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OPTIMIZATION OF ELECTRONIC SPEED GOVERNORS SENSITIVITY FOR MARINE DIESEL ENGINES

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The object of the study is multicylinder marine diesel installations equipped with electronic speed governors (ESGs) operating under wave disturbance conditions. Modern marine diesel engines used in ship power plants are equipped with ESGs which have the technical capability to adjust the sensitivity of the governor's input signal. This parameter allows modifying the governor's response to high-frequency disturbances, which is a characteristic feature of diesel engine operation. However, assuming constant engine speed throughout the working cycle overly idealizes the governor's input signal. This leads to distorted optimal settings and reduced speed stability, especially under variable load torque conditions on the propeller shaft. To improve the efficiency of the automatic speed control system, a specialized model of a multicylinder marine diesel engine as a speed control object has been developed. This model takes into account the influence of cyclic torque instability on the governor's input signal across the entire operating range of diesel engines of various stroke types, speeds, and numbers of cylinders. For the two- and four-stroke marine main diesel engines HYUNDAI-MAN B&W 6S60MC-C7 and MaK 9M25C under study, modeling determined the governor sensitivity optimal settings for different sea wave disturbance intensities and periods. The model's capabilities for calculating changes in cylinder gas pressure in diesel engines of different stroke types enable an analysis of non-uniformity in working processes during the optimization of ESGs and determining the optimal combination of their tuning parameters. These findings allow improving the stability of automatic speed regulation over the entire range of possible operating conditions of main marine diesel engines

Keywords: vessel's main engine, electronic speed governor, cyclic instability, deadband control

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1. Introduction

The vast majority of vessels currently in operation are equipped with marine diesel engines [1], as they represent the most promising prime movers in water transport. In the speed control systems of modern marine diesel engines, ESGs with advanced operating algorithms are widely used. However, their tuning is often performed without considering the specific design features of individual diesel engines and the probabilistic nature of their operating modes. In some cases, the built-in adjustment capabilities adjustment is not utilized at all. As a result, ship personnel face an uncertain situation, as they are forced to configure ESGs without properly accounting for the interdependencies of their parameters, relying primarily on personal experience and intuition. Consequently, the governors fail to ensure adequate stability of speed modes under various wave conditions, which are characterized by different intensities and periodicities of the load torque fluctuations on the propeller shaft. This ultimately leads to the operation of diesel engines in suboptimal modes. Consequently, the problem of optimally tuning ESGs for main marine diesel engines operating under oscillatory motion caused by waves remains highly relevant.

2. Literature review and problem statement

Analyzing modern research in the field of speed regulation for marine diesel engines, a number of unresolved issues requiring further development can be identified. According to [2], there is currently a trend in maritime and inland water transport toward the adoption of electronic component bases, particularly the widespread use of controllers. This has led to the gradual replacement of hydraulic speed governors by electronic ones, especially in advanced marine diesel engine designs, which contributes to reducing harmful exhaust gas emissions [3]. A distinctive feature of ESGs is their ability to adjust the sensitivity to the input signal during operation. This parameter enables altering the governors' response to high-frequency disturbances [4]. In diesel engines with a camshaft, such disturbances occur due to the interaction between the cams and rollers of high-pressure fuel pumps (HPFPs). In modern marine diesel engines with a common-rail fuel injection system, these disturbances are caused by using inductive sensors with a serrated tape on the shaft for rotational speed measurement. Technical documentation for electronic governors' states that under moderate wave conditions, the deadband level could be increased to 3–5 %. However, such guidelines do not take into account that both the nature and magnitude of changes in diesel engine load under sea state influence depend on many variable external factors, and any preset sensitivity value of the governor input signal is optimal only for a particular vessel motion scenario. However, the reviewed studies do not comprehensively address to design features of diesel engines and the specific conditions of their operation when configuring electronic speed governors. As a result, existing recommendations for adjusting governor sensitivity remain insufficiently substantiated and unadapted to a wide range of operating modes.

The problem of optimizing the operation of ESGs can be addressed through mathematical modeling. However, in practice, the assumption of a constant engine speed throughout the working cycle does not realistically reflect the changes in the governor's input signal [5]. Neglecting inter-cycle fluctuations of the ESG input signal may lead to distorted optimal settings [6], reduced efficiency and service life of marine diesel engines, increased fuel consumption, and significant errors in diagnosing the technical condition. This implies that when tuning electronic ESGs, it is necessary to account for the cyclic component of the input signal caused by the instability of the diesel engine torque during the working cycle [7]. The instability arises from several factors, including variations in combustion processes across cylinders, the presence of torsional vibrations in shafts and shaft lines, uneven distribution of mechanical loads, the presence of unbalanced forces and moments, as well as external influences such as fluctuations in propeller resistance due to sea waves [8]. However, in practice, modeling approaches often oversimplify the importance of considering the cyclic component of the input governor signal and are based on the assumption of constant diesel engine speed throughout the working cycle. This leads to significant errors in determining the governor sensitivity setting, as the influence of inter-cycle oscillations and torque variations is not taken into account.

Moreover, the natural instability of engine speed can be exacerbated by unsatisfactory performance of the automatic speed control system (ASCS), which is common issue for most marine diesel engines, especially under partial load conditions, primarily due to time delay of governor response [9]. According to [10], one of the reasons for the deterioration of marine diesel engine performance is that the determination of optimal tuning parameters of the ASCS did not consider the impact of crankshaft speed instability, leading to reduced regulation efficiency. However, the studies do not address the issue of minimizing the impact of diesel engine speed instability by adjusting the sensitivity to imbalance of input signal in the ESG.

As noted in [11, 12], unsatisfactory dynamics of the main marine diesel engine's speed governor under transient operating conditions can lead to increased smoke opacity as well as mechanical and thermal overloads of cylinder-piston group components. In [13], it was established that considering the dynamic instability of the ESG's input signal during the settings optimization, can improve the stability of the crankshaft rotation speed over a wide range of changes in load characteristics and magnitude caused by sea wave disturbances. However, the studies do not examine the impact of crankshaft rotational speed instability on the distortion of sensitivity setting of ESGs.

