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Towing-tank experiment and analysis of nonlinear roll damping for a drillship with different appendages

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ABSTRACT

Offshore platforms with ship-like hull structures have relatively low roll damping moment. In this paper, variations of roll reduction appendages based on increasing damping strategy are proposed. The appendages are an ordinary bilge keel, a newly adopted variation involving extended platforms with ship-like hull structures, such as drillships or reversed flaps, and a stinger type. To validate the roll damping performance of newly designed appendages, a series of free-decay data for the roll motion in calm water and in regular waves are obtained from towing tank tests. The free-decay data for the roll motion is analyzed using a linear-plus-quadratic damping method as well as an alternative method based on the Hilbert transform in order to overcome the possible problem of nonlinearity for non-conventional roll stabilizers. The Hilbert transform technique has the advantage over polynomial damping models for not assuming the form of the roll characteristics. A comparison of the analysis methods for the different appendages is carried out for linear, nonlinear, and equivalent linear damping methods. The results are crosschecked in regular beam waves for different amplitudes near their resonant frequencies. From the experimental analysis, the linear and nonlinear roll characteristics for various appendages are discussed.

1. Introduction

Over the last decades, many studies have been conducted concerning roll reduction or stabilization as well as a roll performance estimation method for ships and offshore structures. However, high nonlinearity in roll characteristics leads to complexity and difficulty for research in the field of roll motion. Even now, excessive roll motion is a significant issue for many ships and offshore structures. Offshore platforms, such as drillship, have a relatively large length-to-beam ratio to take advantage of mobility that causes low damping performance. Both the dynamic stability and operability of drillship have a close relationship with the characteristics of roll motion.

Ship roll reduction or stabilization has a long history and can be divided into two categories: the first is the roll reduction or stabilization method, and the second is the evaluation or modeling method of the roll performance. In this study, among various roll reduction methods, the investigation is focused on passive roll damping devices such as a bilge keel and the analysis method for roll damping. Roll motion and related topics have been studied since the late-mid 1800's, starting with Froude (1981). Between the end of the 1950's and the 80's, a Japanese group, e.g. Tanaka (1961), Kato (1965), and Ikeda et al. (1978), studied roll damping based on theory, numerical calculation, and experimentation and suggested an empirical formula including the effect of a bilge keel. Particularly, Himeno (1981) summarized these studies, and Ikeda et al. (2004) suggested a modified model. The dynamic roll characteristic has been one of the most central topics in seakeeping study. However, owing to the complexity induced by high nonlinearity, potential flow methods cannot solve the roll motion issue effectively. Up to date, many research groups have adopted various methodologies, including the advanced experimental method, empirical formula, or computational fluid dynamics (CFD). One of the topics is related to the characteristics of roll motion for bare hull and with different appendages. Another branch of the research has been focused on the analysis method for roll damping, which includes higher polynomial roll damping model, finite differential model, or hyperbola model. Recently, CFD–based analyses have been used for the analysis of local phenomena, e.g. vortex shedding around bilge keels (Yeung et al., 1997; Yeung, 2002). Several authors have studied roll damping experimentally with particle image velocimetry

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(PIV) for local flow visualization (Aloisio and Felice, 2006; Bassler et al., 2007; Oliveira and Fernandes, 2012). Another branch of this field of study is roll damping modeling: Oliveira and Fernandes, 2014 used the bi-linear or hyperbola fitting method and Agarwal (2015) used fractional differential equation (FDE) instead of ordinary differential equation (ODE). In addition, several joint industry projects (JIPs) for floating production storage and offloading (FPSO), such as the CLAROM JIP (Ledoux et al., 2004) or Non-linear Roll JIP(Rezende, 2012), have been initiated.

All these methods have advantages and/or limitations, especially for newer hull designs or non-typical appendages in terms of shape and size. The ordinary method for a typical design has not been fully validated yet. Damping in the second-order ODE for motion is usually treated as a quadratic model, and it is widely accepted that this generally accommodates ordinary cases well. However, as recently stated by Oliveira and Fernandes (2014), the above quadratic modeling cannot be fully fit extended bilge keel examples. An empirical formula was also constructed based upon the database and usual shape series data; therefore, the physical interpretation based on the empirical formula for newer appendages may not produce accurate insights. When designing a new appendage, more general tools or scopes for identifying the characteristics of dynamic systems are needed.

In this study, the performance of the original model in roll and the efficiency of a passive appendage for increasing roll damping are evaluated using the experimental results. To capture the nonlinear roll characteristics of the ship-shaped platform with and without appendages in the zero speed condition more reliably, systematic towing tank model test programs are required and nonlinear analyses methods are examined to produce the experimental results. The test layout with wire and soft spring is adopted to minimize the unexpected drift due to yaw and sway, and their coupling with roll. The time series for the roll motion is measured for free-decay of roll in calm water and for harmonic oscillatory motion in regular beam waves and is analyzed based on the 1-DOF roll motion equation. From repeated free-decay roll tests with different appendages, the nonlinear characteristics are analyzed using different methods for crosscheck purposes: the high-order polynomial damping model proposed by Froude (1981), and the Hilbert transform (HT) method (Feldman, 1994; Lewandowski, 2011; Kim and Park, 2015). The HT is adopted for a series of experiments including non-typical appendages because the HT method can show instantaneous damping and restoring moments. The HT method has been studied with regard to signal processing by Feldman (1994), as well as others, and this method has been adopted for ship and offshore research by a few authors (Lewandowski, 2011; Kim and Park, 2015). These analysis methods are adopted for the free-decay experimental results based on the 1-DOF equation for roll motion. These results are compared to the roll motion responses measured in various wave frequencies and amplitudes. The appendage performance regarding the roll motion can be evaluated by Fourier analysis. Motion responses show corresponding results with roll damping from the free-decay test. From the experimental analysis, linear and nonlinear roll characteristics and possible parameters related to roll motion responses are discussed. Roll damping from the free-decay roll test conducted with various appendages can be used to estimate the performance relating to the roll motion to analyze the nonlinear nature of the roll damping characteristic.

