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Review

Analytical and numerical study of the effects of an elastically-linked body on sloshing

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ABSTRACT

In order to investigate the effects of an elastically-linked moving body on liquid sloshing inside a tank, an analytical formulation and a numerical approach were proposed to assess hydrodynamic loads in a partially filled rectangular tank with a body connected to the tank by springs. The analytical approach was developed based on the potential theory to calculate fluid velocity field, and the dynamics of the liquid sloshing coupled to the moving body are described as a mechanical system with two degrees of freedom. The coupling between the fluid and the moving body is given by a damping force calculated based on the body geometry and the fluid velocity field. The proposed numerical approach is based on the Moving Particle Semi-implicit (MPS) method, which is a Lagrangian particle-based method and very effective to model nonlinear hydrodynamics due to fluid–structure interaction. In the numerical approach, the rigid body is modeled as a cluster of particles and the motions are calculated considering its mass, moment of inertia, hydrodynamic loads and springs restoring forces. The elastic link between the body and tank is modeled by applying Hooke's law. Simple cases of floating body motion were used to validate the numerical method. Finally, analytical and numerical results were compared. Despite its simplicity, the analytical approach proposed in the present work is an efficient approach to provide qualitative understanding and a first estimate of the moving body effects on the sloshing inside the tank. On the other hand, the numerical approach can provide more detailed information about the coupling phenomena, and it is an effective mean for the assessment of the reduction of the sloshing loads due to the moving body with elastic link. Finally, the effectiveness of the concept as a sloshing suppressing device is also investigated.

Contents

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1. Introduction

Sloshing is a phenomenon of great concern in the design of liquid containers such as large fuel storage tanks subjected to earthquakes and liquid cargo vessels in rough seas. In order to reduce hydrodynamic loads due to sloshing, internal structures such as swash bulkheads and internal girders may be adopted to provide additional damping on the flow or to change the resonant frequency. However, as fixed structures, these solutions only work in a limited range of tank filling levels.

There are several analytical and numerical solutions to calculate the sloshing flow. Among the analytical solutions, a method based on a mechanical system was used to model the fuel motion inside tanks of aircrafts [1]. Silverman and Abramson [2] and Dodge [3] modeled the sloshing phenomenon by using the potential theory. This approach was also used to calculate the flow in a tank with a fixed obstacle [4,5].

In the 1960s and 1970s, experimental studies were carried out by several researchers [6–10]. From the 1980s, with advances in computer simulation, most of the experimental studies were directed towards the validation of numerical methods.

In the 1980s, several numerical studies were published considering sloshing in prismatic tanks, the effects of internal structures and experimental validation of bidimensional numerical methods [11–16]. Besides the investigation of sloshing inside tanks with complex geometry [17], recently, more accurate modeling of the free surface by using volume of fluid method (VOF) [18–20], smooth particle hydrodynamics (SPH) [21], Moving Particle Semi-implicit (MPS) method [22] and the multiphase modeling [23] were reported.

Unlike the numerical methods based on Eulerian description and mesh, Lagrangian particle-based methods are advantageous in the modeling of the boundaries with large displacements or deformations, fluid fragmentation and merging. Also, there is no diffusion due to the advection term because of the Lagrangian representation. Among the particle methods, SPH [24,25] and MPS [26] have shown promising results in this field. Several simulations of the interactions between fluid and moving bodies carried out by applying the MPS method have been reported [27,28]. Simulation based on the MPS method was successfully validated when compared with experimental results for wave-induced motion of a floating body [29] and for shipping water (Green water) on static [30] and moving ships [31].

In the present study, in order to reduce the undesirable sloshing for a wider range of filling level, the behavior of a moving baffle connected to the tank structure by springs were analyzed by analytical and numerical approaches.

The analytical approach was developed from the connection of two mass-spring-damper systems by a damping force, in which the first system is the sloshing motion of the liquid inside the tank, and the second is the mechanical system that represents the body connected to the tank by springs.

The proposed numerical approach is based on the MPS method. It is a method for the simulation of incompressible fluid using a semi-implicit algorithm to calculate the motion and pressure of the particles. In the numerical approach, the hydrodynamic loads on the floating body are calculated by using the MPS method and the forces of the springs are calculated directly by Hooke's law. Next, the proposed analytical and numerical approaches are described in detail, and the results showing the effects of the elastically-linked moving body are presented and discussed.

2. Analytical approach

A partially filled rectangular tank excited by a horizontal sinusoidal motion is considered in the present study.

In this system, a rigid body is positioned in the fluid, considering that the body is connected to the tank structure through very slender springs, so that the hydrodynamic loads on the springs are negligible. Also, it is assumed that the body is always submerged and its motions do not affect the free surface. The rigid body with springs works as a sloshing baffle that potentially blocks the fluid flow.

The system can be interpreted as the composition of two different groups linked together by damping force. The first system is composed of the tank with liquid and the second is composed of the moving body connected to the tank by springs.

Two different approaches were used in this work. In the first approach, the velocity field of the fluid is calculated by the potential theory, which is useful to identify positions that a suppressor may be more efficient and to calculate the damping force between the moving body and the fluid. In the second approach, the liquid sloshing is considered as a mechanical system to assess the lateral force on the tank in the frequency domain.

Details of the analytical development, assumptions and formulations will be presented as follows, based on the analytical model proposed by Graham and Rodriguez [1].

2.1. Sloshing velocity field

In order to identify the best positions to place the moving body that works as a baffle, an analytical solution based on the potential theory was considered. Assuming a two-dimensional rectangular rigid tank with filling level H and width B, and the origin of the coordinate system located at the geometric center of the fluid as shown in Fig. 1. The incompressible, inviscid and irrotational flow inside the tank can be described using the velocity potential ϕ that may be the solution of the Laplace equation considering small displacements, velocities and slopes of the free surface:

$$\nabla^2\phi = 0. \tag{1}$$

The free surface may be modeled by the linearized condition by assuming small amplitude of motion: