IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

SPECIAL SECTION ON NEW DEVELOPMENTS ON RELIABLE CONTROL AND FILTERING OF COMPLEX NONLINEAR SYSTEMS

Received October 6, 2017, accepted November 23, 2017, date of publication November 28, 2017, date of current version February 28, 2018.

Digital Object Identifier 10.1109/ACCESS.2017.2778180

Design and Experimental Testing of a Free-Running Ship Motion Control Platform

JIAN ZHENG [1], FEI MENG [2], (Member, IEEE), AND YUN LI [2]
[1]College of Transport and Communications, Shanghai Maritime University, Shanghai 200135, China
[2]Merchant Marine College, Shanghai Maritime University, Shanghai 200135, China

Corresponding author: Yun Li (liyun@shmtu.edu.cn)

This work was supported by the National Natural Science Foundation of China under Grant 51709166.

ABSTRACT In recent years, ship motion control has been used in unmanned merchant ships. It is a key issue in the sailing performance and navigation cost of unmanned vessels. The merchant ship trajectory and attitude are always generated from the response mechanism for ship motion, which uses one rudder and one propeller as the actuator. Therefore, it is a typical underactuated ship. However, there is not a specialized control test platform for unmanned merchant ships, in particular container ships. A precise merchant ship motion control platform is crucial; its computing power and motion attitude monitoring are difficult to solve by ship-borne computers. To solve this problem, a new free-running ship motion control platform is proposed, which realizes ship attitude monitoring and various motion control experiments. The proposed platform is novel as it embeds ship motion parameters and control parameters in the ship motion model, which successfully solves the precise control of the ship motion control experiment with linear or nonlinear dynamics. In this paper, the design scheme of the ship motion control platform is first presented. Then, the operating principle of the platform is shown, and the adaptive model of the ship plane motion is selected. A series of free-running model experiments and simulations is conducted to test performance of the new platform. To this end, the proposed platform can meet the requirements.

INDEX TERMS Ship motion control, ship free-running test, ship motion model, unmanned vessel.

I. INTRODUCTION

The unmanned ship has been a hot research topic in the area of intelligent ships in recent years. There are many applications for unmanned surface vessels, including military applications, maritime security, special operations forces support, and environmental monitoring [1]. Environmental perception technology, communication & navigation technology and monitoring & diagnosis technology are maturing gradually and are currently being applied to unmanned surface vessels. Intelligent navigation controlling technology and routes planning technology have yet to develop, but these technologies are not used in the field of merchant ships.

Furthermore, the shipping economy has been increasingly emphasized due to the rising fuel costs resulting from the low sulfur fuel requirements of the MARPOL international convention. In order to reduce the personnel costs and improve operating efficiency, the Rolls-Royce Company began designing an unmanned container ship in 2017. Therefore, merchant ship motion controlling is now demanded by the economy as well as the field of artificial intelligence; stabilization, accuracy and speediness are no longer the sole focus. While sailing, because of the distractions of complex sea conditions such as wind, waves and currents, the ship's trajectory tracking control is difficult. After decades of research, the trajectory control system has become more high precision and networked. High-precision, efficient and intelligent ship motion control with multi-system joint control and multi-sensor data integration technology is now a popular topic of research. Hence, the ship motion control platform aims to support the design and verification of the ship motion control system.

The difficulty of researching ship motion control is adopting the appropriate research platform. A free-running ship control platform can be suitable for designing and verifying the ship motion control system. There are two design methods for free-running ship platforms. One is the computer simulation platform. It is commonly applied to establish unmanned ship motion systems & intelligent controlling simulation platforms with visual simulation functions [2]. And a numerical method based on CFD technic is applied to forecast ship manoeuvrability in manoeuvring motion [3]–[6]. In these studies, a KCS container ship is always chosen as the experiment object [7], [8]. The other method is to use a free-running ship model, which is designed so that the ship-shore information is transmitted via a pair of wireless transmitters, the propeller and rudder are processed by an actuator and the course and position are measured by an electric gyro-compass and GPS [9]. This can be the test platform of a ship motion control system. However, the related ship attitude measurement and motion controlling system are still under development. There is also no container ship model to apply to the unmanned container ship design when the container ship is designed as an unmanned merchant ship for the first time.

