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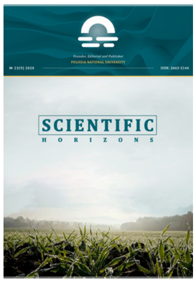

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Sensitivity Optimisation of a Main Marine Diesel Engine Electronic Speed Governor

Sergii Gorb[1*], Maksym Levinskyi[1], Mykola Budurov[2]

[1]National University "Odessa Maritime Academy"
65029, 8 Didrikhson Str., Odesa, Ukraine

[2]Eastern Pacific Shipping Pte. Ltd. (EPS)
039192, 1 Temasek Ave., Singapore, Singapore

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Abstract. Electronic speed governors have become widespread on marine diesel engines. In comparison with hydromechanical ones, they have an additional setting parameter – input signal sensitivity. This parameter allows changing the response of governors to high-frequency disturbances. In camshaft diesel engines, such disturbances are generated when the cams run over fuels pump push rods, while in ME (MAN Energy Solutions) or RT-flex (Wärtsilä) engines they result from the use of inductive sensors with a serrated tape on the diesel shaft for speed measurement. If the engine is used as a main engine on vessels, the governor's sensitivity additionally allows governors to vary the response to propeller shaft resistance moment fluctuations in sea waves conditions. In practice the value of sensitivity of electronic speed governors of main marine engines is selected intuitively. As a result, the adjustment of governors doesn't provide satisfactory stability of speed modes at the change of sea conditions. The study aims to develop a methodology for adjusting the sensitivity of main engines electronic speed governors with considering the stochasticity of the load on the diesel engine in sea waves state. The study was carried out using the systems of automatic speed control model, which is based on the assumption of relatively small deviations of diesel engine shaft rotation speed and load parameters at sea waves conditions. Considering the character and magnitude of change of load on diesel engine at sea waves conditions depend on many variables of external conditions (waves levels, course of a vessel in relation to wind-wave conditions, wind gusts, vessel's loading condition, given speed of a vessel), any set value of sensitivity of electronic speed governors appears to be optimum only for a particular case of vessel movement in sea waves state. The scientific novelty is defined by the fact that recommendations on the choice of governor sensitivity are determined with considering stochasticity of propeller shaft resistance moment fluctuations at sea waves conditions, that increased accuracy, and validity of recommendations. The practical significance of the research consist in the increase of stability of speed modes of the main engine with electronic speed governor at various sea waves conditions

Keywords: marine vessels, marine diesel engine, internal combustion reciprocating engine, automatic speed control system, electronic speed governor, speed control

Corresponding author

INTRODUCTION

Main marine diesel engines operate in sea waves conditions for a considerable part of the operational period, when propeller shaft resistance moment fluctuates in wide ranges of amplitude and fluctuations period. Based on statistical data of wind force values and waves height distribution repeatability of wind speeds (in Beaufort scale points) on lines of transport vessels, for example, of Black Sea Shipping Company in the third quarter of the year 1988 was: 0 … 4 grade – 63.8%, 5 grade – 18.1%, 6 grade – 9.9%, and 10 or more grade – 0.2%. For propulsion systems of transport vessels, a wave of a 5 grade or more is considered to be tangible. That is why it can be approximately considered that propulsion systems work 1/3 of running time on unsteady modes, connected with sea waves state [1]. It means that systems of automatic speed control (ASCS) of main marine diesel engines should provide stability of speed mode at various amplitudes and periods of fluctuations of load on the diesel engine. At that, it is necessary to consider that amplitudes and periods of fluctuations of loading on main marine diesel engine at sea waves are random values depending on wave levels, course, and yaw of a vessel, gust of wind, and speed of a vessel. Therefore, if ASCS operation is optimised for specific deterministic rather than random disturbances, the stability of the diesel engine speed mode may deteriorate as the sailing conditions change. Electronic speed governors (ESG), in comparison with hydromechanical ones, has additional configuration parameters: the value of the reduced sensitivity range, which can usually vary from 0 to 5 … 10%; the signal transfer coefficient in this range, which can be set from 0.1 to 1.0.

Decreasing the sensitivity increases the stability of the ASCS in the calm waving state but deteriorates the dynamics of the ESG in the rough sea especially with a small waving period. Normally, this parameter is selected intuitively, which does not provide optimum control under variable sailing conditions. One of the reserves for optimisation of diesel plants control in sea wave conditions is the consideration of stochastic characteristics of disturbing propeller action. The present study is devoted to this problem [2]. Merchant vessels often undertake lasting voyages in difficult operating conditions because of sea waves, where thermal stress values can reach extremes [3]. The rotation frequency of a main engines (ME) shaft at sea waves can be accompanied by mechanical overloads of details of the cranking mechanism [4], which leads to a decrease in efficiency and reliability of the work of the engine [5]. Besides, as a result of the decrease in excess air coefficient quality of fuel combustion processes worsens causing coking of a gas-air path and the increased wear of details of a cylinder-piston group. The problem of ensuring the quality of diesel engine speed control, taking into account the operational conditions of their work, remains relevant [6]. At the same time, electronic governors implementing proportional-integral-derivative (PID) control law provide the greatest opportunities for adaptation of ASCS operation to the working conditions [7]. Stabilisation of diesel engine shaft rotation speed, continuous monitoring, and automatic maintenance of the same load on all cylinders increase the reliability of engine operation as a whole and increase periods between inspections of cylinders and exhaust gas tract [8]. During the operation of an automated engine, it is also advisable to ensure systematic monitoring of its power utilisation and the effectiveness of the ESG configurations [9].

Quality and accuracy of engine rotation speed control are standardised by the international standard ISO 3046-4:2009 "Reciprocating internal combustion engines – Performance – Part 4: Speed governing" [10]. ESG not only provides stabilisation of speed mode of a diesel engine but also allows prevention of mechanical and thermal overload of a diesel engine on variable modes of operation [11], which also provides a decrease in the volume of harmful emissions with exhaust gases [12]. ESG using an electric motor as an actuator have a performance capability sufficient for engines of almost any capacity [13]. In sea waves conditions due to variable weather, it is often necessary to readjust the ESG to ensure the stability of the diesel engine speed mode [14]. However, the problem of ensuring maximum operational reliability, optimum control in conditions of sharply pronounced load dynamics, quality of operation of main marine diesel engines in sea waves conditions remains unsolved [15]. Unsatisfactory governor dynamics can cause increased fuming and thermal overloading of details of a cylinder-piston group [16], exchange power fluctuations between diesel engines working in parallel, and insufficient capacity of the unit. In the study S.I. Gorb [17], methods to improve the accuracy of simulation of ASCS dynamics are proposed to optimise the operation of governors under deterministic disturbances. These methods can be used for optimisation of hydromechanical governors or optimisation of ESG in S.I. Gorb and M.I. Budurov [18]. However, the proposed models for accounting for ASCS nonlinearities with refinement can also be used to optimise ASCS operation under stochastic variations in the main engine load under sea waves conditions.

