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CFD Analysis and Experimental Validation on the Effectiveness of Bilge Keel as a Roll Stabilizer

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ABSTRACT

RANSE solvers are being increasingly applied to test solutions to ship hydrodynamic problems, and one such application is the modelling for the performance of the bilge keel, considering the viscous effects. This includes the drag on the hull form as it rolls and the flow separation from the bilge and keel where subsequent vortex formation accounts for a large amount of the roll damping. This paper presents a numerical modelling effort to estimate the oscillations of a ship subjected to beam waves. Using CFD tool, the model defines transient boundary conditions that simulate waves on the free surface. The wave model generates a number of field functions based on wave parameters and these field functions are used as initial and boundary conditions. It generates a linear wave given by a first order approximation from the Stokes wave theory with regular periodic sinusoidal profile. The solver calculates the resultant force and moment acting on the model due to the pressure and shear forces exerted by the fluid and by solving the governing equations, finds the new position of the model. As a validation effort, model scale experiments were carried out on a 500t displacement ship hull with and without bilge keels in beam sea conditions. Numerical and experimental roll decay tests are also simulated for comparison to bring out the modelling efficiency of the bilge keel. The flow around the bilge keel is presented showing the velocity vectors and vorticity contours around the hull.

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I. INTRODUCTION

The prediction of ship motions in seaway involves the coupled interaction between the structure and the surrounding fluid. Wide variety of techniques have been using for the seakeeping computations - strip theory is still most widely used, however in many situations it does not give adequate results and more advanced techniques, like RANSE must be used. Strip theory is based on potential flow, but most of the fluid and structure interaction problems, the viscous effect between the fluid and the body plays an important role. In many of these problems, the dynamics of both entities are intimately bound, and the knowledge of the both the nonlinear and viscous behaviour of the fluid are essential. Hence full unsteady Navier-Stokes equations must be solved simultaneously with the equations of the body. Strip theory's principal weaknesses are the lack of three dimensional effects, the inability to account for the above water hull form, the forward speed corrections, and the lack of viscous effects. In theory, unsteady RANSE with fully nonlinear free-surface boundary conditions can account for all of these but only a few results are presently available. The challenge in the simulations of viscous free-surface ship flows is that both the viscous effects and deformation of free surface should be carefully modelled. Development of such a tool will allow the merging of traditionally separate Naval Architecture sub-disciplines for resistance and propulsion, maneuvering, and seakeeping, and when combined with CFD based optimization, will likely revolutionize the ship design process. When comparing with other sub-disciplines areas, the application of RANSE methods to maneuvering and seakeeping is less mature due to obstacles from unsteady flows, ship motions, and complex marine environment. When the vessel motions are large in amplitude, motion prediction will bring various non-linearities which cannot be predicted by even the most successful two-dimensional methods or three dimensional methods based on linear theories (see Salvesen et al., 1970; Chang, 1977).

The development of bilge keel has become one of the most operational and normally used passive roll stabilizers so far, invariably fitted to every class of ships and attached almost perpendicular to the hull at or near the bilge.

The length of the bilge keel is normally one third of the ship's length and the width varies from 0.3 to 1.2m. Detailed explanations of bilge keels are available in Tanaka (1955), Himeno (1981) and Lewis (1989). The present study details the numerical analysis and experimental validation carried out with a fuel barge with and without the bilge keel using the RANSE based CFD solver.

II. COMPUTATIONAL METHOD

The numerical modelling and computation has been performed using the general purpose RANSE solver STAR-CCM+. The geometry was modelled and imported from GAMBIT. All studies have been performed on model scale in order to facilitate direct comparison of numerical and experimental results. The mesh around the body is created using hexahedral cells. Additional prism layers have been included next to the wall boundaries around the bilge keels. The minimum and maximum cell sizes are 0.006 m and 0.3 m respectively. Volume sources using shapes as rectangles have been included to increase the mesh density locally around the ship hull, bilge keel and free-surface region. Along the free surface, a region at the oscillating wave region ie., between x = -0.074 m and x = 0.044 is defined for refining. The total mesh volume in the domain consists of 1.52 million cells for the hull including bilge keels. See Fig. 1 for the meshing details.

