Ship maneuverability modeling for Autonomous Navigation

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***Abstract*— Maritime Autonomous Surface Ships (MASS) have great potential, representing a significant advancement in maritime technology with promises of enhanced efficiency, safety, and operational flexibility. The primary technical objective is to improve life safety by reducing human error. This paper contributes by developing a simplified maneuverability simulation model specifically for MASS. This model strikes a balance between complexity and computational efficiency, crucial for optimizing control strategies and ensuring reliable autonomous navigation while accounting for the real maneuvering capabilities of MASS. The developed 3-degree of freedom (DOF) simplified model is compared with a reference complex model to assess performance under defined conditions. The analysis focuses on integrating the model into route planning and automatic motion control systems to optimize vessel design and ensure operational safety. Simulation results from both models are compared using typical sea trials maneuvers, such as ZIG-ZAG and turning circles, with rudder angles up to 20°. These simulations demonstrate the simplified model's accuracy and computational efficiency in predicting vessel behavior under specific conditions.**

Keywords—Autonomous Navigation, Ship maneuverability modeling, USV, MASS, naval ships

I. Introduction

Describing the maneuverability of a vessel is crucial for various applications, particularly for optimizing the control system of Maritime Autonomous Surface Ships (MASS) or Unmanned Surface Vehicles in general (USVs). The controlling algorithm and philosophy for autonomous vessels is complex, as it must account for numerous variables, scenarios, and safety considerations to ensure the reliable and safe operation of the vessel [3]. This complexity stems from the need for real-time decisions in complex dynamic scenarios, including maneuvers of the vessel at constant speed, speed variation, the effect of the environmental forces (waves, currents, and wind), or a combination of those. For the need to have a safe, stable, and reliable model in all the previous conditions with standard computational power, it's necessary to simplify the algorithm as far as possible. By simplifying and optimizing the model, we can reduce the likelihood of computational errors, improve the algorithm's stability, and enhance the predictability of MASS behavior.

The most complex and close to reality ship's manoeuvrability model is commonly recognized as a rigid body with 6 degrees of freedom (includes the motions of surge, sway, heave, roll, pitch, and yaw) [16]. In 1964, Abkowitz [1] simplified the model using a third-order Taylor expansion, where the hull, rudder, and propellers are modeled as distinct components of the rigid body [15]. Forces and moments applied on the rigid body are measured or calculated to predict the ship's movements. The unified theory was applied to model loads and motions in the 3 DOF model [10] taking into account only the surge, sway, and yaw motions. For solve the problem of the autopilot system, a response model by Nomoto [14] relating changes in the ship's heading to the rudder angle with 1 DOF was introduced. Various scientific approaches have been proposed for reactive collision avoidance in marine vessels, including Dijkstra's algorithm [7], visibility graphs [6], rapidly exploring random trees (RRT) [11], potential field [18] and population-based heuristics [5]. A common method in the literature to describe a ship's route or maneuvers is through a sequence of waypoints [3] [9]. Most of these algorithms don't take into account the real maneuvering capabilities of the MASS, imposing only maximum curvature radii constraint to define the spectrum of possible trajectories [17] [2]. Therefore, this paper aims to identify a maneuverability simulation model that offers a good compromise between model complexity and the fidelity of results, for effective control of a MASS vessel during the navigation phase in a time domain simulation.

II. Methodology and Simulation

One of the requirements to control MASS includes the integration between route planning and automatic motion control. In the design phase, understanding the maneuverability of the vessel is essential to evaluate the geometrical constraints of the planned route due to the vessel dynamic. Simulation has been widely used in ship control system design [12], [4]. The maneuverability model have to accurately simulate all the possible maneuvers to provide designers with reliable data to optimize hull design, propulsion, and steering system and identify the geometrical constraints for the route planning. During navigation, the maneuverability model becomes a core component of the vessel's control system. It is an active role that integrates all the vessel motion data with the route planning, provides real-time data that allows the mass to control the vessel's trajectory and propulsion setpoint. This integration ensures that the MASS can adapt to changing environmental conditions and potential navigational hazards, maintaining track accuracy and operational safety. To address these needs, a new 3 DOF maneuverability model based on a few essential parameters has been developed with the aim of reducing the total computational power and increase the stability of the MASS algorithm. The new compact algorithm is compared with a well-validated more complex maneuverability model described in [8] and validated in full scale during the control system tests [12]. The problem of ship's maneuverability models is widely studied, and supported by a rich body of literature. The vessel maneuverability characteristics vary at different speeds and different manoeuvrability models must be considered. We can identify 2 main different model families:

- "medium-high speed" maneuverability model: where the head speed of the vessel is greater than the other's velocity due to the ship's motion.

