Modelling reasonable operation regimes of the main propulsion plant main diesel engine - propeller - hull on the general cargo ship

Prof. DSc. Do Duc Luu, Prof. Dr. Luong Cong Nho, Dr. Tran Ngoc Tu

Vietnam Maritime University
luudoduc@gmail.com; luongcongnho@vimaru.edu.com;tutn.dt@vimaru.edu.vn

Abstract: The article presents the modeling results of the characteristics of main propulsion plant Diesel Engine – Propeller – Hull, based on the combination of the analytical method and regressive analysis of the empirical data. The authors create the algorithms on the base of the created models to select the reasonable operating regime of the main propulsion plant (MPP) according to the different operating conditions (in still water, in sea wave, in the canal, etc.). This paper provides the numerical simulation results of the drawn combination characteristics of MPP on the 34000 DWT general cargo ship built in Vietnam with the main engine MAN 6S 46 MCC, and of the selected regime respectively the desired operated conditions. The research results would be used for the simulation of monitoring and controlling the MPP on the general cargo ship, in order to improve the education quality of the electrical and marine engineering field at Vietnam Maritime University.

Keywords: Main Engine, Propeller, Hull resistance, Main Propulsion Plant.

1. Basis of selecting reasonable exploitation regime

Choosing reasonable working regime of the combination of hull – propeller - main engine under different exploitation regimes ensures the safety of diesel main engine (DME), so that mechanical and thermal overload may not be occurred. In addition, the proposing voyage efficiency of (time, economy) for a cargo ship and sea-going cargo fleet can be achieved by choosing reasonable exploitation regime of engine's revolutions and ship's speeds in different environmental conditions, in which MPP works. Further more, the efficiency of reasonably exploiting working regime of MPP is not only suitable for ship's working purpose from the concepts of safety, high reliability and economy, but also ensures environmental norms set by International Association of Classification Societies (IACS).

The frequent regimes in MPP's exploitation of a marine vessel: working in still water, carrying cargo (Cargo Load Index, CLI) from ballast (CLI = 0) to full load (CLI = 100%); working in sea wave and wind with given CLI; working in canal; vessel in shallow water. In working process, the resistance states of ship hull and propeller are deteriorated. In this case, the reasonable exploitation regime of MPP may varies from normal exploitation regime (normal regime).

During operating the marine vessel's MPP, the captain chooses the revolution regime of the DME (from the Control Bridge) or gives a command to the engine control room (ECR), which is recommended by the Chief Engineer in order to have the desired velocity in practice. The engineer- officer staff, who chooses the exploitation revolution regime of main propulsion shaft (MPS), firstly follows the captain bidding, but need to ensure the working safety of MPP: DME is not overloaded, MPS does not fall into the area of dangerous revolutions; secondly ensures the Specific Fuel Oil Consumption (S.F.O.C) with possible minimum, attached to supervision of environmental norms in chosen DME regime.

To have necessary knowledge and skills to manage and operate the MPP in different operating regimes, the education and training electro-mechanical crew, as well as deck officer with the management level is only deployed by independent simulation software for self-studying, self-improving ability or by intergraded software's module built in the simulation system of ECR. The essence of building imitation software is to establish mathematical model and algorithm to select reasonable exploitation regime for MPP in all situations that may happen in reality. In the process of researching this complicated issue, we can choose one of mathematical models with different accuracy and coherence, which is illustrated by general cargo ship 34000 DWT, used DME of brand MAN 6S 46MCC built in 2013 (in Pha Rung Shipyard, Hai Phong city, Vietnam).

Choosing reasonable exploitation regime for MPP of marine vessel, which is set up for educating and training engineering cadets, and officer training courses, is a fundamental problem. In different levels of training programme, the principle of diesel operation follows the guide of diesel operation provided by the engine manufacturer [**1**, **2, 3**] to ensure the DME the thermo-mechanical safety, the working regime with the minimum S.F.O.C ($\mathbf{g_e}$ =min). In technical file provided by the ship builder or diesel manufacturer as well as the data of sea trial test and the certification of the diesel, there are characteristic curves that allows to exploit engine, by which we may assess the area of the MPP exploitation. For example, for the ship 34000 DWT mentioned above, following the engine document of MAN 6S 45MCC, engine factory [**6**] provides the table of test data in 4 loading regimes with power 25-50-75-100% of the normal power and the measured parameters: engine revolution ($\mathbf{n}_E$, rpm); fuel pump index (FPI, $\mathbf{h}_p$), maximum combustion pressure ($\mathbf{P}_z$, Bar), maximum compression pressure ($\mathbf{P}_c$, Bar), mean effective pressure (**MEP**, $\mathbf{P}_{me}$, Bar), the Specific Fuel Oil Consumption (S.F.O.C, $\mathbf{g}_e$, g/kWh), air intake pressure ($\mathbf{P_{scav}}$, Bar), speed of turbo-changer (n_T, rpm). In the ship sea trial test document [**7**], the data table of measured test regimes and parameters: mean revolution of propeller ($\mathbf{n}_p$, rpm), ship speed (**V**, mile/h, or $\mathbf{V}_p$, m/s), torque (**M**, kNm), relatively the 4 test regimes of consumption power (N_p%) is given. In addition, the operation guidance of DME – engine MAN 6S 46 MCC [**5**] shows the characteristics of DME working limit and characteristics of propeller limited by operating revolution as figure 1.