Other than the analysis found in the literature, there is little work about merchant ship motion control platform design, modeling and testing. The maneuverability and response characteristics of the ship motion control platform are critical to meet and verify the testing requirements. In this study, a new free-running ship motion control platform is proposed to address this problem. It realizes the movement attitudes of ships based on sensor measurement. The proposed platform can embed all the controlled variables in the ship planar motion, which is a good solution for high-performance control of the ship motion control with a linear or nonlinear structure.

The rest of the paper is organized as follows. In section II, the platform design scheme and working principle of the free-running ship motion control platform are presented. In section III, the ship motion response model is selected. To this end, the free-running experiment and simulation test are conducted, and the results are shown in Section IV to show the maneuverability characteristic of the proposed platform.

II. PLATFORM DESIGN SCHEME AND WORKING PRINCIPLE

We will present the design scheme of the proposed free-running ship motion control system first. Then, the working principle and advantages of the ship motion control platform will be explained.

A. PLATFORM DESCRIPTION

The platform is based on a container ship type because the container ship may be the earliest unmanned ship to be applied in the field of merchant shipping. It is an underactuated ship motion control platform that uses a rudder and a propeller as actuators to control the 3 degrees of freedom planar motion. The Micro Autobox II real-time control system is used as a controller. The platform's movement attitudes and position are collected by GPS and the inertial navigation system. These actuators, controller and data collection systems are linked by CANBUS (Controller Area Network). And the wireless communication system is applied to transfer data between platform and shore. The diagram provides for the free-running ship platform is showing figure 1.

B. PLATFORM DESIGN

A simplified experimental platform of a free-running ship is shown in Fig. 3. It has four subsystems: ship hull, propelling system, maneuvering system and data monitor/control unit.

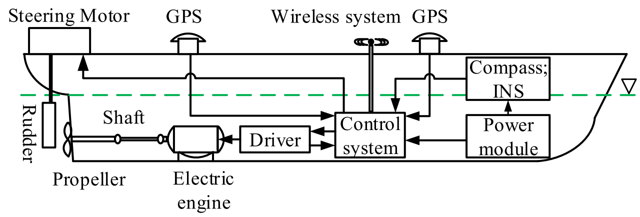


FIGURE 1. The principle diagram of the free-running ship platform.

1) The ship hull is based on a standard ship type, which is a KCS container ship from SIMMAN 2008. The scale ratio of the platform is 1:75.5, and the ship parameters are shown in Table 1. [10]
2) The propelling system contains a standard propeller KP505, the ship shafting, an electric propulsion motor (DC servo motor) and its actuator (servo driver) 2. The system is shown in Fig. 2
3) The maneuvering system includes the rudder (a semi-suspended rudder), electric steering gear (stepper motor) and actuator (closed-loop step drive). The system is shown in Fig. 2. Both actuators of the propulsion motor and steering gear have under voltage, over voltage, overload, over temperature, encoder abnormal protection function.
4) The data monitor/control subsystem receives the position and speed signal from the RTK+GPS; the sway velocity from the inertial navigation system; and the ship course and turning rate signal from the compass. According to the signal from these devices, the ship motion remote controller will calculate the required control signal and then transfer the control signal to the rudder and propeller.

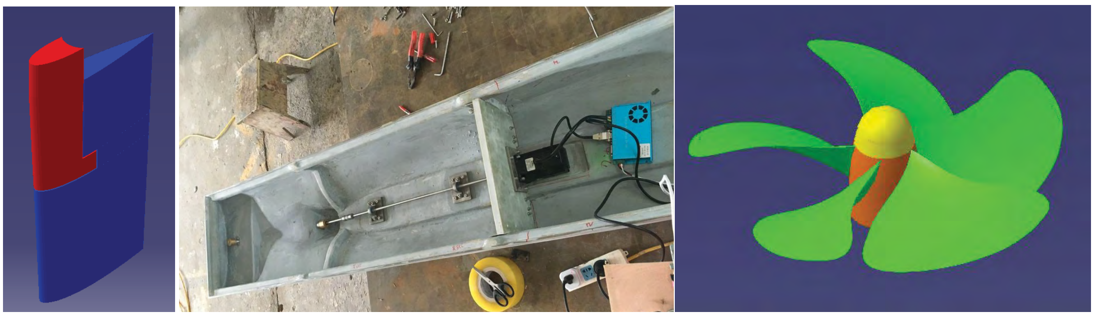
C. PLATFORM WORKING PRINCIPLE

The following are the operating principles of the platform as shown in Fig. 4.

