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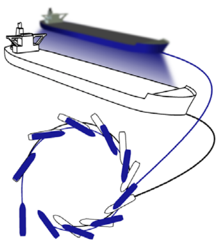
Physics informed grey box modelling of ship dynamics



A prestudy carried out within the Swedish Transport Administration's industry program Sustainable Shipping, operated by Lighthouse, published in June 2025

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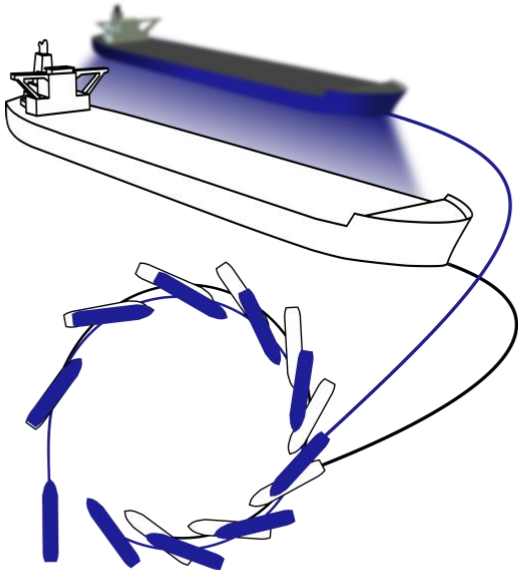

This project improves ship manoeuvring models by integrating prior knowledge and semiempirical formulas, enhancing accuracy and generalization through advanced parameter identification techniques.

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Summary

This project investigates the enhancement of ship manoeuvring models through the integration of prior knowledge embedded in parametric model structures and semiempirical formulas. The research is driven by the question: How can prior knowledge be used to enhance the generalization of ship manoeuvring models?

The study begins focusing on one degree of freedom in ship roll motion, aiming to develop parameter identification techniques and propose a parametric model structure with good generalization. This knowledge is then extended to the manoeuvring problem, with objectives including the development of parameter identification techniques for ship manoeuvring models, proposing a generalizable parametric model structure, mitigating multicollinearity between model parameters, and identifying added masses.

Methodologically, the research employs various parametric model structures for roll motion and manoeuvring, investigated through free running model tests and virtual captive tests (VCT). A novel parameter identification method combining inverse dynamics with an extended Kalman filter (EKF) is proposed. Additionally, a deterministic semi-empirical rudder model is introduced to address multicollinearity issues.

Key findings indicate that inverse dynamics regression is an efficient method for parameter identification in parametric models. The proposed quadratic model structure for roll motion demonstrates good generalization, and the new parameter identification method accurately predicts manoeuvring models from standard manoeuvres. However, challenges with multicollinearity and the need for more informative data are highlighted. The study concludes that semi-empirical formulas can guide identification towards more physically correct models, and VCT can provide the necessary data for accurate model identification.

The implications of this research suggest that integrating semi-empirical rudder models and utilizing VCT can significantly enhance the accuracy and generalization of ship manoeuvring models, contributing to more reliable and physically accurate simulations in maritime engineering.

Sammanfattning

Detta projekt undersöker hur fartygsmanövreringsmodeller kan förbättras genom integration av tidigare kunskap inbäddad i parametriska modellstrukturer och semiempiriska formler. Forskningen drivs av frågan: Hur kan tidigare kunskap användas för att förbättra generaliseringen av fartygsmanövreringsmodeller?

Studien börjar med att fokusera på en frihetsgrad i fartygs rullningsrörelse, med målet att utveckla tekniker för parameteridentifiering och föreslå en parametrisk modellstruktur med god generalisering. Denna kunskap utökas sedan till manövreringsproblemet, med mål som inkluderar utveckling av tekniker för parameteridentifiering för fartygsmanövreringsmodeller, föreslå en generaliserbar parametrisk modellstruktur, minska multikollineariteten mellan modellens parametrar och identifiera adderad massa.

Metodologiskt använder forskningen olika parametriska modellstrukturer för rullningsrörelse och manövrering, undersökta genom modelltester och ”virtual captive tests” (VCT). En ny metod för parameteridentifiering som kombinerar ”inverse dynamics” med ett ”extended Kalman-filter” (EKF) föreslås. Dessutom introduceras en deterministisk semiempirisk rodermodell för att hantera multikollinearitetsproblem.

Viktiga fynd visar att invers dynamikregression är en effektiv metod för parameteridentifiering i parametriska modeller. Den föreslagna kvadratiska modellstrukturen för rullningsrörelse visar god generalisering, och den nya metoden för parameteridentifiering förutsäger noggrant manövreringsmodeller från standardmanövrer. Dock framhävs utmaningar med multikollinearitet och behovet av mer informativ data. Studien visar att semiempiriska formler kan vägleda identifiering mot mer fysiskt korrekta modeller, och VCT kan tillhandahålla den nödvändiga data för noggrann modellidentifiering.

Implikationerna av denna forskning tyder på att integrering av semiempiriska rodermodeller och användning av VCT kan avsevärt förbättra noggrannheten och generaliseringen av fartygsmanövreringsmodeller, vilket bidrar till mer pålitliga och fysiskt korrekta simuleringar inom maritim ingenjörskonst.

