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ASSESSMENT OF OPERATION OF ENERGY SYSTEM OF SERIAL RELIABILITY STRUCTURE ON THE EXAMPLE OF SHIP MAIN PROPULSION SYSTEM

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Abstract

This paper presents a development of the known qualitative method for assessment of energy system operation, applied to ship main propulsion system as an example. According to this interpretation operation can be presented as a physical quantity. In this aspect , based on the selected functional system of the ship, was assessed usefulness of the quantity for description reliability features of the system. To the analysis was applied Poisson's uniform process which made it possible to elaborate a model of run of worsening the considered system's operation taken as a random process of identical independent decreases of energy efficiency within a given time interval.

Keywords: *reliability, operation, Poisson processes, ship power plant*

Introduction

During realization of a transport task by a ship to consider operation not only of particular elements of its propulsion system but also (and first of all) of full set of them which constitutes a functional entity, is necessary.

The existing publications [6, 7] pay special attention to main propulsion engine, other ones – to propeller and only a few – to the entire functional power plant subsystem.

High differentiation of contemporary ship propulsion systems makes it difficult to consider problems in this field generally, however an analysis of applied design solutions indicates that majority of solutions applied to typical transport ships (tankers, containerships, bulk carriers) still comprise only one driving unit (because of simplicity and lower investment and operational costs of such solution) which can be schematically presented as follows :

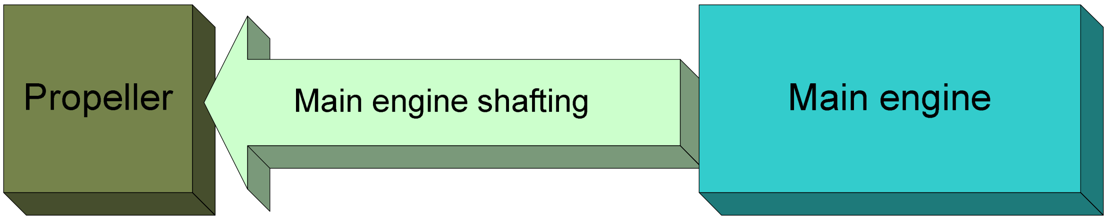

Fig.1. The functional structure of the typical solution of the ship propulsion

The solution shown in Fig. 1 constitutes a classical serial reliability structure of distinguished elements and this way role of each of them is very important in the aspect of realization of objective function of the entire system. Therefore it seems justified to consider the entire structure apart from analyses which concern first of all its weakest elements.

Reliability assessment procedures of each device and system make it necessary to apply a valuation approach to the problem and to search for appropriate measures [3, 5, 9, 10].

Necessity of precise determination of a task requires to determine its duration time , apart from assuming conditions in which the task would be realized. The problem is this much important that specificity of sea shipping tasks is as a rule connected with necessity of functioning the crucial mechanisms and devices of ship for a long time.

Hence not only the problem of how large amount of energy can be deliver to the propeller but also that of duration time in which it can be delivered , becomes especially important.

Therefore it seems reasonable, apart from taking into acount commonly used reliability indices, to consider operation of propulsion system in such a way as it could be determined in function of energy and time simultaneously. The problems related to selected elements of ship power plant are described in [6, 7, 8], however publications presenting the above described approach to the entire propulsion system have been so far lacking (they are unknown to this author at least). In such case, operation of a given system (D) within the period [t_1, t_2] can be interpreted as a physical quantity determined by the product of the time-variable energy $E = f(t)$ and time, which can be generally described by the following relation, [6]:

$$D = \int_{t_1}^{t_2} E(\tau)d\tau \qquad (1)$$

The so interpreted operation of a real technical object exposed to wear processes can be presented in the form of the diagram [6] shown in Fig.2a.

