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Wet damping estimation of the scaled segmented hull model using the random decrement technique

Yooil Kim [a,*], Sung-Gun Park [b]

[a] Department of Naval Architecture and Ocean Engineering, INHA University, 100, Inha-Ro, Nam-Gu, Incheon, South Korea
[b] DSME R&D Institute, Daewoo Shipbuilding and Marine Engineering Co., Ltd., 221-17, Nonhyun-Dong, Gangnam-Gu, Seoul, South Korea

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ABSTRACT

Damping is one of the most uncertain factors in structural dynamic problems, and plays a very important role in resonance phenomena such as springing. This paper presents the wet damping estimation of a segmented hull model using a random decrement technique together with continuous wavelet transform. The 16 sea states were grouped together based on the speed of the ship to determine the possible influence of the ship speed on the damping ratio. The measured time histories of the vertical bending moment for each tested sea state were processed using the random decrement technique to derive the free decay signal, from which the damping ratios were estimated. In addition, the autocorrelation functions of the filtered signal were calculated and a comparison was made with the free decay signal obtained from the random decrement technique. The wet damping ratios for each sea state group, as well as precise wet natural frequencies, were estimated using a continuous wavelet transform. The wet natural frequencies derived from the measured signal did not show any significant discrepancy compared to those obtained using the wet hammering test, whereas a significant discrepancy was observed with the damping ratio. The discrepancy of the damping ratio between in calm and moving water might be due to the viscous effects caused by the dramatically different flow patterns and relative velocity between the vibrating structure and surrounding fluid particles.

1. Introduction

As modern merchant ships are increasing in size and speed, more attention is being paid to the global vibratory response of the ship structure under a wave load. The vibratory response of large, flexible ships can be categorized into two types, i.e., springing and whipping. The former is the steady-state resonant vibration of a flexible hull and the latter is transient vibration excited by an impulsive slamming load. The slamming load is defined as an impulsive load acting either on the bottom, flare, or stern of the hull when the bow or the stern of the ship plunges into a wave. In general, the springing phenomenon is more relevant to the fatigue strength of the ship structure whereas the whipping phenomenon is more relevant to the ultimate strength of the ship structure, even though the cross relationship, e.g., the effect of whipping on fatigue is not negligible. Although two different vibratory responses have different effects on the structure, both cause additional fatigue damage to the ship structure on top of the wave-induced portion because both phenomena induce stress fluctuations near the fatigue prone area of the ship structure.

The additional fatigue damage induced by the above-mentioned hydroelasticity effect needs to be considered during the design stage to avoid unexpected premature fatigue failure at the critical location inside the hull structure. The influence of the hydroelasticity effect on the fatigue damage can be determined in two ways. The first is an experimental approach and the other is the numerical approach. In the experimental approach, a scaled, segmented model is tested in the model basin and the vertical bending moments and shear forces at the junction are measured and analyzed (Storhaug, 2007). This is considered to be the most reliable method because the model test itself can consider all possible complicated physical phenomena, including highly nonlinear slamming events as well as higher order springing excitations. On the other hand, from model fabrication and calibration up to the sea state selection, the test procedure is not straightforward so that care needs to be taken in carrying out the experiment. Numerical analysis has become mature enough to replace the experimental approach, even though the versatility is still limited by some nonlinear effects that are difficult to consider (Price and Temarel, 1982; Malenica et al., 2003; Hirdaris et al., 2003; Kim, 2009). For an accurate prediction of the additional fatigue damage by numerical analysis, damping is considered to be of prime importance because both springing and whipping are the dynamic behavior of the flexible hull at the natural frequencies of the hull.

* Corresponding author. Tel.: +82 32 860 7347; fax: +82 32 864 5850.
E-mail addresses: yooilkim@inha.ac.kr (Y. Kim), sgpark8@dsme.co.kr (S.-G. Park).

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The damping identification of a vibrating structure, including other modal parameters such as the natural frequencies and mode shapes, has been a key research topic in many engineering fields and the two key techniques are deeply entangled with this, the random decrement technique and wavelet transform. The random decrement technique was originally developed by Cole (1968, 1971), to identify the dynamic characteristics and in-service damage detection of the space structure from the measured response only. He detected the damage of a structure based on the envelope change in the autocorrelation function of the measured signal. Ibrahim and Mikulcik (1977) later introduced the concept of the auto and cross random decrement signature and enabled the identification of mode shapes and natural frequencies of a multi-DOF system. Vandiver et al. (1982) proved mathematically that a random decrement signature is related to the auto and cross correlation function of the signal with some factors involved that are dependent on the triggering condition. Kareem and Gurley (1996) carried out uncertainty analysis on the estimated damping in the structure using the random decrement technique. Material damping as well as the aerodynamic- and hydrodynamic-induced damping was also considered in their study. Zubaydi et al. (2000) used the autocorrelation function scheme to identify the damage in the side shell of a ship hull and confirmed the relationship between the autocorrelation function and the random decrement signature. Elshafey et al. (2009) applied the random decrement technique to determine the characteristics of the dynamic response of the offshore jacket structure in both air and water. The correspondence between the results obtained from the random decrement technique and finite element analysis was acceptable.

