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Calculation of hydrodynamic coefficients of ship sections in roll motion using Navier-Stokes equations

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ABSTRACT

The flow in the vicinity of 2D ship sections carrying out forced roll motions is simulated using the solution of the Navier-Stokes equations implemented in OpenFOAM. A hybrid Lagrangian-Eulerian adaptive mesh scheme is applied to solve forced motions on ship sections oscillating in calm water as well as the free surface capturing problem. Three sections of a containership, with differing geometrical properties, are investigated by comparing viscous unsteady results with potential flow solutions. The method presented in this study has been validated by comparing numerical results with experiments performed on a rectangular section. The influence of viscosity, particularly on vortex shedding, on the roll motion is investigated for an array of oscillation frequencies.

1. Introduction

Several 3D boundary element methods, incorporating a potential flow approach, have been developed to solve the radiation (and diffraction) problem. The frequency domain approaches proposed by Inglis and Price (1981), Newman and Sclavounos (1988) and Nakos and Sclavounos (1990), and the time domain methods developed by Lin and Yue (1990) and Nakos et al. (1993) represent some of the most significant milestones in applying Boundary Element Methods for the solution of ship motions.

Nonetheless, 2D methodologies to compute hydrodynamic coefficients are still very much in use nowadays. This undoubtedly comes from the high speed in computation, due to the simplification of the domain, but also one should bear in mind that 3D methods also pose specific problems. An example is the inclusion of forward speed effects in 3D methods similar to that by Papanikolaou and Schellin (1992). In their method, usage is done of zero speed Green functions formulations with the advance speed being accounted in a somewhat similar manner to that of strip theory (Salvesen et al., 1970). The method is valid, in all frequencies, for slender bodies where lengthwise hydrodynamic pressure variation is small relative to its girthwise variation. Another factor to take into consideration is that evaluating the finite depth Green's function for the zero speed 3D radiation-diffraction problem is extremely complicated, as is the evaluation of the forward speed frequency domain Green's function for the 3D ship motion problem (Datta et al., 2011).

The earliest of these two dimensional methods were based on conformal mapping. From the seminal works of Lewis (1929), Tasai (1959,1961) and Ursell (1949), several conformal mapping techniques have been proposed and benchmarked throughout the years (Ramos and Guedes Soares, 1997); examples of recent studies using multi-conformal mapping are the ones by Rajendran et al. (2015a,2015b). However, conformal mapping methods present limitations regarding the geometry of the ships' sections to be assessed: Frank's close fit method (Frank, 1967) surpasses those limitations but suffers from the phenomenon of irregular frequencies (John, 1950). The method by Yeung (1973) is immune to this problem while fulfilling an arbitrary section geometry requirement in addition to implementing the possibility of shallow water consideration. The method was further developed by Sutulo and Guedes Soares (2004), and applied to the study of a set of sections of the S175 hull in different depths and bottom geometries in Sutulo et al. (2009, 2010).

All the above mentioned methods are based on the idea that the fluid is ideal and implement the potential flow paradigm, failing to account for the viscous damping in roll, which typically becomes substantial relative to the (small) wave damping contribution by slender, ship-like, bodies (Lewandowski, 2004).

So, to include the viscous damping component it is necessary to resort to forced roll or roll decay model tests, as discussed, for example, by Uzunoglu and Guedes Soares (2015), whenever the application of semi-empirical methods, e.g. Miller (1974) and Ikeda et al. (1978), are not deemed accurate. Experimental tests consistently acknowledge the nonlinear nature of such a coefficient, with 2nd or 3rd order polynomial regressions being usually proposed. However, Fernandes and

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Oliveira (2009) and Oliveira and Fernandes (2011) question the ability of the application of polynomials to properly account for the viscous damping in large roll amplitudes, even though the traditional quadratic approach is seen to remain accurate for V shaped hulls. A (non-polynomial) bi-linear approach, which acknowledges the existence of two vortex shedding regimes separated by a roll amplitude threshold, has been developed and tested by the same authors (Oliveira and Fernandes, 2013).

Still, the time and cost necessary to carry out such tests may be significant: Computational Fluid Dynamics (CFD) based calculations become attractive - e.g. Wanderley et al. (2007). CFD methods are, thus, being increasingly used nowadays for roll damping estimation in an effort to improve, or substitute entirely, the application of traditional semi-empirical approaches to it.

Few CFD based studies on the roll radiation problem consider a domain incorporating the whole vessel. The complexity of the domain discretization, problem setup and the cumbersome computational burden result in a strip-wise approach being the standard. Chen et al. (2001) carried out time domain simulations of the entire ship using Reynolds-Averaged-Navier-Stokes equations (RANS) and applying a Chimera domain decomposition approach with approx. 65,000 cells. In their study, forced large amplitude roll motions of a ship fitted with bilge keels with a hull presenting a skeg were simulated. The authors realized the high viscosity and low wave damping generated by the bilge keels, while both damping effects were seen significant as a result of the skeg.

Also using RANS, the roll motion of a surface combatant ship was numerically predicted by Wilson et al. (2006), but a much larger number of cells was part of the domain: approx. 2.3 million. In both studies, the strong viscous effect of bilge keels was evident; furthermore, it was shown that such methods are accurate for practical geometries.

Studies dealing with 2D roll motion using CFD typically carry out simulations concerning the effect of bilge keels fitted amidships of vessels with a long midbody having a close to rectangular sectional shape.

