Fault Simulation of Main Engine System for Engine Room Simulator

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ABSTRACT

An engine room simulator has recently been developed to simulate the behaviors of a 2700 TEU container ship under different performance faults and different running conditions. This paper introduces the mathematical models of the main diesel engine including chamber combustion model, variable injection timing model and hull-propeller-engine model. A real time simulation algorithm is described to meet the demands of rapid response, long running duration and little error accumulation of the simulator. Typical performance failures, structural faults and boundary conditions of main engine were simulated and their simulation models are briefly mentioned in this paper. Seafarers operation to the simulated faults can be assessed and operation-assessing algorithm is also introduced in this paper.

1. Introduction

The demands of modern ship operations require that deck and engineering officers should be taught more than the standard technical skills of their craft. Statistical data from the United States National Transportation Safety Board as well as several international organizations site human factors as the cause of 75% ~ 80% of all investigated commercial marine casualties. In 1995 the International Maritime Organization (abbreviated to IMO) amended the implementation of the international convention on Standards of Training, Certification Convention and Watch-keeping (abbreviated to STCW) for seafarers (1978) and formed the STCW 78/95 convention. This convention stressed the importance and the necessity of simulator training in examination and assessment for certification of competency.

To satisfy the requirement responsible for the training, examination and assessment of competency certification of seafarers in eastern China, a marine engine room simulator has been accomplished which includes main engine system, power plant station and auxiliary machinery system and alarm system. The simulated ship is a 2700 TEU container carrier of Shanghai ocean shipping company, which is 236 meters long and 32.2 meters wide .The main engine is MAN B&W 6L80MC two stroke diesel engine, whose bore is 0.8 meter and stroke is 2.592 meters. Fitted with two VTR-564-32 exhaust gas turbochargers its rated speed is 88 r/min and rated power is 16668 kW.

2. Mathematical Models

2.1 Engine Models

The engine model referred to in this paper is a general-purpose engine thermodynamic simulation code. The model is control volume type, which treats a multi-cylinder engine as a series of thermodynamic control volumes interconnected through valves and ports. Several modifications have been made to meet the demand for fault simulation within full running range briefly described below.

To take into account the influence of performance faults to combustion procedure, a term called combustion efficiency was inducted into the heat release. The term is defined as the ratio of completely burned fuel to injected fuel, which is the function of excess air factor_defined as

$$\eta_u = \begin{cases} 3\alpha / 5 & (\alpha < 1.25) \\ (\alpha + 1) / 3 & (1.25 \le \alpha \le 2) \\ 1 & (\alpha > 2) \end{cases} \tag{1}$$

Then the rate of heat release can be defined as

$$\frac{dQ_f}{d\varphi} = \begin{cases} \eta_u \cdot \frac{M_{x0}}{0.35\Delta\varphi}(\varphi - \varphi_{VB}) & \varphi < 0.35\Delta\varphi \\ -\eta_u \cdot \frac{0.85 M_{x0}}{0.35\Delta\varphi}(\varphi - \varphi_{VB} - 0.35\Delta\varphi) + \eta_u \cdot M_{x0} & 0.35 \le \varphi \le 0.65\Delta\varphi \\ -\eta_u \cdot \frac{0.15 M_{x0}}{0.35\Delta\varphi}(\varphi - \varphi_{VB} - \Delta\varphi) & \varphi > 0.65\Delta\varphi \end{cases} \tag{2}$$

Where the maximum heat release rate is

$$M_{x0} = \frac{2}{0.7475\Delta\varphi} \tag{3}$$

The ignition angle is

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

The heat release duration angle is

$$\Delta\varphi = \Delta\varphi_0 (n/n_0)^{0.5} \tag{5}$$

The mechanical efficiency is

$$\eta_m = 0.4(n - 60) \times 0.01 + 0.82 \tag{6}$$

Where,

$\Delta\varphi_0$: Heat release duration angle at rated condition with no performance failure_

n_0: Running speed at rated condition_

n: Running speed at calculated condition_

e: Cyclical fuel charge ratio of calculated condition to rated condition.

