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POLISH MARITIME RESEARCH 4 (120) 2023 Vol. 30; pp. 110-119
10.2478/pomr-2023-0064

QUANTUMNESS IN DIAGNOSTICS OF MARINE INTERNAL COMBUSTION ENGINES AND OTHER SHIP POWER PLANT MACHINES

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ABSTRACT

The article provides proof that the diagnostics of marine internal combustion engines and other ship power plant machines should take into account the randomness and unpredictability of certain events, such as wear, damage, the variations of mechanical and thermal loads, etc., which take place during machine operation. In the article, the energy E, like the other forms (methods) that it can be converted into (heat and work), is considered the random variable E_t; at time t, this variable has the mean value $\overline{E}_t$, which is the observed value of the statistic $\overline{E}_{st}$ with an asymptotically normal distribution $\mathrm{N}\left(\mathrm{E}(E_t), \frac{\sigma_t}{\sqrt{n}}\right)$, irrespective of the functional form of the random variable E_t. A proof is given that shows that the expected value estimated in the above way, considering the time t of the performance of task Z by a marine internal combustion engine or other ship power plant machine, can be used to determine the machine's possible action (D_M). When compared to the required action (D_W) needed for task Z to be performed, this possible action makes it possible to formulate an operating diagnosis concerning whether the engine or machine of concern is able to perform task Z. It is assumed that an energy device of this type is able to perform a given task when the inequality $D_M \geq D_W$ holds. Otherwise, when $D_M < D_W$, the device cannot perform the task for which it was adopted in the design and manufacturing phase, which means that it is in the incapability state, although it still can be started and convert energy into the form of heat or work..

Keywords: diagnostics, stochastic process, internal combustion engine, random variable

INTRODUCTION

During the operation of any marine internal combustion engine or ship power plant machine, irrespective of the applied diagnosis system (*SDG*), collecting the information needed to formulate the diagnosis of the state of the engine or machine that is the diagnosed system (*SDN*) requires the initiation and continuation of the diagnostic process. This process [2], [6], [10], [11] is a two-dimensional stochastic process $\{D(t, \vartheta): t \geq 0, \vartheta \geq 0\}$. It consists of the process $\{B(t): t \geq 0\}$, which represents the *SDG* operation, and the process $\{C(\vartheta): \vartheta \geq 0\}$, which represents data collection by *SDG* and the formulation of a diagnosis about the state of *SDN*.

The process $\{B(t): t \geq 0\}$ is the process resulting from the use of *SDG* during the operation of the engine or machine performing a given task (*SDN*). This process is considered a long-term process, and it can but does not have to involve generating short-term diagnoses and/or formulating prognoses or geneses. The course of this process has a fundamental impact on the reliability of the diagnosis [12]–[14], [25], [38]. The process $\{C(\vartheta): \vartheta \geq 0\}$ is connected with performing measurements of the current values of diagnostic parameters (physical quantities such as temperatures, pressures, vibrations, etc.), with further diagnostic reasoning performed in the short term, i.e. the time interval of the *SDG* operation (work) in which the diagnosis is obtained.

The process $\{C(\vartheta): \vartheta \geq 0\}$ always consists of the following realisations: diagnostic testing and diagnostic reasoning (of the signal, measurement, symptom, structural, and operating type) [4]. The output of the process $\{C(\vartheta): \vartheta \geq 0\}$ is a diagnosis, the reliability of which is highest when, during the testing process, *SDG* works reliably and the disturbances resulting from environmental influences can be omitted due to the sufficient resistance of *SDG* to these influences.

In a general case, diagnostic reasoning is carried out using the following types of reasoning in the following order: the signal, measurement, symptom, structural, and operating reasoning types [4]. Each of the above types of reasoning is characterised by the diagnostic uncertainty, resulting from the fact that diagnostic reasoning can be (and, as a rule, is) burdened with errors. As a result, diagnostic reasoning can lead to one of two possible mistakes to be made by the user (diagnostician) of the engine or machine:

- a first-type mistake, which consists of diagnosing the engine or machine as being in the incapability state, although it is still able to perform the given task, i.e. it is in the state of capability;
- a second-type mistake, which consists of diagnosing the engine or machine as being in the state of capability, although it is already unable to perform the given task, i.e. it is in the incapability state.

The above interpretation of the process $\{C(\vartheta): \vartheta \geq 0\}$ shows that this process has values (states) that correspond to diagnostic tests and the above types of reasoning, and the durations of the diagnostic tests and the above types of reasoning are the execution times of these states. A characteristic feature of this process is that certain probabilities of occurrence can (and should) be attributed to its states, while the duration of each of these states is a random variable.

During each diagnostic test, the measurements are made with a certain accuracy, which depends on the applied measuring methods and devices, as well as on the measurement conditions and the experience and qualifications of the people performing the test; all of these factors are possible sources of inaccuracy in the measurement. This inaccuracy results from both the inaccuracy of the applied measuring methods and devices, and changes in the characteristics of the tested engine or machine that take place during the measurement. The main causes of inaccuracy include the limited resolution of the measuring devices (resulting from their sensitivity threshold and the randomness of the examined phenomena) and errors such as the quantisation error, aperture error, and sampling time error when a digital signal is used in the measurement [27]. Hence, the diagnostic testing of a marine engine or other ship power plant machine is burdened with a certain measurement inaccuracy. This inaccuracy should be recognised well enough to determine its main cause, i.e. whether it is mainly caused by [26], [27]

- errors in the applied measuring methods and devices, which are known to depend mainly on the accuracy and sensitivity of the measuring sensors and transducers, the inaccuracy of the measuring devices, given by their inaccuracy class, and the stability and reliability of the measuring devices; or
- changes in the characteristics of the tested engine or machine that take place during the measurement.