When conducting the experiment in a pool or outdoor water area, the wireless transmission module receives the motion controlling signal, which are the rudder angle and propeller rotating speed sent from the motion controller of the free-running ship model; the signal is then transmitted to the central data control & acquisition module. The signals are transformed via this central data module before being sent to the motor driver and steering gear. Afterward, the motor actuates the BLDCM (brush-less direct current motor) to drive the propeller, and the steering gear turns the rudder. At the same time, the motor speed and rudder angle data are sent back to the data monitor/control subsystem. While the ship model is moving, GPS monitors the shipping trajectory and speed. The inertial navigation system and compass measure the attitude of the ship movement including sway velocity, ship course, and turning rate and send the record to the shore and controller in the platform. The central module could store

TABLE 1. KCS ship parameters.

parameters	real ship	free-running ship platform
Hull particulars parameters		
L_{pp} (m)	230.0	3.0464
L_{wl} (m)	232.5	2.0791
$BreadthMoulded$ (m)	32.2	0.4265
$DepthMoulded$ (m)	19.0	0.2517
$Draght$ (m)	10.8	0.1430
Rudder parameters		
Type	semi-balanced horn rudder	semi-balanced horn rudder
S *of rudder* (m^2)	115	0.0202
Turn rate (deg/s)	2.32	20.2
Propeller parameters		
Type	FP	FP
No.of blades	5	5
Diameter (m)	7.9	0.105
Rotation	Right hand	Right hand
Hub ratio	0.180	0.180
Design_speed	24kn	1.1m/s



Rudder Ship shafting Propeller

FIGURE 2. The rudder, propeller and ship shafting in the free-running ship platform.

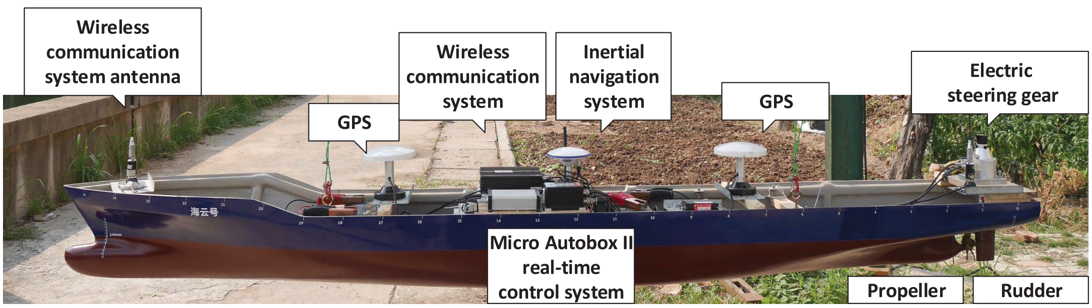


FIGURE 3. The diagram of the free-running ship platform.

the record data and then output it to the motion controller once the ship model has returned to shore; or it could send the data to the onshore mainframe via the wireless transmission module.

D. ADVANTAGES OF THE PLATFORM

The free-running ship motion control platform aims at verifying the unmanned ship's performance, especially the controlling and responding performance, based on the online identification algorithm, ship track controller and cloud control system. It is also used to verify the feasibility and practicability of the simulation model and control algorithm. By comparing the results of free-running test and target control, the controller parameters are corrected. As a result, the improvements to the algorithm lay the foundation for the on-board application.

III. SYSTEM MODELING

Ship motion can be approximately considered as a planar motion from the perspective of open-loop control or closed-loop control [11]–[14]. Also, the ship can be considered as a dynamic system. The system uses rudder angle and propeller speed as the system input and the course, sway velocity and surge velocity as outputs. The ship motion controller

