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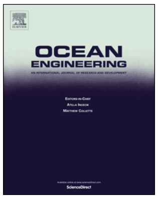

Automated processing of free roll decay experimental data

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ABSTRACT

This work presents an efficient numerical and modular approach to assessing viscous roll damping coefficients from free decay tests. In order to reduce the time consumed during analysis, numerical pre-processing of the data without visual inspection is suggested. The method involves breaking down multiple decay motions recorded in a single time series, numerically determining the beginning and the end of valid decay motion, eliminating the outlying data from the experimental analysis and obtaining the linear and non-linear roll damping coefficients. None of the pre-processing steps depend on each other and they can be used separately in a modular structure. The process is exemplified using decay test samples of a fishing vessel. To use these analysis results in numerical simulations that extend beyond identical conditions with the experiments, a 3D surface approach is examined. The surface also reveals the effect of speed on the coefficients obtained from the sample set.

1. Introduction

Hydrodynamic coefficients affect the responses of a floating structure significantly. In terms of roll motion, potential flow theory makes it possible to calculate the potential roll damping; however viscous roll damping proves to be more elusive. There are various estimation methods to calculate the coefficients, including Miller (1974), Ikeda et al. (1978b), and Ikeda (2004). To obtain the real values as opposed to estimates, forced roll or roll decay tests are conducted and analysed.

One of the pioneers of estimating roll damping coefficients from this experimental data is William Froude, who utilized a single degree of freedom equation (Froude, 1872). Over the years, various authors have discussed different approaches and solutions to the analysis of experimental data. It is known that the behaviour of the viscous roll damping coefficient is not linear. For this reason, different degrees of non-linearity were considered at analysis stage. A method to derive the non-linear damping coefficients from free decay experiments was discussed by Ikeda et al. (1977). The case of a general nonlinear restoring moment using the energy method was treated by Bass and Haddara (1988) who considered the entire time history curve and delivered very accurate results. Despite the actual non-linear behaviour, Lloyd (1989) explained how an equivalent linearized roll damping coefficient may be related to the dissipated energy. Comparative studies have shown which method of analysis provided more accurate results (Spouge, 1988). In addition to assessing different degrees of non-linearity, the effect of initial conditions was also studied in detail by several authors over the years (Cardo et al., 1982; Chan et al., 1995; Söder et al., 2012).

As detailed, there are different approaches to the analysis of the experimental data to different degrees of accuracy using different degrees of non-linearity. These publications deal with the analysis process after the data has been reduced to the valid free-decay motion from the experimental files. However they do offer information on how to extract the valid motion in an efficient way, which becomes important as the number of experiments increase.

The analysis of free roll decay experiments are frequently carried out in batches. Initial roll angle and the speed of the vessel factor in the resulting viscous roll damping coefficient, increasing the number of experiments to understand the behaviour of the vessel. Before starting the analysis, the beginning and the end of the decay motion is marked from the recorded time series, the rest of the motion is omitted and the analysis method is employed on this reduced data. Once the number of tests to analyse increase for any of the reasons above, such as testing different methods or having a large number of experimental data, time limitations come into consideration. It is relatively less time consuming to do the post processing of roll damping values once the decay motion curves are isolated from rest of the time series. The calculations are mostly analytical and may be carried through implemented computer codes. However, significant time is lost at the pre-processing stage due to the need of visual analysis to isolate the decay motion. Therefore, this work places emphasis on pre-processing of the data numerically. It suggests multiple pre-processing steps. They provide a modular structure and each of these steps can be applied individually, apart from following the complete methodology. This offers a flexible multi-step solution in place of a rigid approach.

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At the end of the analysis, the calculated viscous roll damping coefficients are often used in numerical simulations (Uzunoglu et al., 2013, 2015; Turk et al., 2014). There are two possibilities in such cases. The first option is to carry out numerical simulations under identical conditions to the experiments. Alternatively, the roll damping values will be interpolated or extrapolated to deliver a range of values. If the second option is to be followed, from a functional point of view, a way to feed this extended experimental data into the simulation program has to be devised. The final section examines a method suggested for this purpose.

2. Calculation of linear and non-linear roll damping coefficients

The method of calculation of linear and linear-plus-quadratic roll damping terms used in this study has been outlined in detail in by Ribeiro e Silva and Guedes Soares (2013). The approach in this work is identical and is briefly described here. It is possible to substitute this method with another choice or to provide a comparison by implementing multiple methods after the pre-processing stage.

When the equation of motion of roll motion is written, the non-linear damping terms $B_{44}(\xi_4\dot{\xi}_4)$ is expressed as a series of expansions of $\dot{\xi}_4$ and $|\dot{\xi}_4|$. Therefore, the governing equation of a free decay experiment is presented in the form:

$$(M_{44}+A_{44})\ddot{\xi}+B_{44_1}\dot{\xi}i_4+B_{44_2}\dot{\xi}_4|\dot{\xi}_4|+C_{44}(\xi_4)\xi_4=0 \tag{1}$$

where, B_{44_1} is the linear damping term, and B_{44_2} is the quadratic damping term. Using appropriate parametric identification techniques, the linear and quadratic terms are obtained by fitting Eq. (1) to the recorded free-decay experiment data. A common approach to analysis is the energy balance method, as it is advantageous due to the fact that it requires a small number of oscillations. It is based on the concept that the rate of change of the total energy in roll motion equals the rate of energy dissipated by the roll damping due to radiated waves.

When the roll Eq. (1) is divided by the inertial term $(M_{44}+A_{44})$, the damping term may be written as follows, defining the p_1 and p_2 coefficients:

$$B_{44}=p_1\dot{\xi}_4+p_2\dot{\xi}_4|\dot{\xi}_4| \tag{2}$$

By extracting the roll maxima and minima from each half cycle of the free decay test, the mean roll amplitude decrease and roll amplitude decrement per half cycle is calculated from:

$$\xi_{4m}=\frac{|\xi_{4_j}|+|\xi_{4_{j+1}}|}{2} \tag{3}$$

$$\delta\xi_{j+1}=|\xi_{4_j}|-|\xi_{4_{j+1}}| \tag{4}$$

The magnitude of the roll motion is represented by (ξ_{4_j}). By integrating the roll equation over half period and equating the energy dissipated by damping to the work done by the restoring moment, the following expression for roll decrement (Eq. (4)) as a function of the mean roll amplitude (Eq. (3)) is obtained:

$$\delta\xi_{4_{j+1}}=\frac{\pi}{2\omega_{44_n}}p_1\xi_{4m}+\frac{4}{3}p_2\xi_{4m}^2=a_1\xi_{4m}^2+a_2\xi_{4m}^2 \tag{5}$$

Krylov–Bogoliubov's solution (Bogoliubov and Mitropolskiy, 1961; Flower and Sabati Aljaff, 1980) to the linear and quadratic roll damping coefficients p_1 and p_2 are given by:

$$p_1=\frac{B_{44_1}}{(M_{44}+A_{44})}=\frac{2\omega_{44_n}}{\pi}a_1 \tag{6}$$

$$p_2=\frac{B_{44_2}}{(M_{44}+A_{44})}=\frac{3}{4}a_2 \tag{7}$$

As in Eq. (5), when the roll decrement is expressed as a function of roll amplitude (i.e. $\delta\xi_{4_{j+1}}=f(\xi_{4_m})$), the experimental data may be evaluated by fitting a regression curve. The coefficients (a_1) and (a_2) are obtained by equating the linear and quadratic coefficients of this curve to the coefficients in Eqs. (6) and (7).

The roll inertia (M_{44}) is calculated utilizing the transverse metacentric height of the vessel and the displacement weight. The undamped natural frequency (ω_{44_n}) is considered to be equal to the mean frequency of the decay record (Mathisen and Price, 1984) and is determined from the time series using the average period of the decay motion (T_m):

$$\omega_{44_n}=\frac{2\pi}{T_m} \tag{8}$$

Added inertia (A_{44}) may be obtained from forced oscillation experiments or through numerical methods. Alternatively, it may be estimated in a simplified manner using the average period of decay of that particular test, considering the average frequency of the decay motion equals the undamped natural frequency as stated above:

$$\omega_{44_n}=\sqrt{\frac{C_{44}}{A_{44}+M_{44}}} \tag{9}$$

$$A_{44}=\frac{C_{44}}{\omega_{44_n}^2}-M_{44} \tag{10}$$

The solution to finding the linear equivalent of the non-linear damping is provided by Lloyd (1989). Eq. (8) is used in conjunction with Eqs. (6) and (7) to deliver the linear roll damping coefficient, defining ϕ_0 as the initial roll angle of the decay motion:

$$B_{44_{eq}}=B_{44_1}+\frac{3\pi}{8}\omega_n\phi_0B_{44_2} \tag{11}$$

3. Pre-processing of the experimental data

The pre-processing stage is composed of three steps: "separating multiple decay motions in time series", "isolating the valid free decay motion" and "iterative regression analysis of the reduced time series". The following sections detail the full modular numerical approach where each of these steps can be employed separately.

The free decay tests are carried out by setting the vessel at a predefined initial roll angle and letting the motion commence without using any external force. The resulting motion is similar to that of Fig. 1 in a typical unprocessed time series of an individual test. For practical purposes, it is possible that the towing tank personnel perform multiple tests in one experimental run and save all of the data in a single file. In such cases, as in this work, the first step is to separate the full record into multiple records that roughly represent individual free decay tests.

Once the full record is reduced to individual tests, the valid free decay motion is isolated by removing the data at the beginning and the end of the record that may be named as "experimental noise". To clarify, in Fig. 1, the valid free decay motion is not at the beginning of the recorded time series. Before the decay motion, a calmly rolling vessel is taken and pushed to the desired test angle (8 degrees). Unintentionally, the required angle was overshoot to 10 degrees. Then it was readjusted and let to roll at approximately 125 s, marking the valid beginning of the experiment. Any data coming before is "experimental noise". This starting point is simple to identify visually. It can also be determined numerically through an iterative process by the help of parameters without visual inspection. Similarly, the end of the decay motion is also numerically identifiable.

After reducing the full record into the valid motion, the data can be restudied by regression analysis to spot out the outliers. Representing the data with a polynomial defining the decay