The correct identification of the causes of the inaccuracy of the performed measurement is necessary for the accurate evaluation of the current inaccuracy of the characteristics of the tested machine and that of the applied measuring devices, with the further correct selection of the proportions of these inaccuracies. The difficulty in evaluating the inaccuracy of a measurement related to the properties of the applied measuring method and devices and that related to the current characteristics of the diagnosed machine originates from the quantum nature of their changes, which leads to randomness and the unpredictability of events in the diagnostics of marine internal combustion engines and other ship power plant machines. Therefore, this issue needs to be thoroughly considered.

RANDOMNESS AND UNPREDICTABILITY OF EVENTS IN DIAGNOSTICS OF MARINE INTERNAL COMBUSTION ENGINES AND OTHER SHIP POWER PLANT MACHINES

In the diagnostics of not only marine internal combustion engines but also those used in cars, airplanes, etc., as well as other machines of all types, it is advisable to stop using the deterministic approach for the identification of the technical state of these machines and focus on the probabilistic aspects of their diagnostics [3], [6], [11], [17], [21], [24], [29], [30], [38]–[40]. The deterministic approach to the diagnostics of marine engines and machines, as well as those used in other branches of technology, results from the traditional perception of changes in their technical state, according to which it is believed that, in general, randomness and unpredictability can be omitted in technical diagnostics intended to assess the technical state of these types of devices. One of the main reasons for such an approach to the diagnostics of energy devices was the fact that until the 20th century, a deterministic theory of the description of phenomena, events, and processes was in force. This theory was developed by Pierre Simon de Laplace, who assumed that similar laws of physics exist in both the macroworld and microworld, and all changes take place according to these laws. They control the appearance and disappearance of each phenomenon, and the course of all events (facts) and processes. According to this theory, the entire universe is totally deterministic on both the microscale and macroscale. This vision of changes taking place in space and time was the basis for the development of science until the early 1920s – it was a basic methodological assumption made by physicists. This view led to the foundation of mechanics, which now is referred to as classical, or non-quantum, mechanics – in contrast to quantum mechanics, which was developed later. It also led to the conviction that all the laws of motion and any other changes can be expressed as differential equations that have unique solutions. This determinism can be found in the principles formulated by Isaac Newton to describe the laws of nature, in the partial differential equation proposed by Erwin Schrödinger (1926), the solution of which is the wave function determining the quantum state of a particle at an arbitrary time in a deterministic aspect, and in Albert Einstein's equations describing the photoelectric effect and the relationship between energy, mass, and velocity [36], [37]. All these equations are not only deterministic but also time-reversible [22], [34]. However, despite the efforts of many mathematicians, researchers have failed to prove the existence of unique solutions to differential equations, which was the inspiration for searching for a concept of the probabilistic interpretation of reality. An example of such an approach is the probabilistic interpretation of the wave function proposed as the solution to Schrödinger's wave equation by Max Born (in 1926), who could not accept the fact that this function represents a 'real' electron wave, even though other physicists accepted this equation as a tool for solving quantum mechanics problems. In Max Born's interpretation, the wave function Ψ is a product with complex numbers as values [5], [17], [19], such that $|\Psi|^2$ is the probability of finding a particle in a given area (point) in space. That means that there is no certainty about the exact position of an electron, but the probability that the electron is at a given point in space can be calculated, provided that the wave function Ψ is known. This interpretation corresponded to Niels Bohr's opinion; he accepted partial and wave theoretical models of the existence of particles. He also believed that we cannot predict an exact result of an empirical examination; in his opinion, we can only calculate the probability that the result of a given experiment will take a given value and not another value.

However, the final blow to the deterministic theory of Laplace came from the uncertainty principle formulated by Werner Heinsenberg (1926). Along with Max Planck's quantum hypothesis (1900), which explained the nature of electromagnetic radiation generated by hot bodies, the uncertainty principle became one of fundamental elements (achievements) of quantum mechanics. Today, this theory is the basis for contemporary science and technology. It was developed in the 1920s by Werner Heinsenberg, Erwin Schrödinger, and Paul Dirac, as well as by Wolfgang Pauli and Niels Bohr. Additionally, Albert Einstein and Richard Feynman contributed to the development of this theory (the latter being the creator of nanotechnology). Its principles explain, for instance, the functioning of transistors and integrated circuits, i.e. most important components of electronic devices, without which modern diagnostics (not just technical) could not exist. These principles also apply in modern chemistry (quantum chemistry) [23], cryophysics (quantum liquid), and biology (medical diagnostics). Among the physical sciences, only the theory of gravity and cosmology has not been fully aligned with quantum mechanics [20]. However, it may be expected that one day this will happen. The general theory of relativity describes observations well, due to the fact that gravitational fields existing in ordinary conditions are weak. However, according to the singularity theorems, the gravitational field is very strong in two situations, at least: in the areas of black holes, and during and directly after the Big Bang [20]. Evidently, quantum effects cannot be neglected in these fields [17], [20], [40]. We can expect that the classical theory of relativity should finally collapse because of the above space-time singularities. Currently, research is in progress to develop the quantum gravity theory. Classical (non-quantum) mechanics was questioned because it assumed that atoms should collapse to the state of infinite density. According to that theory, a hot body should emit electromagnetic waves with the same intensity at all wave frequencies, which means that the total energy emitted by this body is infinite. This conclusion is not true, and this was why Max Planck formulated a hypothesis that electromagnetic waves cannot be emitted at an arbitrary rate but only as strictly defined portions, which he called quanta (hence the name: quantum hypothesis).