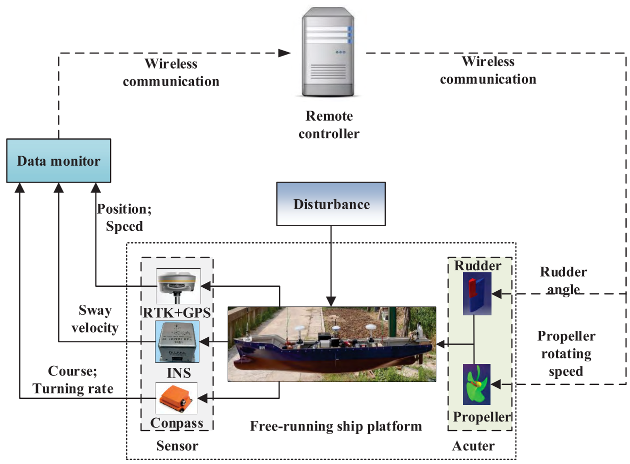


FIGURE 4. System motion control strategy.

uses ship course errors, heading rate, trajectory error, speed error as input, and rudder angle, propeller speed as output. This controller can realizes ship trajectory tracking control which is shown in Fig. 5. Then, the second-order ship motion response model was set up from the state space model of the linear mathematical model of ship motion. It also could be simplified to a first-order model. This model has the advantage that the model parameters can be obtained from the maneuvering test.

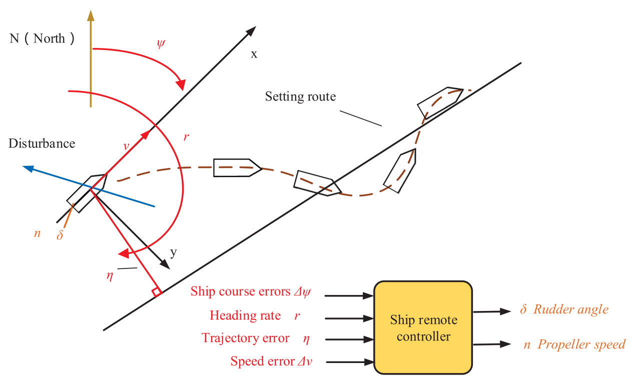


FIGURE 5. Simplified diagram of ship motion controller.

In this section, the response motion model for the free-running ship motion control system are presented based on the platform design and analysis. This ship motion model has been divided into two sections: the ship course motion response model and the speed response model. The sway velocity can be ignored because it is too slow. In the next section, the maneuvering test will be carried out to obtain the model parameters.

A. SHIP COURSE MOTION RESPONDING MODEL

The issue of ship maneuverability from the perspective of control engineering is studied by Nomoto. And T and K are used to stand for ship maneuverability based on the second-order ship response model, which uses the rudder angle as a system input and course angle as the output.

$$\ddot{\psi} + (\frac{1}{T_1} + \frac{1}{T_2})\dot{\psi} + \frac{1}{T_1 T_2}\psi = \frac{K}{T_1 T_2}(T_3\dot{\delta} + \delta) \quad (1)$$

where ψ stands for the course angle, δ for the ship rudder angle, and T and K for the ship maneuvering coefficients.

Then, the second-order ship course motion response model (Eq. (1)) can also be reduced to first-order.

$$T\ddot{\psi} + \dot{\psi} = K\delta \quad (2)$$

B. SPEED RESPONDING MODEL

Also, there is a response relationship between the speed and hydrodynamic force derivatives, which is related to propeller speed.

$$m_x \Delta\dot{u} = X_u \Delta u \quad (3)$$

where m_x stands for associated mass and u for speed and X_u are the hydrodynamic force derivatives.

IV. EXPERIMENTAL TEST

A. TEST CONDITION

The designed platform is fabricated for experimental verification. The free-running test is shown in Fig. 6. Then, the turning test, crash stopping test and zigzag test are conducted. The ship test speed is designed for speed 1.1m/s at the electric engine 900 rmp/min. In addition, the test conditions are as follows: the draft is 0.143m; the ship displacement is 0.121m^3; and the initial metacentric height is 0.097m.

FIGURE 6. Experimental test.

B. TEST TURNING TESTS

The turning test results can show the turning motion performance of the platform. The experimental process is as follows: When the electric steering gear and engine are in working condition, the test should be performed at a going ahead speed of 1.1m/s. Then, the rudder angle is turned to hard starboard (35degree) and held until the ship heading angle changes to 540 degree; the test is finished, the straight course is resumed until speed recovery. In the second group of tests, the rudder angle is turned to hard portside (35degree) and held until the ship heading angle changes to 540 degree;

the test is finished, and the straight course is resumed until speed recovery. The transfer distance, advance distance, turning diameter and speed reduction are measured and recorded. The test result is shown in Tab. 2 and Fig. 7. The turning tests pattern parameters, shown in Tab. 2, can be the critical parameters in the ship motion controller design and controller precision verification.

