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LOADS OF SHIP MAIN DIESEL ENGINE IN THE ASPECT OF PRACTICAL ASSESSMENT OF ITS OPERATION

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Abstract

This paper presents a concept of method intended for the assessing of operation of engine which works under partial load. A valuation (quantitative) approach to the operation interpreted as a physical quantity was applied to determine existing margins of operational parameters of engine as well as additional costs associated with degradation of its technical state, born by engine's user.

Keywords: *operation, diesel engine*

Introduction

From the point of view of operation aims generated by operational system in the form of transport tasks for ship considered as a technical system, ship propulsion system is intended for realization of assumed sailing speeds of the ship within a given period and determined range of changeability of external conditions.

Hence the functioning of the ship in steady motion with speed v is determined by description of a system of forces acting on ship's hull, that can be analytically represented (on assumption of neglecting the gravity and buoyancy forces) as follows [3, 10]:

$$T = R_T + \Delta T \tag{1}$$

gdzie:
T – thrust of the propeller,
ΔT – thrust deduction,
R_T – total hull resistance.

The interdependence of ship resistance and effective power of main propulsion engine for steady sailing speed is described by the following equation [3, 10]:

$$N_e = \frac{R_T \cdot v}{\eta_{lw} \cdot \eta_s} \tag{2}$$

where:
v – speed of ship,
η_{lw} – efficiency of shaftline,
η_s – propeller efficiency.

Knowledge of the quantities appearing in Eq.(2) makes it possible to properly select all elements of propulsion system in the designing stage [9, 10]. Considering the sailing speed to be an independent variable which definitely determines two main factors associated with realization of objective function, namely :

- duration time of realization of transport task, which definitely influences costs of its realization and potential profits to ship's owner,
- possibility of maintaining an assumed ship course in heavy weather conditions, which first of all influences occurrence probability of an emergency situation,

one should observe that during ship operation all remaining quantities undergo changes due to degradation processes which involve evolution of the process of technical state changes towards technical unserviceability states. It obviously influences serviceability of system's elements and ,consequently, of the entire system.

On assumption that main propulsion system of ship has been correctly selected, the hull resistance characteristics $R_T = f(v)$ constitute the factor which generates demand for effective power developed by propulsion engine for reaching a given sailing speed of the ship [4]. The characteristics determine, for assumed conditions, value of developed effective power of engine neccessary to reach a demanded sailing speed. If a relatively short period is taken into account then it can be assumed , without any large error, that the representation is invariable.

In practice, an important change of the relation $R_T = f(v)$, resulting from influence of the environment and physical ageing processes (especially of wear, e.g. corrosion), occurs , whose external symptom is a rise of value of the force R_T at given values of the speed v in comparable sailing conditions. Long time intervals between successive ship hull docking surveys (possible repairs) are of special importance because such intervals , depending on a type (class) of ship and given classification rules, vary from 3 to 5 years [e.g. 12].

In selecting the main engine in the stage of ship designing the above desrcibed processes are taken obviously into account, that is manifested by skillfully selected design characteristics of ship hull resistance as well as by application of the so-called sea margin during determination of the main engine contractual power N_x [9, 10], which makes that the main engine usually has certain power surplus as compared with assumed design values of hull resistance. It means that in the case of typical transport task for a given ship its main engine will be used in a load state lower than rated one [1].

However, the existing power margin which guarantees ship safety, is systematically decreasing due to the above described phenomena and the worsening of operational characteristics of engine itself.

Hence, it seems rational to elaborate a method for determining the existing margin of operational engine parameters associated with degradation of its technical state, and the additional costs born by its user.

Influence of change of technical state of engine on its operation

Worth mentioning, in the light of the above described power surplus of main propulsion engine, that for the engine running under partial loads the process of decreasing the available output power will develop in two phases:

- in the first phase hourly fuel oil consumption will rise solely (at a relatively constant value of developed torque), and in consequence operational costs will be also higher;
- in the second phase a limitation of value of effective power developed by the engine will occur because of constructional constraints and lack of possibility to increase fuel charge.