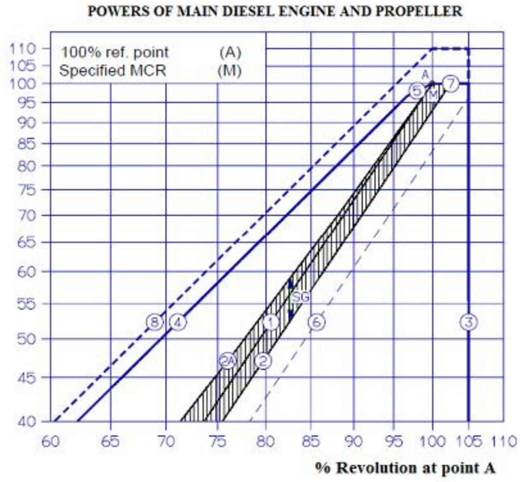

Figure 1 Power Diagram for MPP, used MAN 6S 46 MCC [5]

Line 1- Propeller curve through point A; Line 2 – Propeller curve, heavy running, recommended limit for founled hull at calm weather condition; Line 3 –Speed limit; Line 4- Torque /speed limit; Line 5 –Mean Effective pressure limit; Line 6 –Propeller curve, light running (rang 2.5 -5.0%) for clean hull and calm weather condition; Line 7 –Power limit for continuous running; Line 8 –Overload limit.

The limited power characteristics, given in the figure 1, provide us rather full information to maintain safely exploitation DME and propeller. However, characteristic line $g_e(n)$ and speed area of dangerous resonance are still not given.

It is essential for exploitation to get the information and maintain ship speed according to the propeller's revolution (through engine revolution and the transmission ratio of gear-box). Therefore, the graph of characteristic V-n combined with power characteristics ($\mathbf{N_E(n)}$, $\mathbf{N_p(n)}$) [**1**,**2**,**4**] is often used.

In essence, the problem of choosing reasonable exploitation regime is optimal control problem, the main control parameter is revolution of main engine $\Omega=\omega/\omega_n$ (relative revolution Ω by normal revolution ω_n (radian/s), n – rpm) in the reality of exploitation conditions (X- vector of parameters affecting the choice of control law), consists of choosing parameters in order to set up initial control regime for the voyage (slow change): x_1– CLI (Cargo Load Index, from 0 -100%); x_2 and x_3– surface roughness state of hull and propeller relatively (changing by the number of working months after the ship last dry dock); x_4– vessel in shallow water; x_5– vessel in canal with limited depth and width and fast changing parameters (or stochastic) in the voyage; x_6 –wave and wind, $X=[x_1, x_2, ..., x_6]$. Two parameters, which are affected directly to control the engine revolution in the MPP with DME (with turbo-changer), are the fuel pump index, h_p (or relative position $\lambda=h_p/h_{pn}$) and scavenge air pressure (P_k (Bar), or $\rho = P_k/P_{kn}$) to ensure working process of DME in the revolution regime n (rpm), or relative revolution ($\Omega=n/n_n$, or $\Omega= \omega/\omega_n$), at the same time ensure appropriate economical, technical and environmental parameters. Model of control exploitation revolution is chosen as one of these following formal equations:

$$t = \Omega(\mathbf{X}); \tag{1}$$

$$t = \Omega({}^{a}, {}^{\circ}, \mathbf{X}), \tag{2}$$

The next model depends on rotational current velocity state μ_c(rad/s):

$$t = \Omega({}^{a}, {}^{\circ}, \mathbf{X}, \mu_c) \tag{3}$$

The system of essential models in controlling exploitation regime consists of:
- Limiting characteristic models in exploiting engine, propeller and ship hull relatively on the coordinates of power- revolution- velocity;
- Current state models of engine power, propeller's consumption power, ship speed following real exploitation condition $\mathbf{X}=[x_1, x_2, ..., x_6]$;
- Models that give the solution for reasonable operation regime.

In this article, the authors present the establishing the basic models as above and some results received for MPP of general cargo ship 34000 DWT used DME 6S46 MCC, which was built in Vietnam in 2013.

2. Mathematical models of characteristics on the coordinates N –n –V

2.1 Limited characteristics

Input database (DB) in building model is limited characteristic curves, given by engine manufacturer and shipyard. This DB is relative and contains noises, thus the data, obtained from the graph and used to input into the DB input data table, does not require high accuracy. It is important to investigate the reliability of the model according to the appropriate standard statistic, such as Fisher standards. The building method of regression models bases on the Least Square of Errors Method (LSEM) .

Mathematical basis of building regression model of experimental data in function $\mathbf{y_m}=\boldsymbol{f(a, x)}$, contains required coefficient vector $a=[a_1, a_2,\ldots, a_n]$, at a time $x_1, x_2,\ldots, x_N$ and measuring value relatively $y_1, y_2,\ldots, y_N$ is paraphrased shortly as below:

Error between required regression model and measuring values at a certain measured time k: $£_k = \boldsymbol{f(a, x_k) - y_k}$. The coefficient vector $\boldsymbol{a}$ is found in order to minimize the sum of squares of the errors so we have function: $J = \sum_{k=1}^{N} (f(a, x_k) - y_k)^2 \rightarrow \min$

Since then, we take the partial derivative of each coefficient a_m, with $m=1\rightarrow$ n, $n: \partial J / \partial a_m = 0$ and receive the system of $\boldsymbol{m}$ simple linear equations with m unknowns of elements in vector $\boldsymbol{a}$. Resolve this equation system we get vector with solution $\boldsymbol{a}$. Received solution of regressive equation is checked reliability (accuracy) by statistical method, Fisher function.