TABLE 2. Ship turning tests pattern parameters extraction.

Rudder angle ()	Left rudder 35	Right rudder 35
Final Diameter (m)	2.527	2.774
Tactical Diameter (m)	2.883	3.296
Advance (m)	2.524	3.104
Transfer (m)	1.310	1.336
angular velocity (m/s)	-9.639	8.426
reduction of speed (%)	49.63	41.33

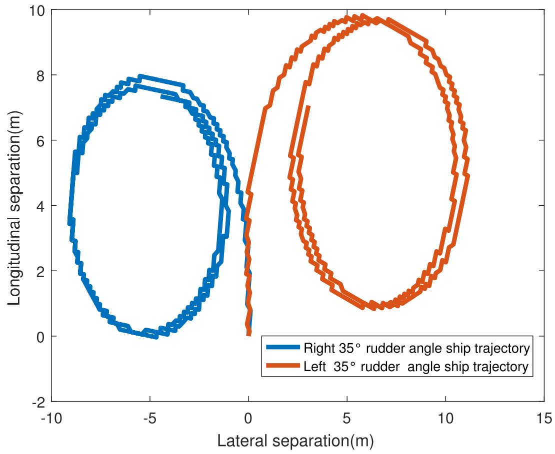


FIGURE 7. Ship turning test trajectory.

C. SHIP CRASH STOPPING TEST

To realize the crash stopping distance, time and trajectory, the ship crash stopping test is performed. These parameters are important in unmanned ship automatic collision avoidance controller design. The propeller starts to reverse at full speed (900 rpm.) when the ship platform maintains a stable maximum speed of advance. The test is not over until the speed of advance drops to a negative value. Then, the crash stopping distance, time and trajectory can be acquired by the monitor/control unit(Tab. 3, Fig. 8). The trajectory of ship crash stopping shifts to the right because the propeller, which is the right-hand propeller, inverts (Fig.7).

TABLE 3. The result of ship crash stopping test.

Parameters of crash stopping test	
Crash stopping instantaneous speed	1.113m/s
Dimensionless crash stopping distance	3.537
Dimensionless crash stopping time	5.350

D. ZIGZAG TESTS

A 20/20 zigzag test is conducted in this section. When the vessel is running ahead at a speed of 1.1m/s, the test is carried

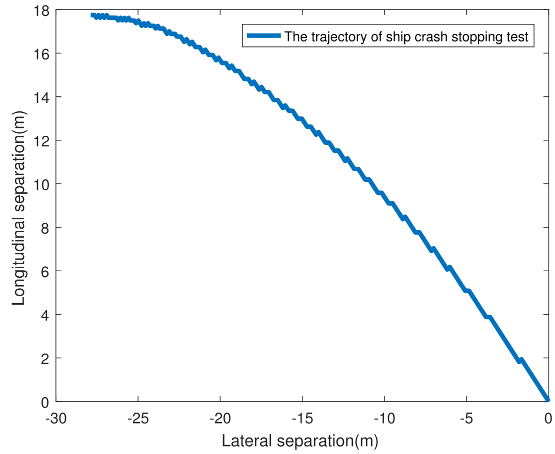


FIGURE 8. Ship crash stopping test trajectory.

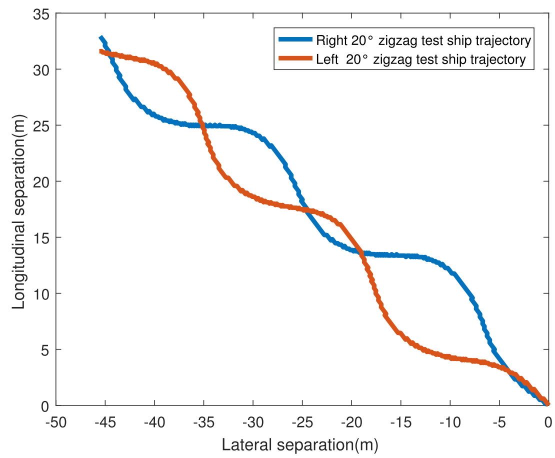


FIGURE 9. Ship Zzigzag test trajectory.