It results from quantum mechanics that physical quantities such as energy or angular momentum can only change in steps. Moreover, the quantities referred to as complementary have an important property: the simultaneous and accurate measurement of their values is impossible. For instance, the more accurate the position measurement of a microparticle (subatomic particle) is, the less accurate the measurement of its momentum and, consequently, velocity will be. This is according to the Heisenberg's uncertainty principle, which defines the inaccuracy degree of the measurement of the above basic physical quantities (the position and momentum of a particle, as well as energy and time). This inaccuracy has nothing in common with the accuracy of the applied measuring methods and/or devices [5], [17], [19], [20]. The uncertainty principle says that in the microworld, we cannot predict exactly the future position of a particle smaller than an atom, which is important, for instance, in controlling the stream of neutrons in a kinescope. Therefore, it is understandable that the atom models proposed first by Joseph John Thompson and then by Ernest Rutherford and Bohr (although Bohr's model quite precisely described the structure of the hydrogen atom, as it is the simplest atom) were replaced by the quantum mechanical model of atom structure. In this model, the electrons in atoms do not move on specific orbits; instead, they move in so-called orbitals, which are space regions around the nucleus in which the probability of the existence of (finding) an electron at a given moment has a precisely defined value. Following the proposal of Richard Feynman, it was assumed that the particle does not move on one track but on all possible trajectories (permissible orbits) [1], [17], [20], [34]. These permissible orbits, called the orbitals of electrons in atoms, are understood as space regions around the nucleus in which the electron can appear at a given time with a certain probability [1], [19], [34].

Transferring these conclusions to the macroscale research area, we can say that, according to Heisenberg's uncertainty principle, we cannot expect the same result when repeating any empirical research, regardless of whether it is observational or an active experiment. Thus, the question of how different the obtained results can be arises. The answer is that the range of this difference depends on the adopted testing method, the accuracy of the measuring devices, the current measurement conditions and their repeatability, the experience of the person conducting the test, the number of measurements made, the duration time of the measurement, etc. All of this means that when an empirical test is repeated, in a particular experiment and in given conditions, different results are always to be expected. This also means that obtaining a specific test result is a random event, and the measured quantities should be considered random variables. Indeed, when the variability of the measurement results is small, it can be neglected, but in each case, this decision should be justified. Formulating a diagnosis first requires the diagnostic test to be performed, as it is the first link in the diagnosis chain. The diagnostic test consists of measurements made using a proper measuring device or the organoleptic identification of the values of diagnostic parameters [3], [4], [11], [17], [21], [24], [29], [30], [38]–[40]. The results of this test make it possible, using diagnostic reasoning, to formulate a relevant diagnosis (of the signal, measurement, symptom, structural, and operating type) [4]. At each stage of the diagnostic procedure, including diagnostic tests and the subsequent types of diagnostic reasoning, the obtained results are burdened with the above-mentioned uncertainty and with errors caused by various disturbances. Therefore, the randomness of a diagnosis, prognosis, or genesis should be considered an indispensable attribute.

The quantum mechanics based on Heisenberg's uncertainty principle introduce unavoidable randomness and unpredictability to science and engineering practice.

A more general uncertainty than that defined by Heisenberg's principle is introduced by the phenomenon known as deterministic chaos [35]. This phenomenon can be observed when the tested model is a system of differential equations, especially nonlinear equations of the 2nd, 3rd, and 4th order. It is a well-known fact that the solution to a deterministic system of differential equations can take the form of very complicated oscillations; the reason for this is not a large number of degrees of freedom, nor local disturbances, but the increasing instability depending on the precision with which the initial state is determined, which, in turn, depends on time-related initial conditions and time-dependent equation coefficients. Deterministic chaos is closely connected with the occurrence of so-called attractors, which usually have the form of aperiodic trajectories that attract other trajectories from their environment [1], [38]. The detection of attractors enables better prediction of the appearance of random events. Therefore, recognising the fact that a given empirical system develops chaotically may facilitate the study of its evolution. This means that chaos is not always a negative phenomenon. Adding noise with random parameters to the non-disturbed empirical system can lead to statistical stabilisation or the periodicity of the evolution of this system. This requires as new look at relations between deterministic diagnostic models and those representing statistical and probabilistic approaches.

