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Identification of the nonlinear roll damping and restoring moment of a FPSO using Hilbert transform

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ABSTRACT

Roll motion is a major concern of ship and offshore operators because it has a direct impact on the boarding comfort of crews, downtime of the process plant and structural integrity of the hull and appurtenance system. Nevertheless, the nonlinear effects involved in the roll motion of ship and offshore structures are not only incompletely understood, but also inaccurately predicted during the design stage. Therefore, efforts have been made to identify the dynamic characteristics of the roll motion of a FPSO using a novel dynamic system identification scheme based upon the Hilbert transform. First, the system identification scheme using the Hilbert transform was applied to the idealized single DOF nonlinear oscillator problem with quadratic damping and quintic stiffness terms. The solution of the single DOF problem was solved numerically using the 4th order Runge–Kutta method and the target damping and stiffness coefficients were determined by applying the Hilbert transform to the numerically obtained free decay signal. A comparison was also made with traditional logarithmic decrement technique for the damping coefficient. Second, the system identification method was applied to the model test results of a FPSO with a bilge keel, where the nonlinear effect of roll damping and restoring is expected to be dominant. This methodology can be applied to full scale measurement data to achieve a clearer understanding on the nonlinear effect of roll motion.

1. Introduction

Roll motion of a ship-like floating structure under wave excitation is one of the most important factors that affects the production downtime, boarding comfort of crews and the structural safety of moorings and risers. Therefore, an accurate prediction of roll motion is very important during the design stage of a structure, which has prompted extensive research efforts. Recently, the joint industry project named Nonlinear Roll JIP (Oliveira et al., 2014) was initiated and has attracted considerable attention from ship owners and builders. The project covers a broad range of topics, which are closely related to the accurate prediction of roll motion under wave excitation, such as roll damping estimation, influence of the riser on roll motion, second order effect and structural assessments. Model basin tests, computation fluid dynamics simulations and full scale measurements were considered as methodologies.

The major technical difficulties related to the roll motion of a floating body are the nonlinear effects of roll damping. Unlike other motions, where damping is dominated significantly by the propagation of radiated waves, the roll damping is influenced mainly by the viscosity-induced vortexes between the hull surface and water particles. Normally, the viscous damping force acting on the rolling structure is known to be proportional to both the angular velocity of the body and the product with its modulus eventually making the problem nonlinear. In addition, when roll motion becomes considerably large, beyond the limit of linearity, the restoring moment, which is no longer proportional to the roll angle itself, is influenced by the higher order terms of odd numbers.

The majority of the prior research efforts related to the nonlinear roll response of a floating body focused more on the solution of the roll response, either by analytic (Taylan, 1999; Taylan, 2000; Bulian, 2004), experimental (Chun et al., 2000) or numerical ways (Wilson et al., 2006; Veer and Fathi, 2010; Yang et al., 2012; Avalos et al., 2014). Less research has been done to identify the roll characteristics by an inverse technique through which the nonlinear system parameters can be determined by analyzing the free decay signal obtained either by numerical or experimental methods. Chan et al. (1995) proposed a new asymptotic method through which the nonlinear damping coefficient and restoring moment can be predicted accurately. They applied the methodology to a nonlinear ordinary differential equation representing the motion of a rolling body, and found that the proposed methodology can determine the coefficients of differential

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equation accurately when the motion is large. Mahfouz (2004) applied the random decrement technique combined with auto- and cross-correlation functions together with a neural network in identifying the system parameters that govern the roll motion of a ship voyaging through the wave. He tested the methodology by applying it to the data generated both numerically and experimentally, and reported that the proposed method can identify the parameters of roll damping and restoring moment with nonlinearity. Jang et al. (2010) proposed an inverse formulism to identify the function form of nonlinear roll damping for a ship. They examined the experimental data obtained for a particular ship using an integral equation of the first kind and proposed a regularization term to avoid the stability problem invoked by the ill-posedness.