Contents

1 Introduction

Constructing a model of a ship offers numerous benefits. For example, a digital twin serves as a dynamic, real-time digital replica of a physical ship, continuously receiving data from its physical counterpart via sensors. This concept, originally developed by NASA to enhance spacecraft simulations, is now widely used across various industries, including manufacturing, urban planning, and healthcare. Digital twins help organizations simulate real-world scenarios and make informed decisions using real-time data and insights. A virtual prototype, similar to a digital twin, is primarily used for simulation and testing during the design phase and does not necessarily receive real-time data from a physical counterpart, making it useful before the actual ship exists.

The core purpose of a model is to predict outcomes that are too dangerous, difficult, or costly to test with a real ship. For instance, when evaluating millions of alternative scenarios during optimization, a cost-effective model is essential. Building a model before constructing the real ship is a prudent approach, akin to how an architect creates a model of a house before construction. Scale model testing at facilities like the RISE SSPA Maritime Center is often conducted before ships are built to study ship dynamics. However, this process is expensive, time-consuming, and limited by the physical constraints of the facilities.

Therefore, a more theoretical approach is often adopted. Computational fluid dynamics (CFD) describes the hydrodynamics of ships based on fundamental physics principles. However, CFD can be impractical due to high computational costs or insufficiently defined geometries, calculation domains, or boundary conditions. In such cases, a data-driven model that mimics the system's behavior from observations is used. This project has explored these data-driven models, establishing appropriate mathematical model structures to describe the underlying physics and proposing methods to identify them from either CFD calculations or recorded ship trajectories.

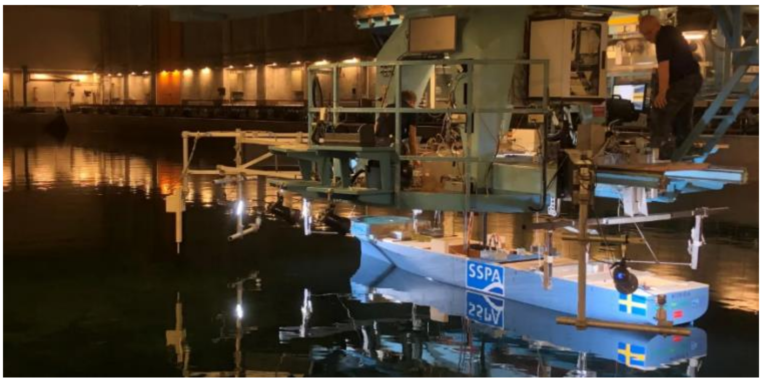

Figure 1 RISE SSPA Maritime Center.

The term “model” is frequently used in this report, but it carries different meanings across various engineering disciplines. To avoid confusion, this report adopts a more precise definition by distinguishing between “model structure” – defined for mathematical models by “model equations” – and “identified model”, which refers to the complete model, including the identified parameters within the model equations.

Model structures are often categorized in the literature as either parametric models (Figure 2) or non-parametric models (Figure 3). A third category, hybrid models, combines parametric models with non-parametric models. The following definitions have therefore been adopted in this project: if the model structure is defined by explicit mathematical formulas that have parameters in it, it is categorized as a parametric model; all other model structures are categorized as either non-parametric or hybrid models.

$$X'_H = X'_0 + X'_{rr}r'^2 + X'_u u' + X'_{vr}r'v' + X'_{vv}v'^2$$
$$Y'_H = Y'_0 + Y'_{rrr}r'^3 + Y'_r r' + Y'_{vrr}r'^2 v' + Y'_{vvr}r'v'^2 + Y'_{vvv}v'^3 + Y'_v \dots$$
$$N'_H = N'_0 + N'_{rrr}r'^3 + N'_r r' + N'_{vrr}r'^2 v' + N'_{vvr}r'v'^2 + N'_{vvv}v'^3 + N \dots$$

Figure 2 Ex. parametric model.

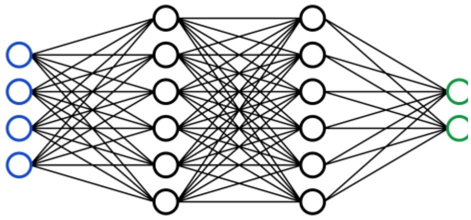

Figure 3 Ex. non-parametric model.

Multicollinearity refers to a situation in statistical modelling where two or more predictor variables are highly correlated, making it difficult to isolate the individual effects of each predictor on the dependent variable. An example is when the ship has a drift angle so that the total side force Y acting on the ship from the oblique flow generates lift forces on both the hull Y_H and the rudder Y_R, as shown in Figure 4. The hull force and rudder force will be highly correlated in this situation, and it will be hard to identify their individual contributions when only the total force is measured. This issue is particularly relevant in the field of ship modelling, where numerous hydrodynamic coefficients and parameters are involved. The higher correlation of parameter is, or the stronger multicollinearity exists, the more difficult it is to identify regression coefficients separately (Yoon and Rhee, 2003).

Yaw rate and drift angle are correlated during manoeuvres, as shown in Figure 5, which makes it difficult to separate their influences. The best option to mitigate multicollinearity is to get more informative data with persistence of excitation including conditions where the input signals used in system identification are sufficiently rich in frequency content to excite all the modes of the system. This ensures that the system's response contains enough information to uniquely identify the system parameters. Without persistence of excitation, the identified model may not accurately represent the ship's behavior in all scenarios. For instance, even though there might be millions of datapoints available, if nothing has happened for a long time, the data is not very informative and cannot be used to identify a model.