Another source of chaos can be inaccuracy in determining the model parameters. This fact is connected with the phenomenon of bifurcation (splitting between the real and expected test results), which can be observed during the state identification of machines such as marine piston or turbine engines, as well as positive displacement or rotary compressors, pumps, fans, electric motors, generators, etc. This phenomenon is an obstacle to obtaining a credible diagnosis, prognosis, or genesis.

The discovery of the principle of ambiguous causality in science has led to the questioning of the earlier belief of unequivocal determinism (i.e. unequivocal effect resulting from each cause) and the adoption of ambiguous determinism, i.e. determinism resulting from the probabilistic laws of quantum mechanics, which accepts the existence of choice (as a known rule).

It results from the above considerations that when constructing and using the diagnostic model of a marine engine or machine to formulate a complete diagnosis (i.e. current diagnosis, genesis, and prognosis), the following laws (principles) should be taken into account:

- ambiguous causality, i.e. the existence of the randomness of events (including events such as machine state diagnosis), which indicates a need to accept at least ambiguous determinism,
- the uncertainty formulated by Heinsenberg,
- the existence of the general randomness of natural phenomena resulting from their infinite complexity,
- the existence of deterministic chaos resulting from the so-called sensitivity of models of empirical systems, in particular internal combustion engines but also other machines (not only those installed in ship's engine rooms), to their initial state,
- the limited, as a rule, accuracy of the measuring methods and devices, which leads to the limited accuracy of the measurements made using these methods and devices,
- the operating inaccuracy of the marine engine or ship power plant machine that is the diagnosed system (*SDN*),
- the unreliability of the diagnosing systems (*SDG*) adopted to identify the technical state of a marine engine or ship power plant machine.

The measurements are associated with certain diagnostic procedures, during which some mistakes can be made as a result of the following:

- performing a diagnostic test in highly disturbed conditions,
- using an incorrect course of measurements and incorrect error assessment (e.g. neglecting quantisation, aperture, and sampling time errors), as a result of the application of measuring devices with insufficient (inadequate) accuracy and/or the omission of some measurements,
- incorrectly recording the results of measurements that have been correctly performed and correctly signalled by the measuring devices,

- incorrectly interpreting the results of diagnostic tests both during the diagnostic test and in the further steps of diagnostic reasoning, which is the result of the inaccurate (incorrect) reading of the indicators of the measuring sensors (devices) and the application of inaccurate data processing algorithms,
- incorrectly identifying the state of the engine or machine that is the diagnosed system (*SDN*), despite correctly performing the measurements and obtaining correct results from the diagnostic tests.

All of this means that in empirical diagnostic testing, making use of certain measuring methods and devices, there is a problem of measurement inaccuracy that results from changes in the characteristics of the tested machine that take place during the measurement and errors associated with the use of certain measuring methods and devices [20], [21]. As a consequence, an indeterminacy appears that should be explained. In particular, the main cause of this indeterminacy should be recognised, i.e. it should be determined whether it results from

- a change in the characteristics of the engine or machine that is the object of diagnostic testing that took place during the measurement, or
- errors associated with the use of the given measuring methods and devices.

Therefore, it is of high importance in this type of testing to [28]

1. estimate the value of the operating uncertainty of the marine engine or other ship power plant machine that is the object of the diagnostic test,
2. estimate the value of the inaccuracy of the utilised measuring technique (measuring method and devices),
3. select adequate proportions between the accuracy of the applied measuring technique and the current inaccuracy of the tested object (a marine engine or machine).

It follows from the above that when using diagnostic methods to determine the technical state of an engine or machine that is the diagnosed system (*SDN*) via an appropriate diagnosis system (*SDG*), it is difficult to obtain sufficiently unambiguous answers to the following questions:

- What is the current structure of the tested machine (*SDN*) and its resulting technical state ?
- What were the causes that led to the present technical state of the machine ?
- What will the specific properties of the SDN state be during and after its future evolution ?

In this situation, formulating a specific diagnosis, especially an operational diagnosis, requires the application of mathematical statistics, probability calculus, and stochastic processes. Additionally, formulating the operational diagnosis requires knowledge on the consequences of making a given decision that belongs to the set of possible decisions. Nevertheless, a deterministic approach can be applied to determine the symptoms of the technical state of the machine; for instance, integral calculus can be used to calculate the value of the machine's operation. In this case, further considerations concerning the diagnostics of machines will focus on demonstrating the suitability of the generalised diagnostic system, which can be the operation of a given marine engine or other ship power plant machine, for determining the operational capability of these devices, i.e. their ability to perform a given task in a given amount of time and given operating conditions.

THE ISSUE OF OPERATION OF MARINE INTERNAL COMBUSTION ENGINES AND OTHER SHIP POWER PLANT MACHINES IN TERMS OF THEIR DIAGNOSTICS

The operation of an arbitrary marine internal combustion engine or ship power plant machine can be interpreted as of conversion of the energy E into the form of heat and/or work and its delivery to a receiver in a given time t (heat and work are forms, or – in other words – methods of energy conversion) [15], [16], [31]. In this interpretation, the operation of each ship power plant machine, including the marine internal combustion engine, can be described (in an evaluative approach) using a physical quantity with a given numerical value and a unit of measure called the *joule-second* [joule×second].

