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Heave and sway hydrodynamic coefficients of ship hull sections in deep and shallow water using Navier-Stokes equations

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ABSTRACT

A methodology is presented to numerically determine the hydrodynamic coefficients of ship hull sections using a time domain Navier-Stokes model. Results are presented for three topologically distinct sections of a ship hull (skeg, midship and bulbous bow) subjected to heave and sway motions in shallow and deep water. The simulations have been performed with the open source Computational Fluid Dynamics OpenFOAM software. A preliminary assessment of the necessity of viscosity consideration on the determination of the hydrodynamic coefficients, which should depend on the section topology and depth, is carried out. Results demonstrate an overall good agreement of the added mass and damping coefficients between the calculated values and the ones obtained with a boundary equation method potential flow formulation. An exception is the skeg section in shallow waters.

1. Introduction

The vast majority of methods applying direct three-dimensional approaches to seakeeping predictions consider the potential flow idealization to the fluid motion. They are typically based on body, or body plus free-surface, discretization by panels making use of Gauss and Green's theorems together with disturbance potential formulations that vanish at large distances from the body. This is in contrast to field methods, which apply a Computational Fluid Dynamics (CFD) approach with its difficult numerical domain preparation and cumbersome computational time involved. In those methods, coarser meshes are typically used to impose the far-field boundary conditions and to resolve the flow away from the hull, with a refinement of these applied near the ship. Still, in Sadat-Hosseini et al. (2013) this resolves to between 37.9 M and 45.1 M grid points for computing the added resistance in short waves for the MOERI Tanker KVLCC2.

The problem can be solved in the frequency domain, where a linear consideration of all quantities involved is introduced, although 2nd order mean drift forces may be computed from using just the linear solution, for example Newman (1967). In addition, Inglis and Price (1981), Newman and Sclavounos (1988) and Nakos and Sclavounos (1990) are some of the most important studies of this kind. It can also be solved in time domain, whether directly or through the use of some linear quantities, such as the radiation and diffraction forces; e.g. Lin and Yue (1990) and Nakos et al. (1993). From the totally linear approach to the usage of full Navier-Stokes Equations based algorithms, several levels of introducing nonlinearities on the system can be outlined, as those by Hirdaris et al. (2014) with their 6 levels: (1) linear; (2) nonlinear Froude-Krylov; (3) body nonlinear; (4) body exact; (5) fully nonlinear with smooth waves; (6) fully nonlinear.

From the aforementioned studies, it is clear that 3D methods are presently well established. Nonetheless, 2D formulations, such as level 2 methods by Fonseca and Guedes Soares (1998) and Rajendran et al. (2015, 2016), the latter using a nonlinear approach to the hydrodynamic coefficients, are still valuable options, for they are extremely fast to compute.

In what regards sectional hydrodynamic coefficients of semi-submerged bodies, its earliest calculation approach is that by Ursell (1949) where an analytical solution was found for an oscillating circle based on multiple expansions. Haskind (1953) used an analytic scheme to calculate the force and moment acting on steady oscillating contours of ship-like sections by use of an auxiliary continuous function on the whole complex plane domain, whereas Grim (1953) obtained added mass and damping coefficients for real ship sections, by assuming a least square fitting of the solutions to comply with the Neumann conditions on the contours. By applying conformal mapping of close-to-ship-like sections, Tasai (1959, 1961) generalized the application of Ursell's (1949) formulation. Such sections were created by approximating real ship

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sections to analytic functions in the lower complex half-plane, following Lewis (1929), for which conformal mappings to a circle were available. Crude approximations often occurred, as the conformal process only considered two parameters based on the breadth, draft and area of the section. Even though efforts have been made to improve the realism of the sections by increasing the number of parameters, e.g. Landweber and Macagno (1967); Ramos and Guedes Soares (1997), it was Frank (1967) who formulated an approach that allowed for arbitrary sections to be considered. The method accepts arbitrary shaped contours, approximated by segments, on which Green pulsating sources (Wehausen and Laitone, 1960), fulfilling the radiation and free surface boundary conditions automatically, are distributed. However, as evidenced by John (1950), Frank's close fit method suffers from the irregular frequencies phenomenon. 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, without actually considering any singularity distribution directly. The method was further developed by Sutulo and Guedes Soares (2004), where the body boundary condition was applied on the segments discretizing the oscillating contour, instead of their collocation points. It was then applied to the study of a set of sections of the S175 hull: firstly in simple bottom geometries (Sutulo et al., 2009), secondly in stepped and ramp bottom topologies (Sutulo et al., 2010).

All the above methods implement the potential flow assumption and disregard viscous effects entirely. Added mass can typically be approximated to not dependent on viscosity for the special case of a sinusoidal relative motion between the flow and object (Fackrell, 2011). Similarly, viscous effects are negligible in radiated gravity waves due to the body motion, but the same is not always true for damping. It is known that viscous damping in roll is, typically, the most significant viscous effect on a ship motion. Lavrov et al. (2016) carried out CFD calculations, using Navier-Stokes equations implemented in OpenFOAM, to study the flow in the vicinity of 2D ship sections subjected to forced roll motions. They concluded that for the same shapes, a 10–20% difference in the added mass was observed throughout the whole frequency range compared to results from the application of a linear frequency domain potential flow code.