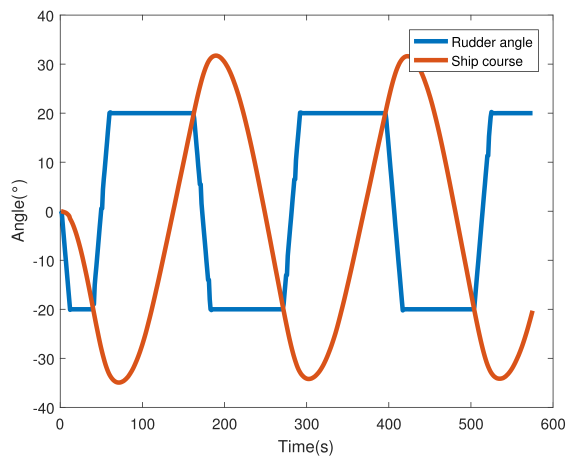


FIGURE 10. Ship left rudder 20 zigzag test course and rudder angle.

out in accordance with the following steps: The rudder angle is turned from its zero position to 20 starboard and held until the course of the vessel changes to an angle of 20 starboard to the original course; in the second group of tests, the rudder angle is turned from 10q starboard to 20 port and held until the course of the vessel changes to an angle of 20 port to the

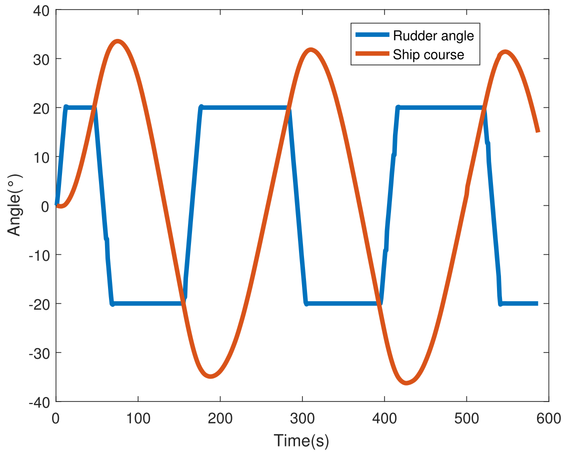


FIGURE 11. Ship right rudder 20 zigzag test course and rudder angle.

TABLE 4. Ship turning tests pattern parameters extraction.

Rudder angle	Left rudder	Right rudder
K_Indice	1.3353	1.2593
T_Indice	1.3187	1.2478

original course. The rudder angle is turned from 20 port to 20 starboard and held until the course of the vessel changes to an angle of 20 starboard to the original course. The rudder angle is turned from 20 starboard to its zero position and held until the vessel runs in the original course. The K-T indices and ship course are measured, recorded and calculated. The result is showing on figure9,figure11 and table 4.

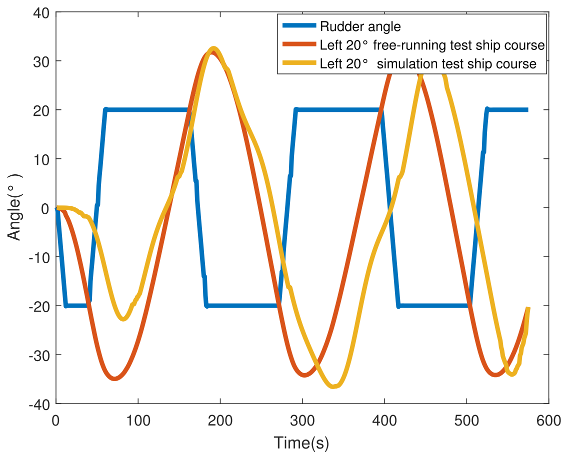


FIGURE 12. Ship right rudder 20 zigzag test course and rudder angle.