A three-zone scavenging mode with fresh air, exhaust gas and mixing zones was used. Turbocharger compressor and turbine experimental performance maps were included in digitized form and the code can interpolate within the data to find the operating point.

2.2 Hull-propeller-engine Model

According to the ship trial when ship draft was 5.86 meters with clean hull, no ocean current, no wave, no excess 2 scale wind the ship sailing speed was 21.16 knot and the main engine speed was 93.3 r/min. Then the propeller rotating torque M_p, propeller propulsive force T_p, ship drag force R, propeller consuming power P_p and the engine indicated power P_i can be as

$$M_p = 3294 K_M n_p^{\ 2} \tag{7}$$

$$T_p = 3059.4 K_T n_p^{\ 2} \tag{8}$$

$$R = 6.627 v_s^2 \cdot Y_R \tag{9}$$

$$P_p = 20686 K_M n_p^3 \cdot Y_R \tag{10}$$

$$P_i = P_p / (\eta_m \eta_{rt} \eta_w) = 24393.6 K_M n_p^3 \cdot Y_R \tag{11}$$

Where Y_R is a gain factor which can express different navigation conditions and hull conditions of the ship as:

a) Hull cleanliness

$$Y_R = 1 + (0.50931\text{g}\,\tfrac{20t+125}{125}) \tag{12}$$

Where t is the duration since the latest hull cleaning in terms of year.

b) Wind scale

$$Y_R = \begin{cases} 1.0^{-\cos\alpha} & \textit{Light breeze} \\ 1.5^{-\cos\alpha} & \textit{Fresh breeze} \\ 1.8^{-\cos\alpha} & \textit{Gale} \\ 2.5^{-\cos\alpha} & \textit{Voilent storm} \end{cases} \tag{13}$$

Where_is the angle from wind direction to ship sailing direction.

c) Rudder angle

$$Y_R = \begin{cases} 1.0 & 0^0 \\ 1.12 & 7^0 \\ 1.25 & 25^0 \\ 1.40 & 30^0 \end{cases} \tag{14}$$

d) Shallow and narrow navigation channel

$$Y_R = \begin{cases} -11.11x^2 + 13.33x - 2.0 & h/T < 4 \ , \ v_s > 0.3\sqrt{gh} \ , \ v_s < \sqrt{gh} \\ -4x^2 + 8x - 2.0 & b/B < 20 \ , \ v_s > 0.5\sqrt{gh} \ , \ v_s < 1.5\sqrt{gh} \end{cases} \tag{15}$$

$$x = v_s / \sqrt{gh} \tag{16}$$

Where,

v_s :Ship sailing speed(m/s)_

h: Channel depth(m)_

T :Ship draft(m)_

b: Channel width(m)_

B: Ship width (m).

e) Ship draft

$$Y_R = Y_R / T_s \tag{17}$$

Where T_s is ballast draft.

2.3 Real time Simulation Algorithm

To meet the demand of rapid operational response, long running duration and little error accumulation for engine room simulator, a new algorithm was made based on the control volume engine model. Within the possible running range of main engine, running speeds n_1, n_2, , n_{10} and fuel racks S_1, S_2, S_{10} were selected and thermodynamic variables under each running speed n_i and each fuel rack S_i (i=1,2, ,10) were calculated with the control volume method which formed a variable matrix A

$$A = \begin{array}{c} \\ n_1 \\ n_2 \\ \cdot \\ \cdot \\ \cdot \\ n_m \end{array} \begin{array}{c} \begin{array}{cccccc} s_1 & s_2 & \cdot & \cdot & \cdot & s_n \end{array} \\ \begin{bmatrix} a_{1,1} & a_{1,2} & \cdot & \cdot & \cdot & a_{1,n} \\ a_{2,1} & a_{2,2} & \cdot & \cdot & \cdot & a_{2,n} \\ \cdot & \cdot & & & & \cdot \\ \cdot & \cdot & & & & \cdot \\ \cdot & \cdot & & & & \cdot \\ a_{m,1} & a_{m,2} & \cdot & \cdot & \cdot & a_{m,n} \end{bmatrix} \end{array} \tag{18}$$

