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The influence of inertial effects on the mean forces and moments on a ship sailing in oblique waves part A: A new measurement device for wave forces

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ABSTRACT

A new experimental device designed and built at Technische Universität Berlin for measuring forces and moments on a ship in waves is described and results of a comprehensive test campaign with the model of cruise ship are discussed. Forces, moments and motions on/of the model have been obtained during tests at forward speed in head waves and at zero speed in oblique incoming waves. Single motions have been restrained during these tests in order to analyse their influence on the mean forces and on other motions. The device allows for extracting non hydrodynamic inertial force contributions from the measured signals. The mean values of these inertial forces are not always zero, but often very significant, and must therefore be subtracted for a reliable comparison with mean wave forces and moments predicted by numerical simulations.

1. Introduction

A ship is exposed to waves across its entire service life. The prediction of wave forces and moments acting on the ship and thereby of ship motions is still a challenge in naval architecture. Determining these forces for a ship at forward speed provides knowledge about the resistance increase in waves, permits identifying limiting wave heights for safe operation and allows for predicting rudder manoeuvres in waves, when appropriately implemented into a simulator tool. When designing a new ship, mainly the added resistance in head seas is investigated by means of model tests or numerical calculations in order to estimate the increase in engine power needed in a given scenario. Moreover, if the mean forces and moments due to waves at a desired mean forward speed for several wave lengths and encountering angles are known, it is possible to use them for numerical manoeuvring prediction in waves, as shown by Yasukawa and Nakayama (2009) or by Cura Hochbaum and Uharek (2016).

For a thorough experimental prediction of wave forces an adequate set-up and knowledge about its peculiarities is essential, especially the influence of the measurement method on the resulting motions and hence forces is of importance. Such information about implemented test set-ups is difficult to obtain and rarely found in available publications. Early experimental research activities on added resistance were performed by Sibul (1971), where different Series 60 ships were investigated in long waves (compared to the ship length) at different Froude numbers. The measurements were performed letting the model free to surge, heave and pitch and repeated with restricted surge motion, yielding the same mean forces. A similar study was performed by Gerritsma and Beukelman (1972) for a fast general cargo ship at different speeds, wave lengths and amplitudes. A very comprehensive experimental study on added resistance was performed by Strom-Tejsen et al. (1973) for a destroyer, a high speed vessel and five Series 60 shapes, tested at different speeds in regular waves of different lengths and also in long crested seaways of given sea spectra.

Extensive campaigns on mean wave forces at zero speed were performed by Pinkster (1980) for a tanker and other floating structures and by Huijsmans (1996) for a tanker at different loading conditions. Both authors used basic active and passive restraints to keep the ship in a mean position in order to validate numerical predictions models. In both works, a set-up with passive restraints was chosen where the springs are directly connected to the model to keep it in a mean position. It was stated that in this case the system resonance frequency should be at least five times lower than the wave encounter frequency.

A different approach for measuring mean wave forces was presented by Kashiwagi (2013), where forces are measured directly as well as by deriving them from the energy of the wave system generated by the ship, for two modified Wigley Hull models sailing in waves in fixed and free condition. The experiments were able to quantify the diffraction and radiation wave resistance components of the ship by assigning them to the different ship generated wave systems.

Tello Ruiz et al. (2016) performed model tests at small forward speed in the shallow water seakeeping basin of Flanders Hydraulics

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Research, measuring mean forces in a horizontal reference frame. Tested situations were head and oblique regular waves at small angles of incidence, using a test setup fixed in surge, sway and yaw, but free in heave pitch and roll. A soft-mooring arrangement described in Sprenger et al. (2016) was used at MARINTEK and CEHIPAR to determine wave added resistance and mean forces at zero speed during the European research project SHOPERA. They measured the forces in a ship fixed manner and the spring stiffness was varied.

As can be seen, many different test set-ups have been used for force measurements in waves so far, but little to none information is available on their peculiarities and the influence of the devices on the measured quantities. Therefore it was targeted to develop a measuring device capable of quantifying the effects of the device on the model motions and measured forces. Furthermore, it should be possible to restrain single motions, and parameters of influence should be variable by the experimenter. Due to the absence of an adequate and precise motion measurement equipment, a reliable mechanism for motion capturing has to be included in the device allowing to subtract non hydrodynamic inertial forces and moments from the measurements whenever required. Thus a system of slides that can be fixed if desired was considered to be the best option. The ship model can be attached to these slides via vertical towing connectors, allowing a ship fixed force measurement.

Some devices satisfying the described requirements have been built and used for tank tests, however, it is not clear if and how measurements are influenced by the used set-up. Fujii and Takahashi (1975) showed a new measuring apparatus called resistance dynamometer, which consisted of a vertical towing rod connected to the model and supported by carriages capable of surging and swaying simultaneously. With this set-up it was possible to measure at several incident wave angles.

