Jurnal
Teknologi

Full paper

Simulation on Model Performance of Ship's Diesel Engine Propulsion in Calm Water

NurIzzuddin[a], Sunarsih[a], Agoes Priyanto[a*], Rahimuddin[b]

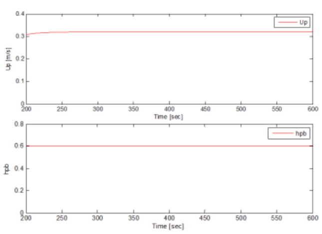
[a]*Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia*
[b]*Universitas Hasanudin, Makassar, Indonesia*

*Corresponding author: agoes@fkm.utm.my

Article history

Received :23 March 2014
Received in revised form :
3 April 2014
Accepted :2 June 2014

Graphical abstract



Abstract

Ship performance is prevalently evaluated during calm water condition though contrarily the ships operated in actual rough sea environments. The paper elaborates a mathematical model of marine diesel engine propulsion system to estimate real performance of ships in calm water through the proposed computer-simulated model. A post Panamax container ship and LNG tanker are employed as target ships of this study. The analysis of the model includes propeller rotating speed and torque from which the required engine power is estimated to achieve the target speed. These input and output are real-time control system of propeller rotating speed reflecting the characteristics of marine diesel engine. The result has established ultimate limit of affecting features of a real-time control system to control ship speed, power and propeller torque. Further use of the model is advantageous to analyse different condition of ship speed for finding better design characteristics.

Keywords: Real-time control; dynamics simulation; diesel engine model; numerical test; ship propulsion system

1.0 INTRODUCTION

Generally, ship has to demonstrate the behavior of efficient and safe operation both in steady and transient conditions during sea trials. The impact of environmental sea conditions to the system is significant to be considered[1], starting from the phases of ship construction and building to the stage of ship's control system design and implementation. The task becomes crucial for design optimization of the single propulsion system and the whole ship as in fact that the propulsion system is a key aspect of the global behavior of the whole ship.

From this point of view, PC-based equipment can be used to simulate the functions of real ship[2]. It greatly reduces the need of conducting costly and time consuming of full scale trials. Ship propulsion simulation as one of its application, is one of the most useful ways to predict and investigate the dynamic of the ship and the system at design stage[3-5], mainly when it deals with new system configurations.

Maftei *et al.*[3] and Altosole and Figari[4] agreed that numerical simulation of ship propulsion system gives benefit on a variety of purposes. The simulation has ability to do some experiments which are rather difficult to or even not allowed conducting in real ships, get practical experiences in short time which require long term accumulation in real ship, fault recognition and exclusion which cannot be done in real ship. These are advantageous since it is desirable to work with onboard diagnosis and control modeled by an accurate but not complicated propulsion system[6].

The paper proposed a computer-simulated model of marine diesel engine to control the speed of engine rotation and thus the rotating speed and propeller torque. However, to obtain a complete simulation as well as a full view over the dynamic behavior of the ship propulsion system, the engine should be coupled to the propulsion system.

2.0 MARINE DIESEL ENGINE SIMULATION

A generic ship propulsion plant is basically considered to be made up of three main components; the engine the transmission gear, and the propulsor. Figure 1 shows a simple but more comprehensive model of ship propulsion system[1]. The model consists of five main elements which are treated as separated blocks with external disturbances contributing to the ship dynamic. As claimed by Figari and Altosole[8], one of the most useful ways for the prediction of the dynamic behavior of the system is numerical situation. The method requires detail knowledge of the system and great efforts in human and computational resources. Altosole *et al.*[6] further emphasized that this simulation method is based on detail model of the system and its control logic.

It is then a real-time simulation offers a more precise estimation of the real system behavior. Regarding to such objective, the paper developed a numerical test of marine diesel engine simulation and adopted the simulator established by

Tanizawa *et al.*[7] where the mathematical model adopted from Bondarenko *et al.*[5] On this simulator, the engine model is composed of rotating motion of whole shaft line (1), torque generation by fuel combustion (2) and speed control by mechanical governor (3).

The propulsion plant and its ship dynamics can be represented by longitudinal motion of the ship speed V and rotational motion of the shaft line n. The equation of the rotational motion of the shaft line n can be written as

$$2\pi I \frac{dn_e}{dt} = Q_e(n, hp) - Q_p \qquad (1)$$

where I is moment of inertia of whole rotating shaft line composed of rotating machinery of engine, propeller shaft and propeller, ne is engine rotating speed, Qe is engine torque as a function of rotating speed n and fuel flow hp, and Qp is propeller torque. Since we assume no reduction gear, number of propeller rotation is identical to that of engine rotation.

Engine torque is given by the following non-dimensional form

$$\left.\begin{aligned} \bar{Q}_e &= 0.5\bar{h}_p^{\frac{2}{3}} + 1.5\bar{h}_p^{\frac{1}{3}}\bar{n} + \bar{n}^2 \\ \bar{Q}_e = \frac{Q_e}{Q_{mcr}};\ \bar{h}_p &= \frac{h_p}{h_{mcr}}\ ;\ \bar{n} = \frac{n_e}{n_{mcr}} \end{aligned}\right\} \qquad (2)$$

WhereQe-mcr, hp-mcr and nmcr are value of the engine torque, stroke of fuel pump rack and rotating speed at the Maximum Continuous Rating (MCR).

The system is controlled by a control system that normally provides a set point for the rotational speed of the engine; the engine governor which compares the desired and actual shaft speeds and adjusts the fuel flowrate in order to maintain the desired shaft speed. The speed control by mechanical governor is shown on Figure 2 and its mathematical model of the fuel flow as a function of the shaft speed n is expressed by (3) corresponding to each block number from [i] to [vi].

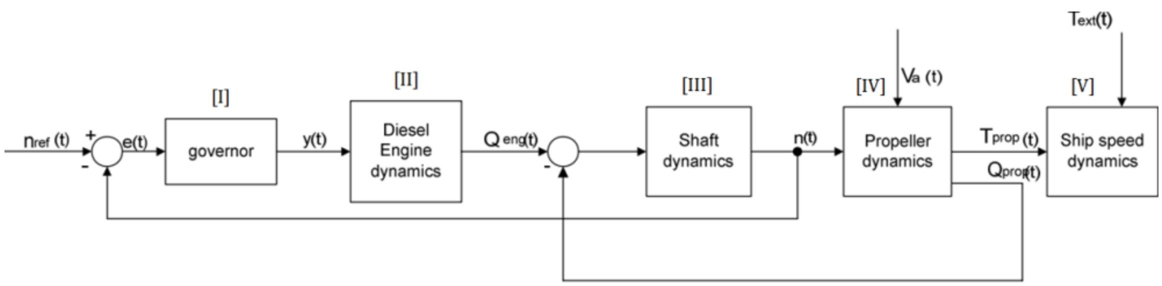


Figure 1 Block diagram of the ship propulsion system

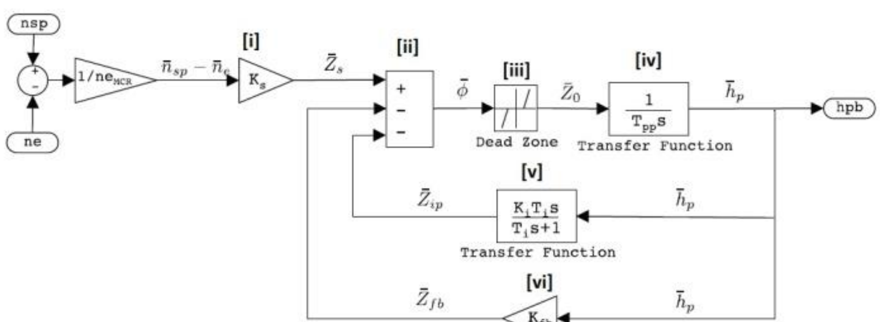


Figure 2 Block diagram of speed control system

[i] $\bar{Z}_s = K_s(\bar{n}_s - \bar{n})$

[ii] $\bar{\phi} = \bar{Z}_s - \bar{Z}_{ip} - \bar{Z}_{fb}$

[iii] $\bar{Z}_0 = \begin{cases} \bar{\phi} - \frac{\epsilon}{2}, & if \epsilon > \frac{\epsilon}{2} \\ 0, & if |\epsilon| \le \frac{\epsilon}{2} \\ \bar{\phi} + \frac{\epsilon}{2}, & if \epsilon < \frac{\epsilon}{2} \end{cases}$

[iv] $T_{pp}\frac{d\bar{h}_p}{dt} = \bar{Z}_0$

[v] $T_i\frac{d\bar{Z}_{ip}}{dt} + \bar{Z}_{ip} = K_iT_i\frac{d\bar{h}_p}{dt}$

[vi] $\bar{Z}_{fb} = K_{fb}\bar{h}_p$ (3)

where Ks is speed sensor gain coefficient, Tpp is time constant of the power piston, Ti and Ki are time constant and gain coefficient of isodromic feedback respectively and Kfb is gain coefficient of the proportional feedback.

■3.0 NUMERICAL STUDY OF SHIP PROPULSION SIMULATION

3.1 Target Ships and Diesel Engine Specifications

Two types of ship of post Panamax container and LNG tanker are chosen as the target ships of this study and hence namely as Target Ship 1 and Target Ship 2. Service speeds of the target ships are 25kt and 19kt respectively. Target Ship 1 and currently used diesel engine are adopted from previous study conducted by Tanizawa *et al.*[7] while Target Ship 2 is taken as comparison. The principle dimension of the target ships and diesel engine specifications used are given in Table 1 and Table 2. Table 3 shows the coefficient of governor model adopted from Bondarenko *et al.*[5]

Table 1 Particulars of Target Ship 1 and the model

Item	Target Ship 1 Ship	Model
Hull		
Length between P [m]	300.0	4.000
Breadth [m]	40.0	0.533
Draft [m]	14.0	0.187
Block Coefficient	0.65	
Displacement [t]	111,930.0	0.2650
Wet surface Area [m^2]	15,879.7	2.8279
Propeller		
Propeller Diameter [m]	9.0	0.120
Blade Number	5	
Blade Section	MAU	
Self-Propulsion Factors		
1-w	0.7042	
1- t	0.8335	
Diesel Engine		
Power (MCR) [W]	6.622E07	1.770E01
Torque (MCR) [Nm]	6.080E06	1.877E-01
Num. of Rotation (MCR) [rps]	1.73	15.01
Moment of inertia, Propeller, Shaft and Engine [kg m^2]	6.618E05	2.723E-04

Table 2 Particulars of Target Ship 2 and the model

Item	Target Ship 2 Ship	Model
Hull		
Length between P [m]	266.00	3.325
Breadth [m]	41.60	0.520
Draft [m]	11.13	0.139
Block Coefficient	0.746	
Displacement [t]	94,174.0	0.184
Wet surface Area [m^2]	13,970.0	2.183
Propeller		
Propeller Diameter [m]	7.7	0.096
Blade Number	5	
Blade Section	B-Series	
Self-Propulsion Factors		
1-w	0.530	
1- t	0.800	
Diesel Engine		
Power (MCR) [W]	6.622E07	1.446E01
Torque (MCR) [Nm]	6.080E06	1.521E-01
Num. of Rotation (MCR) [rps]	1.73	15.473
Moment of inertia, Propeller, Shaft and Engine [kg m^2]	6.618E05	2.02E-04

Table 3 Coefficient of governor model

Item	Target Ship 1 Ship	Model		Target Ship 2 Ship	Model
K_S			12.5		
T_{PP} [s]	0.120	0.014		0.120	0.013
K_i			1.4		
T_i [s]	2.500	0.289		2.500	0.280
$K_{f.b}$			0.75		

3.2 Numerical Test of the Engine Model

The simulation model is shown on Figure 3 where block [a] to [f] are treated separately and refer to target speed, governor control, diesel engine dynamics, shaft dynamics and propeller dynamics respectively. The test simulated ship speed from zero and slowly accelerates up to the service speed.Block [a]: Calculate number of engine rotation nsp to control the acceleration process and final target speed.

Block [b]: The governor model to calculate the non-dimensional stroke of fuel pump rack (h)¯_p where input is nsp and current engine rotation number ne. Block [c]: Calculate engine power Pe and engine torque Qe by 2 where input is (h)¯_p and ne.

Block [d]: Calculate number of engine rotation ne using (1) by considering added moment of inertia of propeller where input is difference between Qe and propeller torque Qp.

Block [e]: Propeller model based on POT result to calculate Qp and propeller thrust Tp where inputs are ne and propeller inflow velocity Up using (4).

$$J = \frac{U_p}{n_e D}$$
$$K_T = \frac{T}{\rho . {n_e}^2 D^4}$$
$$K_Q = \frac{Q}{\rho . {n_e}^2 D^5} \quad (4)$$

where J is advance coefficients, D is the nominal diameter of the propeller and ρ is mass density of the water in the tank set to 1000kg/m3. Thrust coefficient KT and torque coefficient KQ obtained by interpolating the propeller model shown in Figure 4 and Figure 5.

Block [f]: Calculate Up using (5) where input is Tp engaging with ship resistance Rt.

$$M_S \frac{dV_s}{dt} = (1-t)T_p - R_t$$
$$R_t = \frac{1}{2}\rho S V_s C_t$$
$$U_p = (1-w)V_s \quad (5)$$

Where Ms is mass of the model ship, (1-t) is thrust deduction factor, S is wet surface area, Vs is advancingspeed, Ct is coefficient of total resistance and (1-w) is wake fraction. Values of (1-t) and (1-w) are as given in Table 1 and Table 2 of each target ship while Ct are obtained by interpolating values given in Table 4.

Table 4 Coefficient of total resistance

Target Ship 1 Fn	C_t	Target Ship 2 Fn	C_t
0.125	0.00412	0.1309	0.005821
0.145	0.00399	0.1450	0.005534
0.156	0.00399	0.1554	0.005598
0.165	0.00396	0.1657	0.005435
0.175	0.00394	0.1761	0.005439
0.186	0.00392	0.1865	0.005367
0.205	0.00389	0.1968	0.005430
0.215	0.00388	0.2072	0.005643

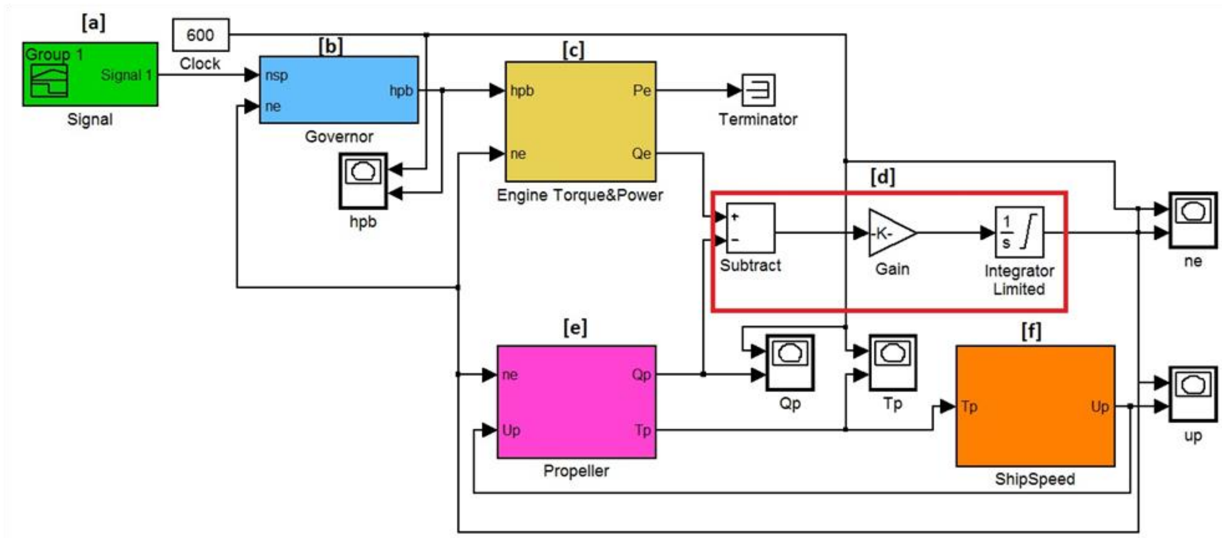


Figure 3 Block diagram of ship propulsion simulation

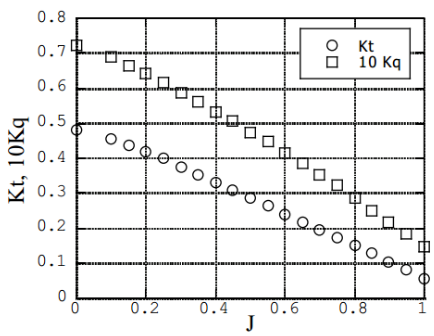


Figure 4 Propeller Open Test of Target Ship 1

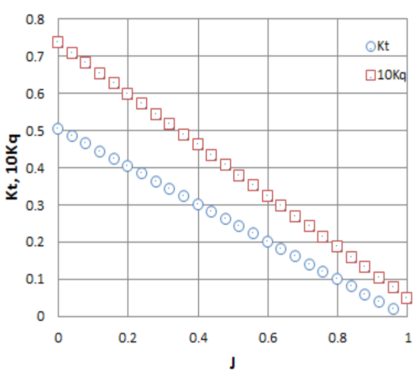


Figure 5 Propeller Open Test of Target Ship 2

■4.0 RESULT

Numerical test are simulated to two target ships which are of different types and dimensions, defined as Target Ship 1 and Target Ship 2. The simulation performed using the same diesel engine and governor specifications. Results of the simulated time histories of both target ships for 600 sec of the process are presented on Figure 6 to Figure 9. Figure 6 and Figure 7 show the rotational speed, propeller torque and thrust of Target Ship 1 and Target Ship 2 respectively while Figure 8 and Figure 9 display the propeller inflow velocity and stroke of fuel pump rack during steady state from 200 sec to 600 sec.

■5.0 DISCUSSION

In this paper, we propose a computer-simulated marine diesel engine model. The simulation is conducted based on the same initial condition for both target ships; a post Panamax Container ship and LNG Tanker. Target number of diesel engine rotational speed for both target ships are set to 13 rps and the result of propeller thrust and torque are analysed.

The simulation result shows that the rotational speed accelerates in the first 180 sec to a maximum value of 12.3 rps and periodically constant to the end of simulation process. This phenomenon occurred due to the stabilization of diesel engine speed to approach the target speed. At the same time, this behavior affects the characteristic of the torque and thrust as well.