The described phenomena result from control action of fuel apparatus which will increase, within a given range of values, the instantaneous fuel charge $g_p^{i\%}$ ($g_p^{i\%}$ - fuel charge for *i%* load of engine being in the technical serviceability state under assumption that the maximum engine load amounts to 110% of its rated value, *i <110*) up to the instant of reaching its maximum value G_{pmax}. Every successive decrease of value of engine total efficiency will result in a recordable decrease of its torque M_o.

If to assume the engine partial load to be constant (e.g. for 9RT–flex60C–B engine : 85% engine load, the contractual output power N_x = 80% N_{R1} = 17370 kW, the contractual engine speed n_x = 90% n_{R1} = 102,6 rpm [13]) the phenomenon in question can be presented in the form of the diagram (Fig. 1) of the following interpretation :

- the time-dependent drop of the engine's total efficiency (in the case in question by about 9%) results , in the first phase, mainly in an increased hourly fuel oil consumption (specific fuel oil consumption). It can be represented as the occurrence of the successive recordable events F which consist in increasing the fuel charge $g_p^{i\%}$ by the value Δg_p at a relatively constant , relevant to a given engine load state, value of the torque M_o. This way, increased operational costs are generated rather without imposing limitations on the ship motion parameters described by Eqs. (1) and (2).
- the degradation processes progressing along with time of further use of engine result in occurrence of the recordable events U which consist in decreasing values of the engine torque M_o at constant fuel oil consumption (at $g_p = G_{p\,max}$). Further long-lasting use of the engine results in the significant worsening of its characteristics which definitely impose limitations on ship motion at an assumed speed or course. In heavy weather conditions such situation will obviously form an important circumstance for occurrence of state of danger to ship safety.

