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A study on the fatigue damage model for Gaussian wideband process of two peaks by an artificial neural network

Yooil Kim *, Hosoung Kim, In-Gyu Ahn

Department of Naval Architecture and Ocean Engineering, INHA University, 100, Inha-Ro, Nam-Gu, Incheon, South Korea

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ABSTRACT

Calculations of the fatigue damage on marine structures with a wideband nature are difficult to be done in spectral approach point of view because the link between the spectrum of stress and the probability distribution is difficult to define. This paper addresses the methodology through which the functional relationship between the probability density function and the response spectrum of a bimodal wide-band process by using the artificial neural network technique. An artificial neural network scheme was used to identify the multivariate functional relationship between the two continuously varying functions. For this, the spectra were idealized as the superposition of two triangles with an arbitrary location, height and width and the probability density functions were represented by the linear combination of equally spaced Gaussian basis functions. To train the network under supervision, a variety of different wide-band spectra were assumed and the converged probability density function of the stress range was derived using the rainflow counting method and all these data sets were fed into the three layer perceptron model. It turned out that the network trained using the given data set could reproduce the probability density function of an arbitrary wide-band spectrum of two triangles with great success.

1. Introduction

The calculation of the fatigue damage of marine structure is now in pretty much mature stage owing to the advances in the numerical technology together with the increase of the computing power. On the other hand, there still seems to be a long way to reach full time domain fatigue analysis because the computation time required for the full time domain analysis is not practically acceptable. With regard to this, the long term fatigue analysis of the marine structure significantly relies on the spectral approach, which is basically a frequency domain concept. One of the barriers to the spectral method when applied to the marine structures, such as FPSOs, semi-submersibles and large container carriers, is the relationship between the stress spectrum and the probability density of the stress range. Unlike the narrow band spectrum case, where the mathematical relationship between the two is clearly defined, the wide band spectrum causes some difficulties in defining the links between the two even under a Gaussian assumption of the process.

It is well known that the probability distribution of the peaks of Gaussian random process follows the Rayleigh distribution provided that the Fourier transform of the autocorrelation of the signal is a narrow banded one. This is owing to the fact that, in a narrow band process, a single peak corresponds to a single zero up-crossing enabling the replacement of the peak frequency with the zero up-crossing frequency during the derivation process. A narrow band assumption also allows us to relate the probability distribution of peaks and its ranges, which are in a similar form.

On the contrary, the problem of wide-band process is the relation between the probability distribution of the peaks and ranges, the former one has some explicit expression in terms of the bandwidth parameter, whereas the latter one does not. In order to overcome the difficulties related to the wide-band process, considerable research efforts have been made over the past several decades. Wirsching and Light (1980) proposed an empirical model through which one can estimate the fatigue damage based on the equivalent narrow-band process approach. The basic assumption behind their method was to approximate the fatigue damage of a wide-band process to be same as that of a narrow-band process with the same zero up-crossing rate and RMS, with empirically determined correction factors multiplied to it. A great deal of research efforts has been made to derive the probability density of the stress range for either a general or multi-modal spectrum. A multi-modal spectrum is defined as a well-separated multiple narrow band spectra, each of which possesses narrow-band spectral characteristics. Jiao and Moan (1990) analytically derived the correction factor applicable to the case of a bi-modal

* Corresponding author. Tel.: +82 32 860 7347; fax: +82 32 864 5850.
E-mail addresses: yooilkim@inha.ac.kr (Y. Kim), enang18@nate.com (H. Kim), aig4518@naver.com (I.-G. Ahn).

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spectrum, which is multiplied to the fatigue damage obtained from the narrow-band assumption. The correction factor was given as a function of the 0th moment of each narrow-band spectrum together with the zero up-crossing frequency of both the envelope and original signal. However, the methodology is suitable for cases when both high and low frequency induced fatigue damages are equally significant. Gao and Moan (2008) extended Jiao and Moan's approach and applied it to the case of a tri-modal spectrum. They also tried to extend their tri-modal solution to the general wide-band case by dividing the spectrum into three segments with the same variances.

Others proposed empirical formulae applicable to the general wide-band Gaussian process, which fits best the probability distributions obtained from the rainflow counting method (Dirlik, 1985; Zhao and Baker, 1992; Benasciutti and Tovo, 2005, 2006). Dirlik (1985) proposed a probability density function model composed of three terms, i.e., an exponential function, a Rayleigh probability density function with variable parameter and a standard Rayleigh probability density function. He introduced the concept of the moments of the rainflow range distribution to find the coefficients of each function that best approximates the probability out of the rainflow counting method. Zhao and Baker (1992) proposed a linear combination of the Rayleigh distribution and Weibull distribution as a probability density function of a general wide-band process. Benasciutti and Tovo (2005, 2006) proposed a probability density function composed of two Rayleigh distribution functions, one of which takes unity as the variance.