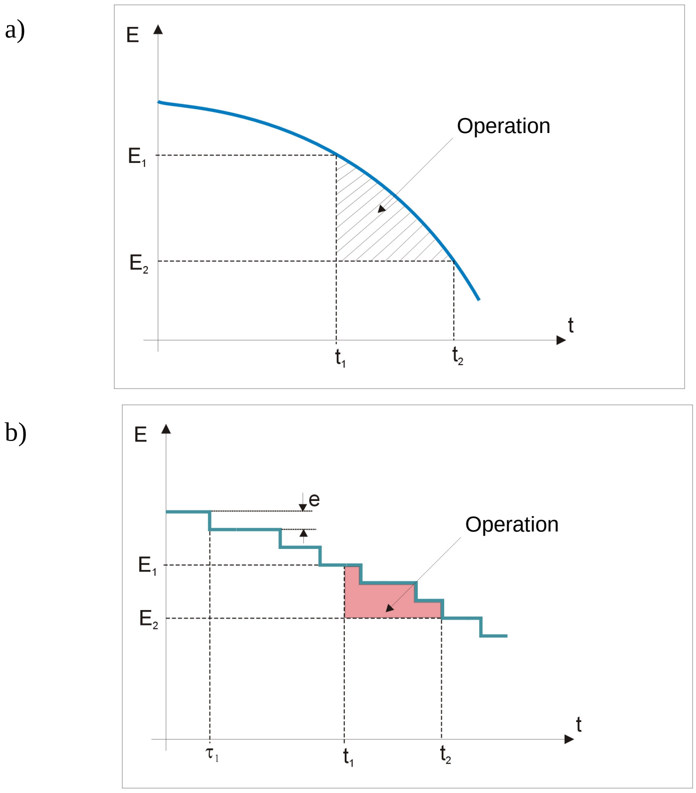

Fig.2. Operation by means of valuation. E – energy, t –time, e – elementary recordable constant value by which effective energy decreases in the random instants t_i. [6]

As the technical state change process is continuous with respect to time and states, the curve in Fig. 2a , which shows decreasing the effective energy E , is smooth. However in practice, as accuracy of measuring instruments is limited, its run will look like that shown in Fig. 2b.

Assessment of operation of main propulsion engine

In the case of analysis of operation of a self-ignition engine it can be consider that the energy released during fuel combustion in its cylinders makes it possible to develop torque by the engine. As a result of delivering the torque from the engine to the consumer the work L_e, is done, which can be determined from the relation:

$$L_e = M_o \cdot 2\pi\, n \cdot t \tag{2}$$

where:
L_e – effective work,
M_o – engine torque,
n – rotational speed of engine.

The product $M_o \cdot 2\pi\, n$ which appears in the relation (2) , is equivalent to value of the effective power N_e developed by the engine during realization of a given transport task, whose demanded value depends on a kind of task and can be determined , for an assumed ship speed , e.g. from the relation (3) which takes into account value of the thrust T developed by the propeller [11]:

$$N_e = \frac{T \cdot (1 - \varphi) \cdot v}{\xi_K \cdot \eta_p \cdot \xi_{rot} \cdot \eta_{lw}} \tag{3}$$

where:
T – propeller thrust,
φ – thrust deduction factor,
v – ship speed,
η_{lw} – efficiency of shaft line,
η_p – efficiency of free propeller,
ξ_{rot} – relative rotative efficiency,
ξ_k – hull efficiency.

In such case, as results from the relations (1) and (2), the engine operation D_S can be determined by the formula (4), [6]:

$$D_S = 2\pi \int_{t_1}^{t_2} M_0\, n\, t\, dt \tag{4}$$

Further by introducing the following notions :

- the demanded operation D_W, i.e. that necessary for realization of a task , e.g. cargo shipping by sea within a given period, that is equivalent to maintaining a given average ship speed, hence also a relevant value of power developed by ship main propulsion engine (- s);
- the possible operation D_M, i.e. that can be realized by an engine being in a given technical state and given functioning conditions , and which can be obtained by checking the relation (5), [6]:

$$D_M \geq D_W \tag{5}$$

i.e. the serviceability assessment criterion whose detail interpretation is highlighted in [6, 7, 8].

Along with time of engine operation its total efficiency defined for instance as [2, 11]:

$$\eta_e = \frac{1}{g_e \cdot W_d} \tag{6}$$

where:

g_e – specific fuel oil consumption,

W_d – fuel lower calorific value,

decreases first of all due to the degradation resulting from wear processes [2, 11], which leads to changes with respect to the above defined value of the possible operation D_M.