According to [14], the implementation of modern programmable logic controllers equipped with wireless interfaces and built-in analog-to-digital converters enables real-time parametric diagnostics of marine diesel engines at a fundamentally higher level. Using such portable systems for parametric diagnostics can account for high-frequency pulsations of the governor's input signal instability during speed governor adjustment. This can contribute to refining recommendations for regulating the sensitivity of ESG under sea wave conditions, thereby improving the effectiveness of measures aimed at preventing emergency situations on vessels [15, 16]. Although the studies propose approaches for applying parametric diagnostics to improve the ASCS efficiency, their implementation remains limited due to the necessity of improving the approach to integration with modern programmable logic controllers.

These aspects shape the overall scientific problem, which consists in optimizing of the ESG while considering the instability of the governor's input signal throughout the entire operational range of marine diesel engines with different stroke types and operational specific under sea wave disturbances. Solving this problem will enhance the stability of main engines ASCS during operation in rough weather conditions.

3. The aim and objectives of the study

The aim of the study is to develop a specialized model of multicylinder marine diesel engine as an object of speed regulation, which accurately replicates changes in the shaft rotational speed both within a working cycle and under wide-range variations in fuel supply, to optimize ESGs sensitivity.

To achieve the research aim, the following objectives were set:

– determine the impact of crankshaft speed instability on the ESG input signal across the entire operational range of marine diesel engines with different stroke types, rotational speeds, and cylinder numbers;

– develop an approach for optimizing the reduced sensitivity zone (RSZ) of the ESG to minimize the negative effects of diesel engine`s speed fluctuations under wave-induced disturbances.

4. Materials and methods of research

The study was carried out on two different main engines (MEs): a two-stroke HYUNDAI-MAN B&W 6S60MC-C7 installed on the tanker "CATALAN SEA" operated by Eastern Pacific Shipping Pte. Ltd., and a four-stroke MaK 9M25C on the vessel "TIMBER NAVIGATOR" owned by ForestWave Navigation B.V. The two-stroke diesel engine is equipped with Nabtesco electronic control system, comprising the M-800-III remote automatic control system, MG-800 type ESG, and protection system. The four-stroke diesel engine drives a controllable pitch propeller through a reduction gear, which delivers an output speed of 130 rpm under normal operating conditions. It is equipped with a Regulateurs Europa Viking 35 type ESG with a RE 2231-1GH hydraulic actuator. The governor interacts with BERG PROPULSION ERC3000 remote automatic control system. The main technical specifications of the HYUNDAI-MAN B&W 6S60MC-C7 and MaK 9M25C main diesel engines were obtained from the design documentation [17, 18] and are presented in Table 1.

The speed instability can be reduced by increasing the engine's flywheel moment of inertia. However, this solution is not effective, as it inevitably deteriorates the engine's starting characteristics, increases the response time of the automatic speed control system, and complicates the governor's operation under variable load conditions. In this regard, the hypothesis of the study is that ensuring the diesel's speed stability without negatively affecting the engine's dynamic performance and starting characteristics can be achieved by optimizing the ESG sensitivity.

Table 1

Technical specifications of the HYUNDAI-MAN B&W 6S60MC-C7 and MaK 9M25C

Parameter/engine model	HYUNDAI-MAN B&W 6S60MC-C7	MaK 9M25C
Nominal power, kW	13560	2970
Nominal speed, rpm	105	750
Number of cylinders	6	9
Cylinder bore, m	0.6	0.25
Piston stroke, m	2.4	0.4
Nominal combustion pressure, MPa	15	19.5

The study was conducted considering the results of [19], which substantiated the validity of assumptions regarding the stationarity and normality of the disturbance acting on the marine diesel engine installation under wave conditions. This is explained by the fact that the investigated system contains linear inertial elements that normalize the distribution law of random signals. From that same work, quantitative dependencies were adopted for the variance of the disturbance as it changes with Beaufort wind scale levels, as well as the relationship between the parameters α and β ($\alpha \approx 0.16\beta$), which characterize the correlation function of the disturbance. The disturbance's spectral density was defined using the Firsov approximation formula, which accurately represents the physical nature of the phenomenon, as it provides the lowest density at low frequencies compared to other formulas [20].

Since the model is not intended for analyzing engine loads, it assumes that under the diesel operating modes selected for ESG tuning, the turbocharging system ensures satisfactory fuel combustion. This assumption allows for excluding the description of dynamic processes in the charge air system, significantly simplifying both the model itself and the associated modeling tasks. Such a model can produce a signal close to the real one received at the ESG input for diesel engines of different stroke types, operating speeds, and numbers of cylinders.

As a disturbance in the model, the dependency from [21] can be used, which accounts for the feedback influence of the marine diesel engine on the perturbation. However, research [22] with a hydromechanical speed governor demonstrated that the results of ASCS optimization using this dependency and a standard sinusoidal function were practically identical. In this regard, the assumption has been made regarding the disturbance function, which, during the model validation process, was assumed to be sinusoidal.

Since the objective of modeling is to improve the governor's dynamic response to near-harmonic disturbances, the structural diagram does not account for permissible actuator travel limitations as: a function of the measured rotational speed, a function of the boost air pressure and a fixed constraint set on the control panel.

The study was carried out using the shaft motion calculation algorithm described in [23], according to which the indicated torque of the diesel engine is calculated according to the following dependency:

$$M_i = sign(n) z \frac{\pi D^2 s}{8\varphi_c} \int_0^{\varphi_c} (p - p_a) b \, d\varphi, \quad (1)$$

where n – diesel engine speed, rpm; z – number of cylinders; D – cylinder bore, m; s – piston stroke, m; φ_c – crank angle per cycle, degrees; p – in-cylinder gas pressure, Pa; p_a – atmospheric pressure (assumed to be 101,325), Pa; b – relative piston speed.