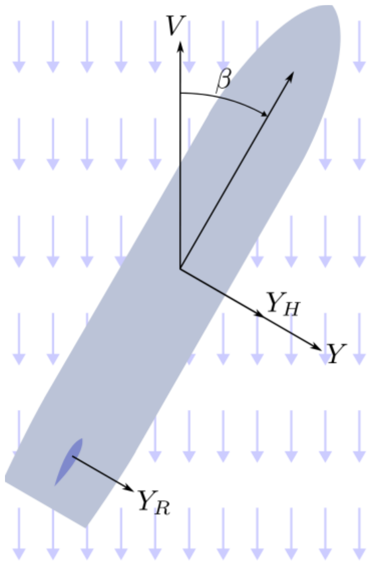

Figure 4 Multicollinearity between hull and rudder forces.

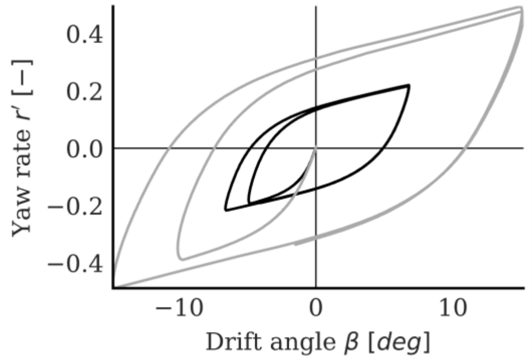

Figure 5 Yaw rate and drift angle are correlated during zigzag manoeuvring tests.

1.1 Motivation and objectives

System identifications of parametric models has been conducted since the late 1970s from free running tests, and for even longer times from captive tests. The first papers about non-parametric models were published in the late 1990s, with an increasing popularity during the past 15 years, especially within the field of autonomous vessels. Today there are still papers being published about both these approaches, so there seems to be no consensus which one is the better. Further progress within machine learning can be expected within the coming years, with a bright future for the non-parametric models and the hybrid approaches. The lack of informative data and persistence of excitation will however remain a big challenge.

One aspect of indirect informative data that is often overlooked is the prior knowledge about ship hydrodynamics from previous experimental works and other physical insights. This indirect informative data is often embedded in the parametric model structures, which parameters should be included or excluded from a model have often been chosen with careful consideration from experimental works or physical reasoning. There are also semi-empirical formulas in the literature that could potentially be used to add more informative data. This is a subject that needs further investigation, and the research question of this project has therefore been formulated in the following way:

How should prior knowledge embedded in parametric model structures and semiempirical formulas be used to enhance the generalization of ship manoeuvring models?

To provide a clear path through this research, the research question has been broken down into the following research objectives:

A. Develop parameter identification techniques for ship manoeuvring models from FT data that can generalize from simpler to more complicated maneuvers.
B. Propose a parametric model structure with good generalization that is identifiable from standard maneuvers. The model structure should be based on physical insights from CFD and FRMT inverse dynamics.
C. Mitigate multicollinearity and enhance generalization by introducing semiempirical formulas.

1.2 Assumptions and limitations

Finding the true model of the ship system is an unreachable goal, which is also an undesirable goal since we don't want to model everything about the ship, just the things relevant for the question at hand. This project focus on the ship's dynamics, which describes the motion of the ship and the forces that cause this motion. The ship's dynamics is closely related to the energy consumption and controllability of the ship. Modelling of the ship dynamics for a ship at sea is a very complex task that involves large uncertainties regarding the environmental conditions from the wave, winds and currents. The ship's dynamics has therefore been studied in calm water conditions, as a simplification in this project. This addresses the manoeuvring performance of the ship, where the calm water dynamics can be studied in isolation from the remaining components at sea.

2 Model structures

The model structures in this project are expressed as memory-less state space models, following the Markov process assumption. This assumption implies that the forces acting on the ship at each time instant depend only on the current state – so that previous events do not affect the current state. The state space model can therefore express the change of state $\dot{\boldsymbol{x}}$ from the current state vector $\boldsymbol{x}$ and the input vector $\boldsymbol{u}$ through the transition function $f(\boldsymbol{x},\boldsymbol{u})$:

$$\dot{x} = f(x,u)$$

The change of state, estimated by the transition function, can be used to simulate the ship motions with time integration. The position and orientation, velocities and turning rate defines the state of the ship in three degrees of freedom $\boldsymbol{x} = [x_0, y_0, \Psi, u, v, r]^T$ as shown in Figure 6. The ship kinematics can be expressed as function of a velocity vector $\boldsymbol{v} = [u \quad v \quad r]^T$. The ship acceleration $\dot{\boldsymbol{v}}$ is expressed with the inverse mass matrix $\boldsymbol{M}^{-1}$ and force vector $\boldsymbol{F}$ through the equation of motion.

$$\dot{\boldsymbol{v}} = \mathbf{M}^{-1}\mathbf{F}$$

The ship acceleration vector $\dot{\boldsymbol{v}}$ can be used together with the global velocities $\dot{x_0}$, $\dot{y}_0$, and r to form the transition function.

$$f(\boldsymbol{x}, \boldsymbol{u}) = [\dot{x_0}, \dot{y_0}, \mathrm{r}, \dot{\boldsymbol{v}}]^T$$

The system identification can now be split into the problem of determine the mass matrix $\boldsymbol{M}$ and the problem to determine a parametric model of the forces $\mathbf{F}$ acting on the ship as explained in the next section.

