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An experimental study of hull girder loads on an intact and damaged naval ship

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ABSTRACT

The study reported in this paper is focused on experimental investigation of the hull girder loads on an intact and damaged naval ship DTMB 5415 at zero speed. The experimental campaign was carried out in head and beam regular waves at the University of Strathclyde. The effect of the use of moorings in the model experimental setup was investigated in the context of loads assessment, and the moorings are shown to influence the measured hull girder loads at some wave frequencies compared to the free drift case. Therefore the tests in beam seas are performed with free drifting model while the moored model setup was adopted for head seas. The results for ship motions are compared with those from a previous campaign giving an insight into repeatability and uncertainty of measurements. The roll decay of the ship in both intact and damaged conditions is analysed and the linear and quadratic extinction coefficients for the model and the ship scale are reported and detailed discussion on intact-versus-damaged ship roll damping behaviour is given. The results for the hull girder loads are presented for intact and damaged ship. An investigation of the nonlinear effects due to wave height variation in the range wave height to wave length from 1/50 to 1/22 on the shear force and bending moment values was carried out for a range of wave lengths to ship length ratios from 0.8 to 1.4. The results of the extensive campaign are compared against similar experimental studies forming a benchmark data for validation of numerical methods.

1. Introduction

The determination of the hydrodynamic loads and the evaluation of structural responses are key elements in a sound design procedure for ships and offshore structures. A growing interest in accurate prediction of hydrodynamic loads was highlighted by Hirdaris et al. (2014) who reported that approximately 47% of papers published in the period from 2008 to 2012 in international peer-reviewed journals are dedicated to research and development activities related to the computation of wave-induced loads, followed by specialist ship structure topics (slamming, sloshing, etc.), fatigue loads and uncertainties in wave load modelling and validation. Although wave load prediction can be implemented at a wide range of levels of complexity, starting from simple potential strip theory up to fully nonlinear methods (e.g. RANS CFD simulations), the authors pointed out that the numerous partly nonlinear or blended methods require verification against experimental data. Furthermore they highlighted the necessity for quality benchmark data, particularly for measurements of global hull girder loads from model tests.

A variety of experimental results (Fonseca and Guades Soares, 2002) has demonstrated that the wave induced vertical bending moments (VBM) shows a nonlinear behaviour for ships with small block coefficients, such as container ships, naval ships, frigates and destroyers, and some passenger ships. The nonlinearities of vertical bending moment relate to three different aspects: the asymmetry of the peaks in the time series, a non-linear variation of the transfer function with the wave amplitude, and higher order harmonics of the time signals.

Among the first studies dealing with experimental data on the vertical responses of ship models in regular and irregular waves with an emphasis on the nonlinear effects are Watanabe et al. (1989) and O'Dea et al. (1992). Both authors tested the S-175 ITTC benchmark container ship, reporting for the first time second order harmonics of VBMs and systematic variation of the first harmonic and phase angle with the wave steepness.

Fonseca and Guades Soares (2002) presented a partly-nonlinear time domain method, accounting for nonlinear hydrostatic restoring and calculating Froude-Krylov forces on the instantaneous wetted

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Nomenclature

A	wave amplitude, m
B_{OA}	beam over all, m
B_{WL}	beam at waterline, m
C_B	block coefficient
C_M	midship section coefficient
C_P	prismatic coefficient
D	depth, m
g	acceleration of gravity, 9.80665 m/s^2
GM	transversal metacentric height, m
H	wave height, m
HBM	horizontal bending moment, N m
HSF	horizontal shear force, N
H/λ_W	ratio between wave height and wave length
k	wave number, $2\pi/\lambda_W$
KG	vertical position of the centre of gravity, from BL, m
KM	vertical position of the metacentre, from BL, m
k_{XX}	radius of gyration with respect to x axis, m, $k_{XX} = \sqrt{\frac{I_{XX}}{\Delta}}$
k_{YY}	radius of gyration with respect to y axis, m, $k_{YY} = \sqrt{\frac{I_{YY}}{\Delta}}$
k_{ZZ}	radius of gyration with respect to z axis, m, $k_{ZZ} = \sqrt{\frac{I_{ZZ}}{\Delta}}$
LCG	longitudinal position of the centre of gravity from transom, m
L_{OA}	length over all, m
L_{PP}	length between perpendiculars, m
T	draught, m
T_ϕ	natural roll period, s
T_W	incident wave period, s
TM	torsional moment, N m
V	displacement volume, m^3
VBM	vertical bending moment, N m
VSF	vertical shear force, N
Δ	displacement, kg, tons for ship scale
ϕ	roll angle, rad
η_3/A	non-dimensional heave response
η_4/kA	non-dimensional roll response
η_5/kA	non-dimensional pitch response
η_i	measured motion, i=3, 4, 5 corresponds to heave, roll and pitch respectively
λ	ship model scale factor
λ_W	wave length, m
λ_w/L_{OA}	wave length to ship length ratio
ρ	water density, kg/m^3
$\omega_E(L_{PP}/g)^{0.5}$	non-dimensional encounter wave frequency
ω	wave frequency, rad/s
ω_E	encounter wave frequency, rad/s
$\omega_{\phi 0}$	roll natural circular frequency, rad/s
ω_ϕ	roll damped circular frequency, rad/s $\omega_\phi = \sqrt{\omega_{\phi 0}^2 - \alpha_{eq}^2}$
α	linear extinction coefficient, 1/s, $\alpha = \frac{B_1}{2I_\varphi}$
α_{eq}	equivalent linear extinction coefficient, $\alpha_{eq} = 2\alpha + \frac{4}{3\pi}\omega_\phi \phi_a \beta + \frac{3}{8}{\omega_\phi}^2 \phi_a^2 \gamma$
β	quadratic extinction coefficient, 1/rad, $\beta = \frac{B_2}{I_\varphi}$
γ	cubic extinction coefficient, 1/rad^2, $\gamma = \frac{B_3}{I_\varphi}$
ϕ_{MEAN}	mean roll angle, rad, $\phi_{MEAN} = \frac{\lvert\phi_i\rvert + \lvert\phi_{i+1}\rvert}{2}$