In [24], the results of calculating the main parameters of the working processes of a marine two-stroke low-speed diesel engine were compared using both an exact and an approximate expression for the dimensionless parameter defining the piston speed. As a result, it was concluded that although the approximate expression reproduces the actual one with reasonable accuracy, its use slightly reduces the accuracy of calculating the working processes of the investigated diesel engine. Therefore, in the developed specialized model, the current piston stroke is expressed in terms of the crank angle (CA) using the exact expression:

$$\frac{dV}{dt} = \frac{\pi D^2}{4} \frac{s}{2} \left[\sin\varphi + \frac{\lambda \sin(2\varphi)}{2\sqrt{1 - \lambda^2 \cdot \sin^2\varphi}} \right] \frac{d\varphi}{dt}, \quad (2)$$

where V – current cylinder volume, m^3; φ – crank angle, degrees; λ – ratio of the crank radius to the connecting rod length.

The study was carried out using the ASCS model [25], according to which the delay in the change of the diesel engine's relative indicated torque with respect to the change in the relative travel of the HPFP racks $\bar{h}_r$ is calculated by following formula:

$$\tau_{del} = \frac{20 - 10\bar{h}}{6 n_{d0} \bar{\omega}_d}, \quad (3)$$

where n_{d0} – diesel engine speed at the nominal mode, rpm; $\bar{\omega}_d$ – relative angular velocity of the diesel engine shaft.

In [26], ESG model was presented, which is detailed down to all tuning parameters and accounts for the dynamic properties of its elements. The model enables the implementation of any control law, taking into account the sensitivity to imbalance signals between the actual and preset rotational speed. This, in turn, facilitates the optimization of electronic governors across a wide range of varying load conditions. A specialized model of a multicylinder marine diesel engine as a speed-controlled object, where the working cycles of all cylinders are calculated but remain uniquely dependent on fuel supply (i. e., the ESG output signal), has been integrated into this framework. The calculation of gas pressure variations in the marine diesel engine cylinder is performed using the method described in [27].

5. Research results of ESG RSZ optimization in marine diesel engines

5. 1. Approach to considering crankshaft speed instability in ESG optimization for marine diesels

Fig. 1 shows the structural diagram of the HYUNDAI-MAN B&W 6S60MC-C7 marine diesel engine's ASCS with

Nabtesco MG-800 electronic governor and the developed cyclic operation accounting module, which receives the following signals:

– time-varying control signal defining the fuel supply;

– constant signal for the fuel injection timing angle, corresponding to the diesel operating mode;

– cyclically varying crankshaft angle signal is calculated by expression (2), which changes over time within the range characteristic of different diesel stroke types, proportional to the crankshaft's angular velocity.

The disturbance is applied to the system via the load channel by modifying the relative resistance torque on the diesel shaft $\bar{M}_r$. The main engine (ME) is represented as integrating link 2 with the diesel acceleration time T_d, which was calculated with consideration of the inertia moments of the crankshaft-connecting rod mechanism, the flywheel, the intermediate and propeller shafts, the propeller, the entrained water mass during propeller rotation, and other attached mechanisms. Elements 3–9 generate the required actuator travel $\bar{z}'_c$, which is executed by elements 10–20. Links 5, 6, and 7 form the control signal based on the proportional-integral-derivative control law. The actuator mechanism has two feedback loops: one for the position of the roller nut (the output signal $\bar{z}_c$) and one for the rotational speed of the electric motor $\bar{n}_e$. The electric motor is represented as integrating link 15. The converter that translates the motor speed into the nut stroke is shown as integrating link 17. Feedback via link 21 is used if parallel operation of multiple diesel engines is required. Link 4 sets the RSZ value for the imbalance of actual $\bar{\omega}_d$ and preset $\bar{\omega}_s$ speed signals within the range of 0 to 10 rpm (i.e., from 0 to 0.095 in relative units for the two-stroke diesel under study). The signal gain coefficient in this zone can be set within the range 0.1…1.0 (i. e., sensitivity can be reduced by up to 90 %). The reduced sensitivity to signal imbalance follows the transformation algorithm:

$$\bar{z}_{RSZ} = \begin{cases} \bar{z}_0 + \frac{\varepsilon}{2}\left(1-k_g\right) \text{ for } \bar{z}_0 < -\frac{\varepsilon}{2}; \\ k_g \bar{z}_0 \text{ for } -\frac{\varepsilon}{2} \le \bar{z}_0 \le \frac{\varepsilon}{2}; \\ \bar{z}_0 - \frac{\varepsilon}{2}\left(1-k_g\right) \text{ for } \bar{z}_0 > \frac{\varepsilon}{2}, \end{cases} \quad (4)$$

where ε – width of the relative RSZ; k_g – gain of the relative RSZ; $\bar{z}_0$ – imbalance between the preset and actual rotational speed signals.

Fig. 2 presents the ASCS model of the HYUNDAI-MAN B&W 6S60MC-C7 marine diesel engine with the NABTESCO MG-800 electronic governor and the developed cyclic operation accounting module, which reproduces the cyclic torque instability causing governor's input-signal fluctuations.