Limited characteristic in figure 1, although graphs' figure can be seen as straight lines, but in fact they could be high-order polynomial functions, for example, characteristic lines of propeller are often exponential function $N_p = c.n^3$. As researching results of choosing model, the authors realized that power characteristics of diesel propullsion plant - propeller have general figure and the best suitable is third-order polynomial [**2**]:

$$\boldsymbol{y = (a_1 + a_2.x + a_3.x^2)x} \tag{4}$$

in which, coefficients $\boldsymbol{a_j}$ (j=1,2, 3) are found by input data and algorithm use LSEM
The authors create file writing in MATLAB for statistical processing and establishing regressive functions.The result of models applied to ship 34000 DWT is shown in the table 1 by input data corresponding to lines (Line 1 → 8) in the figure 1.

Table 1 Regression model of limiting characteristics for MPP used MAN 6S46MCC

Name of characteristic lines	Model's coefficient (2)			$F_{ref.}(4,n_s,0.99)$	$F_{calculate}$
	a_1	a_2	a_3		
Line 1- Propeller curve through point A	0.0000	0.0350	0.9661	12.06; n_s=5	7.11e+03
Line 2 –Propeller curve, heavy running	0.0001	-0.1493	1.1058	12.06; n_s=5	1.51e+03
Line 2A –Total Load curve, heavy running, $N_L = N_P + N_{Gen.}$	0.0001	0.2077	0.7913	12.06; n_s=5	5.27e+03
Line 3 –Speed limit, t **= 1.05**	-	-	-	-	-
Line 4- Torque /speed limit	-0.0002	1.0707	-0.0420	6.22; n_s=10	1.02e+03
Line 5 –Mean Effective pressure limit	1.0000				
Line 6 –Propeller curve, light running (range 2.5 -5.0%) for clean hull and calm weather condition	0.0000	0.0037	0.8320	12.06; n_s=4	4.10e+03
Line 7 –Power limit for continuous running, 1.0 < t *<1.05*	1.1	0	0	-	-
Line 8 –Overload limit.	-0.0001	1.0979	0.0064	5.95; n_s=11	1.97e+03

Utilization characteristic when exploit MPP of vessel 34000 DWT with DME MAN 6S46MCC is the revolution's area of torsional vibration with dangerous resonance $a\mu_{BARR(1)}$=(33 – 43) (rpm), or $a\,t_{BARR}$ =[0.26, 0.33] in case of all cylinders work normally and only one misfire cylinder (the worse is cylinder number 5), the area of torsional vibration with additional dangerous resonance: $a\mu_{BARR(2)} > 66$ (rpm), or$a\,t_{BARR(2)} >$ 0,51 (by calculating table of shaft's torsional vibration, approved by Register DNV [**7**]).

Choosing operation revolution regime following the fuel-saving norm expressed by the S.F.O.C. g_e (g/kWh, SFOC). Hence, models $g_e(\Omega)$ are reference characteristics. According to document [**5**], we build model in the form of second-order polynomial with input data of 16 samples from graphs and get results of relative quantities $SFOC_{rel.} = SFOC_{abs.}/SFOC_{min}$:

$$SFOC_{rel.} = 1.1425 - 0.3982\Omega + 0.2781\Omega^2,$$

with high reliability, because: Ft = 5.98e+03 >> F(3, 11, 0.99) = 6.2.
According to received model, we have values in the table below

Table 2 Calculated parameters $g_{e\bullet rel.}$(t)

t %	**50**	**55**	**60**	**65**	**70**	**75**	**80**	**85**	**90**	**95**	**100**
$g_{e\bullet rel.}$	**1.0129**	**1.0076**	**1.0037**	**1.0011**	**1.0000**	**1.0003**	**1.0019**	**1.0049**	**1.0094**	**1.0152**	**1.0224**

In order to select the operation regime, we perform chracteristics of engine power, propeller and ship speed by rotational velocity (relative Ω) of engine [**1**, **3**].

Limited characteristic of ship speed according to revolution of engine determined through revolution of propeller (by the ratio of transmiting velocity $i_{Ep} = \omega_E/\omega_P$, which is always determined in each regime of gearbox, i_{Ep} =1 without gearbox using clutch- direct propeller). Ship limit speed [$V(\Omega_P)$] (knots) received when propeller's revolution chosen by changing band, in accordance with propeller's revolution band Ω_P, in the condition of exploiting that relative to building limited power characteristics (in figure 1).

It is seen that when the engine (propeller) revolution is less than some value Ω_{P0}, ship speed does not exist (V=0) because the propeller thrust is not dominant the hull resistance. From the value $\Omega > \Omega_{P0}$, ship speed is determined by the relationship between propeller power and hull:

$$RV = \eta_H \eta_R M_p \mu_p ; \eta_H = \frac{1-t}{(1-w_t)},$$

where: V – ship speed (m/s);M_p– moment of propeller (Nm); R – ship hull resistance (N); η_H – Hull hydrodynamic efficiency; η_R – Relative rotative efficiency; t – Thrust deduction; w_t – wake fraction.

