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Fluid damping in rectangular tank fitted with various internal objects – An experimental investigation

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ABSTRACT

The potential of internal objects in changing the dynamic system characteristics of mobile liquid carrying rectangular containers is experimentally investigated in the present study. This study involves identification of system characteristics such as natural frequency and damping. Three different configurations of centrally installed internal objects; bottom-mounted vertical baffles, surface-piercing wall-mounted vertical baffles, and bottom-mounted submerged-blocks have been tried out as potential passive slosh damping devices. A series of painstaking experiments has been conducted in a rigid rectangular tank model on a shake table under lateral harmonic excitation. A frequency response of various internal object arrangements on free surface elevation has been studied. Having identified the system characteristics, the sloshing responses of liquid (water) to harmonic sinusoidal loading for different baffle configurations are investigated. The time variation of the free surface elevation to the baffle configuration and height have been highlighted. Sine sweep and Logarithmic decay method have been resorted to in the experimental discourse. The parametric study shows that the surface-piercing wall mounted baffles are the most effective one in slosh damping among the three configurations.

1. Introduction

Low frequency fluctuation of free surface liquid in a partially filled liquid container is regarded as sloshing, which becomes violent under favourable condition. Sloshing is an important physical phenomenon in many fields of engineering interest in which a partially filled liquid container is an important structural component of the system. The problem of liquid sloshing in containers of various shapes has received considerable attention in transportation engineering from the middle of the last century. To begin with, the requirement for a precise assessment of the sloshing induced hydrodynamic forces was felt in aerospace applications. The vicious motion of the liquid fuel in the tanks of aerospace vehicles was studied by Graham and Rodriguez (1952). In offshore applications, the effect of free surface liquids on board can create problems that may lead to loss of stability of the ocean going vessels (Cleary, 1982; Bass et al., 1980).

Liquid carrying road tankers constitute an important problem and have dragged the attention of many researchers involved in the field of slosh dynamics. Sloshing has often been a potential source of danger for road tankers resulting in accidents due to poor manoeuvrability. Precise estimation of sloshing related hydrodynamic loads is one of the major design issues of liquid transporting containers. The sloshing and its associated forces depend on a wide variety of variables such as shape and dimension of the container, liquid fill depth, amplitude and frequency of external excitation, flexibility of the container, etc. The slosh generated on account of the possible critical combination of the above parameters, should not exceed a certain prescribed maximum value; and if it so does, it needs to be suppressed by some means. The inherent damping due to liquid viscosity is very useful in small size containers. In relatively large containers, natural damping on account of the viscous boundary layers has often been found inadequate to counter violent sloshing and hence several artificial means have been tried to undermine this threat. The use of passive anti-slosh devices such as baffles, floating cans, floating lids and mats are the most sought after means for slosh suppression. Baffles and other such flow obstructing internal objects are found to have given promising results in controlling and preventing the vehicle instability during manoeuvring which has inspired many researchers to conduct analytical, numerical and experimental methods of investigation to corroborate the reliability of these damping devices.

The damping of bare wall containers owes its origin to three sources: (i) viscous dissipation at the free surface of liquid, (ii) viscous dissipation at the side walls and bottom of the tank, and

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(iii) viscous dissipation in the interior of the tank. In case of a baffled tank, an additional source due to relative motion between the liquid and the baffle wall comes into the damping domain. It is often not feasible analytically to accommodate damping contribution from so many sources. Hence, the effect of different types of baffles is usually determined experimentally.

