Real-time Simulation of Ship Propulsion System

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This paper deals with the mathematical models of a ship propulsion system in an Engine Room Simulator (ERS). The main modeled elements are the main diesel engine, the fixed pitch propeller, the ship’s hull, the remote/local control levers, the dynamic systems and control system. The hull-engine-propeller matching model, marine diesel engine model, dynamic and control system models are introduced respectively. At the same time, a real-time simulation algorithm is described to meet the demands of rapid response, long running duration and little error accumulation of the simulator. These mathematical models of the ship propulsion system have been realized by the real-time simulation algorithm in microcomputer, have been conformed by experiment in applications of the Propulsion System Simulator (PSS), and have obtained satisfactory results. This simulation system can also simulate most of typical malfunctions and accidents of the ship propulsion system. It has been used as a necessary training tool for Maritime Education and Training (MET), and has benefited engineers in treating with emergency situations.

1. Introduction

The ultimate goal of MET is to train cadet as a responsible and well-educated licensed seafarer who is certified to be compliant with the International Convention on Standards of Training, Certification and Watchkeeping for seafarers (STCW95) and the related International regulations. During the latest decades, experts, who are engaged in MET, are bending themselves to research and discuss how to improve the effect of MET with an effective and convenient method. Most of them tend to use marine simulator as an alternative.

In order to comply with the related International regulations, to gain higher safety in management and operation of propulsion system, and benefit for engineers and operators in acquiring skills of propulsion system, a real-time PSS system has been developed as one of the most important sub-systems of ERS. This paper deals with the characters of propulsion plants, and establishes the real-time simulated mathematical models of propulsion plants based on the method of control volume. The main modeled elements consist of the main diesel engine, the fixed pitch propeller, the ship hull, the remote/local control levers, the dynamic and control systems which serve for main diesel engine, i.e. fuel oil system, lubricating oil system, starting and control air system, cooling water system, scavenge air system and exhaust gas system. Especially, the hull-engine-propeller matching model, the marine diesel engine model, the dynamic and control system models are introduced in detail. At the same time, a real-time simulation algorithm is described to meet the demands of rapid response, long running duration and little error accumulation of simulator.

2. Physical Model

The simulated physical model is able to represent the various elements of the propulsion system linked together in a way where the functional relationship between input and output variables are described in terms of functions and differential or algebraic equations[1]. The modeled ship propulsion system and overall functional scheme are shown in Fig.1.
3. Mathematical Models

3.1 Hull-Engine-Propeller Matching Model

According to the actual data of ship trial (shown in table 1), the corrected propeller rotating torque $M_p$, propeller propulsive force $T_p$, ship resistance force $R$, propeller consumed power $P_p$ and the engine indicated power $P_i$ can be defined as [2]:

$$M_p = 3294.0C_Rn_p^2$$
$$T_p = 3059.4C_Tn_p^3$$
$$R = 6.627C_Rv_i^2$$
$$P_p = 20686.0C_RC_mp^3$$
$$P_i = 24393.6C_RC_mp^3$$

(1)

Where, $C_R$ is a gain factor, which can express different navigation conditions and hull conditions of the modeled ship. It is described as:

$$C_R = C_{R1}C_{R2}C_{R3}C_{R4}C_{R5}C_{R6}$$

(2)

Where,

$$C_{R1} = 1 + (0.50931g\frac{2081.125}{125})$$

(3)

$$C_{R2} = \begin{cases} 1.0 & \text{Light breeze} \\ 1.5 & \text{Fresh breeze} \\ 1.8 & \text{Gale} \\ 2.5 & \text{Violent storm} \end{cases}$$

(4)

$$C_{R3} = \begin{cases} 1.0 & \phi = 0^\circ \\ 1.12 & 0 < \phi < 7^\circ \\ 1.25 & 7^\circ < \phi < 25^\circ \\ 1.40 & 25^\circ < \phi < 30^\circ \end{cases}$$

(5)

$$C_{R4} = T_s / T_h$$

(6)

$$C_{R5} = -1111.1x^2 + 1333x - 20 \quad (h/T < 4, 0.3\sqrt{gh} < v_s < \sqrt{gh})$$

(7)

$$C_{R6} = -4x^2 + 8x - 20 \quad (h/T < 3, 0.5\sqrt{gh} < v_s < 1.5\sqrt{gh})$$

(8)

Where,

$$x = v_s / \sqrt{gh}$$

(9)

The distance traveled by the ship:

$$S = \int v_s dt$$

(10)

3.2 Engine Model

The modeled main engine is MAN-B&W 6L80MC /MCE two-stroke low-speed marine diesel engine, which is fitted with two VTR-564-32 exhaust gas turbochargers at 88 r/min rated speed and 16 668kW rated power.

