Journal of Fluids and Structures ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Journal of Fluids and Structures

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

Time series prediction of nonlinear ship structural responses in irregular seaways using a third-order Volterra model

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ARTICLE INFO

Article history:
Received 8 August 2013
Accepted 28 April 2014

Keywords:
Volterra series
Quadratic transfer function (QTF)
Cubic transfer function (CTF)
Neural network
Nonlinear autoregressive with exogenous input (NARX)
Fatigue

ABSTRACT

To predict the nonlinear structural responses of a ship traveling through irregular waves, a third-order Volterra model was applied based on the given irregular data. A nonlinear wave–body interaction system was identified using the nonlinear autoregressive with exogenous input (NARX) technique, which is one of the most commonly used nonlinear system identification schemes. The harmonic probing method was applied to extract the first-, second- and third-order frequency response functions of the system. To achieve this, a given set of time history data of both the irregular wave excitation and the corresponding midship vertical bending moment for a certain sea state was fed into the three-layer perceptron neural network. The network parameters are determined based on the supervised training. Next, the harmonic probing method was applied to the identified system to extract the frequency response function of each order. While applying the harmonic probing method, the nonlinear activation function (i.e., the hyperbolic tangent function) was expanded into a Taylor series for harmonic component matching. After the frequency response functions were obtained, the structural responses of the ship under an arbitrary random wave excitation were easily calculated with rapidity using a third-order Volterra series. Additionally, the methodology was validated through the in-depth analysis of a nonlinear oscillator model for a weak quadratic and cubic stiffness term, whose analytic solutions are known. It was confirmed that the current method effectively predicts the nonlinear structural response of a large container carrier under arbitrary random wave excitation.

1. Introduction

The nonlinear effects in the response of a ship structure in rough seas are deemed very important for both the extreme design wave bending moment and the fatigue strength of the ship. The nonlinear effect prevents the designers from relying on the frequency domain approach for the response analysis of their ship, which is limited to the linear case. Although several nonlinear correction methods, such as Froude–Krylov correction for an exact wet surface, enable the frequency domain approach to consider some nonlinearities, the accuracy of this correction method is always questioned. Therefore, the designers proceed toward the time domain method, where nonlinear effects can be considered with great flexibility. Different approaches for the nonlinear time domain simulation on the ship response in rough seas cover a different degree

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http://dx.doi.org/10.1016/j.jfluidstructs.2014.04.019
0889-9746/

of nonlinearities depending on the numerical schemes. The potential-based method starts from the weakly nonlinear approach where nonlinear Froude–Krylov and restoring pressure on exact wet surface is considered, and moves up to the so called weak-scatterer approach (Pawlowski, 1992) where perturbation is made about incident wave profile so that better accuracy can be obtained for the hydrodynamic pressures. A fully nonlinear approach such as computational fluid dynamics can consider strongly nonlinear phenomena such as water-on-deck and violent slamming event with accuracy. However, these time domain nonlinear approaches always entail high computational cost, even for a potential-based weakly nonlinear approach. When the focus is on the fatigue damage calculation of the ship, the nonlinear time domain simulation is performed for all sea states that will be experienced by the ship during her entire life. Depending on the nonlinearity level considered, the computational cost is unbearably high, and it is practically impossible to purely rely on the time domain simulation for a fatigue damage evaluation with nonlinear effects. Therefore, many research efforts have been devoted to nonlinear ship response prediction without directly relying on the time domain analysis.

The second-order Volterra model was used by many researchers to identify the nonlinear response characteristics of ships and offshore structures, which are mainly exposed to the random wave loads (Hasselmann, 1966; Dalzell, 1975; Pinkster, 1980; Jensen and Pedersen, 1981). Dalzell (1982, 1984) proposed the third-order modeling of a nonlinear ship response in irregular waves. He used the higher-order frequency response function (HFRF) of the given system and derived the probability density function, statistical moments and the distribution of extrema. The prediction of the nonlinear ship structural response using the third-order Volterra model was extensively studied by Adegeest (1997). He started with the assumption that the HFRF can be estimated using a zero-memory quadratic and cubic operation, which dramatically simplifies the identification process of the HFRF. To obtain the HFRF up to the third order, he employed the ship response data under a regular wave so that only the diagonal term of the quadratic and cubic transfer functions are calculated and generalized. It turned out that the results are quite good in terms of the statistical characteristics of the peak sagging moment. Additionally, it was noted that the second order is not sufficient to capture the power spectrum of the nonlinear ship structural response with accuracy. The present study is motivated by the work of Adegeest (1997), but the effort was performed to eliminate the assumption of zero-memory in HFRF. Thus, the full quadratic and cubic transfer function was pursued by using an artificial neural network technique along with the harmonic probing method.

The combination of the artificial neural network, including the nonlinear autoregressive with exogenous input (NARX) or the time-delayed neural network (TDNN), and the harmonic probing method has been studied by several researchers to identify the unknown nonlinear system by mapping the input to the output of the system. Wray and Green (1994) and Marmarelis and Zhao (1997) showed that the nonlinear Volterra kernels could be matched with the weights of the TDNN and derived the closed form relationship between the Volterra kernels and the network weights. Worden et al. (1994) applied the nonlinear autoregressive moving average with exogenous input (NARMAX) model to identify the nonlinear system of a floating structure exposed to wave loading. The unknown system was identified with the NARMAX method based on the vast amount of experimental data in a model basin as well as full-scale measurement data, and a nonlinear frequency response function up to second order was obtained using the harmonic probing method. Chance et al. (1998) extended the correspondence of the Volterra kernels and the TDNN to the NARX, where the output of the system is fed back into the network as an additional input. They identified the nonlinear system using the NARX neural network model and linked it to the frequency response functions of the system using the harmonic probing method. Additionally, they investigated the performance of different activation functions, such as the hyperbolic tangent and the polynomial functions. The proposed model was validated through the analysis of a Duffing-type nonlinear oscillator with quadratic and cubic stiffness.

The present paper addresses the frequency domain system identification of the nonlinear ship structural response using the NARX model and the harmonic probing method proposed by Chance et al. (1998). The method was extended to difference frequency HFRFs to accurately predict the time series of the system response under arbitrary random excitation. To validate the methodology applied in this study, an in-depth analysis of the nonlinear oscillator model of the weak quadratic and cubic stiffness term was performed and was compared with the analytic solutions. Next, the application was performed on the structural response of a large container carrier and focused on the influence of the nonlinearities on both the extreme wave bending moment and its range to check the influence of the nonlinear effect on the fatigue strength of ship. To achieve this result, a set of simulation data obtained using the nonlinear time domain ship motion program was used to determine the parameters of the NARX model, and the linear, quadratic and cubic frequency response functions of both the sum and difference frequency were extracted based on the multi-tone harmonic probing method.

2. Theoretical background

2.1. Volterra model

The Volterra series is widely used in modeling the weakly nonlinear response of a dynamic system. It is similar to the Taylor series but differs in that the Volterra series considers the memory effect of external excitation, which is an important feature in most dynamic problems. In general, the response of a system, $y(t)$, under external excitation, $x(t)$, can be expressed