The phenomenon can be graphically represented in the form of the diagram (Fig. 3) which has the following interpretation:

- the degradation processes which progress for the operation time between successive technical state restorations, result in occurrence of the successive recordable events S_1 which consist in the decreasing of value of the engine torque M_o at a maintained oil fuel consumption, or the events S’ which consist in the increasing of oil fuel consumption in order to achieve the same value of the engine torque M_o.
- long-lasting use of the engine leads by itself to the worsening of its operational characteristics, that , because of a limited accuracy of measuring devices, can be represented by a sequence of the events appearing in the random instants t_i , which consist in either increasing the values B by the same increment $\Delta B' = b$ or decreasing the values M_o by the same decrement $\Delta M_o' = m_o$.

On assumptions on the stationarity , lack of consequences and singularity of flow of the above mentioned processes, the Poisson’s homogeneous process can be applied to their description [1].

In the context of the above defined operation *D* , see the relation (1) , the process of decreasing the available work is of crucial practical importance. Hence, the occurrence , up to the instant *t* , of the number $U_{\Delta M}$ of the events S_1 , that results in the total decreasing of the value M_o by the value ΔM_o , can be represented as follows :

$$\Delta M_o = \Delta M_o' \cdot U_{\Delta M} = m_o \cdot U_{\Delta M} \tag{7}$$

and

$$\Delta L_e = m_o \cdot U_{\Delta M} \cdot 2\pi n \cdot t \tag{8}$$

where :

ΔM_o – the total decreasing of the value M_o after occurrence of $U_{\Delta M}$ number of the events S_1,

$\Delta M_o' = m_o$ – elementary recordable value of torque by which the value M_0 decreases,

and, the random variable $U_{\Delta M}$ has the following distribution [1]:

$$P(U_{\Delta M} = k) = \frac{(\lambda_M \cdot t)^k}{k} \exp(-\lambda_M t); \quad k = 1,2,...,n \tag{9}$$

where:

λ_M – a constant interpreted as the intensity of occurrence of the event S_1 (the decreasing of the value M_o by the elementary value m_o).

The process (on assumption of constant oil fuel charge) can be graphically illustrated in the way presented in Fig. 3. :