E. SIMULATION TESTS

The result of these experiments can describe manoeuvrability of this ship platform. And the data of these experiments can be used in identification of ship motion model. To verify the K-T indices and the ship motion model, which is presented in section III(Eq.2,Eq.3), the simulation model is built in simulink. The left rudder angle 20 degree zigzag test is simulated. In the simulation model, the test speed is a fixed value, which is full speed as necessitated by the zigzag test. So, Eq.3 is set to be a fixed value. The result is shown in Fig.12. The result of simulation lags behind the result of the free-running test because the steering gear delay module is built in the simulation model. The ship motion model is valid. In future work, the model identification method can be used in the second-order ship response model to identify the parameters, thus improving the accuracy of the model greatly.

In general, it can be concluded that the developed platform is promising as it is capable of collecting the ship motion characteristic parameter, which can identify the parameters of the ship motion model and verify the accuracy of the ship motion controller.

V. CONCLUSIONS

In this paper,a merchant container ship motion control platform in which the platform motion can be controlled by the rudder and propeller is presented. The platform can monitor the ship attitude and apply different ship motion control algorithms on the rudder and propeller. The ship motion control algorithm validation can also be easily achieved due to the platform design. Then, we introduce the working principle of the ship motion control platform and select the ship motion response model. Free-running experiments and simulation tests are conducted to demonstrate the maneuverability and fail-safety of the platform, and the results are presented. Future work includes a more compact ship motion control system with unmanned ship design and fabrication.

ACKNOWLEDGMENT

Special thanks should go to the editors and reviewers, who provided constructive suggestions that improved the paper.

REFERENCES

[1] R.-J. Yan, S. Pang, H.-B. Sun, and Y.-J. Pang, "Development and missions of unmanned surface vehicle," *J. Marine Sci. Appl.*, vol. 9, no. 4, pp. 451–457, 2010.
[2] G. X. Wu, "Research on unmanned surface vehicle maneuverability and intelligent control technology," Ph.D. dissertation, Dept. Marine Eng. College, Harbin Eng. Univ., Harbin, China, 2011.
[3] S. Gaggero, D. Villa, and M. Viviani, "An extensive analysis of numerical ship self-propulsion prediction via a coupled bem/rans approach," *Appl. Ocean Res.*, vol. 66, pp. 55–78, Jun. 2017.
[4] K. Jin, I. R. Park, K. S. Kim, S. H. Van, and Y. C. Kim, "Development of a numerical method for the evaluation of ship resistance and self-propulsion performances," *J. Soc. Naval Architects Korea*, vol. 48, no. 2, pp. 147–157, 2011.
[5] P. M. Carrica, H. Fu, and F. Stern, "Computations of self-propulsion free to sink and trim and of motions in head waves of the KRISO container ship (KCS) model," *Appl. Ocean Res.*, vol. 33, no. 4, pp. 309–320, 2011.
[6] C. D. Simonsen, J. F. Otzen, S. Joncquez, and F. Stern, "EFD and CFD for KCS heaving and pitching in regular head waves," *J. Marine Sci. Technol.*, vol. 18, no. 4, pp. 435–459, 2013.
[7] B. Windén, S. R. Turnock, and D. A. Hudson, "Self propulsion modelling of the KCS container ship using an open source framework," in *Proc. Numer. Towing Tank Symp.*, 2014, pp. 199–205.
[8] Z. Shen, P. M. Carrica, and D. Wan, "Ship motions of KCS in head waves with rotating propeller using overset grid method," in *Proc. ASME 33rd Int. Conf. Ocean, Offshore Arctic Eng.*, 2014, p. V002T08A043.
[9] H. Shin, H. S. Park, C. S. Yang, and H. L. Lee, "Motion analysis by free-running model test," Twelfth Int. Offshore Polar Eng. Conf., Kitakyushu, Japan, Tech. Rep. ISOPE-1-02-314, 2002.
[10] Y.-G. Kim, D.-J. Yeo, S.-Y. Kim, K.-H. Yun, and B. I. Oh, "Prediction of maneuverability of KCS by cpmc captive model test," *J. Soc. Naval Architects Korea*, vol. 46, no. 6, pp. 553–561, 2009.
[11] H. R. Karimi, "A computational method for optimal control problem of time-varying state-delayed systems by haar wavelets," *Int. J. Comput. Math.*, vol. 83, no. 2, pp. 235–246, 2006.

