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An experimental study on the effect of confined water on resistance and propulsion of an inland waterway ship

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ABSTRACT

We present an experimental study on resistance and propulsion characteristics of an inland waterway ship in confined water. Physical experiments of resistance and propulsion with an inland waterway ship were performed. The effects of water depth, separation distance to a vertical wall (bank effects) and forward speed are discussed. The objective of the investigation was to generate benchmark data for validation of Computational Fluid Dynamics (CFD) solvers.

1. Introduction

The present study ties in with the investigation of the benchmark test case of a typical inland waterway ship as encountered in European inland shipping, for which geometry and conditions, resistance and propulsion characteristics for a given shallow water condition are publicly available, BAW (2017) and Mucha et al. (2017). The increasing application of Computational Fluid Dynamics (CFD) to predictions of flows around ships in shallow and confined waters and the increasing importance of ship handling simulations for navigability analyses motivated the extension of above test case to include the effect of water depth and separation distance to a vertical wall. These induce powerful hydrodynamic interactions in confined water, and computational predictions require suitable benchmark data for verification and validation. Model tests were planned in collaboration with and conducted by the Development Centre for Ship Technology and Transport Systems (DST) in Duisburg, Germany. The paper is organized as follows. Following the address of relevant references in the field, the test case is introduced in terms of the geometry of the hull, propellers and appendices and the experimental setup. Then, results of resistance, propulsion and near-wall tests are discussed regarding above mentioned sensitivities.

Tuck (1978) is a comprehensive treatise of ship hydrodynamic problems in restricted waters addressing the physical phenomenology of hydrodynamic interactions between ships and flow restrictions. The shallow water effect on the resistance of a slender ship was studied by Graff et al. (1964) by experimental analysis. Ship waves in shallow water were addressed by Chen (1999) and Jiang (2003). Manoeuvrability analyses of ships in shallow water were presented by Eloot et al. (2015) and Tonelli and Quadvlieg (2015). Gronarz (1997) and Mucha (2017) focused on the mathematical modelling of manoeuvring in shallow water. Validation studies on computational methods for the prediction of resistance and squat are found in Deng et al. (2014) and Mucha et al. (2015, 2016). Terziev et al., 2018 present another effort to assess the capabilities of numerical methods to model ship hydrodynamics in shallow water. Lataire and Vantorre (2008) conducted a systematic investigation of the influence of bank geometry on hydrodynamic interactions between ships and banks. These were investigated with respect to suitable auto-pilots by Thomas and Sclavounos (2006). Measurements of squat and bank effects for a similar, albeit smaller inland waterway ship were presented by Eloot et al. (2012). Vantorre et al. (2002) represents a relevant reference with respect to experimental analysis of ship-ship interactions.

1.1. Shallow water effect on resistance

Hydrodynamic interactions in shallow water can be characterized in terms of water-depth dependent changes in the pressure field ambient to the ship. These effects can be related to the principles mass and energy conservation along a streamline in ideal flow, postulated by the

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Bernoulli equation. According to the Bernoulli and continuity equation a decrease of the flow cross-section results in a concurrent increase of the flow velocity and a decrease of pressure. Consequences of Bernoulli's effect for floating bodies are dynamic changes of the floating position and orientation. Ships in forward motion experience a vertical displacement in the heave mode (sinkage) and a rotational displacement in the pitch mode (trim) of motion, accompanied by a decrease of the mean ambient water level, decreasing under-keel clearance (UKC), Fig. 1. Owing to the importance of both water depth H and forward speed V_M,[1] the Depth Froude number $F_{rh} = V_M/\sqrt{gH}$ was established, where g is gravitational acceleration constant. Resistance R_{TM} is affected by above phenomenon by the increase of the dominant contributions defined in the classic decomposition, i.e. friction resistance, viscous pressure resistance and wave resistance, where the total resistance coefficient c_{TM} is defined as

$$c_{TM} = \frac{R_{TM}}{0.5\rho V_M^2 S_M} \quad (1)$$

where ρ is density of water and S_M the wetted surface of the model. The established decomposition of c_{TM} is

$$c_{TM} = c_F(1 + k) + c_W + c_A + c_{AA} \quad (2)$$

where c_F is friction resistance coefficient as in Eq. (3), k form factor, c_W wave resistance coefficient, c_A and c_{AA} are correlation allowance and air resistance coefficients, respectively, ITTC (1999). At higher speeds $V_M > \sqrt{gH}$ the effect of the change in floating position on wave resistance is dominant. Extrapolation procedures for model results to full-scale dimensions, e.g. applying the ITTC 1978 performance prediction method, are considered questionable with regard to the friction resistance coefficient c_F

$$c_F = \frac{0.075}{(\log_{10}Re - 2)^2} \quad (3)$$

and the form factor k, ITTC (1999), which is determined through regression analysis of measurements. Reynolds number is $Re = V_M L_{PP}/\nu$. Above mentioned approach does not consider the influence of limited UKC and was established for deep water.