- "zero–low speed" maneuverability model: the ahead speed is not the prevalent motion of the vessel.

The maneuverability models where the head speed of the vessel is greater than the other's velocity due to the ship's motion, are widely used to evaluate the maneuvering performance of ships to verify the compliance with Resolution MSC.137(76) - Standards for Ship Manoeuvrability and to assist those responsible for the design of the vessel. The condition where the ahead speed is not the prevalent motion of the vessel requires different models that allow to consideration of other hydrodynamical effects on the hull. These models are used for Dynamic Positioning problems or to simulate berthing operations. The aim is to identify the most suitable maneuverability model for the MASS control algorithm: we are now focusing only on the first family maneuverability models. The MASS taken into account has a traditional propulsion and steering system (single propeller and single rudder behind the propeller itself). The model wants to be optimized for standard maneuvering and not for emergency collision avoidance maneuvers and consequently the model is evaluated with the condition of a maximum rudder angle of 20°. The hydrodynamic forces implemented in the model take into account only the linear coefficient due to the motion of sway and yaw (1, 2):

$$YAW_{moment} = N_v v + N_r r, \quad (1)$$

$$SWAY_{force} = Y_v v + (Y_r - \Delta')r. \quad (2)$$

The reference system adopted, the definition of the directions, displacements, speed, and acceleration is reported in Figure 1.

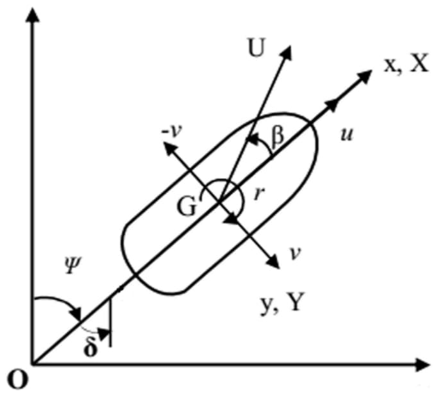

Fig. 1. Coordinate and reference system

Also, the rudder forces are described considering only linear coefficient, a good approximation in case of rudder angles less than 20° as for the aim of this maneuvering model; following the equation considered in the model (3, 4):

$$Y_{rudder} = Y_\delta \delta, \quad (3)$$

$$N_{rudder} = -\tfrac{1}{2} Y_\delta \delta. \quad (4)$$

It's possible to calculate the total forces acting on the vessel due to the rudder and hydrodynamic effect and the sway and yaw acceleration as follows (5-8):

$$Y_{TOT} = Y_{rudder} + SWAY_{force}, \quad (5)$$

$$N_{TOT} = N_{rudder} + YAW_{moment}. \quad (6)$$

$$\dot{v} = \frac{Y_\delta \delta + Y_v v + (Y_r - \Delta')r}{-Y_{\dot{v}} + \Delta'}, \quad (7)$$

$$\dot{r} = \frac{N_\delta \delta + N_v v + N_r r}{-N_{\dot{r}} + I_{zz}}. \quad (8)$$

Defined the acceleration and the velocities for integration the model is solved. Define the other parameter (i.e. position, route angle) it's a trigonometric/cinematic calculation. It is considered a constant advance speed "u". This is the most important simplification: in a real vessel's maneuverability the drifting configuration of the hull creates a lateral force, thus necessarily increasing resistance and consequently reducing the longitudinal speed at a constant number of propeller revolutions/telegraph level input. Due to the non-uniqueness of the solution to the vessel maneuverability problem, a similar dynamic behavior can be simulated with different subdivisions of the forces acting on the hull on linear and non-linear hydrodynamic coefficients.

