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A Study on the Roll Damping of Two-Dimensional Cylinders

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2차원 주상체의 횡요감쇠에 대한 연구

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Abstract

In this paper, roll damping coefficients for a non-conventional cross section, which is herein named as "step" model, are investigated numerically and experimentally. Experiments are extensively carried out to estimate the roll damping coefficients. Numerical estimations are also made with the help of numerical codes. For convenience, the roll damping is divided into wave-making component and viscous component. The wave-making component is determined using a potential code and the viscous component using a viscous flow code, in which the fluid domain is taken as unbounded. In order to validate the present approach, a typical cross section with bilge is considered and our results are compared with published data. The comparison shows a good agreement qualitatively. For the step model, numerical results are compared well with experimental data besides some quantitative discrepancies at a certain range of frequency. It is thought that the discrepancy might be caused by the ignorance of the free surface in viscous computations. It is found in the case of the step model that not only the viscous component but also the wave component increases considerably compared to the section with bilge.

1. INTRODUCTION

The operability becomes an important issue for FPSO, drill ship, and shuttle tanker because they are deployed in deep sea about 1000m or in severe sea state. In order to improve the operability of vessels, an analysis of ship motions is needed, particularly roll motion, because it influences directly the stability of ships. Thus an exact estimation of roll damping is of central interest in the roll motion analysis, because the roll damping coefficients are critical at resonance. As well known, a rolling ship exhibits large list near the resonance, which may lead to capsize, cargo shift, loss of deck cargo and other undesirable consequences. Experimental research on the roll damping of 2D cylinders has been carried out extensively by Vugt(1970) and Ikeda(1977). Vugt measured heave, sway and roll motions for forward, after and midship sections of a vessel with the free surface and analyzed the interaction effects. Ikeda proposed several formulas for the roll damping of ships with bilge and pressure distributions near the ship hull. He divided the roll damping into wave-making damping, viscous damping and eddy-making damping. In the present work, the viscous damping, which involves with a large extent of uncertainty, is determined using an available viscous flow code, in which the fluid domain is taken as unbounded. The wave-making damping is determined separately using a potential code. Eddy-making damping can be derived by subtracting above two components from total damping obtained from experiment. Three types of models- bilge model, box model and step model- are considered. The step model is recently adapted for the midship section of offshore vessels.

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2. EXPERIMENT

2.1 Roll equation

The roll motion of a two dimensional cylinder is described by

$$(I + a_{44})\ddot{\phi} + b_{44}\dot{\phi} + c_{44}\phi = Me^{i(\varpi t-\varepsilon)} \tag{1}$$

where b_{44} is the damping coefficient and M is the amplitude of the forced moment and ε is the phase difference between the roll angle and the forced moment. Substituting $\phi = \phi_a e^{i\varpi t}$ to eq. (1) and taking the imaginary part, we get

$$b_{44} = \frac{M\sin\varepsilon}{\omega\phi_a} \quad (\phi_a \text{ : roll angle}). \tag{2}$$

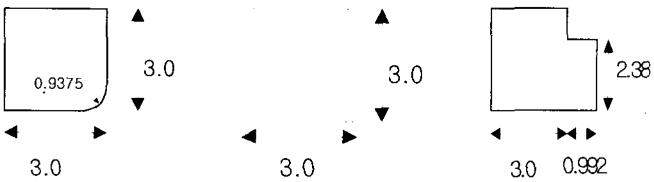
In eq. (2), only the damping coefficient remains at the roll resonance(ε = 90°), since the inertia force cancels out the restoring force. Therefore the roll damping coefficient is easily determined by measuring the forced moment(M) at the resonance frequency. Non-dimensional damping and frequency are defined as

$$b_{44}n = \frac{b_{44}}{\rho WB^2}\sqrt{\frac{B}{2g}}, \quad \omega_n = \omega\sqrt{\frac{B}{2g}} \tag{3}$$

(W : displacement, B : breadth)

2.2 Model

The bilge model, which is similar to the one Vugt(1970) used, is taken as the bench mark test. In this work, a non-conventional midship section, which is herein named as "step" model, is introduced for possible offshore applications. The box model is also considered as a reference for the relative effect of the step model. Each model has the same draft, 15cm, and the same draft-beam ratio, 0.5. The height of roll center is equal to the draft.



Bilge model Box model Step model

Fig.1 Bilge shape of the three models

2.3 Experiment methods

Experiments are carried out in a 2-D tank. The forced oscillating device is used for generating roll moments. Roll moments are evaluated by multiplying the roll arm to the vertically oscillating force measured by an one-axis load cell. Roll angles are measured by a potentio meter. In order to change the resonance frequency, the GM is changed by moving the weight vertically. If the resonance frequency is found, the roll damping coefficients are easily evaluated by dividing the roll moment by the roll angle and the frequency.