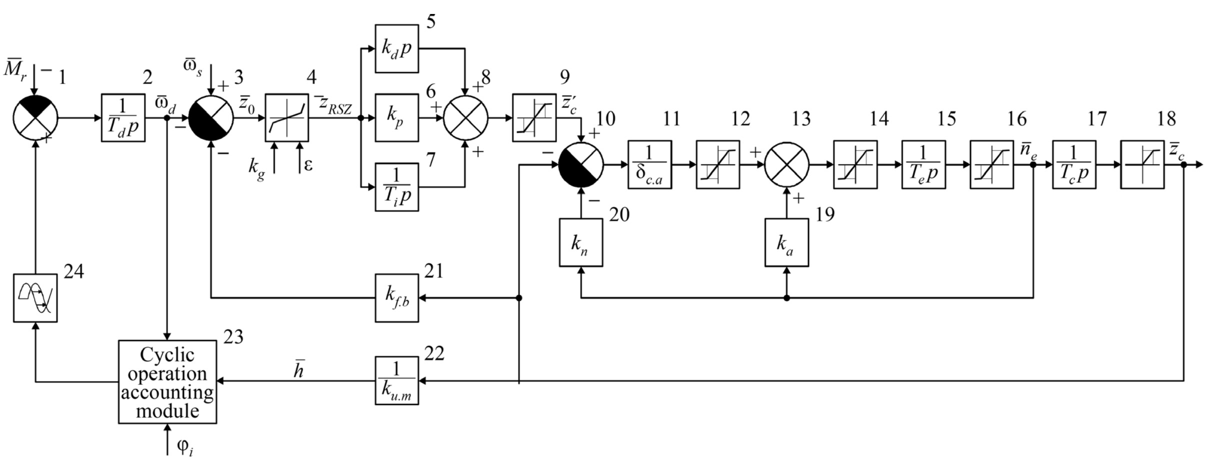


Fig. 1. Structural diagram of the ASCS for the HYUNDAI-MAN B&W 6S60MC-C7 with Nabtesco MG-800 ESG: 1, 3, 8, 10, 13 — summators; 2, 7, 15, 17 — integrating links; 4 — functional converter introducing the RSZ; 5 — differentiating link; 6, 11, 19, 20, 21, 22 — proportional links; 9, 12, 14, 16 — nonlinear links accounting for signal saturation at ±1; 18 — nonlinear link considering signal saturation in the range 0…1; 23 — cyclic operation accounting module; 24 — nonlinear link accounting for delay τ_{del} according to the (3)

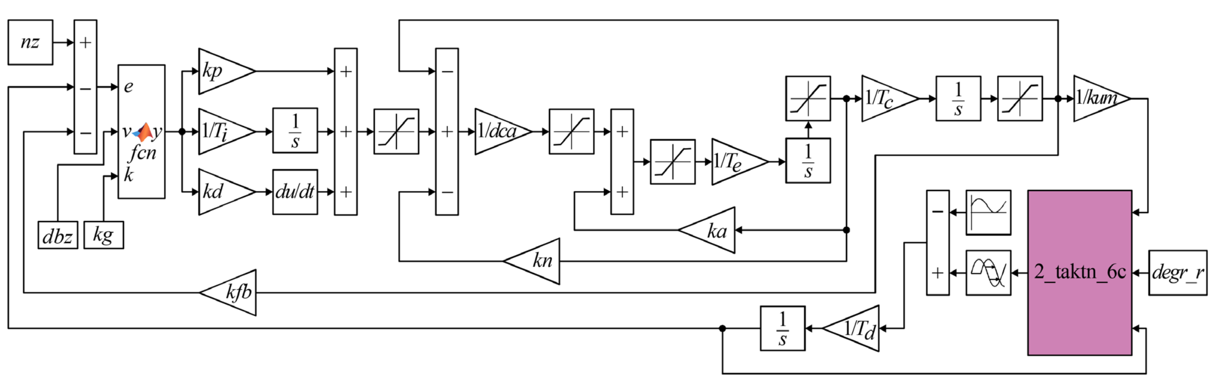


Fig. 2. Model of the ASCS for the HYUNDAI-MAN B&W 6S60MC-C7 with NABTESCO MG-800 and the developed cyclic operation accounting module

In Fig. 3, the calculated values of relative engine speed obtained from the model are compared with experimental data measured using the DOCTOR DK-20 portable diagnostic station by Icon Research. The experiment was conducted under the sea state of Beaufort force 2, with wave heights of approximately 1 m and wind speeds of 5.5–6.5 m/s. The wind direction was northwesterly, and the vessel's heading was 218°. The forward/aft draft was 6.0 m/8.6 m. The engine room air temperature was 34 °C, the seawater temperature was 22 °C, and the barometric pressure was 1020 mbar.

The calculated values were determined under conditions equivalent to the experimental disturbance impact, using the actually set on the control panel governor parameters. The following parameter values were used: ME acceleration time T_d=2.3 s; fuel injection timing angle φ_i=–2.5 CAD; time delay τ_{del}=0.024 s; RSZ width ε=0.005 rel. un.; RSZ gain coefficient k_g=0.5 rel. un.; proportional gain k_p=2.2 rel. un.; integral time T_i=2 s; derivative constant k_d=0 rel. un.; actuator response time T_c=0.4 s; actuator control element non-uniformity $\delta_{c.a}$=0.04 rel. un.; electric motor acceleration time T_e=0.03 s; gain for the acceleration and braking of the electric motor k_a=0.3 rel. un.; feedback gain for the motor speed k_n=0.06 rel. un.; utilization coefficient of the governor's stroke from zero to nominal fuel supply $k_{u.m}$=0.8 rel. un.; feedback gain coefficient $k_{f.b}$=0 rel. un. The study was conducted at an average load of the marine diesel engine, corresponding to the main operating mode of 84 rpm.

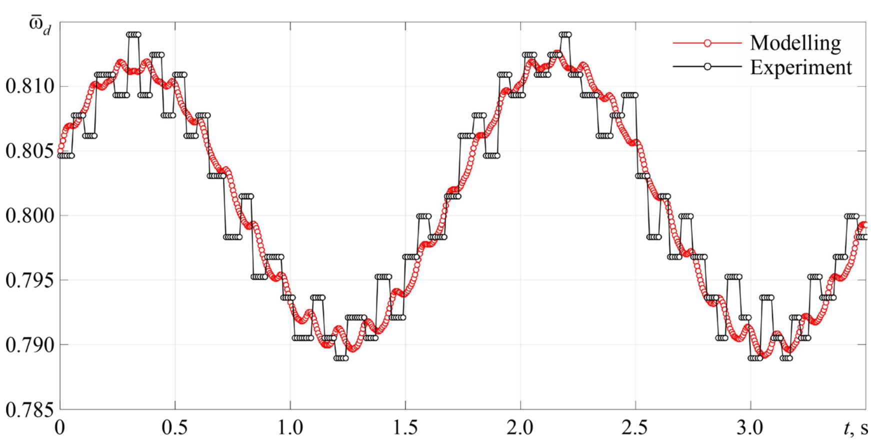


Fig. 3. Validation of the adequacy of the developed specialized model

Analysis of the root-mean-square (RMS) deviations between the experimental and simulated transient processes showed that the RMS does not exceed 9.4 %. This indicates a satisfactory level of model adequacy.

