics during launch for the expected 10° or less angle between thrust vector and tank axis. Very few reports dealt with sloshing in an inclined tank or inclined wall. These types of investigation were recently reported by Behr and Abraham (2002), Taniguchi (2004), Moaleji and Greig (2007), Liu and Lin (2008), and Sweedan (2009).

3.2.2 Excitation

The second important parameter concerns with the types of excitation that produces a free

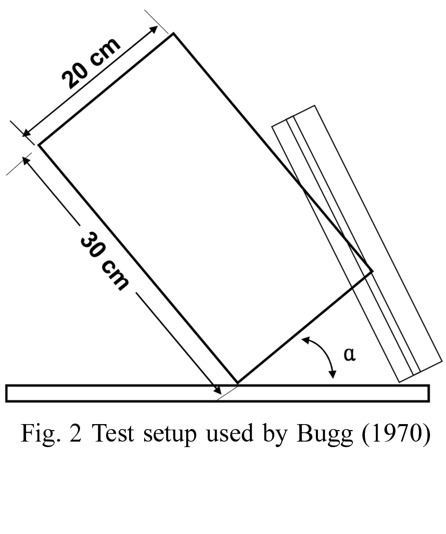


Fig. 2 Test setup used by Bugg (1970)

oscillation or a forced oscillation. A majority of investigators, 12 out of 15 made use of simple harmonic excitation which comes under forced oscillation. Only one of them used linear forced oscillation, while two of them used random forced oscillation. It is worth mentioning here that no participants have chosen rotation as their excitation type. Rotation motions can be considered for space vehicles and ocean going vehicles. The knowledge of natural frequencies for liquid free surface is important in the design of liquid containers subjected to different types of excitation. The dynamic behavior of a free liquid surface depends on the type of excitation and its frequency content. The excitation can be linear, sinusoidal, ramp or random. Its orientation with respect to the tank can be surge, sway, heave or pitch, yaw, roll or a combination of these.

Hashimoto and Sudo (1988) concluded from the vertical vibration of cylindrical liquid container experiments that the first resonant frequency of the axial vibration of the liquid column depends on the excitation acceleration. The first resonant frequency decreases as the excitation acceleration of the container containing liquid increases. The first resonant frequency of the axial vibration of the liquid column decreases as the liquid height in the cylindrical container increases. Colagrossi *et al.* (2004) observed an asymmetric behavior of the wave elevation along the tank, as well as alternation of the breaking phenomenon at the two tank sides. By varying the excitation period T of the sinusoidal horizontal motion of the tank, and by increasing its amplitude of oscillation, some peculiar phenomena were observed for T near the linear sloshing natural period $T1$. Such phenomena are connected with important water-wall interactions and with the vortex generation consequent to the post breaking phenomena. Because of their complex features, they cannot be predicted by potential-flow models.

The ship motions excite sloshing, which in return affects the ship motions. The sloshing induced roll moment on the vessel will cause roll damping by properly choosing the highest natural sloshing period close to the roll natural period. Under the roll excitation, the fluid in the horizontal cylindrical tank does not participate in the tank motion since it is assumed to be inviscid. If the fluid viscosity is considered, then one has to solve the full Navier-strokes equations to estimate the thickness of the fluid participating in the tank motion. Researchers generally applied the simple harmonic motion or linear motion to the sloshing tank.

In many practical situations, a system may undergo sudden changes such as mechanical impact, water hammer, etc. These can be represented and analyzed using an impulse input. In nature, very few things are periodic, even sinusoidal. Sinusoidal make up the particular class of periodic functions. It can be expressed in terms of cosine functions. One should, therefore, know necessarily how a measurement device responds to the sinusoidal input.

3.2.2.1 Excitation direction

There is no necessity to apply all the motions at the same time. It is just adequate that any one or two motions are merely applied to the tank in regard to the application. Type of tank motions is usually preferred based on the applications. For example, vertically excited motion is considered as idealized earthquake condition. Most of works reported are under earthquake condition where the tank is given a vertical motion or a combined excited tank motion (Frandsen and Borthwick 2003, Hashimoto and Sudo 1988).

3.2.3 Flow impediment objects

The third parameter deals with the kind of damping devices used for conducting experiments.

Investigations have been carried out without and with baffles (horizontal and vertical). Modi and

Munshi (1998) used a semi-circular solid damping device with a tuning arrangement. A liquid sloshing damper (TSD), also known as nutation damper or tuned liquid damper, operates on the principle of energy dissipation through liquid sloshing and wave breaking of the free surface. The device consists of a suitably shaped container partially filled with a liquid (e.g., water). When such a system is subjected to acceleration, the liquid is set into sloshing motion, accompanied by waves at the free surface. Such a device, in a sense, is similar to a multiple tuned mass damper (MTMD) because of its effectiveness over a range of frequencies (Modi and Munshi 1998). With a proper design, a tank partially filled with liquid can be used as an effective damper for suppressing horizontal vibration of structures. This type of damper has gained popularity in practical use due to its low cost and simplicity (Fujino *et al.* 1992, Ueda *et al.* 1992). A tuned liquid damper (TLD) had been used to utilize the dynamic effect of liquid sloshing (Warnitchai and Pinkaew 1998). TLD is used to adjust the natural frequency of the system by adding or removing weights.

3.2.3.1 Baffles to reduce the sloshing

Baffles are generally used as passive slosh damping devices in the liquid storage containers to obstruct the vertical velocity of the sloshing fluid. The basic concept of passive sloshing damper is to dissipate the sloshing motion energy by breaking a main sloshing flow into several weaker sub-streams. Different types of baffles viz., horizontal, vertical, and annular or ring baffles have been used in the past (Pal *et al*. 2001, Akyildiz and Unal 2005, Panigrahy *et al.* 2009). They can be either flat or curved structures fixed to the walls of the tank. These structures lie on the liquid-flow path, and hence act as a barrier for the smooth flow of the fluid, and have varied functions depending on the circumstances. They are used for dissipating the kinetic energy of fluid in motion, enhancing the mixing process in a mixing tank and yet sometimes for aggravating convection in heat generating regions. The flow impediment objects drastically reduce the free surface elevation, and also the hydrodynamic pressure.

Cole (1966) conducted ink-trace experiments in a cylindrical tank to study the baffle thickness effects in fuel sloshing. His work on the effectiveness of baffle with respect to amplitude to width ratio (A/W) showed that baffle thickness decreases baffle effectiveness by as much as 50 percent at moderate amplitudes of oscillation (Fig.3). Pal *et al.* (2001) studied the free surface displacement of the liquid with respect to time (Fig. 4) in a tank equipped with ring baffles. Akyildiz and Unal (2005) investigated liquid sloshing in a rectangular tank at a model scale with various fill levels and baffles. Fig. 5 shows the typical arrangement of vertical and horizontal baffles used by Akyildiz and Unal (2005). Fig. 6 shows the pressure distribution curves in a tank with and without baffles. In an experimental study, Panigrahy (2006) investigated the effect of baffles on sloshing behavior of liquids in a rectangular tank by studying pressure variation with respect to time (Fig. 7). The observation shows that the ring baffles are the best choice as they reduce the pressure to the maximum extent. This happens because the ring baffle not only suppresses the velocity of impact of the fluid at the walls, but also retards the vertical motion of the liquid near the other two adjacent walls, thereby suppressing the wave amplitude. The introduction of baffles in the tank decreases the sloshing effect by a considerable amount. This is because the baffles create turbulence in the flow field thereby dissipating the excess kinetic energy to the walls. Baffles can significantly reduce fluid motions, and more investigations are needed to study the effect of the fluid viscosity on impact pressures.

