Journal of Fluids and Structures 57 (2015) 108–126

Contents lists available at ScienceDirect

Journal of Fluids and Structures

journal homepage: www.elsevier.com/locate/jfs

Transient response of a ship to an abrupt flooding accounting for the momentum flux

Teemu Manderbacka [a,*], Tommi Mikkola [a], Pekka Ruponen [b], Jerzy Matusiak [a]

[a] Aalto University, School of Engineering, Department of Applied Mechanics, Helsinki, Finland
[b] Napa Ltd, Helsinki, Finland

ARTICLE INFO

Article history:
Received 7 October 2014
Accepted 2 June 2015
Available online 7 July 2015

Keywords:
Time domain simulation
Floodwater progression
Floodwater motion
Lumped mass
Sloshing
Damage stability

ABSTRACT

Numerical non-linear time domain simulation method for damaged ship motions is presented. Floodwater motion modelling is based on the lumped mass method with a moving free surface. The ship and floodwater motions are fully coupled. The variation of the floodwater mass is accounted for. A model to account for the flooding ingress transporting the momentum is presented. The experiments of abrupt flooding have shown that the ship may experience the first large roll towards the undamaged side, especially when a large undivided compartment is flooded. The presented time domain model is validated against the experimental data on the roll damping of the flooded ship and transient flooding. Two different initial stability conditions and two different compartment layouts are studied. Viscous dissipation of the floodwater motions is modelled with an equivalent friction coefficient. The impact of the viscous damping is studied. Transient flooding tests show that the inflow momentum has to be accounted for when the undivided compartment is flooded. The simulation model is capable of capturing the impact of the inflooding jet and the first roll on the opposite side of the damage is reproduced.

1. Introduction

The loss of hull integrity of a ship leading to flooding can be a severe risk to the ship stability. The flooding process can be divided into three stages; (I) transient stage, where the water starts to ingress the ship, (II) progressive stage, where the flooding is more quasi-static and (III) steady state, where final equilibrium angle is reached but the ship may experience roll motions due to wave excitation (Ruponen, 2007). This study concentrates on the flooding process at the transient stage. The roll response is of particular interest, since it is the most sensitive motion component with regards to the flooding. Collision or grounding can cause a large opening on the ship hull. In this case the flooding can be fast at the beginning. If the damage extent is not large enough, to cause immediate foundering or total loss of stability, the dynamic roll angles may still be dangerously large at the transient stage leading to capsize.

An abrupt asymmetric flooding, when the obstructions in the flooded compartment slow down the cross-flooding, may cause a large roll on the damage side and even a capsize (Spouge, 1985). The asymmetric flooding has been studied experimentally and numerically by Vredeveldt and Journée (1991), Journée et al. (1997), and Santos et al. (2002). In the experiments on the transient

* Corresponding author.
E-mail address: teemu.manderbacka@aalto.fi (T. Manderbacka).

http://dx.doi.org/10.1016/j.jfluidstruct.2015.06.001
0889-9746/

flooding of large open spaces (Ikeda and Ma, 2000; de Kat and van't Veer, 2001; Ikeda and Kamo, 2001; Ikeda et al., 2003; Manderbacka et al., 2015) it has been observed that the ship may also roll first on the opposite side of the damage. The inflooding jet can push the floodwater to the opposite side and cause the first large roll on that side. In this case the flooding may be slowed down or even stopped when the opening is lifted due to the roll on the opposite side. This may lead to a different final equilibrium position. Previous studies point out the fact that the intermediate stages of flooding can vary significantly from the final equilibrium stage depending on the flooding process. This process can be complex (Khaddaj-Mallat et al., 2011), including the inflooding jet, sloshing and viscous effects. These, in turn, are all affected by the ship motions. The ship response and the flooding process are coupled. Inflow jet transports inflooding water with momentum into the damaged ship (ITTC, 2014). The viscous effects and wave breaking may dampen the sloshing (Bouscasse et al., 2014a, 2014b) and affect on the progression of the flooding during the intermediate stages. Furthermore, the trapped air may slow down the flooding process (Palazzi and de Kat, 2004; Ruponen et al., 2013). In addition to the above mentioned effects.