Because the fatigue damage model for a wide-band process is a matter of multivariate functional relationship between the given spectrum and the resulting probability density function, an artificial neural network might be a good approach to tackle this problem. A neural network is a powerful universal function approximation scheme, with a wide range of applicability in many engineering field, such as static/dynamic and linear/nonlinear system identification. Even in cases where the focus is restricted to offshore and marine applications, there are some noteworthy applications where neural network has been successfully applied. The application of a neural network is mainly on a dynamic system identification, such as the global performance of the coupled floater-mooring-riser system etc. Pina et al. (2013) proposed a new surrogate model based on the artificial neural network to predict the force developing in the mooring lines and risers. They used a NARX(Nonlinear Autogressive with Exogenous input) scheme to identify the coupled system, and predicted the top tension of the riser under prescribed motion of the floater. Christiansen et al. (2013) used a similar approach to predict the time series of the mooring line top tension without relying on direct nonlinear time domain FE analysis and showed that the correspondence between the predicted and simulated results is good. There also have been some applications on static system as well. Mazaheri and Downie (2004) employed the artificial neural network method in order to predict the extreme excursion and mooring force of a floating offshore structure due to the multivariate environmental condition. Turning to the wide-band fatigue problems, Kim et al. (2002) proposed a new fatigue damage prediction model using the artificial neural network. They used the three-layer perceptron model to derive the functional relationship between the stress spectrum and probability density function. The network input and output was set to be the parameters of the response spectrum and the resulting fatigue damage, respectively. They claimed that the methodology outperformed the other models when it was applied to the stress spectrum of a vibrating ship structure. Kang et al. (2014) also tried to find the multivariate functional relationship between the stress spectrum and the probability density function using an artificial neural network. Their study began with spectra that are two well separated triangles, i.e., a bimodal one, and both the spectrum and probability density functions were directly discretized with a given bin size.

This paper extends the work of Kang et al. (2014). The wide-band spectrum was idealized as a combination of two triangles with an arbitrary location, height and width, which was represented by 6 variables in total. Unlike the study by Kang et al. (2014), the two triangles representing the wideband spectrum were allowed to overlap, which makes the relationship between the spectrum and probability density function more complicated. Moreover, instead of discretizing the probability density function directly, which asks for many more parameters to numerically represent the continuous probability density function, the probability density function was approximated by a linear combination of equally spaced Gaussian functions with a relatively small variance. The approximation using these Gaussian functions in a row was used in this study targeting to avoid a poor prediction of the network, which usually takes place especially when the damage is relatively small. In this particular case, the damage contribution from the small number of stress cycles with an intermediate or high magnitude is so significant that it is of great importance to capture these low probability stress cycles with precision. The probability model with a combination of two or three standard probability functions misses this and will lead to a relatively poor damage prediction.

The network parameters are determined based on the prepared data sets under supervised training and the performance was checked by feeding the spectrum of arbitrary parameters. The optimal network parameters were determined by solving the nonlinear least square problem using the Levenberg–Marquardt algorithm, which is a modified version of the traditional Gauss–Newton method. The regularization terms was introduced as well in the square error function to avoid the possible overfitting phenomenon, which typically occurs in least square problems without regularization. Finally, a comparison was made on the final fatigue damage obtained by the proposed method and the others found in the open literature to show the superior performance of the proposed method.

2. Fatigue damage of wide-band process

2.1. Peak and range distribution

In the spectral fatigue analysis framework, the fatigue damage at the designated location inside the structure was calculated purely based on the responses represented by the spectrum, i.e., spectral representation of a given time series. If $x(t)$ is a zero-mean stationary Gaussian random process, the level up-crossing frequencies can be given as,

$$\nu_{a^+} = \frac{1}{2\pi}\frac{\sigma_{\dot{x}}}{\sigma_x}\exp\left(-\frac{1}{2}\frac{a^2}{\sigma_x^2}\right), \tag{1}$$

where a is the particular level and σ_x, $\sigma_{\dot{x}}$ are the standard deviation of the $x(t)$ and $\dot{x}(t)$, respectively. If the random process $x(t)$ is a zero-mean narrow-band process, the peak frequency can be replaced by the zero up-crossing frequency because every zero up-crossing corresponds to one peak greater than zero when the process is a narrow-band. Moreover, the Gaussian assumption of $x(t)$ was added on top, one finally reaches

$$f_Z(z) = -\frac{1}{\nu_{0^+}}\frac{d\nu_{z^+}}{dz} = \frac{z}{\sigma_x^2}\exp\left(-\frac{1}{2}\frac{z^2}{\sigma_x^2}\right) \tag{2}$$

Eq. (2) can be converted directly to the probability distribution of the range, or rise from a valley to the following peak, using