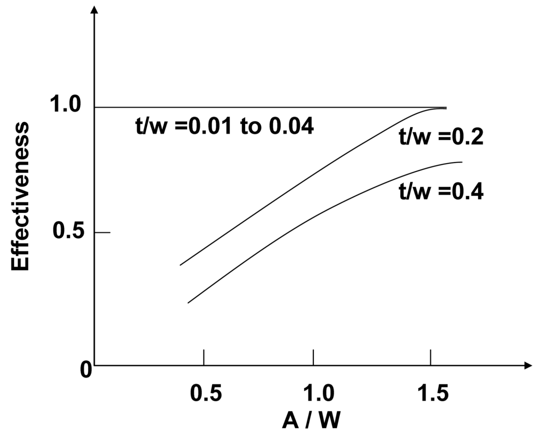


Fig. 3 Variation of the baffle thickness with amplitude to width ratio (Cole 1966)

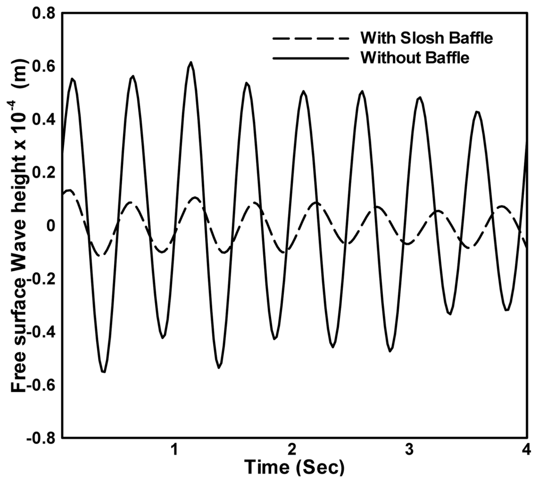


Fig. 4 Experimental observation (Pal *et al.* 2001)

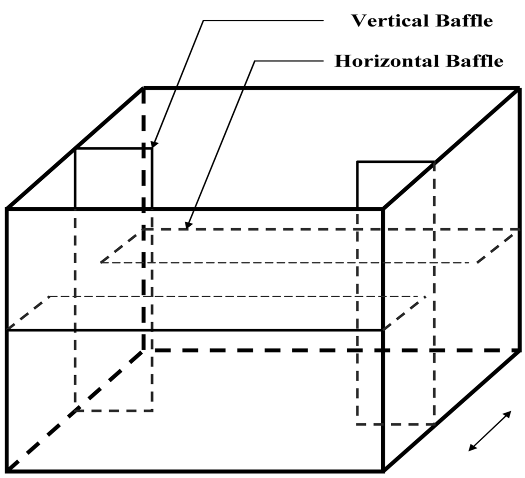


Fig. 5 Tank with vertical and horizontal baffles

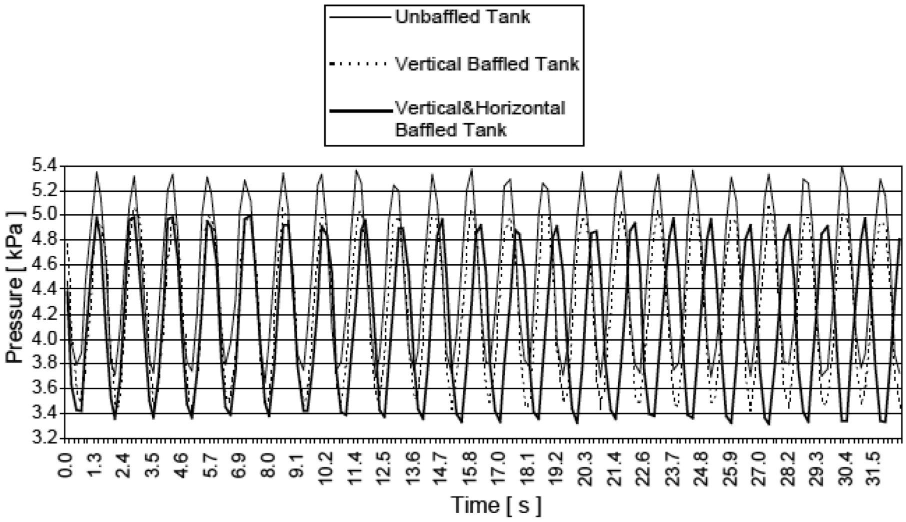


Fig. 6 Experimental data by Akyildiz and Unal (2005)

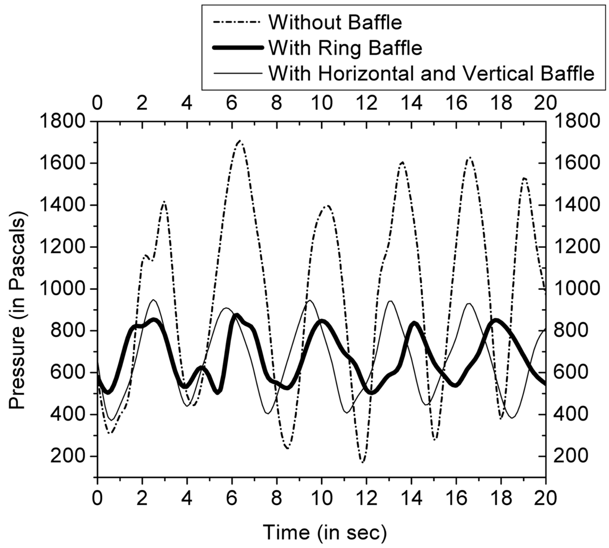


Fig. 7 Experimental observation (Panigrahy *et al.* 2009)

3.2.3.2 Effect of sloshing in tuned liquid dampers

When the fluid imparts forces to its container which in turn are transmitted to the vibrating structure influencing its motion, the imparted forces during sloshing are inertial, gravitational, and dissipative in nature (Sayar and Baumgarten 1982). Use can be made of the inertial forces for vibration absorption and of the dissipative forces for damping. Tuned Liquid Dampers, encompassing both tuned Sloshing dampers (TSDs) and Tuned Liquid Column Dampers (TLCDs), have become the popular form of initial damping device. A tuned sloshing damper (also known as nutation damper) is extremely practical and operates on the principle of energy dissipation through liquid sloshing and wave breaking of the free surface. Fundamental mode frequency of liquid sloshing is tuned to the natural frequency of structure, and the damping ratio of the sloshing mode is set to an optimal value (Vandiver and Mitome 1982, Guzel *et al.,* 2004).

A tank partially filled with water can be used as an effective damper for suppressing horizontal vibration of structures. This damper is called Tuned Liquid Damper (LTD) because it utilizes the dynamic effect of liquid sloshing, which is similar to the effect of a Tuned Mass Damper (TMD). Such dampers are already used in tall structures in Japan and Australia (Modi and Munshi 1998) and in some developed countries, for example, in the John Hancock Tower in Boston and Citicorp Building in the New York city. A conventional TMD is generally tuned to a single frequency. To overcome this limitation, the MTMD (Multiple Tuned Mass Damper) system has been proposed (Fujino 1992). The MTMD consists of an array of small TMD whose natural frequencies are distributed over a certain bandwidth. The advantage is that the MTMD is insensitive to mistuning and errors. The device consists of a suitably shaped container partially filled with a liquid (e.g., water). When such a system subjected to the acceleration, the liquid is set into sloshing motion, accompanied by waves at the free surface. Such a device, in a sense, is similar to a MTMD because of its effectiveness over a range of frequencies.

Modi and Munshi (1998) focused on enhancing the energy dissipation efficiency of a rectangular liquid damper through introduction of an obstacle. He conducted experiments with a family of semicircular cross-section obstacles (Fig. 8), determined their effectiveness in increasing the damping and also evaluated the effectiveness of the improved liquid sloshing damper (in suppressing both vortex resonance and galloping type of FSI instabilities). Fig. 9 shows the performance of the damper as a function of liquid height (h_W) for various r/L ratios (L and r being the length of the tank and the optimum obstacle height respectively). The plot for r/L =0 indicates the results in the absence of an obstacle. His plots shows that for r/L =0, there is a relative sharp peak in the damping factor (ζ) versus h_W/L curve. In comparison, for r/L =0.0162, the peak in ζ extents over the wider range of liquid heights. The peak in r/L =0.0595 is shifted to the right and occurs at a much higher liquid height.