$$(m = 10, n = 10)$$

Suppose the present running speed is n and actual fuel rack is S during simulator s training, thermodynamic variables in vector B under running speed n and 10 fuel racks S_i (i=1,2, ,10) are firstly got with Newton interpolation method as

$$\begin{array}{cccccc} & s_1 & s_2 & \cdot\ \cdot\ \cdot & s_n & \\ B = & \{b_1 & b_2 & \cdot\ \cdot\ \cdot & b_n\} \end{array} \tag{19}$$

Then the actual thermodynamic variable C can be got under actual running speed n and actual fuel rack S as

$$C = \frac{(s-s_{i+1})(s-s_{i+2})}{(s_i-s_{i+1})(s_i-s_{i+2})} b_i + \frac{(s-s_i)(s-s_{i+2})}{(s_{i+1}-s_i)(s_{i+1}-s_{i+2})} b_{i+1} + \frac{(s-s_i)(s-s_{i+1})}{(s_{i+2}-s_i)(s_{i+2}-s_{i+1})} b_{i+2} \tag{20}$$

Where $s_i < s < s_{i+1}$

With 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 avoids error accumulation in computation and satisfies the requirement of long service duration of engine room simulator.

When driven by torque, a new running speed of main engine n and sailing speed of container ship v_s can be got as

$$n = n + (M_e \times \mathrm{sgn}(Dr) - M_p \times \mathrm{sgn}(n) - M_f \times \mathrm{sgn}(n)) / 2 / \pi / Je$$
$$v_s^{'} = v_s + (T \times \mathrm{sgn}(n) - R \times \mathrm{sgn}(v_s)) / m / (1 + 0.06) \tag{21}$$

Where,

M_e: main engine torque moment (N.m);

Dr: main engine running direction;

M_f: propeller resistant moment (N.m);

m: ship mass (kg).

3. Fault Simulation

3.1 Simulated Objectives

Besides routine operations engine room simulator should also execute under emergency situations or with engine performance failures. This kind of training is very difficult to carry out on board ship and therefore very economical in simulator training which can be of great benefit to seafarers calm emotion and strong ability dealing with the urgent situations. The urgent training courses for marine main engine have been stipulated in STCW 78/95 as shown in Table 1.

Table 1. Urgent Training Courses for Marine Main Engine in STCW 78/95

Emergency operations	Local control:	Starting, stopping, accelerating, decelerating, reversing.
	Emergency control:	Over-control, restriction-canceling, emergency-stopping.
	Emergency operation:	Fuel cut-off, piston withdrawing, turbocharger stopping.
	Over speeding and over loading:	
	Abandoning and fleeing:	
Fault Fixing	Main engine fault:	Turbocharger surging, scavenging belt firing, trouble shooting of thrust bearing, cylinder, piston ring, etc.
	Facility fault:	Remote control system, monitoring system, safety system, cooling system, lubricant system etc.
	Axial and propeller fault:	Trouble shooting of main shaft, main journal bearing, fix pitch propeller or controllable pitch propeller.

3.2 Fault Models

Main engine faults can be classified as malfunctions, structural faults and abnormal boundary conditions. By varying input data and model coefficients of the control volume model engine faults can be simulated. The selected input data and model coefficients of some simulated faults referential to normal condition are shown in Table 2 ~ Table 4. Besides thermodynamic variables, some other multi-media symptoms such as exhaust fume, abnormal noises were also used to simulate the faults as shown in Table 5.

