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Long-term correlation structure of wave loads using simulation

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ABSTRACT

This paper proposes a new method for combining the lifetime wave-induced sectional forces and moments that are acting on the ship structure. The method is based on load simulation and can be used to determine the exceedance probabilities of any linear and nonlinear long-term load combination. It can also be used to determine the long-term correlation structure between these loads in the form of the long-term correlation coefficients. They are essential part of the load combination procedures in design and strength evaluations as well as in the fatigue and reliability analysis of ship structures.

The simulation method treats the non-stationary wave elevations during the ship's entire life (long-term) as a sequence of different stationary Gaussian stochastic processes. It uses the rejection sampling technique for the sea state generation, depending on the ship's current position and the season. Ship's operational profile is then determined conditional on the current sea state and the ship's position along its route. The sampling technique significantly reduces the number of sea state–operational profile combinations required for achieving the convergence of the long-term statistical properties of the loads. This technique can even be used in combination with the existing long-term methods in order to reduce the number of required weightings of the short-term CDFs. The simulation method does, however, rely on the assumption that the ship is a linear system, but no assumptions are needed regarding the short-term CDF of the load peaks.

The load time series are simulated from the load spectra in each sea state, taking into account the effects of loading condition, heading, speed, seasonality, voluntary as well as involuntary speed reduction

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in severe sea states and the short-crested nature of the ocean waves. During the simulation procedure, special care has been given to maintaining the correct phase relation between all the loads. Therefore, time series of various load combinations, including the nonlinear ones, can be obtained and their correlation structure examined. The simulation time can be significantly reduced (to the order of minutes rather than hours and days) by introducing the seasonal variations of the ocean waves into a single voyage simulation. The estimate of the long-term correlation coefficient, obtained by simulating only a single voyage with the correct representation of seasonality, approaches the true correlation coefficient in probability. This method can be applied to any ship and any route, or multiple routes as long as the percentage of the ship's total lifetime spent in each of them is known.

A study has been conducted to investigate the effects of ship type, route and the longitudinal position of the loads on the values of the correlation coefficients between six different sectional loads; vertical, horizontal and twisting moments, as well as shear, horizontal and axial forces. Three ocean-going ship types have been considered; bulk carrier, containership and tanker, all navigating on one of the three busy ship routes; North America–Europe, Asia–North America and Asia–Europe. Finally, the correlation coefficient estimates have been calculated for five different positions along the ship's length to investigate the longitudinal variation of the correlation coefficient.

1. Introduction

During the ship's lifetime, which is typically a period of twenty-five years, its structure will be subjected to various non-stationary stochastic loads. There are many ways to categorize these loads, but a very natural one can be obtained by looking at a long time record of, e.g., normal stresses in a longitudinal structural member of the ship's hull structure. A simple Fourier transformation of such a signal would reveal that its variance is mainly distributed around three frequency bands. The first one is very close to zero frequency, the second one is close to the wave encounter frequency (around 0.5 rad/s), while the third one is in the range of high frequencies (around 4 rad/s). Hence, the stationarity and load frequency become the basis for categorization as follows:

- Quasi-stationary loads (stillwater and thermal loads);
- Low-frequency non-stationary loads (wave-induced loads);
- High-frequency non-stationary loads (springing, slamming/whipping, machinery induced vibrational loads).

Low-frequency wave-induced loads are associated with the rigid body motion of the vessel in waves. High-frequency wave-induced loads arise due to slamming and hydroelastic behavior of the vessel known as springing. Ship designer needs to find a realistic estimate of the total combined load effect to which the structure will be subjected in order to properly design it. The estimate that is too conservative will subsequently result in an over-designed structure that has a smaller payload. On the other hand, if the estimate of the total combined load effect is lower than its true value, the resulting ship structure might be unfit for service, expensive to maintain or unsafe to operate. If all the loads acting on the ship structure were deterministic and stationary (or quasi-stationary), then simple addition of the loads would be sufficient to obtain the total combined load effect at a certain point on the structure. That value could then be used in the design of that particular structural member. However, due to the stochastic and non-stationary nature of the ocean waves during the ship's lifetime, both the low- and high-frequency loads will also be stochastic and non-stationary. In order to properly