3.2.4 Fluids used

The fourth parameter associated with sloshing concerns with the type of fluids used in the experiments. Most of the researchers preferred water as a fluid in their studies not only because it is easily available, but also it satisfies their practical needs effectively. For example, even if the real plants like casting industries are considered, it is possible to use water in the study. This is because the Reynolds number of water at normal temperatures is almost the same as that of molten iron or molten aluminum at high temperatures considering the similarity law in fluid dynamics. Demirbilek (1982, 1883) had given a detailed explanation of Reynolds number and Froude number values for

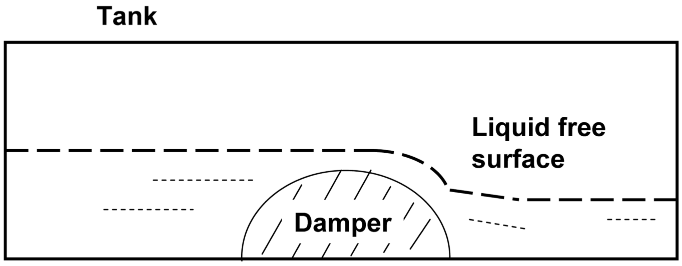


Fig. 8 Liquid sloshing - flow fast an obstacle (Modi and Munshi 1998)

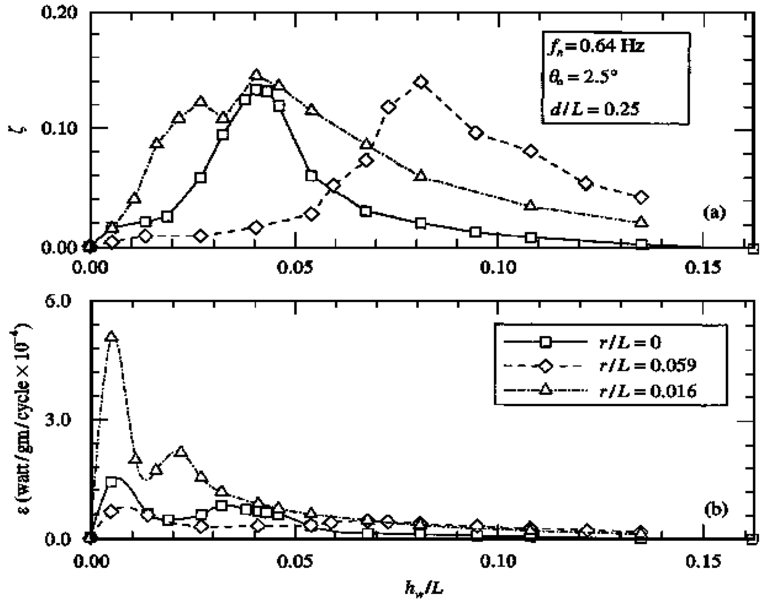


Fig. 9 Performance of the liquid damper as affected by the liquid height (h_W) (Modi and Munshi 1998)

numerous areas. For example, the kinematic viscosities of molten iron metal at 1350 K and 1400 K are 1.365×10^{-6} *mPa.S* and 1.237×10^{-6} *mPa.S*, respectively, while that of water at 293 K is 1.0×10^{-6} *mPa.S* (Yano and Terashima 2005, Terashima and Yano 2001).

3.2.4.1 Effect of compressibility of fluid

Topliss *et al.* (1992) studied the water impact on a wall with air bubble formation and developed a potential flow model to determine the frequency of oscillation of the bubble pressure. As reported by Godderidge *et al.* (2009), Topliss *et al.* (1992) potential flow model overestimates the experimentally observed pressure oscillation frequency. Godderidge *et al.* (2009) studied the effect of compressibility various combinations of compressibility models for air and water and found that the inclusion of fluid compressibility can have a significant effect on the pressure evolution of a sloshing flow. During and immediately after impact, air and water are mixing with a wide range of air bubbles entrained in the water. The air bubble is enclosed and compressed by the bulk fluid motion. The air bubbles increase the compressibility of the impacting fluid mixture (Dias *et al.* 2008) and consequently a lower pressure is observed. This results in the air pressure exceeding the surrounding water pressure. This pressure gradient redirects the water flow away from the air bubble, giving a lower pressure in the air than in the surrounding fluid. The resulting pressure gradient causes the water velocity to change towards the bubble (Godderidge *et al.* 2009). This process is repeated until the air bubble is dissipated or moves to the free surface. When fluid impact is not a significant feature of the sloshing, then an incompressible fluid model can be used for both fluids. When modelling sloshing with significant air entrapment, compressibility of both air and water should be included. An isothermal compressibility model for air may still be preferable. The non-dimensional pressure impact parameter is based on the tank size. When fluid impact with large air bubble formation is a defining flow feature, the flow models need to include compressibility effects. The calculated pressure at the point of impact is higher when incompressible fluid models are used. In the vicinity of the impact bubble, the calculated pressure is approximately 20% greater when using compressible fluid models for air and water (Godderidge *et al.* 2009). So rise of pressure during impact, can be used to determine whether air and water should be modeled as compressible fluids

Hashimoto and Sudo (1988) investigated the bubble cluster formation in the liquid and container wall responses during the vibration. Bubble formation was observed in cylindrical containers. It was found that the resonance frequency of the liquid-container vibration system depended on the excitation acceleration. The response of the liquid pressure and the container wall acceleration was suddenly changed by the formation of a bubble cluster in the oscillating liquid column.

3.2.4.2 Effect of sloshing in magnetic field

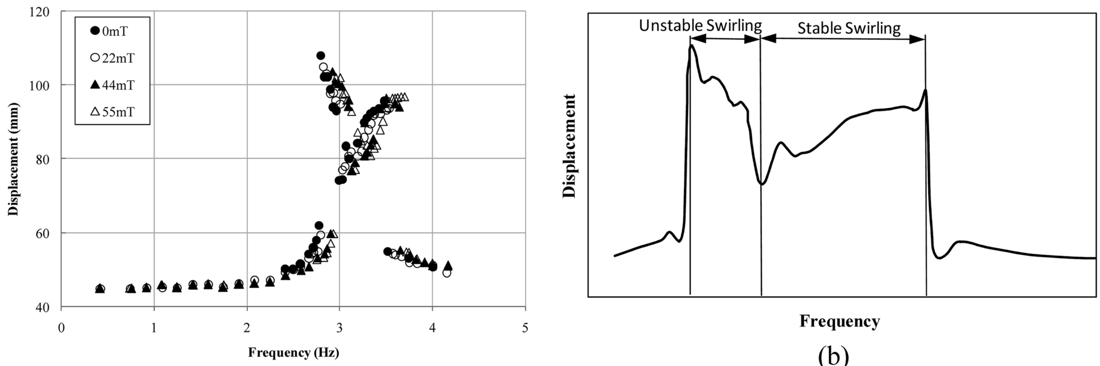
A few articles as shown in Table 1 were concerned with magnetic rhelogical (MR) and electro-rhelogical (ER) fluids. Magnetic fluids were developed as a way to control the position of liquid fuel in space (Papell 1965). In particular, when a magnetic field is applied to a magnetic fluid, several interesting characteristics have been observed because of the combination of the strong magnetism and liquidity (Sawada *et al.* 2002). When the non uniform magnetic field is applied to the container, the resonant frequency of the system will move towards the high frequency region with the magnetic field intensity. ER fluids are same as the magnetic fluids, but it needs electric field instead of magnetic field. From Table 1, it can be seen that only in three cases, investigators used fluids like methanol, carbon tetrachloride (CCl_4) etc., other than water, MR and ER fluids.

Sawada *et al.* (2002) examined sloshing in a magnetic fluid subjected to a magnetic field. They executed the displacement study and calculated power spectra from the measured velocity data in the time and space domains in order to clarify the influence of the magnetic field on the swirling mechanism. For that, three volumes of water based magnetic fluid (W-40) were mixed with two volumes of water and the weight concentration of the magnetic particles (Fe_3O_4) is 27%. They concluded that when the forcing frequency exceeds the first resonance frequency, the free surface begins to rotate around the center axis of the container with no fixed direction. The area labeled "Unstable Swirling" in Fig. 10 corresponds to this phenomenon.