The study aims to develop a methodology for adjusting the sensitivity of main engines ESG with considering the stochasticity of the load on the diesel engine in sea waves state. The realisation is aimed to improve the reliability of main engines, optimise vessel speeds and improve the energy efficiency of the fleet, being in line with the aims of resolution MEPC 77/6/2 as well as "related" resolutions MEPC 73/5/1, MEPC 74/5/5, and MEPC 75/6/2 [19].

MATERIALS AND METHODS

The study was carried out using the ASCS model [17], which is based on the assumption of relatively small deviations of diesel engine shaft rotation speed and load parameters at sea waves conditions. Under this assumption, the propeller characteristics are linearised, and the diesel speed characteristic is assumed horizontal (it is assumed that diesel shaft speed has no influence on fuel supply by high-pressure fuel pumps (HPFP) and on the diesel indicator efficiency, which is typical of modern types of diesel engines). To solve the optimisation problem the model allows analysing the influence of ESG configuration parameters on dynamic properties of ASCS diesel engine. This model provides consideration of delays in the channel of control action transfer from the governor to the diesel engine (due to fuel cycling and peculiarities of torque change in the cranking mechanism). The minimum instability of the regulated parameter was chosen as the criterion of optimality. This minimum must be achieved, first of all, at the most probable fluctuations of the disturbing influence. The study was conducted taking into account the results of S.I. Gorb [20], which substantiated the correctness of assumptions about stationarity and normality of disturbing influence on diesel system at sea waves, including the fact that the system under study contains linear inertial links, which normalise the law of distribution of random signals. Author borrowed from the work S.I. Gorb [20] quantitative dependencies of changes in the disturbance variance D_λ on the wind strength according to the Beaufort scale and the relationship of parameters α and β ($\alpha \approx 0.16\beta$), which characterise the correlation function of the disturbing effect.

The signal dispersions in the ASCS were determined through the spectral densities, which are related in different coordinates of the system by the square of the frequency transfer function modulus. The spectral density of the disturbing effect was set by Firsov's approximation formula, which reflects well the physical picture of the phenomenon, as it gives the lowest density at low frequencies in comparison with other formulas. The mathematical model didn't include the gas turbocharger dynamics, as the charge air pressure remains practically stable [21] in the dynamic modes of transport vessels' ME associated with sea waves state. The presence of non-linear links significantly complicates the calculation of system response to random disturbances because the transfer functions of the links depend on the parameters of random signals. To calculate the nonlinear transformation of random signals a method of statistical linearisation was used, the idea of which is based on the replacement of nonlinear links by linear ones that are equivalent concerning the response to a given random disturbance. As a result of this replacement, the system as a whole is linearised and the apparatus of linear theory can be applied for its investigation. The minimum expectation of the square of the difference between the random processes at the output of a nonlinear link and an equivalent linear link is chosen as the criterion of statistical linearisation for the system under study. This criterion combines satisfactory accuracy of statistical linearisation with the simplicity of calculation expressions for inertia-free links.

In statistical linearisation, each non-linear stage is replaced by two linear stages – one of which transforms the conditional expectation of the input signal and has a transfer ration of k^m and the other transforms the centered random component and has a transfer coefficient of k^D. To make these coefficients time-independent, the disturbing effect on the system under study must be stationary. If, in addition, the random signals in the system have a normal distribution law, the coefficients k^m and k^D are only functions of the conditional expectation and variance of the signals on links input. A closed-loop control system is calculated in the following sequence. First, some values of the coefficients are given k^m and k^D of all nonlinear links. Using transfer functions of the system author determine in first approximation conditional expectations and dispersions of signals at the input of non-linear links. Using the found values of conditional expectations and dispersions of signals author find the coefficients k^m and k^D. Then the cycle of expectation and variance calculations is repeated many times until the values obtained during the approximations coincide with the previous ones with sufficient accuracy. The object of investigation is the main diesel plant of HITACHI ZOSEN MAN – B&W type 6S60MC-6 of the large-capacity oil tanker "KORO SEA", which was built at Namura Ship Building Co. Ltd. in Japan and put into service 27.02.2008 (Table 1). The engine has a vertical cylinder arrangement, is crosshead, reversible, and runs with a direct transfer to a fixed-pitch four-bladed propeller, in increments of 4715 mm and 7300 mm in diameter. Gas turbine charging is provided by a MITSUBISHI HEAVY INDUSTRIES MET66SE series turbocharger.

The main technical data of the HITACHI ZOSEN – MAN B&W 6S60MC-6 engine is taken from the design documentation [22] and provided in Table 2.

***Table 1**. Main characteristics of the large-capacity tanker "KORO SEA"*

Gross register tonnage, tonnes	56355
Net register tonnage, tonnes	32524
Deadweight, t	105905
Displacement, t	121852
Draught, m	14.92
Length, m	241.03
Length between perpendiculars, m	232.0
Width, m	42.0
Submersible propeller draught, m	7.71

Table 2. *Technical data of the HITACHI ZOSEN – MAN B&W 6S60MC-6 engine*

Number of cylinders	6
Cylinder diameter, mm	600
Piston stroke, mm	2292
Nominal power, kW	11770
Nominal speed, min.$^{-1}$	101.0
Average indicator pressure, kgf/cm^2	18.4
Maximum combustion pressure, kgf/cm^2	143
Average piston speed, m/s	7.72

The HITACHI ZOSEN – MAN B&W 6S60MC-6 engine is equipped with the Nabtesco electronic control system which does not contain hydraulic or pneumatic elements and consists of the M-800-III type automatic remote control system, the MG-800 type ESG and engine protection system. The Nabtesco MG-800 ESG [23] is based on a controller and is equipped with an electromechanical servo drive for fuel racks. The actuator with the maximum torque on the output shaft – 330 Nm is an AC electric motor with a planetary reduction gear whose output shaft is connected to the fuel rack. The controller provides PID control law. The ESG setting parameters can be changed according to a preset programme depending on the engine operating mode, allowing the control characteristics to change. For example, the basic setting of the governor ensures that the control law changes from PID to PI (proportional-integral) when the speed increases above 60 min^{-1} by zeroing out the differential time constant. The governor settings such as gain, integration time, and differentiation time are set independently of each other for five engine operating modes (depending on engine rotation speed or fuel supply). The governor is set to a reduced sensitivity zone (RSZ) ranging from 0 to 10 min^{-1} (for the diesel engine in question from 0 to 0.099 relative units).

The transfer coefficient in this zone is set within a range 0.5-1.0 (the sensitivity can be reduced by up to 50%). When the diesel shaft speed stabilises in the specified limits within the recommended time range of 10 ... 30 s, the zone value doubles. It is recommended that the signal transfer coefficient in the doubled zone is set in the range from 0.1 to 0.5 (it is recommended that the sensitivity is reduced by 50-90%). The control panel is equipped with a HIGH GAIN mode key, in which the PID configuration parameters are changed to a more "active" operation of the governor (the setting values in this mode can be changed). This mode is recommended if the governor does not provide the required speed stability in rough sea conditions, especially if a shaft generator is used. The engine speed is measured by an induction converter, whose circuit generates current pulses as the serrated tape mounted on the engine shaft. The pulse frequency is converted into a direct current with a voltage proportional to the engine shaft rotation speed.

RESULTS AND DISCUSSION

The structural scheme of the investigated ASCS is shown in Figure 1. Due to the fact that the modelling aims to improve the dynamics of the ESG under near-harmonic disturbances, the structural scheme did not consider the limitations of the permissible stroke of the actuator: as a function of the measured rotation speed; as a function of the charge air pressure and rigidly set on the control panel. In diesel engines, it is characteristic that the change in the relative torque of the diesel relative against the change in the relative stroke of the fuel pump racks $\bar{h}_r$ is delayed. This lag can be explained by the fact that the torque indicator does not reach its maximum value immediately after the fuel cut-off. The maximum torque value corresponds to the angle of rotation of the crank from the upper dead centre (UDC) 22 ... 32°. Smaller values are characteristic of partial fuel supply. When controlling the fuel supply by changing the end of the supply, the fuel cut-off torque depends on the value of $\bar{h}_r$ and usually varies from UDC to 18° of the crank turn. Considering the above, it can be assumed that with $\bar{h}_r$ close to 1, a delay of change of indicating torque of a diesel engine approximately corresponds to 10° of a turn of a crank, and at $\bar{h}_r$, close to zero, increases to 20°. Then the value of the delay:

$$\tau_{del} = \frac{20 - 10\bar{h}_r}{6n_{d0}\bar{\omega}_d} \quad (1)$$

where: n_{d0} – rotation speed of diesel engine shaft in nominal mode, min^{-1}; $\bar{\omega}_d$ – is a relative angular speed of the diesel shaft.

The study was carried out at an average engine load of 80% of nominal load, which corresponds to the main operating mode of the 93 min^{-1}.

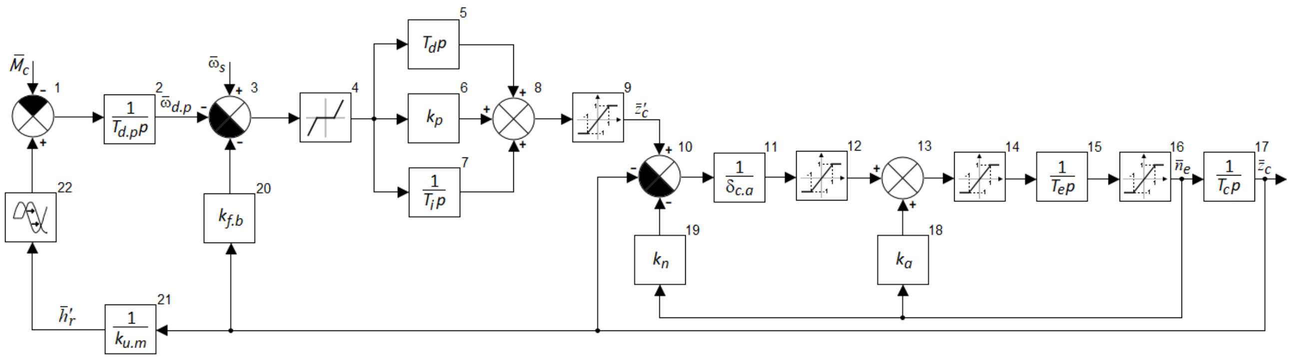

***Figure 1**. Structural scheme of ASCS of marine diesel engine HITACHI ZOSEN – MAN B&W 6S60MC-6 with ESG Nabtesco MG-800*

***Note**: 1, 3, 8, 10, 13, 15 – adders; 2, 7, 15, 17 – integral links; 4 – functional converter, introducing a zone of low sensitivity; 5 – differentiating link; 6, 11, 18, 19, 20, 21 – proportional links; 9, 12, 14, 16 – nonlinear links, which consider signal saturation at level ± 1; 22 – nonlinear link, which consider transport delay* τ_{del}

The system is perturbed by the change in the relative torque on the diesel shaft $\bar{M}_c$ via the adder 1 (by the load channel). Nonlinear transformations of signals are carried out by a link 4 which introduces a zone of the decreased sensitivity of ESG to unbalance signals $\bar{\omega}_s$ and $\bar{\omega}_{d.p}$; links 9, 12, 14 and 16 which limit the signal at a level of relative unity; link 22 which realises a transport time delay of change of the diesel engine torque in relation to the index of fuel pumps. Elements 3-9 produce the required value of the actuator stroke $\bar{z}_c'$. This value is "worked out" by elements 10-20. The value $\bar{z}_c'$ is calculated directly from the signal for angular speed setting $\bar{\omega}_s$. If the signal $\bar{z}_c'$ does not provide the necessary fuel supply to the diesel engine (there is a difference between the set $\bar{\omega}_s$ and the measured $\bar{\omega}_{d.p}$ angular speeds), links 3-7 will generate correction signals to the adder 8. These correction signals allow the signal $\bar{z}_c'$ to be refined. Link 4 realises a zone of reduced sensitivity ε (from 0 to 0.099 relative units) to the input signal with transfer coefficient k_g (from 0.1 to 1 relative units). Links 5, 6 and 7 convert the signal according to the PID control law. With the normal ESG sensitivity set on the control panel, the proportional link gain coefficient k_p, integration time T_i, and the differentiation time T_d are adjustable within the limits of 0.1 … 5 relative units, 0.5 … 30 s and 0 … 2 s respectively.