Table 2. Input Data and Model Coefficients for Structural Faults

Performance Fault	Input Data and Model Coefficients		
	Normal Data	Abnormal Data	Data Descriptions
Fuel injector needle worn	80 °CA/g_f	104 °CA/1.1g_f	Injection duration angle/ Fuel charge
Fuel injector nozzle deposit	-2.5°CA/80 °CA	5.0 °CA/96 °CA	Ignition angle/Injection duration angle
Fuel pump plunger worn	-2.5°CA/80 °CA	-1.25°CA/104 °CA	Ignition angle/Injection duration angle
Turbocharger bearing worn	0.98	0.88	T/C mechanical efficiency
Piston scraping	M_f	0.3M_e	Engine mechanical resistance
Propeller blade taken off	M_p	0.8M_p	Propeller resistance torque

Table 3. Input Data and Model Coefficients for Malfunctions

Performance Fault	Input Data and Model Coefficients		
	Normal Data	Abnormal Data	Data Descriptions
Fuel injection too early	-2.5 ^{o}CA	-15 ^{o}CA	Fuel ignition angle
Fuel injection too late	-2.5 ^{o}CA	15 ^{o}CA	Fuel ignition angle
Scavenging belt deposit	0.45	0.20	Air flow coefficient at inlet port
Exhaust port deposit	0.50	0.40	Air flow coefficient at outlet port
Carbonized piston top	300_	500_	Piston top average temp.
Cylinder jacket air-blocked	1.0	0.20	Heat transfer coefficient to liner wall
Turbocharger air filter blocked	0.1033 MPa	0.095 MPa	Air inlet pressure of T/C
Turbo nozzle foul	$0.0054m^2$	$0.0035m^2$	Flow area of turbine nozzle
Exhaust boiler deposit	0.103MPa	0.1074MPa	T/C exhaust back-pressure
Too much water in fuel	100%	50%	Fuel charge of all cylinders
Main bearing lubricant poor	0.89	0.70	Engine mechanical efficiency
Piston seizuring	M_f	$2.0M_e$	Engine mechanical resistance

Table 4. Input Data and Model Coefficients for Boundary Conditions

Performance Fault	Input Data and Model Coefficients		
	Normal Data	Abnormal Data	Data Descriptions
Ambient temperature too high	27_	45_	Compressor air inlet temp.
Ambient temperature too low	27_	0_	Compressor air inlet temp.
Propeller fishnet-bound	M_p	1.2 M_p	Propeller resistance torque
Cylinder liner cooled poorly	200_	500_	Liner surface average temp.
Piston top cooled poorly	300_	600_	Piston head average temp.
Inter-cooler cooling water inlet temperature too high	45_	70_	Cooling water inlet temperature of inter-cooler
Inter-cooler cooling water inlet temperature too low	45_	0_	Cooling water inlet temperature of inter-cooler

Table 5 Multi-media Symptoms of Simulated Faults

Faults	Abnormal noise	Exhaust fume	Animation
Fuel Injection too early	Knocking inside chamber	Gray gas	
Fuel injection too late		Gray gas	
Scavenge port deposit	Turbocharger surging	Black gas	
Fuel injector needle worn		Block gas	
Fuel pump plunger worn		Block gas	
Piston ring leakage		Block gas	
Exhaust passage deposit	Turbocharger surging	Block gas	
Cylinder liner crack		White gas	
Scavenge case firing	Turbocharger surging	Block gas	Firing in scavenge belt
Piston scrapping	Knock inside chamber	Gray gas	
piston seizuring	Rubbing noise inside	Block gas	
Turbine nozzle foul	Turbocharger surging	Gray gas	
Turbocharger worn		Block gas	
Exhaust boiler deposit	Turbocharger surging	Block gas	
Crankcase explosion	Explosion		Dark smoke at crankcase door
Propeller blade taken-off	Big noise		

3.3 Operation Assessment

Every fault is provided with up to eight choices for seafarers to select. Each choice has an operation description and an assessing score. If selected operation is correct to the simulated fault the assessing score will be counted in; otherwise the assessing score will be discounted. Some incorrect operation choice can even induce consequent faults, that is, if these incorrect operations are selected, other critical faults will occur afterwards and the assessing score will be very low. Table 6 gives out the operation descriptions, corresponding scores and possible consequent fault for the simulated piston-scrapping fault.

