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Volterra series-based system analysis of random wave interaction with a horizontal cylinder

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Abstract

The response of a long flexible cylinder excited by random waves in a large model basin was investigated. The linear and non-linear physical mechanisms associated with the wave–cylinder interaction were analysed using system identification and modelling techniques. A third-order frequency domain Volterra model and its orthogonalized counterpart were used to analyse the relationships between wave elevations at various locations in the vicinity of the cylinder and cylinder acceleration data at various cylinder longitudinal locations. It was found that linear mechanisms dominate, particularly at the frequency band where the majority of the wave energy is located. At higher frequencies, the cubic component of the Volterra model is the main contributor to the total model coherence, i.e. the fraction of the measured output power that can be approximated by the model output, whereas the quadratic component's contribution to the total model coherence was in general quite small. This process of identification and quantification of the non-linear mechanisms of the unknown physical system can lead to the design of improved parametric models for the cylinder response, which should by design simulate non-linearities such as the ones identified by the Volterra model. The estimated linear and non-linear Volterra transfer functions were also used to predict the cylinder acceleration under excitation inputs not used in the estimation of the model transfer functions. The good match between predicted and measured output auto-power spectra suggests that the estimated transfer functions are indeed true models of the underlying physical mechanisms of the interaction. However, the latter can only be achieved if a minimum number of data segments, as determined by an error analysis involving modelling and prediction errors, is used in the estimation of the Volterra transfer functions.

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1. Introduction

In many fluid–structure interaction cases linear and non-linear mechanisms control the response of the structure to a given input. The non-linear mechanisms, in particular, may generate new spectral components in the output which are not present or are not significant in the input, at frequencies which can be quite low or quite high relative to the input spectrum. They may also amplify spectral components in the output which are also linearly excited by the input, through quadratic, cubic, or higher-order interactions of input spectral components at frequencies which satisfy a specific selection rule. It is thus apparent that both the identification and quantification of these non-linear mechanisms are critical to the development of accurate response prediction models.

The most widely used models in offshore engineering to analyse the response of a structure exposed to wave loading are primarily parametric models (Sarpkaya and Isaacson, 1981). A linear or non-linear model structure is assumed, with given or unknown structural parameters, whereas the exciting wave force is modelled either by Morison's equation for small size members relative to the characteristic wavelength, or by the diffraction theory for larger members. It is well known that selecting the force transfer parameters for Morison's equation under different conditions is difficult. Furthermore, the computation of potential forces for larger size members is not an easy task when the effects of waterline, body motion, velocity head, and second-order potential are taken into account (Faltinsen, 1990; Newman, 1995).

In addition to the difficulty of determining the proper structural and force parameter values, which are usually deduced from experimental data, parametric models also exhibit a serious intrinsic limitation in that their mathematical formulation, including the assumptions regarding the change in position or geometry of the structure, predetermines the type and magnitude of the non-linear effects they can simulate in the structural response. For example, a simple model for a vertical cylinder exposed to an irregular wave can be a single-degree-of-freedom structural model with a Morison's equation excitation force. Paik (1994) showed that, for such a response model, the type of the non-linear low frequency response generated depended on which position, i.e. original or displaced cylinder position, the wave kinematics were calculated. Specifically, in the original position calculation, the non-linear response was caused by cubic combination of the wave components, whereas in the displaced position calculation the non-linear response was mainly due to quadratic combination of the input wave frequency.

Non-linear system modelling techniques have also been used for structural response analysis, with the focus mainly on the non-linear restoring force analysis.