The reference model, described in [12], accounts for a more elaborate force computation due to the availability of model scale test data and no constraints on computation time. Total force is computed as the sum of hull hydrodynamic forces, propeller forces, rudder forces, and environmental forces. Hull force accounts for linear as well as nonlinear damping effects. Propeller forces are computed by simulating the complete drive train and its control. Rudder forces are computed taking into account the rudder position with respect to the hull reference frame and the effects of the propeller wake. Environmental forces are only accounted for as an additional hull drag. For the comparison for the two models a 130-meter long navy vessel has been considered. All the hydrodynamic data of the hull, the rudder, and the propulsion system, are assumed as described in [12] In the performed simulations, have been also considered maneuvers highly affected by non-linear effects (i.e. the turning circle and the 20/20 ZIG-ZAG maneuvers), while for better simulate the maneuvering capabilities of the MASS during it's operational life a 10/10 ZIG ZAG maneuver has been simulated.

The 10/10 ZIG-ZAG test is the maneuver where a defined rudder angle (10°) to either side when a known heading rotation (10°) from the initial heading is reached. During the test, the initial turning time, yaw checking time, and overshoot angle due to the rotation inertia of the ship. For a better simulation and measurement, the simulation manoeuvre starts after a steady approach. Then the rudder is set over to starboard at 10° (first execute) and in the moment that the heading angle of the ship is 10° from the initial course, the rudder angle is reversed to the same set point value but to port (second execute). After that opposite helm was applied but the ship due to its inertia continues turning in the original direction (overshoot) but decreasing the turning speed up to the yaw direction changes rotation and due to the continuous rudder effect, the ship turns again to port. Again, when the compass is 10° over the initial route, the rudder is moved to starboard (third execute). The 20/20 ZIG-ZAG test is carried out with the same procedure but with a rudder angle set point of 20° and the reversing is applied at the change of heading of 20°.

III. Results

The core of this work is the comparison of the results obtained with the two models, on the same vessel, modeling the same real-navigation scenarios. Some typical sea trial maneuvers ZIG-ZAG and turning circles with a rudder angle limited to 10° and 20° to evaluate the model accuracy in maneuvers closest to a real scenario have been simulated. In the following plot are shown part of the result obtained. The first simulation is a ZIG ZAG manoeuvre with a rudder angle of 10°. Here Figure 2 illustrates the ship trajectory, with the simplified model represented in blue and the complex model in red. The difference between the two trajectories during the maneuver is slightly small during the initial part of the maneuver. The lateral displacement during the maneuver evaluated with the developed model is 0,66 times the length of the ship and it's about 15% greater compared to the value obtained with the reference model equal to 0.57L. Also,

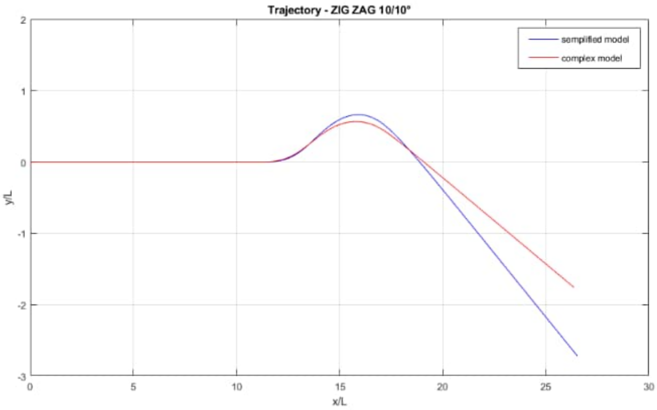

Fig. 2. Trajectory - ZIG/ZAG 10/10

Figure 3 shows the time history of the rudder (same input algorithm for the two models), the vessel speed, the rotation speed, and the angle of rotation of the bow concerning the initial rectilinear motion. The overshoot angle calculated with the developed model due to the rotation inertia of the ship is equal to 16.1° while the same parameter evaluated with the reference model is equal to 13.7°.

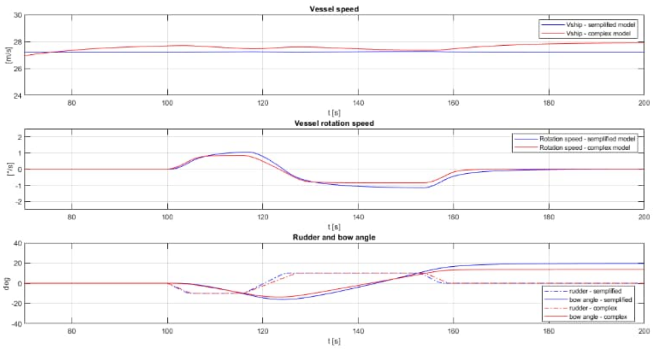

Fig. 3. Velocity and rudder angle - ZIG/ZAG 10/10

Figures 4 and 5 illustrate the same parameter simulated in the same maneuver with a rudder setpoint of 20°. The overshoot angle estimated with the developed model is equal to 32.5° and 30.6° obtained with the reference one. The lateral displacement during the maneuver evaluated with the developed model is 1.85L and it's 20% greater than the value obtained with the reference model equal to 1.55L.

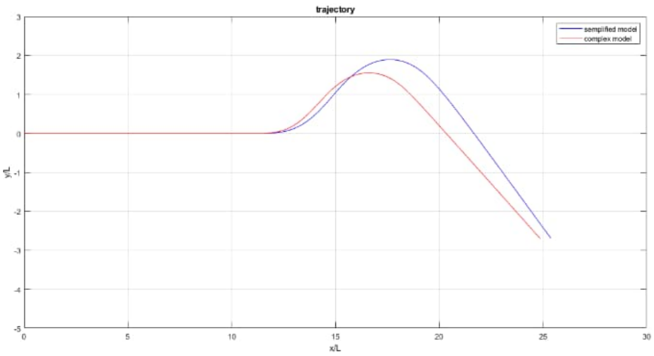

Fig. 4. Trajectory - ZIG/ZAG 20/20

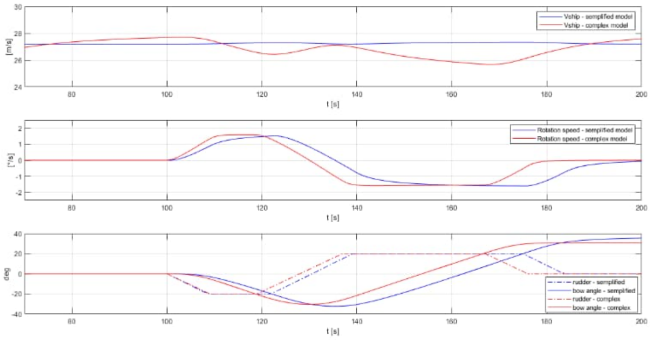

Fig. 5. Velocity and rudder angle - ZIG/ZAG 20/20

IV. CONCLUSION

Autonomous vessels are considered a big step forward in shipping to enhance navigation safety. The autonomous navigation requires a huge effort in developing control algorithms able to handle all possible scenario in a safe way and simulation is the appropriate tool to investigate the phenomena. The paper shows a simplified model to represents the overall ship maneuvering characteristics. specifically, we show that under certain assumptions and operating conditions, the simplified model provides sufficiently accurate predictions of vessel behavior. By presenting these results, we contribute to the ongoing discourse on maneuverability modeling and control strategies for autonomous surface vessels. Our results offer practical insights into the design and implementation of control systems for MASS, emphasizing the importance of balancing model complexity with computational efficiency and real-world applicability.

REFERENCES

[1] Abkowitz, M. A. (1964). Lectures on Ship Hydrodynamics - Steering and Maneuverability. Technical Report Hy-5. Hydro- and Aerodynamic's Laboratory. Lyngby, Denmark.