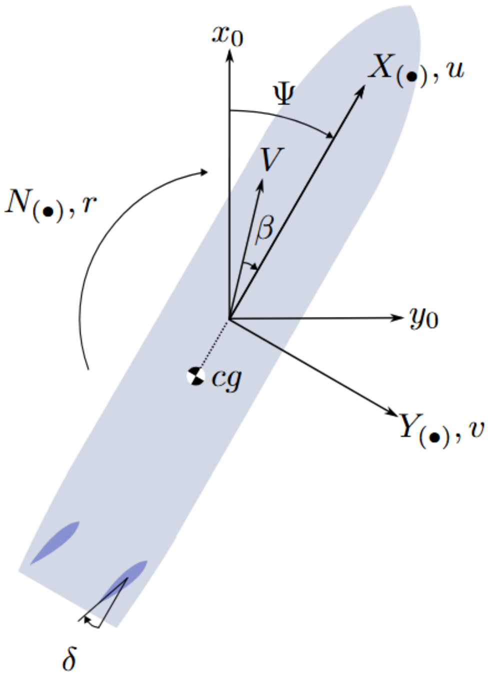

Figure 6 Relations between the earth fixed and ship fixed reference frames, showing the velocities and forced in the ship fixed frame.

3 Parameter identification

The rigid body part of the mass matrix was determined by swing tests in air and the added masses were determined with potential flow calculations.

In this project, the force models were identified from either captive test (CT) or the free-running test (FT). Captive model tests (CMT) are the classical way of conducting captive tests, which can be performed in various ways: with an XY-carriage, rotating arm, or planar motion mechanism (PMM). CT can also be performed with CFD in virtual captive tests (VCT). FT data are collected from either model tests full-scale tests, or operational data. CT data is generally more applicable in virtual prototyping when assessing the manoeuvring performance before ships are built. FT data, on the other hand, are generally more applicable for existing ships, in a digital twin context.

3.1 System identification from captive tests

As a consequence of the Markov assumption, the force model m can be expressed as a function surface of the input velocities, rudder angle δ, and the propeller thrust T.

$$F = [X_D, Y_D, N_D]^T = m(u, v, r, \delta, T)$$

The inputs are varied during the captive tests to identify the function surface as shown in Figure 7. The function surface is assumed to be expressible with a predefined model structure, containing a set of polynomials to express the forces. There are a many such mathematical models proposed in the literature (Abkowitz, 1964; Nomoto et al., 1957; Norrbin, 1971; Yasukawa and Yoshimura, 2015). The data from the captive tests is used to identify the parameters within the mathematical force model with linear regression.

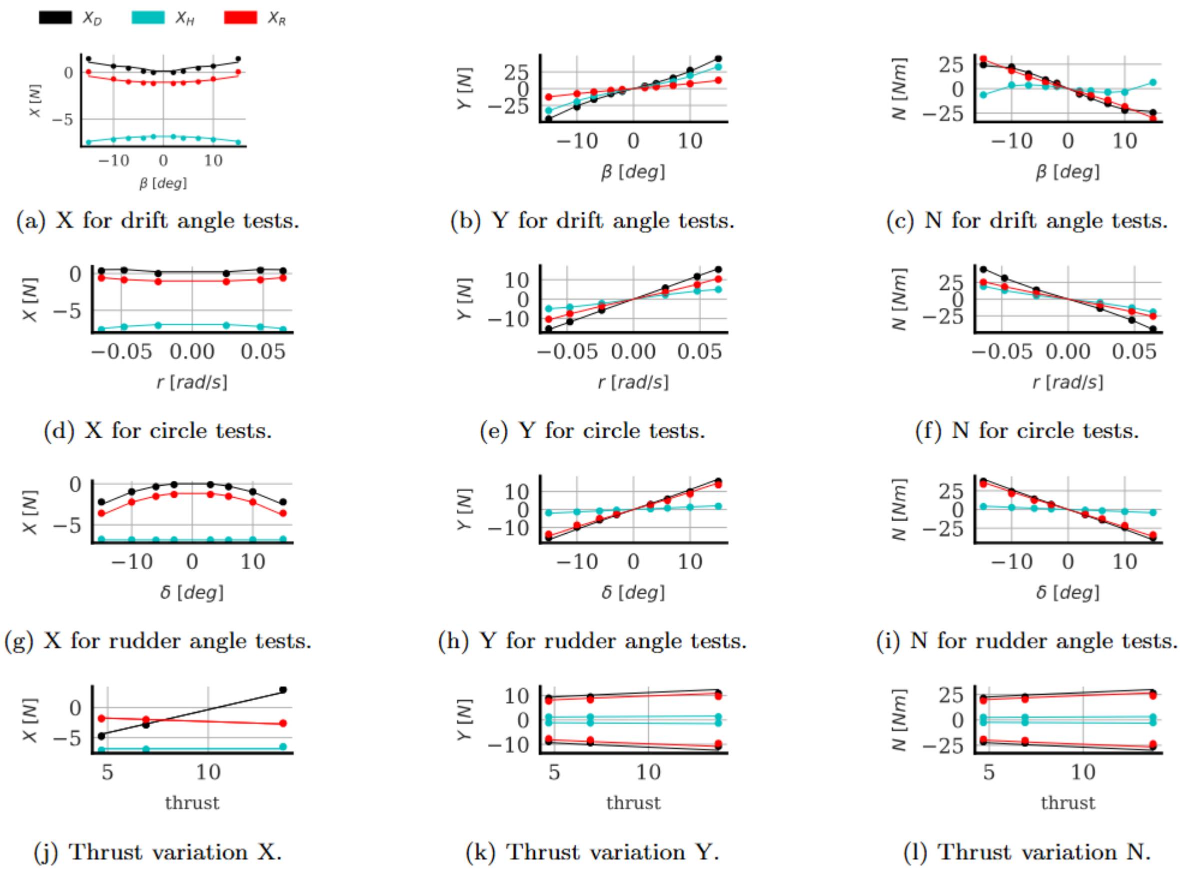

Figure 7 Forces obtained from captive tests.

