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The mathematical model of the shipping main engine as the drive of the shaft-generator. Assumptions and the methodology of the description

Bogdan Nienartowicz

Maritime University of Szczecin
70-500 Szczecin, ul. Wały Chrobrego 1–2, e-mail: b.nienartowicz@am.szczecin.pl

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Abstract

The contemporary shipping technics wide applies the systems electromagnetic with the shaft-generator. The simulating investigations of transitory processes electromagnetic in such system need the complex model mathematical study, describing the dynamics of objects in him contained. The following article is the first part of the final description of the mathematical model of the shipping system electromagnetics with the shaft-generator. The paper describes external conditions, which can influencing on the course of electromagnetic processes in the systems and there is giving the proposed mathematical model of the Shipping Main Engine as the drive of the Shaft-Generator.

Introduction

Water transport is considered to be cost-effective. Electric energy takes the considerable part among various factors influencing the cost of the ship's exploitation. There is simply dependence between the quantity of electric receivers and both, installed electric power and the quantity of current generators included in the ship's power plant.

Modern ships are characterized by the high stage of installed electric power. The growth in amount of the ship's electrical devices, in turn, affects the range and the stage of the automation of the power plant [1, 2]. It means sharper requirements for quality and costs of the electro-energy.

Electric energy production cost on modern ships, especially specialist, takes an increasing part of the ship's daily operating costs. That is the reason why the ship-owners are so interested in the electro-energetic systems with the shaft-generator.

Simulation studies of transitory processes in such systems become the necessity [2]. This requires creating a complex mathematical model for the whole electro-energetic system, not only for individual objects. The article presents description of the adopted methodology and requirements, which should be met by the model to obtain reliable results.

Initial assumptions

Assumptions that should be met to create useful model description:

- the structure of model must contain all the important objects that have an impact on the transitory processes in the electro-energetic system;
- model should include the influence of external conditions, i.e.: rolling of the sea, wind and it's direction, ship's transverse and longitudinal swinging, ship's propeller ascending. This results in the change of the rotary speed of the Main Engine (ME);
- created model should be useful for ship with the adjusting propeller, as well as non-adjusting propeller;
- adoption of proper description methods of dynamic conditions of the principal components of the system, i.e.: main engine, auxiliary engines (AE); ship's power station and electric receipts with the division on static and dynamic receiver;

- possibility to analyze working conditions of ship's power station, i.e.: lonely work or parallel work of the ship's generators in various configurations;
- model should have open structure to be able to be expanded with the additional objects or steering systems;
- and mainly it should fulfill the criterion of credibility and liability. This condition imposes the necessity of use widely recognized and proven methodology of description.

Fulfillment of above assumptions will enable the study of electromagnetic transitory processes, which result will let to approach to conditions stepping out in real ship's systems.

Specific of the work of the shaft-generator

Advantages and disadvantages of the generator shafts are well known. However, the mathematical description of the dynamics is complex due to the specific of main engine drive and its location in the electro-energetic system. Getting the knowledge about the dynamic processes of shaft-generator and its influence on the work of the fleet by the experiments, is not only inconvenient, but also expensive. It forces us to build:

- laboratory workstation, which research results are greatly doubtful;
- or a prototype to test it on a ship, which is expensive and risky, what it is expensive in the turn and burdened with the risk. After that, knowledge of certain symptoms is most needed at the stage of design work.

Therefore, the most purposeful is computer simulation [2], and this requires mathematical model. The shaft-generator (SG) is unit joining two physically different arrangements – electric net and the propulsive complex in the type-matter: main engine – main shaft (MSh) – adjustable or non-adjustable propeller.

In result, the shaft-generator subject to two principal forces:

- from the side of the electric net, because of the change of active and passive electric power;
- from the side of the drive of shaft-generator, because of the change of the resistory moment on the shipping screw, what causes the labile rotary speed of the main shaft.

The first force is influences on the change of voltage of shaft-generator. The second influences both, on the tension and the frequency of the electric current. Summing up, we should affirm, that the dynamics of shaft-generator depends on the dynamic properties of the propulsive complex. This in turn, subjects to the influence of the whole sequence of external factors. One can here enumerate principal influences:

- condition of the sea and strength of the wind;
- transverse and longitudinal swing of the ship;
- level of immersion of the ship and its propeller;
- periodical raising out of the propeller of the water;
- the displacement the center of gravity of the ship called out by the loading etc.

The situation is being complicated by the fact, that one can't subordinate the work of the main engine to the exploration requirements of the shaft-generator. This results from the conditions of the safety of navigation. In effect, labile rotary speed of the main shaft causes labile frequency in the electric net, what is harmful.

Taking into account these circumstances sets certain requirements for the mathematical model, which contains the description of the shaft-generator.

The choice of the type of the ship adjustable propeller or steady propeller

It is believed that the adjustable propeller system favors the use of shaft-generator. It is not so obvious. It depends on the specific solution and adopted criterion of propeller control. Propeller type selection is dictated by kind of ship and its destination (scheduled jobs). There is a considerable number of solutions of adjustable propeller systems. Generally, adjustable propeller systems can be divided into:

- separate steering of the stroke of the propeller spades (h) and rotary speed (n);
- adjustment by the stroke of the propeller only ($h \neq$ const), near the stabile rotary speed ($n =$ const);
- simultaneously program control of both parameters ($h \neq$ const; $n \neq$ const);
- automated, self-regulating systems.

While separate steering, operator gives both the parameters separately, with the support of suitable charts and diagrams, with regard to the conditions of navigation and the technical condition of the main engine. The last two systems from the principle enter the changes of both parameters. This results in a labile rotary speed of the main shaft. This situation is usually accompanied by a control based on the criteria:

- reaching optimum ship's speed;
- the optimum fuel consumption.

There is no doubt that, the hardest working conditions of shaft-generator take place on ship with steady propeller. This case should be considered and included in the mathematical model.

Only second type of adjustable propeller provides supportive conditions of work for the shaft--generator. This kind of steering the adjustable propeller had been chosen as the object of the description.

Principles of description of the propulsive complex

The propulsive complex contains the main motor, main-shaft and the propeller. As it had been already mentioned, rotational speed of this complex depends on operating conditions – including sea state. Decisive impact has undulation of the sea that often causes periodical propeller's raising out of the water.

It is the most difficult enforcement operating on the shaft generator because in practice it means suddenly changing working conditions of the propulsive complex – from 100% unload to 100% load. This is accompanied by a sudden, wide range change of the rotational speed of the main shaft. There is direct relation between rotational speed of the main shaft and the frequency (*f*) of the electricity network. Rotational speed also affects the fluctuation of active power produced by the shaft generator.

The above analysis shows an important conclusion. Main engine should be described as main shaft's variable speed control object.

Such an approach avoids taking into account the impact of combustion, supplying of air and discharging exhaust gases on rotational speed of the shaft generator.

The "Woodward" UG–CTL controller had been chosen as the main shaft's rotational speed controller. It is one-parameter controller with rigid feedback. Its choice determines the relative simplicity of operation, reliability, high power of executive and the fact that it is still widely used in fleets of many countries.

B1 Description of dynamics of a ship's main engine

Upon analyzing dynamic processes taking place in the system regulating the propulsion system, it is convenient [3, 4, 5, 6] to split the latter to the following components:

- the main engine (SG) with the compressor;
- the hulk of the ship;
- the regulator of turns SG;
- the mechanism of the change of the stroke of the screw.

B2 Dynamics equations for the main engine – the ship's hull relation

The starting equation has the following form (1):

$$2\pi\left(J_{gb}+J_b\right)\frac{\mathrm{d}n}{\mathrm{d}t}=M_e-M_T-M_b-\Delta M_f(t) \quad (1)$$

where:

M_e – effective moment SG in the function of parameters n, p_k, h;

n – the speed rotatory SG;

h – the position of the lever of fuel pumps;

p_k – the pressure of the air behind compressor;

M_T – the moment of the friction in the transmission in dependence from the rotatory speed;

M_b – the resistory moment of screw in function n, λ_p the move of the screw and H/D of the jump of the screw;

$\Delta M_f(t)$ – the additional change of the moment called out the swing of the ship;

$(J_{gb}+J_b)$ – moment of inertia SG with the regard adjacent masses of water.

As shown above, this equation needs to be expressed in relative units (2):

$\varphi=\Delta n/n_0$ – the relative change of the speed rotatory SG;

$\varphi_p=\Delta p_k/p_k$ – the relative change of the pressure of the air;

$\mu=\Delta h/h_0$ – the relative change of the position of the fuel lever;

$\chi=(\Delta H/D)/(H/D)$ – the relative change of the jump of the screw;

$f_1=\Delta M/M_b$ – the relative change of moment near the change of the hulk of the ship;

T_d – the constancy of the time SG.

After application of the relative units (2), the equation takes up the following form of an ordinary differential equation (3):

$$T_d\varphi^*+\varphi=-\alpha_1\chi+\alpha_2\nu_\lambda+\alpha_3\mu+K_{pg}\varphi_p+\alpha_4 f_1(t) \quad (3)$$

B4 Dynamics equation for the turbocharger

The dynamics equation for the ME turbocharger can be derived based on the methodology presented in item [5]. The starting equation has the following form (4):

$$J_k\frac{\mathrm{d}(\Delta\omega_k)}{\mathrm{d}t}=\Delta M_T-\Delta M_k \quad (4)$$

where:

$\Delta\omega_k$ – the increase of the angular speed of the shaft of the turbocharger;

J_k – moment of the inertia of masses whirling turbokompresora;
ΔM_T – the increase of the moment of the gas turbine;
ΔM_k – the increase of the resistory moment of the turbine.

Taking into account the relative values, an ordinary differential equation is generated (5):

$$T_{TK}\overset{*}{\varphi}_{TK} + Z_{TK}\varphi_{TK} = K_{hTK}\mu + K_{\omega TK}\varphi - K_{pTK}\varphi \quad (5)$$

where:
φ_{TK} – the relative change of the angular speed of the shaft of the turbocharger;
Z_{TK} – the coefficient of the self-compensation of the turbocharger;
K_{hTK} – the relative angular coefficient of the static profile of the influence of the regulator;
$K_{\omega TK}$ – the relative angular coefficient of the static profile $M_T = M_T(\omega)$;
K_{pTK} – the relative angular coefficient of the static profil of the charger $M_K = M_K(p_K)$.

Dynamics equations for the receiver of compressor

The dynamics equation for the receiver of compressor, one describes following dependence (6):

$$\Delta G_K - \Delta G_D = 0 \quad (6)$$

where:
G_K – the efficiency of the compressor;
G_D – the consumption of the air by SG.

Take into the account relative sizes and transforming the equation, we receive dependences in figure (7):

$$Z_R\varphi_p = K_K^G\varphi_{TK} - K_D^G\varphi \quad (7)$$

where:
z_R – the coefficient of the self-compensation of the receiver of compressor;
K_K^G – the relative angular coefficient of the static profile of the receiver after the side ingoing;
K_D^G – the relative angular coefficient of the static profile of the receiver after the side Main Engine SG (the exit).

The equation of the dynamics of the movement of the ship

The equation of the dynamics of the movement of the ship [3, 7, 8, 9] going out from equality of strengths reacting on and strengths of resistances existing (8):

$$(1+\alpha)\vartheta\frac{d\vartheta}{dt} = -C_w\vartheta\frac{\rho}{2}V^{2/3} + P_e + \Delta P_f(t) \quad (8)$$

where:
ϑ – the speed of the ship [m/s];
P_e – the drag (move) of the shipping screw [kgs];
$\Delta P_f(t)$ – the additional change of the resistance of the ship near rolling the sea;
α – the coefficient of the adjacent mass of water to the hulk of the ship;
V – the draught of the ship [m^3];
ρ – the density of water;
C_w – coefficient of the resistance of the hulk of the ship;
T_s – the constancy of the time of the ship.

