Computer modeling of ship combined propulsion plants

Andrey Grigoryev^{1,2,3,*} and Dmitry Ulitovsky^{3,4}

¹Admiral Makarov State University of Maritime and Inland Shipping, St. Petersburg, Russian Federation,

²Saint Petersburg Electrotechnical University, St. Petersburg, Russian Federation

³JSC "RPC "Ship electric propulsion", St. Petersburg, Russian Federation

⁴Branch "Central scientific research institute of ship electrical engineering and technology " of FSUE «Krylov State Research Centre", St. Petersburg, Russian Federation

Abstract. Combined propulsion plants (CPP) are increasingly being used on modern ships of foreign and domestic construction. A feature of such plants is that the energy for the movement of the vessel is generated in them in two (or more) different types of ship engines - heat and electric ones, working on a common propulsor. Combined plants are complex electromechanical systems designed to provide propulsion in various modes of ship operation and generate electricity in a cruising mode or during a lay-up. CPP combine the advantages of traditional propulsion plant with heat main engines and electric propulsion plants. The study of the physical properties and the principle of operation of CPP without a comprehensive study of the object using the model is impossible. Computer models and computer modeling are widely used to study the properties of complex objects. Nowadays, personal digital computers are widely used for computer modeling. Standard packages and programs are used as programs and packages for computer modeling.

1 Introduction

A propulsion plant is a complex of mechanisms and devices designed to ensure the movement of the vessel. A ship propulsion plant consists of a propulsor, a shaft line, main ship gears, main heat or propulsion electric motors.

Various types of propulsion plants are used on ships. Nowadays, the most widespread are plants with main heat engines and electric propulsion systems of the ship. These propulsion plants have well-known advantages and disadvantages, which determine their area of application [1,2].

The desire to combine the advantages of different types of propulsion plants stimulated the creation of combined propulsion plants (CPP). CPP is a plant in which energy for the movement of a ship is generated in two (or more) different types of ship engines - heat and electric ones. These plants combine the advantages of propulsion plants based on heat main

* Corresponding author: a.grigorev@eds-marine.ru

engines and electric propulsion plants (EPP), which allows the ship to operate with high technical and economic indicators in various operating modes [3.4].

CPPs are complex electromechanical systems designed to ensure movement in various modes of operation of the vessel and the production of electricity in a cruising mode or during a lay-up [5.6].

The study of the physical properties and the principle of operation of CPP without a comprehensive study of the object using the model is impossible. Computer models and computer modeling are widely used to study the properties of complex objects. Nowadays, personal digital computers are widely used for computer modeling. Standard packages and programs are used as programs and packages for computer modeling.

In the design process, it is necessary to select the technical characteristics of the equipment, determine the quality of transient processes, and study the dynamic characteristics of CPP. The solution to the problem is associated with computer modeling of CPP and conducting computational experimental studies [7.8].

2 Methods and Materials

The traditional CPP includes the main engine (ME), as which a diesel engine is usually used, and an electric propulsion motor (EPM), which are connected to the propeller (P). ME and EPM can be located on the same propeller shaft or connected to the propeller through a reduction gear [9,10].

Block diagrams of traditional CPPs are shown in Fig. 1.

In the first case, a low-speed ME is used as a part of CPP, in the second - a medium-speed one.

Fig. 1. Structural diagrams of CPP: 1 – heat ME; 2 – propeller; 3 – EPM; 4 – reduction gear.

The main operating mode of CPP is the motor operating mode. ME and EPM can autonomously or jointly set in motion a common propulsor [11,12]. The following operating modes can be implemented in CPP:

- autonomous (separate) operation of ME and EPM;
- joint work of ME and EPM on the propeller;
- shaft-generating mode of EPM operation with power take-off from ME (cruising mode);
- starting ME from EPM (starter start).

The combination of different modes of operation ME and EPM can significantly increase the efficiency of the propulsion plant and its control characteristics.

Computer models and computer modeling are widely used to study the properties of complex objects. The computer model includes a mathematical model of the object, software and a computer.

Nowadays, personal digital computers are widely used for computer modeling. Standard packages and programs are used as programs and packages for computer modeling.