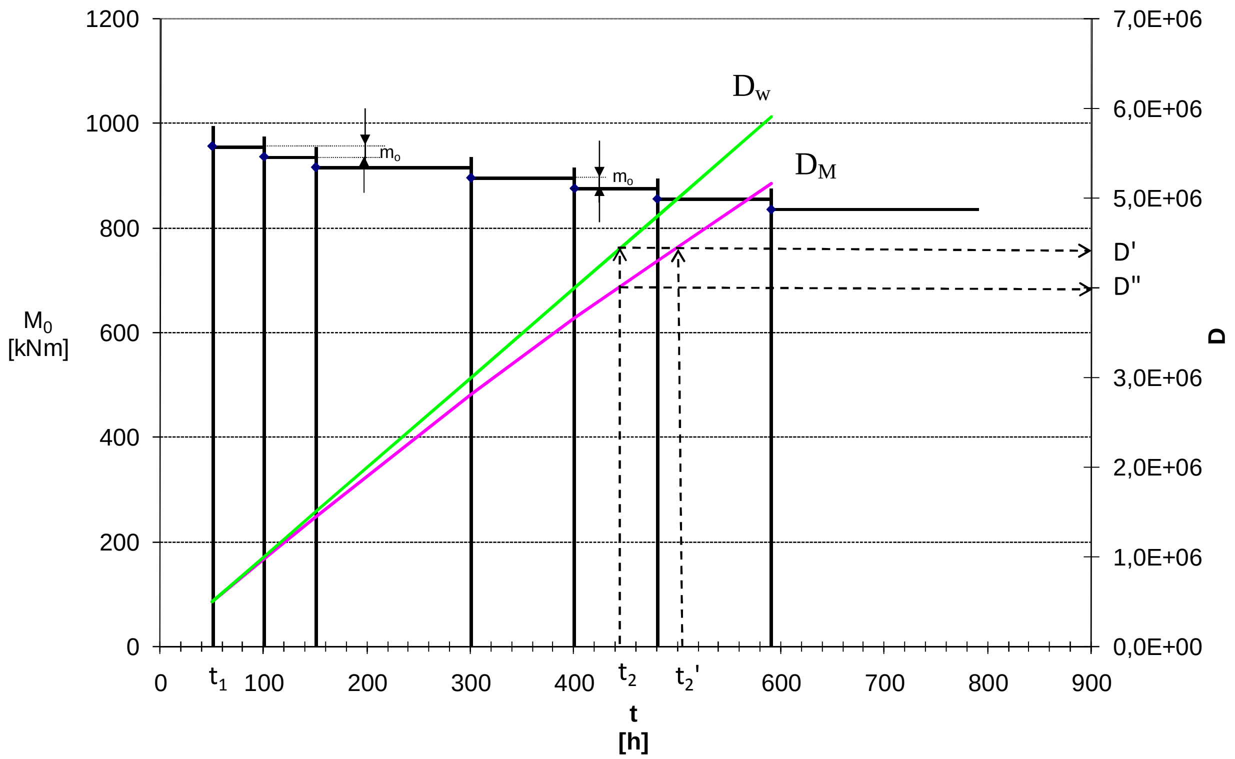

Fig.3.Main engine torque M_o and possible operation D_M decrease. D_w – demanded operation

As observed in Fig. 3, the difference between the demanded operation of the engine , D_w , and that possible one , D_M , is growing with time , that results in shifting the end of realization of transport task from the instant t_2 to t_2’.

Assessment of operation of power transmission line devices (shaft line)

As regards the power transmission line, the operation D_{LW} can be determined by the following relation:

$$D_{LW} = 2\pi \int_{t_1}^{t_2} Q\, n_S\, t\, dt \qquad (10)$$

where:

Q – torque delivered to screw propeller,

n_S – rotational speed of screw propeller (for direct drive systems : $n_S = n$).

In the case of shaft line devices whose solution typical for aft ship power plant is schematically shown in Fig. 4a, the load-carrying (intermediate) bearings and stern tube bearings constitute the elements which potentially generate loss of power.

Also, as regards the objects in question, despite their relatively high efficiency (close to 100%), can be enumerated many processes leading to gradual change of their technical state and in consequence to occurrence , in random instants t , of the events S_2 which consist in decreasing the values of the transmitted torque Q by the same values $\Delta Q' = q$. The process is presented in Fig. 5b.

Therefore the occurrence , up to the instant *t* , of $U_{\Delta Q}$ number of the events which cause the total decreasing of the value Q by the value ΔQ , can be represented as follows:

$$\Delta Q = \Delta Q' \cdot U_{\Delta Q} = q \cdot U_{\Delta Q} \qquad (11)$$

and consequently – the effective transmitted energy L_{e1} as :

$$\Delta L_{e1} = q \cdot U_{\Delta Q} \cdot 2\pi\, n \cdot t \qquad (12)$$

where:

ΔQ – the total decreasing of the value Q after occurrence of $U_{\Delta Q}$ number of the events S_2,

$\Delta Q' = q$ – elementary recordable value of torque by which the value Q decreases,

where the random variable $U_{\Delta Q}$ has the following distribution, [1]:

$$P\left(U_{\Delta Q} = k\right) = \frac{\left(\lambda_Q \cdot t\right)^k}{k} \exp\left(-\lambda_Q t\right); \quad k = 1,2,...,n \tag{13}$$

and :

λ_Q – a constant interpreted as the intensity of occurrence of the event S_2 (the decreasing of the value Q by the elementary value q).