Final figure of equation (8), after transformations and introduction of relative individuals (9):

$$T_s\overset{*}{\nu}_\lambda + \nu_\lambda = -T_s\varphi + b_1\chi + b_2 f_2(t) \quad (9)$$

where:
ν_λ – the relative change of the step of the shipping screw;
φ – the relative change of the speed rotatory SG;
b_1, b_2 – coefficients expressed separate formulas.

The equation of the dynamics of the regulator of the turns of the main engine (SG)

B5 Following the adopted rules, the description pertains a Woodward governor type UG – 40 TL, because of its faultless performance and common use. The final equation should contain equations for its individual components, i.e.:

- the dynamics of the sensor of the rotatory speed;
- the dynamics of the hydraulic amplifier;
- the dynamics of the flexible feedback;
- the dynamics of the stiff. feedback.

The methodology of the description is introduced in the position in the detail [5], that is why I, because of the limited frames of the report, give final differential equation (10):

$$T_iT_s\delta_i\mu^{**} + \left[T_s\delta_s + T_i\left(jK_\psi\delta_i + \delta_p\right)\right]\mu^* + \delta_p\mu = = -\left(T_i\varphi^* + \varphi\right) \quad (10)$$

where:
δ_i – the degree of the inequality of the sensor;
δ_p – the degree of the inequality of the regulator;
T_i – the constancy of the time of the flexible feedback;
T_s – the constancy of the time of the servomotor;
φ – the change of the regulated entrance parameter;
K_ψ – the coefficient of strengthener of the flexible feedback;

j – un-dimensional, they stood the coefficient, even the relative volume of the cylinders-entrance and exit.

B6 Mathematical description of varied loads acting on the propeller in rough sea

A mathematical model of a ship operating when the sea is rolling irregularly is difficult to describe for strong non-linearities. The task becomes easier, when regular sea rolling and only the most important non-linearities are assumed. Such a simplification is possible [8], because it does not wangle the physical picture of the transient processes occurring in the shaft-generator (PW) significantly. For this reason, the following non-linear function type (11) was used for the description:

$$f(t,\varphi) = \frac{\Delta M_b}{M_0} \tag{11}$$

which takes into account the vertical dislocation of the propeller when the sea is rolling regularly.

This function was described in the publications [8, 10]. The final form of the equation is as follows (12):

$$f(t,\varphi) = 2\varphi - \varphi^2 + (1-\varphi)[\gamma_a(1-m_a) - \gamma_a\varphi]\sin \omega t \tag{12}$$

where:

φ – the relative change of the rotatory speed;

ω – the frequency of the swing of the ship;

γ_a; m_a – definite coefficients separate formulas, formed in the result of transforming the equations.

B7 Final equation system, being the mathematical model for the shaft-generator drive

The equation system (3), (5), (7), (9), (10), (12) makes for a complete model of dynamics of an adjustable pitch propeller, operating in rough sea. However, for the fact that the shaft-generator drive is analyzed as a subject to the main shaft speed controlling, one may abandon the ship's motion dynamics equation [9]. The ship's time constant is many times higher than the time constants for other components. One must also neglect the dynamics equations for the turbocharger or the receiver, because processes taking place inside the cylinders are not analyzed.

Conclusions

The development of computer technology had allowed develop new research method – simulation of technical facilities. The benefits of simulation studies do not require comment. The aim of every simulation is to create an accurate mathematical model of testing object or system. However, like any research method, this technique has its limitations.

They are associated with the problem of the credibility of results. Therefore, it is very important to use of mathematical description of various parts of the system commonly recognized methodology. Then we will receive a new quality – a comprehensive and reliable model of the whole system.

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