Fig. 4 shows the structural diagram of the ASCS for the MaK 9M25C, equipped with Regulateurs Europa Viking 35 ESG and RE 2231-1GH hydraulic actuator, along with the developed cyclic operation accounting module. In turn, the hydraulic actuator was modeled as a first-order aperiodic link, where the time constant is determined by the product of the control element's non-uniformity and its response time. Since the load limiter protects the ME from overloads by reducing the propeller pitch when the HPFP rack travel exceeds the permissible fuel supply, defined as a function of the engine speed and the setpoint from the control panel, the study was conducted at an average engine load corresponding to 80 % of the nominal rating. In this ESG, the RSZ width is set within the range of 0 to 40 rpm (i. e., for the four-stroke diesel engine under study, from 0 to 0.05 rel. un.), with gain coefficient ranging from 0.1 to 1.0 rel. un. The reduced sensitivity of the input signal transforms the signal according to equation (4).

Fig. 5 presents the ASCS model of the four-stroke MaK 9M25C marine diesel engine, equipped with the Regulateurs Europa Viking 35 ESG and the RE 2231-1GH hydraulic actuator, along with the developed cyclic operation accounting module. The study was carried out under average ME load, corresponding to 80 % of the nominal power.

The default parameters of the logical unit of the ESG were used during the simulation: proportional gain k_p=2.5 rel. un.; integral time T_i=2 s; derivative constant k_d=0 rel. un. The numerical values of the other model parameters correspond to the design documentation for the diesel engine and its ESG under study: diesel acceleration time T_d=1.9 s; fuel injection timing angle φ_i=–9.5 CAD; time delay τ_{del}=0.004 s; relative RSZ width ε=0...0.04 rel. un.; RSZ gain coefficient k_g=0.5 rel. un.; actuator response time T_c=0.37 s; non-uniformity of the actuator control element $\delta_{c.a}$=0.04 rel. un.; utilization coefficient of the governor's stroke from zero to nominal fuel supply $k_{u.m}$=0.75 rel. un.; feedback gain coefficient $k_{f.b}$=0 rel. un.

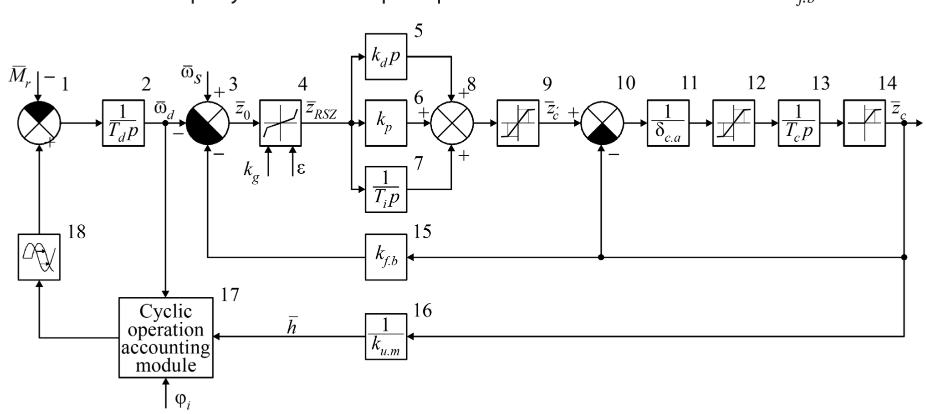


Fig. 4. Structural diagram of the ASCS for the MaK 9M25C with Viking 35 ESG and RE 2231-1GH hydraulic actuator: 1, 3, 8, 10 – summators; 2, 7, 13 – integrating links; 4 – functional converter that introduces the RSZ; 5 – differentiating link; 6, 11, 15, 16 – proportional links; 9, 12 – nonlinear links accounting for signal saturation at ±1; 14 – nonlinear link accounting for signal saturation in the range 0...1; 17 – cyclic operation accounting module; 18 – nonlinear link accounting for delay τ_{del} according to the (3)

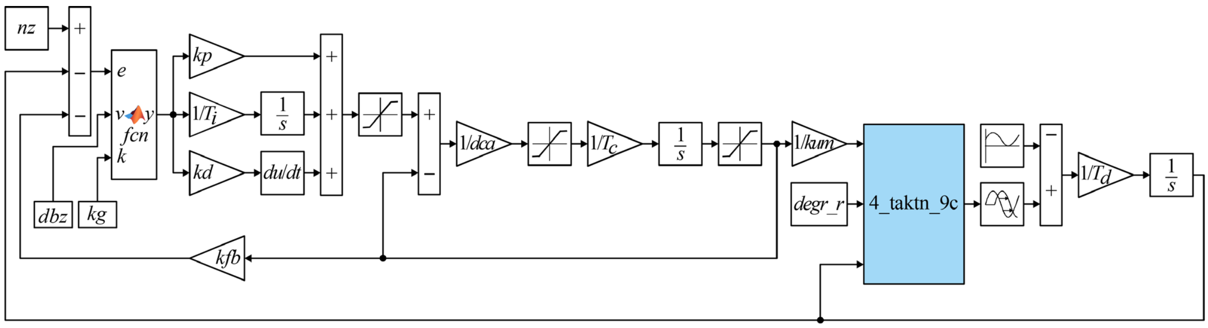
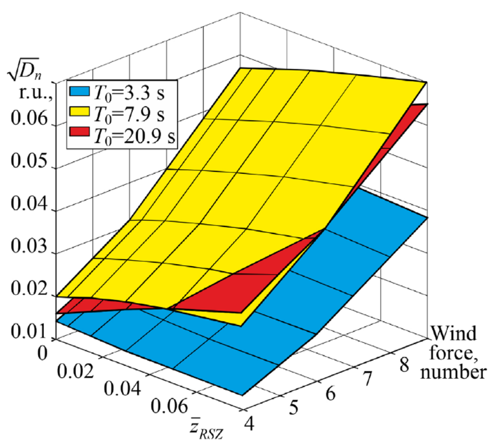