In Sarkar and Vassalos (2000) a RANS-based technique for simulation of the flow near a 2D rolling rectangular cylinder was applied; only approx. 8000 cells were required for successful comparisons with Vugts (1968) experiments and Yeung et al. (1998) inviscid calculations. A relatively accurate RANS based numerical prediction of the time history of the roll motion of a rectangular cylinder, fitted with bilge keels, was achieved by Yeung et al. (2001). However, a total of 40,000 cells were necessary for a good comparison with experimental data, despite the slight over estimation of the motion amplitude. Kakar (2002) solved the Euler equations regarding the inviscid flow around a 2D rectangular section, with and without bilge keels, under forced roll motion. Grids with 37, 74 and 118 thousand elements were tested and the results revealed a convergence to the damping coefficients obtained by Yeung et al. (1998), though much higher values of added mass were observed, especially in low frequency range. On the other hand, Vugts (1968) reports the less accurate experimental results of the hydrodynamic coefficients in roll, due to the mechanical difficulties of the tests, which adds to the smaller order of these values relative to translational modes.

Later, Kacham (2004) resorted to Navier-Stokes equations (NSEQ) to solve the same problem, using three grids with 17, 21 and 25 thousand cells. Comparisons with Kakar (2002) and Vugts (1968) confirmed the over prediction of added mass coefficients experienced by Kakar (2002) for large periods and revealed some inaccuracies in the damping coefficient as well. Finally, Kinnas (2004) further developed the code used by Kacham (2004) and Kakar (2002) and managed to achieve good results for all frequency values.

Vinayan et al. (2005) studied the combined effect of the free surface and flow separation at the bilge keels and Kinnas et al. (2007) found that in the case of roll motion nonlinear effects are considerable, even for very small roll amplitudes: time domain methods were deemed inevitable for proper levels of accuracy. Yu (2008) obtained a good correlation of his NSEQ code's results with the hydrodynamic coefficients computed with FLUENT, considering laminar and turbulent flow, for ship-shaped hull sections without bilge keels – turbulent effect was found small. Results were not so good for low frequency oscillations when bilge keels are present, though.

Also worth of mention is the investigation of roll damping decay of an FPSO, fitted with bilge keels, by Avalos et al. (2014) by means of the incompressible two-dimensional Navier-Stokes equations. A strong dependence of the damping coefficient on the bilge radius was reported and, more interestingly, the occurrence of the so-called damping coefficient saturation phenomenon. This means that a fixed value of this quantity, irrespective of the roll motion amplitude, was observed, in agreement with the conclusions of Oliveira and Fernandes (2011).

In what relates to the application of distributed applications, Quérard et al. (2008) carried out RANS based simulations with ANSYS-CFX 11.0, and concluded on the superiority of their predictions compared to potential flow analysis. Four sections' geometries were investigated: rectangular, triangular, chine and bulbous bow; however, the bulbous bow section did not exhibit an actual protruding bulb. In Quérard et al. (2010), the same tool was used to simulate the roll motion of 2D FPSO sections. Another important study is that of Henning (2011), where predictions of large motions of simple shapes (triangle, square and demi-circle) were carried out resorting to the proprietary program FLUENT. The latter compared worse with the experimental results by Vugts (1968), probably due to the large amplitudes tested. Bonfiglio and Brizzolara (2013), have carried out comparisons between monohull, catamaran and SWATH midship sections, using OpenFOAM. However, only the heave motion is considered.

More recently, when OpenFOAM was used by Kwon et al. (2014) to simulate the forced roll motion of a circular cylinder, a mesh with approx. 200 thousand cells resulted in moment amplitudes with errors ranging from 30% to 80%. In the following year, a study on forced motion of a circular cylinder, was carried out by Gadelho et al. (2015), where the potential flow damping coefficient was meant to be estimated by measuring the height of the radiated waves. OpenFOAM was used to calculate the flow for the heave and sway motions of the body, which provided good results for lower frequencies. But divergences with Sutulo et al. (2009) were witnessed for higher frequencies, probably due to the high wave slope of the corresponding radiated waves which violate the linear free surface assumption made.

From the above, it is clear that research on forced roll motions of 2D sections, by using CFD techniques, has been mainly focused on, but not limited to, the effect of bilge keels on midship sections of FPSO hulls.

In the present paper, three typical mono-hull sections, with clearly distinct geometrical topologies, are considered: bulbous bow, midship and skeg. OpenFOAM is used to determine the moment amplitude of forced roll motions of each, with comparisons between viscous unsteady results with potential flow solutions being carried out. The methodology applied is described and validated by comparing numerical results with experiments performed on a rectangular section.

A laminar flow is considered while solving the Navier-Stokes equations using OpenFoam's *interDyMFoam* solver in an incompressible isothermal fluid; at each time step, the mesh is morphed, according to the motion lay imposed at the hull surface, following a hybrid Lagrangian-Eulerian approach.

The ultimate objective of the present paper is the preliminary assessment of the need for CFD computations of roll motion hydrodynamic coefficients and its dependence on the sections topology. These are to be applied to methods resorting to 2D formulations of the coefficients, where such a formulation is regarded as sufficiently accurate for the specific problem being solved in the first place. Applying a full 3D viscous approach, with its much heavier computa-