3.2 System identification from free running tests

Unlike the captive test, free running test cannot measure the forces directly. The forces were instead estimated by using the equation of motion to calculate the inverse dynamics.

$$\mathbf{F} = \mathbf{M}\dot{\boldsymbol{v}}$$

The acceleration vector $\dot{\boldsymbol{v}}$ was estimated by an extended Kalman filter. An example of the inverse dynamics forces is shown in Figure 8, where the forces during a turning circle manoeuvre have been estimated. The estimated forces can be used to identify a force model in a similar way as the captive test, which is referred to as inverse dynamics regression.

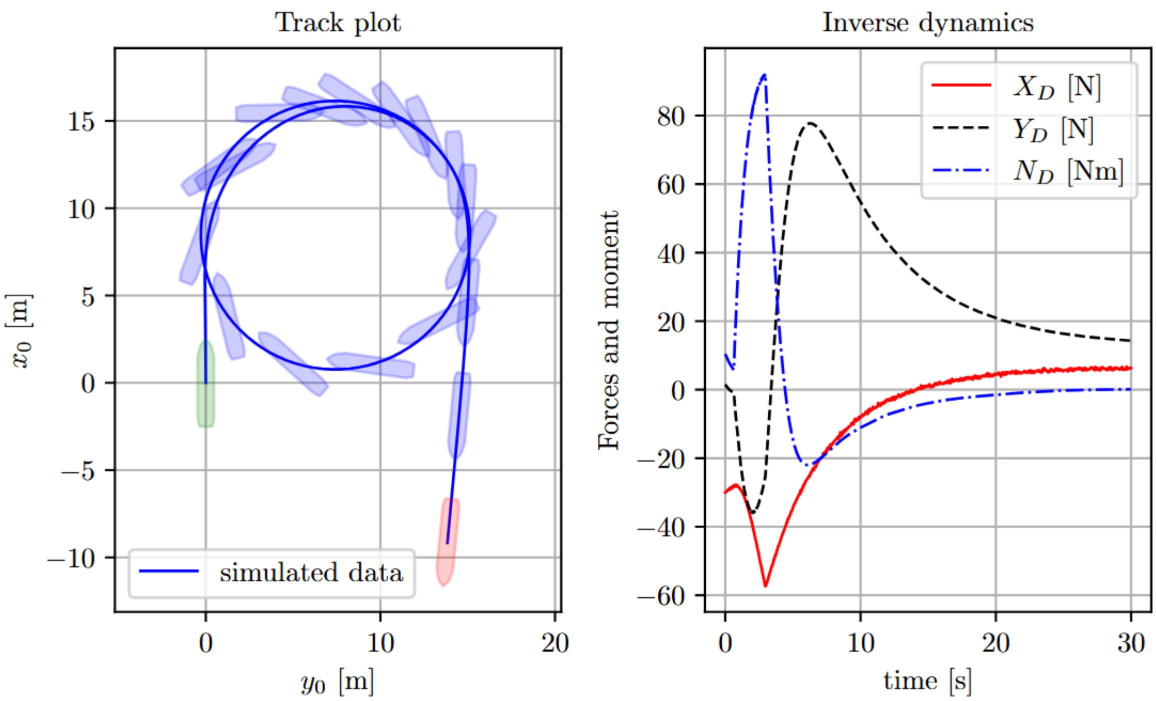

Figure 8 Forces and moments calculated with inverse dynamics on data from a turning circle test.

4 Results

The wPCC test case (Figure 9) is a ship that was designed for a wind-assisted propulsion system (WAPS) and can alter between a fully sailing mode, and a fully motoring mode, and in between. However, only the motoring mode was considered in this project. Because of the WAPS, the wPCC design differs slightly from conventional motoring cargo ship designs. The wPCC has two very large rudders, two to three times larger than needed for a conventional ship. System identification was conducted on data from free running model tests with the wPCC (Figure 9). The wPCC model test data was split into training-, validation-, and testing-sets as shown in Figure 10. The model structure was established by identifying various competing mathematical model structures on the training set and evaluating their accuracy on the validation set. The best performing model was retrained on all the data from the training and validation sets. The accuracy of this final model was evaluated with the test set, predicting the turning circle test as shown in Figure 11. The final model could estimate the turning circle tests with less than 5% deviation.

Figure 9 wPCC tested at RISE SSPA Maritime center. Copyright 2020 by RISE.