System identification is a branch of research that is dedicated to the identification of the parameters that governs the characteristics of a given dynamic system. Modal parameters, such as the natural frequencies, mode shapes, damping and restoring forces, and moments, are the main targets of identification, which is done by analyzing the measured data using range of different signal processing techniques. A Fourier transform enables one to capture the dynamic nature of a system by handling the complicated time series in far simpler frequency domain. Owing to the drawback of Fourier transform, i.e., the loss of temporal characteristic of signal, significant attention has been paid to other advanced methods, such as wavelet transform (Staszewski, 1997; Slavic and Boltezar, 2011), Hilbert transform (Feldman, 2011) and Hilbert–Huang transform (Huang, 1971). Staszewski and Cooper (1995) originally proposed the application of the continuous wavelet transform for dynamic system identification. Staszewski (1997) later derived the relationship between the modal parameters, such as the damping ratio and natural frequency, and continuous Morlet wavelet transform of the system's impulse response based on the asymptotic technique. A relationship was also found to hold for the multi-DOF system due to the frequency localization property of the wavelet transform. This system identification method was applied successfully to bridges (Ruzzene et al., 1997), aircraft (Staszewski and Cooper, 1997) and tall buildings (Lardies and Gouttebroze, 2002). Kim and Park (2014) applied the random decrement technique to the measured vertical bending moment of a bulk carrier model with segmentation towed in a model basin and derived the free decay signal of its first and second vertical bending modes. They identified the natural frequencies and damping coefficient of the vibrating flexible hull using the wavelet transform. The derived natural frequencies matched well with those obtained from the wet hammering test results, but the estimated linear damping coefficient was larger than that of the still water hammering test due to the forward speed effect. Feldman (1994a) proposed the Hilbert transform-based methodology through which the nonlinear damping and restoring coefficients of a single DOF nonlinear dynamic system can be obtained. He derived analytically the mathematical relationship between a free decay signal and its nonlinear damping and restoring coefficients based on the Hilbert transform. He also developed a method that could predict the nonlinear damping and restoring coefficient under forced vibration conditions (Feldman, 1994b). Lewandowski (2011) identified the roll damping coefficient of a ship with or without a bilge keel using the experimental data obtained in the model basin. He applied both classical logarithmic decrement technique and the Hilbert transform method to predict the roll damping coefficients of both linear and quadratic terms. Shi et al. (2009) applied the Hilbert transform together with the empirical mode decomposition method to identify the linear time-varying multi-DOF dynamic system under forced excitation. They reported that the proposed method worked well for identification of the dynamics parameters but some errors were introduced due to the lack of complete orthogonality of any two intrinsic mode functions.

In this paper, efforts were made to predict the nonlinear damping and restoring coefficients of a single DOF rolling FPSO by applying the Hilbert transform to the free decay signal obtained by a free roll decay test. In addition, to confirm the validity of the methodology, a nonlinear single DOF ordinary differential equation of second order with nonlinear damping and restoring terms was solved numerically and the numerical free decay signal was obtained. Applying the Hilbert transform to this signal, the nonlinear damping and restoring coefficients used in the original differential equation were estimated. For the damping coefficients, traditional logarithmic decrement technique was used and cross-compared with that obtained by the Hilbert transform. After validation, the methodology was applied directly to the free decay signal obtained from the model basin test of a rolling FPSO with a bilge keel performed by Oliveira and Fernandes (2014).

2. Theoretical background

2.1. Hilbert transform

The Hilbert transform enables one to derive the analytic signal out of an arbitrary real signal. The analytic signal means that the form of a signal contains information on the so called instantaneous frequency and amplitude so the signal characteristics in the framework of time-frequency domain can be understood better. The Hilbert transform is a key mathematical process that leads a given real signal to the analytic signal of complex form. For a given real signal in time domain, $g(t)$, the Hilbert transform is defined as the convolution integral of $g(t)$ and $1/t$, as shown in Eq. (1).

$$\hat{g}(t) = \mathscr{H}[g(t)] = \frac{1}{\pi} PV \int_{-\infty}^{\infty} \frac{g(\tau)}{t-\tau} d\tau = \frac{1}{\pi t} * g(t) \tag{1}$$

where PV means the Cauchy integral and the asterisk stands for the convolution integral. The nature of the Hilbert transform can be easily understood once both sides of Eq. (1) are Fourier transformed. Because the Fourier transform of the convolution integral of any two function is the product of the Fourier transform of each function, Eq. (1) leads to

$$\mathscr{F}\left[\hat{g}(t)\right] = \mathscr{F}\left[\frac{1}{\pi t} * g(t)\right] = \mathscr{F}\left[\frac{1}{\pi t}\right]\mathscr{F}[g(t)] \tag{2}$$

Fourier transform of $1/\pi t$ is given as Eq. (3)

$$\mathscr{F}\left[\frac{1}{\pi t}\right] = -i sgn(f) = \begin{cases} -i \text{ for } f > 0 \\ +i \text{ for } f < 0 \end{cases} \tag{3}$$

where the function $sgn(f)$ stands for a sign function that gives positive unity for positive arguments and negative unity for negative arguments. The Fourier transform of $\hat{g}(t)$ is given as Eq. (4).

$$\mathscr{F}\left[\hat{g}(t)\right] = \begin{cases} -iG(f) \text{ for } f > 0 \\ +iG(f) \text{ for } f < 0 \end{cases} \tag{4}$$

Eq. (4) means that the Hilbert transformed signal can be obtained by rotating the original signal by $-90°$ for the positive frequency component and by $+90°$ for the negative frequency component in the frequency domain. The Hilbert transform enables one to construct the analytic signal by taking the original signal, $g(t)$, as the real part and its transformed one, $\hat{g}(t)$, as the imaginary part of a complex signal, so that one can reach the complex analytic signal, as shown in Eq. (5).

$$z(t) = g(t) + i\hat{g}(t) = A(t)e^{i\phi(t)} \tag{5}$$

The modulus of the analytic signal, $A(t)$, is the instantaneous amplitude or envelope of the given signal and $\phi(t)$ is the phase angle, both of which are expressed as the original signal and its