2. Theoretical background

Two series of experiment, including the free-decay test in calm water and the seakeeping test, in regular beam waves are carried out in order to evaluate the roll damping coefficients of bare hull with and without appendages. Since the roll signal from the free-decay test generally lies within a narrow banded frequency and roll viscous damping has nonlinear characteristics, two different analysis methods are applied to crosscheck the nonlinearity of the test result: the high-order polynomial model proposed by Froude and a more sophisticated method based on the Hilbert transform.

2.1. Analysis of nonlinear damping: free-roll decay test

In this analysis, the decoupled 1-DOF equation of motion is considered for roll motion as equation (1), and the experimental scheme is also set to satisfy this condition.

$$\ddot{\phi}+\frac{B_\phi(\dot{\phi})}{I+I_a}+\frac{C_\phi(\phi)}{I+I_a}\phi=\ddot{\phi}+2b(\dot{\phi})+c(\phi)=0 \tag{1}$$

where I is the moment of inertia, I_a is the added moment of inertia, B_ϕ and C_ϕ are the roll damping and restoring function, respectively. Here, c becomes ω_n^2 where ω_n means the roll natural frequency.

2.1.1. High-order polynomial method

The main difference between the high-order polynomial method and the Hilbert transform is whether the method pre-assumes the form of the roll damping or not. As well known, the high-order polynomial method assumes the damping term b is the polynomial function of roll velocity including the linear and nonlinear terms as below.

$$\ddot{\phi}+2b(\dot{\phi})+c\phi=0 \quad \text{where} \quad b(\dot{\phi})=b_1\dot{\phi}+b_2|\dot{\phi}|\dot{\phi}+b_3\dot{\phi}^3+\cdots \tag{2}$$

In the free-decay test, a small decrement between each cycle due to small damping may be assumed; therefore the roll angle can be modeled as a harmonic function, i.e. $\phi(t)=\phi_a\cos(\omega t)$ where ϕ_a is the average amplitude in one or a half roll period and ω is motion frequency.

In the half cycle of a roll decay signal, the decrement in total energy can be assumed to be solely induced by energy dissipation with damping. The total energy, E_{total}, and time derivative of the total energy, $dE_{total}/_{dt}$, can be written as equations (3) and (4) respectively. Then, the change of total energy in a half roll decay cycle can be obtained from equation (5) (see Fig. 1(a)). Furthermore the energy dissipation for a half cycle, $E_{dissipation}$, can be estimated by the mean value as shown in equation (6). Since the change of total energy must be the energy dissipation, equation (7) can be led. That is, the linear coefficient b_1 and quadratic coefficient b_2 can be determined from equation (7) and curve fitting as shown in Fig. 1(b).

$$E_{total}=E_{kinetic}+E_{potential}=\frac{1}{2}\dot{\phi}^2+\frac{1}{2}\omega_n^2\phi^2 \tag{3}$$

$$\frac{dE_{total}}{dt}=\dot{\phi}\ddot{\phi}+\omega_n^2\phi\dot{\phi}=-2b(\dot{\phi})\dot{\phi}=\frac{dE_{dissipation}}{dt} \tag{4}$$

$$\begin{aligned}\Delta E_{total}&=\int_{\phi_{\max}}^{\phi_{\min}}\omega^2\phi d\phi=-\frac{\omega^2}{2}\left(\phi_{\min}^2-\phi_{\max}^2\right)=-\omega^2\phi_a\delta\phi \quad \text{where} \quad \phi_a\\&=1/2(\phi_{\max}+\phi_{\min}),\ \ \delta\phi=\phi_{\min}-\phi_{\max}\end{aligned} \tag{5}$$

$$\begin{aligned}E_{dissipation}&=-4\int_0^{\frac{T}{2}}\left(b_1\dot{\phi}+b_2\dot{\phi}|\dot{\phi}|+b_3\dot{\phi}^3+\cdots\right)\dot{\phi}dt\\&=-\left(2\pi b_1\omega\phi_a^2+\frac{16}{3}b_2\omega^2\phi_a^3+\frac{3\pi}{2}b_3\omega^3\phi_a^4+\cdots\right)\end{aligned} \tag{6}$$

$$\Delta E_{total}=E_{dissipation}: \quad \frac{\delta\phi}{\phi_a}=\left(\frac{2}{\omega}\pi b_1\right)+\left(\frac{16}{3}b_2\right)\phi_a+\cdots \tag{7}$$

2.1.2. Hilbert transform method

The analysis adopting the Hilbert transform has no assumption like the polynomial function approximation, constant oscillation frequency, or restoring moment. In this approach, only the harmonic oscillation vibration signal and narrow banded signal are assumed. Then, the Hilbert transform of the original time-series y(t) is defined as below: