ShipSIM: A Modelica Library for Ship Maneuverability Modeling and Simulation

Basilio Puente Varela [1] M. Dolores Fernández Ballesteros [1] M. Isabel Lamas Galdo [2] Luis Carral [3]

[1]PhD undergraduate, Universidade da Coruña, Spain, {basilio.puente,dolores.fernandez}@udc.es
[1]Ekium - Techno Pro Hispania S.L., Spain, {bpuente,mdfernandez}@tphispania.com
[2]Departamento de Ciencias de la Navegación e Ingeniería Marina, Universidade da Coruña, Spain, {isabel.lamas.galdo}@udc.es
[3]Departamento de Ingeniería Naval e Industrial, Universidade da Coruña, Spain, {l.carral}@udc.es

Abstract

This paper introduces the ShipSIM, a novel free (standard conforming) Modelica library for modeling and simulation of ship maneuverability. This first Modelica library in the field of ship propulsion and maneuverability provides the components and flexibility to model the ship propulsion, hydrostatics and hydrodynamics to develop ship maneuvering simulations fully compatible with the Modelica Standard Library components.

In this paper is presented the library's key features and structure and introduce the underlying physical and mathematical foundations and modeling approaches. In addition, current implementation status, applicability limits and future development is discussed.

The library development is coordinated by the authors and it is used in several MSc thesis. ShipSIM library is available on https://github.com/BasilioPV/ShipSIM

Keywords: Modelica Library, ship maneuverability, marine engineering, ShipSIM

1 Introduction

Navigation safety is essential for all ships and specially for those that carry dangerous goods. On this sense, maneuverability is recognised as an ability to avoid dangerous situations specially near ports, where the coast, traffic and harbour facilities produces significative hazards.

For this reason, the International Maritime Organization (IMO) was increasing the maneuvering requirements to ships by means of A.601(15) (Organization 1987) [1] and later by MSC.137(76) (Organization 2002a) [2] and their associated guidelines (Organization 2002b) [3] where mathematical models can be used to demonstrate manoeuvring compliance on design stages. In addition, the same mathematical models can be used to correct sea trials performed with environmental conditions that deviate to those indicated on the regulations. On this sense, the integration of 1D simulation on Model Based Systems Engineering (MBSE) is clearly an advantage on shipbuilding.

Computational Fluid Dynamics (CFD) has great relevance on marine industry and nowadays is essential to estimate ship resistance in conceptual and basic designs, prior to towing tank tests and, in some cases, replacing them. But CFD has the disadvantage of large computation time, more man hours to produce a model, and low reusability when compared with 1D simulation. On the other hand, CFD can capture small design details that 1D simulation parameter cannot and the results was in general more precise than 1D simulations, especially when flow shedding phenomena occurs.

Previous approaches on ship specific simulation libraries using Modelica was SEECAT[4] from Bureau Veritas (Marty et al. 2012). This library provides a full set of ship specific components to simulate a power plant from the energy and fuel consumption perspective on a determined route. The main difference with ShipSIM is that on SEECAT only 1DoF is modelled, so manoeuvrability simulations are not possible.

DNV R&D in Greece has developed COSSMOS[5] library in gPROMS language (Dimopoulos and Kakalis 2010)(Dimopoulos, Georgopoulou, et al. 2014) focused on process simulation of ship energy systems. This tool is used in several ship types, such as LNG carriers (Dimopoulos, Stefanatos, and Kakalis 2016) to analyse from process point of view the ship systems. COSSMOS does not provide movements or navigation simulation, so manoeuvring or alternative means of propulsion, such as wingsails, are not possible to simulate.

Other applications can be found in MANSIM software (Aksu and Türkay 2017), that uses the same methodology of ShipSIM, but it lacks connectivity with other components or software. This inconvenience is found in other commercial software, such as MARIN SHIPMA 7 or ProteusDS ShipMo3D toolset.

[1]A.601(15) Provisions and display of manoeuvring information on board ships, 1987
[2]MSC.137(76) Standards for ship manoeuvrability, 2002
[3]MSC/Circ. 1053 Explanatory notes to the standards for ship manoeuvrability, 2002
[4]Ship Energy Efficiency Calculation and Analysis Tool
[5]COmplex Ship Systems MOdelling and Simulation

The rise of the digital twin technology on shipbuilding industry creates the needs of develop simulation models that can run at a speed several times less than real time to aid the operators into their decisions (predictive) or check if the system behaviour is the expected (diagnostic). Ship systems are composed by several components from many manufacturers, so the simulation model needs to integrate component from different sources. For this reason, the use of Modelica Association technologies, such as FMI (Modelica Association 2014) Standard[6] enables reusability of components and efficient system simulation model development.

