TECHNICAL NOTE

A STUDY ON VISCOUS ROLL DAMPING OF A BOX-SHAPED VESSEL IN THE FREQUENCY DOMAIN USING THE DISCRETE VORTEX METHOD

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SUMMARY

This paper presents a study on viscous roll damping of a floating box-shaped vessel in the frequency domain. The application of the discrete vortex method (DVM) for calculation of the viscous roll damping in regular seas has been validated by model tests. Equivalent roll RAOs associated with a range of regular wave amplitudes are calculated to assess behaviour of the viscous roll damping in relation to incident wave amplitude linearisation. A model test is conducted using the model test facilities of the Marine Hydrodynamics Laboratory at Newcastle University to validate the applicability of the DVM in calculating the roll RAO in regular waves and to study the application of this method to irregular waves. Results of these model tests are presented in this paper.

NOMENCLATURE

μ	Schwartz-Christoffel ratio
ρ	Density of the fluid field
a_4	Vortex induced added mass coefficient
b_4	Vortex induced damping coefficient
b	Breadth of the barge
f_{v4}	Vortex force at shedding edge
$f(t)$	Time series
h	Draught of the barge
q	Coupled motion fluid velocity at shedding edge
q_j	Forced motion fluid velocity at shedding edge
s	Distance of shedding edge to centre of the facet
x	Width of the facet
AR	Aspect ratio of the barge cross section
H	Linearised damping wave height
N	Number of samples in time series
$S(w)$	Power spectrum in frequency domain

1. INTRODUCTION

Prediction of roll damping has been a challenging task for naval architects. Froude [1] studied the effect of wave height and steepness on the rolling of ships and the influence of this phenomenon on the design of ship hull shape.

For floating offshore installations accurate estimate of the roll damping is important as the roll motion governs the transverse loads and this has direct impact on the design of hull, topside structures and process plant on board. Furthermore, noting the calculation limitations and time constraints for conducting motion analysis of a floating vessel in the time domain, frequency domain calculations have become the norm in the industry. Although most vessel responses can be calculated with acceptable accuracy in the frequency domain, this is more difficult for roll response due to the nonlinear behaviour of roll damping.

Theoretically the total roll damping of a floating vessel can be divided into potential and viscous components. The potential component can be predicted accurately since it has a linear characteristic, however the viscous component is non-linear and prediction of this is more problematic.

The challenge is to develop a reliable method for calculating the equivalent linearised roll damping which enables the required response statistics to be calculated in the frequency domain for operational strength and fatigue analysis.

It is a common practice to divide the viscous roll damping into several components such as vortex shedding damping, skin friction damping, eddy damping, etc. [2]. For the case of a rolling box shaped floating vessel, vortex shedding is the dominant roll damping component.

In order to estimate the vortex force on the shedding edge of a box shaped model, Graham [3] implemented a simple discrete vortex analysis for flow about an infinite wedge in oscillatory flow in which the flow in an infinite half-plane, the ς-plane, was transformed to flow about an isolated edge. The method enabled him to calculate a generalised vortex force on the infinite wedge from which he inferred the total force on a finite body with flow separation from its edges. The approach was developed further by Downie et al. [4, 5]. Hajiarab et al. [6] applied the method to a 3-D numerical model for wave diffraction and demonstrated that it produces results that compare well with model test results in regular waves.

In order to eliminate any uncertainty in the model test results used in [6], further model tests were conducted to validate the application of this methodology in regular waves. In this case the roll damping has been linearised for a given wave amplitude in each frequency. Results of these model tests are presented in this paper.

In line with the Lloyd's Register Response Based Analysis (RBA) methodology [7], the longer term objective of this work is to develop a procedure for linearization of the roll damping to enable spectral analysis of response to be undertaken for given seastates. The progress made towards this is presented in this paper.

2. METHODOLOGY

As outlined in [6], the generated vortex force due to roll at the shedding edge of the box shaped vessel can be formulated as:

$$f_{v4} = a_4 + ib_4 = \frac{3^{\frac{5}{3}}}{2^{\frac{4}{3}}} \cdot \frac{(1.566 - i0.157)}{\pi^2} \cdot \rho \cdot b^2$$

$$\cdot \left(\frac{1-\mu^2}{\mu \cdot I_2}\right)^{\frac{1}{3}} \cdot \left(\frac{\mu \cdot b \cdot I_c}{4I_2}\right) \cdot \left|\frac{q \cdot s^{\frac{1}{3}}}{b^{\frac{1}{3}}}\right| \left(\frac{q_j \cdot s^{\frac{1}{3}}}{b^{\frac{1}{3}}}\right) \cdot x \cdot \frac{H}{2}$$

where μ, the Schwartz-Christoffel ratio, can be calculated by iteration for a given barge aspect ratio. In this case if the aspect ratio of the cross section of the barge is defined as:

$$AR = \frac{b}{2h}$$

then from a Schwartz-Christoffel transformation it can be shown [5] that:

$$AR = \frac{I_2}{I_1} = \frac{E(\mu^2) - (1-\mu^2)K(\mu^2)}{E(1-\mu^2) - \mu^2 K(1-\mu^2)}$$

where E and K are elliptic integrals of the first and second kind respectively.