The purpose of computer modeling is to study the properties of CPP. The tasks of computer modeling are to carry out computational experiments in order to obtain transient processes of the main and emergency modes of CPP operation. The hardware part of the computer model is a digital personal computer, the software is the MatLab scientific modeling package with the Simulink application.

The mathematical model of CPP is based on the equation of the dynamics of the ship's propulsive complex as an object of regulation of the propeller shaft rotation frequency.

Mathematical model of CPP:

$J \times dN/dt = M_d + M_e - M_c$, where

J – total moment of inertia;

M_d – moment developed by ME;

M_e – moment developed by EPM;

M_c – moment of resistance on a propeller.

A computer CPP created in the Simulink environment is shown in Fig. 2.

Computer ME and EPM developed in the Simulink environment are shown in Fig. 3, 4.

In computer models, the torque characteristics of ME, EPM and propeller are implemented. The torque characteristic of the main engine is shown in Fig. 5.

At the first moment of starting up to a rotation speed of 0.4 - 0.5 of the nominal value, at which the fuel mixture ignites, the diesel does not develop torque. The minimum starting speed of the crankshaft of marine diesel engines is 1/3 of the nominal, i.e. not less than 0.35% of the nominal frequency.

Fig. 2. Computer model of CPP in the Simulink environment.

With air starting, the diesel engine develops a torque of about 0.4 of the nominal value, which is enough to pick up the rotational speed together with the propeller to the starting torque. After starting, the torque of the diesel engine increases to 0.6 of the nominal value and continue to increase with increasing speed to the nominal value (at a speed of about 0.5 of the nominal value).

Fig. 3. Computer model of the main engine in the Simulink environment.

Fig. 4. Computer model of EPM.

Then, in the speed range from 0.5 to 0.9, the diesel torque remains at the nominal value. With a further increase in the speed to 1.0 of the nominal value, a slight decrease in torque occurs.

Fig. 5. Moment characteristic of the main engine.

Where: 1 – air starting; 2 - acceleration with increasing torque; 3 - acceleration with constant torque; 4 - decrease in torque with increasing frequency

The propeller characteristic is shown in Fig. 6.

Fig. 6. Propeller characteristic.

EPM can develop the rated torque at almost zero speed. The rise time of the torque from zero to the nominal value (for example, vector with constant flux linkage) can be calculated in milliseconds. In the simulation, we assume that the torque of EPM remains constant (nominal) over the entire range of rotation frequency.

3 Results and Discussion

The main modes of CPP operation are calculated using the computer model of CPP, including:

- acceleration of CPP with separate and joint work of ME and EPM;
- interaction of CPP with ice during separate and joint work of ME and EPM;
- the course of the vessel in waves;
- breakage of the propeller blade during separate and joint operation of ME and EPM;
- braking of CPP during separate and joint work of ME and EPM;
- the reverse of CPP with separate and joint work of ME and EPM.

The processes of starting up EPM, ME and the joint starting up and acceleration of ME and EPM was modeled in turn. When modeling autonomous starting up of ME and EPM, for clarity, it is assumed that the power of each engine separately is equal to the power of CPP, taken as 100%.

When working together and starting ME and EPM, it is assumed that the power of EPM is equal to 30% of the CPP power, the power of the main engine is 70%.

The transient response of starting and accelerating EPM with a power of 100% of the CPP power to the rated speed is shown in Fig. 7.

Fig. 7. The transient response of starting and accelerating EPM to the rated speed.

Fig. 7 shows that EPM acceleration occurs smoothly and at the nominal torque, the acceleration time is about 15 s.

The maximum rotational speed of EPM with a power of 30% when operating according to a propeller characteristic is about 0.55.

The transient response of starting and accelerating the main engine with a capacity of 100% of the CPP power to the rated speed is shown in Fig. 8.

Fig. 8. The transient response of starting and accelerating the main engine to the rated speed.

The start takes place according to the torque characteristic shown in Fig. 5. At a rotation frequency of up to 0.4, acceleration and air starting of the main engine take place. Let’s assume that in this frequency range from 0 to the starting one, the main engine accelerates with a constant torque equal to 0.4 of the nominal value.

The acceleration time of the main engine to the rated speed is about 25 s, which is 10 s more than when accelerating EPM. The increase in the main engine speed occurs in two stages. At the first stage, with the air starting method, which lasts about 10 s, a low rate of

rise in the rotational speed is observed. After starting the main engine, the rate of rise increases. The acceleration time of the main engine in the second section is about 15 s.