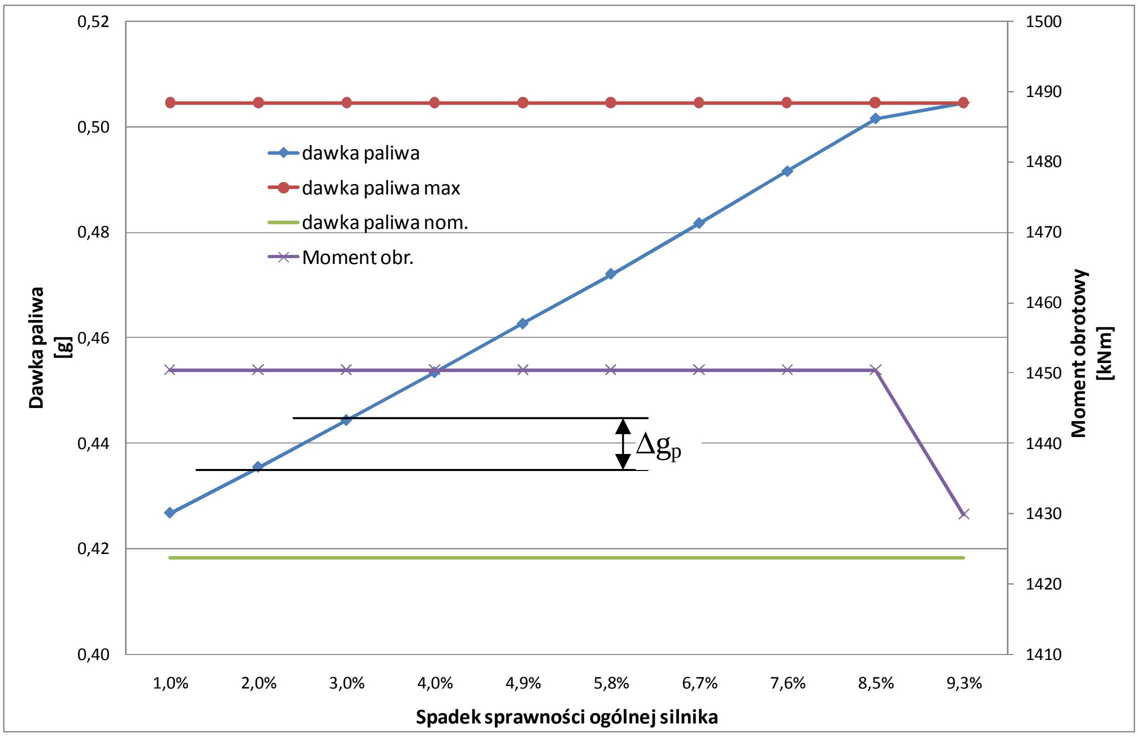

Fig. 1 Changes of engine fuel charge and torque , which result in changes of total efficiency of the engine running under partial load

Assessment of available power margin and additional operational costs of engine

The number of repetitions of the event F, $N_{\Delta gp}$, within the time interval (0, t) is a random variable of non-negative integral values. The dependence of the random variable on time constitutes the stochastic process $\{N(t): t \geq 0\}$. On the assumption on its stationarity, lack of consequences and flow singularity [5] the Poisson homogeneous process [2] can be applied to description of the process of increasing the fuel charge $g_p^{i\%}$ (6) resulting from the decreasing of the total engine efficiency η_e (in maintained engine load conditions).

Hence, in the case if the number of the events F ,$N_{\Delta gp}$, occur up to the instant *t*, the total increase of the fuel charge $g_p^{i\%}$, up to the instant, can be expressed as follows:

$$\Delta G_p = \Delta g_p \cdot N_{\Delta gp} \tag{3}$$

where:

ΔG_p - total increase of the fuel charge g_p after occurrence of $N_{\Delta gp}$ number of the events F,

Δg_p – elementary recordable fuel increment by which the fuel charge $g_p^{i\%}$ increases , whereas the random variable $N_{\Delta gp}$ has the following distribution [1]:

$$P\left(N_{\Delta gp} = k\right) = \frac{\left(\lambda_f \cdot t\right)^k}{k} \exp\left(-\lambda_f t\right); \quad k = 1,2,\ldots,n \tag{4}$$

where:

λ_f – a constant interpreted as the intensity of occurrence of the event F (i.e. increase of the fuel charge $g_p^{i\%}$ by Δg_p value).

Assuming that the unit fuel charge increase by Δg_p value generates the additional unit cost φ (realization of the same task at an increased fuel oil consumption) one can determine its total value Φ, up to the instant *t* , as follows:

$$\Phi = \varphi \cdot \Delta g_p \cdot N_{\Delta gp} \tag{5}$$

For the engine load smaller than maximum, the summary fuel charge increase $\Delta G_{p\max}$ and occurrence of certain number , $N'_{\Delta gp}$, of the events F affecting solely the increasing of the unit fuel oil consumption g_e and hourly fuel oil consumption B_h , can be determined by the following relation :

$$\Delta G_{p\max} + g_p^{i\%} = \Delta g_p \cdot N'_{\Delta gp} + g_p^{i\%} = G_{p\max} \tag{6}$$

where:

$g_p^{i\%}$ – fuel charge relevant to a given engine load *i* % (under assumption that the maximum engine load is equal to 110% of its rated load, i.e. $i<110$)

$G_{p\max}$ - maximum fuel charge possible to be realized by injection apparatus within existing constructional and control limitations.

Occurrence of the successive event F ($N_{\Delta gp} = N'_{\Delta gp} + 1$) for the current engine load *i %* will be associated with occurrence of certain limitation in developing the demanded power of the engine , and in consequence limitations for motion of the entire ship, will occur.