Finally if $\lambda = \dfrac{1}{\mu}$ then:

$$I_c = \int_1^{\lambda} \left\{ \int_{\sigma}^{\lambda} \left(\frac{\sigma'^2 - 1}{\lambda^2 - \sigma'^2} \right)^{\frac{1}{2}} d\sigma' \right\} \frac{2\sigma \cdot d\sigma}{\left[(\lambda^2 - \sigma^2)(\sigma^2 - 1) \right]^{\frac{1}{2}}}$$

$$+ \int_0^{1} \left\{ \int_{1}^{\sigma} \left(\frac{1 - \sigma'^2}{\sigma'^2 - \lambda^2} \right)^{\frac{1}{2}} d\sigma' \right\} \frac{2\sigma \cdot d\sigma}{\left[(\lambda^2 - \sigma^2)(1 - \sigma^2) \right]^{\frac{1}{2}}}$$

In order to compute the strength of the velocity singularity at the tip of the shedding edge in the sharp edged potential flow model, weighted averaging of the velocity at the two facets on each side of the vortex shedding edge is employed to calculate q and q_j. The weights are based on the distance between the centre of the facet to the shedding edge, s.

The extent of the hydrodynamic panel model of the barge is presented in Figure 1.

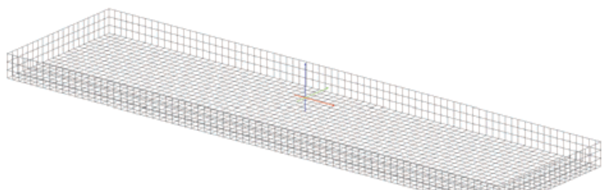

Figure1: Hydrodynamic model of the barge

In this method, for each frequency q and q_j are calculated individually for each strip of panels along the length of the barge and at each iteration. Then by using the weighted averaging approach, the fluid velocity relative to the vessel at the shedding edge is estimated. The estimated relative fluid velocity is then used to calculate the vortex induced damping coefficient for each strip of panels on the port and starboard side of the model. These vortex induced damping coefficients are summed up along the length of the model to calculate the total vortex induced damping coefficient for the frequency under investigation. Finally the total vortex induced damping is inserted back into the hydrodynamic model for the next iteration of calculations. This process is repeated iteratively until the difference in calculated roll RAO in two consecutive iterations is less than 0.1 degrees per meter.

3. CASE STUDY

A box shaped model was used in this study to conduct model tests in the Marine Hydrodynamics Laboratory at Newcastle University. The main characteristics of the model are outlined in Table 1.

Table 1: Main characteristics of the model

Main characteristic	-
Length (m)	1.538
Beam (m)	0.403
Draught(m)	0.064
Mass (kg)	39.67
Longitudinal Centre of Gravity from midship (m)	0.004
Vertical Centre of Gravity from keel (m)	0.032
Roll Radius of Gyration (m)	0.1405
Pitch Radius of Gyration (m)	0.4306
Yaw Radius of Gyration (m)	0.4306

Two separate model tests were conducted to measure the response of the model in regular waves and irregular waves. A wave amplitude probe was situated in the vicinity of the model to measure the incident wave amplitude generated by the wave maker. The motion response of the model was measured using an optical tracking system.

4. RESULTS

4.1 ROLL RESPONSE IN REGULAR WAVES

The measured regular incident wave amplitudes and the measured motion responses were used to calculate the Model Test RAO for each frequency. Comparison of the measured Model Test RAO and the calculated Damped RAO together with the Potential RAO are presented in Figure 2. The measured incident wave amplitudes at each frequency are presented in Table 2. The measured incident wave amplitudes were used to calculated the Damped RAO.

Table 2: Measured incident wave amplitudes at each frequency

Freq. (rad/s)	5.03	5.34	5.65	5.97	6.28	6.60
Wave Amp. (mm)	10.73	11.59	10.86	9.07	10.09	9.45

Freq. (rad/s)	6.91	7.23	7.54	7.85	8.17	8.80
Wave Amp. (mm)	12.97	11.14	7.27	12.23	14.43	13.98

Freq. (rad/s)	9.42	10.05	12.57
Wave Amp. (mm)	8.66	9.27	4.90

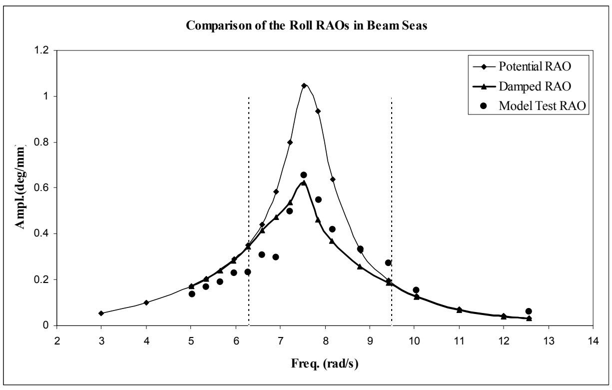

Figure 2: Comparison of Roll RAO in Beam Seas

4.2 ROLL RESPONSE IN IRREGULAR WAVES

Further to the model test in regular waves, an irregular wave train was generated in the wave maker and the time series of the incident irregular wave as well as the roll response were recorded. Using the Fast Fourier Transformation (FFT) technique the incident irregular wave and the associated roll time series were transformed to a power spectrum using:

$$S(w) = \left[\left| FFT\left(f(t)\right) \right| / \frac{N}{2} \right]^2$$

The calculated incident irregular wave and the associated roll response spectra are presented in Figures 3 and 4.