[2] Alessandri A., Donnarumma S., Vignolo S., Figari M., Martelli M., Chiti R., Sebastiani L., System control design of autopilot and speed pilot for a patrol vessel by using lmis, (2015) Towards Green Marine Technology and Transport - Proceedings of the 16th International Congress of the International Maritime Association of the Mediterranean, IMAM 2015, pp. 577 - 583, DOI: 10.1201/b18855-76

[3] Martin Alexandersson, Daiyong Zhang, Wengang Mao & Jonas W. Ringsberg (2022): A comparison of ship manoeuvrability models to approximate ship navigation trajectories, Ships and Offshore Structures, DOI: 10.1080/17445302.2022.2067409

[4] Altosole M., Benvenuto G., Figari M., Campora U., Bagnasco A., D'Arco S., Giuliano M., Giuffra V., Spadoni A., Zanichelli A., Michetti S., Ratto M., Real time simulation of the propulsion plant dynamic behaviour of the Aircraft Carrier "Cavour", (2008) Conference Proceedings of the Institute of Marine Engineering, Science and Technology - INEC 2008: Embracing the Future, https://www.scopus.com/inward/record.uri?eid=2-s2.0-

78650828358&partnerID=40&md5=0a6d3ec4cc38f10df4061aa29be778bb

[5] Alvarez, A., Caiti, A., Onken, R.; IEEE J. Oceanic Eng., « Evolutionary path planning for autonomous underwater vehicles in a variable ocean,» 2004.

[6] S. Campbell et al. Energy, Power and Intelligent Control, School of Electronics, Electrical Engineering and Computer Science, Queen's University Belfast, « A review on improving the autonomy of unmanned surface vehicles through intelligent collision avoidance manoeuvres,» Belfast, 2012.

[7] R. Bellman, «The theory of dynamic programming. Bull. Am. Math. Soc. , 60, 503–515. [CrossRef],» 1954.

[8] A. Coraddu, G. Dubbioso, S. Mauro, M. Viviani. Analysis of twin screw ships' asymmetric propeller behaviour by means of free running model tests. Ocean Engineering 68 (2013), pp. 47–64

[9] Loïck Degorre, Emmanuel Delaleau and Olivier Chocron. A Survey on Model-Based Control and Guidance Principles for Autonomous Marine Vehicles. IEEE J. Mar. Sci. Eng. 2023, 11, 430.

[10] Fossen TI. 2011. Handbook of marine craft hydrodynamics and motion control. Chichester: Wiley. https://doi.org/10.1002/9781119994138.

[11] Jacoby Larson, Michael Bruch, and John Ebken; Space and Naval Warfare Systems Center, «Autonomous Navigation and Obstacle Avoidance for Unmanned Surface Vehicles,» San Diego, 2006.

[12] Martelli M., Figari M., Real-Time model-based design for CODLAG propulsion control strategies, (2017) Ocean Engineering, 141, pp. 265 - 276, DOI: 10.1016/j.oceaneng.2017.06.029, https://www.scopus.com/inward/record.uri?eid=2-s2.0-85020982629&doi=10.1016%2fj.oceaneng.2017.06.029&partnerID=40&md5=ff74d0478f63626bce6e224362b9f977

[13] Michetti S., Ratto M., Spadoni A., Figari M., Altosole M., Marcilli G., Ship Control system wide integration and the use of dynamic simulation techniques in the Fremm project, (2010) International Conference on Electrical Systems for Aircraft, Railway and Ship Propulsion, ESARS 2010, art. no. 5665266, DOI: 10.1109/ESARS.2010.5665266

[14] Nomoto K, Taguchi T, Keinosuke H, Susumu H. 1957. On the steering qualities of ships. Int Shipbuild Prog. 4(35):354–370.

[15] Ogawa A, Koyama T, Kijima K. 1977. MMG report-I, on the mathematical model of ship manoeuvring. Bull Soc Naval Archit Japan. 575:22–28

[16] Skjetne R, Øyvind S, Fossen TI. 2004. Modeling, identification, and adaptive maneuvering of cybership II: a complete design with experiments. IFAC Proc. 37(10):203–208

[17] Zaccone, R. COLREG-Compliant Optimal Path Planning for Real-Time Guidance and Control of Autonomous Ships. J. Mar. Sci. Eng. 2021, 9, 405. https://doi.org/10.3390/jmse9040405

[18] Zhuang J. Y, Su, Y. M., Liao, Y. L., & Sun, H. B; Journal of Shanghai Jiaotong University, «Unmanned Surface Vehicles Local Path Planning Based on Maritime Radar,» Shanghai, 2012.

[1]