The configuration of slosh suppression devices such as shape, size, stiffness, perforation, gaps, and location has been discussed extensively in NASA Space Vehicle Design Criteria, NASA-SP-8031 (1969). Laws and Livesey (1978) studied the effects of the screen on velocity distribution that effects a change in the flow direction and a reduction in pressure. Evans and McIver (1987) presented an approximate solution based on eigenfunction and Galerkin expansions and studied the effect of vertical baffle on sloshing frequencies in a rectangular water tank. Watson and Evans (1991) further extended this technique to study the resonant frequencies of fluid in rectangular and circular containers having internal bodies such as surface or bottom-mounted rectangular blocks and submerged circular cylinders. Jeyakumaran and McIver (1995) offered an approximate method for the calculation of the oscillation frequencies in a rectangular tank with a cylinder as an internal structure. Porter and Evans (1995) presented a Galerkin based approximate method to study sloshing problems in rectangular tanks with internal structures. Using linear water wave theory, Choun and Yun (1996, 1999) studied the effects of the dimension and location of the submerged block on the sloshing characteristics of the liquid in a rectangular tank. Their findings show that the existence of internal block decreases the sloshing frequencies. The wave elevations increase in the vicinity of the block and a large hydrodynamic force can be exerted on the tank wall and block when the block is closer to the wall. Armenio and Rocca (1996) adopted the finite difference method (FDM) to solve the two-dimensional Reynolds averaged Navier–Stokes (RANS) equations in order to account for the viscosity and vorticity, both of which play a dominant role in liquid tank with internal element. They reported that the presence of a vertical baffle considerably reduced the sloshing loads in the whole range of roll frequencies. Tait et al. (2005) developed numerical flow models to simulate tuned liquid dampers (TLD) with slat screens and assessed the model efficiency with experimental results. Gavrilyuk et al. (2006) proposed fundamental solutions of the linearised problem on fluid sloshing in a vertical cylindrical container having a thin rigid-ring horizontal baffle. The analytically oriented approach not only provided good approximations of natural frequencies and modes but also captured the singular asymptotic behaviour of the velocity potential at the sharp baffle edge. Mitra and Sinhamahapatra (2007) developed a pressure-based finite element method and analysed the slosh dynamics of a partially filled rigid rectangular container with rectangular shaped bottom-mounted submerged components. Gavrilyuk et al. (2007) used a nonlinear asymptotic modal method based on the Moiseev asymptotic ordering to study the nonlinear resonant sloshing in the baffled cylindrical tank. They studied the influence of size and the vertical location of the baffle on the effective frequency domains of the steady state resonant waves. Askari and Daneshmand (2009) analytically investigated the coupled vibration of a partially filled cylindrical container with a thin-walled and open-ended cylindrical shell as an internal body. Askari and Daneshmand (2010) and Askari et al. (2011) investigated the effects of a rigid internal body on dynamic characteristics of a cylindrical container partially filled with liquid. Mitra et al. (2010) made a numerical assessment of the slosh dynamics of a liquid filled container due to the presence of multiple submerged block and baffle over a partition wall. Hasheminejad and Aghabeigi (2012) studied the effect of vertical baffles on two-dimensional liquid sloshing characteristics in a half–full non-deformable horizontal cylindrical container of elliptical cross section. They employed the linear potential theory in conjunction with the successive conformal transformation technique to arrive at the solution. Wang et al. (2012) proposed an improved semi-analytical scheme to study the frequencies and modes of liquid sloshing in a rigid cylindrical container with multiple rigid annular baffles.

Gedikli and Erguven (1999) developed a numerical model based on linear boundary element method to study the effect of rigid ring baffle in damping liquid oscillation in a rigid cylindrical tank. Studied the slosh damping potential of different baffle configurations in heavy-duty trucks with circular and elliptical tanks of various fill depths using the commercial CFD solver FLUENT. Cho and Lee (2003a, 2003b) employed a coupled ALE finite element method to examine numerically the damping effects of disc-type elastic baffle on the dynamic characteristics of cylindrical fuel-storage tank boosting with uniform vertical acceleration. Cho and Lee (2004) carried out a parametric investigation on the two-dimensional nonlinear liquid sloshing in a baffled tank under horizontal forced excitation. A time-incremental nonlinear finite element method (FEM), based on the fully nonlinear potential flow theory in the semi-Lagrangian numerical approach, was used for numerical analysis. They showed that the liquid motion and dynamic pressure variation above the baffle were more significant than those below the baffle. In addition, they suggested that the quantities of interest in the liquid sloshing are strongly dependent on the baffle design parameters. Cho et al. (2005) conducted a frequency domain parametric investigation of sloshing damping characteristics in 2-D baffled tank subjected to forced lateral excitation. Finite element method based on the linearised potential flow theory was used as the numerical tool for the study. An artificial damping term was employed to the kinematic free surface condition to reflect the imminent dissipation effect in resonant sloshing. Biswal et al. (2003) studied the natural frequencies and modes of liquid in a liquid-filled rigid cylindrical container with and without baffles by using the finite element method. Using FEM, Biswal et al. (2006) studied 2D nonlinear sloshing response of the liquid in non-deformable cylindrical and rectangular tanks with rigid baffles subjected to harmonic base excitation. Baffles close to the free surface of the fluid were found more effective in reducing the effect of sloshing. Belakroum et al. (2010) studied the vibratory behaviour of three different configurations of tanks equipped with baffles using a Galerkin Least Square (GLS) finite element model based on Arbitrary Lagrangian–Eulerian (ALE) description of the Navier–Stokes equations.

Strandberg (1978) carried out an experimental investigation on dynamic performance and stability of horizontal circular, elliptical, and super-elliptical tank shapes of equal capacity. He also examined the overturning limit for half–full elliptical containers with various baffle configurations and established the preference of vertical baffle over a horizontal one as an anti-sloshing device in the elliptical container. Warnitchai (1998) used both analytical and experimental investigations to determine the damping ratios of various flow dampening devices: tank with two circular section poles, a tank with a flat plate, and tank with a wire-mesh screen with a specific wire diameter and solidity ratio. Experimentally studied the pressure distribution on the walls of baffled and unbaffled cylindrical tank. Maleki and Ziyaeifar (2008) proposed a theoretical damping model to investigate the damping effect of baffles in circular cylindrical liquid storage tanks, and simultaneously carried out experiments for verification of the theoretical models. Their study concerned two kinds of baffles; horizontal ring and vertical blade baffles. They observed that the damping ratio of the sloshing mode in the presence of these baffles depended on the tank and baffle dimensions in addition to the location of the baffle. The ring baffles were found to be more effective in reducing the sloshing oscillations. They also showed