An uncertainty analysis of measured mean wave forces was performed by Park et al. (2014) for a VLCC in head seas. The experimental set-up has a 'sub-carriage' with springs for a surge motion relative to the towing carriage and the model is free to heave and pitch by means of a heave rod with a pitch gimbal at the end, placed in the centre of gravity of the model. The spring stiffness is chosen carefully, but the influence of the additional carriage mass in longitudinal direction and it's influence on the models surge motion is not discussed. This set-up meets many of the criteria described above, but is only suitable for head waves.

Another innovative approach stems from Xu et al. (2007), who presented an alternative PMM for waves. Here two slides (carriages) supported by springs allow for surge and sway motions while the device is connected to a classical PMM. Heave and pitch motions are free by means of heave rods and pitch gimbals. The set-up is used for dynamic pure sway tests in waves and mean forces are evaluated for different sway periods and wave amplitudes.

During the German research project PERSEE the HSVA developed a similar device than described in the present work, see Valanto and Hong (2015). The measurement device consists of slides supported by springs, allowing surge, sway and yaw motions. The connection of the device with the model allows for free heave, pitch and roll motions. At HSVA oblique waves can be generated in the towing tank by means of a 40 m long side wave generator. During the test campaign, mean forces and yaw moments on a ship model in waves at various encounter angles were measured at relatively high forward speed.

A discussion on the influence of the used experimental set-up on the measured quantities is not found in any publication known to the authors. Moreover, non hydrodynamic inertial effects stemming from model motions are not mentioned in any publication on wave force measurement. CFD based methods and panel code predictions have improved greatly in the past two decades and it is important to correctly compare results when using experimental data for validation purposes. During force measurements of a ship model moving in waves, inertial forces are included in the measurements. They consist of an oscillating and a mean (non-zero) part. The mean value mainly results from superposed motions being (at least) partially in phase. This aspect of measuring forces in a body fixed frame will be discussed thoroughly in section 3.3.

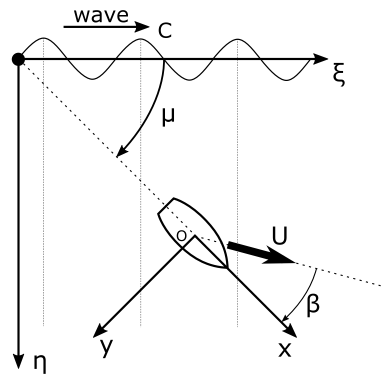

Fig. 1. Coordinate system of the ship in waves.

After a brief outline of the theoretical background, the new measurement device for mean forces on ships in waves and the involved measurement technique is presented. Finally, the results of a measuring campaign with a cruise ship model are presented, discussed and some conclusions are drawn.

2. Equations for model test analysis

To describe ship motions in waves two coordinate systems are used. An earth fixed system considered as an inertial reference system with coordinates (ξ, η, ζ) and a ship fixed system with coordinates (x, y, z), see Fig. 1. The ship fixed origin O is at design water line, amidships at $L_{PP}/2$, the x-axis is defined positive towards the bow, the y-axis towards starboard and the z-axis positive downwards. The wave encounter angle μ is defined between the wave propagation direction and ship fixed x-axis, therefore $\mu = 180°$ describes the head sea case and $\mu = 90°$ corresponds to waves from starboard. The drift angle β is defined between the ships velocity vector U and the positive x-axis.

The encounter frequency ω_e in waves of length λ is $\omega_e = \omega - k\, u_0 \cos\mu$, where ω is the wave angular frequency, $u_0 = U \cos\beta$ is the velocity component in positive x-direction and $k = 2\pi/\lambda$ is the wave number. To transform coordinates (x, y, z) from the ship fixed system to the inertial system equation (1) is applied. The values (ξ_0, η_0, ζ_0) are the coordinates of the origin 0 in the inertial frame.

$$\begin{pmatrix} \xi \\ \eta \\ \zeta \end{pmatrix} = \begin{pmatrix} \xi_0 \\ \eta_0 \\ \zeta_0 \end{pmatrix} + \mathbf{T} \begin{pmatrix} x \\ y \\ z \end{pmatrix} \tag{1}$$

The transformation matrix $\mathbf{T}$ from the ship fixed system to the inertial coordinate system in equation (2) results from the composition of three rotations, namely roll about the ship fixed longitudinal axis, pitch about the Eulerian line of nodes (here always horizontal) and yaw about the vertical axis of the inertial system.

$$\mathbf{T} = \begin{pmatrix} \cos\vartheta\cos\psi & -\cos\varphi\sin\psi + \sin\varphi\sin\vartheta\cos\psi & \sin\varphi\sin\psi + \cos\varphi\sin\vartheta\cos\psi \\ \cos\vartheta\sin\psi & \cos\varphi\cos\psi + \sin\varphi\sin\vartheta\sin\psi & -\cos\psi\sin\varphi + \sin\vartheta\sin\psi\cos\varphi \\ -\sin\vartheta & \sin\varphi\cos\vartheta & \cos\varphi\cos\vartheta \end{pmatrix} \tag{2}$$

In an inertial coordinate frame the sum of forces acting on a rigid