2 ShipSIM library

ShipSIM Modelica library start this development on early 2021 as an technology demonstrator of the use of Modelica(Modelica Association 2021) in maritime industry, where the digital twin technology was started to gain attention. On July 2021, a webpage[7] was created to spread the use of Modelica in this sector. On April 2023, the authors and other significant Modelica users found *Modelica User's Group of Spain*[8] to spread the use of Modelica languaje and associated technologies in Spanish.

This library is licensed under 3-clause BSD license and the latest ShipSIM library version is available on `https://github.com/BasilioPV/ShipSIM`

2.1 Overview

ShipSIM library is built on top of MSL multibody library (Otter, Elmqvist, and Mattsson 2003) to provide an easier and seamless integration with other components of the Modelica Standard Library. The library is extensively documented for each component, in both documentation section and source code, where description of variables and parameters and main equations comments aids to understand the inner working of the library. Additionally, some parameters default value expression was taken from literature to aid in modelling on conceptual stages or training, where only few data is available.

2.2 Modelica library structure

Library structure adheres to usual MSL structure, where the library is presented to the user with a users guide, license, main authors, release notes, references and contact points. Next on the library are the examples, which provide sample systems that uses the main ShipSIM components. Validation and debugging sections are provided to check the proper working of some models when validated against the literature or test data.

Components section provides the main models developed for this library: ship hydrostatics, inertia, hydrodynamics, propellers and rudders. These components are the core of the library that enables simulation of ship manoeuvring.

3 Methods

The authors of this library considers two main features that deviates from the usual mathematical models found on the literature.

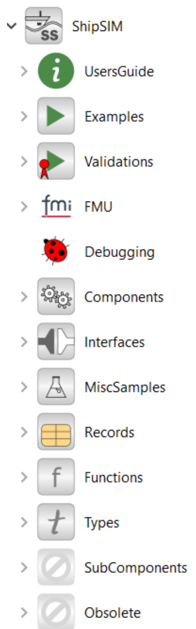

Figure 1. Main ShipSIM library structure.

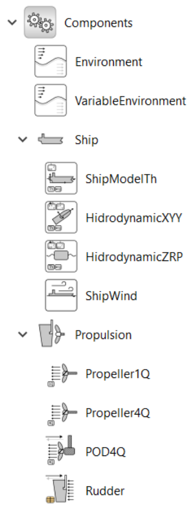

Figure 2. Hydrodynamics and propulsion components.

Usually ship movements are divided in two pair of 3DoF systems, to complete the 6DoF ship movement axis shown in Figure 3. The first one is the surge-sway-yaw, that represents the movement on the floatation plane, which is used for *manoeuvring* calculations. This 3DoF system has no restoring forces (*spring*) and only present *mass* and *damper* forces. The other 3DoF system is the roll-pitch-heave motion, which defines the *seakeeping* ability of the ship. These movements can be modeled as an *spring-mass-damper* system that oscillates around the equilibrium position.

The first feature is to provide a 6DoF enabled model from beginning, where the *manoeuvring* and *seakeeping* forces are modeled separately in order to enable only one 3DoF ability or both. This implementation requires to split the equivalent *mass-spring-damper* system into three main components:

1. Mass, inertia and hydrostatic restoring forces (corresponding to heave, pitch and roll movements)

[6] Functional Mock-up Interface
[7] *www.ShipTwin.com*, now offline and moved to *modelica-spain.org*
[8] *modelica-spain.org*

2. Hydrodynamic damping forces relative to maneuvering (corresponding to surge, sway and yaw movements)

3. Hydrodynamic damping forces relative to seakeeping (corresponding to roll, pitch and heave movements)

This decomposition enables that different methods can be implemented into the library in order to have components with several fidelity levels or adjust the behavioural equations in other situations, such as shallow waters.

