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THE CONCEPTION OF ENERGETIC INVESTIGATIONS OF THE MULTISYMPTOM FATIGUE OF THE SIMPLE MECHANICAL SYSTEMS' CONSTRUCTIONAL MATERIALS

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Abstract

The article presents the basic assumptions of the research project aimed, as the main scientific purpose, an identification of the slow-changeable energy processes surrounding the high-cycle fatigue of constructional materials within the plain mechanical system, especially the marine one, for diagnostic purposes. There is foreseen an application of alternative diagnostic methods based on energetic observations of the multi-symptom, continuous and irreversible alterations of the fatigue state within the material and construction of the elements transmitting the stream of mechanical energy from the propulsion engine to the propeller. Such methods will represent an essential supplement of already existing diagnosing systems of marine engines as well as marine propulsions. Only then an implementation of the condition based maintenance within the marine propulsion operation can be seen fit to approve.

Second part of the paper demonstrates the results of preliminary experimental investigations conducted on the Schenck fatigue machine. The machine has been especially adapted for the purposes of the planned energy research and equipped with measuring apparatus of vibration, acoustic emission and thermal emission.

Keywords: mechanical system, high-cycle fatigue, diagnostics.

1. Introduction

Within the period of intensive works engaged upon the improvement of reliability, durability and economy of marine combustion engines' action, a problem of the effective diagnostic methods gets the more and more larger meaning - especially, because last several years there was observed getting off the engines' planned maintenance operation instead of their operation according to the actual technical state (MAN Diesel&Turbo - „CoCoS-EDS - **Co**mputer **Co**ntrolled **S**urveillance - **E**ngine **D**iagnostic **S**ystem", Wärtsilä - „CBM - **C**ondition-**B**ased **M**aintenance", General Electric - „ICAS - **I**ntegrated **C**ondition **A**ssessment **S**ystem"). This is a desirable activity especially in case of the unforeseen damage inputs the large hazard degree. It also concerns fatigue damages within the engine's mechanical system and its driving line where possibilities of early recognizing the diagnostic symptoms are extremely limited because of the very little supervisory susceptibility.

Hence, despite hearing more and more often about implementation into operation system a so-called complex (defined in such a way with a decidedly excessive, exaggeratedly manner), multisymptom diagnostic systems of the marine engines they still involve the working spaces mainly or the fuel fed systems eventually. Furthermore, a key diagnostic problem concerning an evaluation of the fatigue state of the elements within the engine's mechanical system (and within the whole propulsion system) still remains unsolved. These elements being exposed to cyclic, changeable loads undergo fatigue failures (cracks) [Hebda and Wachal, 1999]. This kind of failure seems to be foreseeable which results from a clear interdependence between the failure formation's intensity and the engine's worktime. Additionally, a dispersion of the occurring failures is contained in the narrow time interval - Fig. 1. However numerous deviations from this rule occur. They result most often from the post technological lattice defects within the constructional material, and also, what happens more often, from the long-lasting usage of the ship's propulsion system in conditions of a stability loss within the mechanical system and consequently, the resonance vibrations [Cudny, 1976; Drganantchev, 2000; Korczewski and Rudnicki, 2012].