The actuator has two feedbacks: barrel nut position (output signal $\bar{z}_c$') and electric motor speed $\bar{n}_e$. In steady states $\bar{z}_c$=$\bar{z}_c'$ and $\bar{n}_e=0$. Therefore, the adder 10 output signal is zero. If an imbalance between the set and the exhausted signals occurs ($\bar{z}_c'$ and $\bar{z}_c$) the output signal of the adder 10 becomes non-zero. This signal is amplified by the control element 11, having the output signal limitation at the relative unity level. The occurrence of the signal at the output of element 11 causes the acceleration of the electric motor which in the circuit is represented by an integral link 15. The electric motor moves the barrel nut. The speed converter of the electric motor into the nut stroke is represented by an integral link 17 in the scheme. The barrel nut is moved until the signal $\bar{z}_c$ equals $\bar{z}_c'$. Rotation speed feedback of the motor ensures its quick acceleration and quick braking. Braking starts when the barrel nut approaches the desired position. The scheme explains it as follows. When the signal value $\bar{z}_c$ is approached to the value $\bar{z}_c'$ the output signal of element 19 on the adder 10 will become dominant. This will cause the signal at the output of element 11 to decrease sharply and be reversed. The maximum level of the output signal of element 18 is approximately equal 0.4. When the output signal of element 11 which has received the opposite sign exceeds this value in absolute value, the motor will start to decelerate. A reduction in the motor speed will reduce the signal at element 18 output, which will reduce the speed even more. When accelerating the motor, element 18 will only accelerate the process if the relative output signal of element 11 is less than unity. This is because the adder 13 output signal is also limited at the relative unity level. The signal is also limited to one $\bar{n}_e$.

Transfer coefficient k_n determines the level of signal unbalance $\bar{z}_c'$ and $\bar{z}_c$ at which the electric motor is braked (speed limitation – during acceleration). If k_n=0.08, braking begins at approximately the unbalance of the $\bar{z}_c'$ and $\bar{z}_c$, equal to 0.08 (at k_n<0.04 the electric motor may not have time to stop and overshoot occurs). Control element unbalance $\delta_{c.a}$ is several times lower than k_n. Link 20 feedback is used in the governor to ensure parallel operation of main engines. If a single main engine is used, its transfer coefficient $k_{f.b}$ can be zero. Link 21 takes into account the value of the stroke utilisation of the ESG during the transition from zero to nominal fuel supply, which is recommended in the design documentation [23] ($k_{u.m}$ – relative stroke utilisation). ASCS model of the HITACHI ZOSEN – MAN B&W 6S60MC-6 marine diesel engine with Nabtesco MG-800 electronic governor is shown in Figure 2.

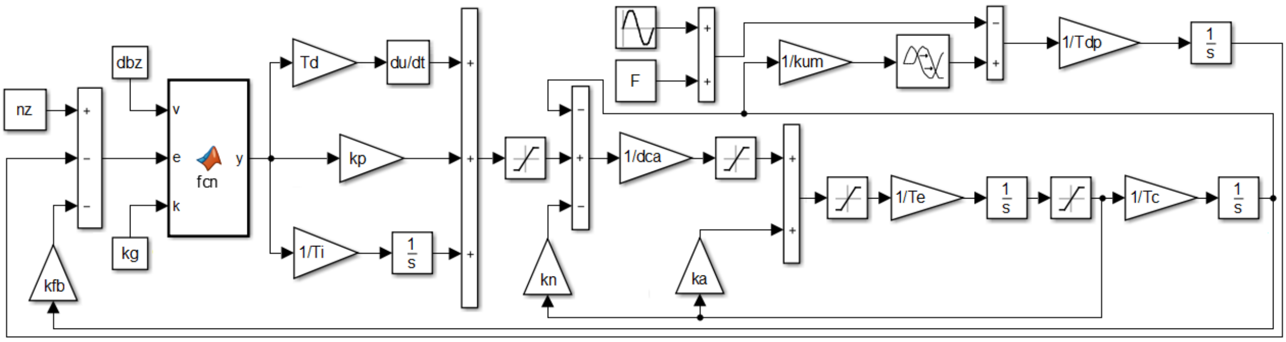

***Figure 2**. Model of automatic speed control system for HITACHI ZOSEN – MAN B&W 6S60MC-6 marine diesel engine with Nabtesco MG-800 electronic governor*

The following values are used in the model: diesel acceleration time $T_{d.p}$=2.3 s; delay time τ_{del}=0.02 rel. un.; relative value of RSZ ε (dbz)=0.001 ... 0.099 rel. un.; coefficient of RSZ transfer k_g=0.1 ... 1 rel. un.; proportional link gain coefficient k_p=0.5 ... 5 rel. un.; integration link time T_i=0.5 ... 8 s; differential link time T_d=0 s; ESG actuator time T_c=0.4 s; inequality of control element of the actuator $\delta_{c.a}$=0.04 rel. un.; electric motor acceleration time T_e=0.03 s; transfer link coefficient for acceleration and deceleration of electric motor k_a=0.3 rel. un.; feedback transfer coefficient in electric motor speed k_n=0.06 rel. un.; governor stroke utilisation coefficient $k_{u.m}$=0.75 rel. un.; feedback coefficient $k_{f.b}$= 0 rel. un. Figure 3 shows the dependence of mean square deviation of the shaft rotation speed $\sqrt{D_n}$ and relative stroke of HPFP rack $\sqrt{D_h}$, on the value of RSZ (with fixed k_g=0.5 rel. un.) ESG (with configuration parameters k_p=2.2 rel. un.; T_i=2.0 s; T_d=0 s), defined by modelling. The results are obtained with three average fluctuation periods of perturbation T_0=3.3; 7.9 and 20.9 s, which practically cover the entire range of values encountered in operation.