Other main feature is the segregation of the rudder from the manoeuvring model. Usually, all papers treat both components together, but for a sake of clarity the best is to be splitted in order to model non-conventional propulsion systems. In addition, the ship connection is placed at the common ship axis origin (rudder stock end at baseline) instead of the middle of the ship or the centre of gravity. With this position is easier to add other ship systems (rudder, propeller, cranes, etc...) because their position onboard is commonly described using these axis reference.

3.1 Ship hydrostatics and inertia

To calculate the new position of the centre of buoyancy, small rotations around equilibrium flotation theory was used. From this approach, the centre of buoyancy rotates around the longitudinal and transverse metacentre of the ship. This is the usual way to calculate hydrostatics forces and moments (Lewis et al. 1988).

Inertia matrix of the ship is usually simplified to only the main three axis inertia, discarding any cross inertia.

Hydrostatic data depends of the middle draft of the ship. Values of displacement, centre of bouyancy and metacentre position was provided using a custom expandable polynomial fit, with real custom numbers for the exponents. Hydrostatic data needs to be fitted previously to this kind of equation to be used.

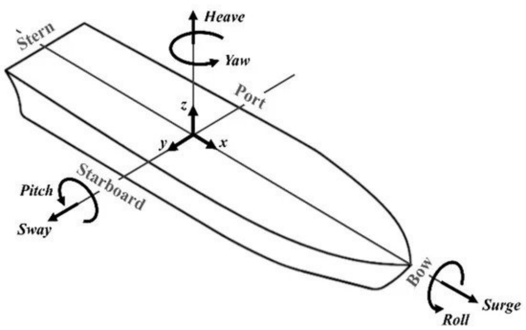

Figure 3. Ship movement axis.

3.2 Ship maneuvering hydrodynamics

Since the 1970's various mathematical models have been developed and validated to reproduce the ship motions during maneuvering (Norrbin 1970). Modern methods are based on the Maneuvering Modeling Group (MMG) standard methodology (Yoshimura 2005; Yasukawa 2015; Taimuri et al. 2020). This method accounts coupled effects from movements in different axis by polynomial functions where the coefficients can be obtained by standard tests.

This method is based on the following assumptions:

1. Hull in-plane forces are represented by quasi-steady flow reactions and described by non-dimensional coefficients referring to motion velocities and accelerations.

2. No shallow water effects are considered

3. Heave, pitch and roll motions are assumed to be small and represented by the linear relations of forces and motion components.

4. Memory effects are not taken under consideration.

Since mass and inertia effects are provided by other component, this component only accounts for the hydrodynamic force due to ship motion. According to MMG method (Yoshimura 2005; Yasukawa 2015), these in plane hull forces was defined by the following empirical equations:

$$X'_{Hull} = X'_{vv} v'^2 + X'_{vr} v' r' + X'_{rr} r'^2 + X'_{vvvv} v'^4 \quad (1)$$

$$Y'_{Hull} = Y'_v v' + Y'_r r' + Y'_{vvv} v'^3 + Y'_{vvr} v'^2 r' + Y'_{vrr} v' r'^2 + Y'_{rrr} r'^3 \quad (2)$$

$$N'_{Hull} = N'_v v' + N'_{vvr} v'^2 r' + N'_{vvv} v'^3 + N'_r r' + N'_{vrr} v' r'^2 + N'_{rrr} r'^3 \quad (3)$$

These equations provide the hydrodynamic forces as a function of several ship specific hydrodynamic parameters for surge ($X'_{vv}, X'_{vr}, X'_{rr}, X'_{vvvv}$), sway ($Y'_v, Y'_r, Y'_{vvv}, Y'_{vvr}, Y'_{vrr}, Y'_{rrr}$) and yaw ($N'_v, N'_{vvr}, N'_{vvv}, N'_r, N'_{vrr}, N'_{rrr}$), when multiplied to non-dimensional sway speed (v') and yaw (r'), raised to the power up to three. This methodology accounts for coupled response of the sway, surge and yaw movements. On MMG method, only the above mentioned coefficients were found relevant to define the behaviour of the ship when manoeuvring.

Ship resistance is modelled into the MMG method as a drag factor that multiplies the square of the vessel speed, to be added to the X'_{Hull} of Equation 1. Ship resistance is usually obtained from CFD studies and towing tank test. The results of ship resistance versus speed does not fit exactly with a square function. For this reason, on this library a custom polynomial function is introduced to fit the resistance results and enhance the precision. The end user shall perform a curve regression fit on the resistance curve data obtained by CFD or towing tank test, by using a polynomial function where the number of terms and power factors are not restricted to get a best fit of the data.

