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Global force and moment in rectangular tanks through a modal method for wave sloshing

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ABSTRACT

Basing on a modal description of the sloshing phenomenon, formulas for the global force and moment acting on two-dimensional rectangular tanks are proposed. These are extensively validated through comparison with experimental data for roll motions at different angles of excitement. Moreover, to extend the applicability of the modal method to the most violent breaking cases, a diffusive variant of the scheme is proposed. This relies on the use of a proper diffusive term in the continuity equation and allows for the overcoming of some numerical issues related to the sloshing dynamics in very shallow waters. Finally, a qualitative description of the interaction between diffusion, dispersion and nonlinearities has been proposed for the present modal scheme, along with a physical interpretation of the diffusive term.

1. Introduction

Sloshing is the resonant phenomenon of the liquid motion in a tank excited by an external forcing. Even small excitation amplitudes can induce large free-surface deformation when the forcing frequency is close to the lowest natural sloshing frequency. This is of concern for liquid transportation in ship carrier and LNG ship.

Depending on the excitation features and the filling depth ratio h_0^*/L^*, with h_0^* the water depth and L^* the tank length, several scenarios may occur. As described in Faltinsen and Timokha (2009), nonlinear standing waves characterize the internal wave evolution at high filling ratios, i.e. $h_0^*/L^* > 0.25$. As a consequence of the strong runup at the lateral walls and, however for large filling level, tank roof impacts, possibly with large gas cavity entrapped, may happen (e.g. Abrahamsen and Faltinsen 2011). Near the critical depth, that is at $h_0^*/L^* \approx 0.3368$, nonlinear violent free-surface deformation originates breaking waves, rotational flow, super- and sub-harmonic behaviours (see, for example, Colagrossi et al. 2004).

Conversely, at low filling depth, i.e. $h_0^*/L^* < 0.1 - 0.15$, a breaking bore travels back and forth in the tank (e.g. Bouscasse et al. 2013), inducing rotational flow and viscous diffusion. The occurrence of the bore has been explained in Faltinsen and Timokha (2009) as a shock wave phenomenon, consequence of a *commensurate* spectrum characterizing the shallow water resonance in a tank. This means that all the sloshing natural frequencies are multiples of the lowest natural frequency and are nonlinearly excited by the harmonic excitation of the lowest mode (i.e. secondary resonance, Faltinsen and Timokha 2009). The interaction of the breaking wave with lateral walls causes large local loads (see, for example, Lugni et al. 2006, 2010b, a), and hydroelastic effects when the typical temporal duration of the local load is comparable with a natural period of the structural mode contributing to large local stressing (e.g. Lugni et al. 2014). At intermediate depth, that

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is $0.1 - 0.15 < h_0^*/L^* < 0.25$, a nearly-commensurate spectrum, more similar to the shallow water case, or a non-commensurate spectrum, more similar to the high-filling depth case, can be activated, depending on the natural frequencies for which dispersion matters (e.g. Faltinsen and Timokha 2002).

The above observations strongly influence the choice of the suitable mathematical model to be used on each regime. Although at high and intermediate filling depth, the nonlinear multimodal theory by Faltinsen and Timokha (2009) is a reliable and extremely efficient tool for the description of the sloshing flows, it becomes less accurate for the shallow water case and even not converging for really shallow depth conditions. In any case, it fails when wave breaks.

A reliable approach for the description of the sloshing motion in shallow water conditions is based on the use of depth-averaged equations and on their reformulation as a modal scheme. A first pioneering work in this direction is that of Hill (2003) which, however, is limited to the analysis of the sway motion in the neighbourhood of the first resonant frequency. A more general result is given in Antuono et al. (2012a) where a generic two-dimensional motion is considered, along with the description of a coherent inclusion of the forcing terms in the depth-averaged equations. The above schemes are both limited to the modelling of non-breaking waves and, consequently, can only describe the evolution of rather weak sloshing phenomena. This issue is overcome in the work of Antuono et al. (2014) where a modal scheme based on the depth-averaged equations of Antuono and Brocchini (2013) is implemented along with a semi-analytical solution for the vorticity injected at the free-surface during wave breaking. The above model provides a fairly good match with experimental measurements for moderate wave breaking.