Studying propeller's power characteristic $N_p(\mu_p)$ for general cargo ship, we can choose the model $N_p(\mu_p) = C(\mu_p)^3$, where: C- coefficient, which represents ship resistance-propeller, depends on: their roughness state, cargo loading and marine condition. We build the model: **C** =**C**(**X**).

The total ship resistance is summation of component resistances and each component is proportional to square of ship speed. We have relationship between ship speed and propeller revolution: $k_H^{1/3} V = (\eta_H \cdot \eta_p \cdot C)^{1/3} \mu_p$, in which, hull resistance's coefficient k_H depends on density of water ρ (kg/m^3), wetted surface S (m^2) and received from experiment or analytical model of hull total resistance in exploitation conditions. This coefficient also depends on **X**, so we have: $\mathbf{k_H}$=$\mathbf{k_H}$(**X**).

Then, we have first-order relation between ship speed and propeller revolution:

$$V = \sigma\omega_p; \; v = \sigma_\Omega \Omega_p, \tag{5}$$

Concerning the hysteresis of system, we build the model in the following equations:

$$V = \sigma(\Omega_p - \Omega_{p0}) = \sigma\Omega_p - \sigma_0 \tag{6}$$

$$v = \sigma_\Omega \Omega_p - \sigma_{\Omega 0}; \text{ or } v = \sigma_X \Omega_p - \sigma_{X0} \tag{7}$$

where: perfomance operating characteristics curve $\sigma = \sigma_X = \sigma(X)$ may be derived by experimental or analytical methods; V(m/s) and $v = V/V_n$ are absolute and relative ship speed, V_n - speed of ship at nominal operating condition $\mathbf{V_n = V(\mathit{X}=\mathit{X_n})}$.

We use the limited resistance coefficient $[\sigma_n]$ to describe the ship limited speed when the propeller works on the maximum propeller characteristics with nominal operating condition $\boldsymbol{X_n}$ (curve 2, fig. 1). Likely to equation (7), we change to equation for the limited speed:

$$[v_n] = [\sigma_n]\,\Omega_p - [\sigma_{n0}] \tag{8}$$

The significant factor is that, in the most severe, the main engine can sustain upper DME limited power characteristics. The method to establish this perfomance operating characteristics curve is as follows: Propeller torque $M = \rho D^5 n^2 K_Q$, K_Q - Propeller torque coefficient. This coeficient can be described approximately with a line form. $K_Q = a_2 - b_2(v/n)$ therefore, we obtain the computational models of the power of main engine, which Prof. Emil Stanchev defined [2, page 13]:

$$M = A_{20} n_2 - B_{20} nV, \text{ (Nm)} \tag{9}$$

where: A_{20}, B_{20} - coefficients depending on propeller parameters.

$$A_{20} = \rho D^5 a_2, \text{ (kg.m}^2\text{)}; \quad B_{20} = \rho D^4 b_2, \text{ (kg.m)} \tag{10}$$

Where ρ - density of seawater, kg/m^3 (ρ =1025 kg/m^3); D – diameter of propeller (m); a_2 and b_2 can be calculated from propeller torque coefficient.

From (9), we have the limited speed equals the power of main engine with limited torque characteristics $M_0(\omega) = N_0/\omega$; $\omega = \pi n/30$:

$$[V] = (A_{20}/B_{20})\omega - M_0(\omega)/B_{20}\omega, \text{ (m/s)} \qquad (11)$$

Hence:

$$[v] = k_\Omega^1 \frac{A_{20}}{B_{20}}\Omega - k_\Omega^2 \frac{M_0}{B_{20}\Omega}$$

The coefficients k_Ω^1 and k_Ω^1 can be changed to dimensionless.
The curve of limited speed based on torque characteristics of engine is a hyperbol curve.
Then, we define A_{20} and B_{20} from equation (9) base on sea trial data with LSEM.

With 34000DWT ship using DME, MAN 6S46 MCC, base on the sea trial data [7], we obtain A_{20} = 6.1374 and B_{20} = 6.0041 with the following model:

$$M = 6.1374\,\omega^2 - 6.0041\omega V, \text{ (kN.m)}; \qquad (12)$$

Fisher standard: Fr = 878.67 >> F(2,4,0.99) = 18, prove that the reliability of model is 99%.

The limited speed equation (11) with limited torque of engine:

$$[V] = 1.0222\omega - 0{,}1666\, M_0(\omega)/\omega, \text{ (m/s)} \qquad (13)$$

If "**Fuel Pump Index**" unchanges at the maximum value, the limited speed curve is hyperbol form.

2.2. The current operation characteristics

To establish the mathematical model of MPP in real operation condition by assuming X vector and the operation conditions are determined (or set up the concrete operation), we will establish the operating characteristics of engine power, propeller and ship speed.

$$\mathbf{N_E}(t, \mathbf{X_E}),\ \mathbf{N_P}(t, \mathbf{X_P}), \text{ and } V(t, \mathbf{X_H}), \qquad (14)$$

Where: $\mathbf{X_E}$,$\mathbf{X_P}$ and $\mathbf{X_H}$ - the concrete operation condition vectors for engine, propeller and ship hull, corresponding to the factor condition of ***X*** vector which was mentioned above.

Models are established (14) by analytical methods or experimental method, and by combination of analytical and experimental methods.