Hydrodynamics coefficients can be obtained from PMM (Conference 2017) [9] tests for a given ship. By default, this library provides an estimation based on several literature sources (Taimuri et al. 2020) that can be used for large ships with one rudder-propeller configuration in advance speed.

3.3 Ship propulsion and steering

Over years, Wageningen B-series propellers was used as default propellers on conceptual designs. The availability of propeller data and geometry makes easy to implement into simulation software (Oosterveld and Oossanen 1975). On this library, Wageningen B-series was implemented in both one-quadrant (Oosterveld and Oossanen 1975) and four-quadrant (Roddy, Hess, and Faller 2006) behaviour. One-quadrant represent the usual situation where the propeller has positive advance ratio and the ship is moving ahead. On the other hand, four-quadrant depends on the blade attack angle, and can be used for all the propeller situations, such as reversed thrust in a crash stop.

[9] Planar Motion Mechanism tests, see *ITTC Procedures 7.5-02-06-02 Rev05*

On this component, main propeller characteristics are defined, such as diameter, pitch ratio, number of blades and blade area ratio to select the Wageningen B-series propeller from the catalogue. Propeller inertia and added mass inertia can be also defined. By default, these parameters are calculated using built in correlation formulas for this kind of propellers.

To correct the behaviour of the propeller from open water test to propeller behind hull arrangement, coefficients of wake fraction, thrust deduction and rotative relative are used. Wake fraction represents the percentage of the ship advance speed that reach the propeller disc due to turbulence produced by ship hull. When the propeller is producing thrust, the water is accelerated by suction just ahead of the propeller disc. On this situation, the hull drag on the small part of the hull near the propeller is increased and treated as a propeller thrust deduction. Finally, the ship's hull is surrounding the propeller by above, which usually benefits the propeller working, produces a change in the propeller efficiency accounted with the rotative relative factor.

By default, these three factors are calculated using empirical formulaes (Harvald 1983; Holtrop 1984; Brix 1993) with main ship dimensions, but letting to the final user substitute for real values obtained from self-propulsion tests or CFD.

Finally, the water stream accelerated by the propeller directly impacts on the rudder, modifying the water speed on a determined zone. This rudder zone affected by the propeller is calculated by using flow straightening theory (*vena contracta*) (Taimuri et al. 2020).

Figure 4 shows the representation of rudder forces and flow velocity at the rudder plane. On this figure $V_R, V_{X,R}$ and $V_{Y,R}$ are the flow velocity of the water to the rudder, and their components in X and Y reference axis. The flow drift angle at rudder, β_R, is represented among with the rudder angle δ. Then, the hydrodynamic profile of the rudder will produce a lift force represented by $Y_r ud$.

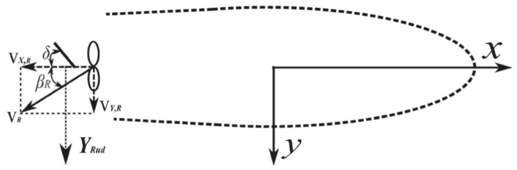

Figure 4. Representation of the rudder forces and flow velocity at the rudder plane. (Taimuri et al. 2020)

Ship steering model is composed by an hydrodynamic profile that rotates about a vertical axis, producing both lift and drag (Liu, Quadvlieg, and Hekkenberg 2016). This library contains several NACA 00xx symmetrical profiles lift and drag data, obtained for a range of Reynolds numbers and for attack angles from zero to 180 degrees (Sheldahl and Klimas 1981). In addition, a quick check of cavitation warning was implemented (Burrill 1955).

The water speed and direction is corrected with the propeller thrust affected zone to account for propeller-rudder interaction effect. In the relevant literature (Taimuri et al. 2020), lift reduction factor in way of the slip-stream radius is included. In a same manner, the influence of the hull ahead of the rudder can be included in the rudder force as a factor that represents the increase of the lateral force due to the presence of the hull above the rudder root. Also, the flow passing through the hull of the ship reduces the angle of attack on the rudder. This effect is usually accounted using flow straightening coefficient. This library tends to implement an interchangeable rudder profile data, that instead use a unique coefficient for lift and drag, uses a results table for full 180 degree angle of attack and several Reynolds number. For this reason, direct implementation of the formulae provided in the literature is not possible and adaptations are needed. At the time of this paper was written, neither lift reduction factor, increase of lateral force and flow straightening coefficient was included into the models.

