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Operational modal analysis on the hydroelastic response of a segmented container carrier model under oblique waves

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ABSTRACT

Both vertical and torsional mode shapes of a segmented container carrier model towed in a model basin are estimated using the operational modal analysis. The operational modal analysis targets to identify the modal properties of a structure using measured data collected during the operation without any information about the excitation. The proper orthogonal decomposition, which is also known as Karhunen–Loeve decomposition, was used for the extraction of mode shapes, and the random decrement technique was applied for the derivation of free decay signal. The segmented hull model of 10,000 TEU container carrier with the scale of 1/60 was towed in a model basin under head and oblique waves and the strain time histories at the designated locations along the continuous backbone were measured. The sectional load, which was estimated based upon the measured strain, was processed using the proper orthogonal decomposition to obtain both vertical and torsional vibration modes. Finally, the free decay signal of each modes was extracted out of the processed data using the random decrement technique and wet damping ratios as well as damped natural frequencies were estimated.

1. Introduction

Traditionally, hydroelasticity has not been considered in significant way in the design of sea going vessels, since so called 'wet-mode' natural frequency of the commercial ship is still in the frequency range far higher than those of wave in open sea. Due to this frequency gap between ocean wave and wet-mode natural frequency of sea going vessel, it is less likely that ships go through resonance problem which eventually leads to excessive vibratory response. However, as ships get faster and faster, encounter frequency tends to be larger moving closer to the frequency range of ship's hull girder vibration. Moreover, as ship size gets bigger and bigger, her natural frequency tends to be lower due to relatively low stiffness level compared to her total mass contributing to the increasing likelihood of resonance between hull girder vibration and wave excitation.

One of the most critical situations among others is the case of ultra-large container carrier. There is high demand that container carrier should travel faster than other types of commercial vessel meaning that encounter frequency of it can easily become high. On the other hand, unlike other types of vessel, container carriers have very low torsional natural frequencies due to large hatch openings on deck, under which condition it is highly likely to meet resonance problem under oblique sea condition. However, it is well known that full scale measurement always shows high frequency peak which is caused by hydroelastic response of flexible hull regardless of ship type.

In order to enhance the understanding on this hydroelasticity problem, considerable research efforts have been devoted over the past decade. Majority of research activities related to this topic may be classified into two categories, i.e., computational method and experimental methods. The recent achievements of the computational method on the hydroelasticity (Price and Temarel, 1982; Jensen and Dogliani, 1996; Wu and Moan, 1996; Malenica et al., 2003; Hirdaris et al., 2003; Kim, 2009; Kim et al., 2013) have been rather dramatic thanks to the rapid increase in computer resource. On the other hand, both full scale measurement and model basin test have also been actively conducted (Remy et al., 2006; Iijima et al., 2009a, 2009b; Miyaka et al., 2009; Oka et al., 2009; Hong and Kim, 2014). The dynamic modal parameters, such as natural frequencies, damping coefficients and mode shapes, are of prime interest from the viewpoint of the dynamic response of a vibrating hull structure. However, these dynamic modal parameters need to be extracted from the response of a vibrating ship structure without any information about the excitation because excitations are difficult to know. This becomes even more important when analyzing the full scale measurement data (Hirdaris et al., 2009;

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Miyake et al., 2010; Drummen et al., 2009; Jensen, 2009), where the dynamic modal parameters should be extracted from the measured response only.

Operational modal analysis is an emerging technology through which the unknown modal parameters can be estimated with output data only. Among others, the proper orthogonal decomposition(POD) and random decrement technique(RDT) is popularly used signal processing techniques for the identification of modal parameters, such as mode shapes, natural frequencies and damping ratios. POD is a statistics-based order reduction technique through which the motion of a dynamic system of large DOF can be approximated by the combination of lower order descriptions. The basic principle behind this method is that the eigenvector of a spatial coherence matrix of certain physical quantities measured at several different locations becomes the mode shapes, or basis function of the system, which may then be used in the Galerkin procedure. This is an important technique for data reduction, feature extraction, and it has been used widely in many engineering fields, such as image processing, signal analysis, system identification, adaptive control, etc. The starting engineering application of the POD was based on an analysis of the spatial distribution of turbulence in a fluid field (Lumley, 1970), and later an extension was made toward the mode shape extraction of a vibrating structure (Feeny and Kappagantu, 1998; Feeny, 2002). Another interesting technique that can be used to extract the mode shapes is RDT. This technique was developed originally by Cole (1968, 1971) in the form of an 'auto' random decrement to identify the dynamic characteristics and in-service damage detection of the space structure from the measured response only. Ibrahim and Mikulcik (1977) later introduced the concept of the cross random decrement signature that enabled the identification of the mode shapes of a multi-DOF system.

Kim and Park (2013) applied random decrement technique together with wavelet transform to identify modal parameters of hydroelastically responding ship structure. They reported that the derived natural frequencies did not show any significant discrepancy compared to those obtained by still water wet hammering test results, but the damping ratios under wet towing conditions were up to 20% higher than those obtained by wet hammering test. Mariani and Dessi (2012) estimated the mode shapes of a vibrating hull structure on a small scale model. They applied the proper orthogonal decomposition (POD) method to extract the mode shapes of a segmented hull model connected to a backbone structure running from bow to stern. The first, second and third vertical mode shapes were estimated by processing both the measured vertical bending moment (VBM) and acceleration using POD, and they determined that both matched each other well. Kim et al. (2015) applied the proper orthogonal decomposition method and cross random decrement technique to extract mode shapes of a segmented ship model of 400 K ore carrier. It was found that the vertical bending modes of 2 and 3 node vibration were clearly captured and correspondence between the two results was very good.