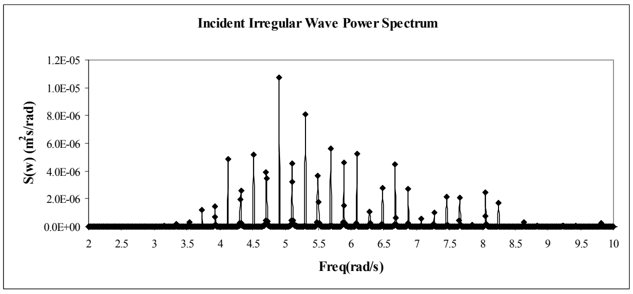

Figure 3: Incident Irregular Wave Power Spectrum

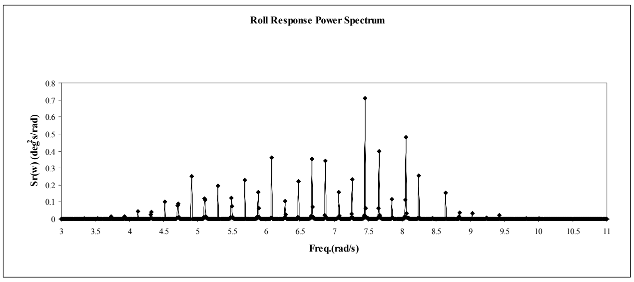

Figure 4: Roll Response Power Spectrum

Assuming a linear system response, the relationship between the incident wave spectrum and the response spectrum may be considered as:

$$S(w)_{response} = RAO_{Equivalent}{}^2 \times S(w)_{wave}$$

and the roll RAO associated with the recorded response (i.e. Equivalent RAO) calculated.

Noting the good agreement of the mathematical model in predicting the Damped RAO in Figure 2, a range of Damped RAOs, linearised for regular wave amplitudes of 5mm, 8mm, 10mm, 12mm and 14mm were calculated to assess the effect of linearizing with respect to wave amplitude. These RAOs are illustrated in Figure 5 together with the Equivalent RAO from the model test.

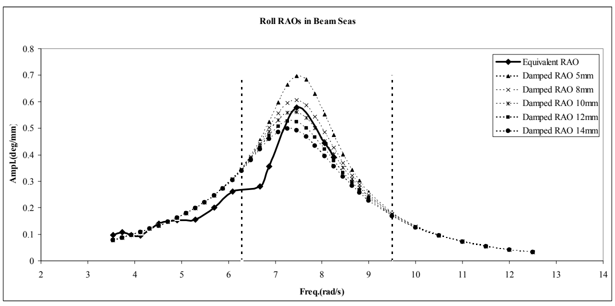

Figure 5: Comparison of Roll RAO database

5. DISCUSSIONS AND CONCLUSIONS

The good agreement between the Model Test RAO and the Damped RAO presented in Figure 2, provides further evidence of the applicability of the DVM for calculating the viscous roll damping of an oscillating box shaped vessel due to vortex shedding from its edges in regular waves. Although the skin friction damping is considered to be negligible and is ignored in the damped RAO in this study, as tangential relative fluid velocities are used in this method, the same final velocities could be used to calculate skin friction damping.

Investigation of the applicable roll RAO of the box shaped vessel in irregular wave is presented in Figures 5. Figure 5 demonstrates the effect of roll damping linearisation for a range of constant wave amplitudes. It can be observed that the effect of viscous damping increases with increase in the regular wave amplitudes, especially in the peak region of the RAO. This is an expected relationship between the amplitude of the linearisation wave and the roll RAO. It can be observed from Figure 5 that the amplitude of the roll RAO varies with wave amplitude in a certain frequency band only. The frequency band in this case lies between 6.3 rad/s and 9.5 rad/s. The same frequency band can be observed in Figure 2 between the Potential RAO and the Model Test and Damped RAOs. Therefore it can be concluded that the effect of linearisation of roll damping for a sea state may be focused on a frequency band around the peak of the RAO.

Further study will be undertaken to confirm the validity of assuming a linear systems approach (i.e. $RAO_{Equivalent}$) between the incident wave spectrum (i.e. $S(w)_{wave}$) and the response spectrum (i.e. $S(w)_{response}$) for non-linear behaviour such as roll damping. If such an assumption can be shown to provide the correct roll response statistics then a design methodology can be established for strength and fatigue analyses based on spectral methods.

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The opinions expressed in this paper are those of the authors and are not necessarily those of Lloyd's Register.

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