3.4 Environment forces

Current speed and direction is used to calculate the relative water speed and direction and, therefore, include the current into the simulation. Apparent wind forces, composed by external wind speed and direction and ship's speed, can be estimated by the method presented in (Fujiwara, Ueno, and Nimura 1998). On this method, windage areas of the ship over the floatation and their respective centers of gravity was used. At the time of this paper was written, no sea waves forces was included into the library.

4 Application

4.1 Case study description

Turning circle is a classical maneuvering test that consist of turn the rudder up to maximum angle when the ship is navigating at full speed. The ships starts to navigate in circles where the following conditions shall be met (Organization 2002a):

1. The test speed (V) used in the Standards is a speed of at least 90% of the ship's speed corresponding to 85% of the maximum engine output.

2. Turning circle manoeuvre is the manoeuvre to be performed to both starboard and port with 35° rudder angle or the maximum rudder angle permissible at the test speed, following a steady approach with zero yaw rate.

3. The test shall be performed at deep, unrestricted water; calm environment; full load (summer load line draught), even keel condition and steady approach at the test speed.

Under the above conditions, the following criteria shall be complied:

1. Advance is the distance travelled in the direction of the original course by the midship point of a ship from the position at which the rudder order is given to the position at which the heading has changed 90° from the original course. The advance should not exceed 4.5 ship lengths (L).

2. Tactical diameter is the distance travelled by the midship point of a ship from the position at which the rudder order is given to the position at which the heading has changed 180° from the original course. It is measured in a direction perpendicular to the original heading of the ship. The tactical diameter should not exceed 5 ship lengths in the turning circle manoeuvre.

Figure 5 shows a graphical description of the definitions used above.

The ship selected for this example is a single shaft and rudder propulsion configuration. Main ship dimensions are described in

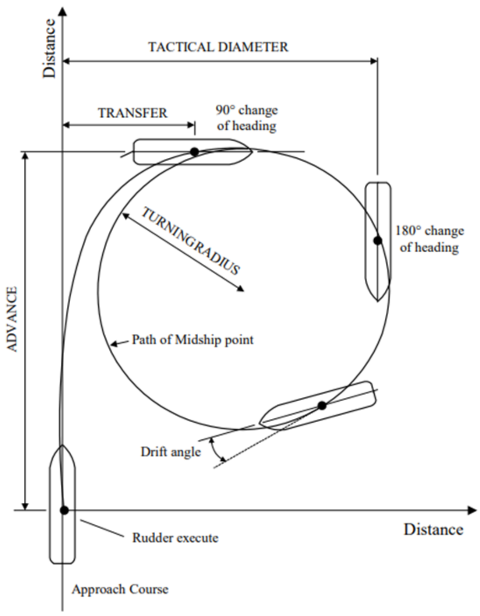

Figure 5. Turning circle manoeuvre. (Organization 2002a)

the Table 1. Hydrostatics was calculated by designing a custom hull lines with the main data shown in the table and fitting the values of displacement, metacentre radious and bouyance centre with polymonial fit. Windage areas was also included in the simulation model.

Propeller characteristics are defined in the Table 2, where a *Wageningen-B* propeller type was selected. Similarly, the rudder selected is a *NACA 0015* profile with a chord of 2 metres and a span of 3.5 meters. The rate of turn of the rudder comply with IMO regulations and was set to 2.5º/s, with a maximum rudder angle of 35º. Table 3 shows rudder main data.

Table 1. Main ship characteristics

Parameter	*Value*
Length	100 m
Beam	20 m
Draft	4 m
Block coefficient	0.693
Displacement	5,681ton
Num. of propellers	1
Num. of rudders	1
Trans. wind area	316 m^2
Lateral wind area	1,337 m^2

Figure 6 shows the simulation model diagram developed with ShipSIM library. The ship is modeled using three components. The first component is the mass, inertia and floatation forces that define the static floatation forces and inertia. The second one is the hydrodynamic forces, that define the forces induced by the movement of the ship in the water. In addition, a wind resistance force is added to the simulation. This wind force is lesser when comparing to the hull hydrodynamics forces.

The propulsion system is modeled using a four-quadrant propeller coupled with a rudder. The propeller speed is controlled by a constant signal and the rudder angle is controlled also by a constant signal that actuates from the beginning of the simulation.