This paper is an extension of the work by Kim et al. (2015) targeting the identification of wet mode shapes of a segmented hull model under oblique waves using the proper orthogonal decomposition method. The experimental data used in this study is the output of WILS II JIP where extensive experiment on the segmented container carrier model was carried out. The experimental campaign was carried out KRISO in Korea and the details of the experiment may be found in Hong and Kim (2014). Based upon the experimental data, both vertical bending and torsional vibration modes up to 3rd mode were extracted by the applying POD method. Also, free decay signals for each mode were reconstructed using RDT and they were further processed eventually estimating the damped wet natural frequencies and damping ratios for each modes.

2. Theoretical background

2.1. Proper orthogonal decomposition

The POD starts with the spatial coherence matrix of a certain physical quantity, such as torsional moment (TM), VBM at different locations along the ship length in this particular case. The ensemble matrix of measured sectional loads at M different locations along the ship is defined in Eq. (1).

$$\mathbf{X}=[\mathbf{x}_1, \mathbf{x}_2, \mathbf{x}_3 \ldots, \mathbf{x}_M] \tag{1}$$

where the column vector, $\mathbf{x}_i$, stands for the sectional load time history of N discrete time intervals, and can be represented by Eq. (2).

$$\mathbf{x}_i=\left[x_i(t_1), x_i(t_2), x_i(t_3)\ldots, x_i(t_N)\right]^T \tag{2}$$

Time histories of the sectional load may be assumed as a linear combination of the normal modes so that one has

$$\mathbf{x}(t)=e_1(t)\mathbf{v}_1+e_2(t)\mathbf{v}_2+\ldots+e_M(t)\mathbf{v}_M \tag{3}$$

where $e_i(t)$ is the time modulation of the ith mode. The ensemble matrix given in Eq. (1) has the form,

$$\mathbf{X}=\left[\mathbf{x}(t_1), \mathbf{x}(t_2),\ldots, \mathbf{x}(t_N)\right]^{\boldsymbol{T}}=\left[\mathbf{e}_1\mathbf{v}_1^T+\mathbf{e}_2\mathbf{v}_2^T+\ldots+\mathbf{e}_M\mathbf{v}_M^T\right], \tag{4}$$

where the row vector $\mathbf{e}_i$ is defined as $\left[e_i(t_1), e_i(t_2),\ldots,e_i(t_N)\right]$. The spatial coherence matrix post multiplied by $\mathbf{v}_j$ gives,

$$\mathbf{R}\mathbf{v}_j=\frac{1}{N}\mathbf{X}^T\mathbf{X}\mathbf{v}_j=\frac{1}{N}\left[\mathbf{e}_1\mathbf{v}_1^T+\mathbf{e}_2\mathbf{v}_2^T+\ldots+\mathbf{e}_M\mathbf{v}_M^T\right]^T \left[\mathbf{e}_1\mathbf{v}_1^T+\mathbf{e}_2\mathbf{v}_2^T+\ldots+\mathbf{e}_M\mathbf{v}_M^T\right]\mathbf{v}_j \tag{5}$$

where the matrix, $\mathbf{R}$, is defined as a spatial coherence matrix, i.e. $\frac{1}{N}\mathbf{X}^T\mathbf{X}$. Each entry of the coherence matrix, R_{ij}, is the inner product of the two measured VBM time histories at locations i and j, which indicates the correlation of the VBM of two locations. Considering the orthonormality of the eigenvectors, the far right term of Eq. (5) becomes,

$$\mathbf{R}\mathbf{v}_j=\frac{1}{N}\left(\mathbf{v}_1\mathbf{e}_1^T\mathbf{e}_j+\mathbf{v}_2\mathbf{e}_2^T\mathbf{e}_j+\ldots\mathbf{v}_M\mathbf{e}_M^T\mathbf{e}_j\right) \tag{6}$$

All terms of Eq. (6) except for $\mathbf{v}_j\mathbf{e}_j^T\mathbf{e}_j$ will disappear because of the distinct frequency of each vibration mode when the signal record length is long enough. Hence,

$$\lim_{N\to\infty}\frac{1}{N}\mathbf{v}_i\mathbf{e}_i^T\mathbf{e}_j=0 \qquad when\ \ i\neq j \tag{7}$$

Taking advantage of Eq. (7), Eq. (6) finally becomes,

$$\mathbf{R}\mathbf{v}_j=\frac{\mathbf{e}_j^T\mathbf{e}_j}{N}\mathbf{v}_j=\lambda\mathbf{v}_j \tag{8}$$

Eq. (8) implies that the eigenvectors of the coherence matrix, $\mathbf{R}$, which is called the proper orthogonal mode (POM), becomes the modal vector of the given system that the measurement was made on. Eq. (8) holds only when the external excitation is absent, i.e., free vibration case, but most of the real world situations is a forced vibration. In the case that the external harmonic excitation is present, different mode shapes may be excited with the same frequency so that Eq. (7) would not hold any longer. Nevertheless, if one of the modes resonates with a predominantly large magnitude, the POM becomes a good approximation of the mode shape. The accuracy of the approximation depends strongly on the relative magnitude of the resonant vibration and non-resonant one. The hydroelastic response of a flexible ship is a resonance dominant one with relatively small damping, which can be