When the forcing frequency raises the past frequency B, the unstable swirling changes to "stable swirling" in which the rotation direction is fixed. The surface elevation reaches a local maximum at a forcing frequency A, and rapidly decreases. The frequency of points A and B at various magnetic field intensities is indicated in Table 2. This increase in frequency is caused by the increase in effective gravity due to the magnetic force. Most dominant peak in power spectra is moved to the higher frequencies as the magnetic field intensity was increased. Many researchers (Sudo *et al.* 1987, Papell 1965, Sawada *et al.* 1993, 2002, Rosenweig 1997) proposed and used this approach. Magnetic field has been used as slosh damping devices in the liquid storage containers to reduce the impact load on walls of the container and to reduce the surface displacement.

3.2.4.3 Effect of sloshing in electric field

Electro-Rheological (ER) fluids change their physical properties in the presence of an electric field. The effect is sometimes called the Winslow effect, after its discoverer, who obtained a US patent on the effect in 1947 and published an article in 1949 (Winslow 1949). Sakamoto *et al.* (2001) proposed the Tuned Sloshing Damper (TSD) utilizing an electro-rheological (ER) fluid as a sloshing liquid (ER-TSD) and carried out the experiments for the forced and free vibration tests



(a) (b)

Fig. 10 Frequency response of the free surface Sawada *et al*. (2002)

with and without ER-TSD. In the course of the experiments, the electric field between the electrodes and fill levels were varied to find the maximum displacement.

ER-TSD sloshing frequency can be controlled by applying the electric field to the ER fluid as shown in Fig. 11. By controlling electric field, the ER-TSD can suppress the vibrations of the structure even when the natural frequency of the structure changes. The sloshing frequency of the rectangular tank generally characterized by its length l and depth h is given by

Table 2 Frequencies of the highest and lowest free surface displacements in stable swirling (Sawada *et al.* 2002)

Magnetic field induction (mT)	Highest elevation (A) (Hz)	Lowest elevation (B) (Hz)
0	3.50	3.00
22	3.53	3.03
44	3.63	3.13
55	3.70	3.17

$$f = \frac{1}{2\pi}\sqrt{\frac{\pi g}{l} tanh\left(\frac{\pi h}{l}\right)} \qquad (1)$$

where g is the acceleration of gravity. Experimental observations of ER-TSR sloshing frequency for varying fill levels are presented in the Table 3. The experimental value of the sloshing frequency at zero electric field is almost the same as that calculated theoretically for the tank of a length of 180 mm. When an electric field of 600 V mm^{-1} is applied, the measured sloshing frequency at different liquid levels appears to be in close agreement with that predicted from the calculations of the sloshing frequency in a tank of 120 mm in length. This means that after the application of the 600 V mm^{-1} electric field to the ER fluid, the apparent length of the tank changes from 180 to 120 mm. The sloshing frequency is determined as a frequency corresponding to the maximum liquid displacement.

It is seen from Fig. 12 that when an electric field is applied, the sloshing frequency can be increased. When the ER fluid between the electrodes is solidified completely, the apparent length of the tank can be considered as 120 mm. The vibrations of structure B were most effectively

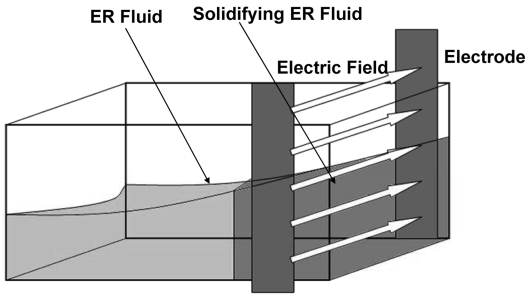


Fig. 11 Principle of ER-TSD (Sakamato *et al.* 2001)

suppressed when an electric field of 600 V mm^1 was applied to the ER fluid (Fig. 13).

3.2.5 Container wall

The fifth item concerns with the type of tank wall which can be either rigid or flexible. A majority of the investigators used rigid wall tank. Distribution of hydrodynamic pressure due to excitation gets influenced by wall flexibility. Chiba (1992) conducted experiments for studying the effect of wall flexibility in the nonlinear hydro elastic vibration of a cylindrical tank with elastic bottom containing liquid. However, in most of the researches, the tank was made up of plastic like perspex, acrylic or glass material. Usually, these materials are considered as rigid walls. The rigid and flexible walls also one of factors effecting the sloshing forces, moments and pressure at the tank wall.

3.2.6 Field

The last item under consideration deals with the field where most of the experiments have been conducted in gravity fields. Dodge (1966) conducted experiments with high bond number by varying the radius of the tank as applicable in space. The problems of liquid slosh dynamics under microgravity are different from those encountered in a regular gravitational field. These problems include liquid reorientation and the difficulty of moving and handling, since body force is almost negligible.

3.3 Sloshing Under Micro and Zero Gravity Fields

The earliest calculations of sloshing on spacecraft were concerned with propellant in launch

Table 3 Experimental observations of ER-TSD sloshing frequency (Sakamoto *et al.* 2001)

Parameter	Applied electric field (V mm^{-1})	Liquid level (mm)			
		20	30	40	50
Experimental sloshing frequency (Hz)	0	1.20	1.45	1.60	1.75
	200	1.70	1.95	2.10	2.25
	400	1.75	2.00	2.20	2.30
	600	1.75	2.05	2.20	2.35
Theoretical sloshing frequency (Hz) (From Eqn. 1)	Tank length : 180 mm	1.21	1.44	1.62	1.75
	Tank length : 120 mm	1.77	2.06	2.25	2.37

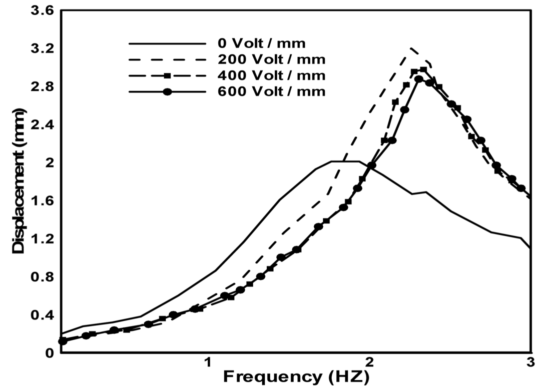


Fig. 12 Displacement vs. frequency (Sakamoto *et al.* 2001)

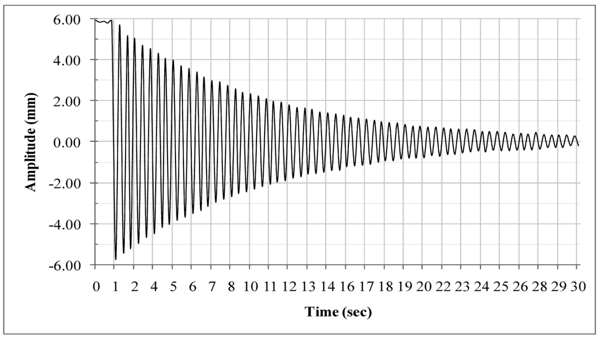


Fig. 13 Amplitude vs. time (Sakamoto *et al.* 2001)

vehicles. This work dates to the 1960s when the NASA Saturn class vehicles had problems with uncontrollable oscillations due to sloshing. These studies considered only the gravitational force, with g-levels of one and larger; surface tension and rotation were neglected (Snyder 2004). In low-gravity sloshing, the surface tension of the liquid plays an overwhelming role in comparison to the gravitational force (Utsumi 2004). While modeling numerically, the curved static liquid surface, which is called the meniscus, makes the problem geometrically more complicated than the sloshing problem under normal gravity, especially for an arbitrary axisymmetrical container with curved walls and top (Utsumi 2000).

Under microgravity, the surface tension forces become predominant. The bond number, given by the ratio of the gravitational to capillarity forces (Eq. 2), plays a major role in the free surface liquid characteristics, where, R is the radius of the tank and g is the gravitational acceleration and ρ is the liquid density and σ is the surface tension coefficient.

$$Bo = \frac{\rho g R^2}{\sigma} \tag{2}$$

The behavior of liquid sloshing in microgravity was studied on several occasions by Bradford (1999), Snyder (1999, 2004), Luppes *et al.* (2006), Yuanjun *et al.* (2007), Utsumi (2008).