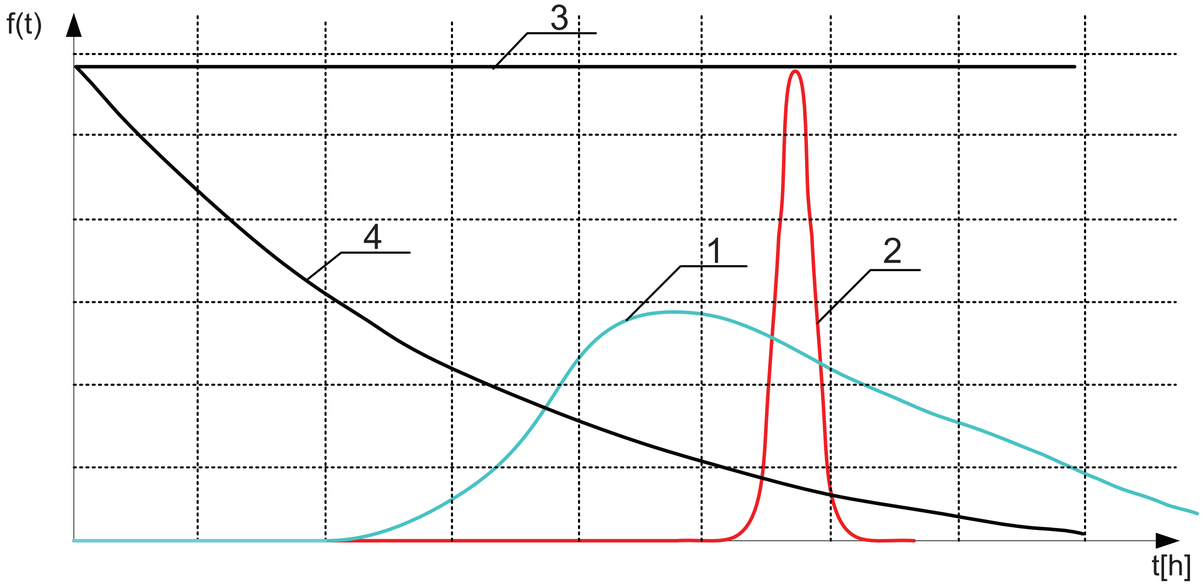


Fig. 1. Characteristic time courses of a probability density function of the worktime up to the failure for the marine combustion engines basic functional systems [Czajgucki, 1984].
1 – thermal-flow system (working spaces), 2 – mechanical system, 3 i 4 – control system.

Then, the occurring maximum amplitudes of changeable internal tensions cause a considerable limitation of the load alterations cycles' number, at which the elements transmitting a torque from the engine to the propeller undergo the accelerated fatigue wear and tear, up to the irreversible damages (cracks, deterioration of the constructional material's mechanical properties etc.) - Fig. 2. What is interesting, the fatigue state, in a sense of dislocations within the lattice, caused by amplitudes of the cyclically changeable tensions, is "memorized" by the constructional material and in spite of removal of the primary reasons extorting vibrations a spontaneous restoration of the primary mechanical properties does not follow. On the contrary, a fatigue weakening constructional structure becomes more sensitive to strenuous load alterations because the initial Wöhlera curve moves in the direction of more and more lower values of the transferred tensions as well as the smaller cycle number at which a fatigue cracks initiation follows, and so the smaller fatigue durability.

The problem of fatigue consequences of vibrations, as an energy "microdynamic" phenomena (quickchangeable), occurring within the material microstructure related to one cycle of the changeable load, has been represented in numerous publications within the range of the Materials' Strength for many years now [Kocańda and Szala, 1997; Kaleta, 1998; Boroński and Szala, 2008; Maciejewski et al., 2003]. However, there is still noticeable the lack of bibliographic positions presenting this issue in an aspect of identification of the "macrodynamic" processes (slowchangeable), describing the material behavior in a macroscopic scale, during a continuous, transient flow of the mechanical energy flux (along with the energy's dissipation and accumulation) from the engine to the propeller.