surface of the ship. The numerical method was verified with the experimental results of Watanabe and O'Dea, showing that the method is able to capture the nonlinearities in vertical motions, accelerations and vertical bending moment values. Important experimental studies on the assessment of vertical loads acting on the ITTC S-175 container ship in regular and irregular waves were presented by Fonseca and Guades Soares (2004a, 2004b). Tests in regular waves were performed over a range of non-dimensional wave frequencies, with waves varying from λ/L_{PP}=0.5–3. For each wave frequency several wave amplitudes were used ranging from small to large amplitude and thus the influence of the wave amplitude on the nonlinear characteristics of the responses was assessed. The measured responses include the absolute and relative motions, vertical accelerations, and cross-sectional loads at midship and 1/4 L_{PP} from the forward perpendicular. Irregular wave tests were carried out for three sea states; the reported probability distributions of the positive and negative peaks of motions and loads, indicated that the Rayleigh distribution cannot be used for wave-induced vertical loads.

Song et al. (2011) presented a weakly nonlinear 3D time domain Rankine panel method validation on a 6500 TEU container ship segmented model in small and large wave amplitudes over a wide range of wave frequencies. Results were presented as first-order response amplitude operators (RAOs) and time histories; second order harmonics were not reported. The authors reported that the nonlinear effects were observed for the three highest waves (wave heights of 5, 7 and 10 m in ship scale). They concluded that the weakly-nonlinear method developed shows a very good overall agreement with the experimental data, and in particular better agreement for vertical than for horizontal and torsional loads for moderate wave heights, and acceptable to poor agreement at the steepest wave.

Kukkanen and Matusiak (2014) presented a nonlinear time domain calculation method based on Green's functions to predict the RoPax hull girder loads. Model test results of ship motions, vertical shear forces and bending moments at two sections at zero speed and Fr=0.25 were given for calm water, regular and irregular head waves. The results were presented for the first order RAO and phases for motions and loads. The results obtained from the numerical method are in good agreement with the reported experimental data, although authors did not comment on the ability of the numerical method to predict the effect of wave height variation.

Zhu and Moan, (2013, 2014) presented extensive model tests on ultra-large containerships of 8600-TEU and 13000-TEU conducted in head seas in regular and irregular waves with focus on the nonlinear vertical responses in severe seas. The authors reported that in irregular waves, the motion peaks and troughs generally follow a Rayleigh distribution and that the asymmetries between positive and negative peaks are limited and less pronounced than expected from existing empirical formulas or state of the art tools.

It should be noted that the majority of works on structural responses have addressed intact ship loads; however in the last decade some investigations on loads in damaged conditions have been presented. Korkut et al. (2004) presented experimental results for motions of an intact and damaged RoRo ship in regular waves at zero speed. The effects of wave amplitude variation in head, beam and quartering seas were investigated. In Korkut et al. (2005) experimental results for the global loads on an intact and damaged Ro-Ro ship model in regular waves are presented. The very extensive experimental campaign comprises nine frequencies in head, beam and stern quartering seas varied over four wave heights. The conclusions highlight the main experimental findings illustrating the effect of damage on the loads; in general the structural response of the damaged model are greater than those for the intact ship for most of the headings with the exception of the horizontal bending moments in beam seas. The results also show the variation of the load responses with the wave amplitude depending on the wave frequency.

Lee et al. (2012) developed a computational tool based on a two-dimensional linear method to predict the hydrodynamic loads on damaged ships. The results of the theoretical method and an experi-