According to the results of modeling the process of a single start-up of EPM ME, it can be seen that with the same power equal to 100%, the starting of EPM is 15 s, the starting of ME - 25 s.

When starting together, we assume that the torques of EPM and ME are summed up. In this case, the power of ME is 70%, and the power of EPM is 30% of the CPP power.

The transient response of the combined starting of EPM and ME up to the rated rotation frequency is shown in Fig. 9.

Fig. 9. Transient response of the combined starting and acceleration of ME and EPM up to the rated speed of CPP.

The acceleration time to the rated frequency of CPP with the combined start of ME and EPM is about 20 s, which is 5 s less than when starting the main engine with a power of 100% of the CPP power. Thus, the acceleration time of CPP to the rated speed with the combined operation of ME and EPM is reduced by 25% in comparison with the use of a propulsion plant based on the main engine.

4 Conclusions

1. To study the physical properties and modes of operation of the combined propulsion plants, a computer model of CPP has been developed. Using a computer model of CPP, it is possible to carry out computational experimental studies of the main operating modes. The mathematical model of CPP is based on the equation of the dynamics of the ship propulsion complex, as an object of regulation of the propeller shaft rotation frequency.
2. In the process of carrying out experimental studies on a computer model, transient processes of acceleration, stopping, reverse of CPP were obtained with joint and separate operation of ME and EPM. Computational experiments were carried out on the interaction of CPP with ice, the movement of the ship in waves, as well as the emergency shutdown of EM and EPM.
3. The developed computer model of CPP and the results of experimental studies of the main and emergency modes of operation can be used at the stage of technical design to select equipment and study transient processes.

References

1. F. Baldi, F. Ahlgren, F. Melino, C. Gabriellii, K. Andersson, *Energy Conversion and Management* **124**, 344–356 (2016) DOI: 10.1016/j.enconman.2016.07.009
2. M.A. Ancona, *Energy Conversion and Management* **164**, 42–58 (2018) DOI: 10.1016/j.enconman.2018.02.080
3. C. Capasso, E. Notti, O. Veneri, *Energy Procedia* **158**, 954–2959 (2019) DOI: 10.1016/j.egypro.2019.01.958
4. R.D. Geertsma, R.R. Negenborn, K. Visser, J.J. Hopman, *Applied Energy* **194**, 30–54 (2017) DOI: 10.1016/j.apenergy.2017.02.060
5. J. Ling-Chin, A.P. Roskilly, *Energy Conversion and Management* **117**, 305–318 (2016) DOI: 10.1016/j.enconman.2016.03.032
6. S. Jafarzadeh, I. Schjølberg, *Transportation Research Part D: Transport and Environment* **65**, 500 – 523 (2018) DOI: <https://doi.org/10.1016/j.trd.2018.09.021>
7. M. Kalikatzarakisa, R.D. Geertsmaab, E.J. Boonenc, K. Visserab, R.R. Negenborn, *Control Engineering Practice* **76**, 122-154 (2018) DOI: 10.1016/j.conengprac.2018.04.009
8. R.D. Geertsma, R.R. Negenborn, K. Visser, J.J. Hopman, *IFAC-PapersOnLine* **50**, 2296 – 2303 (2017) DOI: 10.1016/j.ifacol.2017.08.229
9. P. Wu, R. Bucknall, *International Journal of Hydrogen Energy* **45(4)**, 3193-3208 (2020) DOI: 10.1016/j.ijhydene.2019.11.152
10. G. Papalambrou, S. Samokhin, S. Topaloglou, N. Planakis, N. Kyrtatos, K. Zenger, *IFAC-PapersOnLine* **50(1)**, 11064-11069 (2017) DOI: 10.1016/j.ifacol.2017.08.2488
11. Jun Houa, Jing Sunab, Heath Hofmann, *Energy* **150**, 877 – 889 (2018) DOI: 10.1016/j.energy.2018.03.019
12. R.D. Geertsmaab, R.R. Negenborna, K. Visserab, J.J. Hopmana, *Applied Energy* **194**, 30-54 (2017) DOI: 10.1016/j.apenergy.2017.02.060