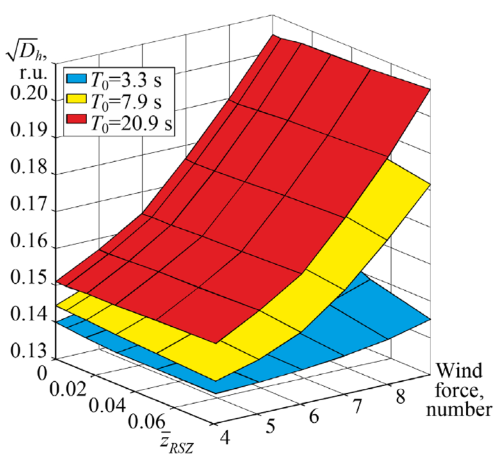
Fig. 5. Model of the ASCS for MaK 9M25C with Regulateurs Europa Viking 35 ESG and the RE 2231-1GH hydraulic actuator, along with the developed cyclic operation accounting module

5. 2. Framework for optimal ESG sensitivity adjustment in marine diesel engines under waves

In Fig. 6, the simulation results for the studied two-stroke main marine diesel engine are presented. The figure illustrates the influence of the ESG relative RSZ value – $\bar{z}_{RSZ}$ (width is variable, gain coefficient is set at 0.5), on the RMS of the diesel engine's relative speed – $\sqrt{D_n}$ and the RMS of the HPFP rack's relative travel – $\sqrt{D_h}$ under varying wave intensity and period T_0.



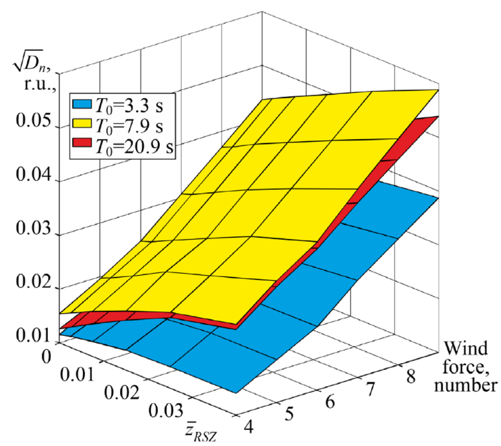
a



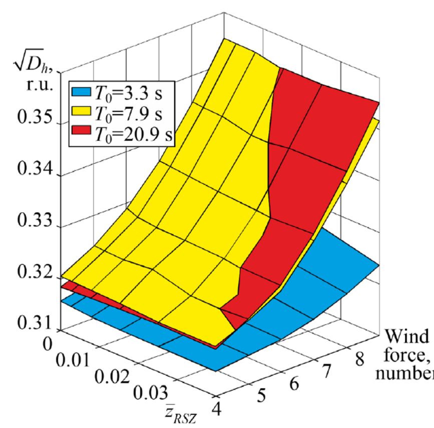
b

Fig. 6. Influence of the ESG RSZ value under varying wave intensity and period on: *a* — RMS of the engine's relative speed; *b* — RMS of the HPHP rack's relative travel

Fig. 7 shows the results of simulating the four-stroke ME under study, illustrating the effect of the ESG relative RSZ value – $\bar{z}_{RSZ}$ (width is variable, gain coefficient is set at 0.5) on the RMS of the engine's relative speed – $\sqrt{D_n}$ and the RMS of the HPFP rack's relative travel – $\sqrt{D_h}$ under varying wave intensity and periods T_0.



a



b

Fig. 7. Influence of the ESG RSZ value under varying wave intensity and periods on: *a* — RMS of the engine's relative speed; *b* — RMS of the HPFP rack's relative travel

Fig. 8 present the indicator diagrams for the two- and four-stroke MEs under study, plotted based on the calculated changes in cylinder gas pressure for the first cylinder.

As a result, the proposed approach to optimizing electronic speed governors of marine main diesel engines with different stroke types allowed for the determination of optimal governor's sensitivity settings under sea wave conditions of varying intensity and disturbance periods.

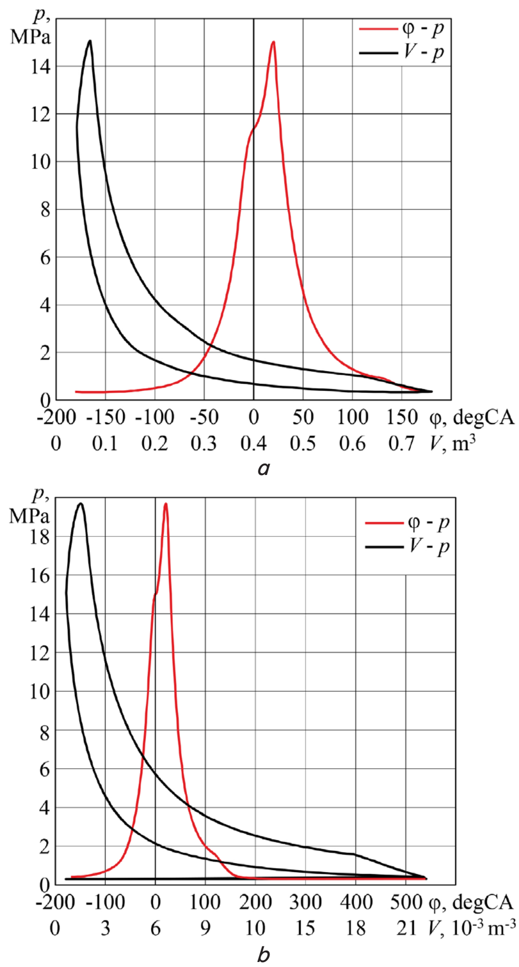


Fig. 8. Calculated indicator diagrams of: *a* – two-stroke engine HYUNDAI-MAN B&W 6S60MC-C7; *b* – four-stroke engine MaK 9M25C

6. Discussion of ESG sensitivity optimization results in marine diesel engines under waves

The structural diagram of the two-stroke ME HYUNDAI-MAN B&W 6S60MC-C7 with the ESG Nabtesco MG-800 and the developed cyclic operation accounting module is shown in Fig. 1. It enables the consideration of cyclic torque instability which leads to fluctuations of governor input signal during modeling. This factor directly affects the determination of the optimal governor sensitivity setting and can improve the stability of the rotational speed regulation of two-stroke MEs under actual sea conditions.