In order to assess the consequences of a flooding accident, water ingress and ship motions need to be simulated in time domain. Flooding simulation tools of increasing complexity can be divided into four main groups. (1) Quasi-static methods assume horizontal water surface in flooded compartments. They are mainly aimed to simulate the progressive stage of the flooding (de Kat, 2000; Veer and de Kat, 2000; Santos et al., 2002; Ruponen et al., 2007; Santos and Guedes Soares, 2009; Ypma and Turner, 2010; Schreuder et al., 2011; Dankowski, 2012). These numerical methods have been applied to simulate transient flooding in the asymmetric flooding cases. The roll response to the asymmetric flooding has been captured by these codes when the floodwater motions are limited due to the obstructions in the compartments. (2) Lumped mass models with a moving plane free surface (Papanikolaou et al., 2000; Spanos and Papanikolaou, 2001; Jasionowski, 2001; Fujiwara and Haraguchi, 2005; Valanto, 2008) account for the dynamic effect of the floodwater motions by a moving point mass concentrated at the center of gravity of floodwater as presented by Zaraphonitis et al. (1997). (3) Shallow water equation models (Dillingham, 1981; Chang and Blume, 1998; Santos and Guedes Soares, 2008; Valanto, 2008) for sloshing apply a random choice method (Glimm's method) to solve the shallow water equations in a numerical grid in the flooded compartment. Chang and Blume (1998) apply the method for floodwater depths smaller than 15% of the compartment width, while Valanto (2008) sets the limit to 25%.

Lumped mass models with moving free surface (2) and shallow water equation models (3) have been mainly applied to simulate the damage ship response in waves. In these cases the transient flooding stage has not been covered. The transient stage of flooding has been simulated by (4) Computational Fluid Dynamics (CFD) codes only for very specific problems. Naito and Sueyoshi (2001) show the applicability of the Smoothed Particle Hydrodynamics (SPH) method to simulate the sloshing on deck in forced ship motions. Shen and Vassalos (2009) apply Volume of Fluid (VOF) and SPH simulations for a 2D box case. Gao et al. (2011) simulate the progressive flooding of the ITTC benchmark barge (Ruponen et al., 2007). They show the applicability of the VOF method to simulate the free floating ship motions. However, in this case the measured roll angles were less than 0.25°. Several flooding cases are simulated with CFD by Sadat-Hosseini et al. (2012) applying single-phase level set approach. In their study there were some differences with roll motion in the flooding simulation but the free surface shape was well captured. Three dimensional SPH simulation has been applied by Touzé et al. (2010) for a stationary compartment abrupt flooding. Hashimoto et al. (2013) simulate the abrupt flooding with moving particle semi-implicit method (MPS) coupled with potential flow model. Souto-Iglesias et al. (2013, 2014) discuss the consistency of the MPS method and the equivalence between the SPH and MPS methods.

A number of studies cover the damage ship motions in waves. However, there is very little information on the transient flooding. In the benchmark studies of the 23rd and 24th ITTC (2002, 2005) it was noted that the detailed modelling of the coupled ship and floodwater motions should be studied more carefully. Benchmark study by the 24th ITTC (2005) compared the performance of five different codes to predict the dynamic motions of damaged ship. Participating codes included (1) quasi-static, (2) lumped mass with a moving free surface and (3) shallow water equation methods. The lumped mass with a moving free surface methods were noted to have the best agreement with the experimental data. Later, ITTC (2008, 2011) report several improvements in the codes simulating progressive flooding and damaged ship in waves. The 27th ITTC (2014) points out the importance of correct modelling of the floodwater effects on damping of roll and the inertia of floodwater entering the ship. The first three of the above mentioned categories of tools apply the Bernoulli equation based hydraulic model to calculate the flooding rate through the openings. In CFD application no separate model for the flow through the opening is required. CFD methods are often proposed to solve the complicated coupled problems. Still, the required calculation times are long. The modelling of compartment spaces is cumbersome, even more so in case of complicated compartment spaces, like the ones of the cruise vessels.

An effective method is needed in practice for the purpose of marine traffic safety analysis. It is important to study in which conditions the simplified methods can be applied and is it possible to extend their limits with adequate submodels. This work aims to validate the applicability of the lumped mass with moving free surface method to predict the transient response on the abrupt flooding. It concentrates on the ship motions coupled with the inflooding jet, floodwater motions and the flow through the openings. A model accounting for the mass variation in the compartment and the in/egress momentum flux is presented. This allows for the simulation of the inflooding jet. The transient flooding cases where the inflooding jet plays an important role have not been simulated before to the authors knowledge.

Damaged ship motions are simulated for the system consisting of the ship considered as a rigid body with constant inertia properties and of the lumped masses representing the water at each flooded space in the ship. Degrees of freedom for the system are dependent on the number of flooded spaces in the ship. First the equations of motion for an intact ship