2.2.1. Establishing the charateristics of MPP using analytical method

The advantage of analytical method is that, it is more flexible and has the sense of initiative to describe the different conditions from X operation condition to obtain the relationships (4). The only difficulty of analytical method is that, we need experimental data with a large of range fluctuation, or the reliability is low. To overcome that disadvantage, we need to take test in some favourable conditions, therefore, the analytical data can be confirmed.

Ship resistance at various operation conditions
The total resistance in the still water. The total resistance in the still water includes the following components:

$$R = R_F + R_V + R_W + R_{APP} + R_A + R_{AA}, \text{kN} \qquad (15)$$

Where: R_F – frictional resistance; R_V – form resistance; R_{APP} – appendage resistance; R_A – roughness resistance; R_{AA} – Air resistance.

The discussion of selecting the formulas to determine the resistance components in (15) is represented concretely in [4].

Added resistance in waves: when ship operates in the condition of wave and wind, ship resistance increases. The increase of resistance will depends on height of wave, the direction of wave propagation in comparison with the movement of ship. According to [10], the added resistance due to wave influence is determined as follows:

$$R_{AW} = \chi_\beta \; R^0_{AW} \tag{16}$$

where: χ_β - is a function taking into account operation angle compared to propagation direction of wave (β), determined by using Fig. 2; R^0_{AW} - is added resistance of ship in the irregular incoming wave (that means head-on incoming wave 180° compared with movement direction). These quantities are determined by formula (17) and (18) as follows:

$$\begin{aligned} R^0_{AW} = \rho g(1-t)(L/100)^3(1/q_w^2)\{A_0 + 100(C_B - 0{,}5)^2 A_1 + A_2(L/B) + \\ + A_3(L/10T) + A_4(x_B/10L) + 10A_5(r_y/L) + M[A_6 + A_7(L/10T)] + 10A_8 F_r\} \end{aligned} \tag{17}$$

$$\chi_R = (1{,}2 - 0{,}1\sqrt{C_{WP}}) - (2{,}9\sqrt{C_{WP}} - 1{,}9)\mathrm{Fr}. \tag{18}$$

Coefficients in (17) and (18) are determined as follows:

$$q_w = k_s^2;\; r_y = \sqrt{\frac{J_y}{\rho\nabla}} = \sqrt{\left(\frac{L^2 C_{WL}^2}{11{,}4 C_B} + \frac{D^2}{12}\right)};\; A_i = \sum_{m=1}^{5} B_{im}\left(q_w \frac{10h_{3\%}}{L}\right)^m \quad (i = 0,1,\ldots,8).$$

where: k_s – coefficient depending on the wave type (k_s = 1 with developed wave, k_s = 0.6 with developing wave); J_y – mass inertia moment for the axis Oy; L, B, D, T – is length, width, depth and draft in turn; ρ – density of water; t – thrust deduction; M – effective coefficient of bulbous bow (M=1 if a ship has bulbous bow; conversely, M = 0); B_{im} – coefficient, determined by Table 3.

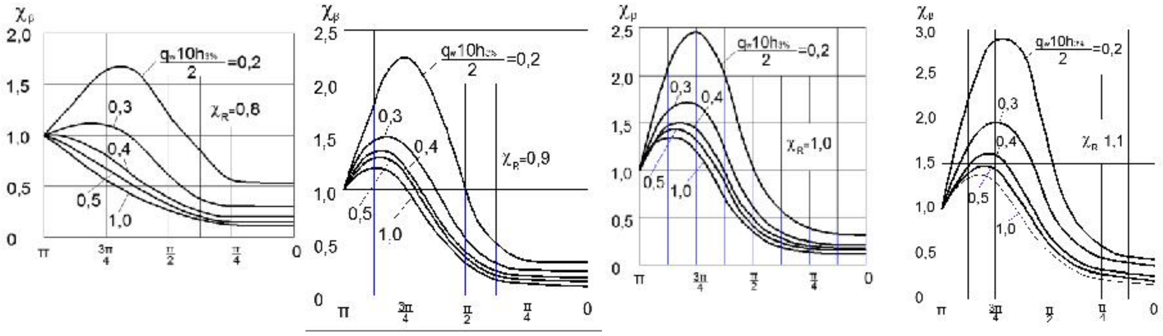

Figure 2 The curve determining the influence of angle of attack *[10]*

Table 3 The value of B_{im} [10]

i	*m*				
	1	2	3	4	5
0	13.1320	-103.71	222.0600	-170.78	44.981
1	-1.6109	33.442	-49.2910	35.4960	-9.9726
2	1.5981	-14.900	7.8786	-0.6628	-0.0248
3	0.1151	6.5228	-7.6263	5.0745	-1.5133
4	-5.5428	48.5920	-74.5600	52.5470	-14.0310
5	-11.1200	98.9780	-152.070	105.25	-27.5260
6	-7.5139	51.670	-58.0050	28.5910	-5.1947
7	2.0858	-16.263	-17.7170	-9.6519	2.2724
8	-8.843	62.3330	-73.3620	-37.075	-6.7179

Added wind resistance being head-on a ship are determined as follows [10]:

$$R_{WAA} = C_{WAA}\frac{\rho_a}{2}V_A^2 S_A,$$

where: C_{WAA} –added wind resistance coefficient (C_{WAA} = 0,7 – for cargo ship); ρ_a – air density; V_W – wind velocity; S_A – the projection area of ship above water line to the midship section.

