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BEM and FEM analysis of fluid–structure interaction in a double tank

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ABSTRACT

In this paper we present a fluid–structure interaction analysis of shell structures with compartments partially filled with a liquid. The compound shell was a simplified model of a fuel tank. The shell is considered to be thin and Kirghoff–Lave linear theory hypotheses are applied. The liquid is ideal and incompressible. Its properties and the filling levels may be different in each compartment. The shell vibrations coupled with liquid sloshing under the force of gravity were considered. The shell and sloshing modes were analysed simultaneously. The coupled problem is solved using a coupled BEM and FEM in-house solver. The tank structure is modeled by FEM and the liquid sloshing in the fluid domain is described by BEM. The method relies on determining the fluid pressure from the system of singular integral equations. For its numerical solution, the boundary element method was applied. The boundary of the liquid computational domain is discretized by nine-node boundary elements. The quadratic interpolation of functions and linear interpolation of flux are involved. The natural frequencies were obtained for the cylindrical double tank with two compartments.

1. Introduction

Fuel tanks and containers for storage of oil and other dangerous liquids are extensively used in different engineering areas such as aerospace industry, chemical and oil–gas industry, power machine building and transport. These reservoirs operate under excess process loads, and are filled with oil, flammable or toxic liquids.

The influences of both shell and fluid on each other must not be neglected in stress–strength analysis of these structural elements. Therefore, the interaction between the sloshing liquid and the shell structure has been a challenging field of research in many engineering applications.

Liquid sloshing is an interesting physical phenomenon of enormous practical interest that has far reaching applications in a wide field of technologies and engineering disciplines. It occurs in moving tanks with contained liquid masses such as rocket tanks, marine and space vehicles as well as in seismically excited storage tanks, dams, reactors, and nuclear vessels. The book of Ibrahim [1] gives a detailed summary of the theory and fundamentals of sloshing under widely various conditions.

Many different types of model tests at different scales and with different objectives were proposed and performed in the last years in this research area. Since the launch of the early high-efficient rockets in 1957, controlling liquid fuel slosh during a vehicle launch has been a major design concern. Moreover, with today's large and complex spacecrafts, a substantial mass of fuel is required to place them into orbit and to perform orbital maneuvers. The mass of fuel contained in the tanks of a geosynchronous satellite amounts to approximately 40% of its total mass as it was shown by Sidi [2]. When the fuel tanks are only partially filled, large quantities of fuel move inside the tanks under translational and rotational accelerations and generate the fuel slosh dynamics. Slosh control of propellant is a significant challenge to spacecraft stability. Robinson et al. [3] and Space Exploration Technologies Corp. [4] proved that in several cases mission failure has been attributed to slosh-induced instabilities.

As the propellant level decreases throughout a mission, the effects of sloshing forces on the remaining fuel become more prominent. When the fuel tank is full or nearly so, the fuel lacks the open space to slosh. But, in the latter stages of the mission, when most of the fuel has been consumed, the fuel has sufficient volume to slosh and possibly disturb the flight trajectory. This sloshing can ultimately lead to wobble in a spinning spacecraft and self-amplifying oscillations that can result in failure of separate parts or the whole structure. The dynamics of a fluid interacting with the walls of its container is complicated and challenging to predict. The effects of sloshing are significant and in some cases remain prominent even when the propellant volume

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represents only 0.3% of the total spacecraft mass as reported by Vreeburg [5].

In order to suppress sloshing a variety of methods have been proposed, simulated and tested. The effects of baffle on sloshing frequency have been studied by Biswal et al. [6]. The mathematical technique used here is based on the velocity potential function; the problem was solved using finite-element analysis.

The motion of liquid within a partially filled tank was investigated by Ranganathan et al. [7] by representing the fluid slosh through an equivalent mechanical system using a pendulum analogy model. The model parameters were computed based on inviscid fluid flow conditions and the dynamic fluid slosh forces arising due to the dynamics of the vehicle during a given maneuver were computed using the equivalent mechanical system.

Liquid sloshing in partially filled horizontal cylindrical tanks with circular cross sections is a common problem in the road transportation industry that has been extensively studied for many years [8–10]. A recent review on liquid sloshing in horizontal cylindrical tanks was presented by Hasheminejad et al. [11].

In order to restrain the fluid sloshing motion a common technique is to place additional sub-structures called baffles or separators within the tank, as it was demonstrated by Strandberg [8]. Thus, we must consider the problem of sloshing in so-called double tanks or tanks with the compartments.

The issue of suppression of sloshing behavior using baffles goes back to late 50s when lots of experimental and theoretical studies were concerned with the effect of baffles on the sloshing in fuel containers of space vehicles [12,13].