The model in Fig. 2 is detailed to ESG tuning parameters and takes into account the dynamic properties of its components. It also allows for analyzing the impact of governor tuning parameters on the dynamic properties of the ASCS. This model ensures the consideration of delays in the control signal transmission from the governor to the diesel engine, which are related to the cyclic fuel injection and the specific characteristics of torque variation in the crankshaft mechanism.

The calculated transient processes of the ME relative rotational speed, compared with the experimental ones in Fig. 3, demonstrated an adequate level of model accuracy. This enables the model use for developing recommendations of adjusting the sensitivity of ESGs for MEs under varying operating conditions.

Fig. 4 shows the structural diagram of the ASCS for the four-stroke ME MaK 9M25C, equipped with the ESG Regulateurs Europa Viking 35 and the RE 2231-1GH hydraulic actuator, as well as the developed cyclic operation accounting module, which enables the consideration of torque variation during modeling. In turn, accounting for the cyclic changes caused by the specific operational characteristics of the diesel engines allows for determining the optimal governor sensitivity settings across a wide range of loads for the four-stroke MEs.

Fig. 5 presents the model of ASCS for the MaK 9M25C marine four-stroke diesel engine with the Regulateurs Europa Viking 35 governor, along with the developed cyclic operation accounting module. This module includes the input control signals for fuel injection, the fuel injection advance angle, and the cyclically varying signal of the CA degrees. The developed model can be used to enhance the engine's stability under sea wave conditions by adjusting the sensitivity of the governor's input signal.

From Fig. 6, *a*, it follows that at a short period of oscillatory disturbance (T_0=3.3 s), increasing the RSZ value (i. e., reducing the ESG's sensitivity) improves the speed stability of the two-stroke ME across the entire range of wind-induced wave intensities. For example, under sea state conditions caused by wind force of 7 on the Beaufort scale, increasing the RSZ value from 0 to 0.05 rel. un. led to reduction of $\sqrt{D_n}$ from 0.0284 to 0.0269 rel. un. Further decreasing sensitivity to 0.08 rel. un. does not noticeably improve speed stability (i. e., $\sqrt{D_n}$ remains essentially unchanged). From Fig. 6, *b*, it can be seen that under short T_0, a similar stabilization trend is observed for the thermal regime of the two-stroke marine diesel engine, when adjusting the ESG sensitivity across the entire range of wind-induced wave intensities. For instance, when varying ESG sensitivity from 0 to 0.05 rel. un., under wave conditions caused by wind force of 7 on the Beaufort scale, the $\sqrt{D_h}$ decreased from 0.1486 to 0.1412 rel. un. This occurs because the governor stops responding to low-amplitude disturbances. Further increases in the RSZ value produce no significant changes in $\sqrt{D_h}$ across the entire wind-wave range.

From Fig. 6, *a, b*, it also follows that under an average disturbance period (T_0=7.9 s), reducing the sensitivity of the two-stroke diesel engine's ESG leads to decreased speed stability for any intensity of wave disturbance, while simultaneously improving thermal stability. For example, during rolling motion caused by wind force of 5 on the Beaufort scale, raising the RSZ value from 0 to 0.08 rel. un. led to an increase in $\sqrt{D_n}$ from 0.0257 to 0.0364 rel. un., while the $\sqrt{D_h}$ decreased from 0.1489 to 0.1445 rel. un. Thus, at an average wave period for two-stroke ME, decreasing the ESG's sensitivity is accompanied by growing speed instability (especially pronounced under intense wave disturbances). Consequently, a compromise RSZ value might only be recommended to stabilize the engine's thermal regime under moderate wave conditions. Conversely, at a long period of oscillatory disturbance (T_0=20.9 s), setting the minimum RSZ value of the ESG improves both speed and thermal stability of the two-stroke marine diesel engine. For example, under sea state conditions caused by wind force 9, reducing the RSZ value from 0.08 to 0 rel. un. led to a decrease in $\sqrt{D_n}$ from 0.0649 to 0.0456 rel. un., while the $\sqrt{D_h}$ decreased from 0.2077 to 0.203 rel. un. Therefore, under conditions of a long wave period, minimizing the RSZ value is recommended so that the ESG more actively regulates the engine's speed while simultaneously stabilizing the thermal regime.

From Fig. 7, *a*, it follows that at a short-wave period, reducing the governor's sensitivity (i. e., increasing the RSZ value) does not improve the speed stability of the four-stroke ME across the entire range of wind-induced wave intensities. For instance, under wave conditions caused by wind force of 5 on the Beaufort scale, increasing the RSZ value from 0 to 0.02 rel. un. changes $\sqrt{D_n}$ from 0.0148 to 0.0171 rel. un. This can be explained by the fact that when the ESG's sensitivity is reduced, the HPFP rack travels with delay but in abrupt shifts, which does not reduce the amplitude of its movements. From Fig. 7, *b*, it appears that with short wave period, reducing the ESG's sensitivity tends to improve the diesel's thermal regime across the entire range of wave intensities. For example, under sea state conditions induced by wind force 5, increasing the RSZ value from 0 to 0.02 rel. un. decreases $\sqrt{D_h}$ from 0.3176 to 0.3158 rel. un.

Further, from Fig. 7, *a, b*, under average wave period, increasing the RSZ value lowers speed stability while simultaneously improving the thermal regime. For example, under waves caused by wind force 4, raising the RSZ value from 0 to 0.04 rel. un. led to an increase in $\sqrt{D_n}$ from 0.0153 to 0.0266 rel. un., as well as a decrease in $\sqrt{D_h}$ from 0.3205 to 0.3181 rel. un. Hence, since increasing the RSZ value results in a slight rise in speed instability under both short and average wave periods, a compromise setting of reduced ESG's sensitivity could be recommended for stabilizing the thermal regime of a four-stroke marine diesel engine in moderate wave conditions. Conversely, at a long wave period, increasing the ESG's sensitivity leads to a deterioration in both speed and thermal stability of the four-stroke ME. For example, in wave conditions induced by wind force 9, reducing the RSZ value from 0.04 to 0 rel. un. lowers $\sqrt{D_n}$ from 0.0538 to 0.036 rel. un. and $\sqrt{D_h}$ from 0.3547 to 0.3526 rel. un. Therefore, under long wave period, it is recommended to minimize the RSZ value to enhance ASCS stability, while maintaining the diesel's thermal regime stability.

