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Dynamics of rectangular tank with perforated vertical baffle

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ABSTRACT

Slosh dynamics of liquid filled tanks is of paramount importance in the study of fluid-structure interaction. Since beginning sectors and compartments are used in fuel tanks of rockets and massive sea ferrying liquid carriers to control dynamic properties of liquid filled tanks. Compartmentalization is also considered essential to control yaw and pitching of sea vessels by controlling bilge water level. However, Solid partition walls are subjected to considerably high hydrodynamic loads and require increased thickness of material thereby causes increased cost and weight. Perforation is one of the methods for reducing ill effects of compartmentalization. Perforation reduces pressure drop across the baffle which in turn reduces required structural strength of the baffle. Screens with optimum perforation placed appropriately may ensure greater dynamic stability without reduction in damping. Screens are widely used as damping devices in TLD in structural engineering, as Propellant Management and Acquisition Devices (PMAD) in aerospace engineering.

Several experimental and theoretical studies are carried out to analyze the effects of surface-piercing and bottom-mounted vertical baffles, screens but no well-established numerical method is developed so far. In this paper a finite element method using pressure formulation is adopted to study dynamic properties of rectangular rigid containers with single-slotted internal elements and screens

1. Introduction

Dynamics of partially filled rigid container is of fundamental importance and an interesting study in many branches of engineering due to the role the dynamics play in determining design parameters of the container. Stresses acting on a container depend upon displacement that the fluid free surface undergoes. Hence, most of stress control and design optimization techniques mainly consist of methods to control free surface displacement.

Various methods exist that control dynamic characteristics of a rigid rectangular tank. These include provision of horizontal and vertical submerged baffles that are widely studied by Jeyakumaran and Mciver (1995), Porter and Evan (1995), Choun and Yun (1999), Biswal et al. (2003a,b, 2006), Arafa (2006), and Mitra et al. (2010). These baffles are advantageous as they offer enhanced stiffness, stability and dynamic strength to a vessel. Vertical baffle also serves the secondary purpose of separating a fluid volume in different parts (compartmentalization) to ensure stability of the tank. However, associated self-weight becomes a major cause of concern and forces to look for a better option compromising the best dynamic condition (Abramson, 1969). Optimization between dynamic advantages with least self-weight is a vast field of study. Such optimization is experimentally studied in early 60's by Abramson (1966) for dynamic design of spacecraft propellant tanks. Experimental studies revealed various effects of perforation in active dynamic control devices. Simultaneously, it also proved that despite reduction in effectiveness due to perforation, it can be effectively used as dynamic control devices with reduced weight penalty by proper arrangement and optimum perforation. Perforation is not only capable of reducing weight penalty but it also reduces various ill effects such as flow distortion, blockage and undesired sedimentation (Dodge, 2000). In view of tremendous practical utility of perforated baffles the dynamics of these elements is studied by several researchers using various methods.

Depending upon size of perforation a perforated plate can be classified as slat screen or plate with opening/orifice. Solidity ratio, S_n, defined as the ratio of total shaded area to that of full area of screen, is an important parameter for classification of perforated elements. Porosity P_s is another term which is applied to categorize screens and it is equal to $1\text{-}S_n$ Perforation also causes additional damping due to loss of pressure across perforation. Viscosity does add to the damping in such cases Faltinsen and Timokha (2009).

Screens and perforated plates are also applied as anti-roll devices in sea going vessel. Anti-roll effect is produced by perforated baffles through the damping caused by pressure loss due to cross flow. Similarly, it also acts as effective damping device in TLD which produces synchronized damping in high rise structures of vital importance Maravani and Hamed (2011). Screens or perforated plates or tubes are also very effective tools to control free surface configura-

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Nomenclature

B_{sf}	Base shear force
L	Width of tank
L_b	Height of baffle
M_o	Overturning moment
P_s	Porosity
S_n	Solidity ratio
$Z_1{}^*$	Distance of centerline of opening
N	Number of perforation
X	Width of solid portion of screen
X_o	Width of open portion of screen
$Z_1{}''$	Coordinate of top edge of opening
$Z_1{}'$	Coordinate of bottom edge of opening
k_n	Wave number
f_n	Resonant frequency
K_3	3D wave number
$\overline{Z_1^*}$	Mean average depth of perforation in a baffle
h	Height of tank
h_p	Depth of perforation
Ω	Frequency related to root mean square value of resonant amplitude
γ_s	Slosh damping ratio
ς	Free surface elevation

tion in low gravity. Perforated baffles or screens are also used to control orientation and location of propellant in propellant tanks. Screens are capable of holding propellant inside due to surface tension acting around the openings which prevents propellant from leaving out of screen. Therefore, it is very widely used in various propellant management and acquisition devices (PMAD) essential for satellite and spacecraft maneuver in space (Fester et al., N77-17680).