Table 2. Propeller characteristics

Parameter	*Value*
Diameter	4 m
Type	*Wageningen-B*
Num. blades	4
Blade area ratio	1.0
Pitch diameter ratio	1.0

Table 3. Rudder characteristics

Parameter	*Value*
Chord	2 m
Span	3.5 m
Profile	*NACA 0015*
Rate of turn	$2.5^{o}/s$
Max. rudder angle	35º

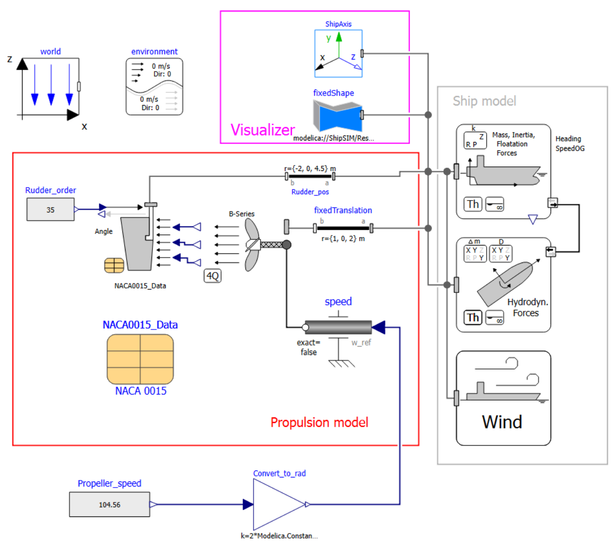

Figure 6. Simulation model diagram.

The ship is navigating at steady state with constant propeller r.p.m. where the rudder order is set to maximum rudder angle. In this condition, the rudder starts to rotate from the initial zero angle to maximum. Then, the ship start to turn and after a transient movement the ship start to navigate in circles, with a constant diameter.

4.2 Results and discussion

The simulation setup is set to a total time of 800 seconds with a time step of 0.2 seconds, using DASSL integration method with variable step size and order on OpenModelica v1.25.0. After compilation, the simulation time lasts less than 2 seconds, thus 400x faster than real time. Figure 7 shows the turning circle

Table 4. Initial conditions

Parameter	*Value*
Ship speed	13 *knot*
Propeller speed	104.56 *r.p.m.*
Rudder angle	0º
Initial rudder angle order	35º

result from this simulation.

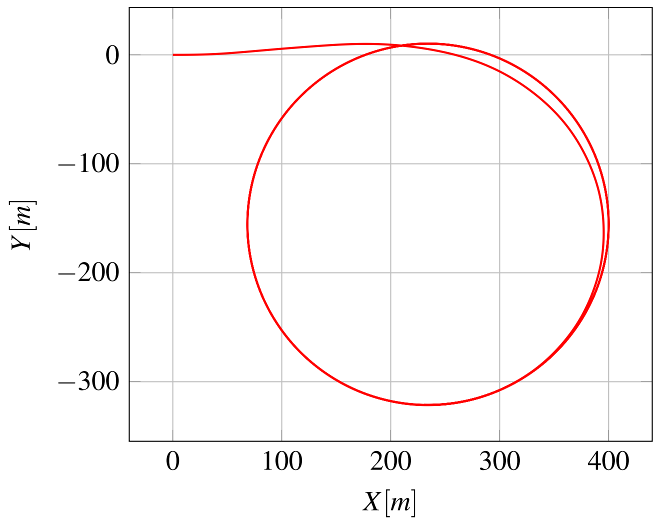

Figure 7. Turning circle test.

To check the compliance with the IMO regulations, Figure 8 shows the heading angle (Yaw) in red, surge position (X) in blue and sway position (Y) in green. As explained before, when the heading angle is equal to 90º, at 65.6 sec, the advance is 361.2 m (less than 4.5 times the ship length). In a similar way, when the heading angle is equal to 180º, at 138.8 sec, the tactical diameter is 291.3 m (less than 5 times the ship length).

This example demonstrate the benefits of perform quick simulation on conceptual design phase of ships to comply with IMO regulations regarding manoeuvrability.

5 Conclusion and outlook

This paper shows a proof of concept for the use of Modelica language into marine industry simulations. After describing the main maneuverability methods an application case is developed and their results presented. Some components need to have further development and validation to achieve the quality required to be used in real scenarios. This paper proves that physics 1D simulation is a reliable and fast method to provide simulation models to digital twin technologies, because the fast computation enables predictive usage.