3. NUNMERICAL ANALYSIS

3.1 Wave damping

As well known, the wave-damping coefficient can be estimated correctly by potential theory. First, the velocity potential is introduced, which must satisfy the Laplace equation, the free surface boundary condition, the bottom boundary condition and the radiation condition. The boundary conditions are linearized. The Wave damping coefficients are derived from the radiation potential, which is normally evaluated by Green's function method.

$$\alpha\phi(x) + \int_s \phi(\xi)\frac{\partial G(x;\xi)}{\partial n}ds = \int_s \frac{\partial \phi(\xi)}{\partial n}G(x;\xi)ds\,, \tag{4}$$

where $G(x;\xi)$ is Green function.

In order to eliminate the irregular frequency, the modified Green's integral is used. Once the potential is determined, the dynamic pressure is evaluated from the Bernoulli equation and hydrodynamic forces are obtained by integrating the pressure with respect to wetted surfaces. Hydrodynamic forces are divided into added mass and damping coefficient depending on the phase.

$$b_{44} = -\rho\int\int_s \mathrm{Re}(\phi_j n_i)ds \tag{5}$$

3.2 Viscous damping

A viscous flow code, FLOW-3D, is used to calculate the frictional and eddy damping. It numerically solves flow equations using finite difference(or finite volume) approximations. The flow region is divided into meshes of fixed rectangular cells. For each cell, local values of all dependent variables are associated. FLOW-3D has a specific strategy for analyzing flow due to moving objects. For roll motion, the model is set to rotate in the computational domain and FLOW-3D embeds the meshes in a non-inertial reference frame that moves with the entire domain. Physical laws describing flow fields are the continuity equation and the Navier-Stokes equation.

$$\nabla\cdot(\mathbf{AV}) = 0 \tag{6}$$

$$\frac{\partial \mathbf{V}}{\partial t} + \frac{1}{\mathbf{V}_F}(\mathbf{V}\cdot\nabla)\mathbf{V} = -\frac{1}{\rho}\nabla p + \mathbf{F} + \mathbf{G}\,, \tag{7}$$

where $\mathbf{F}$ is the viscous acceleration and $\mathbf{G}$ is the body acceleration.

The present study is concerned with the roll of 2-D cylinders in an unbounded flow region, and thus the model section is modeled as a double body. The computation domain is truncated by an outer boundary, which is a circular form and far away from the body. All models are of square shape of 30cm and they have different bilge shapes. Grid system is defined by Cartesian coordinates. Grids are not uniform and the cell size is varying depending on the location. Near the object, the cell is the smallest.

The Roll moment generally consists of three components; inertia term, restoring term and damping term. Since there is no free surface, the restoring force does not exist. Therefore roll moments are divided into terms proportioned to the acceleration(inertia term) and proportioned to the velocity(damping term).

$$M_I\cos\omega t + M_D\sin\omega t = M(t)\,, \tag{8}$$

(M_I : inertial moment, M_D : damping moment)

The total moment, $M(t)$, is estimated from the viscous computation. In order to extract its amplitude, M_D , the both sides of eq.(5) is multiplies by $\sin\omega t$ and then integrated for five periods to determine the frictional and eddy damping coefficients, $b_{44} = M_D/\omega\phi_a$.

3.3 Convergence test

Convergence tests are carried out to validate numerical results. First, the domain size is examined in order to check if the outer boundary affects flow. Fig. 2 indicates that the outer boundary does not affect the roll damping significantly when the domain range is larger than 150cm. In all calculations, the domain range is taken to be 200cm.

In order to enhance the numerical accuracy, the number of grids near objects must be dense in order to reflect the boundary layer correctly. Grid resolutions are tested to check if the boundary layer is properly represented. The roll damping coefficient converges to some values when the resolution is larger than 10 as shown in Fig 3. In the present study, the resolution of grids is taken as 10.

