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Measurements in a container ship of wave-induced hull girder stresses in excess of design values

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A B S T R A C T

This paper describes full-scale measurements of the wave-induced vertical bending moment amidships a 9400 TEU container carrier and focuses on the effect of the hydro-elastic high-frequency vibration on the extreme hogging wave bending moment. One extreme event, where the vertical wave-induced hogging bending moment amidships slightly exceeds the design value, is analysed and the measurements are verified by the use of the relationship between measurements of accelerations and strains and simple beam theory. The measurements are found to be reliable. In the extreme case, the high-frequency vibrations caused by impulsive loads are observed to be of the same magnitude as the rigid-body wave-induced response and thus acts to double the total vertical bending moment amidships. It was also found that even though the ship is sailing in bow quartering seas, only the 2-node vertical vibration mode is apparently excited. Following the extreme event analysis and verification, three hours of strain measurements are used for establishing a Gumbel distribution for the extreme value prediction, and it is found that the probability of exceeding the rule design wave bending moment by 50% in the given sea state is quite significant. Finally, the hydro-elastic behaviour of the hull girder is assessed by simple approximations using the measured statistical properties and closed-form expressions and the agreement with the actual measurements is found to be good.

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1. Introduction

During recent years, the length of container ships has increased to about 400 m for the longest ships of today. With increasing length, the container ship structure becomes relatively "softer" with reduced natural hull girder vibration frequencies. The importance of the hull girder vibrations is of concern regarding fatigue as well as the extreme wave-induced bending moment.

About two years of full scale data comprising measurements of hull girder strains, motions, navigational data and the encountered sea state from a 9400 TEU container ship has been made available through the EU FP7 project TULCS (*Tools for Ultra Large Container Ships*) which was finalised in the spring of 2013. The principal data and main dimensions of the vessel can be found in Table 1.

Hydro-elastic effects are difficult to account for and are not directly taken into account in the current class rules for container ships. It can be a concern if the current design values for the wave-induced bending moment for container ships are too low due to partial negligence of hydro-elastic effects.

A ship sailing in a seaway is subject to wave-induced random excitations of the hull. The hull mainly becomes excited at two main frequencies: The wave encounter frequency and at the 2-node vertical bending natural frequency of the hull. The high-frequency (HF) response obviously occurs simultaneously with the wave-frequency (WF) response as illustrated in e.g. Fig. 9, and the HF vibration part is superimposed onto the WF part and thus adds to the total load cycle.

Slamming loads on ships with forward speed are difficult to predict numerically due to the complexity of treating quasi-static and dynamic responses under linear, non-linear and impulsive wave loads simultaneously, see e.g. Ref. [9]. The fluid-structure interaction can be modelled using 3D boundary element or CFD codes coupled with finite element tools as the leading-edge procedures, but direct calculation in the time domain is still computationally very heavy, see e.g. Refs. [13,10]; especially in stochastic seas.

Hydro-elastic response of ships has been studied extensively by different means, see e.g. Refs. [20,19] who focus on analysis of full scale measurements of strains and structural vibrations from vessels operating in harsh environments. Significant contribution to the expected fatigue damage was found as well as to the extreme stress peaks from the high-frequency vibrations in both hogging and sagging. Storhaug et al. (2007) [19] conclude that the vibration-induced fatigue damage is of similar order of magnitude as the wave-induced damage for the ore carrier considered.

Although mainly dealing with the fatigue damage when assessing the influence of whipping Okada et al. (2006) [11] also investigated the additional stresses due to whipping on the long-term distribution of vertical bending stresses and concluded that much more attention should be paid to whipping stresses. A simple procedure for prediction of extreme vibration-induced hull girder loads in container ships outlined in Ref. [6] shows good agreement with the measurements carried out by Ref. [11].

Senjanović et al. (2008) [15] investigated the flexibility of a large container ship using a fairly complex mathematical beam model and a 3D finite element analysis. Impulse loads were not directly assessed, but it was concluded that whipping caused by impulsive loads is important to consider. Zhu and Moan (2012) [23] conclude, based on analysis of model tests of two large container vessels in regular and irregular waves, that the contribution from high-frequency vibrations cause the vertical bending moment amidships to be slightly more affected in sagging than in hogging. However, in short

Table 1
Principal data of considered container ship.

Deadweight	113,000 ton
GT	99,500 ton
L_{oa}	349.0 m
L_{pp}	333.4 m
Beam	42.8 m
Design draught	14.5 m
Design speed	25.4 knots