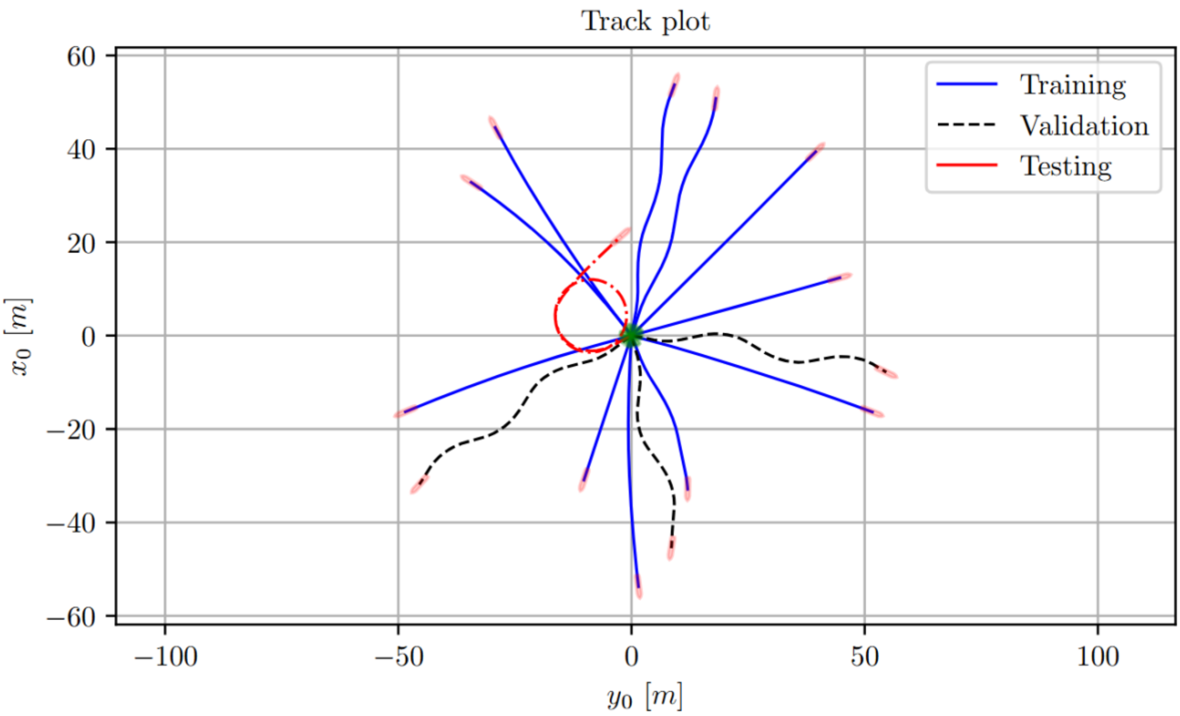

Figure 10 wPCC training, validation and testing datasets.

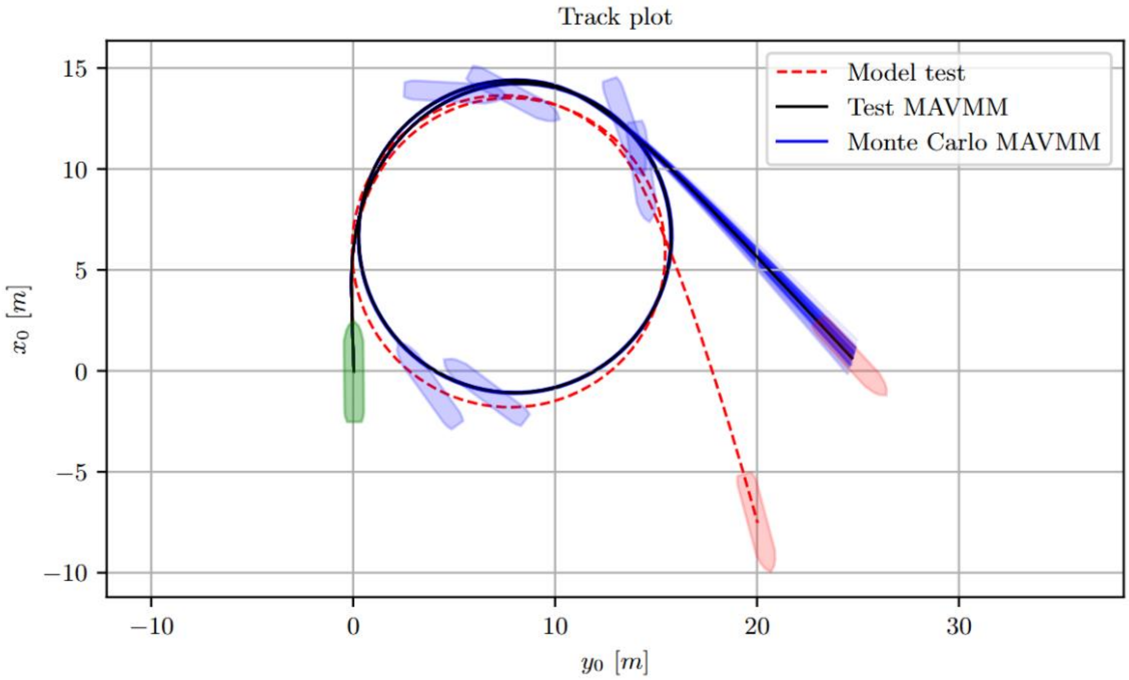

Figure 11 Turning circle test case for wPCC, track plots from model test and simulation.

However, it was found that the identified model was physically incorrect, as shown in Figure 13, despite yielding good results. Therefore, a physics-informed (PI) model was proposed, incorporating a semi-empirical rudder model. Figure 13 compares the forces from the PI model and the original physics-uninformed (PU) model. The identification of the PU model resulted in a physically incorrect decomposition between the hull yawing moment N_H and the rudder yawing moment N_R due to multicollinearity, as discussed in the introduction of this report. In contrast, the PI model correctly decomposed the rudder and hull forces. Additionally, the decomposition between drift-dependent hull forces $N_H(v)$ and yaw rate-dependent hull forces $N_H(r)$ was more accurate in the PI model compared to the PU model, as shown in Figure 13.

