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Evaluation of inter-facility uncertainty for ship manoeuvring performance prediction

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ABSTRACT

Ship manoeuvring, like many engineering problems, requires the prediction of motion performance through time-domain simulation based on force derivatives obtained by experiment. Procedures for obtaining the experimental uncertainty in the force measurements are typically given by the relevant national metrology institutions. However, the propagation of uncertainty from force measurements through to the predicted derivatives and onward into motion performance predictions, is less well defined. This paper presents a Monte-Carlo type approach for evaluating the propagation of uncertainty from force derivatives through to predicted performance parameters. Then, using a case study together with the published results from an inter-facility bias test, the paper identifies the like sources of uncertainty. The results show that, while some experimental uncertainty is evident, the likely cause of scatter (between facilities) is systematic in nature. That is to say, the current experimental procedures are ill contrived or insufficiently defined.

1. Background

Prediction of the manoeuvring performance of ships at the design stage is both desirable (from a commercial point of view) and a requirement of the International Maritime Organisation (IMO, 2002). However, recent studies have shown significant scatter in the predicted results from different institutions (Stern et al., 2011). To better establish the context of this paper, specific results from Stern et al. (2011) are represented in Fig. 1, together with 'NEW DATA' to be discussed later herein. The figure presents estimated turning circles for the same ship by various institutions and by various methods.

Such predictions are typically made with time-domain simulations of specific manoeuvres based on force coefficients obtained by various methods. This may include captive testing by Circular Motion Tests (CMT), by Planar Motion Mechanism (PMM) or with terms obtained by Computational Fluid Dynamics (CFD). Currently, the industry provides agreed standard methods for estimating the experimental uncertainty in captive testing for an individual force measurement (ITTC, 2008a). However, while providing a useful first step in identifying ways to best improve experimental testing, this tells us nothing about the uncertainty in predicted ship manoeuvring parameters.

2. Aims and objectives

The aim is to investigate the likely causes of the scatter found in the inter-facility tests using a systematic approach. The objective is to understand the likely sources of uncertainty in ship manoeuvring performance prediction. This is achieved by, firstly, re-evaluating the data published in Stern et al. (2011) using the Youden plot techniques (Youden, 1959), to better establish the causes of uncertainty. Secondly, a Monte-Carlo type approach is established for identifying the propagation of uncertainty from the force coefficients through to the performance parameters. Next, a case study is performed to explore both the sensitivities and the significant combined uncertainties. Also, the proposed Monte-Carlo approach is utilised to explore the uncertainty of simulated manoeuvring parameters. Finally, the estimated expanded uncertainty is compared with the scatter observed in inter-facility tests and used to draw conclusion as to the likely sources of uncertainty.

3. Overview of experimental procedures

The hydrodynamic forces acting on ships are typically examined using scale-model tests in dedicated facilities. The type of test dictates if the experiment should be conducted using Froude scaling or Reynolds scaling, depending on whether the potential flow forces or the viscous flow forces (respectively) are considered to be dominant. It is impossible to satisfy both simultaneously at

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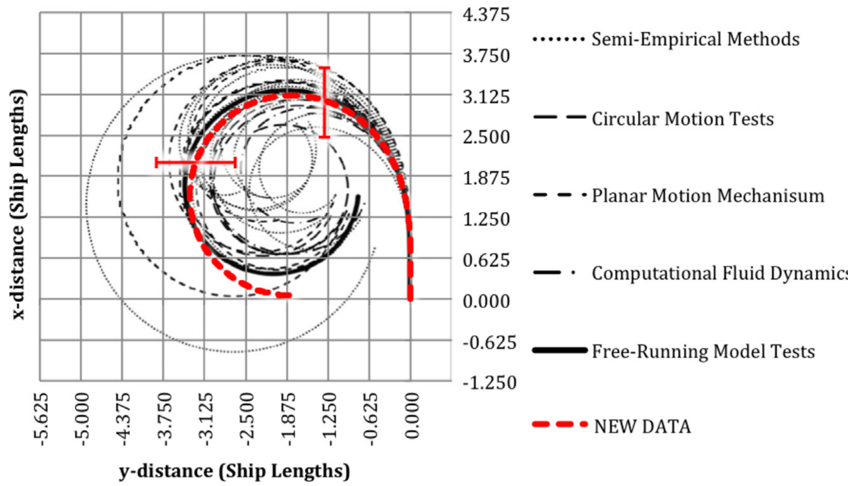