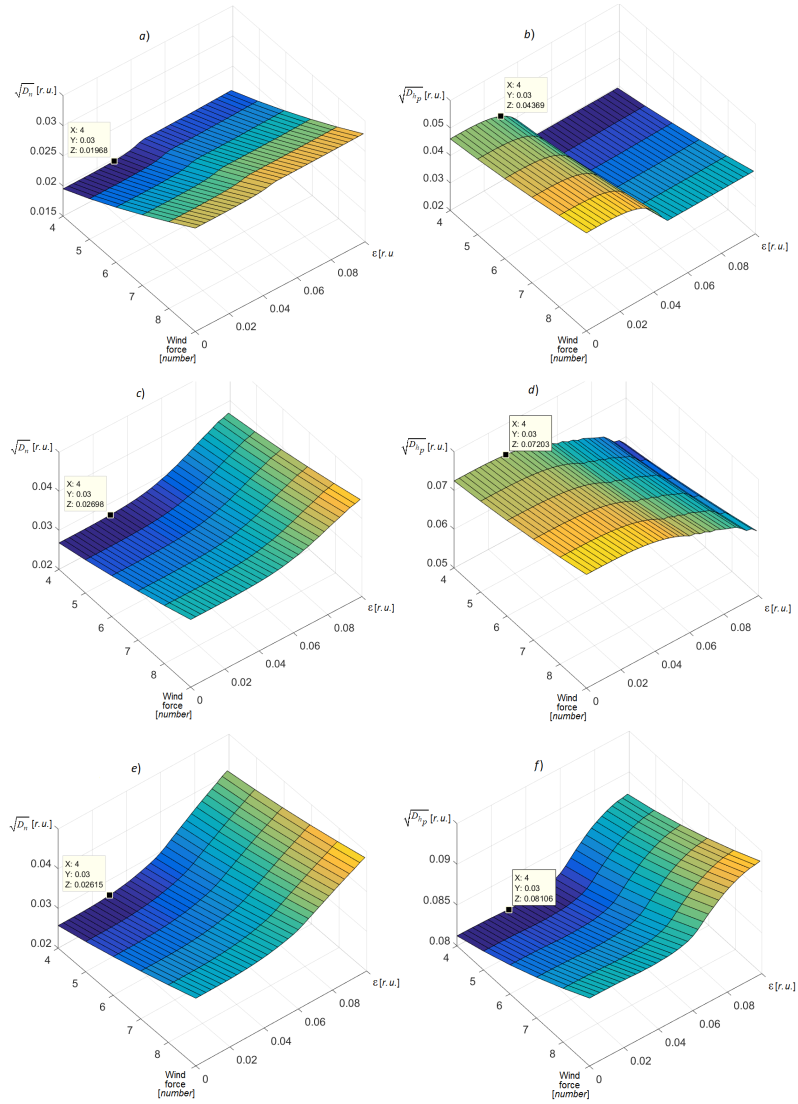

***Figure 3**. Effect of sea waves levels on the mean square deviation of relative shaft rotation speed $\sqrt{D_n}$ and relative stroke of HPFP rack $\sqrt{D_{hp}}$ when changing the value of RSZ ESG – ε, rel. un. (transfer coefficient RSZ k_g=0.5 rel. un.)*

***Note**: for wave condition with period: a, b –T_0=3.3 s; c, d –T_0=7.9 s; e, f –T_0=20.9 s*

Figure 3, *a* shows that for a period of fluctuations of the disturbing effect T_0=3.3 s, decrease of sensitivity in ESG from RSZ value of 0.099 to 0.03 rel. un. (with the ESG transfer coefficient of 0.5 rel. un.) increases stability of the speed mode of operation of the ME within the whole range of wind-wave conditions. For example, in a wave caused by 4-grade wind $\sqrt{D_n}$ has decreased from 0.0211 to 0.0197 rel. un. Decrease in RSZ value from 0.03 to 0.01 rel. un. practically does not lead to improvement of stability of the speed mode $\sqrt{D_n}$ does not change). The further reduction does not lead to the change of $\sqrt{D_n}$ in the whole range of the wind wave, it is not expedient to decrease the governor sensitivity at small deviations of the controlled parameter. Figure 3, *b* shows that at T_0=3.3 s throughout the entire range of wind-wave, a similar to speed mode tendency to stabilise the thermal regime is observed with a decrease in the sensitivity of the ESG. For example, in sea waves caused by 4-grade wind, $\sqrt{D_{hp}}$ is stabilised at the level of 0.0296 rel. un. The reason for this is that the ESG no more responds to low amplitude disturbances. If, however, the sensitivity of ESG is decreased in the range of values of RSZ from up 0.05 to 0.001 rel. un., there is a tendency of deterioration of stability of the ME thermal regime, for example, at a waves caused by the 4-grade wind, $\sqrt{D_{hp}}$ increased from 0.0296 to 0.0461 rel. un. This is explained by the fact that when the sensitivity decreases, the ESG moves the HPFP rail with a delay, but in spurts, which does not reduce the amplitude of its movements. Consequently, it can be concluded that since the increase in sensitivity of ESG is accompanied by an excessive increase in instability of speed mode (especially at rough seas), an increase in sensitivity of ESG cannot be recommended for stabilisation of thermal mode of diesel engine.

Figure 3, *c*, and *d* demonstrate that for the period of fluctuations of the disturbing effect T_0=7.9 s in ESG there is a similar tendency (as well as at T_0=3.3 s) to increase the stability of a speed mode and to decrease the stability of a thermal mode at the decrease of sensitivity of ESG. For example, in a waves caused by 4-grade wind, with a decrease in RSZ from 0.099 to 0.03 rel. un. (with RSZ transfer coefficient k_g=0.5 rel. un.) $\sqrt{D_n}$ decreases from 0.037 to 0.027 rel. un. and $\sqrt{D_{hp}}$ increases from 0.060 to 0.072 rel. un. Figure 3, *e*, and *f* show that at a period of fluctuations of disturbing effect T_0=20.9 s with the decrease of ESG sensitivity, improvement of both speed and thermal regimes of the ME is observed. For example, in the case of waves caused by 4-grade wind decrease and the decrease of RSZ from 0.099 to 0.03 rel. un. (with RSZ transfer coefficient of k_g=0.5 rel. un.) $\sqrt{D_n}$ decreases from 0.0410 to 0.0262 rel. un., and $\sqrt{D_{hp}}$ decreases from 0.0874 to 0.0811 rel. un. Further decrease in sensitivity of ESG practically does not lead to the change of stability of both speed and thermal modes of the ME.