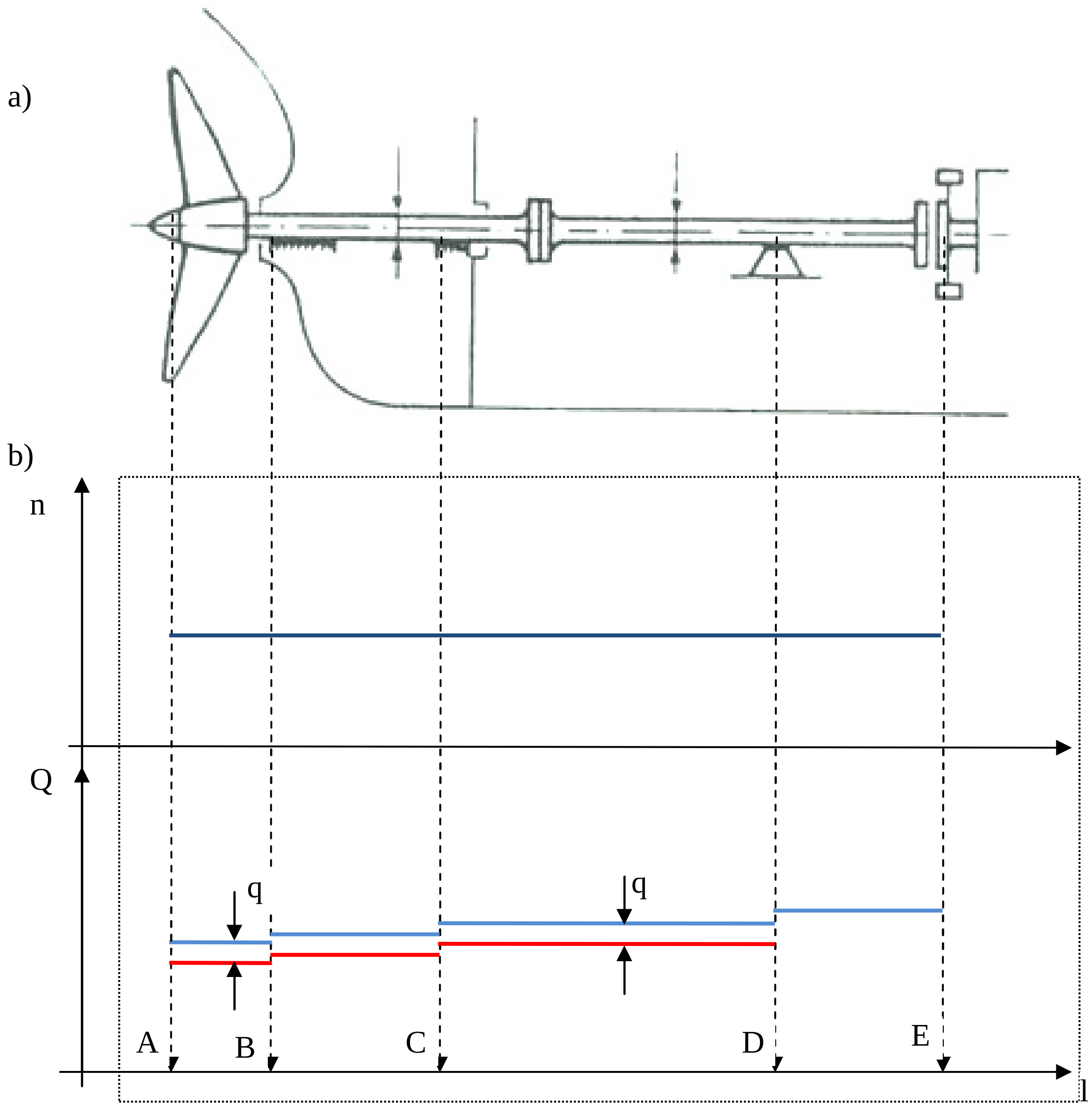

Fig.4. The single decreasing , by the elementary value q, of the torque in the power transmission line of ship propulsion system, resulting from wear and drop of efficiency of load-carrying bearings . A – screw propeller, B- aft stern tube bearing, C – fore stern tube bearing, D – load-carrying bearing, E – end terminal of engine power reception,

Assessment of operation of screw propeller

Similarly, an analysis of screw propeller operation leads to the conclusion that its operation D_P (in the sense of functioning) can be represented by the relation:

$$D_P = \int_{t_1}^{t_2} N_T \, t \, dt \qquad (14)$$

where:
N_T – thrust horse - power [11],

$$N_T = 2\pi \cdot Q \cdot n \cdot \eta_P \cdot \xi_{rot} = T \cdot v \cdot (1 - w) \qquad (15)$$

Q – torque delivered to screw propeller,
n – rotational speed of screw propeller,
η_P – efficiency of free propeller,
ξ_{rot} – relative rotative efficiency of propeller,
T – thrust,
v – ship speed,
w – wake coefficient.