Taylor (1944) reported initial studies on air resistance offered by perforated plate. Abramson (1966, 1969) studied effects of compartmentalization in cylindrical tank and observed that a porous compartmental wall can effectively reduce weight penalty without much loss in structural stiffness and other dynamic benefits such as reduction in natural frequency. Garza (1966) measured baffle forces in cylindrical tank experimentally and observed that there is substantial reduction in baffle forces due to perforation.

Laws and Livesey (1978) studied flow through porous media and observed that screens can be effective tools to control velocity and pressure distribution in a flow field. A screen also causes pressure loss across it. Roach (1987) studied grid turbulence and derived design guidelines by synthesis of experimental data with simple analysis. Fediw et al. (1950) carried out a scaled model analysis to understand the effects of tuned water damper. A theoretical model was developed based on linear wave theory.

Warnitchai and Pinkaew (1998) carried out analytical studies on damping produced by various damping devices in rectangular tank and verified the results by experiments. Subsequent to detail examination of performance of several devices, forced vibration analysis and natural dynamic characteristics of a wire mesh screen was carried out. Kaneko and Ishikawa (1999) developed a nonlinear model of tuned liquid damper with submerged net.

Rakheja (2004) along with a team of researchers prepared a report on studies carried out for tank size optimization for liquid carrier. Effect of various arrangements of baffles on sloshing load is studied. Studies included details of dynamic effects of single-bore and multi-bore arrangement of perforated baffles with the help of the commercial software Fluent. Applying volume of fluid method Morsy et al. (2008) investigated damping introduced by screens in a tuned liquid damper and observed substantial damping introduced by screen.

Yan and Rakheja (2010) experimentally studied effects of coupling of lateral and longitudinal sloshing in an optimized tank. Tait et al. (2005) compared numerical results from models developed by Fediw et al. (1995) and Kaneko and Ishikawa (1999) with experimental measurement and determined damping produced by a series of screens in a tank. Cassolato et al. (2011) proposed a mechanical mass and spring model for determining loss co-efficient of inclined screens arranged at different angle of inclination. Maravani and Hamed (2011) developed a finite difference numerical model using volume-of-fluid method to study the effects of screen. Faltinsen and Timokha (2011) employed linear sloshing theory and domain decomposition method to analyze accurately the effects of submerged screen on dynamic characteristics of rectangular tank. Subsequently, Faltinsen et al. (2011a, b) developed a quasi-linear model with linear free surface condition and quadratic pressure drop condition at screen to study the effects of screens of varying solidity ratio on dynamic characteristics of rigid rectangular tank. The authors also experimentally verified their theory and determined the effects of perforation on damping.

Crowley and Porter (2012) developed a mechanical spring mass system to study effect of submerged screens assuming linear conditions. Different arrangement of screens with different porosity was examined and best orientation was obtained. Kumar and Sinhamahapatra (2013) applied finite element pressure formulation to study free and forced dynamic characteristics of rectangular tanks with horizontal baffle with varying degrees of porosity and arrangements of perforation. Optimized perforation distribution with least weight penalty and maximum dynamic advantages was obtained.

Jin et al. (2014) carried out experimental studies on effects of horizontal screens on slosh response of free surface in a rectangular tank and concluded that horizontal screens are capable of reducing slosh response considerably. The effectiveness reduces as the screen solidity ratio is reduced or screen is placed away from free surface. Nayak and Biswal (2015) also studied experimentally the effects of surface-piercing and bottom-mounted vertical baffles on dynamics of rectangular tank and recorded free surface response with frequency. They also measured damping by recording damped response and measured reduction in response in two consequent cycles.

In the present paper a numerical method using finite element pressure formulation is developed to analyze the dynamic effects of single-opening slotted baffles, treated as a combination of surface-piercing and bottom-mounted vertical baffles on the same plane, and slat screens. Inviscid linearized theory is adopted in the present simulations to keep the analysis simple. Effects of solidity ratio on free and forced dynamic characteristics such as natural frequency, slosh damping, base shear, overturning moment and free surface elevation are estimated and analyzed.

2. Formulation

A two-dimensional rectangular tank with width of $L=2a$ is considered. A vertical baffle is placed at the middle of the two side walls. Depth of baffle is denoted as L_b. The origin of the coordinate system is placed at the intersection of line of symmetry and free surface. Fluid domain is subjected to external excitation at structure-fluid interface boundary.

Assuming incompressible and inviscid motion of fluid in a container the governing equation in terms of excess pressure is given by the Laplace equation