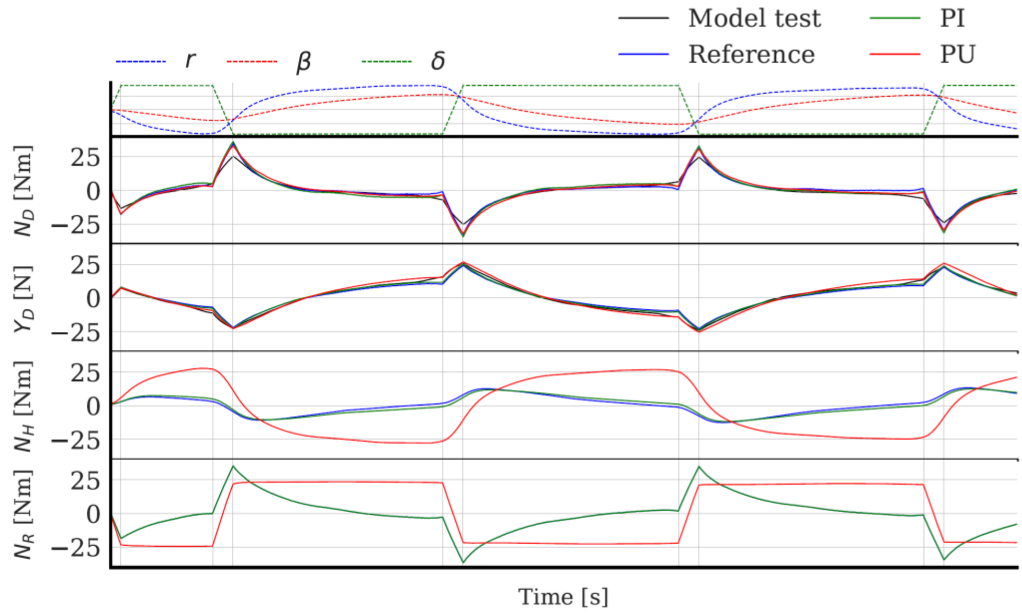

Figure 12 estimations of forces during a zigzag10/10 model test compared with model predictions.

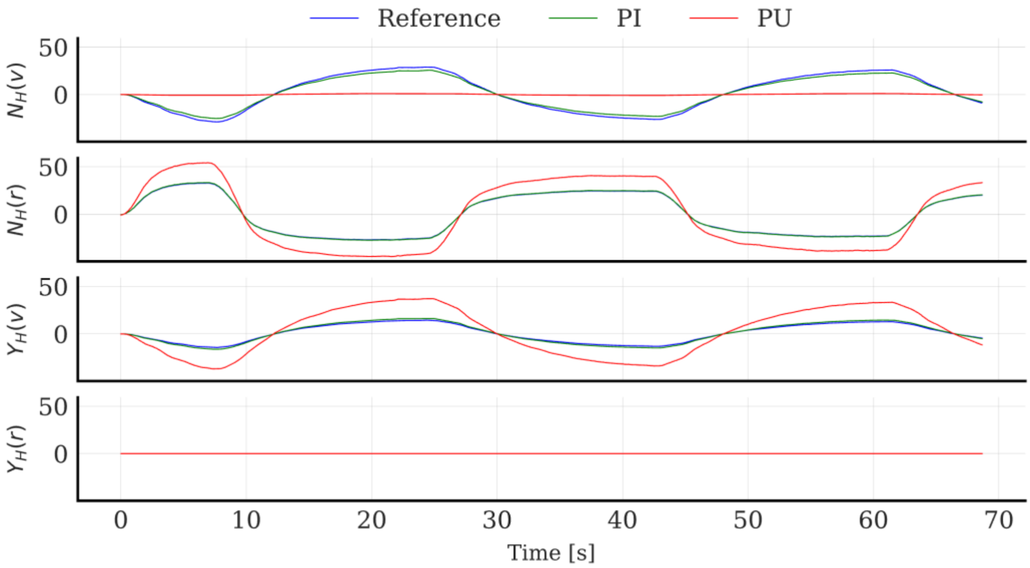

Figure 13 Decomposition of hull forces and moments during a zigzag20/20 test for parameters related to drift, yaw rate, and the prediction models.

System identification was also conducted on data from captive tests with another test case called Optiwise. This test case involved an ordinary VLCC tanker but with a larger rudder size adopted for WAPS. Significant effort was made to develop an accurate prediction model for the rudder forces. Based on the MMG original rudder model (Yasukawa and Yoshimura, 2015), an enhanced quadratic model was proposed. Figure 14 shows a comparison between the rudder forces measured during the Optiwise tests and the predictions from both the MMG original and the enhanced quadratic models. Some states were also calculated using CFD in the state VCTs. There was good agreement between the measured and predicted rudder forces.

The identified rudder models could be combined with a hull force prediction model to form a modular manoeuvring model for the entire ship. The total forces from this model were in good agreement with the inverse dynamics forces from the free-running model tests (FRMT), as shown in Figure 15. Additionally, zigzag tests were compared with closed-loop simulations using the developed models, as shown in Figure 16. The experiments and simulations were in good agreement for the zigzag 20/20 test, though there was slightly less agreement for the 10/10 test.

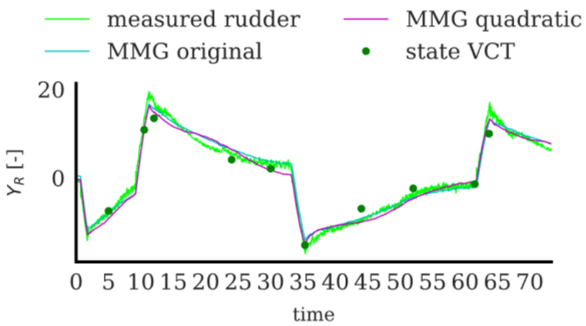

Figure 14 Rudder forces during a zigzag test compared to predictions with the MMG models.