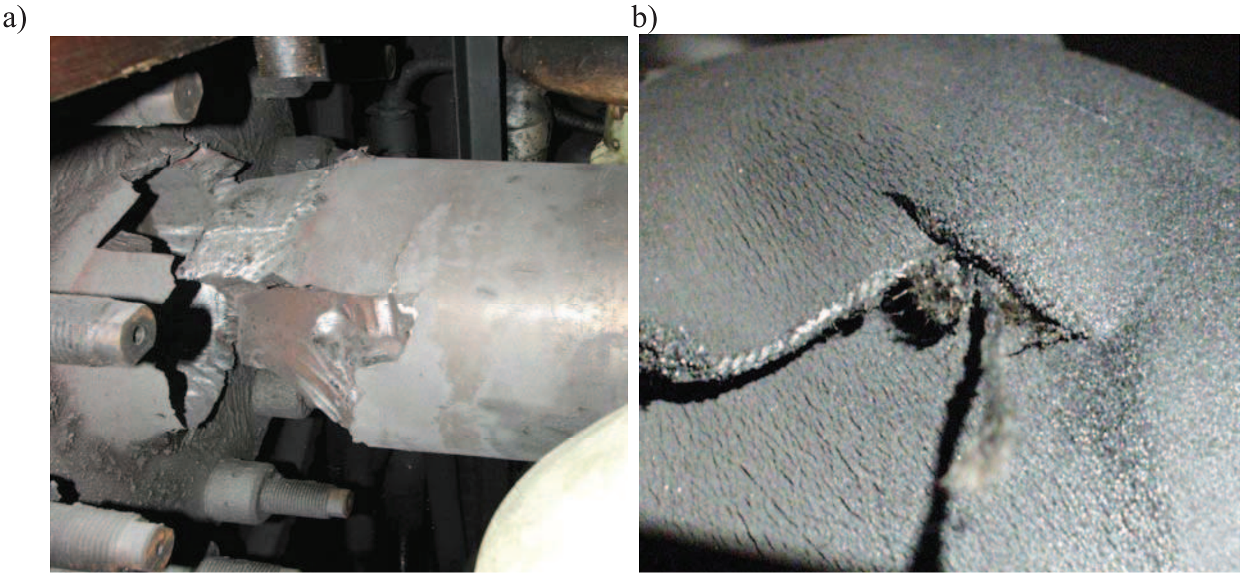


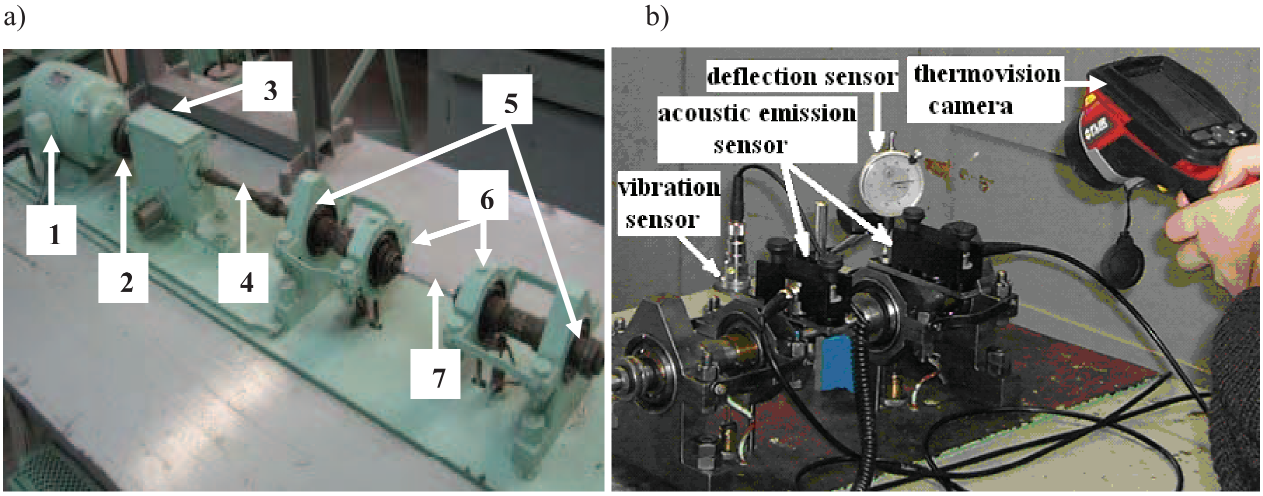
Fig. 2. Fatigue failures of the shaftings' elements within the marine propulsion unit:
a) broken propeller shaft of the marine propulsion unit as a consequence of the structural material's high-cycle fatigue (mechanical), b) rubber flexible element of the Vulkan RATO coupling along with fatigue wear traces [Korczewski, 2008].