The long-lasting use of screw propeller (time between successive repairs usually results from the ship dock overhaul schedule, i.e. every 3rd ÷5 th year, on average, [12]) is accompanied by many detrimental phenomena among which the following should be first of all numbered [4]:

- various modes of corrosion (electrochemical, of fatigue origin),
- erosion,
- cavitation,
- impact loads,
- transverse – torsional vibrations.

The phenomena contribute to degradation of technical state of screw propellers (as shown in Fig. 5) and the worsening of their serviceability characteristics, that results first of all from changes in hydrodynamical characteristics of screw propellers and their efficiency defined as follows, [2]:

$$\eta_p = \frac{J}{2 \cdot \pi} \cdot \frac{K_T}{K_Q} \qquad (16)$$

where:
J – speed coefficient,
K_T – thrust coefficient,
K_Q – torque coefficient.

Fig.5. The examples of propeller wear and damages
(źródło: http://home.xtra.co.nz/hosts/henleyspropellers/prop_damage.htm)

Character of the above mentioned changes is presented in Fig. 6.

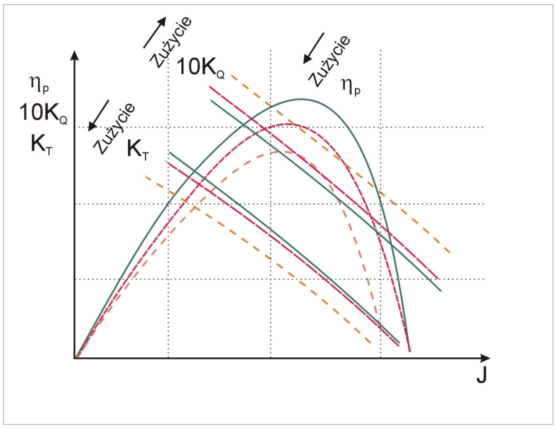

Fig. 6. Changes of hydrodynamical characteristics of screw propeller resulting from influence of wear processes [2]

As a result of the processes, propeller capability of transforming the delivered power N_D into designed value of the thrust T , diminishes. Hence on assumption of constant value of the power N_D and relatively constant ship sailing conditions (J = const) the screw propeller will produce smaller and smaller value of the thrust T and - in consequence - ship's speed will be also smaller at almost unchanged (or increased – see Fig. 17) engine load. Therefore also in relation to screw propeller, the process of occurrence, in random instants t , of the events S_3 which consist in decreasing values of produced thrust T by the constant values ΔT' = δ , can be considered.

Therefore the occurrence , up to the instant *t* , of $U_{\Delta T}$ number of the events causing the total decrease of the thrust value T by the value ΔT , can be expressed as follows:

$$\Delta T = \Delta T' \cdot U_{\Delta T} = \delta \cdot U_{\Delta T} \tag{17}$$

where:

ΔT – total decrease of the thrust value T after occurrence of $U_{\Delta T}$ number of the events S_3,

ΔT' = δ – elementary recordable thrust value by which the thrust decreases, whereas the random variable $U_{\Delta T}$ has the following distribution [1]:

$$P(U_{\Delta T} = k) = \frac{(\lambda_T \cdot t)^k}{k} \exp(-\lambda_T t); \quad k = 1,2,\ldots,n \tag{18}$$

where:

λ_T – a constant interpreted as the intensity of occurrence of the event S_3 (decreasing the thrust value T by the elementary value δ).

Operation of ship propulsion system as a serial reliability structure

As all main elements of ship propulsion system form a functional entity, a complex description of the entire system in the aspect of the defined operation seems to be necessary.