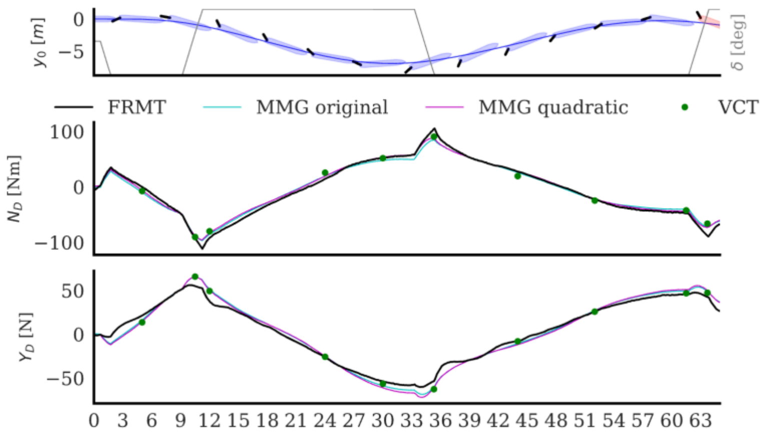

Figure 15 Inverse dynamics forces during the zigzag tests compared to predictions with the MMG models.

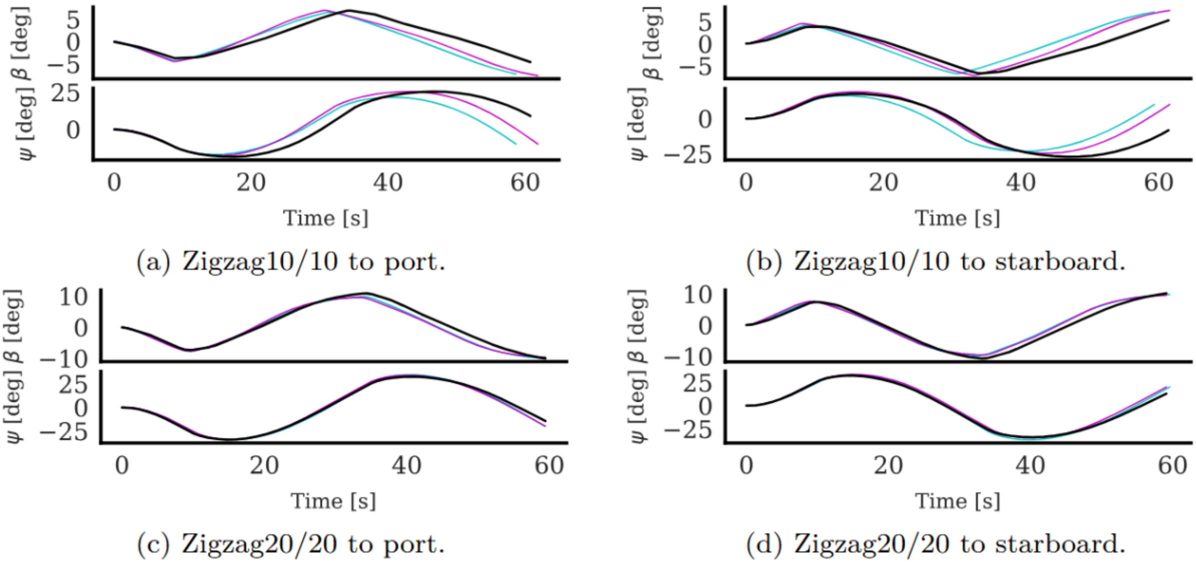

Figure 16 Comparison of zigzag tests between Optiwise experiments (black) and simulations with the MMG original (cyan) and MMG quadratic (purple).

5 Concluding remarks

This project explored the enhancement of ship manoeuvring models by integrating prior knowledge embedded in parametric model structures and semi-empirical formulas. The main conclusions are that physically accurate models can be derived from these structures when prior knowledge about ship hydrodynamics and semi-empirical formulas are incorporated, provided the observed data is correct and informative, as demonstrated with VCT data. It was also found that physically accurate models could not be identified from standard maneuvers due to insufficient informative data. However, incorporating a semi-empirical rudder model guided the identification process towards a more physically accurate model.

Key findings indicate that inverse dynamics regression is an efficient method for parameter identification in parametric models. The proposed quadratic model structure for roll motion demonstrates good generalization, and the new parameter identification method accurately predicts manoeuvring models from standard maneuvers. However, challenges with multicollinearity and the need for more informative data are highlighted. The study concludes that semi-empirical formulas can guide identification towards more physically correct models, and VCT can provide the necessary data for accurate model identification.

The implications of this research suggest that integrating semi-empirical rudder models and utilizing VCT can significantly enhance the accuracy and generalization of ship manoeuvring models, leading to more reliable and physically accurate simulations in maritime engineering.

5.1 Detailed report

This work has been carried out in the framework of a PhD thesis by Martin Alexandersson. The research project (DEMOPS) has been financed in two different stages (Part I, 2010-2023 and Part II ,2023-2025) financed by the Swedish Transport Administration, in the industry programme Sustainable shipping operated by Lighthouse. The detailed explanation of the methods and findings from this research project is reported in Martin Alexandersson's PhD thesis (Alexandersson, 2025) (https://research.chalmers.se/publication/545492).

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