In an ideal marine propulsion unit the whole energy delivered to the propulsion engine is transformed into the effective, basic rotational motion of the propulsive line's mechanical system. As the result of the progressive technical state degradation of the line's constructional elements accompanying motions are generated additionally. They are undesirable from the efficiency viewpoint of energy transformation and transmission processes within the whole propulsion unit. Moreover they represent a reason for the kinetic energy's dissipation of the masses within the rotational motion as well as the internal energy's accumulation within the constructional materials. After crossing the critical values of these energies the fatigue damage follows. Its course is characterized with residual energy processes: vibroacoustic and thermal that induce the observable diagnostic symptoms of technical state alterations.

Therefore, how to estimate quantitatively a current fatigue state of the constructional material of elements transmitting a torque within a simple mechanical unit of the marine propulsion system in operation condition? More and more perfect measuring apparatus unlocks completely new horizons in this regard. Its application in diagnostic investigations enables the user to observe precisely the course of residual energy processes within the mechanical unit. It aims to evaluate the measures' patterns (estimators) of diagnostic signals (vibration, acoustic and radiant emission) for the given high-cycle fatigue of the constructional elements' material. Consequently, this is also possible to evaluate a diagnostic inference method about the technical state of the simple mechanical units within the marine propulsion systems, and not only, in their operation conditions. This is the main aim which shone the Author of the present article during planning the investigative project.

2. Research test stand

In the first stage of diagnostic investigations of the real marine propulsion mechanical arrangements at high-cycle fatigue conditions it was necessary to built, in a certain scale, a physical model of the simplified mechanical system. The model preserving essential dynamic features of the real object enables an observation of the realized energy processes' course. There were good reasons for the decision to apply Schenck fatigue machine to this aim. The Schenck machine is mainly designed to evaluate the fatigue boundary of the constructional materials at the double-sided bending - Fig. 3a. During the standard fatigue test a standardized sample of the constructional material is subject to the clear bending-torsion moment of the constant value, on its whole length. It means, that the same fatigue stress exists in its every section. In this way, by relating the conditions of the laboratory fatigue test to the real running conditions of the marine propulsion unit shafts misalignment or deflection might be simulated. Such undesirable malfunctions take the effect on the growing trust forces in bearings and therefore a growth of the mechanical losses moment for overcoming friction forces within the mechanical system takes place. The alterations of the driveline's rotational speed represent an observable result of the unestablished balance of the system's mechanical energy. Transverse vibrations generated in the bearing nodes, acoustic emission of disappearing springy waves as well as thermal emission (infra-red radiation) of the system's elements accumulating the internal energy, increasing as a result of the work executed over the system stand for the additional consequences of the sample's enforced springy and plastic deformations. A manner of the measuring apparatus sensors' assembly on the test stand is shown in Fig. 3b.



Rys. 3. Schenck fatigue-testing machine designed to exam a fatigue boundary of the constructional materials at the double-sided bending
1 – propulsion engine (shunt direct-current motor), 2 – silent-block flexible disk coupling (pins along with rubber pads), 3 – rev-counter worm gear (transmission ratio 1:100), 4 – spring-actuated flexible coupling, 5 – immovable rolling bearing (ball bearing), 6 – self-aligning rolling bearing (ball bearing), 7 – sample under investigation.

During a fatigue test completion there are registered diagnostic signals reflecting energy consequences of the progressive degradation process of the sample's structure material which is subject to rotatory bending, in successive stages of the fatigue process: from an appearing the first slips in grains, across an initiation and development of the mikro- and macro-cracks, until to the total fatigue destruction. A flow of energy streams within of the considered mechanical system illustrates Fig. 4.

After starting-up a propulsion engine and getting-out the mechanical system from the standstill to the settled rotational speed 2000 rev/min the sample's loading with the bending moment follows. The sample's cyclic sinusoidal load induces cyclic fatigue deformations and stresses in it. An initial growth and subsequent fall of the system's rotational speed, as a measure of appropriate alterations of the accumulated kinetic energy of the masses in rotatory motion, represents, among other things, their observable diagnostic symptoms - Fig. 5.