The engine model referred to this paper is a general-purpose engine thermodynamic simulation mode, which is defined as a

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control volume type to treat a multi-cylinder engine as a series of thermo- dynamic control volumes/elements interconnected through valves and ports [3]. All those controllable volumes/elements serve for energy conversion and power output with fuel oil injection, air supply, combustion, heat release and exhaust gas reuse. In the paper, they are described as fuel oil injecting system, combustion system and exhaust turbocharger system, respectively.

3.2.1 Fuel Oil Injecting System
Fuel oil injecting system is to supply the high quality, controllable quantity fuel oil to the combustion chamber during the well-timed shaft angles. It includes the fuel injector pump, the high pressure pipes and the injectors [4] (shown in Fig.2).

Fuel injector pump equations can be described as:

\[
\begin{align*}
\int \rho \cdot udA & = 0 \\
m_f \frac{d^2 h}{dt^2} & = F_0 + \sum p_i A_i - C_x \frac{dh}{dt} \\
dp & = -\beta \frac{dV}{V}
\end{align*}
\]

The fuel oil flow equations in high pressure pipes are described as:

\[
\begin{align*}
\rho \frac{\partial u}{\partial t} + \rho u \frac{\partial u}{\partial x} + \frac{\partial p}{\partial x} + 2k \mu \rho = 0 \\
\rho \frac{\partial u}{\partial x} + \frac{1}{\alpha^2} \left[ \frac{\partial p}{\partial t} + \mu \frac{\partial p}{\partial x} \right] = 0 \\
\frac{\partial \rho}{\partial t} + \frac{\partial p}{\partial x} + \frac{1}{\alpha^2} \left[ \frac{\partial \rho}{\partial t} + \mu \frac{\partial \rho}{\partial x} \right] = 0
\end{align*}
\]

Where, the equations (12) and (13) can be simplified as:

\[
\frac{\partial^2 \mu}{\partial x^2} \left[ \frac{\partial^2 \mu}{\partial t^2} + 2k \frac{\partial \mu}{\partial t} \right] = 0
\]

Fuel injector equations can be described as:

\[
\alpha \frac{dp_f}{dt} = f, \mu_i - \beta \frac{dz}{dt} - \xi \mu_i f, \frac{2}{\rho} |p_f - p_i| \\
m_f \frac{d^2 z}{dt^2} = f, p_f - C_a (z + z_0)
\]

Where,

\[
\beta = \begin{cases} 
0 & \text{When the needle is running} \\
1 & \text{When the needle isn't running} 
\end{cases}
\]

\[
\xi = \begin{cases} 
0 & (p_f - p_i \leq 0) \\
1 & (p_f - p_i > 0)
\end{cases}
\]

The real fuel injection delay angle can be calculated from the initial fuel injection delay angle and the main engine speed, which is defined as:

\[
\Delta \phi_{ev} = \Delta \phi_{ev0} \left( \frac{n}{n_0} \right)
\]
3.2.2 Combustion System

In this section, the triangular combustion model is applied (shown in Fig.3). At the same time, several modifications have been made to meet the demand for failure simulation in full running range described briefly below.

Considering the influence of performance failures to combustion procedure, a term called combustion efficiency is introduced into the heat releasing process. The term is defined as the ratio of completely burned fuel to injected fuel, which is the function of excess air factor $\alpha$ defined in the reference [5]:

$$\eta_v = \begin{cases} \frac{3\alpha}{5} & (\alpha < 1.25) \\ \frac{(\alpha + 1)}{3} & (1.25 \leq \alpha \leq 2) \\ 1 & (\alpha > 2) \end{cases}$$

(21)

Then the rate of released heat can be defined as

$$\frac{dq_f}{d\varphi} = \begin{cases} \eta_v \cdot q_1 & \varphi < 0.35\Delta \varphi \\ -\eta_v \cdot q_2 & 0.35 \leq \varphi \leq 0.65\Delta \varphi \\ -\eta_v \cdot q_3 & \varphi > 0.65\Delta \varphi \end{cases}$$

(22)

Where,

$$q_1 = \frac{q_{\text{in}}}{0.35\Delta \varphi} (\varphi - \varphi_{VB})$$

(23)

$$q_2 = -\frac{0.85q_{\text{in}}}{0.35\Delta \varphi} (\varphi - \varphi_{VB} - 0.35\Delta \varphi) + q_{\text{max}}$$

(24)

$$q_3 = -\frac{0.15q_{\text{in}}}{0.35\Delta \varphi} (\varphi - \varphi_{VB} - \Delta \varphi)$$

(25)

Where, the maximum rate of released heat is:

$$q_{\text{max}} = \frac{2}{0.7475\Delta \varphi}$$

(26)

The ignition angle is defined as:

$$\varphi_{VB} = \begin{cases} -2 & e < 0.66 \\ 4(e - 0.66) - 2 & 0.66 \leq e \leq 0.91 \\ 50(e - 0.91) / 9 - 3 & e > 0.91 \end{cases}$$

(27)

The heat release duration angle is defined as:

$$\Delta \varphi = \Delta \varphi_0 (\alpha_{m0}/\alpha_m)^{0.5} (n/n_0)^{0.5}$$

(28)

The combustion ratio of fuel oil is defined as:

$$m = m_0 (\Delta \varphi_{z1}/\Delta \varphi_{z2})^{0.5} (n_0/n)^{0.5} (p_a/p_{a0})(T_{a0}/T_a)$$

(29)

The mechanical efficiency is defined as:

$$\eta_m = 0.4(n - 60) \times 0.01 + 0.82$$

(30)

3.2.3 Exhaust Turbocharger System

The basic theory of mathematical model to exhaust turbocharger is still the conservation of energy and mass. The mass and energy accumulation in the control volume is considered by means of equations (31) and (32) respectively [1].

$$\frac{d(\rho V)}{dt} = M_i - M_o$$

(31)
The power of turbocharger compressor is defined as:

\[ P_r = \frac{d\dot{m}_r}{dt} (h_3 - h_4) \eta_{TS} \eta_{rot} \]  

(33)

The variety ratio of mass flowrate of exhaust gas from turbocharger is defined as:

\[ \frac{d\dot{m}_r}{dt} = C_r \pi_2 \psi \frac{p_3}{\sqrt{RT_3}} \]  

(34)

The variety ratio of mass flowrate of air from air compressor is defined as:

\[ \frac{d\dot{m}_k}{dt} = \frac{P_k}{h_3 - h_2} \eta_{KS} \eta_{ak} \]  

(35)

The increased temperature of compressed air is defined as:

\[ T_2 - T_1 = T_1 \left( \frac{P_2}{P_1} \right)^{\frac{k-1}{k}} - 1 \]  

\[ \frac{1}{\epsilon \eta_{KS}} \]  

(36)

The turbocharger rotational speed is defined as:

\[ n_{tk} = n_k \frac{T_1}{288} \]  

(37)

### 3.3 Dynamic and Control Systems

#### 3.3.1 Manoeuvring System

The control of propulsion system is performed by the levers: the telegraphs and engine side manoeuvring buttons and handwheel. The lever on the “Engine side manoeuvring console” can be set to either Manual or Remote position. In the Manual position, the engine is controlled from the engine side manoeuvring console by the push buttons START, STOP, and AHEAD/ASTERN. The speed is set by the “Emergency speed setting” by the handwheel. In the Remote position, all signals to the engine are electronic, the START, STOP, AHEAD and ASTERN signals activate the solenoid valves, and the speed setting signal via the electronic governor and the actuator. The electrical signal comes from the remote control system, i.e. the Bridge Control (BC) console, or from the Engine Control Room (ECR), if any.

In order to realize the safe manoeuvring, the seafarers must learn about the requirements of engine manoeuvring. Therefore, the safe manoeuvring sequence of propulsion system with telegraph is emphasized here (shown in Fig.4). The employed manoeuvring sequence diagram\[6\], given by the engine manufacturer, shows the functions as well as the delays which must be considered in respect to starting Ahead and starting Astern, as well as for the activation of the slow down and shut down functions. On the right of the diagram, a situation is shown where the order Astern is over-ridden by an Ahead order.

#### 3.3.2 Dynamic Systems

The level equation of fuel oil tank is described as:

\[ L_f(t) = L_{yo} - \int_{t_0}^{t} C_{mo} \frac{F_m}{A_r} dt + \int_{t_0}^{t} C_{mf} \frac{F_m(t)}{A_r} dt \]  

(38)

Here, only the level of fuel oil tank is given as an example. Other tank’s equations are defined as the same method.

PID controller equation is described as \[7\]:

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a. 105%MCR  b. 100%MCR  c. 90%MCR  d. Braking air level (15-30%)  e. Fuel level (8-12%)  f. Max. astern rotation  g. Start failure  h. Repeated start  i. Slow down  j. Shut down  k. Min. one revolution  m. Approx. 30 minute  n. 6-8 second

Fig. 4 Manoeuvring Sequence Diagram with Remote Control

\[ y_1 = y_0 + \int_{t_0}^{t_1} \left( K_p (x_2 - x_1) + 1/T_i (x_2 + x_1 + x) dt + T_d (x_2 - x_1) + x_0/\partial t \right) \]

Heat exchanger equation is:

\[ t_o(t) = t_x(t) - \frac{1.16 \cdot g \cdot F_{FW} \cdot (t_{V,2} - t_{V,1})}{\omega \cdot A_p} \]

Here only gives an example of static model of steam condenser.

Pump equation is described as [7]:

\[ Q = F_M \cdot C_{PV} \]

The difference of filter pressure between inlet and outlet is described as:

\[ DP(t) = DP_0 + \int_0^t C \cdot F_M(t) \cdot C_{PV} \cdot dt \]

3.4 Equation Solution

The fourth-order Runge-Kutta method is applied in the algorithm of differential equation. This method is reasonably simple and robust and is known to be very accurate and well-behaved for numerical solution of differential equations. Suppose that \( x_n \) is the value of the variable at time \( t_n \), the Runge-Kutta formula takes \( x_n \) and \( t_n \) and calculates an approximation for \( x_{n+1} \) at a brief time later, \( t_{n+1} \). It uses a weighted average of approximated values of \( f(t, x) \) at several times within the interval \( (t_n, t_{n+1}) \). The formula is given by [8]:

\[ x_{n+1} = x_n + \frac{h}{6} \left( k_1 + 2k_2 + 2k_3 + k_4 \right) \]

Where,

\[ k_1 = f \left( t_n, x_n \right) \]

Heat exchanger equation is:

\[ V = V + \int_0^t T = T + \frac{1}{2} \]

\[ t \]

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4. Real-time Simulation Algorithm

In order to meet the demand of rapid operational response, long running duration and little error accumulation for PSS, a new algorithm was made based on the control volume model. Within the possible running range of propulsion plant, running speeds \( n_1, n_2, \ldots, n_{10} \) and fuel racks of engine \( s_1, s_2, \ldots, s_{10} \) were selected, and thermodynamic variables under each running speed \( n_i (i=1,2,\ldots,10) \) and each fuel rack \( s_i (i=1,2,\ldots,10) \) were calculated with the control volume method which formed a variable matrix \( A \) [2]:

\[
A = \begin{bmatrix}
a_{11} & a_{12} & \cdots & a_{1n} \\
a_{21} & a_{22} & \cdots & a_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
a_{n1} & a_{n2} & \cdots & a_{nn}
\end{bmatrix}
\]  \( (m=n=10) \) (48)

Assume the present running speed is \( n \) and actual fuel rack is \( s \) during simulation, thermodynamic variables in vector \( B \) under running speed \( n \) and the fuel racks \( s_i (i=1,2,\ldots,10) \) are firstly gotten with the Newton interpolation method as:

\[
B = \{b_1, b_2, \ldots, b_n\}
\]  \( (50) \)

Then the actual thermodynamic variable \( C \) can be gotten under actual running speed \( n \) and actual fuel rack \( s \) as

\[
C = \left[\frac{(s-s_{i1})(s-s_{i2})}{(s_{i1}-s_{i2})(s-s_{i1}+s_{i2})}\right] b_1 + \left[\frac{(s-s_{i1})(s-s_{i2})}{(s_{i1}-s_{i2})(s-s_{i1}+s_{i2})}\right] b_{i+1} + \left[\frac{(s-s_{i1})(s-s_{i2})}{(s_{i1}-s_{i2})(s-s_{i1}+s_{i2})}\right] b_{i+2}
\]  \( (51) \)

Where \( s_i < s < s_{i+1} \)

A new running speed of diesel engine \( n' \) and the ship speed \( v_r \) can be calculated as:

\[
n' = n + (M_p \times \text{sgn}(D) - M_p \times \text{sgn}(n) - M_v \times \text{sgn}(n))/2 + \pi/Je
\]  \( (52) \)

By this algorithm, thermodynamic variables under any performance condition can be obtained with only eleven interpolating calculations and without plenty of iteration calculation of differential equation which meets the demand of real-time simulation. As every performance condition is computed from the variable matrix \( A \) and has nothing to do with the former running points, it can avoid error accumulation in computation and satisfies the requirement of long running duration of PSS.

The mathematical models of propulsion system discussed in this paper have been realized by suitable algorithm in microcomputer, which have been confirmed by experiment in applications of PSS, and have obtained satisfactory result. The calculated results are compared with the data of ship trial and shown in table 2 [9]. They can realize the requirement of rapid response, long running duration and little error accumulation. One of the Man-Machine Interfaces is shown in Fig.5 as an example.
5. Failure Simulation

It is well known that one of the major factors of accident prevention on board is the perfect theoretical and practical knowledge learned by marine engineers. However, mere theories of propulsion system are not enough. Marine engineers must acquire a feel of physical sense in the operating condition. If the propulsion system is broken, the ship turns into nothing more than a drifting object, which is an extremely dangerous situation [10]. Therefore, PSS should also execute under emergency situation besides routine operation. This kind of training is very difficult to carry out on board ship and is therefore very economical in simulator training which can be of great benefit to seafarers’ calm emotion and strong ability dealing with the urgent situations.

Those who have experience in simulator training recognize that it is an economical and safe way to gain years of sea skills in several weeks of intensive simulator training. It is widely known that it can reduce human errors and prevent catastrophic accidents or loss of life and property through the use of simulator-based training. The simulation system can simulate most of failures or accidents of propulsion system which happen scarcely on board ship and reinforce seafarers’ ability to treat with emergency situations and casualties which can be of great significant to safe navigation at sea. The training of real-time simulation of ship propulsion system can help prevent equipment damage, reduce vessel downtime and increase operational reliability.

6. Functions

Based on the analysis of physical and mathematical models, the software of real-time propulsion system simulator is developed. Its main missions are to realize Man-Machine Interfaces, mathematical models and data transfer among hardware, software and other ERS workstations.

PSS system can provide a cost-efficient shore-based training and evaluation platform for the training and evaluation of ship propulsion system rather than on ships in service.

Combining with automatic control characteristics and operation requirement of propulsion system on ships in service, PSS system can execute the functions of starting, stopping, remote control, manual control and emergency control, safety protection, fault simulation, ACK(acknowledgement), operation recording, operation evaluation and fault alarming, etc [11].

The functions of PSS are based on two objectives: training function and evaluation function.

Training function especially stresses controllable operation environment and reality. It can provide a training platform for the trainees to improve operation skills, master operation methods and processes at some normal and abnormal conditions, and especially be proficient in emergency procedure and safety management.

Evaluation function particularly emphasizes on test and evaluation of trainee abilities about operation, management and problems solutions. PSS system can set some special operation condition, i.e. normal, abnormal and emergency work condition, to evaluate trainee’s general ability (refer to Fig.6).
7. Conclusions

Different from other scientific educations, MET puts more emphasises on the training for practical skills to cultivate responsible and well-educated licensed seafarers who are certified to be compliant with requirements of the STCW95 Convention and the related Codes. It is now becoming common sense in maritime societies to use the simulators as testing tools in granting certificates.

Based on the mathematical model of propulsion system and the real-time simulation algorithm, a new real-time propulsion system simulator is developed. This simulator can provide a cost-effective shore-based training and evaluation platform for testing, evaluating and debugging for propulsion system rather than on ships in service. It can simulate most of failures or accidents of ship propulsion system and reinforce seafarers’ ability to treat with emergency situations and reduce accidents due to human factors, which may have significant impact on the safety and efficiency of navigation at sea. The trainees can not only acquire the knowledge regarding the operation of propulsion system in normal conditions, but also familiarize with emergency situations. In consequence, the trainee can be better prepared to deal with emergencies during operations on board ship. Especially, the emergency situations may be simulated and repeated as many times as it is necessary for the trainees to achieve proper training goals.

PSS system has been used successfully as one of MET tools not only in training marine engineering students, but also in training engineers since 2000, with which trainees have possibilities to develop operation skills, and be proficient in emergency procedures and safety management. It is benefited in preventing ship damage and catastrophic accidents, reducing human errors in operation and maintenance of ship propulsion system, and making ships safer.

Notations

\( A \) area \( m^2 \) general air constant in Eq.34 \( kJ/(kg.k) \)

\( b \) channel width \( m \) actual fuel rack ---

\( B \) ship width \( m \) sailing distance \( m \)

\( C \) coefficient --- \( t \) time \( s \)

\( D \) main engine running direction --- temperature in Eq.40 \( K \)

\( e \) cyclical fuel charge ratio of calculated condition to rated condition --- \( T \) thrust in Eq.1 \( kN \)

\( f \) sectional area \( m^2 \) temperature in Eq.37 \( K \)

\( F \) flowrate \( m^3/h \) \( T_d \) derivative gain \( s \)

\( g \) indicated value in Eq.41-42 \( kg/h \) \( T_i \) integral gain \( s \)

\( h \) the acceleration of grvity \( m/s^2 \) \( u \) flow velocity \( m/s \)

\( k \) channel depth in Eq.7-9 \( m \) specific internal energy in Eq.32 \( kJ/kg \)

\( k \) stroke of injector pump in Eq.11 \( m \) speed in Eq.1,9 \( m/s \)

\( k \) specific enthalpy in Eq.32-33 \( m \) specific volume in Eq.31 \( m^3/kg \)

\( k \) the step size of calculation in Eq.43-47 --- \( V \) volume \( m^3 \)

\( K_p \) proportional gain --- \( \alpha \) velocity of sound in Eq.13-16 \( m/s \)

\( L \) depth \( m \) instant excess air factor ---

\( m \) mass \( kg \) \( \alpha_{ex} \) instant excess air factor ---

\( M \) torque in Eq.1 \( Nm \) \( \beta \) =0, when the needle valve closed ---

\( M \) mass flowrate in Eq.31-32 \( kg/s \) \( \beta \) =1, when the needle valve opened ---

\( n \) rotation speed \( r/min \) \( \Delta \) difference \( ^\circ \)

\( p \) pressure \( Pa \) \( \phi \) rudder angle in Eq.5 \( ^\circ \)

\( P \) power \( kW \) angle in Eq.22-28 \( ^\circ \)

\( Q \) released heat in Eq.22 \( kJ \) \( \phi_{in} \) ignition angle \( ^\circ \)

\( R \) pump displacement in Eq.41 \( m^3 \) \( \eta \) efficiency \( % \)

\( R \) resistance \( kN \) \( n_e \) combustion efficiency \( % \)

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AP7: Real-time Simulation of Ship Propulsion System

\[ \pi_t \] expending ratio in turbocharger

\[ \Theta \] angle from wind direction to ship sailing direction

\[ \rho \] density in kg/m³

\[ \tau \] duration since the latest hull cleaning in terms of year

\[ \tau_i \] = 1.04~1.10

\[ \omega \] mean coefficient for heat exchange of liquid film on pipe’s surface $W/(m²·K)$

\[ \xi \] = 0, when $P_f - P_z \leq 0$

\[ \psi \] function affected by air flow

\[ \Theta \] heat flow $kJ/s$

\[ \Delta \phi \] duration angle

Indices:

\[ FVI \] inlet valve of fuel oil tank

\[ FVO \] outlet valve of fuel oil tank

\[ FW \] fresh water

\[ K \] turbo compressor

\[ l \] level

\[ i \] indication

\[ M \] torque in Eq.1

\[ P \] propeller in Eq.1

\[ PV \] pump in Eq.38,41

\[ P' \] flow coefficient

\[ s \] ship

\[ S \] saturation steam

Subscripts:

\[ \hat{\Theta} \] initialization value

\[ i \] sequence

\[ a \] air

\[ B \] ballast

\[ c \] coefficient

\[ e \] engine

\[ EV \] fuel injection delay angle

\[ f, F \] fuel oil

\[ t \] time

\[ T \] thrust in Eq.1

\[ V \] valve

\[ W \] water

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