The development of these physical models in Modelica has the big advantage of the acausal model definition, which enables a higher reusability and is easier to describe the equations that governs the behaviour of each model. On the other hand, collaboration between professionals is a key factor to develop high quality simulation models.

Acknowledgements

The diffusion of this work has been supported by Ekium - Techno Pro Hispania S.L.

The authors would also like to thank to the MSc students of Universidade da Coruña and Universidad Politécnica de Madrid for their support developing some components and using this library on their MSc thesis.

References

Aksu, Sinan and Semih Türkay (2017). *Theoretical Background and Application of MANSIM for Ship Maneuvering Simulations*. Accessed: 2025-07-12. URL: https://mansim.org/articles/Theoretical%20background%20and%20application%20of%20MANSIM%20for%20ship%20maneuvering%20simulations.pdf.

Brix, J. (1993). *Manoeuvring Technical Manual*. Hamburg: Seehafen Verlag.

Burrill, L.C. (1955). "The Phenomenon of Cavitation". In: *International Shipbuilding Progress* 2.15.

Conference, International Towing Tank (2017). *7.5-02-06-02 Rev.05 Procedure Captive Model Test*.

Dimopoulos, George G., Chariklia A. Georgopoulou, et al. (2014). "A general-purpose process modelling framework for marine energy systems". In: *Energy Conversion and Management* 86, pp. 325–339. DOI: 10.1016/j.enconman.2014.04.046.

Dimopoulos, George G. and Nikolaos M. P. Kakalis (2010). "An integrated modelling framework for the design, operation and control of marine energy systems". In: *26th CIMAC World Congress*. Bergen, Norway.

Dimopoulos, George G., Iason V. Stefanatos, and Nikolaos M. P. Kakalis (2016-09). "A process modelling approach to the evaluation of ship machinery configuration alternatives of LNG carriers". In: *International Journal of Thermodynamics* 19.3, pp. 146–156. DOI: 10.5541/ijot.5000156256.

Fujiwara, T., M. Ueno, and T. Nimura (1998-01). "An estimation method of wind forces and moments acting on ships". In: *Journal of the Society of Naval Architects of Japan*. DOI: 10.2534/jjasnaoe1968.1998.77.

Harvald, S.A. (1983). *Resistance and Propulsion of Ships*. Wiley. ISBN: 0-89464-754-7.

Holtrop, J. (1984). "A Statistical Re-analysis of Resistance and Propulsion Data". In: *International Shipbuilding Progress* 31.

Lewis, Edward V. et al. (1988). *Principles of Naval Architecture*. Second Revision. SNAME.

Liu, Jialun, Frans Quadvlieg, and Robert Hekkenberg (2016). "Impacts of the rudder profile on manoeuvring performance of ships". In: *Ocean Engineering*. DOI: 10.1016/j.oceaneng.2016.07.064.

Marty, Pierre et al. (2012-01). "Modelling of energy flows and fuel consumption on board ships: Application to a large modern cruise vessel and comparison with sea monitoring data". In: *Proceedings of the 11th International Marine Design Conference*. Bureau Veritas / STX France. Glasgow, UK.

Modelica Association (2014-07). *Functional Mock-up Interface for Model Exchange and Co-Simulation Version 2.0*. Tech. rep. Linköping: Modelica Association. URL: https://fmi-standard.org.

Modelica Association (2021-02). *Modelica – A Unified Object-Oriented Language for Systems Modeling. Language Specification Version 3.5*. Tech. rep. Linköping: Modelica Associa-