Table 4 Comparative analysis of experimental investigations in gravity field

Author details	Aim	Force Applied, details of tank and baffles	Instruments, materials and varying parameters	Remarks
Cole (1966)	To study the effect of baffle thickness from forced oscillations 2D tank (Analytical) Free oscillation-cylindrical tank (Analytical & Experimental)	Sinusoidal motion. Tank: 1) A plate 1/16 inch thick. 2) 3-foot-diameter cylindrical tank. **Fluid:** Water **Baffle:** length 6.1" and thickness 1.2" 2D tank -spanning the width of the tank. Cylindrical-ring baffles.	India ink was introduced. **Motion** -16 mm movie camera. **Variables**: Amplitude (A) / width (W) ratios - 0.33 to 2.5. Reynolds no. $5x10^3$ to $40X10^3$.	1. Moderate baffle thickness Reduce the baffle effectiveness by as much as 50%. 2. The effectiveness of fuel-sloshing baffles depends on the thickness of the baffle and the amplitude of oscillation. 3. In comparison of theory and experiment in small-scale tests, results are not reliable unless actual similarity of flow is established.
Bugg (1970)	To determine the effect on liquid oscillation frequency of changes in the angle between the tank axis and the body force vector.	Longitudinal excitation. **Tank**: Plexiglass right circular cylindrical. 20 cm inner dia 38 cm tall. **Fluid:** distilled water with two parts per thousand Aerosol MA. **Baffle:** ---- No------	**Viscosity**: Oswalt-type viscometer. Period of oscillation: Stop watch. **Inclination** of the Tank 0^o, 30^o, 45^o and 60^o.	1) The longitudinal mode, the frequency parameter (w^2) was reduced, by inclining the tank at 60°, to 27°% of its value with the tank upright. 2) Tank tilt should have only a small effect on Shuttle propellant dynamics during launch for the expected 10^o or less angle between thrust vector and tank axis.
Chiba (1992)	To find out the influence of elastic bottom wall in a tank by varying sheet thickness.	Harmonic vibration **Tank**: Cylindrical container inner R = 144 mm L=520 mm, sidewall thick 6 mm. Flexible bottom wall Polyester sheet of thick (i) 0.254 (ii) 0.357. **Fluid:** Water	**Displacement**: Optical Displacement sensor Oscilloscope. Variables: (i) Bottom wall thickness (ii) Height of the bottom wall. (iii) water height (iv) frequency	1. Center of the bottom plate is excited with constant frequency, then the amplitude is increased the free surface loses its stability and sways in a horizontal direction, its peak vibrating in the radial direction of the free surface. 2. The nonlinear characteristics of liquid exhibits a softening behavior for large liquid heights, while for decreased liquid heights it changes to a hardening type.
Warnitchai and Pinkaew (1998)	To develop a new mathematical model of liquid sloshing in rectangular tanks for TLD applications. Experimental and analytical investigations to check the effects of flow-dampening devices.	Sinusoidal motion **Tank:** Rectangular acrylic tank with 40 X 20cm. **Fluid:** Plain water. Damping ratios obtained from: (a) a plain tank. (b) A tank with two circular section poles of d = 22 mm. (c) A tank with a flat plate of d= 50 mm and thickness = 3 mm. (d) A tank with a wire-mesh screen with wire diameter = 0.26 mm and solidity ratio = 0.29.	**Feedback**-control hydraulic actuator –drive the shaking table (one-dimensional type). **Displacement** transducer - the motion of tank. The force transducer-(steel pipe attached with two semiconductor strain gauges). **Variables:** Water depth ratio was set to 0.3. (All cases).	Damper application, a new mathematical model of liquid sloshing in rectangular tanks has been developed. 1. Model can accurately represent the complex behavior of liquid sloshing. 2. Increase in sloshing damping, the non-linear characteristics of the damping, and the slight reduction in sloshing frequency.

Table 4 Continued-1

Author details	Aim	Force applied, details of tank and baffles	Instruments, materials and varying parameters	Remarks
Modi and Munshi (1998)	1. Study the performance characteristics of a rectangular liquid sloshing damper, without any obstacle. 2. Experiments with a family of semicircular cross-section obstacles, their effectiveness in increasing the damping. 3. To evaluate the effectiveness of the improved liquid sloshing damper.	Angular vibration. **Tank:** Rectangular L=370 mm, W=166 mm, and H=125 mm. **Obstacles:** family of obstacles (r = 6-22 mm). **Fluid:** Plain water.	**Displacement** of the rod - strain-gauged beam -output is processed by - signal conditioning – **amplification**- spectrum analyzer- computer. Variables: Height of the liquid-0–60 mm. **Angular displacement**-1°-2.5°.	1) Increased up to 60%, in the energy dissipation capacity of the liquid sloshing damper by introduction of an optimum obstacle. 2) The presence of an obstacle leads to a wider peak, i.e., to higher damping over an extended range of liquid frequencies. 3) The performance of the damper depends on both the frequency ratio (f_n/f_l) and initial displacement (h_o). 4) Optimum size and location of the obstacle as r/L=0.016 and d/L=0 (i.e., one obstacle).
Grundelius and Bernhardsson (1999)	To capture the free surface elevation using techniques from optimal control both numerically and analytically. To calculate the acceleration profile for the container using optimal control techniques.	**Tank:** Rectangular container. Height of fluid = 0.2 m and Width of the tank = 0.07 m.	**Surface elevation:** Infrared laser displacement sensor. Small video camera. Carriage is mounted on a belt driven by a servo system. **Variables**: 1. Max. Acceleration = 9.81 m. 2. Max. Slosh = 0.035 m. 3. Initial State= [0 0 0 0] m Final state-[0 0 0 L]. Movement distance L= 0.2 m. $a(t) = \begin{cases} 6 & 0 \geq t < 0.05 \\ -6 & 0.05 \geq t < 0.1 \\ 0 & 0.1 \geq t \end{cases}$	1) Open container with liquid should be moved quickly without excessive slosh. 2) The calculated controllers have been implemented and verified in an industrial test bed and give better performance than previous controllers.
Pal *et al.* (2001).	To conduct experiments for measuring some of the basic parameters of sloshing, and to verify certain parametric relationships with numerical computations.	(Horizontal) excitation and sinusoidal motion. **Tank:** Perspex cylindrical tank. (R=96 mm) Fluid: water. Baffle: ring baffle of 25 mm width and 6 mm thickness.	Shaking- a lathe machine Cam mechanism- Circular to a linear movement of the platform. **Platform**- linear variable differential transducer. DAS-32-channel dynamic data acquisition system. **Displacement**- wave height sensors. Varying Parameters: Fill level =30-30-150.	1. Experimental studies allow researchers to check the validity of assumptions of the mathematical model and to employ the model effectively for design applications. 2. Measurement of free-surface liquid response in absence of any excitation source is done to assess possible slosh suppression techniques from the rate of decay of the slosh amplitude.