Fig. 1. KVLCC1 simulation of 35 deg turning circle test, reproduced from Stern et al. (2011).

any scale (except unity) as the required model speed scales up for Reynolds and down for Froude scaling. For ship manoeuvring studies this presents difficulties. Free-running model tests (FRMT) use large [typically 6 to 12 m length] models to perform specific manoeuvres and, with appropriate scaling, predict ship performance. However, to propel the ship model at the correct Froude scale speed, the propeller must be run in an overloaded condition. This substantially changes the flow velocity over the rudder (which is typically situated behind the propeller) causing a scaling error. One solution to this problem is found through captive testing, wherein the constrained model is actuated and the resultant forces measured. Forces are obtained for a range of motions in the horizontal plane and regression analysis is used to identify the specific force derivatives which are then used to simulate motion in the full-scale. As the speed of the model is controlled by the experimental apparatus (carriage) the propeller-rate can be selected to best represent the correct flow velocity over the rudder.

In addition to the above, methods are developed for estimations based on CFD. With the current state-of-the-art, simulation of the full time-domain manoeuver is too demanding requiring sometimes weeks of processor time. Nevertheless, methods are developed for modelling the described captive tests and the results can be used to simulate the manoeuvres in the same way as with the experimental results. More typically used at the preliminary design stage, Semi-Empirical Tools (SET) can provide useful insight into expected manoeuvring performance. Regression methods can be used to estimate the relationship between manoeuvring derivatives and specific non-dimensional ship characteristics. Once a significant number of tests have been performed on a range of similar ships, multi-variant analysis can yield prediction equations providing interpolative values for ships with similar characteristics.

The following sections will outline the typical tests used to obtain force derivatives that are used to simulate ship-manoeuvring performance. For simplicity the explanation will be limited to the sideways movement of the ship (sway motion) and rotation in the horizontal plane (yaw motion), though a more comprehensive model would include additional degrees-of-freedom.

3.1. Static drift angle tests

A Static Drift-angle Test (SDT) entails towing the captive model, at constant carriage speed U_0, for a range of drift-angles (resulting in different sway velocities v). The induced sway force Y, and yaw moment N are measured directly, from which the partial derivatives[1] Y_v and N_v are constructed. Due to the lateral symmetry of both the model and of the test arrangement, the system lends itself to an odd-function Taylor series expansion (typical taken to third-order) yielding also the partial derivatives Y_{vvv} and N_{vvv}. Alternatively or in addition, commonly, modulus 'pseudo odd-functions' are used in the form of $Y_{v|v|}$ and $Y_{r|r|}$ having perhaps more physical meaning because drag and is known to be proportional to the square of the velocity. The tests are also conducted for various rudder angles δ, with a zero drift-angle, yielding the partial derivatives Y_δ and N_δ. Higher order terms relating to coupling between the sway velocities, the yaw rate and the rudder angle are also typically obtained via this process [but are omitted here for clarity].

3.2. Circular motion tests

A circular motion test (CMT) entails towing the captive model along a circular path at constant carriage speed U_0, for a range of yaw rates r (achieved by varying the circular path radius). The induced sway force Y, and yaw moment N are measured directly, from which the partial derivatives Y_r and N_r are constructed together with the third-order terms Y_{rrr} and N_{rrr}. Within this test it is also possible to combine drift angles, and thus sway velocities as well as the yaw rates. The case as the radius tends to infinity is the same as the static drift test corresponding to when the rate-of-turn tends to zero. By performing tests both clockwise and anti-clockwise we obtain both positive and negative values allowing the zero yaw-rate case to be interpolated. By this process it is possible to obtain also the first- and third-order sway velocity derivatives described for the static drift test. In addition, by this process, it is possible to obtain the coupling-terms Y_{vvr}, Y_{vrr}, N_{vvr} and N_{vrr} (and/or modulus terms). The described tests are ideally repeated in various conditions including bare-hull, hull with rudder and hull with rudder and with the propeller (loaded to provide the correct flow over the rudder); though commercial pressures often preclude such an extensive programme. Actually, a more comprehensive derivation would typically include surge and roll force terms, but neglecting them herein simplifies the explanation without detracting from the applicability.

[1] Typically in ship manoeuvring studies, and in accordance with the ITTC, the derivative $\partial Y/\partial v$ is written as Y_v, similarly $\partial^3 N/\partial v \partial r \partial r$ is written as N_{vrr} and so forth.