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Optimal trim control of a high-speed craft by trim tabs/interceptors Part I: Pitch and surge coupled dynamic modelling using sea trial data

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ABSTRACT

A pitch and surge coupled dynamic model of a high-speed craft is not available for dynamic trim control applications in the literature. The existing fluid-structure interaction models of a high-speed craft are not adequate for simulations and control applications, since they require a great deal of computation time, for example more than 20–40 s depending on a vessel particulars. Hence, in this work, we aimed to obtain a dynamic model of a high-speed craft for surge and pitch motions. Then the obtained model will be utilized to design an automatic controller which adjust the command signal on a high-speed craft to increase fuel efficiency, safety and comfort of passengers in a vessel. The coupled pitch and surge motion of a high-speed craft with trim tabs/interceptors was modelled by using full scale sea trial data. The linear parametric modelling using System Identification (SI) Methods and Artificial Neural Network (ANN) modelling were carried out and the comparisons of both the training and validation results are given. High correlation coefficients and low average values of absolute errors in surge and pitch dynamics were obtained by using ANN Method. The ANN model can be improved for further control designs on a marine vessel's operations.

1. Introduction

Marine vessels' motions are generally determined by experimental tests, and direct numerical solutions based on Navier-Stokes Equations by Computational Fluid Dynamics (CFD) (ITTC, 2011a, 2011b). There are many publications in the field of dynamic modelling for displacement type of a ship. The dynamics of a high-speed craft are different from displacement ships. It has displacement, semi-displacement, and planing characteristics according to Froude numbers (Faltinsen, 2005; Fossen, 2011). In this study, it is aimed to model surge and pitch motions of a high speed craft to be able to design dynamic trim controller during planing or semi-planing hull motion using existing trim tabs/interceptors which controlled manually.

Initial studies of a hydrodynamic model for prismatic form of a high speed craft was done with experimental tests for smooth and rough sea conditions (Savitsky, 1964; Savitsky and Brown, 1976). The linearized and empirical equations of a high-speed craft in wave conditions were presented in detail (Lewandowski, 2003; Faltinsen, 2005). A numerical analysis on vertical dynamics of a planing craft in calm sea and in waves was studied (Blake, 2000; Blake and Wilson, 2001). A numerical simulation algorithm based on the finite volume discretisation was presented for analysing 3D nonlinear high-speed vessels motion, and the steady-state forward motion of it was investigated (Panahi, et al., 2009). An interceptor's effectiveness on the hydrodynamic performance for a high-speed craft was investigated (Karimi et al., 2013). The other hydrodynamic designs of interceptor/trim tabs were studied (Tasi and Hwang, 2004; Luca and Pensa, 2012; Mansoori and Fernandes, 2016). Furthermore, an autonomous planning watercraft test bed was developed to improve the controller technologies for a planning craft (Woelfel, et al., 2004; Blank and Bishop, 2008).

In this study, even it is possible to achieve a dynamic model via CFD analysis, generating a dynamic model from sea trials is preferred since it is more suitable for real time controller design. Therefore, the dynamic model in the form of linear and nonlinear identification methods are obtained from full scale sea trials that represent nonlinear, coupled surge and pitch motion depending on the engine speed, trim tab/interceptor position and heave acceleration.

Modelling studies by SI in multidisciplinary area have shown a good level of accuracy according to empirical and theoretical methods (Ljung, 1999). The studies on modelling by (SI) methods of marine

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vessels for controller design purposes are limited. Early studies on identification of a ship's steering dynamics were presented in detail (Aström and Kallström, 1976). Manoeuvring motions of container ships were determined by SI methods afterward. Grey-box modelling (Blanke and Knudsen, 2006), genetic algorithm (Sutulo and Soares, 2014), support vector regression (Wang et al., 2015) and ANN (Simsir and Ertugrul, 2009) methods were used for identification of manoeuvring motions. Identification for a heading autopilot of an autonomous in-scale fast ferry was studied (Velasco et al., 2013). An adaptive autopilot was designed to govern steering of a high speed unmanned personal watercraft by using a grey-box identification model (Svendsen et al., 2012).

The parametric modelling of heave and pitch motions of fast ferries in the frequency domain was done by using a simulator (Pintelon and Schoukens, 2004). The partial differential equation's parameters of the coupled heave-pitch motion of an icebreaker ship were identified by ANN (Haddara and Xu, 1999). Heave and pitch motions of a planing craft with a transom flap in calm sea was modelled as steady-state method by using experimental data and Savitsky's method, and a controller was designed for reduction of porpoising instability in simulation studies (Handa and Jing, 2006). A parametric model of heave, pitch and roll dynamics of a high-speed craft were defined in the frequency domain according to wave excitations with different incidence angles between 90° and 180° by using a simulator (Munoz-Mansilla et al., 2009). Then, the parametric model was utilized for stabilization control to reduce motion sickness associated with heave, pitch and roll accelerations (Munoz-Mansilla et al., 2010).

The purpose of controller design may be to convert a manual trim system to an automatic controller, or to improve an existing controller. The model should represent the dynamic behaviour of a high speed craft and be useful for these control applications. This paper focuses on dynamic modelling of pitch and surge motion of a high-speed craft so that an optimal trim controller could be designed based on the obtained model. The purposes of dynamic trim control are fuel efficiency, safety, comfort of passenger in a vessel. Dynamic modelling of a high speed craft was studied by SI, and ANN methods with sea trial data of Volcano71, in length 10.86 m. The particulars of Volcano71 and experimental system setup are presented in Appendix A.

2. Motivation

In a previous project, an advanced controller design of active fins for ship roll motion reduction was studied. Sea trials in the coastal sea in Tuzla-Istanbul were done to collect data for experimental parameter identification to establish a realistic roll motion equation for Marti, 16.5 m in length. The advanced controller design was tested on the Marti, as a full-scale application, after the real-time computer control was carried out for position control of the hydraulic system. High performances were obtained from the real time tests. Considerable amount of experience has been gained during these projects regarding data acquisition, signal processing, instrumentation, modelling and real time control (Ertogan et al., 2015, 2016; Zihnioglu et al., 2015).

The optimal trim control of a high speed craft in nearly calm water is being studied in the current project. The purpose of the automatic trim control is to improve fuel efficiency, safety and comfort of passengers in a marine vessel. Devices such as trim tabs, interceptors, and sterndrive engines can be used to control the trim of a high speed craft. These devices may be fixed or the system may be manually controlled and position of trim tabs/interceptor can be changed by the captain based on experience. But it is difficult to control both longitudinal and lateral motions of the high speed craft and manipulate the position of trim tabs/interceptors at the same time manually. Therefore, an advanced algorithm is needed to automatically adjust the position of trim tabs/interceptor to maximize the speed for a given throttle position. To be able to develop such advanced, reliable control algorithm, a model representing coupled surge and pitch motions of the craft is required for simulation purposes. The aim of this study is to investigate linear and nonlinear modelling techniques to find an adequate model to study the optimal trim controller design which will increase the fuel efficiency.

Modelling methods are defined as three types; white-box modelling, grey-box modelling, and black-box modelling. White-box modelling obtaines a series of combined differential equations. Grey-box modelling represents a known plant system, but with limits to the possible excitation. Different parameterizations give significantly different model quality for grey-box modelling, because some parameters may not be identifiable. Black-box modelling estimates required variables based on the collected input-output data (Blanke and Knudsen, 2006; Wang et al., 2015).

In the literature, an article directly focused on optimal trim control of a high speed craft could not be found. As nearly related to our project topic, there are few articles which are generally about simulation studies on heave motions' reduction control, and manoeuvring control of a planing craft (Velasco et al., 2003; Handa and Jing, 2006; Svendsen et al., 2012). Generally, a high speed craft was modelled using parametric methods identification from collecting scaled-model test data for control purposes (Munoz-Mansilla et al., 2010).

In this project, the full-scale studies were preferred, because model test results suffer from scale effects (Woelfel et al., 2004; Blanke and Knudsen, 2006). Intelligent, nonlinear methods for modelling were investigated for simulation purposes, since designing and tuning of a controller algorithm via simulations requires less time, cost and effort compared to real time sea trials.

3. Experimental modelling

The discrete-time non-linear model from sea trial data was desired. The Multi-Input-Multi-Output (MIMO) model includes the three input signals as engine speed, interceptors/trim tabs' position, and heave acceleration for each sea-state condition, and the output signals as ship speed, and pitch motions, shown in Fig. 1.

If an acceptable linear model could be obtained for the ship's speed ranges standing for a high-speed craft, it would be very useful for simulation purposes in controller design. Therefore, an attempt has been made to obtain linear parametric models such as State-Space (SS) and ARX using well-established SI theory. However, it is known that ship dynamics involve nonlinearities. Therefore, a non-linear modelling technic such as Neural Network needs to be utilized. A decision should be made about the type of model depending on the results of both linear and non-linear models.

In this paper, the full scale modelling of surge and pitch motions were studied by using the linear parametric models of State-Space and ARX. In order to model the surge and pitch motions of a high-speed craft with the interceptors/trim tabs by these methods, input signals should be persistently exciting. Collecting the sea trial data, the linear parametric modelling and the nonlinear modelling methods are described in the following subtitles.

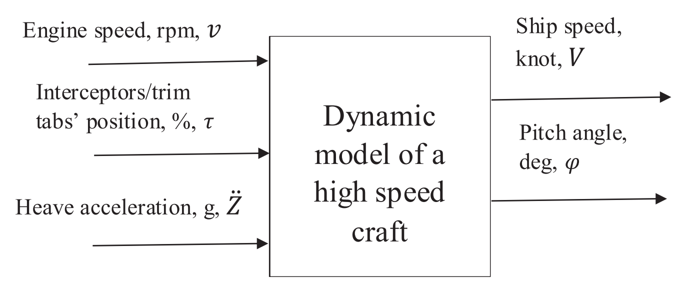

Fig. 1. The input and output signals for a dynamic model of surge and pitch motions of a high-speed craft.