As the effective output power of engine can be expressed as follows [11]:

$$N_e = \frac{\eta_e \cdot w_d \cdot g_p^{i\%} \cdot n}{\tau} \tag{7}$$

where:

η_e – effective efficiency of engine,

w_d – fuel lower calorific value,

$g_p^{i\%}$ - temporary fuel charge (for i% engine load),

n – rotational speed of engine,

τ - a coefficient which takes into account number of strokes realized during one engine working cycle, as well as on assumption that the changing process of engine technical state is continuous over time and states, the situation can be illustrated in the way shown in Fig. 2.

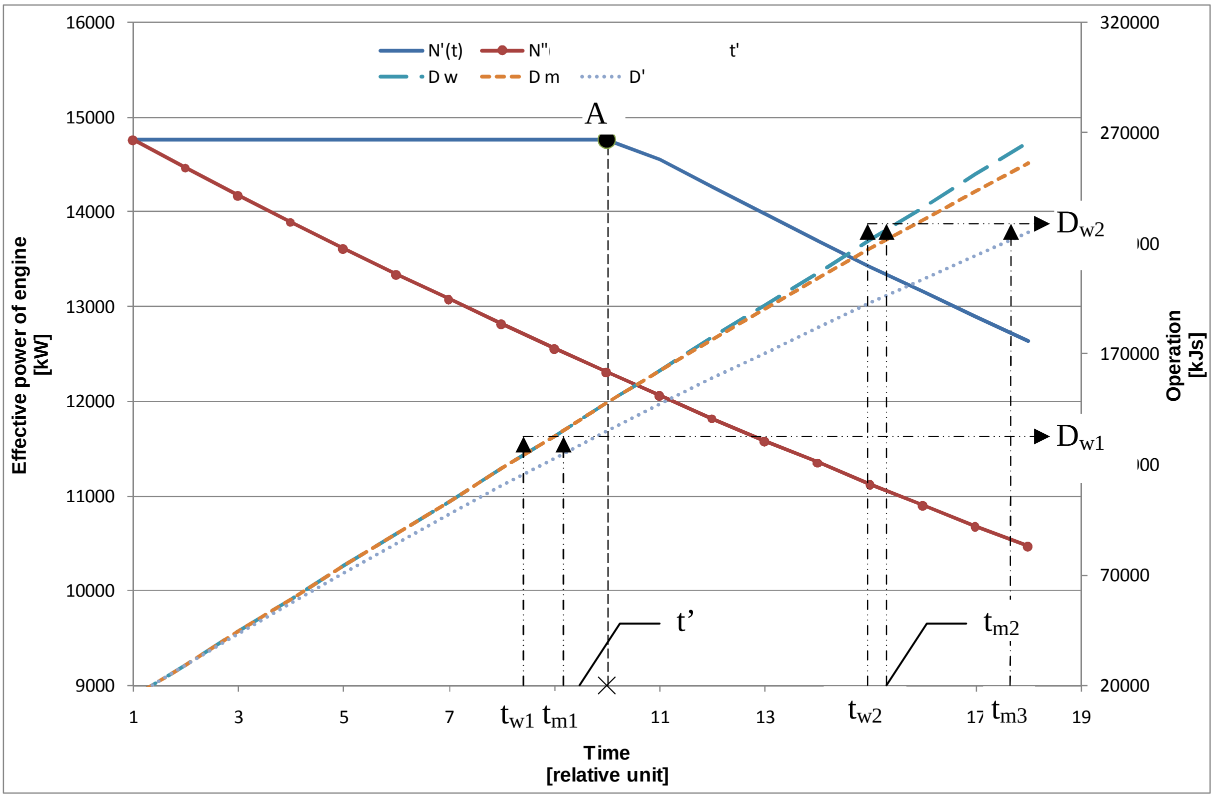

Fig. 2 *Change of engine operational characteristics, which results from degradation of its technical state. t_{w1} – demanded time of realization of the task 1, D_{w1} – demanded value of operation for realization of the task 1, t_{w2} – demanded time of realization of the task 2, t_{m1} – possible time of realization of the task 1 in the situation A (described in the text), t_{m2} – possible time of realization of the task 2 in the situation B (described in the text), t_{m3} – possible time of realization of the task 2 in the situation A (described in the text), D_{w2} – demanded value of operation for realization of the task 2, D_m – possible operation of engine in the situation 2 , D’ – possible operation of engine in the situation A.*