1.2. Shallow water effect on propulsion

The limited UKC might significantly affect propulsion performance. In shallow water the flow field in the propeller plane changes in response to a higher wake with more distinct flow separation and interactions of the flow field ambient to the hull with the tank, canal bottom or seabed, respectively. Thus, to attain the same forward speed as when sailing in deep water, more power has to be delivered. The operating propeller decreases the local pressure on the after body compared to an equivalent flow in bare hull condition or with the propeller not in operation, which gives rise to a bow-up moment about the transverse axis with increasing forward speed. The flow field in the propeller plane in shallow water condition is usually characterized by a widening of isolines of the ratio of longitudinal flow velocity component to flow velocity of the undisturbed flow u_x/u_0, smaller local wake numbers quantified by u_x/u_0 and interaction with the vertical flow restriction. A related CFD analysis based on the solution of Reynolds-averaged Navier-Stokes (RANS) equations was performed by Mucha (2017) to demonstrate the qualitative effects. Fig. 2 shows scalar plots of u_x/u_0 in the propeller plane of the Kriso Containership (KCS) at different water depth to draft ratios H/T.

[1] Index M stands for model and refers to the value of the variable at model scale.

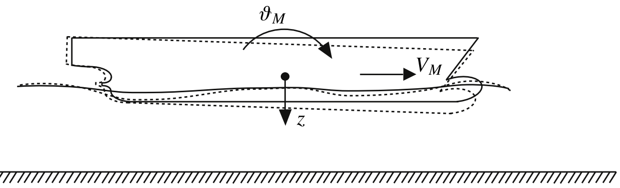

Fig. 1. Schematic of a ship underway experiencing bow-down squat. Dashed lines indicate the orientation of the ship and shape of the ambient water level caused by squat.

1.3. Ship-bank interactions

Analogous interactions occur in horizontal modes of motion in laterally confined water. Forces and moments arising from pressure variations on the ship hull, when traveling at close separation distance to a wall or bank, came to be denoted by the term bank effects. The decreased flow cross-section results in a decrease of pressure on the side of the restriction, inducing a suction force towards the wall and a moment, which for most conventional ship hulls tends to turn the ship bow-out off the wall. Lateral forces on the fore and after body strongly depend on UKC, distance to the restriction and forward speed and, in some cases, might result in an integral force which is repulsive, Lataire (2014). A change in ambient water level accompanies the suction effects, and at high speeds, the difference between the water levels on the open water side and the side facing the restriction dominates the suction forces and increases proportionally to the difference in water level. Fig. 3 is a schematic of a typical ship-bank interaction scenario. The suction force and bow-out moment cause the ship to move closer to the wall and induce a Munk moment. Typically, applying rudder in the direction of the wall while still maintaining a small bow-out drift mitigates the bank effects. In shallow water, bank effects are more pronounced as the blockage of the flow reinforces the change of the pressure field.

2. Test case description

The inland waterway ship used in the present investigation was designed in cooperation with DST and can be used for various ship types, e.g. for a tanker, bulk carrier and container ship, DST report 2112 (2014). No full-scale representation exists. The model is equipped with two ducted propellers and can be configured with single or twin rudders, i.e. a pair of rudders for each propeller. The rudders feature a fishtail and a small geometric aspect ratio of $\Lambda_R = 0.983$, typical for inland waterways ships. Table 1 summarizes the main particulars for the design loading condition, Fig. 4 shows a lines plan and Table 2 describes the appendages geometry. Computational Aided Design (CAD) files are publicly available, BAW (2017). Mucha et al. (2017) provides a comprehensive description of the hull and appendages geometries. A right-handed Cartesian coordinate system $\mathscr{S}$ participating in the forward motion of the model is used, Fig. 5. The origin is located at the midship section, in the centre and calm waterline plane, where x, y, z point forward, to starboard and downward, respectively. Longitudinal measured force is X and equals the negative ship resistance. Trim angle ϑ_M is positive bow-up. The distance between the centreline of the ship and the tank wall is denoted by d, Fig. 6. Midship sinkage is z_{VM}, sinkage at the fore measurement point z_{VF} and at the aft measurement point z_{VA}. Trim angle ϑ_M is given in minutes of arc.

Resistance tests were performed in bare hull condition at three water depths corresponding to H/T of 2.0, 1.5 and 1.2 in the shallow water tank of DST (dimension of the towing tank: 200 m long, 10 m wide, 0–1.1 m deep). Besides, results of towing tests in the deep water tank of the Schiffbauversuchsanstalt (SVA) Potsdam are available. The model was free to heave and pitch, but otherwise constrained. During tests in proximity to the tank wall the model was allowed to roll and the