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An algorithm for offline identification of ship manoeuvring mathematical models from free-running tests

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ABSTRACT

An identification algorithm for ship manoeuvring mathematical models has been developed. The identification procedure is based on the classic genetic algorithm used for minimizing a distance between the reference and recovered time histories. The distance was measured using 5 different metrics including the Hausdorff metric. Validation of the algorithm was carried out using simulated responses artificially polluted with the white noise of various levels. It was demonstrated that by only using the Hausdorff metric it was possible to reach necessary robustness of the identification algorithm.

1. Introduction

Capability to create highly accurate mathematical models for adequate simulation of the manoeuvring motion of real vessels is of great practical value, primarily due to the ever increasing demand by numerous ship handling simulation centres, as well as by enterprises developing computer-based bridge simulators. In the ideal case, the simulated motion must be undistinguishable from the real one as the training process will be then the most effective. Of course the full realism is never reachable but it can and must be approximated as closely as possible. The realism and adequacy of the manoeuvring simulation depends on several factors which include: (1) accurate reproduction of the visual and—to a lesser extent—of the acoustic environment; (2) reproduction of tilts and accelerations possibly felt by the operator during manoeuvring; and (3) identity of responses of the original physical object and of its numerical models to the control actions.

Quality of visualization has increased very strongly during last 30 years resulting in 360° simulators, high-resolution screens and 3D visualization. Although the generated picture is and will remain for long much inferior in resolution to the real one, apparently this already does not represent a major problem that would significantly impair the simulation quality.

The tactile factors rarely are of substantial importance in marine simulations contrary to aeronautical applications but their modelling are desirable for high-speed craft, submarines and underwater vehicles. As there are no means for artificial generation of the gravitational field, the moving floor technique is used for both simulating actual tilts and centrifugal accelerations while the image is adjusted accordingly.

Adequacy of the core manoeuvring mathematical also can only be reached approximately: even the validation itself may present problems especially when it goes about the full model including effects of the hydrodynamic interactions, response to gusty wind and sea waves (Hensen, 1999). When talking about more standard situations, results of simulations can be, in principle, validated against full-scale measurements. But this still does not make simple the task of creation of an adequate mathematical model even when the full-scale data are accurate and reliable (which is rarely the case!). This is fundamentally caused by the fact that hydrodynamics of manoeuvring motion is of ultimate complexity representing a fusion and heavy generalization of the ship resistance, propulsion and seakeeping. All practical manoeuvring mathematical models are highly schematised and although in principle can be tuned to provide a satisfactory reproduction of the true motion, there are no simple theoretical methods for estimating their parameters. An attentive unbiased analysis of the problem soon reveals that the viscosity plays the major role in the formation of hydrodynamic forces related to manoeuvring and presence of strong separation phenomena makes the classic boundary layer theory absolutely insufficient while it used to be rather helpful in ship resistance. Hence, only models based on the full Naviers–Stokes equations can promise reliable prediction of manoeuvring forces.

In spite of great progress in computational fluid dynamics (CFD) and its successful applications to manoeuvrability (Stern

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et al., 2011) practical simulation-oriented mathematical models still are often devised on the basis of experimental data.

Due to various reasons, most modern ship mathematical models can be called "physical" or—to be more precise—"mechanical" as they are based on principles and equations of classic mechanics. Alternative approaches have created purely "input–output" models on the basis of artificial neural networks (ANN) (Faller et al., 1998; Moreira and Guedes Soares, 2003, 2012). The ANN algorithms may have certain advantages as they do not imply any *a priori* structure of the ship mathematical model. But the absence of any physical ground behind the ANN model represents, at the same time, a natural disadvantage of ANN models as they cannot be extended, modified or tuned without full retraining which is not always possible. The latter deficiency is to a large extent neutralized in the hybrid approach where a mechanical model is combined with ANN technique applied, replacing usual regressions, for representation of hydrodynamic forces (Rajesh and Bhattacharyya, 2008; Rajesh et al., 2010). Recently several studies have appeared on application of such a parental and presumably robust method as that of Support Vector Regressions/Machines (Luo and Zou, 2009; Zhang and Zou, 2011) but the validation carried out so far does not permit to draw definite conclusions about the effectiveness of this approach.