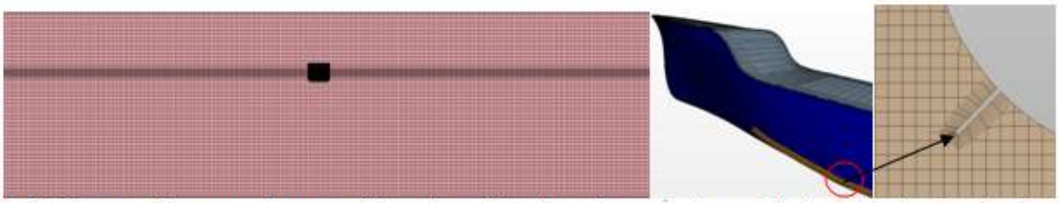


Fig.1 Volume mesh generated on overall domain, and details at the cut section on bilge keel showing the prism layer distribution

The governing equations are available in standard literature. The VOF interface method has been used for capturing the wave formation along the ship geometry. This method assumes that the molecular level mixing is absent and the two media share the same velocity and pressure at the uniform field temperature. In addition to the conservation equation for mass and momentum, a transport equation for void fraction of the liquid phase c is solved:

$$\frac{d}{dt}\int_V c\,dV + \int_S c\,(v - v_b)\,.\,n\,dS = 0 \qquad (1)$$

Here the void fraction of liquid phase c is defined as,

$$c = \frac{\mathrm{V}_1}{\mathrm{V}}, \qquad (2)$$

where V_1 denotes the volume occupied by the liquid phase in a control volume (CV) with volume V. The computational domain extends over water and air phase; void fraction c is equal to 1 when CV is filled with water, it is 0 when CV is filled with air and between 0 and 1 if CV is filled partly with air and water. As it is assumed that both fluids share the same velocity and pressure if $0 < c < 1$, the both fluids are treated as a single effective fluid whose properties vary in space according to the volume fraction of each phase,

$$\rho = \rho_1 c + \rho_2 (1 - c),\ \mu = \mu_1 c + \mu_2 (1 - c) \qquad (3)$$

where subscript 1 denotes for water and subscript 2 denotes for air.

The simulation is limited to beam waves and restrained to a single degree of freedom motion. The main particulars of the ship are given in Table 1. In order to get the response of the model, the appropriate boundary conditions along with the limits of the computational domain are given after carrying out the domain analysis for beam sea condition. A time step of 0.01 sec is used to carry out the simulations. In order to initialize the fluid flow and to minimize the shock effect, the model is released at 0.3 sec giving a ramp time of 0.9 sec for simulations under waves. Velocity boundary condition based on direction components is used for the inlet region. Pressure is used for outlet region.

Table 1. Particulars of the fuel barge

Particulars	Prototype	Model (1/19.1)
Length overall (LOA) (m)	57.88	3.030
Beam (m)	11.00	0.576

Depth (m)	4.20	0.220
Draft (m)	3.00	0.157
Displacement (tons)	1191	0.166
KG (Height of CG above keel) (m)	3.26	0.171
LCG (Longitudinal position of CG from transom) (m)	26.93	1.410
K*xx* (m)	2.98	0.155

III. DESCRIPTION OF EXPERIMENTAL SET-UP AND TEST CONDITIONS

Tests were conducted on a model of scale 1:19.1, the model length being 3.03 m. The experiments were restricted to free stationary conditions tests in beam waves. The model was prepared for seakeeping tests under the fully loaded design condition and by maintaining the appropriate mass moment of inertia characteristics in pitch and roll. The measurement system consists of conductivity type wave probes for wave measurements and THDT (Tilt, Heading, Depth and Temperature) sensor for angle measurement. Free decay tests were carried out with and without bilge keel and compared with numerically obtained decay time series.

IV. RESULTS AND DISCUSSION

The CFD simulations interestingly show the formation of vortices around the bilge keel at instantaneous frames. The growth of vortices for two different cross sections on the starboard side (x/L = 0.729 and x/L = 0.465)and the axial velocity distribution at x/L = 0.729for a full cycle of oscillation for an oscillating period of 5.2 s is shown in Fig 2 and 3 respectively. From these frames, the flow around the bilge keel is evident and the intensity of vortex formation decreases with the amplitude of the roll motion with every new cycle.At the first time instant the vessel is rotating clockwise direction and at frame 1(s) it starts to rotate counter clockwise. A large rotating flow is obvious at the upper face of the bilge keel which is formed due to beginning of reverse flow at frame 1.2(s), this vortex convects away from the boundary layer of the hull surface to the lower surface of the bilge keel.When the ship reaches her maximum roll angle, 1.6(s) the clockwise rotating flow around the bilge keel starts to weaken while the wake of the opposite side of the bilge becomes stronger and at the sequent frame, 2.2(s) the vortex is well developed and at this instant the counter clock-wise motion of the fluid starts to appear.