Added ship resistance in the shallow water. As many previous research suggests that when ship runs in the shallow water, there will be an increase in the resistance. The clear effect of flow depth on resistance will be seen apparently when $\mathrm{Fr}_h > 0,3$ ($\mathrm{Fr}_h = V/\sqrt{gh}$; where: *h*- water depth [m], *V*- ship speed [m/s]) [11].

Added ship resistance in the shallow water is determined as follows [11]:

$$\Delta R_h = \frac{1}{2}(C_{F_h} + C_{R_h})\rho V^2 S. \tag{19}$$

where: C_{F_h} , C_{R_h} - the frictional resistance coefficient and residual added resistance in the shallow water respectively.

$$C_{F_h} = C_F\left[\left(1-\frac{T}{h}\right)^{-b_f} - 1\right];\ C_{R_h} = (C_w + k_1 C_F)(\Delta C_{R_h}^2 - 1), \tag{20}$$

where: C_F – coefficient of frictional resistance in deep water; C_W – coefficient of wave resistance in deep water; k_1C_F – coefficient of viscous resistance; C_F, C_W, k_1 – *refer to [4]*

$$b_f = \left(6,63 + 0,884\frac{L}{B}\right)\frac{\lg \mathrm{Re}}{\lg \mathrm{Re} - 3,35}\frac{B}{T}.10^{-2}; \tag{21}$$

$$\Delta C_{R_h} = \left\{1 - 0,618\left(\frac{T}{h}\right)^{1,644}[2,06 - 11,6(C_B - 0,40)^3]^{0,333} \times \left\{1 + \left[0,314 + 3,59\frac{T}{h} - 5,50\left(\frac{T}{h}\right)^2\right]\ln\left(\frac{B}{6T}\right)\right\}\right\}^{-1}, \tag{22}$$

Added ship resistance in the canal. When a ship runs in a canal, there has an interaction between the ship and the canal because of the limitation of width and depth of the chanel. This impact makes the change in water resistance of a ship. As a result, additional resistance causing by the influence of width and depth is calculated [11]:

$$\Delta R_K = C_K \frac{{}^{\circ}V^2 S}{2}; \tag{23}$$

Where: C_K – the coefficient of water resistance of a ship in the canal, determined as follows:

$$C_K = C_{F_K} + C_{R_K} \tag{24}$$

Where: C_{F_K} , C_{R_K} - the frictional resistance coefficient and residual added resistance in the canal. They are determined as follows:

$$C_{F_K} = 0,285 C_B \left\{ \left(\frac{T}{h_K} \right) + 24,4 m_K^{5/3} \left[\left(1 + \frac{0,335}{1,26 - (v/v_{KP_1})} \right) \times \left(1 + \frac{0,322}{\lg \mathrm{Re} - 3,16} \right) - 0,54 \right] \right\} C_F \tag{25}$$

$$C_{R_K} = (C_W + k_1 C_F) \overline{\Delta V}^2 \tag{26}$$

These quantities in formula (25) and (26) are determined as follows:

$$V_{KP_1} = \frac{1 - 1,195\sqrt{m_K}(1 - 0,345 m_K^2)}{\sqrt{1 + 0,88 b_i}} \sqrt{g h_K},\ \mathrm{Fr}_h = \frac{V}{\sqrt{g h_K}};\ m_K = 2 C_M BT / [h_K (B_W + B_B)].$$

$$\overline{\Delta V} = \frac{m_K}{1 - m_K} \left[1 + (2,44 - 4,48 m_K) \left(1 - \sqrt{1 - \left(\frac{V}{V_{KP1}} \right)^3} \right) \right];\ b_i = (B_W - B_B)/(B_W + B_B)$$

where: $b_i = (B_W - B_B)/(B_W + B_B)$ - Trapezoidal coefficient; B_W – width of canal’s water surface; B_B – width of canal’s bottom; h_K – canal depth; V_{KP1} – first limmited speed of ship in the canal; C_M – midship section coefficient.

Formula (25) and (26) are correct in the range as follows: $10^6 \leq \mathrm{Re} \leq 2.10^9$; $V \leq 0,95 V_{KP1}$; $0,04 \leq m_K \leq 0,30$; $b_i \leq 0,60$; $0,450 \leq C_B \leq 0,920$; $0,2 \leq T/h_K \leq 0,90$.

Ship resistance when there is a change in ship deadweight. Throughout the voyage, deadweight of ship varies incessantly because of the change of fuel, cargo weight and so on,… It leads to the variation in the draft and eventually in ship resistance. In order to assess the change in resistance of a ship due to the change draft we use the following formula [9]:

$$R_i = k_i R \tag{27}$$

where: R_i – ship resistance in the random loading case; R– Ship resistance full loaded condition; coefficient k_i is determined according to [9, page 201].

Characteristic model of propeller

The work of combination “propeller – ship hull – main engine” causes the mechanical and hydrodynamic impact between each component.

Performance of the propulsion combination η is calculated by [12]:

$$\eta = \eta_s \eta_{trd} \eta_p \eta_R \frac{1-t}{1-w_t}, \qquad (28)$$

where: η_s – shaft performance (η_s = 0,97 ÷ 0,98 when engine room locate at the end of a ship); η_{trd} – actuator performance (η_{trd} =1 when engine have no gear box, η_{trd} =0,98 ÷ 0,99 when engine have gear box); η_p – propulsion performance; η_R – relative rotative efficiency; *t* – thrust deduction; w_t – wake fraction.

