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Global hydroelastic model for springing and whipping based on a free-surface CFD code (OpenFOAM)

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ABSTRACT: *The theoretical background and a numerical solution procedure for a time domain hydroelastic code are presented in this paper. The code combines a VOF-based free surface flow solver with a flexible body motion solver where the body linear elastic deformation is described by a modal superposition of dry mode shapes expressed in a local floating frame of reference. These mode shapes can be obtained from any finite element code. The floating frame undergoes a pseudo rigid-body motion which allows for a large rigid body translation and rotation and fully preserves the coupling with the local structural deformation. The formulation relies on the ability of the flow solver to provide the total fluid action on the body including e.g. the viscous forces, hydrostatic and hydrodynamic forces, slamming forces and the fluid damping. A numerical simulation of a flexible barge is provided and compared to experiments to show that the VOF-based flow solver has this ability and the code has the potential to predict the global hydroelastic responses accurately.*

KEY WORDS: Hydroelasticity; Fluid-structure interaction (FSI); Volume of fluid (VOF); CFD; OpenFOAM; Modal superposition.

INTRODUCTION

CFD simulations of free surface flows are gaining more attentions in marine, offshore and ship applications due to the possibility to predict loads and structural responses in realistic sea conditions. Recent publications (Kim et al., 2009; Cabos et al., 2011; Oberhagemann et al., 2012; Piro and Maki, 2013) have extended the capability of the simulations to account for hydroelastic effects as this capability is essential in order to investigate springing and slamming-induced whipping responses in ships. There are several aspects of the numerical implementation which needs to be addressed due to the complicated nature of the hydroelastic phenomena. One of them is the coupling between the structural solver and the flow solver. Although this coupling has been proved manageable (see e.g. Hou et al., 2012) it is still challenging to formulate an efficient and, at the same time, numerically stable Fluid-Structure Interaction (FSI) scheme. Another challenging aspect of the implementation is related to an energy conserving grid-to-grid mapping between the structural solver and the flow solver.

The present work aims for extending the capabilities of OpenFOAM (an open source CFD software package, Weller et al., 1998) to simulate springing and slamming-induced whipping responses on large vessels moving in waves in any heading. A theoretical description of the code is provided which covers:

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- The VOF-based free surface flow solver formulated in an ALE (arbitrary Lagrangian-Eulerian) frame
- The flexible body motion solver where the local deformation is approximated by a modal superposition of dry mode shapes and the rigid body motion is solved for such that nonlinearity in the rigid body motion and its coupling with the local deformation is fully preserved
- A partitioned FSI (fluid-structure interaction) scheme with the Aitken's acceleration (Irons and Tuck, 1969) for a strongly couple FSI solution
- The transferring of the displacement and fluid forces between the flow and motion solver which in the present formulation allows the force distribution from the fluid solver to be transferred in the modal spaces; thus eliminating the need for a grid-to-grid mapping of the force distribution

FLOW SOLVER

The flow field inside the fluid domain, which contains both air and water, is governed by the solution of the incompressible Navier-Stokes equations with the free-surface captured by the volume of fluid method (VOF, Hirt and Nichols, 1981). The flow equations are written in an Arbitrary Lagrangian-Eulerian frame (ALE) as follows:

$$\nabla \cdot \boldsymbol{u} = 0 \tag{1}$$

$$\frac{\partial \alpha}{\partial t} + \boldsymbol{u}_c \cdot \nabla \alpha + \nabla \cdot \left[\alpha (1-\alpha) \boldsymbol{u}_r \right] = 0 \tag{2}$$

$$\frac{\partial (\rho \boldsymbol{u})}{\partial t} + \nabla \cdot \left(\rho \boldsymbol{u} \boldsymbol{u}_c^T \right) - \nabla \cdot \left[\mu \left(\nabla \boldsymbol{u} + \nabla \boldsymbol{u}^T \right) \right] = -\nabla p_d - (\boldsymbol{g} \cdot \boldsymbol{x}) \nabla \rho \tag{3}$$

where $\boldsymbol{u}, \alpha, p_d, g, x$ are the velocity field, the volume phase fraction field, the dynamic pressure field, the gravitational acceleration vector and the position vector, respectively. The effect of the surface tension has been neglected. The convective velocity $\boldsymbol{u}_c$ is evaluated as $\boldsymbol{u}_c = \boldsymbol{u} - \boldsymbol{u}_m$ where $\boldsymbol{u}_m$ is the domain velocity emerged from the ALE formulation. The pressure p_d is the pressure field without the hydrostatic pressure, defined as $p_d = p - \rho \boldsymbol{g} \cdot \boldsymbol{x}$ where p is the static pressure. The fluid properties p and μ are the effective density and dynamic viscosity for the air-water mixture defined as

$$\rho = \alpha \rho_w + (1-\alpha) \rho_a$$

$$\mu = \alpha \mu_w + (1-\alpha) \mu_a \tag{4}$$

where the subscript "w" and "a" indicate the properties of water and air, respectively. The volume phase fraction α is defined according to the VOF formulation as a bounded non-dimensional value between 0 and 1, where the value 0 indicates a control volume filled with air and 1 if the control volume is filled with water. At the air-water interface, α takes an intermediate value between these intervals; elsewhere its value shall be either 0 or 1 exactly. Eq. (2) is the transport equation for α with an artificial compressive term (the third term, see Rusche, 2002) added for the purpose to aid the numerical solution to maintain a sharp interface. With this artificial term, there is no need for special numerical treatments of the convective terms (the second term) e.g. HRIC (Muzaferija et al., 1999), CICSAM (Ubbink and Issa, 1999) or complicated interface reconstruction technique such as PLIC (Youngs, 1982). This term acts against the numerical diffusion at the vicinity of the interface with its compressive velocity field $\boldsymbol{u}_r$ defined to have its direction normal to the instantaneous free surface. The magnitude of $\boldsymbol{u}_r$, however, is not well defined and has been determined empirically. The formulation of $\boldsymbol{u}_r$ applied in this work is described accurately in Berberovic et al. (2009).