In order to address the problem of solving the task of comparing real and mathematical modeling operational processes data during the parametric diagnostics, the calculated indicator diagrams of the studied diesel engines are presented in Fig. 8. Such a comparison enables a qualitative analysis of cylinder performance, allows assessment of its load reserves, and facilitates finding the optimal combination of tuning parameters. During the operation of marine diesel engines, there may be a gradual decrease in power output and an increase in the thermal stress on cylinder-piston group, which inevitably leads to higher fuel consumption. This can occur, in part, because necessary technical measures are not taken in a timely manner due to the lack of detailed information about operating parameters that characterize the quality of thermodynamic processes in the diesel cylinders. Defects that arise and progress over time in the fuel injection system lead to increased differences in cylinder indicated power, causing an imbalance in mechanical and thermal loads among the diesel engine's cylinders. To prevent failure of an overloaded cylinder, the operating power of the entire diesel installation is forcibly reduced. For modern marine diesel engines, parametric diagnostics of the working process, including monitoring fuel injection quality and in-cylinder combustion, makes it possible to standardize loads, analyze cycle irregularities, diagnose the technical condition, and monitor the specific effective fuel consumption.

In contrast to the known models [28–30], which do not account for the instability of the ESG input signal, the results obtained here enable ESG optimization across the entire operational range of marine diesel engines with different stroke types. This is made possible due to the key features of the developed model:

– time-dependent cyclic variation of the crankshaft angle degrees for each cylinder is reproduced within the range of –180…+180 CA deg. for a two-stroke diesel engine and –180…+540 CA deg. for a four-stroke engine;

– discrete changes in the fuel supply per cycle are considered for each cylinder at the crankshaft angle corresponding to the advanced timing of fuel injection;

– calculation of indicator diagrams is performed through programming within Matlab function blocks, with each diagram formed as a set of corresponding polytropic processes depending on the crankshaft angle;

– during the computation the indicator diagrams compression and expansion polytropes are combined with linear approximations of the intake and exhaust processes;

– indicated torque for each cylinder is calculated according to the dependency (1) as a function of the crank-connecting rod mechanism angle and the fuel injection amount, reflecting pressure changes throughout the working cycle;

– indicated torques from all cylinders are algebraically summed and then normalized to unity for the calculation of transient processes in relative units;

– this approach achieves highly accurate reproduction of the multicylinder diesel engine's speed variation both within the working cycle and under wide-ranging changes in fuel supply across a broad spectrum of operating speeds and loads.

Previous studies indicate that under the most probable wave conditions for which the optimization was conducted, the specific fuel consumption remains practically unchanged. Thus, the primary outcome is enhanced stability of the engine speed mode rather than a direct reduction in fuel consumption under typical operating conditions. However, under severe wave conditions or situations involving significant transient processes (e.g., frequent course alterations or rapid transitions between different load levels), optimized electronic governor sensitivity could contribute to fuel savings by minimizing speed fluctuations and preventing over-injection. Preliminary calculations in these cases suggest a potential decrease in specific fuel consumption by an average of 2–5 %, although this value may be refined during full-scale trials in actual service conditions.

The developed mathematical model for ESG optimization is designed for multicylinder marine diesel engines. Therefore, its application to other engine types requires additional validation. The use of the obtained results under extreme maritime conditions may require further analysis. The study focuses on optimizing the RSZ, while other ESG tuning parameters were not considered in this research.

Evaluation of potential long-term effects on engine lifespan and component wear, both essential considerations for extended marine diesel operations, remains outside the scope of this study.

Potential future work involves addressing the ESG tuning optimization problem for main marine diesel engines by adapting the RSZ value to the stochastic characteristics of disturbances.

7. Conclusions

1. A model of an automatic speed control system for a marine diesel engine has been developed, taking into account the variation of the indicator torque in each cylinder throughout

the working cycle. The model is suitable for both two-stroke and four-stroke diesel engines and operates over a wide range of loads and speeds. By considering the changing cyclic processes in the cylinders, it allows for more accurate modeling of high-frequency speed fluctuations in the diesel engine. This is particularly important for tuning the electronic speed governor to ensure the stability of the engine's speed mode in rough sea conditions.

2. For the two-stroke main diesel engine HYUNDAI-MAN B&W 6S60MC-C7 under study, an ESG RSZ width of 0.05 rel. un. with a gain coefficient of 0.5 rel. un. in this zone ensures speed stability during load variations on the engine under short wave period. Meanwhile, under intense wave conditions (wind force 6 and above) with average disturbance period, the recommended values of ESG sensitivity can improve the engine's thermal stability, provided that any resulting speed instability remains within acceptable limits. For the four-stroke diesel engine MaK 9M25C under study, reducing ESG sensitivity under both moderate (wind force up to 6) and intense (wind force 6 and above) wave conditions deteriorates the ESG's dynamics, as confirmed by an increase in the RMS of the diesel shaft's relative speed. However, with small to medium wave periods, there is a consistent trend toward improved thermal stability over a wide range of changing sea state conditions. Therefore, under intense disturbance variance that cause significant engine speed fluctuations, while maintaining an acceptable speed instability level, increasing the ESG RSZ width to 0.02 rel. un. with gain coefficient of 0.5 rel. un. can be recommended. Minimizing the ESG RSZ value during long wave periods is recommended for both two- and four-stroke MEs to enhance ASCS stability while maintaining a stable thermal regime in the diesel engine.

Conflict of interest

The authors declare that they have no conflicts of interest regarding this study, including financial, personal, authorship-related, or any other potential conflicts that could influence the research and its results presented in this article.

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Use of artificial intelligence

The authors confirm that no artificial intelligence technologies were used in the creation of this work.

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