The discussion of selecting the formulas to determine the thrust deduction, wake fraction, coefficient with the effect of erratic wake on hydrodynamic moment Q of propeller and propeller performance of a ship in still water is represented concretely in [4]. In other operation condition, such as in ballast condition (or a part load), the wake fraction tends to be 5–15% larger than the wake fraction in the loaded condition. The value can be determined by equation of Moor and O'Connor [9].

Algorithm determining the relationship between velocity - revolution - engine power

Algorithm determining the relationship between velocity - revolution - engine power in the still water is presented in [4]. In other operation condition, algorithm is the same one, therefore, it is no longer necessary to discuss about it.

Essential input parameters for determining the relationship between velocity - revolution - engine power include: geometric parameters of ship hull and propeller, wave and wind level, water depth, geometric parameters of canal ship pass through.

Example. Using above theory to calculate the relationship between velocity - revolution - engine power of bulk carrier 34000DWT built in PhaRung Shipyard [7].

Input parameters: L = 179.95 m; L_{pp} = 176,75 m; B = 30 m; T_F = 9,75 m; T_A = 9,75 m; T =9,75 m; C_B = 0,8137; C_{WP} = 0,9606; C_M = 0,995; X_B = 3,849 m; A_{BT} = 14,85 m^2; h_B = 5,85 m; C_{stern} = -22; D_P = 5,6 m; Z = 4; Zp = 1; P/D = 0,73; A_E/A_O = 0,85.

Operation condition: when a ship is in the wave and wind $h_{3\%}$ = 6 m, wave propagation compared to ship movement β_w = 135^0, ship type ks =1, wind velocity V_W = 19 m/s; when a ship is in the shallow water: water depth h = 13m; when a ship is in the canal having following parameters: depth h_K = 25 m; surface width Bw = 50 m; bottom width B_B = 40 m; limited velocity in the canal V_{KP1} = 6 m/s; when a ship is in ballast condition: ship draft T_i = 5.51 m.

The calculation results are shown in fig.3.

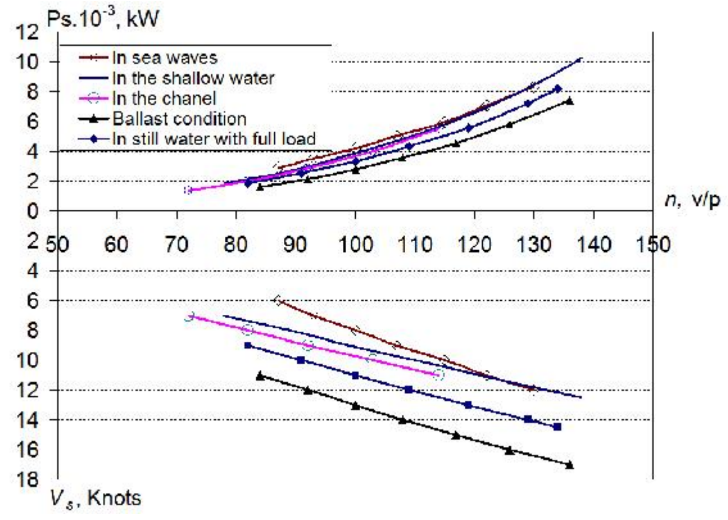

Figure 3 The relationship curves between ship velocity - revolution - engine power in different operation condition

2.2.2. Building the characteristics of MPP by experimental method

In operation condition, in some allowable regime, we measure three basic parameters: Engine power DME, propeller revolution and ship velocity.

By using measured figures (or indirect calculating), some above parameters allow us to estimate the cooperation of components in MPP. Regression model is built based on database measured in experimental condition, using LSEM.

- The propeller characteristics is built by model, formula (4);
- Engine power can be indirectly calculated or measure by available devices;
- Character V =V(n) is modelled in the form of straight line, formula (7).

2.3. Selection the reasonable revolution for operation of MPP

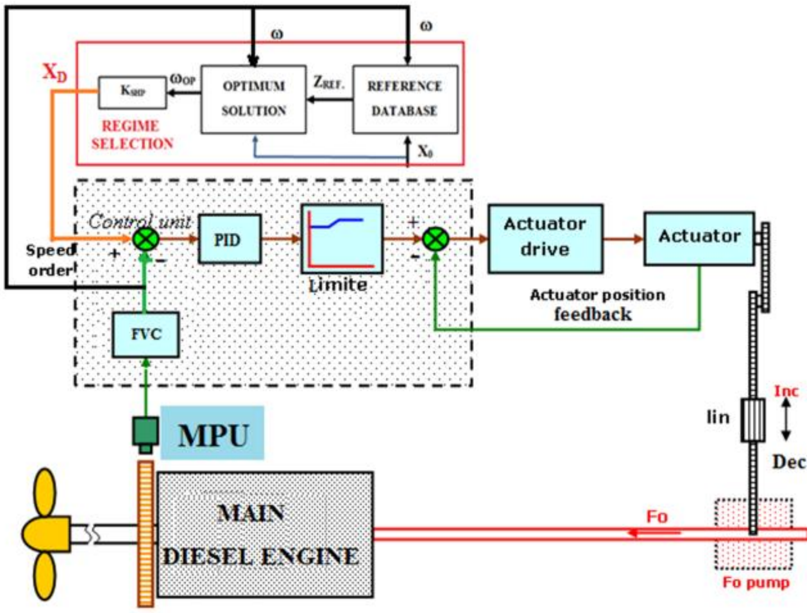

Figure 4 Principle scheme of the automatic selecting the reasonable operation mode of the MPP