Table 4 Continued-2

Author Details	Aim	Force applied, details of tank and baffles	Instruments, Materials and Varying Parameters	Remarks
Sakamoto *et al.* (2001)	To design and fabricate a TSD both experimentally and analytically.	**Tank:** Rectangular tank. Length=120 mm. Depth of fluid = 30 mm **Fluid**: Electro-rheological (TX-2128 ER fluid).	**Displacement:** non-contacting Laser displacement pick-up. Variables: Frequency: 0.1 - 0.05 - 3.0 Hz. Electric field bt. the electrodes: 0, 200, 400 and 600 V mm−1. Four liquid levels: 20, 30, 40 and 50 mm. (*a*) Without the ER-TSD. (*b*) With the ER-TSD and no electric field. (*c*) With the ER-TSD and an electric field of 600Vmm1.	1) Sloshing frequency of the ER-TSD can be controlled by applying the electric field to the ER-TSD. 2) ER-TSD can suppress the vibrations of the structure even when the natural frequency of the structure changes. 3) The effects of the ER-TSD on the structural responses are qualitatively explained in terms of the simplified TMD model.
Akyildiz and Unal (2002)	Experimental investigations on the pressure distribution around a large vertical cylinder fixed on a wave channel, piercing the free surface.	**Tank:** Vertical cylinder: 4.9 m wide and 28.1 m long wave channel with a constant water depth of 0.45 m. Fluid : Water depth 45 cm. d /a = 1.2328. a=radius of tank.	**Pressure:** 0.1 bar pressure transducers. **Data logger:** Agilant 34970 automatic DAS. Variables: a direct current motor; a 1/15.7 reducter of AT32 type with a 4 kW power. Pressure distribution :	1) The experimental results near the free surface do not agree well with the diffraction theory of Akyildiz (1999). 2) Experimental results correlate better with the second-order solution. 3) Linear and the second-order theory give different results for the front and back sides of the cylinder.
Akyildiz and Unal (2005)	To develop an experimental system accounting for the effects of large tank motions, large amplitude wave motions, fluid viscosity and baffle arrangements.	Harmonic excitation. **Tank:** Rectangular tank. 92X62X46 cm model tank. **Baffle:** Bottom transverse - larger baffle - (15.4 cm high) made of 1.5 cm Plexiglas plate. Right side- A smaller baffle (7.6 cm high) 1.5 cm Plexiglas plate. **Fluid:** Water.	**Pressure:** Nine pressure transducers (PT), sensitivity 0 to 1 bar. **Data logger:** Agilant 34970 automatic DAS. **Platform**: Base frame was driven by DC motor (15 kW). **Variables:** Fill level : (d/H)=0.25,0.5,0.75 Pitch angle: 4, 8. Frequency: 0.5 - 3.785.	1) Baffles significantly reduce fluid motion and also more experimental investigations are needed considering the effects of fluid viscosity on impact pressures. 2) Model studies for sloshing under multi-component random excitations with phase difference should be carried out to investigate sloshing load.
Yano and Terashima (2005)	To develop a liquid container transfer system with a 3-D transfer path that suppresses sloshing without vibration feedback.	Linear motion. Tank: 3-D cylindrical container. 0.12 m and its height is 0.3 m. **Fluid**: water. The static liquid level is 0.16 m.	**Displacement:** two-level sensors **Variables:** Proposed gain 34.0, 55.5, and 61.5. Start point [0,0,0] Endpoint [0.3, 0.3, 0].	1) Hybrid shape approach was applied for trajectory control with vibration damping on transfer systems with vibration mechanisms. (With restriction control specifications in both the time and frequency domains, using only feedback on the container's position.)

3.4 Comparative Analysis

Tables 4 and 5 give a vivid picture of the complete summary of investigations highlighting details of experimentation such as type of oscillations, tank dimensions, fluids used, type of baffles, and the their key findings. Table 4 shows the studies carried out for the gravity field, while Table 5 focuses on low or zero gravity.

4. Conclusions

Experimental studies endorse researchers to check the validity of assumptions of the mathematical model, numerical simulations and to employ the model effectively for design applications. Adequate understanding of any complex physical phenomenon such as sloshing is enhanced to a great extent by the use of experimental techniques. A survey of literature has indicated various experimental investigations by several researcher(s) on study of liquid sloshing and its control techniques. The overall observation from these experimental results gives an idea that sloshing in a tank is a function of the liquid depth, the dimensions of the tank, the amplitude, and frequency of excitation and density of the liquid. As the amplitude of excitation is increased, the liquid responds violently such as occurrence of turbulence, hydraulic jump, wave breaking and three-dimensional effects. Therefore, the rolling amplitude and frequency of the tank directly affected the degrees of non-

Table 5 Comparative analysis of experimental investigations on low or zero gravity

Author details	Aim	Force applied, details of tank and baffles	Instruments, materials and varying parameters	Remarks
Luppes *et al.* (2006)	To conduct the experiments with the mini satellite Sloshsat FLEVO, (containing a partially filled water tank). To compare the experimental and numerical results.	Angular velocity and Linear oscillation. **Tank** Cylindrical shaped fluid tank with hemispherical ends. Vol. = 86.9 liter. **Fluid** 33.5 kg of Distilled Water.	Experimental and Numerical Displacement: The result of rotational components in z directions (ω_Z) shows a clear difference between simulation and experiment (Fig. A1). Although the frequency of the nutation in ω_Z is comparable, in the simulation the amplitudes are too small. A proper calibration of the measured data may yield a favorable correction of the measured values of ω, especially with respect to the small value of ω_Z.	1. At low rotational rates and small-scale liquid motion, capillary effects are important for the obtained damping of manoeuvre-induced oscillations in the angular velocities. 2. The use of a dynamic contact angle in the numerical model probably yields a better agreement between simulation and experiments at low rotational velocities and is recommended.
Labus (1969)	To find the natural frequency of liquid sloshing in an annular cylinder by experimental under low gravity condition. To determine the effect Bond no in natural frequency.	Lateral impulse force **Tank** Annular Cylindrical. **Fluid** Freon-TF, and FC-78.	Natural frequency for zero Bond number: The relation between the natural frequency, annulus ratio, and the Bond number was described based on high Bond number theory and low Bond number in Fig. A2.	1. The annular natural frequency parameter depends on the annulus ratio under zero Bond condition. 2. The natural frequency at all Bond numbers was dependent on the annulus ratio.

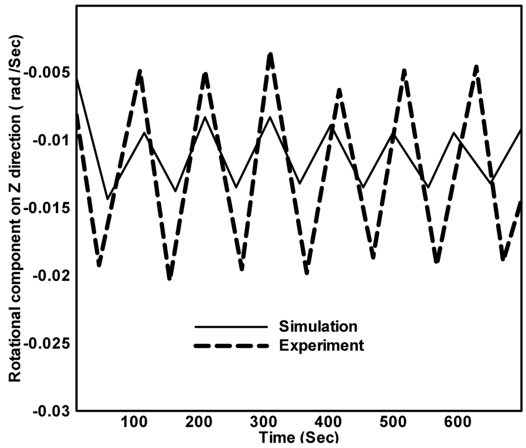


Fig. A1 Experimental and numerical displacement (Luppes *et al.* 2006)

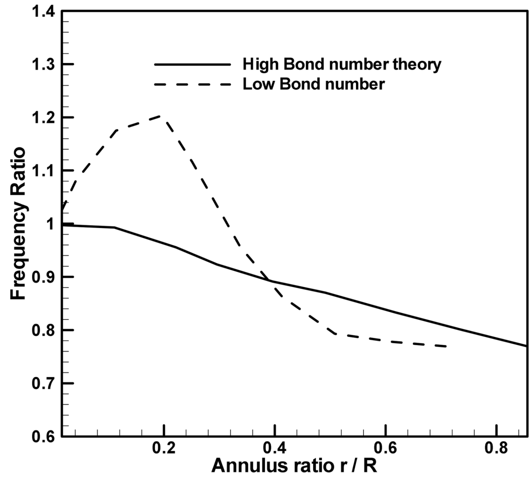


Fig. A2 Natural frequency for zero Bond number (Labus 1969)

linearity of the sloshing.

The suppression of sloshing behavior using baffles is also a subject of interest in the recent years. The effectiveness of fuel-sloshing baffles depends on the thickness of the baffle and the amplitude of oscillation, and these effects should be taken into account in applying model results to full-scale designs and in comparing results of experiments. The baffle has significant effect on the non-linear slosh amplitude of liquid when placed close to the free surface of liquid. The effect is almost negligible when the baffle is moved very close to the bottom of the tank. Modi and Munshi (1998) suggested a significant increase, up to 60%, in the energy dissipation capacity of the liquid sloshing damper by introduction of an optimum obstacle in the path of the moving liquid.

As reported by Bogaert *et al.* (2010), full scale wave impact tests have been carried out at scale 1 to 6 in order to study the scaling effects. These tests are referred to as the large scale tests. The large scale test set-up mimicked as far as possible the full scale setup. The preliminary results were overviewed by Brosset *et al.* (2009).

The sloshing frequency of the ER-TSD system can be controlled by applying the electric field to the ER fluid and we can tune the natural frequency of the system. The ER-TSD can suppress the vibrations of the structure even when the natural frequency of the structure changes. The experimental results concerning the effects of the ER-TSD on the structural responses are qualitatively explained in terms of the simplified TMD model, including the ER-TSD. Magnetic field has been used as slosh damping devices in the liquid storage containers to reduce the impact load on walls of the container and to reduce the surface displacement. Instruments like Doppler anemometry or particle image velocimetry (PIV) have been used to measure the velocity profiles during sloshing. In the view of the microgravity fluid physics, several forces determine the nature of surface waves. When the fluid is not rotating, the relevant forces are surface tension and gravity. With rotation, the centrifugal and coriolis forces are also present. In the space sloshing study, the motion of the container can be specified by three translations and three rotations about the center of mass of the liquid.