[12] H. R. Karimi, "Mixed H_2/H_∞ output-feedback control of second-order neutral systems with time-varying state and input delays," *ISA Trans.*, vol. 47, no. 3, pp. 311–324, 2008.
[13] Y. Wei, J. Qiu, and H. R. Karimi, "Quantized H_∞ filtering for continuous-time Markovian jump systems with deficient mode information," *Asian J. Control*, vol. 17, no. 5, pp. 1914–1923, 2015.
[14] Y. Tang, X. Xing, H. R. Karimi, L. Kocarev, and J. Kurths, "Tracking control of networked multi-agent systems under new characterizations of impulses and its applications in robotic systems," *IEEE Trans. Ind. Electron.*, vol. 63, no. 2, pp. 1299–1307, Feb. 2016.
[15] Y. Xiong and Z. H. Liu, "Numerical prediction of propulsion factors of propelled ship model and full scale ship," *J. Ship Mech.*, vol. 17, no. 1, pp. 14–18, 2013.
[16] Q.-B. Zhu, Z.-D. Wang, H.-J. Ling, and L.-F. Zhuang, "Use of the sliding mesh technique to forecast ship self-propulsion performance with propeller in open water," *Ship Sci. Technol.*, 2016.
[17] M. Ueno, Y. Yoshimura, Y. Tsukada, and H. Miyazaki, "Circular motion tests and uncertainty analysis for ship maneuverability," *J. Marine Sci. Technol.*, vol. 14, p. 469, Dec. 2009.
[18] C. Jian *et al.*, "Parametric estimation of ship maneuvering motion with integral sample structure for identification," *Appl. Ocean Res.*, vol. 52, pp. 212–221, Aug. 2015.
[19] L. P. Perera, P. Oliveira, and C. G. Soares, "Dynamic parameter estimation of a nonlinear vessel steering model for ocean navigation," in *Proc. Int. Conf. Ocean, Offshore Arctic Eng. OMAE*, 2011, pp. 881–888.
[20] M. H. Casado, R. Ferreiro, and F. J. Velasco, "Identification of nonlinear ship model parameters based on the turning circle test," *J. Ship Res.*, vol. 51, no. 2, pp. 174–181, 2007.
[21] C. Liu, Z. Zou, and J. Yin, "Trajectory tracking of underactuated surface vessels based on neural network and hierarchical sliding mode," *J. Marine Sci. Technol.*, vol. 20, no. 2, pp. 322–330, 2015.
[22] Y. Li, C. Wei, Q. Wu, P. Chen, Y. Jiang, and Y. Li, "Study of 3 dimension trajectory tracking of underactuated autonomous underwater vehicle," *Ocean Eng.*, vol. 105, pp. 270–274, Sep. 2015.
[23] W. Ma and F. Meng, "Modeling, analysis, and experimental testing of a selective catalytic reduction dosing system," *IEEE Access*, vol. 5, pp. 1409–1415, 2017.

JIAN ZHENG received the B.Sc. degree in management science, the M.Sc. degree in management science and engineering, and the Ph.D. degree in communications and transportation engineering from Shanghai Maritime University, Shanghai, China, in 2008, 2010, and 2014, respectively.

He is currently a Lecturer with the College of Communications and Transportation, Shanghai Maritime University. His research interests include ship motion control, remote control, unmanned merchant ship, networked control systems, and signal processing.

FEI MENG (M'16) received the Ph.D. degree in mechanical engineering from the Beijing Institute of Technology, Beijing, China, in 2014. He is currently an Assistant Professor with the Merchant Marine College, Shanghai Maritime University, China. His research interests include the control of dynamical systems, optimal control, and networked control system. In the past five years, he has contributed over 20 papers in referred journals and conference proceedings. He serves as a Reviewer for many journals, including the IEEE TRANSACTIONS ON MECHATRONICS, the *ASME Transactions on Mechatronics*, the IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY, the *Mechanical Systems and Signal Processing*, the *Journal of the Franklin Institute*, and the *International Journal of Vehicle Design*.

YUN LI received the B.Sc. degree in communication engineering from the Civil Aviation University of China, Tianjin, China, in 2010, and the M.Sc. degree in traffic information engineering and control and the Ph.D. degree in vehicle operation engineering from Shanghai Maritime University, Shanghai, China, in 2012 and 2016, respectively.

She is currently a Lecturer with the College of Merchant Marine, Shanghai Maritime University. Her research interests include ship motion control, intelligent control, unmanned ship model, ship formation, and signal processing.