Based on modelling the limited characteristics of ship diesel MPP, working characters of ship hull, propeller in the current operation condition (as well as prognose working characters of ship hull, propeller in the alleged condition) allow us to give database Z_{REF} (reference) in order to make a decision of selecting the reasonable operation regime. In the Fig.4, we suggest a principle scheme of the automatic selecting the reasonable operation mode of the MPP, using a electronic governor with the regime (revolution) selection. The Fig.4, we show the principle of controlling revolution of the DME by speed governor including MPU (Magnet Pulse Unit) and FVC (Frequency to Voltage Convector). The control signals DME in the modern diesel engine are usually fuel oil rack and scavenge air pressure (relative quantities are abbreviated by λ and ρ). Based on the decision of optimal selection signal ω_{op}, the desired signal X_D impacts on the PID – controller as a revolution error input.

Block optimum solution (BOS) in above principle diagram plays a key role in selecting the reasonable revolution condition for operation. Input data for BOS is information of current operation condition with the limited condition of X_0 and database as well as character S.F.O.C. of engine. BOS will put forward the best reasonable mode according to the optimal standard so that controlling function is established, for instance, minimum fuel consumption in the safe range of system, or possible maximum velocity in the scope for MPP working safely.

Standard database includes: The limited characters {$[N_e]$, $[N_p]$, [V]} and character SFOC g_e, that are regressive models, some of them are shown in the table №1 in the paper; The basic operation characters are built by the analytical method {$N_e(\omega, X_0)$, $N_p(\omega,X_0)$ and $V(\omega,X_0)$}, according to the above mentional bases in the point 2.2.

3. Conclusion

This paper builds the system of regression models for limited characteristic curve of DME, limited character of the ship speed when engine works above maximum constant moment characteristic curve; characteristic curve of the S.F.O.C. of DME and propeller characteristic curve in the full loaded condition. Those models have an essential reference data for maintaining the operation mode in a safe and economical way.

Based on analytical models determining ship resistance, moment and thrust of propeller in every operation mode MPP will be the prediction of propeller characteristic curve and ship hull so that we are able to select a suitable operation mode.

This article puts forward principle diagram of the automatic selecting the reasonable operation regimes; specifically it puts forth round mode of main engine and propeller according to reference data (standard characteristic model system) as well as actual operation mode of ship hull, propeller (these cases depend on working condition vector X of MPP).

References

[1] Bogdanov H.*Marine Energy Equipment (Operation)*. Military Edition. Sofia, 1983. (In Bulgarian).Богданов Х.Г.*Корабни енергични уредби*. София, «Военно издателство», 1983. 244 с.

[2] Emil Stanchev and others. Dynamic researching on the marine propullsion plants in the exploitation conditions. Military Edition. Sofia, 1982. (In Bulgarian). Емил Станчев и др. *Динамични изледвания на корабния пропилсивен комплекс в эксплуатационни условия*. София, «Военно издателство», 1982. – 284 с.

[3] Ovsianicov M. and Petukhov V. *Marine propulsion plants*. Leningrad, 1987. (In Russian). Овсянников М.К, Петухов В.А. *Дизели в пропульсивном комплексе морских судов*: *Справочник*. Л.: Судостроение, 1987. 256 с.

[4] LuuD.D., Nho L.C, Tu Tr.Ng.*Modelling characteristics of the hull and propeller of sea-going general cargo ship in normal operating conditions*. Maritime Science-Technology Journal, N46, March 2016 (VietNam). ISBN.

[5] MAN DIESEL 6S46 MC-C. VOLUME I. *Operation*.

[6] Hồ sơ tàu 34000 DWT. *Technical File 6S46 MC MK II. HHM*–Shanghai Hujiang Diesel Emission Test Scie-Tech Co.Ltd. Approved DNV 20 -08-2007.

[7] Hồ sơ tàu 34000 DWT. *Hồ sơ thử tàu 34000 DWT*. NMĐT Phà Rừng.2007.

[8] Hồ sơ tàu 34000 DWT. *Torsional Vibration Calculation Report DE 6S46MC –C7860 kW @ 129 r/min 34,000 DWT*. HUDONG HEAVY MACHINERY Co. Ltd. PhaRung Shipyard. DNV (Classification Society) Approved 2007 - 06 -06.

[9] Molland, Anthony F. Ship resistance and propulsion: practical estimation of ship propulsive power . ISBN 978-0-521-76052-2 (hardback).

[10] Под ред. Я.И. Войткунского. Справочник по теории корабля: В трех томах. Том 1. Гидромеханика. Сопротивление движению судов. Судовые движители. (1985). Л.: Судостроение - 768 с.

[11] В.Ф. Бавин, В.И. Зайков и др.; Под ред. В.Г. Павленко.Ходкость и управляемость судов (1991). Учебник для вузов/ – М.: Транспорт. 1991. 397 с.

[12] Гайкович А.И. Теория проектирования водоизмещающих коряблей и судов. ТОМ 2: Изд. НИЦ МОРИНТЕХ, 2014.