On the other side of the system identification, the wavelet transform has gained importance as a powerful signal processing technology over the past few decades in cases where traditional Fourier analysis does not work properly. A wavelet transform has benefits over Fourier transform in that it can adjust both the temporal and spectral resolution. This adjustable time–frequency resolution enables one to analyze the non-stationary signal with great flexibility. Owing to the versatility of the wavelet transform, it is used widely in many fields, such as, fault diagnosis, pattern recognition and modal parameter identification, etc. Staszewski and Cooper (1995) originally proposed to apply the continuous wavelet transform for dynamic system identification. Staszewski (1997) later derived the relationship between the modal parameters, such as damping ratio and natural frequency, and continuous Morlet wavelet transform of the system's impulse response based on the asymptotic technique. The 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 has been applied successfully to bridge (Ruzzene et al., 1997), aircraft (Staszewski and Cooper, 1997) and tall building structures (Lardies and Gouttebroze, 2002).

In this study, the structural responses obtained from the segmented flexible hull model towed in a model basin were processed using the random decrement technique, and the damping ratio was examined based on the continuous wavelet transform of the obtained free decay signal. The vertical bending moment time histories obtained from 16 different sea states with four different towing speeds were analyzed using the random decrement technique to determine the free decay signal of the system. The autocorrelation functions were also calculated to check the relationship with a random decrement signature. The modal parameters, such as natural frequencies and damping ratios, were then obtained based on the continuous wavelet transform of the free decay signal obtained from the random decrement technique.

2. Theoretical background

2.1. Random decrement technique

The random decrement technique is a simple but very powerful method for identifying a dynamic system, and is used widely for modal parameter identification where prior information on excitation is unknown. The random decrement signature, which eventually becomes the free decay signal of a system, was defined as the expected value of a random signal $x(t)$ under certain conditions, which are denoted by $T_{x(t)}$

$$D_{xx}(\tau)=E[x(t+\tau)|T_{x(t)}] \tag{1}$$

The idea behind Eq. (1) is to cancel out the particular solution of the dynamic response of a given system by taking the conditional average across a large number of ensembles, leaving the homogeneous solution to be averaged. While taking the average across the ensembles, a certain condition is imposed so that the cancellation can be achieved with a finite number of ensembles.

Assuming that the process is ergodic, which means the stationarity of the process, Eq. (1) can be rewritten as Eq. (2) so that the conditional averaging across the ensembles can be made within a single sample realization

$$D_{xx}(\tau)=\frac{1}{N}\sum_{i=1}^{N}x(t_i+\tau)|T_{x(t_i)}, \tag{2}$$

where N is the number of points in the random process that satisfies the condition $T_{x(t)}$. The condition, $T_{x(t)}$, under which the mean value of $x(t)$ is taken is called the triggering condition, and there are several different types, such as level crossing triggering, local extremum triggering, positive point triggering and zero crossing triggering, each of which can be expressed mathematically in the following equation:

$$\begin{aligned}
&T^L_{x(t)}=\{x(t)=a\}\\
&T^E_{x(t)}=\{a_1\le x(t)<a_2, \dot{x}(t)=0\}\\
&T^P_{x(t)}=\{a_1\le x(t)<a_2\}\\
&T^Z_{x(t)}=\{x(t)=0, \dot{x}(t)>0\}
\end{aligned} \tag{3}$$

In this study, the level crossing triggering condition was applied to extract the free decay signal out of the measured one owing to its simplicity, and can be rewritten in a general form as follows:

$$T^L_{x(t)}=\{a\le x(t)<a+\Delta a, \; -\infty\le \dot{x}(t)<\infty\} \tag{4}$$

where a is the triggering level and Δa is the triggering range, which was set to be infinitesimally small. If the triggering range, Δa, becomes finite, the level crossing triggering becomes the positive point triggering.

If the excitation is stationary and zero mean Gaussian white noise, the random decrement signature $D_{xx}(\tau)$ is related directly to the autocorrelation function of the given signal (Vandiver et al., 1982)

$$D_{xx}(\tau)=\frac{R_{xx}(\tau)}{\sigma_x^2}\tilde{a}-\frac{R_{xx}'(\tau)}{\sigma_{\dot{x}}^2}\tilde{b}, \tag{5}$$

where $R_{xx}(\tau)$ is the autocorrelation function of the given signal and $R_{xx}^{`}(\tau)$ is the time derivative of the autocorrelation function. The triggering level $\tilde{a}$ and $\tilde{b}$ are determined by the probability density function of the signal $x(t)$ and its time derivative as follows:

$$\tilde{a}=\int_{a_1}^{a_2}xp_x(x)\,dx\Big/\int_{a_1}^{a_2}p_x(x)\,dx, \quad \tilde{b}=\int_{b_1}^{b_2}\dot{x}p_{\dot{x}}(\dot{x})\,d\dot{x}/b_1\int^{b_2}p_{\dot{x}}(\dot{x})\,d\dot{x} \tag{6}$$

where the constants a_1, a_2 and b_1, b_2 are the bounds in the general triggering condition given in the following equation:

$$T^G_{x(t)}=\{a_1\le x(t)<a_2, b_1\le \dot{x}(t)<b_2\} \tag{7}$$