Any mathematical model based on mechanics implies presence of certain forces acting upon the ship and its elements depending on the parameters of motion. Most of these forces can be relatively easily measured on scaled models and their elements during the so-called captive-model tests. Results of these measurements can be used for construction of desired simulation models although these can be distorted by the scale effect (Sutulo and Guedes Soares, 2011). Unfortunately, most of the forces cannot be measured in full scale and while measuring, for instance, the propeller and rudder forces is in principle possible, it is very complicated and costly. At the same time, it is relatively simple to measure kinematical parameters during the motion resulting from some well-defined steering programme. In some sense, such full-scale tests or even tests with scaled free-running models (Moreira and Guedes Soares, 2011; Perera et al., 2012; Obreja et al., 2010; Araki et al., 2012) can be even easier to realize than to perform captive-model tests as no special facilities are required and full-scale data are typically necessary anyway for validation of implemented manoeuvring models. But if nothing more than kinematical measurements are available, the core manoeuvring mathematical model can only be reconstructed indirectly, via an identification procedure. Relatively rarely captive-model tests are combined with the free-running ones. For instance, Skjetne et al. (2004) have determined all forces not dependent on the yaw velocity from oblique captive tests carried out in a normal towing tank while the remaining part of the model was obtained from free-running model tests with online system identification.

If the structure of the mathematical model is established *a priori*, just the values of the parameters of the model are to be estimated and it goes then about the *parametric identification* and most of the applied studies belong to that group.

Primarily the identification problem was formulated and studied in the general system theory aiming at control applications (Ljung, 1987) as sufficient knowledge on the mathematical models of controlled or stabilised objects was necessary for synthesis of optimized and adaptive control laws let alone the importance of the simulation of control processes before final implementation of the synthesized controllers in real objects and systems.

Apparently, for the first time the identification problem with application to ship dynamics problems was formulated by Nomoto et al. (1957) who tried to make the problem treatable by very simple algorithms not requiring computer technology. It was assumed that the model is linear and it was further simplified having finally developed the famous Nomoto equations containing the minimum number of parameters which indeed could be easily estimated after a zigzag test. Although the Nomoto equations proved to be useful in certain applications, like synthesis of controllers and short-term predictions, their linearity and the reduced number of parameters made them unsuitable for realistic simulations. As to the simplest first-order Nomoto equation, it was even demonstrated (Sutulo and Guedes Soares, 2004) that it possesses no non-trivial parameters at all!

That is why, most of the manoeuvring model parameters identification studies were based on more complicated multi-parameter models. Elementary identification is then impossible. Often the models are tuned manually before being implemented in bridge simulators although such approaches are rarely even mentioned in the literature. In these cases, it is possible to talk, in fact, about a kind of interactive manual identification process which is, however, slow, tedious and depending on human skills.

Hence, sophisticated numerical methods were applied, part of them custom-devised but mostly used as they had been developed in the control theory (Ljung, 1978; Garnier and Wang, 2008).

All identification algorithms can be divided into two main groups: *online* procedures and *offline* procedures. According to Ljung and Söderström (1983) "the offline identification is the determination of a model of a system using a batch of measured data where the whole batch is available at all stages of the procedure". This is exactly the situation faced in all experimental studies when the identification becomes part of the post-processing. On the contrary, the online identification presumes the measuring and identification processes running in parallel though typically with a certain lag of the latter. As long as additional data are fed into the identification procedure the quality of the estimated model is constantly improved and/or modified together with the modification of the "true" model. This quality is valuable for applications to optimized and adaptive controllers although in general a suitable offline procedure will be always superior in the situations when the both approaches can be applied.

In spite of this more or less evident consideration, first applications of the system identification to ship dynamics were based on such a classic online method as the Extended Kalman Filter (EKF) (Brinati and Rios Neto, 1975; Åström and Källström, 1976; Källström and Åström, 1981; Abkowitz 1980, 1988). Although this method typically demonstrated slow convergence requiring long records, the EKF or similar recursive estimators like Unscented Kalman Filter, Modified Bryson–Frazier fixed interval smoother and others kept unparalleled popularity (Zhou and Blanke, 1987; Rhee and Kim, 1999; Yoon and Rhee, 2003; Araki et al., 2012; Revestido Herrero and Velasco González, 2012). A characteristic feature of the latter study is that the parametric identification was combined with the significance analysis applied to a rather simple quasi-polynomial model for hydrodynamic forces. In most cases, however, this analysis is performed in advance using available captive-model test results and applying physical considerations.

The adaptive backstepping method was applied by Casado et al. (2007) to only a highly simplified and easy to identify ship mathematical model (1st order Nomoto equation with a simple nonlinearity added), so, in fact, nothing can be said about its real effectiveness.

It was discovered very soon that the problem of identifying parameters of a rather complex and realistic ship manoeuvring model is ill-posed and at high noise levels typical for the sea trials data heavily biased estimates and, as result, useless models could be obtained. Abkowitz (1980, 1988) was only able to fight the observed cancellation effect through elimination of "inconvenient" terms which, however, could lead to models with limited applicability as certain regression terms may only become significant in special conditions like sailing in wind.

The problem of ill-posedness can be easier treated in offline algorithms which are allowed to be slower and more