By decreasing the ESG sensitivity at calm sea conditions in operational conditions, an increase in ASCS stability is observed while maintaining the stability of the engine thermal mode due to the fact that the ESG stops overreacting to load changes on the diesel engine. At rough sea conditions it is recommended to reduce a zone of sensitivity of ESG for it to more "actively" regulate shaft rotation speed, stabilising a diesel engine thermal mode. In this case, there is no gain in thermal mode stability (reduction of $\sqrt{D_{hp}}$, if sensitivity is reduced in a range of small values. This is explained by the fact that when the sensitivity is reduced, the ESG begins to move the HPFP rack with a delay, but in spurts, which does not reduce the amplitude of its movements. As a result of the investigation, it can be concluded for the ESG sensitivity reconfigurations it is recommended to decrease the setpoint unit of ESG sensitivity to the calculated average value of 0.015 ... 0.03 rel. un. (with the RSZ transfer coefficient k_g=0.5 rel. un.) in the wave conditions, which causes intensive and large variations of shaft rotation speed (at a large dispersion of disturbing effect). In turn, the increase in sensitivity of ESG both at low (caused by 6-grade wind or less wind) and at rough seas (caused by 6-grade or more wind) worsens dynamics of ESG, as evidenced by the significant increase in the estimate of mean square deviation of the relative speed of a diesel engine shaft $\sqrt{D_n}$. Figure 4 demonstrates the specified by modelling dependence of mean square deviation of the shaft rotation speed and relative stroke of HPFP rack on the timing of the ESG integrating link at a RSZ value of 0.03 rel. un. with fixed k_g=0.5 rel. un. and ESG setting parameters k_p=2.2 rel. un. and T_d=0 s. Modelling has also been performed for three average fluctuation periods of the disturbance T_0=3.3; 7.9 and 20.9 s.

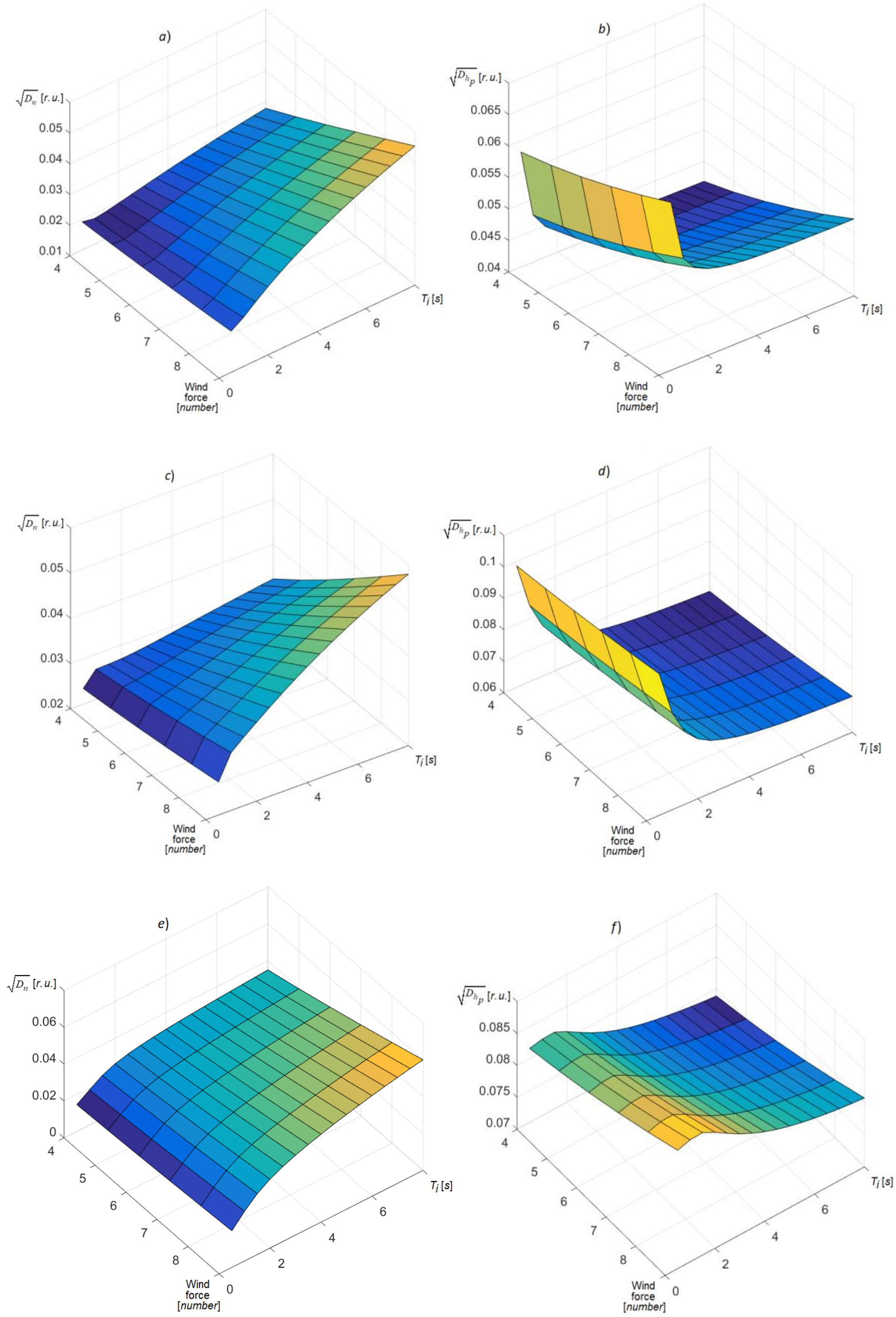

***Figure 4**. Effect of wave levels on mean square deviation of relative shaft rotation speed √D_n and relative stroke of HPFP rack √D_{hp} at ESG integrating link time variation – T_i, s (RSZ value ε=0.03 rel. un. and transfer coefficient of k_g = 0.5 rel. un.)*
***Note**: for wave condition with period: a, b –T_0=3.3 s; c, d –T_0=7.9 s; e, f –T_0=20.9 s*