By introducing the notions of the demanded operation D_w and the possible operation D_m , whose detail interpretation can be found in [6, 7, 8], the phenomena graphically presented in Fig. 2 can be highlighted as follows:

- in the case of a hypothetical lack of possibility of increasing the fuel charge (the situation A) a drop of total engine efficiency will result in a sudden drop of its effective power – the line N”(t) – that , apart from producing a situation hazardous to ship safety , during further degradation of technical state of engine , will cause extending the realization time of transport task from the instant t_{w1} to t_{m1},
- if at engine partial load it is possible to increase the fuel charge within the interval of values $\langle g_p^{i\%}, G_{p\max}\rangle$ (the situation B) , and up to the instant of reaching its maximum value (the point A, instant t’) no noticeable drop of power occurs– the line N’(t), then only an additional cost resulting from increased fuel oil consumption will be generated. Hence it can be stated that if a transport task lasts shorter than up to the instant t’ any lengthening of its realization time will not occur.
- begining from the instant t’ (corresponding with the point A) a limitation of the possible engine operation D_m [6, 7, 8] occurs , that is associated on one hand with the lengthening of realization period of transport task (or lack of possibility of its realization during a given period) on the other hand – with increased costs of engine’s use.

By using the relation (4) and (6) the number of the events F , *k'*, corresponding with that of $N'_{\Delta gp}$ can be expressed as follows :

$$k' = \frac{G_{p\max} - g_p^{i\%}}{\Delta g_p} \tag{8}$$

and its occurrence probability as :

$$P\left(N_{\Delta gp} = k'\right) = \frac{\left(\lambda_f \cdot t\right)^{\left(\frac{G_{p\max} - g_p^{i\%}}{\Delta g_p}\right)}}{\left(\frac{G_{p\max} - g_p^{i\%}}{\Delta g_p}\right)} \exp\left(-\lambda_f t\right) \tag{9}$$

Practically possible determination of stochastic process parameters

From practical point of view the crucial problem is to determine Δg_p and λ_f values. This will be possible if two complementary conditions are satisfied:

- to have access to results of operational investigations carried out with application of standard control measuring instruments and a system for diagnosing the process in question by recording and analyzing changes in values of fuel flow rate within time intervals when engine load is relatively constant;
- to analyze technical documentation of the engine and carry out simulation investigations in order to elaborate a mathematical model of influence of the occurring events F on operational fuel system parameters.

In the presented case Δg_p can be much easier determined , because of its small value, under the assumption that :

$$g_p^{i\%} = \frac{B_h \cdot \tau}{n} \tag{10}$$

where:
B_h – unit fuel oil consumption of engine,
n – rotational speed of engine,
τ - a coefficient which takes into account number of strokes during one engine working cycle.

The relation (10) at assumed class of accuracy (e.g. 0,5) of commonly applied flow meters makes it possible to determine Δg_p value with an accuracy sufficient for practical purposes.

Much greater difficulties are associated with determination of λ_f value, which results first of all from lack of empirical research in this area of engine functioning. However such value can be determined, in a way sufficiently accurate from practical point of view, by means of the following procedure:

- on the assumption that a typical (most frequently occurring) load state of engine is x% [1], the difference between its maximum load and the above mentioned state determines the changeability range of instantaneous fuel charge $\left\langle g_p^{x\%}, G_{p\max} \right\rangle$, hence on the basis of Eqs. (3) and (6) it yields :

$$\Delta G_{p\max} = G_{p\max} - g_p^{x\%} \tag{11}$$

- the period $T_{\Delta Gp\max}$, during which $\Delta G_{p\max}$ value is reached, should be assessed on the basis of technical documentation of engine and its producer's recommendations for overhauls and repairs, as results of relevant empirical research are usually lacking;
- taking all the above into account one can state that within the considered period about

$$N'_{\Delta g_p} = \frac{G_{p\max} - g_p^{x\%}}{\Delta g_p} \tag{12}$$

number of the events F will occur, hence :

$$\lambda_f = \frac{N'_{\Delta g_p}}{T_{\Delta G_{p\max}}} = \frac{\dfrac{G_{p\max} - g_p^{x\%}}{\Delta g_p}}{T_{\Delta G_{p\max}}} \tag{13}$$

Finally , making use of the above presented procedure and basing on the relation (8) one can determine at first the number of the events F, k' , and the probability of their occurrence:

$$P(N_{\Delta gp} = k') = \frac{\left(\dfrac{\dfrac{G_{p\max} - g_p^{x\%}}{\Delta g_p}}{T_{\Delta G_{p\max}}} \cdot t\right)^{\left(\frac{G_{p\max} - g_p^{i\%}}{\Delta g_p}\right)}}{\left(\dfrac{G_{p\max} - g_p^{i\%}}{\Delta g_p}\right)} \exp\left(-\frac{\dfrac{G_{p\max} - g_p^{x\%}}{\Delta g_p}}{T_{\Delta G_{p\max}}} \cdot t\right) \quad , \tag{14}$$

and, the application of the relation (14) is this much practical that in the case of lacking results of empirical research one can approximately (but with a sufficient accuracy) determine $P(N_{\Delta gp} = k')$ value , basing solely on engine's technical documentation.

For example, for the above mentioned 9RT – flex60C – B engine (at the contractual output power N_x = 80% N_{R1} = 17370 kW, the contractual engine speed n_x = 90% n_{R1} = 102,6 rpm , G_{pmax} = 42,3 g, $T_{\Delta Gpmax}$ = 8000 h, Δg_p = 0,004 kg/s [13]) the values calculated by means of the relations (10) and (14) are the following:

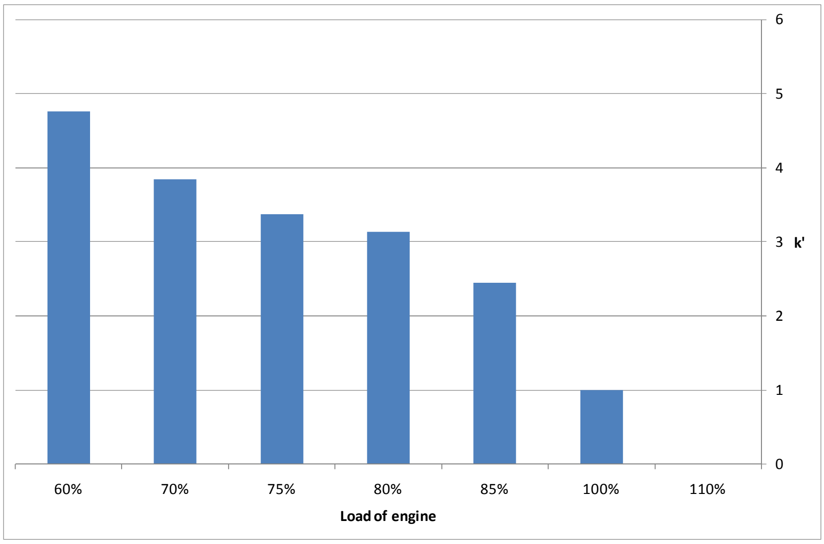

Fig. 3 *Values of the number k' of the events $N_{\Delta gp}$ in function of considered engine load values*