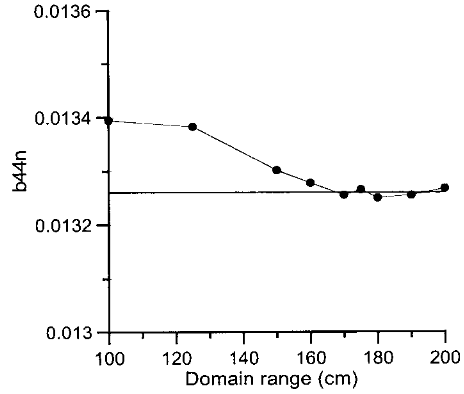


Fig. 2 Convergence tests for the domain range

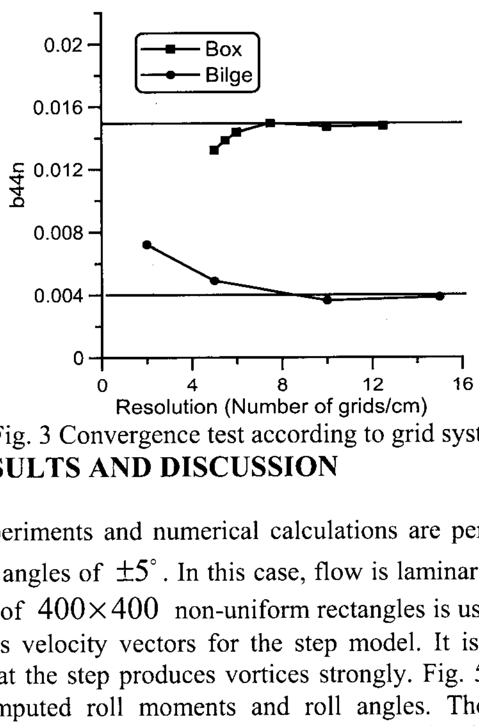


Fig. 3 Convergence test according to grid system

4. RESULTS AND DISCUSSION

Experiments and numerical calculations are performed for roll angles of $\pm 5^{\circ}$. In this case, flow is laminar. A grid system of 400×400 non-uniform rectangles is used. Fig. 4 shows velocity vectors for the step model. It is clearly seen that the step produces vortices strongly. Fig. 5 shows the computed roll moments and roll angles. The phase difference between two curves is caused by the damping. The phase differences are small, which implies that damping forces are small.

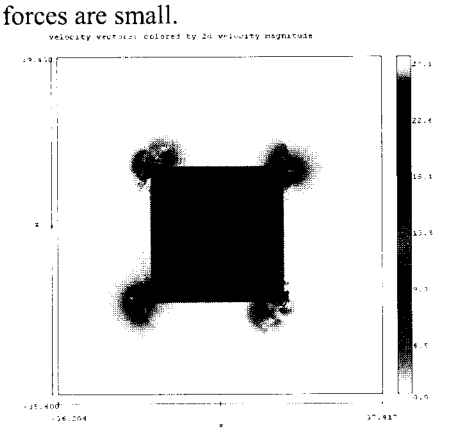


Fig. 4 Velocity vector plots

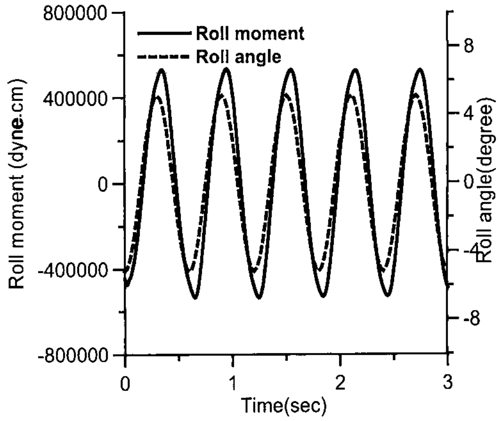


Fig. 5 Roll motion histories at $\omega = 10.47$

Fig. 6 shows the non-dimensional damping coefficient for the bilge model as a function of the non-dimensional frequency. It is to note that our experimental result is quite different from Vugt's one. For the bilge model, the friction and the eddy damping are very small and the most part of the total damping is due to the wave damping. The present result deviates clearly from the experiment. It is also different from other numerical result using COMET (Sarkar and Vassalos,2000). It is thought that the discrepancy might be caused by the ignorance of the free surface in viscous computations, because COMET includes the free surface effects. For the box model, numerical results are compared rather well with experimental data. It is quite different from the previous case. The frictional and eddy damping are comparable with the wave damping. This means that viscous effects became much larger. But our numerical results are again quantitatively different from COMET's (Sarkar and Vassalos, 2000). For the step model, numerical results are not coincide with experimental data at short and long frequencies. It is also thought that the discrepancy might be caused by the ignorance of the free surface in viscous computations. Lastly the damping coefficient for all three models are depicted in Fig. 9. The bilge model has the smallest value because it generates vortices very weakly. The damping coefficient of the step model is the largest, and so the step model is expected to improve roll motions of offshore vessels, if sections with step are adopted as the midship section of offshore vessels.