An initial growth of the system's rotational speed might be explained with the transitional, intensive reinforcement of the sample's material structure in the result of slips' incubation in some grains of the lattice that are unfavorably-oriented in relation to the load direction. Then an equally intensive decrease of the sample's deflection might be observed. In the next phases of the process a thereinafter, moderated reinforcement of the sample's material follows. It results from the plastic deformations extorting the evolution of the lattice's defects along with the mutual blocking dislocations that are moving in different, intersecting slips' planes. Then the sample's deflection is also equally moderate. A continuous growth of temperature and trust forces in bearings causes the anti-torque's growth in the mechanical unit's rotational motion, i.e. the propulsion engine's load torque (shunt direct-current motor).

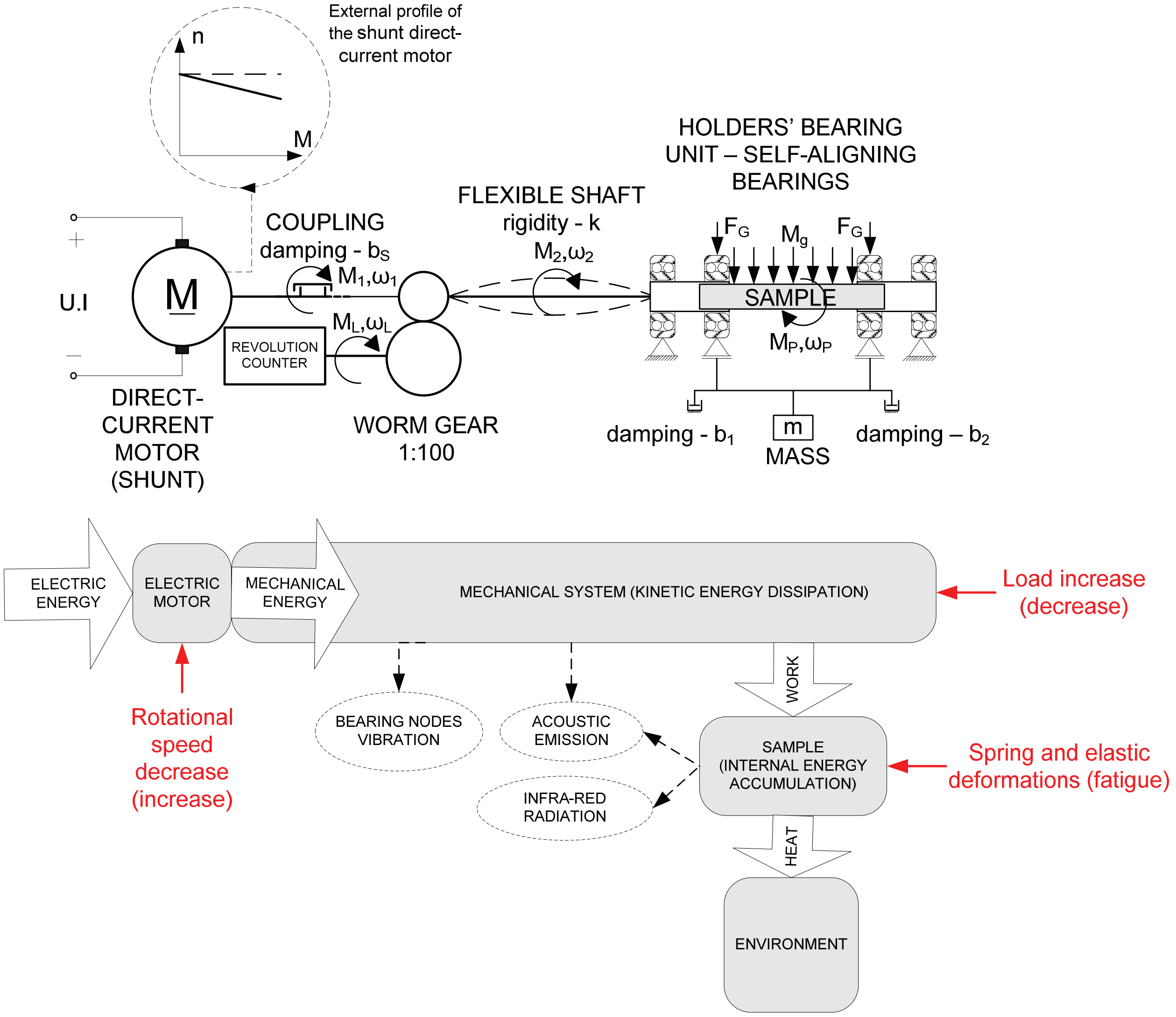


Fig. 4. Mechanical system of the Schenck fatigue-testing machine along with a flow of energy streams