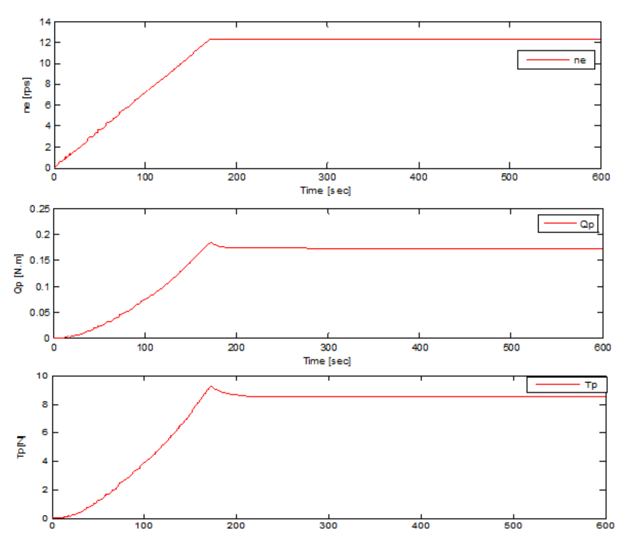


Figure 6 Simulated time histories of Target Ship 1

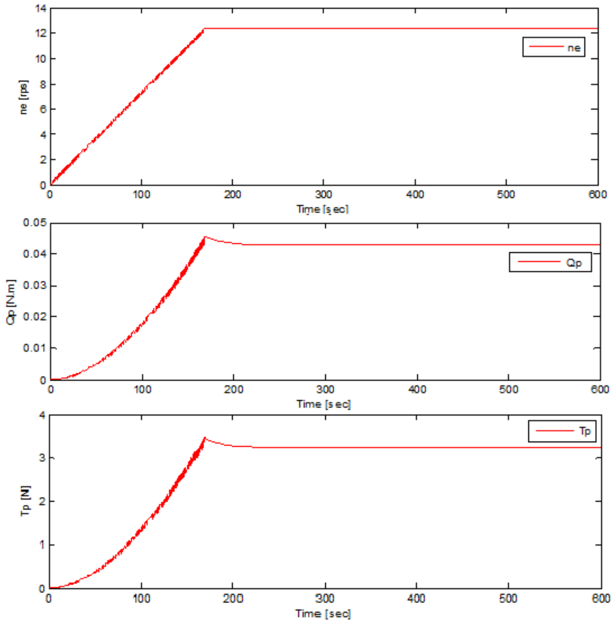


Figure 7 Simulated time histories of Target Ship 2

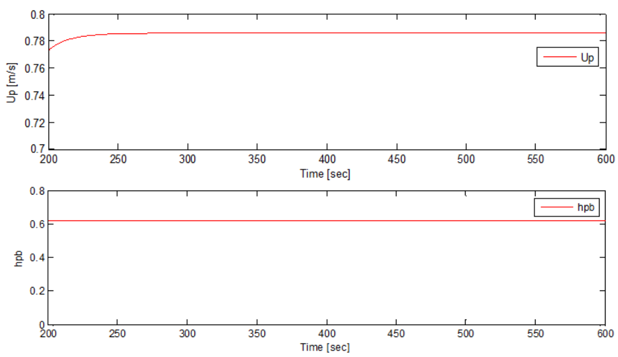


Figure 8 Simulated time histories of Target Ship 1 during steady state

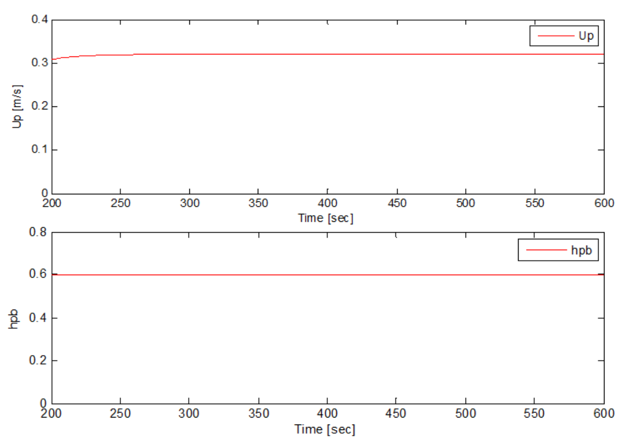


Figure 9 Simulated time histories of Target Ship 2 during steady state

As indicated in Figure 6, Target Ship 1 reached its maximum torque at 0.185 Nm and constant to a value of 0.17 Nm. The maximum and constant value of the thrust is reached at 9.4 N and 8.5 N respectively. Both torque and thrust reached the maximum value at 180 sec.

Figure 7 displays the simulation result of Target Ship 2. A maximum torque of 0.47 Nm and constant of 0.44 Nm are obtained during the simulation process. The thrust attained its maximum value at 3.6 N and constant at 3.3 N.