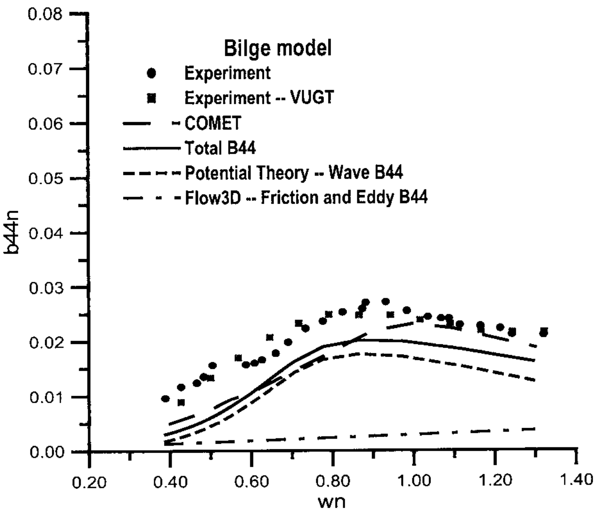


Fig. 6 Non-dimensional damping coefficients of bilge type

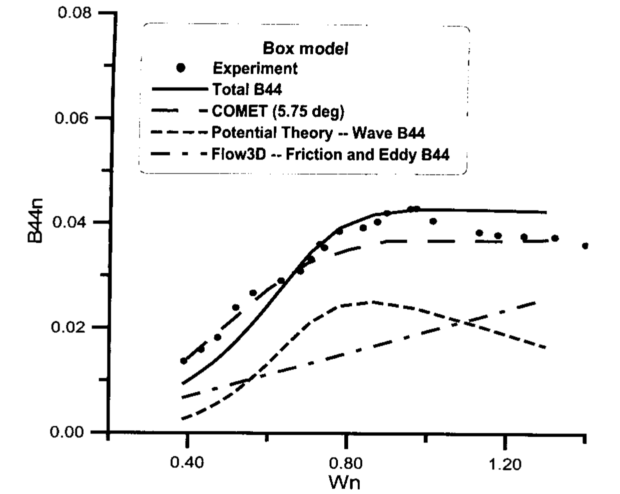


Fig. 7 Non-dimensional damping coefficients of box type

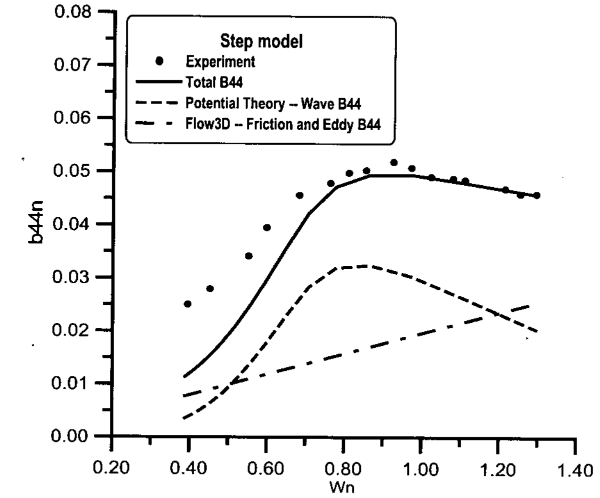


Fig. 8 Non-dimensional damping coefficients of step type

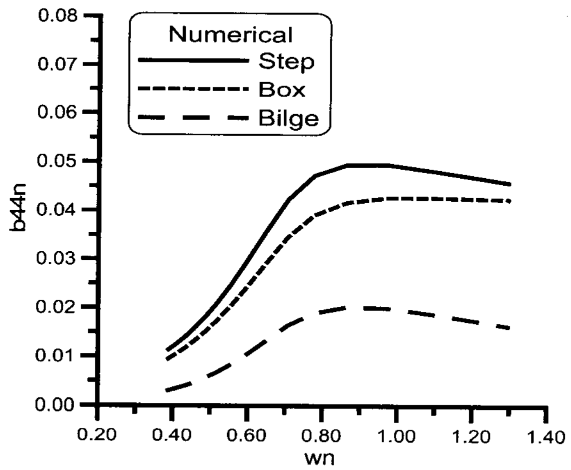


Fig. 9 Comparison of non-dimensional damping coefficients between three models

5. SUMMARY AND CONCLUSIONS

Experiments and numerical calculations are performed for analyzing the roll damping of 2-D cylinders. In numerical calculations, FLOW-3D was used to estimate the friction and the eddy damping without the free surface, and a potential code was used to estimate the wave damping. Compared with the bilge model, the damping coefficient for the step model increased significantly due to enhanced vortices generation. Thus, midship sections with step will contribute to reduce roll motions of offshore vessels.

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