It follows from Figure 4, *a* and *b* that if the fluctuation period of the disturbing effect is T_0=3.3 s reducing the time of the integrating link increases the stability of the speed mode of the ME operation in the whole range of wind-wave conditions from 4 to 6-grade of Beaufort scale. However, a decrease of value T_i below 2 s leads to significant instability of the thermal mode of the ME operation. For example, in a wave caused by a 4-grade wind, the estimate $\sqrt{D_{hp}}$ increases from 0.0418 rel. un.: at T_i=8 s to 0.0437 rel. un.; at T_i=2 s and at T_i= 0.5 s to 0.0583 rel. un. Figure 4, *c*, and *d* show that if the period of fluctuation of the disturbance T_0=7.9 s over the entire range of variation T_i there is an increase in stability of the speed mode of the ME operation. For example, in case of a disturbance caused by 4-grade wind, when decreasing T_i from 8 to 0.5 s, estimate $\sqrt{D_n}$ decreased from 0.03240 to 0.02345 rel. un. The parameter T_i significantly affects the stability of diesel engine thermal conditions, and its influence is especially noticeable in the case of rough sea conditions. For example, at waves caused by 7-grade wind, estimate $\sqrt{D_{hp}}$ increased from 0.068 rel. un.; at T_i=8 s to 0.076 rel. un.; at T_i = 2 s intermittently to 0.102 rel. un.

Figure 4, *e,* and *f* show that when the period of fluctuation of the disturbance T_0=20.9 s in the ESG there is an increase in stability of the speed mode of the ME, in case of sea waves conditions caused by the 4-grade wind, the estimation $\sqrt{D_n}$ has decreased from 0.035 to 0.015 rel. un. At the change of T_i from 8 to 0.5. At the same time, there is a tendency for the stability of the thermal regime of the ME to deteriorate over the entire range of wind waves, e.g., in sea waves conditions caused by 7-grade wind, the estimate $\sqrt{D_{hp}}$ increased from 0.0775 to 0.0853 rel. un. while changing from T_i from 8 to 0.5 s. Figure 5 demonstrates the specified by modelling dependence of mean square deviation of the shaft rotation speed and relative stroke of HPFP rack on the ESG proportional link gain coefficient at a RSZ value of 0.03 rel. un. with fixed k_g=0.5 rel. un. and ESG configuration parameters k_p=2.2 rel. un. and T_d=0 s at three average fluctuation periods of the disturbance T_0=3.3; 7.9 and 20.9 s.

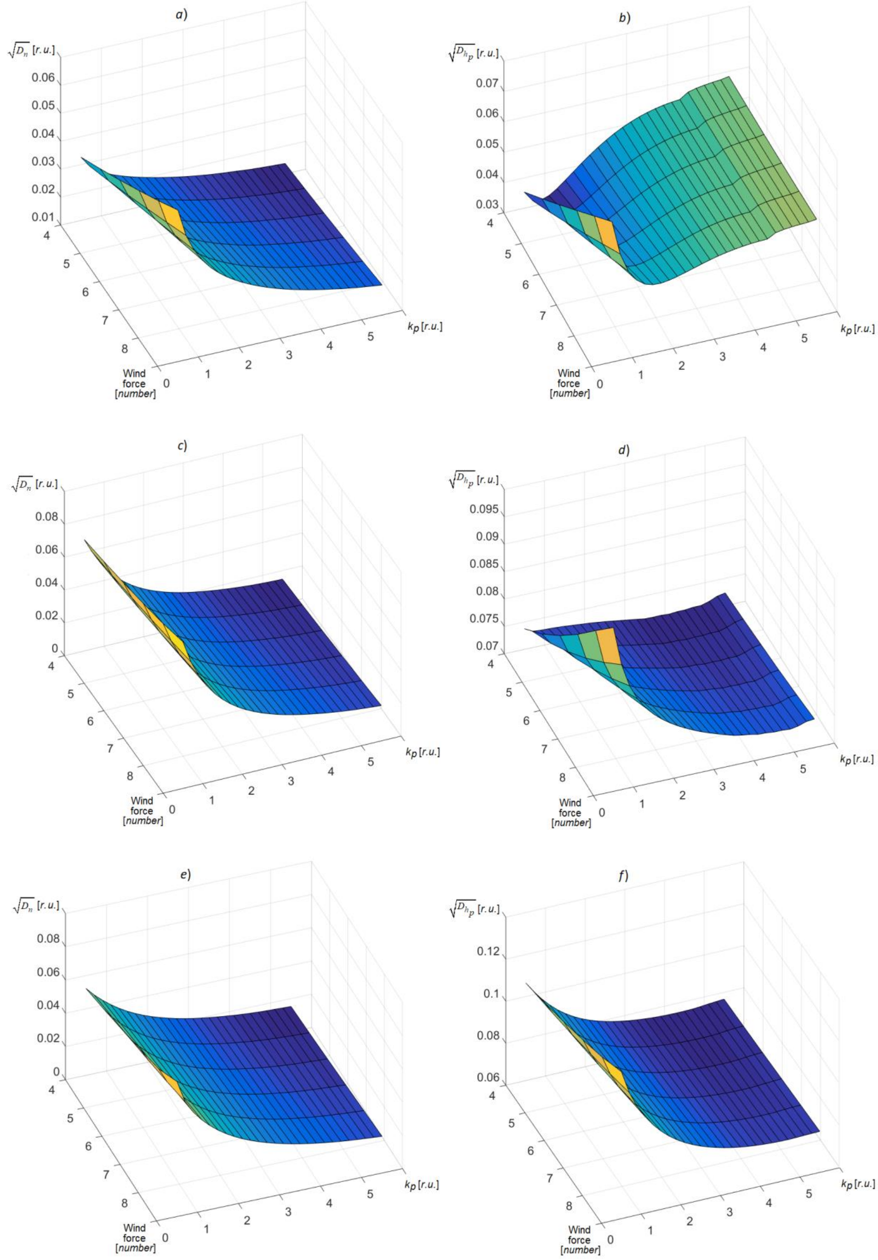

Figure 5*. Effect of wave levels on the mean square deviation of relative shaft rotation speed √D_n and relative stroke of HPFP rack √D_{hp} at ESG proportional link gain coefficient change k_p, rel. un. (RSZ value ε=0.03 rel. un. and transfer coefficient of k_g=0.5 rel. un.)*