In the light of the considerations have been performed so far and as in accordance with the functional structure (Fig. 1) the output from every main component of the system in question constitutes the input to successive component , the occurring processes can be illustrated in the way shown in Fig. 7.

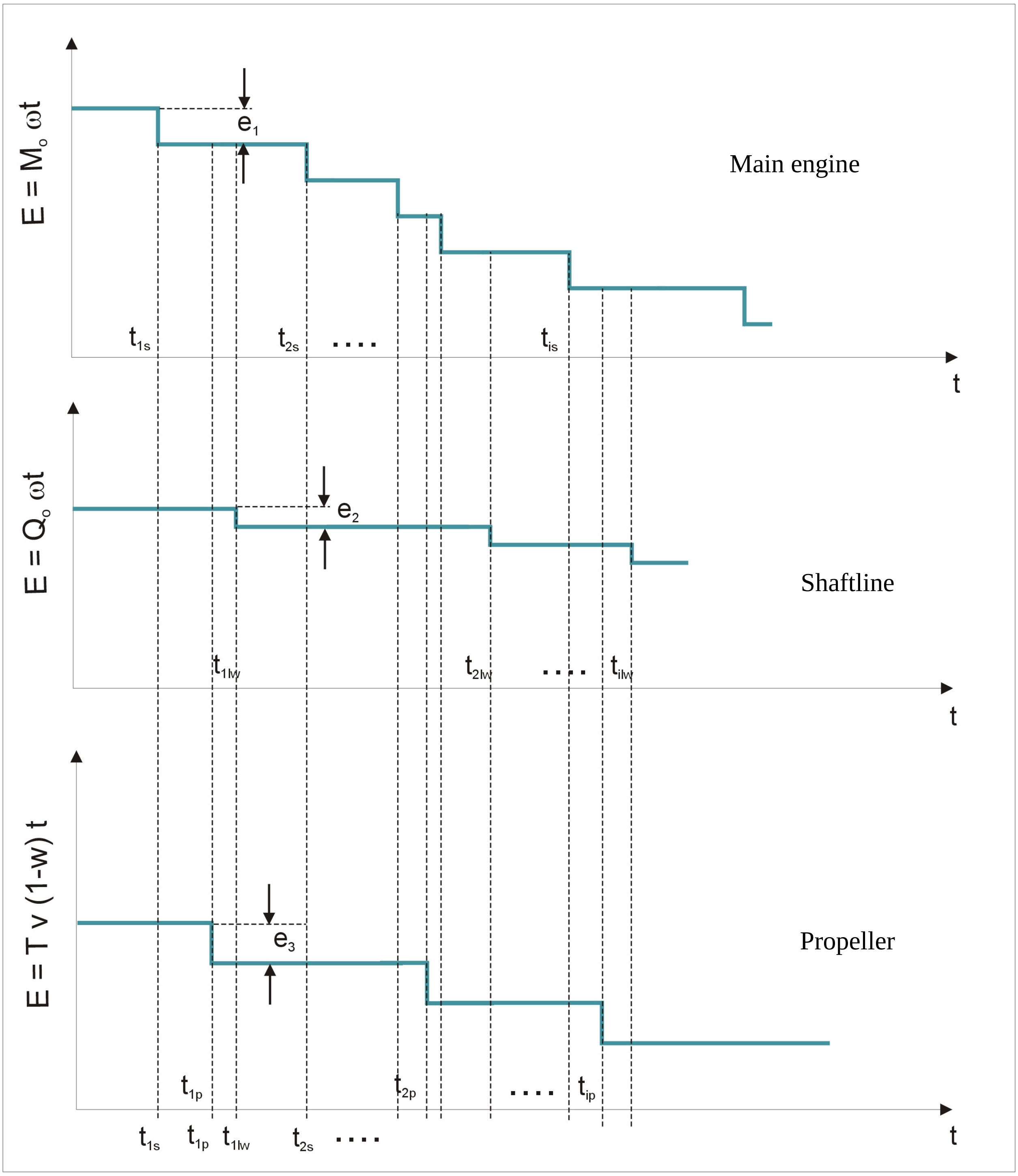

Fig.7. Operation of ship propulsion system as a serial reliability structure presented by means of valuation approach which takes into account the process of diminishing effective energy. e_1 *– elementary recordable constant value by which effective energy of engine decreases in the random instants* t_{is}*,* e_2 *– elementary recordable constant value by which energy transmitted by shaftline decreases in the random instants* t_{ilw} *,* e_3 *– elementary recordable constant value by which energy transformed by screw propeller decreases in the random instants* t_{ip} *,* $i = 1, 2, \ldots$