In this context, the aim of the present contribution is the derivation of proper formulas for global forces and momentum and for the consequent evaluation of the loads on the tank, this being a missing aspect in the work of Antuono et al. (2014). This is a requisite for enabling a successful coupling between an efficient sloshing model and an external flow solver for ship seakeeping and stability (Rognebakke and Faltinsen 2003). Potential flow schemes for the dynamic behaviour of a marine vessel in waves are commonly used for both the design and research purposes (Greco and Lugni 2012), providing highly efficient and accurate alternatives to the use of the time consuming CFD schemes. However, a drastic reduction of the efficiency happens when potential schemes are coupled with a CFD solver used to reproduce the internal flow, i.e. as for the sloshing flows in the tank of a LNG carrier (Kim et al. 2007), or in an antirolling tank of a fishing vessel. On the other hand, too simplistic models, e.g lumped mass model, can lead to inaccurate solutions with loss of precision (Fonfach et al. 2016). The capability of solving efficiently and accurately the internal loads induced by sloshing flows becomes then a fundamental step for the solution of complex problems with a limited computational effort and with a high level of reliability.

Sloshing phenomena in shallow water conditions are important in LNG carriers, when these travel in almost off-load conditions, on the deck of fishing vessels, on the deck of offshore supply vessels, and in wing fuel tanks of aircraft; however, they are usually 3D problems. Despite the 2D approximation, the present model can be used in several practical problems. A relevant application is the design of a free-surface antirolling tank for a fishing vessel. When the lowest natural sloshing frequency is tuned to be close to the roll natural period of the boat, the sloshing-induced roll moment damps the roll oscillation of the vessel and prevents parametric instability (Ghamari et al. 2017). Since the resonant flow within a free-surface antirolling tank is characterized by a hydraulic jump travelling back and forth, a nonlinear shallow water model is required to predict the hydrodynamic flow and the induced loads. Further, the elongated shape of the tank, i.e. its breadth is much larger than the width, enables the use of a 2D model as a good compromise. Another interesting application is the prediction of the sloshing flow behaviour within the dock of a landing ship, i.e. a warfare ship with a dock used for the launching of landing crafts and amphibious boats. The high computational efficiency along with a good accuracy of the algorithm developed, are the fundamental prerequisites to build a simulator for training purpose.

To extend the use of the proposed formulas for global forces and momentum to practical naval problems, we also broaden the applicability of the modal scheme of Antuono et al. (2014) to more violent sloshing phenomena. This latter point is achieved by introducing a diffusive term in the continuity equation of the model, following the approach described in Molteni and Colagrossi (2009); Antuono et al. (2010, 2012b) in the framework of the Smoothed Particle Hydrodynamics (SPH). At the same time, we provide a physical interpretation of the diffusive term and a qualitative description of its interaction with dispersion and nonlinearities of the modal scheme. Finally, the proposed formulas and the diffusive variant of the modal scheme are extensively validated through comparison with the experimental data obtained at the CNR-INSEAN Sloshing Lab.

2. The sloshing model

Hereinafter, unstarred variables indicate dimensionless quantities, while starred variables indicate dimensional ones. The frame of reference is that of the tank and x^* and z^* indicate the horizontal and vertical coordinates respectively (see Fig. 1). The basic model is that described in Antuono et al. (2014). We denote by e_0^* and h_0^* the reference wave amplitude and the mean water depth. Then, ϵ indicates the nonlinearity parameter (i.e. $\epsilon = e_0^*/h_0^*$) and $\mu = h_0^*/L^*$ is the dispersive parameter (here, L^* is the tank length). Denoting by g^* the gravity acceleration, the adopted scaling reads:

$$x^* = L^* x \qquad z^* = h_0^* z \qquad t^* = \frac{L^*}{\sqrt{g^* h_0^*}}\, t \qquad U^* = \epsilon \sqrt{g^* h_0^*}\, U\,,$$

$$\eta^* = e_0^* \eta \qquad h^* = h_0^* h \qquad \omega^* = \epsilon \sqrt{\frac{g^*}{h_0^*}}\, \omega \qquad \nu_T^* = \mu\, h_0^* \sqrt{g^* h_0^*}\, \nu_T\,,$$