Consequently, the operation of any marine internal combustion engine or ship power plant machine can be quantitatively determined using the physical quantity D (D = E · t). This quantity contains information on how long the energy E is or can be converted by a given engine or machine. If we limit the analysis of the conversion of the energy E to only the form of work (L), then, taking into account the time of this energy conversion, we can calculate the operation of the engine or machine as $D_L = L \cdot t$. This type of data on the operation of a given engine or machine contains information on how long the work L is or can be performed. This information is as important as that about the power (N) of a given marine internal propulsion engine or ship power plant machine, as it indicates how fast a given amount of work (L) can be done.

With time, the operation of each marine internal combustion engine and ship power plant machine is becoming worse. Therefore, the issue that may be of a certain interest is the analysis and assessment of the operation of these devices, taking into consideration the above aspect.

The evaluation presented here of the operation of an arbitrary marine internal combustion engine or ship power plant machine has the following advantage: the descriptive evaluation of its operation (the operation of the engine or machine is good, acceptable, not very good, incorrect, bad, etc.) is replaced by an evaluation resulting from comparing the operation of a given engine or machine with another that is used as a reference.

The meaning of such an interpretation of the operation of a marine internal propulsion engine or ship power plant machine can be justified by the following reasoning: the operation D ($D = E \cdot t$) of an engine or machine (due to its technical state) is better if more energy is delivered to the receiver in a given amount of time (t). When the energy transfer has the form of work (L), the operation ($D_L = L \cdot t$) of the machine (due to its technical state) is better if more work (L) is done by this machine in a given amount of time (t).

It is noteworthy that when the energy E is converted into the combined form (method) of work L and heat Q, then, in the evaluative approach, the following equivalence holds:

$$E \equiv L + Q, \tag{1}$$

which means that in this case, the value W_E of the energy E is equal to the sum of the value W_L of the work L and the value W_Q of the heat Q, i.e. $W_E = W_L + W_Q$.

In the case when the energy E is solely used to perform the work L (converted into the form of the work L), then, in the evaluative approach, the following equivalence occurs:

$$E \equiv L, \tag{2}$$

which means that in this case, the value W_E of the energy E is equal to the value W_L of the work L, i.e. $W_E = W_L$.

Similarly, when the energy E is solely used for generating the heat Q, then, in the evaluative approach, the following equivalence occurs:

$$E \equiv Q, \tag{3}$$

which means that in this case, the value W_E of the energy E is equal to the value W_Q of the heat Q, i.e. $W_E = W_Q$.

The operation of a marine internal propulsion engine or other ship power plant machine can be considered using the following terms: required operation (D_W) and possible operation (D_M) [16]. We can conclude that each engine or machine is in the capability state, i.e. it can perform a given task, when

$$D_M \geq D_W. \tag{4}$$

Otherwise, when $D_M < D_W$, we can conclude than the engine or machine is in the incapability state or partial incapability state [15], [16], [32]. The capability of an engine or machine can be assessed after comparing the area of required operation (D_W) with that of possible operation (D_M). This issue is discussed in [16].

In a deterministic approach, the operation of a given marine engine or other ship power plant machine can be described using a general functional relationship describing the change in the energy E at an arbitrary time t of machine operation. The operation of the marine engine or other ship power plant machine analysed for $E(t) = f(t)$ in a given time interval, e.g. $[t_1, t_2]$, is shown as the area in Fig. 1.

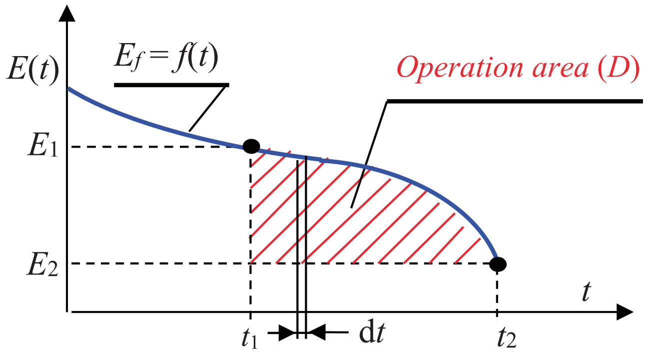

Fig. 1. Machine operation diagram: E – energy, E_1 – energy attributed to time t_1, E_2 – energy attributed to time t_2, t – time

When this energy is converted in the time interval $[t_1, t_2]$, the operation of the engine or machine can be interpreted in general terms as follows [15], [16], [33]:

$$D = \int_{t_1}^{t_2} E(t)\mathrm{d}t\,, \tag{5}$$

where $E(t) = f(t) - E_2$, D is the engine (machine) operation; E is the converted (obtained) energy that allows the realisation of the task in the time interval $[t_1, t_2]$, and t is the time of conversion of the energy E.

