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Early detection of parametric roll by application of the incremental real-time Hilbert–Huang Transform

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A B S T R A C T

This work focuses on the early detection and advance warning of parametric roll in regular and irregular head seas. The time–frequency dependent analysis technique, Hilbert–Huang Transform (HHT) is applied to acquire the so-called "instantaneous frequency", which can be used for the detection of the non-linear parametric roll motion. Firstly, an incremental real-time HHT (IR-HHT) technique is implemented to an artificial time series which is simply composed from the parametric roll and pitch motion time series with its main characteristics: frequency shift and amplitude growth. This is followed by the proposal of a detection scheme aimed at the identification of the frequency shift and amplitude growth between roll and pitch motion. The proposed detection scheme is validated by analyzing parametric roll time series obtained from numerical simulation in regular and irregular head seas. Results show that the onset of parametric roll can be detected successfully through the detection scheme based on IR-HHT technique. Moreover the robustness of the detection scheme is validated.

1. Introduction

Due to the time-varying changes in water plane area and roll restoring moment, parametric resonance will occur in ship roll motion under certain conditions, and is known as parametric roll. Parametric roll occurs with excessive roll motion and even leads to capsizing. It can cause severe cargo loss and damage as investigated by France et al. (2003) on a post-Panamax C11 class containership APL China. Small fishing vessels (Neves et al., 1999), Cruiser ship and PCTC (Ovegård et al., 2012) are also known to be prone to parametric roll.

Initially, theoretical research on parametric roll was conducted based on the Mathieu equation (Kerwin, 1955, Nayfeh, 1988). In recent years especially after the investigation on APL China accident, great efforts were devoted to the numerical simulation and experimental study on parametric roll. Numerical simulation codes with various complexities were developed, including 1-DOF (Umeda et al., 2004), 1.5-DOF (Bulian, 2005), 3-DOF (Neves et al., 1999) and 6-DOF (Spanos and Papanikolaou, 2007). Furthermore Sadat-Hosseini et al. (2010) conducted parametric roll simulation of a surface combatant based on CFD code. Further researches also focused on the various factors concerning with parametric roll, such as non-linear restoring forces (Vidic-Perunovic and Juncher Jensen, 2009), roll damping (Hashimoto and Umeda, 2010), surge and sway motion (Ahmed et al., 2010), time-varying forward speed (Breu et al., 2012; Ma et al., 2012), large amplitude wave dynamics (Ahmed et al., 2010), wave added resistance(Lu et al., 2011) and probabilistic properties in irregular waves (Belenky and Weems 2012; Kim et al., 2011). Meanwhile several systematic experimental studies on containerships (Spanos and Papanikolaou, 2009; Hashimoto et al., 2006), PCTC (Hashimoto et al., 2007) and fishing vessels (Neves et al., 1999) were conducted in various conditions. In the meantime, IMO Sub-Committee on Stability and Load Lines and on Fishing Vessels Safety (IMO SLF) has been working on the multilevel criteria on parametric roll as part of the second generation intact stability for years (Francescutto and Umeda, 2010). Draft vulnerability criteria of level 1 and 2 for parametric roll are proposed in 2013 (SLF55/WP3, 2013).

Although theoretically it is plausible to prevent parametric rolling in the design stage based on certain criteria, some ships can still be vulnerable to parametric roll in real sea. Hence, there is great interest in the research community on studies related to the stabilization of parametric roll after its onset. Outcome of these researches shows that, passive devices including sponson and passive anti-rolling tank (Umeda et al., 2008), and active devices including fin stabilizer (Galeazzi et al., 2009), active anti-rolling tank (Holden et al., 2009) and rudder (Yu et al., 2012; Söder et al., 2013) are confirmed to be effective. However, Söder et al. (2013) and Yu et al. (2012) pointed out that the earlier these devices are

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activated, the more effective the stabilization of parametric roll, which is especially the case in real sea. Therefore, an on-board parametric roll early detection system is needed for the activation of these devices.

Proposed methods for the detection of parametric roll can be generally categorized into two types: model-based method and signal-based method. In the model-based method, certain model for ship parametric rolling is required. McCue and Bulian (2007) investigated the practicality of using finite-time Lyapunov exponents (FTLEs) to detect the onset of parametric roll in irregular seas based on a 1.5 DOF analytical model. Simulation results demonstrated that FTLE time series can be used for parametric roll detection. However, the application of monitoring FTLEs in real time to realistic, e.g., noisy, experimental data needs to be investigated. Based on a nonlinear 2DOF ship model, Belleter et al. (2012) designed a state observer in the form of Extended Kalman filter (EKF) to estimate the wave frequency and wave encounter frequency, which can also be used for the detection of parametric roll. The need for the identification of a ship-specific model is one of the major disadvantages of the model-based method. Moreover, it could be difficult to obtain a robust detection on various types of ships. In order to tackle this issue, Galeazzi et al. (2013) developed a signal-based detection method and obtained robust detection based solely on signals. The detection method possesses one spectral correlation detector in the frequency domain and one phase synchronization detector in the time domain. Robust detection in realistic condition is obtained through adaption of a generalized likelihood ratio test (GLRT) that is derived for a Weibull distribution observed from data. The detection schemes revealed the dynamic properties of parametric roll and are proved to be robust and effective based on validations using yearlong full-scale sea data (Galeazzi, 2014; Galeazzi et al., 2015). For the present study, an alternative method using the signal-based time–frequency dependent analysis method, Hilbert–Huang Transform (HHT), is introduced for the detection of parametric roll.