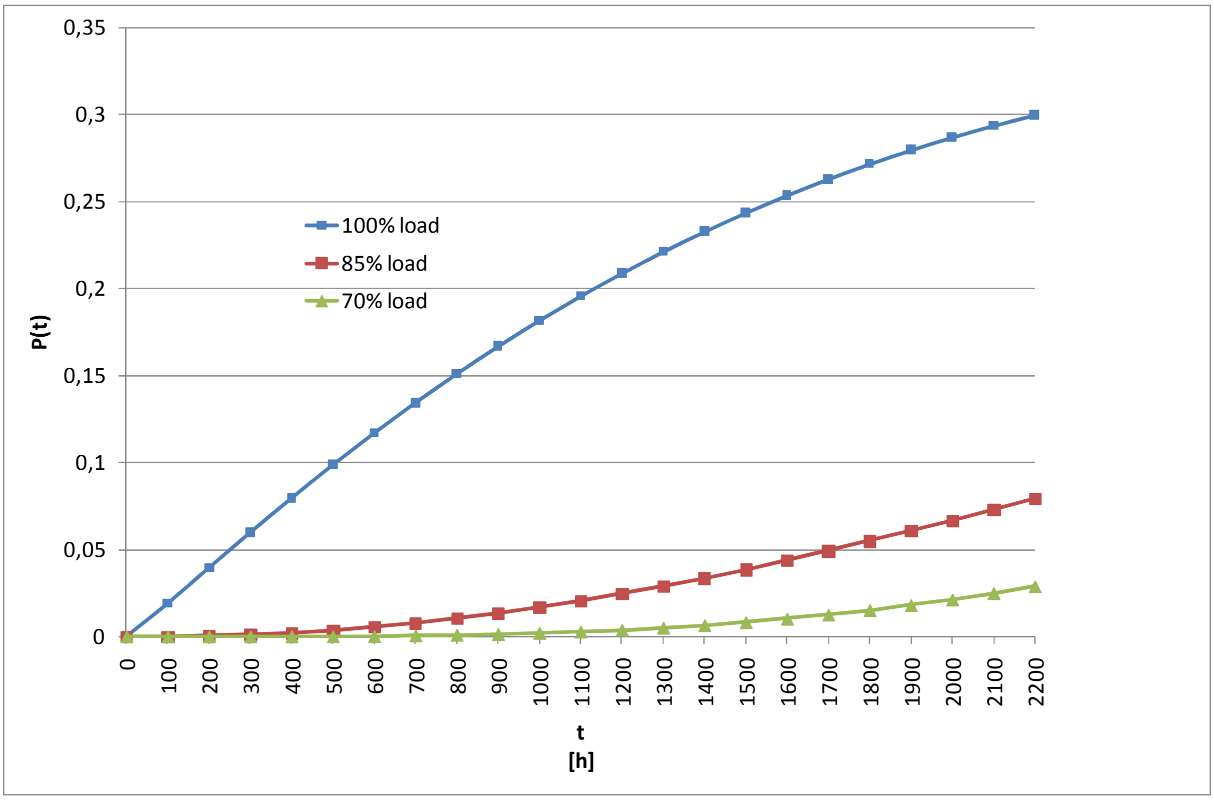

Fig. 4 *Occurrence probability of the number k' of the events $N_{\Delta gp}$ in function of considered engine load values and engine use duration period*

Summary

As already stated, the worsening of operational characteristics of an engine which operates under partial load up to the instant t' (Fig. 2), does not directly influence ship motion parameters.

However such situation generates additional cost born by engine's user , which finally lowers his profit Z resulting from realization of the task. To determine potential losses due to increased fuel oil consumption is possible by assuming that for t = 0 the additional cost Φ = 0 and the profit Z takes its maximum value $Z(0) = Z_{\max}$. By determining the expected value and standard deviation of the random variable which describes the lowering of the profit Z (the increasing of financial losses) as:

$$E[\Delta Z(t)] = \varphi \cdot \Delta g_p \cdot E(N_{\Delta gp}) = \varphi \cdot \Delta q \cdot \frac{\dfrac{G_{p\max} - g_p^{x\%}}{\Delta g_p}}{\mathrm{T}_{\Delta G_{p\max}}} \cdot t$$
$$\sigma_Q = \varphi \cdot \Delta q \sqrt{D^2(N_{\Delta q})} = \varphi \cdot \Delta q \sqrt{\frac{\dfrac{G_{p\max} - g_p^{x\%}}{\Delta g_p}}{\mathrm{T}_{\Delta G_{p\max}}} \cdot t} \qquad (15)$$