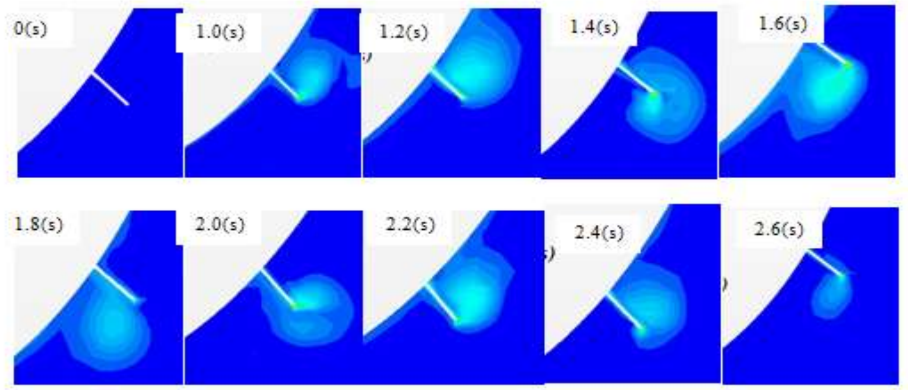


Fig.2 (a) Vorticity (s^{-1}) evolution at section x/L = 0.729, for a wave period of 5.2 sec

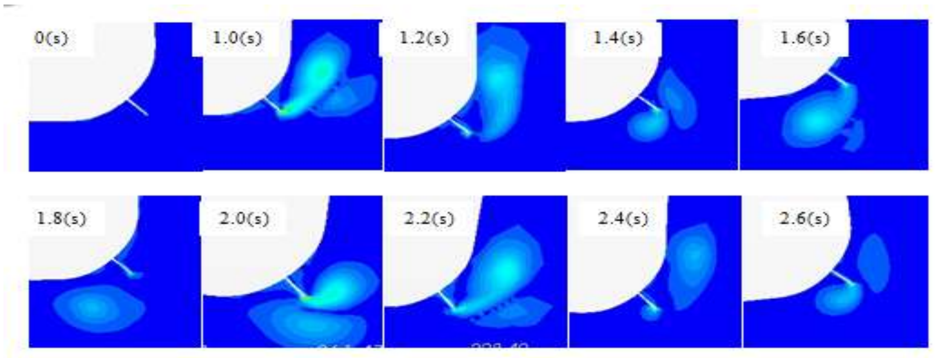


Fig.2 (b) Vorticity (s^{-1}) evolution at section x/L = 0.465, for a wave period of 5.2 sec

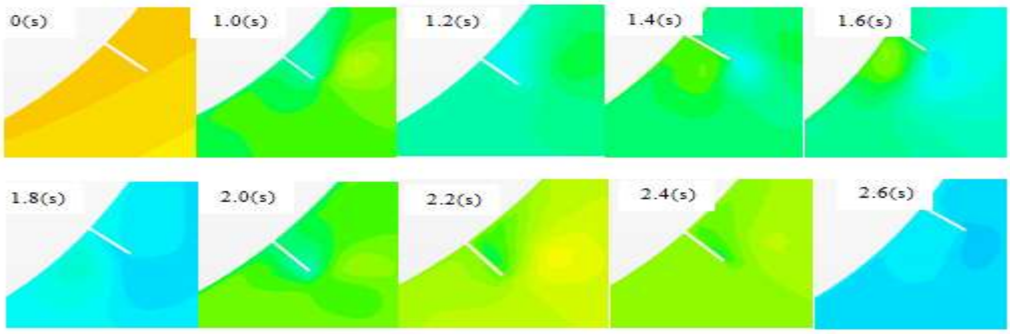
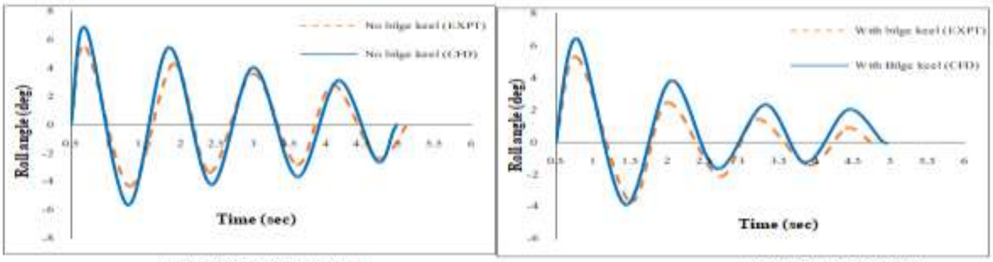