Hilbert–Huang Transform (HHT) (Huang et al., 1998) is a newly developed time–frequency dependent analysis method based on Hilbert transform. Practical applications of the HHT are widely spread in various fields such as transient water waves, earthquake investigation, tsunami research and structure vibration analysis (Dätig and Schlurmann, 2004). These applications involve analysis of time series with properties like nonlinear, non-stationary, transient and multicomponent, which are not suitable for using ordinary, time-invariant Fourier-based techniques. The nonlinear time signals of parametric rolling also possess similar properties. Therefore, the HHT approach is considered to be applicable to detect the frequency shift and amplitude growth during the initial stage of parametric rolling. Using HHT the parametric roll can be detected before roll amplitude grows large and operations for avoidance and stabilization of parametric roll can be implemented promptly.

The main goal of this paper is to develop a robust parametric roll detection scheme based on the time–frequency dependent method Hilbert–Huang Transform (HHT) aiming at the early identification of frequency shift and amplitude growth caused by parametric roll. The detection scheme is initially developed based on an artificial time series simplified from the parametric roll and pitch motion time series. Then the effectiveness and robustness of the detection scheme is validated using the parametric roll numerical simulation results of a 3100TEU containership.

2. Theoretical background

2.1. Mathematical principles of parametric roll

The fundamental dynamics of parametric roll is parametric resonance caused by the time varying of ship roll restoring characteristics. It can be simplified as the Mathieu equation with damping:

$$\phi'' + 2\zeta\phi' + (\omega_0^2 + \epsilon \cos \omega t)\phi = 0 \tag{1}$$

where ϕ is the roll angle, ζ is the roll damping coefficient. ω_0 and ω stand for the roll natural frequency and the exciting frequency respectively. Moreover the equation can be expressed as the following first-order system:

$$x' = A(t)x \quad x = [\phi, \phi']^T; A(t) = \begin{bmatrix} 0 & 1 \\ -(\omega_0^2 + \epsilon \cos \omega t) & -2\zeta \end{bmatrix} \tag{2}$$

Thus the damped Mathieu equation is transferred into a first-order linear equation with periodic coefficients with

$$A(t+T) = A(t)(\text{for all } t) \tag{3}$$

where, the period $T = 2\pi/\omega$. The Floquet theorem (Grimshaw, 1991) can then be applied to the analysis of this first-order system with periodic coefficients.

Theorem 1. *There exists a non-singular constant matrix B such that*

$$X(t+T) = X(t)B \tag{4}$$

Here $X(t)$ is a fundamental matrix for Eq.(2). Also,

$$\det B = \exp \int_0^T \mathrm{tr} A(\tau) d\tau \tag{5}$$

where *det* and *tr* denote the determinant and trace of a matrix respectively.

Thus the matrix B can be expressed in terms of the fundamental matrix by putting $t = 0$:

$$B = X^{-1}(0)X(T) \tag{6}$$

Theorem 2. *For a first-order linear equation with periodic coefficients, there exists a periodic function p(t) (p(t)=p(t+T)) such that a solution x(t) of Eq. (2) can be expressed as:*

$$x(t) = e^{\mu t} p(t) \tag{7}$$

where μ is given by $\rho = e^{\mu T}$, and ρ is an eigenvalue of the matrix B.

The solution of Eq. (1) depends on ω_0, ζ and ε, and can be expressed as: $\phi = \phi(\omega_0, \zeta, \varepsilon)$. It is still complicated to get a complete solution and draw the stability boundaries of Eq. (1). However, because $\phi(\omega_0, \zeta, \varepsilon)$ is analytic in ω_0, ζ and ε, the information about the stability boundaries when ζ and ε is small can be obtained by the solution at $\zeta = 0$ and $\varepsilon = 0$. Therefore Eq. (1) is reduced to a simple second order ODE with constant coefficients which yields a general solution as

$$\phi = c_1 \cos \omega_0 t + c_2 \sin \omega_0 t \tag{8}$$

Hence in Eq. (4), the principal fundamental matrix $X(t)$ can be derived by assuming that $X(0) = E$.

$$X(t) = \begin{bmatrix} \cos \omega_0 t & \sin \omega_0 t/\omega_0 \\ -\omega_0 \sin \omega_0 t & \cos \omega_0 t \end{bmatrix} \tag{9}$$

Furthermore the constant matrix B

$$B = X^{-1}(0)X(T) = \begin{bmatrix} \cos \omega_0 T & \sin \omega_0 T/\omega_0 \\ -\omega_0 \sin \omega_0 T & \cos \omega_0 T \end{bmatrix} \tag{10}$$