Acknowledgements

The authors wish to thank and acknowledge Elsevier for giving permission to reproduce Figs 6 and 9 of this paper from the following two publications, respectively.

Ocean Engineering, Vol. **32,** Akyildiz, H. and Unal E., "Experimental investigation of pressure distribution on rectangular tank due to sloshing", pp. 1503-1516, 2005.

Journal of Fluids and Structures, Vol. **12**, Modi, V.J. and Munshi S.R., "An efficient liquid sloshing damper for vibration control", pp. 1055-1071, 1998.

References

Abramson, H.N. (1966), "The dynamics of liquids in moving containers", Report SP 106, NASA.

Akyildiz, H. and Unal E. (2005), "Experimental investigation of pressure distribution on rectangular tank due to sloshing" , *Ocean Eng.*, **32**(11-12), 1503-1516.

Akyildiz, H. (2002), "Experimental investigation of pressure distribution on a cylinder due to the wave diffraction in a finite water depth", *Ocean Eng.*, **29**(9), 1119–1132.

Baeten, A. (2009), "Optimization of LNG tank shape in terms of sloshing impact pressure", *Proceedings of the 19th International Offshore and Polar Engineering Conference (ISOPE)*, Osaka, Japan, June 21-26.

Behr, M. and Abraham F. (2002), "Free-surface flow simulations in the presence of inclined walls", *Comput. Method. Appl. M.*, **191**(47-48), 5467-5483.

Bogaert H., Léonard S., Brosset L. and Kaminski ML. (2010), "Sloshing and scaling: results from the sloshel project", *Proceedings of the Twentieth (2010) International Offshore and Polar Engineering Conference*, Beijing, China.

Bradford, S.F. (1999), "Numerical simulations of liquid sloshing in microgravity field", Naval Research Laboratory, NRL/MR/7260-99-8387, 1-15.

Brosset, L., Mravak, Z., Kaminski, M., Collins, S. and Finnigan, T. (2009), "Overview of Sloshel project", *Proceedings of the19th International Offshore and Polar Enineering Conference*, Osaka, Japan, ISOPE.

Bugg, F. (1970), "Determination of liquid oscillation frequency in an inclined right circular cylinder", NASA TM X-64540.

Colagrossi A., Palladino F., Greco M., Lugni C. and Faltinsen OM. (2004), "Experimental and numerical investigation of 2D sloshing: scenarios near the critical filling depth", *Proceedings of the 19th International Workshop on Water Waves and Floating Body*, Cortona, Italy.

Chiba, M. (1992), "Nonlinear hydroelastic vibration of a cylindrical tank with elastic bottom containing liquid. Part I Experiment", *J. Fluid. Struct*., **6**(2), 181-206.
Cole, H.A. (1966), "Baffle thickness effects in fuel sloshing experiments", NASA TN D-3716.
Demirbilek Z, (1982), "A linear theory of viscous liquid sloshing", Ph.D.thesis, Texas A&M University, College Station, Texas, USA.
Demirbilek Z, (1983), "Energy dissipation in sloshing waves in a rolling rectangular tank-III.-Results and applications", *Ocean Eng*., **10**(5), 375-382.
Dias F, Dutykh D and Ghidaglia J.M. (2010), "A two-fluid model for violent aerated flows", *Comput. Fluids*, **39**(2), 283-293.
Dodge, F. (1966), "Experimental and theoretical studies of liquid sloshing at simulated low gravities", Technical Report No. 2, Contract No. NAS8-20290, National Aeronautics and Space Administration, Alabama.
Drosos, G.C., Dimas A.A. and Karabalis D.L. (2008), "Discrete models for seismic analysis of liquid storage tanks of arbitrary shape and fill height", *J. Press. Vess-T. ASME*., **130**(4), 041801-1-12.
Faltinsen, O.M. (1974), "A nonlinear theory of sloshing in rectangular tanks", *J. Ship Res*., **18**(4), 224 241.
Feng, G.C. (1973), "Dynamic loads due to moving liquid", AIAA Paper No: 73, 409.
Frandsen, J.B. and Borthwick, A.G.L. (2003), "Simulation of sloshing motions in fixed and vertically excited containers using A 2-D inviscid ó -transformed finite difference solver", *J. Fluid. Struct*., **18**(2), 197-214.
Fujino, Y., Sun, L. and Pacheco, B.M. (1992), "Tuned liquid damper (TLD) for suppressing horizontal motion of structures", *J. Eng. Mech*., **118**(10), 2017-2030.
Godderidge, B., Turnock, S., Earl C. and Tan M. (2009), "The effect of fluid compressibility on the simulation of sloshing impacts", *Ocean Eng*., **36**(8), 578–587.
Godderidge, B., Turnock, S., Tan, M. and Earl, C. (2009), "An investigation of multiphase CFD modelling of a lateral sloshing tank", *Comput. Fluids*, **38**(2),183–193.
Graczyk, M. Moan, T. and Rognebakke, O. (2006), "Probabilistic analysis of characteristic pressure for LNG tanks", *J. Offshore Mech. Arct*.,**128**(2), 133-144.
Graham, E.W. and Rodriquez, A.M. (1952), "The characteristics of fuel motion which affect airplane dynamics", *J. Appl. Mech*., **19**(3), 381–388.
Grundelius, M. and Bernhardsson, B. (1999), "Control of liquid slosh in an industrial packaging machine", *Proceedings of the IEEE International Conference on Control Applications*, 1654-1659.
Guzel, U.B., Gradinscak M., Semercigil S.E. and Turan O.F. (2004), "Control of liquid sloshing in flexible containers part 1. Added mass", *Proceedings of the 15th Australasian Fluid Mechanics Conference*.
Haroun, M.A. (1980), "Dynamic analysis of liquid storage tanks", Report EERL, No. 80-4, California Institute of Technology, Pasadena, Calif.
Haroun, M.A. (1983), "Vibration studies and tests of liquid storage tanks", *Earthq. Eng. Struct. D*., **11**(2), 179–206.
Hashimoto, H., and Sudo, S. (1988), "Violent liquid sloshing in vertically excited cylindrical containers", *Exp. Therm. Fluid Sci*., **1**(2), 159-169.
Hatayama, K., Zama, S., Nishi, H., Yamada, M., Hirokawa, M. and Inoue, R. (2005), "The damages of oil storage tanks during the 2003 tokachi-oki earthquake and the long period ground motions", *Proceedings of the JSCE-AIJ Joint Symposium on Huge Subduction Earthquakes—Wide Area Strong Ground Motion Prediction*.
Hirt, C.W. and Nichols, B.D. (1981), "Volume of fluid (VOF) method for the dynamics of free boundaries", *J. Comp. Phys*., 39, 201-205.
Housner, G.W. (1957), "Dynamic pressures on accelerated fluid containers", *B. Seismol. Soc. Am .,* 47(1), 15-35.
Housner, G.W. (1963), "The dynamic behavior of water tanks", *B. Seismol. Soc. Am .,* **53**(2), 381-387.
Hwang, Y., Jung, J., Kim, D. and Ryu, M. (2008), "An experimental study and numerical simulation on sloshing impact pressures with two identically shaped rectangular 2-dimensional model tanks with different sizes", *Proceedings of the Eighteenth International Offshore and Polar Engineering Conference*, Canada.
Jacobsen, L.S. and Ayre, R.S. (1951), "Hydrodynamic experiments with rigid cylindrical tanks subjected to transient motions", *Bulletin of the Seismological Society of America*, **41**(4), 313-346.
Kimura, K., Ogura, K., Mieda, T., Yamamoto, K., Eguchi, Y., Moriya, S., Hagiwara, Y., Takakuwa, M., Kodama, T. and Kolke, K. (1995), "Experimental and analytical studies on the multi-surface sloshing characteristics of a top entry loop type FBR", *Nucl. Eng. Des*., **157**(1-2), 49-63.