Since then, numerous authors have tackled the subject. Strandberg [8] performed an experimental investigation of dynamic performance and stability of horizontal circular tank. He also studied the overturning limit for half-full elliptical containers with various baffle configurations and concluded that the vertical baffle must be preferred in comparison with the un-baffled or horizontally baffled elliptical container. Evans et al. [14] used the method of eigenfunction series to explore the effect of a thin vertical baffle in a fluid-filled rectangular tank on fluid frequencies. This technique was subsequently extended to consider circular containers having internal baffles by Watson et al. [15]. A mathematical model was developed for the ship rolling motion with free surface liquids on board by Armenio et al. [16]; numerical and experimental results for a rectangular tank with a vertical bottom-mounted internal baffle were presented here. Modaressi-Tehrani et al. [17] used the FLUENT software to develop a three-dimensional nonlinear model of a partly-filled cylindrical tank with and without baffles to investigate the significance of resulting destabilizing forces and moments. The main objective of Sidi [2] was to analyze multi-excitation effects on a cylinder divided by plate on two compartments on the base using BEM and FEM numerical analysis. Diverse multi-exciting forces were applied on this base plate with different frequencies whereas, independently calculated results were superimposed to provide consolidated result.

A semi-analytical approach was presented by Wang [18,19] to obtain both natural frequencies and vibration modes of ideal liquid sloshing and the sloshing response of liquid in a rigid cylindrical container with multiple annual rigid baffles subjected to lateral excitations. The complicated liquid domain was divided into several simple sub-domains. Based on the superposition principle, the analytical solutions of the liquid velocity potential corresponding to each liquid sub-domain were obtained by the method of separation of variables. Analysis of transient lateral slosh in a partially-filled cylindrical tank with different designs of longitudinal partial baffles was performed by Kolaei et al. [20] by using a coupled multimodal and boundary-element method. Shahravi et al. [21] proposed a method to model the influence of different baffle geometries on liquid sloshing. It has been shown that the natural frequencies and the dynamic response of the liquid are drastically changed if the free liquid surface in a cylindrical container is covered with some rigid structural parts. Liquid sloshing in a cubic tank with multiple baffles was investigated numerically in detail by Xue et al. [22] under different external excitation frequencies. Wachowski1 et al. [23] noted that tank sloshing mainly occurs due to maneuvers like stop-and-go traffic or parking; sloshing that is generated depends on the tank geometry, filling level, fuel type and excitation and it leads to the three different types of slosh noise: splash, hit and clonk. Kandasamy et al [24] presented the analysis of effectiveness of different baffle designs in limiting the maneuver-induced transient sloshing in a partly-filled tank. Xue et al. [25] and Eswaran et al. [26] performed the theoretical and experimental research devoted to sloshing problems in a rectangular liquid tank with a perforated baffle. The horizontal ring and vertical blade baffles and their damping effects were investigated by Maleki et al. [27]. After comparing the tank without baffles with the one with baffles, Yan et al. found [28] that the sloshing mode, basic frequencies and free surface shape are all affected by the baffles.

Range of applicability of the linear fluid slosh theory for predicting sloshing vibrations and stability of tank was described by Ibrahim [1], Armenio et al. [16] and Yan et al. [28]. In these papers it was shown that the linear slosh model yields more accurate prediction of dynamic slosh than the pendulum models and it is significantly more computationally efficient than the nonlinear CFD model. Liu et al. [29] adopted finite difference method which solves Navier–Stokes equations to study 2D and 3D viscous and inviscid liquid sloshing in rectangular tanks and verified the results with the linear analytical solution and experimental data. It was demonstrated by [18,28,29] that suppositions about inviscid, incompressible liquid and its irrotational flow are applicable for small amplitude excitations where the wave breaking and the influence of non-linearities do not influence the overall system response significantly. This model can also be used for initial design calculations and in engineering problems regarding to cargo vehicle dynamics, dynamics of road tankers, vehicle fuel tank described in [9,20,23,24,27–29]. So we accept these suppositions hereinafter.

Modeling of sloshing in tanks and reservoirs, as an imprecise and complicated engineering event, has an unfinished evolution history. The above review clearly indicates that there exists a massive body of literature on liquid sloshing in rectangular or upright cylindrical containers with various baffle configurations. With respect to all the numerical work, which has been done, it is fair to say that there is still no fully efficient numerical method to deal with the sloshing in fluid–structure interactions in two-compartmental tanks. Indeed, it appears that, from computational point of view, it is very difficult to account for all the different physical effects at the same time.

In this work, we propose a method of fluid–structure interaction analysis for tanks with compartments partially filled with liquids, that allows us to include elasticity of shell walls, different liquid properties in each compartment, gravity force and to estimate influence of these factors on frequencies of tank vibration. In this paper the free vibration analysis of an elastic cylindrical shell is coupled with liquid sloshing. We use the combination of reduced finite and boundary element methods. The analysis consists of several stages where each stage represents a separate task. The frequencies and modes of empty shell vibrations are defined in the first stage. Displacement vector, that is the solution of the hydrodynamic problem, is sought as a linear combination of natural modes of empty shell. We define the frequencies and free vibrations modes of fluid-filled elastic shell without including the force of gravity. Then, we obtain the frequencies and free