Analysis of fuel consumption of modern electronically controlled high-speed marine engines

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Abstract. The paper presents thermal tests of modern electronically controlled high-speed main engines of Caterpillar 3500 series of marine vessels. During the thermotechnical tests, experimental studies were carried out to change the values of the actual fuel consumption depending on the engine load. The number of engines under study installed on sea tugs during 10 years of operation was 80 units. The accumulated experience in conducting experimental studies of the technical condition control by the CIP method of diagnostics will make it possible to move from the classical approaches of technical operation to the new ones included in the system of remote monitoring and control of ship technical means of autonomous ships in operation. The experimental research methodology includes a classic approach to conducting such tests and a modern approach with remote data transmission to the shipowner's office. Studies have shown that different types of 3500 series engines have different actual fuel consumption values, but for each series, for example, 3512B, the scatter of points is small. The results of experimental studies of Caterpillar 3500 series engines made it possible to construct generalized dependences of the actual fuel consumption for each engine model separately. Experimental studies of ship technical means by the CIP method of diagnostics of sea vessels in operation are the basis for the control system of autonomous ships.

1. Introduction

Optimization of energy consumption and implementation of comprehensive measures to save fuel resources are identified as the most important goal of the transport industry strategy. A possible solution to the implementation of this strategy, and one of the main tasks, is creating a mechanism for monitoring modern methods of fuel consumption of marine engines and their accounting.

Currently, shipowners spend a lot of money and resources to optimize the process of remote monitoring of ships in operation, such as fuel consumption of the main engines of the propulsion complex, and data transfer to the company office.

Providing a fuel consumption control system for each engine is currently a more efficient and economically feasible task of controlling the amount of fuel written off on a ship. The use of such a control system makes it possible to control fuel consumption at various engine loads and transmit all information from the flow meters through the control unit (online mode) to the technical department of the company. The use of such a fuel control system will allow not only to control fuel consumption but also to assess the condition of the engine according to the most general parameter: fuel consumption.
2. Research objects

Table 1 shows the technical data of the Caterpillar engines under study. Table 1 shows that CAT3512 engines have 12 cylinders, CAT 3516 engines have 16 cylinders. The arrangement of the cylinders of the engines is V-shaped at an angle of 60°. Engines mainly differ in power and number of cylinders. All investigated engines run on diesel fuel. The motor is supplied with a data cable (Figure 1). The communication adapter (CAT DataLink) is used to transfer information to external devices, as well as to communicate with ET (Electronic Technician) personal computer software.

Table 1. Technical characteristics of modern main FOS of Caterpillar 3500 series of marine vessels

| Model    | Number of cylinders | Rated speed (n гд), min⁻¹ | Maximum power (N е max.), kW | Cylinder displacement (V h), cm³ | Total working volume, cm³ | TC rotation frequency, min⁻¹ | Fuel injection system | Turbocharging, maximum value of charge air pressure, P н max, kPa | Type of fuel |
|----------|---------------------|---------------------------|-----------------------------|---------------------------------|---------------------------|-----------------------------|---------------------|-----------------------------------------------|--------------|
| CAT 3512B | 12                  | 180                       | 1230                        | 17/19                           | 4,3                       | 51,8                        | Unitinjector        | Simple gasturbine                               | diesel       |
| CAT 3516B | 16                  | 180                       | 1491,5                      | 17/19                           | 4,3                       | 51                          | Unitinjector        | Simple gasturbine                               | diesel       |
| CAT 3516C -HD | 16                  | 160                       | 2110,5                      | 17/21                           | 4,87                      | 78                          | Unitinjector        | Simple gasturbine                               | diesel       |

Figure 1. Location of diagnostic elements

Information about the engine is displayed in the form of the indicated elements: temperature after the cooler; reduced efficiency of the air filter; atmospheric pressure; boost pressure; cold status; refrigerant temperature; crankcase pressure; diagnostic notifications; ESU supply voltage; engine
identifier; engine speed; set revolutions; system status; engine errors; flue gas temperature; oil pressure after filter; fuel pressure; maximum throughput of the air filter; oil pressure; fuel rail indicator reading; fuel supply limit indicator; cycle status; fuel consumption; pressure upstream of the turbocharger; pressure after the turbocharger. CAT DataLink relates to a service connector for communication with the ECU. CAT ET can also be used to display all information in real-time.

To obtain the actual fuel consumption at various engine loads, it is necessary to carry out thermal engineering tests, which will make it possible to create a map of the normalization of fuel consumption for the engines of the investigated vessels.

3. Experimental research technique

The experimental research methodology includes the study of the structures of the fuel system of the engines under study and the operating modes of the experiment itself.

The experimental research methodology includes research of fuel systems and main lines of ships with main FOS from Caterpillar.

Figure 2 shows the fuel system of the CAT 3500 engine. Figure 2 shows that the fuel supply circuit is a design for engines with unit injectors. Fuel is supplied to the engine system through a coarse filter (8) to the fuel transfer pump (10), which creates a pressure in the fuel line of 350–410 kPa. From the pump, the fuel passes through the electronic control unit (ECU) (4), performing the function of a cooler. And then, before the main line (1), the fuel is cleaned in a fine filter system (2). The manual fuel priming pump (3) is designed to fill the system with fuel after the loss of tightness in the system itself has been eliminated. Fuel flows continuously from the fuel manifold (1) through the unit injectors (5) and then, through the return manifold (7), returns to the supply tank. Unused fuel displaced by the injector plunger is also returned through the manifold (7) to the supply tank. At the end of the return system, there is a safety valve (6) set to a pressure of 415–450 kPa, which also ensures that the unit injectors are filled in correctly.

An electronically controlled fuel system with mechanically actuated unit injectors provides full electronic control of injection timing. The engine speed is controlled by adjusting the injection duration. The speed sensor synchronization loop forms part of the aft gear-transmission group and provides information to the electronic control unit (in the form of a signal generated by the engine speed/synchronization sensor) to determine the crankshaft position and engine speed. This data, together with other input signals, allows the ECU to accurately send a signal to the electromagnets of the unit injectors. To start fuel injection, the solenoid is energized; to stop, it is de-energized.

Figure 2. The fuel system of the Caterpillar engines under study
1 - fuel manifolds; 2 - fuel filters; 3 - manual fuel priming pump; 4 - electronic control unit; 5 - pump
injectors; 6 - safety valve (pressure regulator); 7 - fuel return; 8 - coarse fuel filter; 9 - intake pipeline; 10 - fuel pump; 11 - supply line to the hand fuel supply pump; 12 - discharge pipeline.

The fuel systems of all the investigated vessels are approximately the same and consist of storage tanks (storage tanks) and slop tanks (fuel - oil daily service tanks). Fuel supply tanks are designed for storage, control, and reception of fuel on the ship. The fuel is pumped into slop tanks located on the sides of the vessel, from which the main and auxiliary engines are consumed. The main engines have a separate fuel inlet to the engine fuel system, and the fuel return line (return) goes to different supply tanks along the sides. Auxiliary engines also have a separate fuel inlet to the engine fuel system, and the fuel return lines go to the port or starboard supply tanks, depending on how the fuel line is configured. The fuel system of sea tugs provides for the possibility of operation of main and auxiliary engines from service tanks of both sides.

Tests of the vessels were carried out in mooring mode and under the sailing mode, with sea roughness no more than 3 points, wind speed less than 5 m / s.

The test program includes:
- change in the speed of the main engine of the left/right side SAT 3512V (SAT 3516V, SAT 3516C-HD) within 700 - 1500 min⁻¹ with a step of 100 min⁻¹.
- determination of the engine load on the port/starboard side following the set value of the crankshaft rotation speed.
- determination of fuel consumption in each mode following the set value of the crankshaft speed and engine load.

4. Experimental results
Based on the data obtained, when carrying out computer diagnostics during mooring and sea trials, graphs of the dependence of fuel consumption on the crankshaft speed of 80 Caterpillar engines installed on sea tugs were built are shown in Figure 3.

The average values of the parameters for the engines under study were obtained in the form of graphs of the dependences of the averaged values of fuel consumption on the rotational speed of the 3500 series engines: 3512B brand (Figure 3, a); brand 3516V (Figure 3, b); brand 3512C-HD (Figure 3, c).
5. Conclusion

Experimental studies have made it possible to determine the dependence of fuel consumption on the rotational speed of the investigated main FOS of Caterpillar for sea tugs.

Unique data were obtained on the fuel consumption of electronically controlled FOS by Caterpillar during 10 years of operation on 80 engines under study. The results of the noon by the authors in the article will make it possible to apply the accumulated experience of technical operation for remote control systems that will be applied on new autonomous ships.
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