In the light of the considerations have been performed so far the Poisson homogeneous process can be applied as a model of the decreasing of propulsion system's effective energy.

If to assume that :

– the intensity of decreasing the effective energy in particular elements of the system by the value e_i , where : $i = 1$ (engine), 2 (shaftline), 3 (propeller), amounts to λ_i,

– the applied measuring instruments of similar accuracy make it possible to record the values e_1, e_2 and e_3 close to each other, i.e. to assume (without making a large error) that : $e_1 \approx e_2 \approx e_3 = e$,

then the process shown in Fig. 7 , can be represented, with the use of Poisson process features, by a new , summary one of the intensity λ_{UN} [2]:

(19)

in which the events S which consist in decreasing the effective energy by the constant value e, will occur in random instants (e.g. such as t_{1s}, t_{1p}, t_{1lw}, t_{2s} indicated in Fig. 8).

From practical point of view, determination of the values of e_i and λ_i becomes the crucial problem. The determination is possible in the case of satisfying the two complementary conditions :

- to have access to results of operational investigations carried out with application of standard control measuring instruments and diagnostic systems usually installed in ship power plants;
- to analyze technical documentation of the system's components and carry out simulation investigations in order to elaborate a mathematical model of influence of the occurring events $_{Si}$ on parameters of ship motion in given, relatively constant, sailing conditions.

Summary

By assuming that for t = 0 the effective energy E(0) is equal to:

$$E(0) = L_{e\,max} \tag{20}$$

where:

$L_{e\,max}$ – new engine effective work,

and by determining the expected value and standard deviation of the decreasing of the energy in the instant t as :

$$E[\Delta L_e(t)] = e \cdot E(N_{\Delta E}) = e \cdot \lambda_{UN} \cdot t, \qquad \sigma_{Le} = e \cdot \sqrt{D^2(N_{\Delta E})} = e \cdot \sqrt{\lambda_{UN} \cdot t} \tag{21}$$

where :

$N_{\Delta E}$ – random variable which describes cumulated number of the recorded, up to the instant t , events S , having the distribution [1, 6]:

$$P(N_{\Delta E} = k) = \frac{(\lambda_{UN} \cdot t)^k}{k} \exp(-\lambda_{UN} \cdot t); \quad k = 1,2,...,n \tag{22}$$

the relation which describes the decreasing of the energy L_e with time t, can be expressed as follows [6]:

$$L_e(t) = \begin{cases} L_{emax} & \text{dla} \quad t = 0 \\ L_{emax} - e \cdot \left(\lambda_{UN} \cdot t \pm e \cdot \sqrt{\lambda_{UN} \cdot t}\right) & \text{dla} \quad t > 0 \end{cases} \tag{23}$$

Making use of the relation (23) one can determine, for a given instant t , effective work (effective energy) which can be done by the entire propulsion system. Whereas, the relation (22) makes it possible to determine probability of occurrence of such number of the events S which would introduce additional limitations during realization of a given task (by making realization of a given ship speed impossible) or prevent it from realization at all. This way, value of the probability can be taken as a reliability index and used in the process of operational decision making.

The presented method seems to be a valuable supplement to the ways of description of reliability features of ship propulsion system , the crucial subsystem of ship power plant, which have been applied so far. Its basic advantage is the assessment of energy in function of time period during which a task is realized, that is very important in the case of realization of usually long-lasting tasks associated with cargo shipping by sea. An additional advantage is its versatility which makes that the method in question may be applied to reliability analysis of any device or energy subsystem of serial reliability structure, including those which are not machines, e.g. heat exchangers.

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