Therefore, if we assume that $E(t) = f(t) - E_2$, then formula (5) can be written as (Fig. 1)

$$D = \int_{t_1}^{t_2} f(t)\mathrm{d}t - E_2(t_2 - t_1)\,. \tag{6}$$

The use of formula (5) or formula (6) requires the geometric application of a definite integral, and the following inequalities must be taken into account during the integration:

$$E_1 \leq E \leq E_2.$$

The integral given by formula (6) is the Riemann definite integral [7], with the integration interval defined in this case as equal to $[t_1, t_2]$ and the integrand $E(t) = f(t) - E_2$. This function is integrable in the Riemann sense in the above time interval according to the following formula:

$$D = \int_{t_1}^{t_2} f(t)\mathrm{d}t - \int_{t_1}^{t_2} E_2\mathrm{d}t = D(t)\Big|_{t_1}^{t_2} - E_2(t_2 - t_1)\,. \tag{7}$$

Hence, if we can determine the functional relation between the energy (E) and time (t) that characterises the operation of an engine or machine, i.e. the function $E = f(t)$, and this function is continuous, for instance, in a given time interval $[t_1, t_2]$, then, according to the second fundamental theorem of calculus (Newton-Leibniz theorem), we can write

$$\int_{t_1}^{t_2} E(t)\mathrm{d}t = D(t_2) - D(t_1)\,. \tag{8}$$

The application of the Newton-Leibniz theorem is necessary here because it enables the effective calculation of a definite integral of any continuous function if an antiderivative of this function is known.

In general, the functional relationship $E = f(t)$ is not simple. It is also possible that the antiderivative of the integrand describing the relation between energy and time cannot be defined by elementary functions. In that case, calculating the definite integral using the Newton-Leibniz formula is troublesome, and sometimes even impossible. The trouble in this case is that determining the antiderivative requires difficult transformations to be performed. In these cases, similarly to the situation in which the integrand is given in a tabular form, an approximate value of the operation of an engine or machine can be determined as the value of the definite integral calculated using the trapezoidal rule or the Simpson method – the latter is considered more accurate.

Taking into consideration the randomness and unpredictability of events that exists in operating practice and, as a consequence, in the diagnostics of marine internal combustion engines and other ship power plant machines, their operation can also be considered in the way described above. However, in that case, the analysis and the resulting evaluation of machine operation should be presented using a probabilistic approach, making use of the theory of stochastic processes. A stochastic process is a random function with time as a parameter. This approach to the evaluation of the operation of marine engines and other ship power plant machines results from the need to obtain information on the machine operation in the time interval between two arbitrary moments, e.g. $[t_0, t_n]$, where time is the parameter of this process and not a random variable. In this case, to each time t within the given time interval $[t_0, t_n)]$, we can assign the state called the current state of the process, which is the random variable E_t; this variable has an expected value $E(E_t)$ and a variance $D^2(E_t)$ that depend on the current value of t. It is not just the energy (E) that can be the variable in these considerations; its conversion forms, i.e. work (L) or heat (Q), can also be variables. Therefore, the stochastic process is a set of random variables E_t for $t \in [t_0, t_n]$, i.e. for $t_0 \le t \le t_n$. It is worth mentioning here that the expected value $E(E_t)$ and variance $D^2(E_t)$ of the random function $\{E(t): t \in [t_0, t_n]\}$ depend on t, i.e. the values of $E(E_t)$ and $D^2(E_t)$ can be different for different t values. They are not random functions of $E(t)$, because $E(E_t)$ and $D^2(E_t)$ are not random variables, but they are constant for a given value of t and a given set of realisations of the random variable E_t [8], [10].

Examples of the dependence of $E[E(t)]$, $E[E(t)] + \sigma[E(t)]$, and $E[E(t)] - \sigma[E(t)]$ on the time t are shown in Fig. 2 [17]. In this figure, $\sigma[E(t)]$ is the standard deviation of the random variable E, which is calculated as the square root of the variance $D^2[E(t)]$.

Evaluating the expected value of $E(E_t)$ for each time t requires the use of statistical inference, which consists of the use of point or interval estimation.

It is known that the mean value $\overline{E}_t$ can be calculated from the following formula [8], [10]:

$$\overline{E}_t = \frac{1}{n}\sum_{i=1}^{n} E_{ti} \; . \tag{9}$$

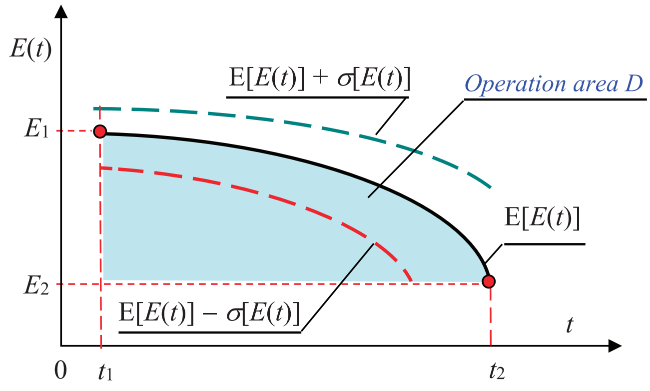

Fig. 2. Example of a stochastic process illustrating the relation E(t), where E is a random variable: E – energy, E_1 – energy assigned to time t_1, E_2 – energy assigned to time t_2, t – time as the process parameter, E[E(t)] – expected value of E, σ[E(t)] – standard deviation of E

The estimation of the expected value of $E(E_t)$, which consists of its evaluation in the form of the arithmetic mean $\overline{E}_t$, is a point estimation. However, this estimation method does not provide opportunities for evaluating the accuracy of the evaluation (estimation) of $E(E_t)$. Such an opportunity is provided by interval estimation, which provides the confidence interval [6], [8], [26].