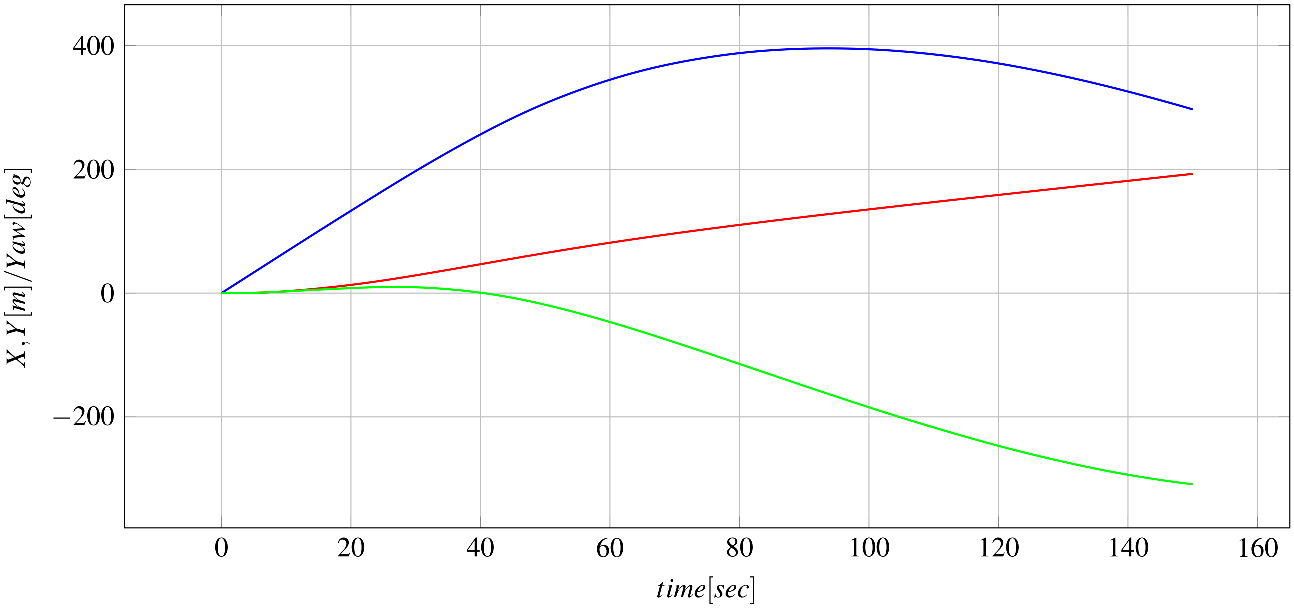

Figure 8. Turning circle test results in yaw, advance and tactical diameter.

tion. URL: https://specification.modelica.org/maint/3.5/MLS.html.

Norrbin, N.H. (1970). "Theory and observations on the use of a mathematical model for ship manoeuvring in deep and confined waters". In: *Proceedings of the 8th Symposium on Naval Hydrodynamics, Pasadena*.

Oosterveld, M.W.C. and P. Van Oossanen (1975-07). "Further computer-analyzed data of the Wageningen B-screw series". In: *International Shipbuilding Progress* 22.251.

Organization, International Maritime (1987). *Res. A.601(15) Provision and display of manoeuvring information on board ships*.

Organization, International Maritime (2002a). *MSC.137(76) Standards for ship manoeuvrability*.

Organization, International Maritime (2002b). *MSC/Circ. 1053 Explanatory notes to the standards for ship manoeuvrability*.

Otter, M., H. Elmqvist, and S.E. Mattsson (2003). "Proceedings of the 3rd International Modelica Conference". In.

Roddy, Robert F., David E. Hess, and Will Faller (2006-04). *Neural network predictions of the 4-quadrant Wageningen propeller series*. Tech. rep. NSWCCD-50-TR-2006/004. David Taylor Model Basin.

Sheldahl, Robert E. and Paul C. Klimas (1981-03). *Aerodynamic Characteristics of Seven Symmetrical Airfoil Sections Through 180-Degree Angle of Attack for Use in Aerodynamic Analysis of Vertical Axis Wind Turbines*. Tech. rep. SAND8O-2144. Sandia National Laboratories. DOI: 10.2172/6548367.

Taimuri, Ghalib et al. (2020). "A 6-DoF maneuvering model for the rapid estimation of hydrodynamic actions in deep and shallow waters". In: *Ocean Engineering*. DOI: 10.1016/j.oceaneng.2020.108103.

Yasukawa, Y. Yoshimura h. (2015). "Introduction of MMG standard method for ship maneuvering predictions". In: *Journal of Marine Science and Technology* 20, pp. 37–52. DOI: 10.1007/s00773-014-0293-y. URL: https://link.springer.com/article/10.1007/s00773-014-0293-y.

Yoshimura, Yasuo (2005). "Mathematical Model for Manoeuvring Ship Motion (MMG Model)". In: *Workshop on Mathematical Models for Operations involving Ship-Ship Interaction, Tokyo*.