Note*: for wave condition with period: a, b –T_0=3.3 s; c, d –T_0=7.9 s; e, f –T_0=20.9 s*

Figure 5, *a*, and *b* demonstrate that for a period of fluctuations of the disturbing effect T_0=3.3 s with a decrease of the proportional link gain coefficient leads to the appearance of self-fluctuating phenomena in the ASCS. It can be explained by the occurrence of reconfiguration in the ASCS (estimates of $\sqrt{D_n}$ and $\sqrt{D_{hp}}$ increase simultaneously). Figure 5, *c*, and *d* show that when the period of fluctuations of the disturbance T_0=7.9 s there is a significant improvement in the stability of both the wind speed and the thermal modes of the ME. For example, if the disturbance is caused by 4-grade wind, by increasing k_p from 0.5 to 5 rel. un. the $\sqrt{D_n}$ estimate decreased from 0.068 to 0.015 rel. un. and the $\sqrt{D_{hp}}$ estimate decreased from 0.0738 to 0.714 rel. un. Also, in the area of small values of k_p, the phenomenon of reconfiguration in ASCS is observed, especially in rough sea conditions. Figure 5, *e*, and *f* show that if the period of fluctuation of the disturbance T_0=20.9 s with increase of k_p there is a positive effect in stabilising the shaft rotation speed and thermal regime. For example, if the disturbance is caused by a 4-grade wind, by increasing k_p from 0.5 to 5 rel. un. the $\sqrt{D_n}$ estimate has decreased from 0.0523 to 0.0156 rel. un. and the $\sqrt{D_{hp}}$ estimate decreased from 0.1065 to 0.0762 rel. un.

CONCLUSIONS

Considering the character and magnitude of change of load on diesel engine at sea wave conditions depend on many variables of external conditions (sea waves levels, course of a vessel in relation to windy conditions, wind gusts, vessel loading, given speed of a vessel), any set value of sensitivity of ESG appears to be optimum only for a particular case of vessel movement in rough sea conditions. At the same time, there is a possibility to optimise the operation of ESG at sea waves with the most probable intensity (for example, for wind waves up to 5-grade including) and fulfilment of the additional condition on tolerable instability of fuel supply to a diesel engine (instability of a thermal mode). For HITACHI ZOSEN – MAN B&W 6S60MC-6 marine diesel system it is recommended a RSZ ESG value of 0.03 rel. un. with a signal transfer coefficient in this zone of 0.5 rel. un. It allows to keep the speed mode stability in rough seas (caused by wind force of 6-grade and higher) and doesn't cause considerable disturbance of the thermal mode stability by changing external sailing conditions (change of course and vessel's speed in relation to the sea waves level).

If in very rough seas (wind force greater than 6-grade) the recommended configuration values do not provide the required stability of the speed mode, the sensitivity zone value can be reduced to 0.015 rel. un. while increasing the proportional gain to 3 rel. un. With a "heavy" propeller (including a fully laden vessel), speed stability can be improved by increasing the proportional link gain and reducing the integration time of the ESG. Further research is planned in the direction of automating the configuration parameters of the ESG, depending on the value of the actual stochastic indicators of changes in diesel engine speed and the ESG output signal.

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Оптимізація чутливості електронного регулятора частоти обертання головного суднового дизеля

Сергій Іванович Горб[1], Максим Валерійович Левінський[1], Микола Будуров[2]

[1]Національний університет «Одеська морська академія»
65029, вул. Дідріхсона, 8, м. Одеса, Україна

[2]Eastern Pacific Shipping Pte. Ltd. (EPS)
039192, просп. Темасек, 1, м. Сінгапур, Сінгапур

Анотація. Електронні регулятори частоти обертання набули широкого поширення на суднових дизелях і, порівняно з гідромеханічними, мають додатковий параметр налаштування чутливості до вхідного сигналу. Цей параметр дозволяє змінювати реакцію регуляторів на високочастотні збурення. У дизелях з розподільним валом такі збурення генеруються при набіганні кулачків на штовхачі паливних насосів, а в двигунах типу ME (MAN Energy Solutions) або RT-flex (Wärtsilä) вони виникають внаслідок використання індуктивних датчиків із зубчастою стрічкою на валу дизеля для вимірювання частоти обертання. Якщо двигун використовується як головний на суднах, то чутливість регулятора додатково дозволяє змінювати реакцію регуляторів на коливання моменту опору гребного валу при хвилюванні. Однак на практиці величина чутливості електронних регуляторів частоти обертання головних суднових дизелів вибирається інтуїтивно. Це призводить до того, що налаштування регуляторів не забезпечує задовільну стабільність швидкісних режимів при зміні морської обстановки. Метою дослідження є розробка методології налаштування чутливості електронних регуляторів частоти обертання головних двигунів з урахуванням стохастичності навантаження на дизельний двигун під час хитавиці на морі. Дослідження проведено з використанням моделі систем автоматичного регулювання швидкості, яка базується на припущенні відносно малих відхилень швидкості обертання валу дизеля та параметрів навантаження в умовах морських хвиль. Врахування характеру та величини зміни навантаження на дизельний двигун в умовах морських хвиль залежить від багатьох змінних зовнішніх умов (бальність моря, курсу судна щодо умов вітрових хвиль, поривів вітру, стану завантаження судна, заданої швидкості руху судна), будь-яке задане значення чутливості електронних регуляторів частоти обертання виявляється оптимальним лише для конкретного випадку руху судна під час хитавиці на морі. Наукова новизна визначається тим, що рекомендації щодо вибору чутливості регуляторів визначені з урахуванням стохастичності коливань моменту опору гребного валу при хвилюванні, що підвищило точність та обґрунтованість рекомендацій. Практична значущість дослідження полягає у підвищенні стабільності швидкісних режимів головного двигуна з електронними регуляторами частоти обертання за різного хвилювання

Ключові слова: морські судна, судновий дизельний двигун, поршневий двигун внутрішнього згоряння, система автоматичного регулювання частоти обертання, електронний регулятор частоти обертання, регулювання швидкості