The confidence interval of an unknown quantity $E(E_t)$ is defined as the interval (E_d, E_g) with random ends; it contains the unknown value of $E(E_t)$ with a predetermined probability β (the so-called confidence level) [8], [26].

It is well known that the average $\overline{E}_t$ calculated from formula (9) is the observed value of the statistic $\overline{E}_{st}$ with an asymptotically normal distribution $N\left(E(E_t), \frac{\sigma_t}{\sqrt{n}}\right)$, irrespective of the functional form of the random variable E_t [6]. The quantities $E(E_t)$ and σ_t represent, respectively, the expected (average) value and the standard (mean) deviation of the energy E, which is a random variable at time t.

If the value of σ_t, is known, then, making use of the distribution $N\left(E(E_t), \frac{\sigma_t}{\sqrt{n}}\right)$ of the statistic $\overline{E}_{st}$, we can calculate the confidence interval for an unknown expected value $E(E_t)$ from the following formula [8], [26]:

$$P\left\{\overline{E}_t - y_\alpha \frac{\sigma_t}{\sqrt{n}} \le E(E_t) \le \overline{E}_t + y_\alpha \frac{\sigma_t}{\sqrt{n}}\right\} = \beta \, , \tag{10}$$

where y_α is the standardised variable of the normal distribution corresponding to the confidence interval $\beta = 1 - \alpha$.

However, the value of σ_t is usually unknown and should be estimated based on the obtained results of tests from the following formula:

$$\sigma_t^* = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(E_{ti} - \overline{E}_t^{\,2}\right)} . \tag{11}$$

Then, assuming that the random variable E_t has a normal distribution $N(E(E_t), \sigma_t)$, we can make use of the fact that the random variable $\frac{\overline{E_t} - \mathrm{E}(E_t)}{\sigma_t^*}\sqrt{n-1}$ has the t-Student distribution with $k = n - 1$ degrees of freedom. The assumption about the normal distribution $\mathrm{N}(\mathrm{E}(E_t), \sigma_t)$ of the random variable E_t imposes no limitations in practice, as the statistic $\overline{E_{st}}$ always has an asymptotically normal distribution $\mathrm{N}\left(\mathrm{E}(E_t), \frac{\sigma_t}{\sqrt{n}}\right)$ and the convergence of this distribution to the normal distribution is very fast. This statistic can be used for values $n \geq 4$, i.e. always in practice [8].

Hence, the confidence interval can be calculated from the following formula [8], [26]:

$$P\left\{\overline{E_t} - t_{\alpha,n-1}\frac{\sigma_t^*}{\sqrt{n-1}} \leq \mathrm{E}(E_t) \leq \overline{E_t} + t_{\alpha,n-1}\frac{\sigma_t^*}{\sqrt{n-1}}\right\} = \beta, \tag{12}$$

where $t_{\alpha,n-1}$ is the coefficient of the t-Student distribution, the values of which are such that $P\{|t| \geq t_\alpha\} = \alpha$.

In the proposed evaluation approach, studying the operation of a marine internal combustion engine or other ship power plant machine (pump, compressor) as a diagnostic symptom of the technical state of this type of energy device requires the collection of relevant statistics, which will make it possible to determine the expected values of the energy converted in these devices and further to attribute these values to the individual times of operation of a given machine. Due to the quantum nature of the measurement resulting from the basic postulate of metrology, which is the assumption that the sensitivity threshold $2\varepsilon > 0$ [27], a sufficiently large number of diagnostic tests repeated over a relatively long period of time during the operation of engines or machines can deliver measurement results that will enable the description of the energy in the form of the realisation of the process $\{E(t): \geq 0\}$, which is discrete in states and continuous in time. When studying the accumulation of the dissipated energy E_r or a decrease in the useful energy E_u for a given engine or machine due to its wear, we can obtain the realisation of this process, which is similar to that shown in Fig. 3.

After collecting a sufficient number of such realisations (Fig. 3), we can calculate the characteristic parameters of the stochastic process describing the relation *E(t)* shown in Fig. 2.

Another option is to use the model of the changes in the operation of an internal combustion engine or other ship power plant machine in the form of a homogeneous Poisson process. This model enables the description of the decrease in the converted energy E in time t by an elementary portion (quantum) e, which can be recorded by a measuring device with a constant intensity $\lambda > 0$ (λ = idem).

Then, the course of the decrease in the energy E can be expressed as follows [2], [9], [15]–[17]:

$$E(t) = \begin{cases} E_{\max} & for \quad t = 0 \\ E_{\max} - e\lambda t \pm e\sqrt{\lambda t} & for \quad t > 0 \end{cases}. \tag{13}$$

A graphical interpretation of relation (13) is given in Fig. 4 for E_i (i = 1, …, 6). It shows that this process is discrete in states and continuous in time.