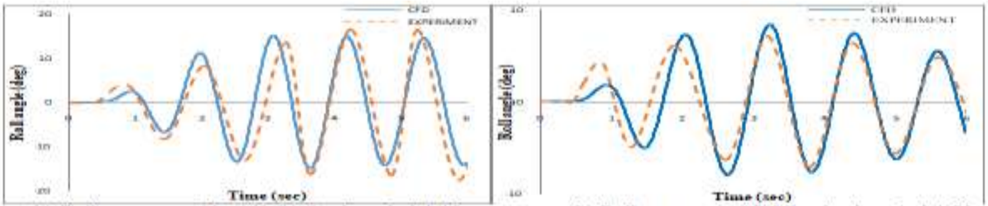
Fig.3 Axial velocity (m/s) contour at section x/L = 0.729, for a wave period of 5.2 sec

The motion response results generally compare well. The use of the turbulence model (k – ξ model) has resulted in closer match of values at the resonance period. A free decay test has been carried out and the test results are also compared between numerical and experimental results, see Fig. 4. As for illustrating the numerical results computed, the time history of the ship model at natural frequency with and without bilge keel for both numerical and experiments are presented in Fig 5.The effect of roll frequency is investigated by performing numerical simulations at 8 different wave frequencies.The response transfer function obtained for these wave frequencies are compared with the experimental results and shown in Fig 6.From the results, it is noticed that for longer wave periods the error percentage with the experiments are higher comparing to smaller wave periods.Error comparison was carried out on experimental with the numerical results and is given in Table 2 and 3.



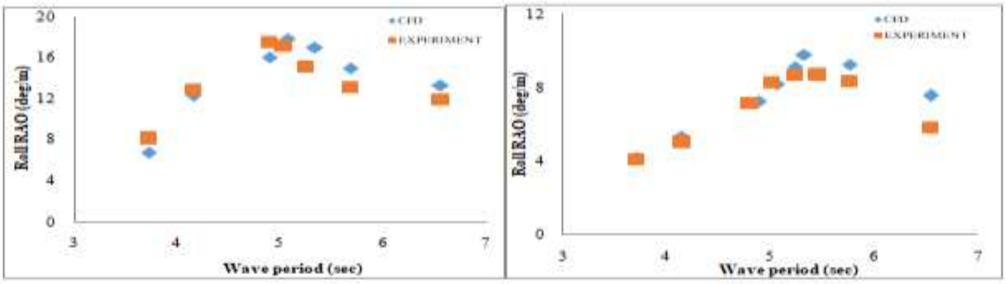
(a) Without bilge keel (b) With bilge keel

Fig.4 Roll decay test time series, with and without bilge keel



(a) Roll response without bilge keel, period 1.12 sec (b) Roll response with bilge keel, period 1.20 sec

Fig.5 Roll time series at respective resonance period with and without bilge keel (model scale)



(a) Without bilge keel (b) With bilge keel

Fig.6 Roll transfer function for prototype with and without bilge keel

Table 2. Natural damped period from roll decay test

	Experimental	Numerical	%Error
Bare hull	1.12 sec	1.15 sec	2.68%
Model with Bilge keel	1.20 sec	1.22 sec	1.70%

Table 3. Roll response transfer function at resonance period

	Experimental	Numerical	%Error
Bare hull	17.5 deg/m	16.0 deg/m	8.6 %
Model with Bilge keel	8.6 deg/m	9.1 deg/m	5.8 %

V. CONCLUSION

A RANSE based method for prediction of motion response of a ship with and without bilge keels is presented. The flow around the bilge keel is captured in the numerical simulation and the instantaneous vortex formation picture is presented. The results obtained are validated by comparing with model experiments. Free roll decay test results are also compared between numerical and experimental results. The natural roll obtained in experiment is reasonably re-produced in the numerical simulation. The CFD based roll simulation with bilge keel shows a certain degree of over-prediction when compared with experimental results, though a RANSE solver has been used.

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