Ocean Engineering 125 (2016) 295–307

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Prediction of structural response of naval vessels based on available structural health monitoring data

Alysson Mondoro [a], Mohamed Soliman [b], Dan M. Frangopol [a,*]

[a] Department of Civil and Environmental Engineering, ATLSS Engineering Research Center, Lehigh University, 117 ATLSS Dr., Bethlehem, PA 18015-4729, United States
[b] School of Civil and Environmental Engineering, College of Engineering, Architecture and Technology, Oklahoma State University, 207 Engineering South, Stillwater, OK 74078-5033, United States

ARTICLE INFO

Article history:
Received 31 March 2016
Received in revised form
3 June 2016
Accepted 7 August 2016

Keywords:
Fatigue
Aluminum vessels
Structural health monitoring
Ocean wave spectra
Power spectral density

ABSTRACT

Structural health monitoring (SHM) can be beneficial in reducing epistemic uncertainties associated with fatigue life prediction. For naval ships, available SHM data can be discretized into operational cells, each referring to a certain navigation speed, heading angle, and sea condition. Cell-based approaches for predicting future fatigue life can be applied if monitoring information is known for all cells. However, available SHM data may populate some, but not all, potential cells. Moreover, since SHM data is only available for a given set of operating conditions, potential changes in climate or operational profiles cannot be accounted for. Accordingly, there is a need for an approach to predict structural responses in unmonitored cells as a function of limited available monitoring data. This paper proposes a methodology to predict the responses of naval vessels in unobserved cells by incorporating data from the limited number of observed cells. The power spectral density (PSD) of the SHM data is fit using generalized functions, based on sea wave spectra, and integrated into the prediction of the PSD for unobserved cells. The proposed methodology enables both spectral and time-domain fatigue methods. The methodology is illustrated on the SHM data from a high speed aluminum catamaran.

1. Introduction

Structural health monitoring (SHM) has recently been integrated into the life-cycle performance assessment program of the U.S. Navy (Sielski, 2012) in an effort to monitor the performance of high-speed, high-performance naval vessels. In both civil and naval structures, SHM data are useful for the detection and diagnosis of damage at various locations throughout the structure (Decò and Frangopol, 2015; Frangopol et al., 2008a, 2008b; Herszberg et al., 2005; Okasha et al., 2011; Reed and Earls, 2015; Vanik et al., 2000). SHM data can provide information regarding the as-built condition of the structure, the actual loads acting on the structure, and, if damage occurs, the current state of the structure. Currently, research efforts have been made to incorporate SHM data into service life predictions of naval ships (Soliman et al., 2015; Nichols et al., 2014).

Fatigue damage in aluminum naval vessels is a major concern. This is due to the high propagation rate of cracks in aluminum details and the considerable cost and effort associated with the repair process of damaged hulls. Deficiencies in fatigue damage prediction models are addressed, in part, through the use of SHM data. SHM directly contains considerations on the operational loads the ship is subjected to, as well as the as-built characteristics of the ship (Lynch and Loh, 2006); thus, epistemic uncertainties associated with load effects can be significantly reduced. Performance updating (e.g., using the Bayesian approach) has also been employed to integrate SHM data into structural predictions of ship performance parameters, such as vertical bending moments and fatigue life estimates, to account for the stochastic nature of the loads and structural materials (Okasha et al., 2010; Ling et al., 2011; Soliman et al., 2016; Zárate et al., 2012; Zhu and Frangopol, 2013a, 2013b). The use of observed SHM data in future service life predictions and management strategies dictates the assumption that future loading conditions are similar to past ones (Soliman et al., 2015). This leads to a distinct issue when operational profiles change. The recent increase in the operational rate and required service life of the vessels operated by the U.S. Navy exemplify some of these potential changes. Additionally, global climate change may increase the occurrence rate of intense storms

---

[*] Corresponding author.

E-mail addresses: alm312@lehigh.edu (A. Mondoro), mohamed.soliman@okstate.edu (M. Soliman), dan.frangopol@lehigh.edu (D.M. Frangopol).

http://dx.doi.org/10.1016/j.oceaneng.2016.08.012
0029-8018/

(McCarthy, 2001) which, consequently, exemplifies another potential change in the operational profile. As a result, vessels operated in these future conditions can experience a larger number of annual cycles and may be exposed to rougher and more extreme seas. Thus, the assumption of past data being indicative of future loads and loading sequences is not always valid.

The lifetime weighted sea method (Hughes, 1983) is used to predict the lifetime load effects for potential future loading sequences. Potential operational conditions are categorized by ship speed, heading angle, and sea state into cells with different probabilities of occurrence based on location and ship routes. These probabilities are developed based on wave scatter diagrams and vary based on location (Hughes, 1983; Kahma et al., 2003). The lifetime load effect is then computed as the summation of the load effect in each cell, weighted by the probability of operating in that cell. In these approaches, SHM information provides a measure of fatigue load effects associated with each operational cell. Previous efforts to include SHM data to reduce epistemic uncertainties in fatigue life assessment rely heavily on past operational conditions and not on future operational profiles. Future operational profiles may include exposure to cells not previously recorded. This is directly addressed in this paper.