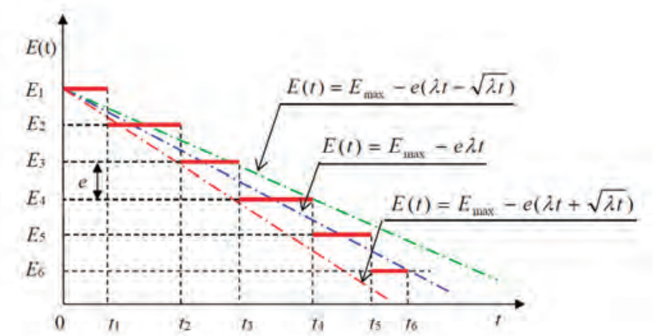

Fig. 4. Graphical interpretation of a sample realisation of the energy decrease of an engine or machine: E – energy, e – energy quantum by which the energy E is decreased, which can be recorded by a measuring device, λ – intensity of the appearance of quanta (e) by which the energy E is decreased, as recorded by the measuring device, t – time, $E_1 = E_{max}$, $E_6 = E_{min}$ [16], [17]

Another possible description of the decrease in the energy delivered by an engine or machine to the receiver, and the resulting worsening of its operation, can have the form of a semi-Markov process, applied as a model of the operation of

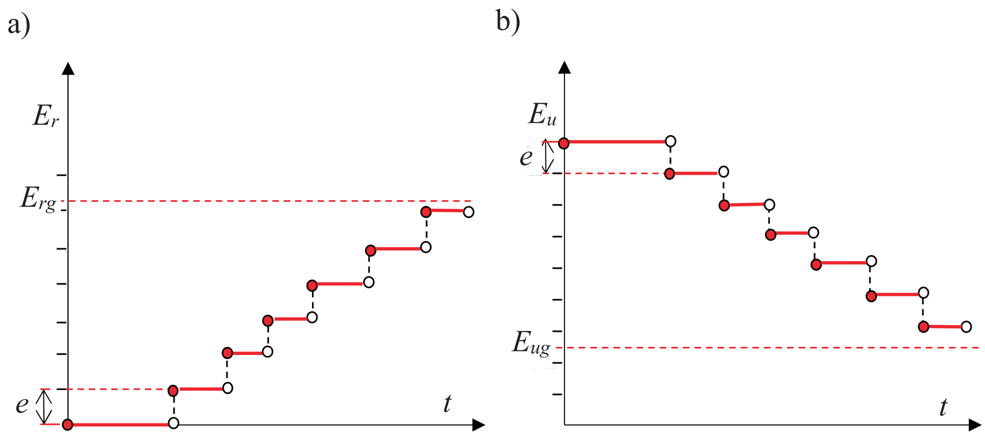

Fig. 3. Interpretation of a) the accumulation of dissipated energy E_r and b) the resulting decrease in the useful energy E_u of an internal combustion engine or other ship power plant machine: e – portion (quantum) of energy by which the energies E_r and E_u change, E_{rg} – dissipated energy limit, E_{ug} – useful energy limit [17]

this type of device [16]–[18].

SUMMARY – REMARKS AND CONCLUSIONS

The diagnostics of marine internal combustion engines and other ship power plant machines should take into account the randomness and unpredictability of the events that occur during their operation. Due to the operational practice of power devices of this type and quantum mechanics, when any empirical research is repeated, regardless of whether it is an observation or active experiment, we cannot expect the same results, but we can expect the same frequency of occurrence of an individual result. This means that obtaining a specific research result is a random event.

When performing diagnostic tests of marine internal combustion engines or other ship power plant machines, the principle of ambiguous causality should be taken into account, which means that there is a need to accept ambiguous determinism, i.e. the determinism resulting from the probabilistic laws of quantum mechanics, which accepts the existence of choice (as a known rule).

Taking into account the results of tests performed in the phase of operation of marine internal combustion engines or other ship power plant machines, a generalised diagnostic symptom has been proposed in the form of the operation of any of the above-mentioned energy devices, assuming that their energy values are becoming worse due to quantum energy dissipation.

The operation of an arbitrary marine internal combustion engine or other ship power plant machine is understood as the conversion of the energy E in a given amount of time t by these devices. This conversion process was compared to a physical quantity that can be expressed with a numerical value and a unit of measure called the *joule-second* [joule×second]. The operation understood in the above way becomes worse with time due to the increase in the wear of the engine or machine. This means that the value of this operation in a given amount of time will decrease due to the decrease in the energy generated by the engine or machine. A suggestion was made that in the case of the application of the theory of stochastic processes to analysing changes in the machine operation understood in the above way, integral calculus can be used to calculate machine operation parameters. A stochastic model of the decrease in the useful energy generated by the engine or machine in the form of a homogeneous Poisson process was proposed to describe the range of the worsening of the operation of the machine. A suggestion was also made to use for this purpose a model in the form of semi-Markov process, which is discrete in states and continuous in time.

When interpreted in the above way, the operation of an arbitrary marine internal propulsion engine or ship power plant machine depends on its technical state and is jointly characterised by the energy converted by this device and the time of its conversion.

In the version presented in this article, the operation of a marine internal propulsion engine or ship power plant machine can be examined by measuring the energy and the time of this energy's conversion; these results can then be presented

- as a number with a unit of measure called the *joule-second* (formulas (5)–(8));
- in a graphic form, as the area of operation (Figs. 1 and 2).

Despite the fact that it was formulated for marine internal propulsion engines and ship power plant machines, the interpretation of machine operation presented in this article can also be used to study the operation of other energy devices.

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