Accounting for viscous effects, 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, especially for sway and roll fluid damping. Four sections' geometries were investigated: rectangular, triangular, chine and bulbous bow. Comparisons were done with Vugts (1968) experimental data and a conformal mapping technique, for the first two, but only to the later regarding the chine a bulbous sections, for which only results in roll are available. Even though overall good results were achieved, the bulbous bow section results showed some significant deviations between the two methods. This, irrespective of these sections being thought to be well approached by potential formulations (Lavrov et al., 2016), in what regards the hydrodynamic coefficients. On the other hand, the bulbous bow section studied did not exhibit an actual protruding bulb.

In the same line of study, Henning (2011) used FLUENT CFD commercial software to determine added mass and viscosity inclusive damping coefficients of three simple contours (triangle, square and semi-circle), arguing these to approximate some typical ship sections. A satisfactory correlation was identified between his results and those experimentally obtained by Vugts (1968), regarding heave and sway motions. However, roll amplitudes in excess of 11° remained largely unresolved. Most importantly, the author reports the inability to achieve good results using a single turbulence model for all hull-motion cases.

Yet another study was carried out by Bonfiglio et al. (2012) for the square and semi-circle, but where the computations were carried out using OpenFOAM open source libraries. Comparison to experiments provided qualitatively similar conclusions to those of Henning (2011). Later, Bonfiglio et al. (2013) carried out another validation of their methodology by comparing satisfactorily their numerical results with experimental values by Hart and Kiesow (1988), regarding a "golf club" section in heave. Finally, the same authors simulate and compare the influence of viscosity in heave induced radiation forces between mono-hull and double-hull versions of a similar section, plus a SWATH section, in heave - Bonfiglio and Brizzolara (2013).

More recently, Gadelho et al. (2015) presented a methodology based on Navier-Stokes equations to determine the hydrodynamic coefficients of an oscillating 2D rigid cylindrical body. The dynamic mesh scheme employed to reproduce the oscillating movement of each section is similar to that of Gadelho et al. (2014a), regarding the performance assessment of a wedge-shaped wave maker in a 2D wave tank. Results demonstrated an overall good agreement of hydrodynamic coefficients with ones obtained by potential formulations, even though deviations were witnessed in higher frequencies.

While the aforementioned studies deal with deep water conditions, the case of shallow water is also important to be assessed (Tezdogan et al., 2016). That is the case of a ship travelling in a channel or inside a harbour, where the low-frequency data corresponding to the horizontal motions can also be useful for maneuvering issues (Sutulo et al., 2009). Viscous effects, which are especially important for the horizontal motions, can be properly assessed by using CFD methods. van Oortmerssen (1976) used 3D potential sources distributed on the surface of vertical oscillating contours, where the sources' Green functions formulation accounted for the presence of a flat bottom or a vertical quay. This was in contrast with Yeung (1973), who considered the following borders to be discretized: body, free surface, bottom and a cylindrical wall away from the body. Though a greater number of equations is present in the later, the method has the ability to include arbitrary shaped bottoms and the case of ships in canals.

Svendsen (1968) had acknowledged the presence of a nonlinear term in the forces induced on a rectangular cylinder under forced heave with draught-depth ratio close to unity, but the validity of a linear strip theory approach to the seakeeping in restricted waters was demonstrated by Hooft (1974) and reiterated by Tuck (1978), at least for heave motion under reasonable bottom clearances. Andersen (1979) used a finite-element for calculating the sectional hydrodynamic properties of a ship with depth-to-draught ratios: infinite, 3 and 1.5 - the approach was concluded to be very suitable. Several studies have since taken place; more recently, one can highlight the works by Kim (1999), Perunovic and Juncher Jensen (2003) and Koo and Kim (2015). The last of these developed a simplified formula of heave added mass coefficients for various two-dimensional body sections in a finite water depth. All studies consider a 2D approach to the problem.

The objective of this paper is to present a Navier-Stokes Equation based methodology applied to the study of two-dimensional hydrodynamic coefficients of a set of three distinct, but paradigmatic, real ship section profiles: skeg, midship and bulbous bow. Heave and sway forced motions are simulated, in deep and shallow water, and results are compared with the potential flow solutions of Sutulo et al. (2009). Analysis of the results allow for a better understanding of the viscous effects and for a preliminary assessment of the necessity of viscosity consideration on the determination of the hydrodynamic coefficients, which should depend on the section topology.

The formulation of the problem is presented in Section 2, followed by the numerical problem description, governing equations, model setup and scheme calibration/validation, in Section 3. Results are shown and compared with the potential flow solutions in Section 4. Finally, conclusions are drawn in Section 5.

2. Formulation of the problem

The hydrodynamic coefficients – added masses and damping coefficients – of ship sections are to be calculated, regarding the heave and sway motions. These are solutions of the (two-dimensional) radiation problem, where the sections are forced to oscillate in still water, generating a flow on the surrounding fluid. The forces necessary to produce