The lifetime structural response of the ship hull to all sea states, heading angles, and speeds is a nonstationary random process. However, when the observed data is discretized by the aforementioned quantities into cells, observed SHM data in each cell can be considered as a stationary process (Naess and Moan, 2012). A full sampling of all potential cells during SHM observations is unlikely due to time restrictions and weather conditions, especially if discrete monitoring practices are in place. An approach which enables predicting the hull response in missing cells, with the goal of developing the full set of SHM data that is necessary for fatigue damage assessment, is still needed.

Data extrapolation techniques for ship response have been developed around cell parameters (i.e., heading angle, ship speed, and sea wave height) and the response parameter of interest (e.g., fatigue damage accumulation). Zhu (2014) proposed a linear interpolation method for identifying the statistical descriptors of vertical bending moments with respect to synthetic data generated using the Large Amplitude Motion Program. This synthetic data does not include information on the as-built condition of the ship or observed loads.

SHM data consists of the recorded time-history of an observed response (e.g., strain and acceleration). The power spectral density (PSD) function is a representation of the same signal in the frequency domain. The PSD function defines the signal energy as a function of the different frequency components. In the design stage, the PSD is determined from the response amplitude operator and the power spectra of the wave heights. An observed PSD, however, can be directly calculated from the SHM data. The observed PSD includes low frequency content, high frequency content, and noise. By developing the PSD for the full set of cells through the prediction method proposed herein, spectral based methods for fatigue assessment can be directly implemented to estimate the damage accumulation through Miner's law (Bendat, 1964; Dirlik, 1985; Lutes and Larsen, 1990). Moreover, time domain predictions can be performed to estimate fatigue damage by generating an instance of the random process, using cycling counting methods to determine the stress range histogram, and then applying Miner's rule. In both cases, the contributions of the low frequency and high frequency response components to the stress range distribution and subsequent fatigue assessment are captured.

This paper presents a methodology for using the SHM data recorded in observed operational cells to estimate the response in unobserved cells. The approach integrates SHM data from sea keeping trials in order to quantify and reduce uncertainties in the prediction of structural response and can be applied to enhance the accuracy of fatigue life estimation of ship details. The approach is capable of capturing the low and high frequency response and using it in fatigue damage predictions. Fitting functions for the PSD of observed responses are proposed for both the low frequency and high frequency content of the signal. The proposed methodology fits the observed PSD with functions based on accepted forms for sea wave spectra and investigates their applicability. The fitting is performed piece-wise: the low frequency content is fitted first, then the high frequency content, and finally summed together for the complete PSD. The estimated parameters for unobserved cells are predicted and a synthetic power spectral density function is developed. By developing the PSD for the full set of cells, both frequency domain and time domain predictions can be performed to estimate fatigue damage. The proposed methodology is applied to the SHM data from the seakeeping trials of the HSV-2 Swift, a 98 m (322 ft), high-speed, aluminum catamaran.

2. Ship response

A naval vessel is exposed to various loading conditions throughout its lifetime based on its operational theater and routes. As a result, the time-history response of the ship is a nonstationary random process for which the life-cycle performance is difficult to assess. The nonstationary time-history can be divided into smaller, stationary processes based on operating conditions such as wave height, vessel speed, and heading angle. For a given operational profile, the lifetime sustained loads and load effects can then be built up with additional information on the wave scatter diagram (Sikora et al., 1983). The lifetime weighted sea method uses the response in each of the stationary cells to evaluate the long term performance (Hughes, 1983).

Structural performance assessment can be performed in either the time domain or the frequency domain. For frequency-based methods, the structural time-history response is analyzed in the frequency domain and represented with a response spectrum. The response spectrum is a function of both the loading conditions (i.e., the random sea waves) and the structural response. In this paper, linear waves are considered and the loading conditions are defined by the sea wave spectrum, $S_\xi(\omega)$, which accounts for the development state of the wave, sea floor topology, fetch limitations, and local currents and swells, among others (Komen et al., 1984). The response spectrum, $S_R(\omega)$, is found through the use of a transfer function applied to the loading spectrum. In the case of the structural response of naval vessels to linear waves, the response amplitude operator $R_A(\omega)$ is used as the linear transfer function, and is different for each cell (Naess and Moan, 2012). Accordingly, the response spectrum, $S_R(\omega)$, is expressed as

$$S_R(\omega) = \left[R_A(\omega)\right]^2 S_\xi(\omega) \tag{1}$$

Characterizing the sea surface and wave heights is a highly investigated field with multiple analytical and experimentally developed forms capable of representing the sea wave spectrum $S_\xi(\omega)$. This paper considers two commonly used spectra: Pierson-Moskowitz and Joint North Sea Wave Observation Project (JONSWAP). The Pierson-Moskowitz wave spectrum is for fully developed seas wherein the waves have come to equilibrium with the wind (Pierson and Moskowitz, 1963). The single sided Pierson-Moskowitz spectrum is

$$S_{PM}^{+}(\omega) = \frac{\alpha g^2}{\omega^5}\exp\left(-\frac{5}{4}\left(\frac{\omega}{\Omega}\right)^{-4}\right) \tag{2}$$