An efficient numerical approach to predict waves in swimming pools on ships

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ABSTRACT

A linear frequency domain approach using the finite difference method (FDM) was developed to predict sloshing in a partially filled tank or a swimming pool excited by ship motions. The method is validated for harmonic and irregular excitation by comparing results with those obtained by solving the unsteady Navier-Stokes (URANS) equations combined with the volume of fluid technique, and with the results of model tests. The present approach yields predictions of acceptable accuracy efficiently. Its limitations are discussed.

KEY WORDS: sloshing; finite difference method; frequency domain; free surface elevation; model test.

INTRODUCTION

In recent years, yachts have been equipped increasingly with swimming pools. The waves in pools caused by the ship’s motions are investigated to ensure the safety and comfort of people on board. Computational fluid dynamic (CFD) simulations can accurately predict these waves and their loads on tank walls. Chen et al. (2009) and Elahi et al. (2015) investigated sloshing in a partially filled tank by solving the unsteady Reynolds-averaged Navier-Stokes (URANS) equations combined with the volume-of-fluid (VOF) technique. Other numerical methods were applied also; for example, Rafiee et al. (2011) used the smoothed particle hydrodynamics (SPH) method. Lyu et al. (2020) computed coupled sloshing and ship motions by solving the URANS equations. Such simulations take much computer time; hence, their application is often limited because a large number of cases must be considered. Our investigation, on the other hand, is focused on waves in moderately moving tanks instead of violent sloshing.

Many researchers developed analytical models to solve sloshing problems. For example, Faltinsen (1974) and Park et al. (2020) carried out a modal analysis for sloshing in rectangular tanks. These methods are restricted to small excitations for which tank water motions are proportional to the exciting tank motions. The same holds for our method. In such cases, it is best to investigate sloshing for periodical tank motions of many different frequencies. Fluid motions for arbitrary tank motions can then be determined by superimposing the responses in regular waves, using a Fourier decomposition of the tank motion.

OUR APPROACH

We use a finite difference scheme to satisfy the conservation equations for fluid volume and momentum in longitudinal and transverse direction for a large number of fluid cells. The cells move with the tank, have a rectangular floor plan, and reach from the tank bottom up to the fluid surface. The dependence of fluid velocity on the vertical coordinate is assumed as known: like in periodical shallow-water waves for the local depth and the actual frequency. This concept is applicable if the tank motions are so small that the fluid surface does not touch the tank bottom or the tank top (if present). Further, the side walls of the tank must be approximately vertical. Non-rectangular tank shapes, moving side walls (flaps) and an arbitrary bottom topography can be taken into account if the bottom inclination is small everywhere. The linearity assumption, and the reduction from three to two space dimensions for the unknown fields surface height and horizontal velocity, are the reasons for the small computing effort of the method.

Fig. 1 shows the ship-fixed coordinate system \((x, y, z)\) used in the model. The origin of the coordinate system is located on the ship’s centerline in height of the average fluid surface in the tank. The \(x\)-axis points in the ship’s longitudinal direction, the \(y\)- and \(z\)-axis to starboard and downward, respectively. Ship translations are defined as the displacements of the coordinate origin in an inertial system \((\xi, \eta, \zeta)\) whose origin follows the ship’s average speed.

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\xi = \xi_0 + T \tilde{x},
\]

Fig. 1: Top view of the ship (left) and a cross section of the tank (right) defining the ship-fixed coordinate system

The relation between ship-fixed coordinates \(\tilde{x} = (x, y, z)^T\) and inertial coordinates \(\xi = (\xi, \eta, \zeta)^T\) of the same point is