the relation which describes the lowering of the profit Z along with time *t* can be expressed as follows:

$$Z(t) = \begin{cases} Z_{\max} & dla \quad t = 0 \\ Z_{\max} - \varphi \cdot \Delta g_p \left(\dfrac{\dfrac{G_{p\max} - g_p^{x\%}}{\Delta g_p}}{\mathrm{T}_{\Delta \mathrm{G}_{\mathrm{p}_{\max}}}} \cdot t \pm \varphi \cdot \Delta g_p \sqrt{\dfrac{\dfrac{G_{p\max} - g_p^{x\%}}{\Delta g_p}}{\mathrm{T}_{\Delta \mathrm{G}_{\mathrm{p}_{\max}}}} \cdot t} \right) & dla \quad t > 0 \end{cases} \tag{16}$$

Making use of the relation (16) one can determine , for a given instant t , costs generated as a result of increased fuel oil consumption; and the relation (14) makes it possible to determine occurrence probability of such number of the events F which will generate additional limitations during realization of the task (e.g. lack of possibility of arbitrary loading the engine within its working area), or will make its realization impossible at all.

References

[1] Balcerski A., *Modele probabilistyczne w teroii projektowania i eksploatacji spalinowych siłowni okrętowych,* Fundacja promocji Przemysłu Okrętowego i Gospodarki Morskiej, Gdańsk 2007.

[2] Bielajew, J. K., Gniedenko, B. W., Sołowiew, A. D., *Metody matematyczne w teorii niezawodności*, Wydawnictwa Naukowo – Techniczne, Warszawa 1968.

[3] Chachulski, K., *Podstawy napędu okrętowego,* Wydawnictwo Morskie, Gdańsk 1988.

[4] Chachulski K., *Metody i algorytmy rozwiązywania problemów eksploatacyjno – ruchowych okrętowych układów napędowych,* Wydawnictwo WSM w Szczecinie, Szczecin 1992.

[5] Fidelis E., Firkowicz S., Grzesiak K., Kołodziejski J., Wiśniewski K., *Matematyczne podstawy oceny niezawodności,* PWN, Warszawa 1966.

[6] Girtler, J., Kuszmider, S., Plewiński, L., *Wybrane zagadnienia eksploatacji statków morskich w aspekcie bezpieczeństwa żeglugi,* Wyższa Szkoła Morska w Szczecinie, Szczecin 2003.

[7] Rudnicki, J., *Energy – Time Method for Assessment of Main Diesel Engine Operation,* Journal of KONES. Powertrain and Transport. - Vol. 14, nr 3 (2007), Warszawa 2007.

[8] Rudnicki J., *Ocena działania siłowni okrętowej w aspekcie energetyczno - czasowym* XXVIII Sympozjum Siłowni Okrętowych Gdynia 15-16 listopada 2007,Wydawnictwo Akademii Morskiej Gdynia 2007.

[9] Watson D.G.M., *Practical Ship Design*, Elsevier 1998.

[10] Urbański, P., *Podstawy napędu statków,* Fundacja Rozwoju Akademii Morskiej w Gdyni, Gdynia 2005.

[11] Włodarski J.K., *Okrętowe silniki spalinowe. Obciążenia eksploatacyjne,* Wydawnictwo Wyższej Szkoły Morskiej w Gdyni, Gdynia 1995.

[12] Przepisy klasyfikacji i budowy statków morskich. Część I, Zasady klasyfikacji. Wyd. PRS, Gdańsk 2006.

[13] *General Technical Data. WinGTD ver. 2.9,* Wärtsilä Switzerland Ltd 2004.