Table 6 Operation Assessment for Piston Scrapping Fault

Provision Operations	Score	Consequent Fault
Check the temperature of each jacket cooling water, cut off fuel to this cylinder and run M/E continuously at lower speed.	40	
Increase piston-cooling lubricant to this cylinder.	40	
Check and increase cylinder lubricant to this cylinder.	20	
Increase jacket-cooling water to cylinder to strengthen liner cooling.	-80	Piston seizure
Open the indicator cock to get rid off accumulated air and dirtiness.	20	
Stop M/E gradually, lift out the piston and examine it carefully.	20	
Stop M/E immediately, lift out the piston and examine it carefully.	-70	
Pour kerosene to piston s interface firstly if the piston is stuck and then lift out the piston slowly.	30	

Assume the assessment score matrix is B and selection item vector is C

$$B=\begin{bmatrix} s_{11} & s_{12} & . & . & . & s_{1n} \\ s_{21} & s_{22} & . & . & . & s_{2n} \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ s_{m1} & s_{m1} & . & . & . & s_{mn} \end{bmatrix} \tag{20}$$

$(m{=}33, n{=}8)$

$$C=\{c_1\ c_2\ \quad c_n\} \tag{21}$$

Where,

$$c_i=\begin{cases} 0 & not \quad selected \\ 1 & selected \end{cases} \tag{22}$$

If $i^{\#}$ fault is simulated and operation choices are selected, the assessment score w will be

$$w=\sum_{k=1}^{8} s_{ik}\cdot c_k \tag{23}$$

The assessment report can be printed out after training, which includes trainee name, training course, selected operations and assessed score.

4. Software Design

Developed in Visual Basic visible programming language, the main engine simulation system includes 20 software interfaces such as gas combustion chamber, supercharging and air exchanging, oil lubricating, gas pressure indicating, fuel pressure indicating, bar graph variable, piston ring wearing, condition monitoring, thermodynamic report and fault operation.

With timer1, timer2, timer3 software timers, main engine system keeps contact with other hardware facilities such as dynamic MIMMC panel, audio devices, local control console, remote control console, bridge control console, power distribution board. It also keeps contact with other simulation software systems such as instructor system, auxiliary machinery system, alarm system and instruction system.

According to instructor s commands, main engine simulation system can run under different models as

- l Testing model: Self-testing the software function with standard data file. This model is used for self-checking of simulation system when necessary.
- l Online model: Communication is kept with all the hardware facilities and software systems via network. Any operation on hardware facilities can take effect upon all simulation systems. This model is used for full-scale training of marine engine room.
- l Isolation model: Simulation system is divided into power station system, main engine system and auxiliary machinery system isolated from each other. This model is used for small-scale training for some a specific system.
- l Offline model: Communications between hardware and software systems are cut off and all the operation can be only executed on software interfaces. This model is used in the student training terminals where landlubbers can get to know some background knowledge and basic operation rules.

With timerl the software system continuously obtains commands such as running model, ship navigation condition, time scale and fault code from instructor system at 5 seconds intervals. With timer2 it receives boundary variables from auxiliary machinery system and sends out calculated results to auxiliary system and alarm system. With timer3 it gets user operation on hardware consoles and sends out digital parameters to hardware gauges or indicators. As mentioned above the simulation system can emulate most of faults or accidents of marine main engine, which happen scarcely on board ship and reinforce seafarers ability to treat with emergency situations and casualties. This can be of great significance to safe navigation at sea.

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Author s Biography

Hu Yihuai, Male, born in 1964. He got his Ph.D. from Wuhan Science & Technology University in 1993 and worked as a postdoctoral researcher in Huazhong University of Science & Technology during 1993 to 1995. He works now in Shanghai Maritime University as a teacher, especially in the research into fault diagnosis of machinery systems, development of engine room simulator and teaching in marine engineering.