Figure 8 and Figure 9 demonstrate the propeller inflow velocity and non-dimensional stroke of fuel pump rack of Target Ship 1 and Target Ship 2. Designed at higher velocity of service of 25kt, Target Ship 1 exhibits higher propeller inflow velocity compared to Target Ship 2 of 19kt. The values are 0.78 6m/s and 0.32 m/s. While the value of number of engine rotation is constant from 180 sec, the propeller inflow velocity of both target ships accelerates to 230 sec. As represented by the figures of the stroke of fuel pump rack, it is obvious that their values are constant during simulated time histories as number of engine rotation is run to constant. Both figures pointed a slight difference value of 0.017.

Result of the simulation resembles the approximation of test design expressed by (4). Occupying the same number of engine rotation, the value of torque and thrust are determined by the values of propeller inflow velocity, as well as velocity of service and propeller diameter. The value of propeller inflow velocity itself is directly proportional to the size of propeller diameter.

■6.0 CONCLUSIONS

The paper introduces marine diesel engine simulator based on mathematical model of marine diesel engine developed by Bondarenko *et al.*[5] using MATLAB Simulink. A test has been done to Panamax container ship and LNG tanker. The speed of diesel engine rotation, propeller thrust and torque are analysed with respect to the simulated time histories. The diesel engine simulator developed has worked as designed and successfully control propeller rotation to achieve the target speed. Hence, the diesel engine simulator developed confirmed as a real-time control system.

Acknowledgement

The author wish to acknowledge financial support of Universiti Teknologi Malaysia and Ministry of Higher Education through Tier 1 Research University Grant Vot 04H20. For this assistance, the authors are very grateful.

References

[1] R. Antonić, A. Cibilić, I. Golub, Z. Kulenović, V. Tomas. 2011. Impact of The Environmental Sea Conditions to Ship's Propulsion Engine Dynamics. Paper Presented at the 15th International Research/expert Conference. Trends in the Development of Machinery and Associated technology-TMT 2011.

[2] Y. Yang, C. Guo, J.-B. Sun, D.-W. Yan. 2011. A Novel Simulation System for Marine Main Diesel Propulsion Remote Control. International Conference on Virtual Reality and Visualization (ICVRV) 2011, IEEE. 57–62.

[3] C. Maftei, I. Moreira, C.G. Soares. 2009. Simulation of the Dynamics of A Marine Diesel Engine. Proceedings of IMarEST-Part A. *Journal of Marine Engineering and Technology*. 29–43.

[4] M. Altosole and M. Figari. 2011. Effective Simple Methods for Numerical Modeling of Marine Engines in Ship Propulsion Control Systems Design. *Journal of Naval Architecture and Marine Engineering*. 8: 129–147.

[5] O. Bondarenko, M. Kashiwagi, S. Naito. 2009. Dynamics of Diesel Engine in the Framework of Ship Propulsion Plant, Conference Proceedings. *The Japan Society of Naval Architects and Ocean Engineers*. 335–338.

[6] M. Altosole, G. Benvenuto, M. Figari, U. 2009. Campora, Real-time Simulation of a COGAG Naval Ship Propulsion System, Proceedings of

The Institution of Mechanical Engineers, Part M. *Journal of Engineering for the Maritime Environment.* 223: 47–62.

[7] K. Tanizawa, Y. Kitagawa, T. Takimoto, Y. Tsukada. 2012. Development of an Experimental Methodology for Self-propulsion Test with a Marine Diesel Engine Simulator, The Twenty-second (2012) International Offshore and Polar Engineering Conference, June 17–22, 2012, Rhodes, Greece, International Society of Offshore and Polar Engineers (ISOPE). 921–928.

[8] M. Figari, M. Altosole. 2007. Dynamic Behaviour and Stability of Marine Propulsion Systems, Proceedings of the Institution of Mechanical Engineers, Part M. *Journal of Engineering for the Maritime Environment*. 221(4): 187–20.