Labus, T. (1969), "Natural frequency of liquids in annular cylinders under low gravitational conditions", Lewis Research Center, NASA TN-D-5412.

Lamb, H., (1932), *Hydrodynamics,* (6th ed.), Cambridge University Press, Cambridge.

Lee, S.J., Kim, M.H., Lee, D.H., Kim, J.W. and Kim, J.H. (2007), "The effects of LNG-tank sloshing on the global motions of LNG carriers", *Ocean Eng*., **34**(1), 10–20.

Liu, D., and Lin, P. (2008), "A numerical study of three-dimensional liquid sloshing in tanks", *J. Comput. Phys*., **227**(8), 3921–3939.

Luppes, R., Helder, J.A. and Veldman, A.E.P. (2006), "The numerical simulation of liquid sloshing in microgravity", *Proceedings of the European Conference on Computational Fluid Dynamics*, 1-19.

Matsui, T. (2007), "Sloshing in a cylindrical liquid storage tank with a floating roof under seismic excitation", *J. Press. Vess-T. ASME*, **129**(4), 557-566.

Matsui, T. (2009), "Sloshing in a cylindrical liquid storage tank with a single-deck type floating roof under seismic excitation", *J. Press. Vess-T. ASME*, **131**(2), 021303-1-10.

Moaleji, R. and Greig A.R. (2007), "On the development of ship anti-roll tanks", *Ocean Eng*., **34**(1), 103-121.

Modi, V.J. and Munshi S.R. (1998), "An efficient liquid sloshing damper for vibration control", *J. Fluid. Struct*.,**12**(8), 1055-1071.

Nasar, T., Sannasiraj, S.A., and Sundar, V. (2008), "Experimental study of liquid sloshing dynamics in a barge carrying tank", *Fluid Dyn. Res*., **40**(6), 427–458.

Pal, N.C., Bhattacharyya, S.K. and Sinha, R.K. (2001), "Experimental investigation of slosh dynamics of liquidfilled containers", *Exp. Mech*., **41**(1), 63-69.

Panigrahy, P.K. (2006), "Development of a test setup to study the sloshing behaviour of liquids in baffled tanks", M.Tech thesis, IIT Guwahati.

Panigrahy, P.K., Saha U.K. and Maity D. (2009), "Experimental studies on sloshing behavior due to horizontal movement of liquids in baffled tanks", *Ocean Eng*., **36**(3-4), 213–222.

Papell, S.S. (1965), "Low viscosity magnetic fluid obtained by the colloidal suspension of magnetic particles", *U.S. Patent*, 3215, 572.

Partom, L.S. (1987), "Application of the VOF method to the sloshing of a fluid in a partially filled cylindrical container", *Int. J. Numer. Meth. Fl*., 7(6), 535-550.

Popov, G., Sankar, S., Sankar, T.S. and Vatista, G.H. (1992), "Liquid sloshing in rectangular road containers", *Comput. Fluids*, **21**(4), 551-569.

Rhee, S.H. (2005), "Unstructured grid-based Reynolds-averaged Navier–Stokes method for liquid tank sloshing", *J. Fluis Eng*., **127**(3), 572–582.

Romero, J.A., Ramýrez, O., Fortanell, J.M., Martinez, M. and Lozano, A. (2005), "Analysis of lateral sloshing forces within road containers with high fill levels", *Proceedings of the IMechE , Part D: J. Automobile Engineering*, 220, 303-312.

Rosenweig, R.E., Popplewell, J. and Johnston, R.J. (1997), "Magnetic fluid motion in rotating field", *J. Magnet. Magnet. Mater*., **85**(1-3), 171-180.

Sakamoto, D., Oshima N. and Fukuda T. (2001), "Tuned sloshing damper using electro-rheological fluid", *Smart Mater. Struct*.,**10**(5), 963–969.

Sawada, T., Kikura, H., Shibata, S. and Tanahashi, T. (1993), "Lateral sloshing of a magnetic fluid in a container", *Journal of Magnetism and Magnetic Materials*, **122**(1-3), 424-427.

Sawada, T., Ohira, Y. and Houda, H. (2002), "Sloshing motion of the magnetic fluid in a cylindrical container due to the horizontal oscillation", *Energ. Convers. Manage*., **43**(3), 299-308.

Sayar, B.A. and Baumgarten J.R. (1982), "Linear and nonlinear analysis of fluid slosh dampers", *AIAA J*., **20**(11), 1534.

Snyder, H.A. (1999), "Sloshing in microgravity", *Cryogenics*, **39**, 1047-1055.

Snyder, H.A. (2004), "Effect of rotation on sloshing in low-gravity", *Cryogenics*, **44**, 525-536.

Sudo, S., Hashimoto, H., Ikeda, A. and Katagiri, K. (1987), "Some studies on magnetic Liquid Sloshing", *J. Magnet. Magnet. Mater*, **65**, 219-222.

Sweedan, A.M.J. (2009), "Equivalent mechanical model for seismic forces in combined tanks subjected to vertical earthquake excitation", *Thin Wall Struct*., **47**(8-9), 942-952.

Taniguchi, T. (2004), "Rocking behavior of unanchored flat-bottom cylindrical shell tanks under action of horizontal base excitation", *Eng. Struct*., **26**(4), 415–426.

Terashima, K. and Yano, K. (2001), "Sloshing analysis and suppression control of tilting-type automatic pouring machine", *Control. Eng. Pract*., **9**(6), 607–620.

Topliss, M.E., Cooker, M.J. and Peregrine, D.H. (1992), "Pressure oscillations during wave impact on vertical walls", *Proceedings of the 23th International Conference on Coastal Engineering*, ASCE.

Ueda, T., Nakagaki, R. and Koshida, K. (1992), "Suppression of wind-induced vibration by dynamic dampers in tower-like structures", *J. Wind Eng. Ind. Aerod*., 41-44, 1907-1918.

Utsumi, M. (2000), "Low-gravity sloshing in an axisymmetrical container excited in the axial direction", *J. Appl. Mech*., **67**(2), 344-354.

Utsumi, M. (2004), "A mechanical model for low-gravity sloshing in an axisymmetric tank", *J. Appl. Mech*., **71**(5), 724-730.

Utsumi, M. (2008), "Low gravity low-gravity slosh analysis for cylindrical tanks with hemiellipsoidal top and bottom", *J. Spacecraft Rockets*, **45**(4), 813-821.

Utsumi, M. and Ishida K. (2008), "Vibration analysis of a floating roof taking into account the nonlinearity of sloshing", *J. Appl. Mech*., **75**(4), 041008-1-10.

Valentine, D.T. (2005), "Numerical investigation of two-dimensional sloshing: nonlinear internal waves", *J. Offshore Mech. Arct*.,**127**(4), 300-305.

Vandiver, J.K. and Mitome, S. (1982), "Effect of liquid storage tanks on the dynamic response of offshore platforms. In: C.L. Kirk, Editor, 1st ed., D*ynamic Analysis of Offshore Structures: Recent Developments, Progress in Engineering Sciences* **1**, CML Publications, Southampton, 25–32.

Veldman, A.E.P., Gerrits, J., Luppes, R., Helder, J.A. and Vreeburg, J.P.B. (2007), "The numerical simulation of iquid sloshing on board spacecraft", *J. Comput. Phys*., **224**(1), 82-99.

Warnitchai, P. and Pinkaew T. (1998), "Modeling of the liquid sloshing in rectangular tanks with flow damping device", *Eng. Struct*., **20**(2), 593-600.

Wiesche, S. (2006), "Noise due to sloshing with in automotive fuel tanks", *Forsch Ingenieurwes*, **70**(1), 13–24.

Winslow, W.M. (1949), "Induced vibrations of suspensions", *J. Appl. Phys*., **20**, 1137-1140.

Yano, K. and Terashima, K. (2005), "Sloshing suppression control of liquid transfer systems considering a 3-D transfer path", *IEEE/ASME Transactions on Mechatronics*, **10**(1), 8-16.

Yuanjun, H., Xingrui, M., Pingping, W. and Benli, W. (2007), "Low-gravity liquid nonlinear sloshing analysis in a tank under pitching excitation", *J. Sound Vib*., **299**(1-2), 164–177.