According to the right of angular momentum alterations for the considered propulsion unit a kinetic energy dissipation in its mechanical system and decrease in rotational speed follows. In case of a shunt direct-current motor for the reduced rotational speed, at unchanged magnetical stream, responds the smaller counter-electromotive force which counteracts against the voltage. In such a situation the larger current flows through the engine's armature enlarging a turning moment generated in the engine. The unsteady process will be lasted till the balance between breaking torque from the mechanical system (moment of mechanical losses) and the engine's propulsion torque. Considering this process in an aspect of electric energy transformation into mechanical one what is worked out in the propulsion engine it goes without saying that the more is the load torque the more is the current's amount consumed by the propulsion engine from the electric net (the larger feed electric energy stream to the engine).

An alteration of the temperature field in a deformed material as well as the permanent growth the sample's averaged temperature stands for the thermal consequence of the mechanical fatigue. Observable distribution temperature alterations on the sample's surface (learning on the infra-red radiation detection) represent, on a macroscopic level, the adequate diagnostic symptom of microscopic phenomena setting within the material's crystalline structure. The phenomena are mainly associated with the dislocations' movement as well as their interaction (an influence of the point defects is negligible small) [Boroński and Szala, 2008]. According to the first law of thermodynamics an alteration of the internal energy amount that is accumulated during the fatigue test realization is calculated as a sum of the heat flux emitted to surroundings and the power needed on the sample's material deformation handiwork. Taking into considerations energy hypotheses of the fatigue damages, presented in publications of scientific teams directed by S. Kocańda and J. Szala as well as J. Kaleta a constructional element undergoes the fatigue destruction, when a total internal energy accumulated in its material reaches the critical value [Kocańda and Szala, 1997; Kaleta, 1998].

A measurement and analysis of the vibration generated by the mechanical system's bearing nodes stands for the particularly complex metrological aspect of the high-cycle fatigue process's energy consequences in the conditions of growing lattice's defects of the material sample. This is also very complex to investigate impulses of disappearing springy waves of the acoustic emission that are locally freed, from the intermolecular bonds' energy release. What, in turn, is caused by the lattice's deformations and its defects' displacements (pointwise and linear). Then, the root-mean-square value (rms value) of the registered amplitude spectrum constitutes the basic diagnostic parameter, as a measure of dissipated kinetic energy of the mechanical system in rotational motion devoted to the vibration and acoustic emission enforcing. Within L. Rogera publications presenting the comparative analyses of both the methods in an aspect of the fatigue cracks identification of the rolling bearings you can find unequivocal conclusions confirming a decidedly larger efficiency of observation of the acoustic emission phenomenon, which is more tender and unambiguous in the material defects evaluation [Roger, 1979 and 2001].

Because of the continuous alterations of the lattice structure as well as temperatures of the getting warm material sample follow the suitable alterations of the natural vibration frequency follow. This frequency gets smaller along with the sample temperature, as a result of the material stiffness's decrease (a value of the material's longitudinal modulus of elasticity gets smaller). It results, from the conducted calculations, that in a range of the material temperature's changeability of the sample and bearing nodes, the natural vibration frequencies change in the range of a dozen or so, or even tens percentage during realization of the accelerated fatigue test. It can lead to the considerable "wander" of resonance frequencies. Hence, a frequency analysis of the registered amplitude spectrum does not bring in essential diagnostic information.

The representative time courses of the observed control parameters registered during the pilot fatigue test execution on the Schenck test stand were introduced in Fig. 5.

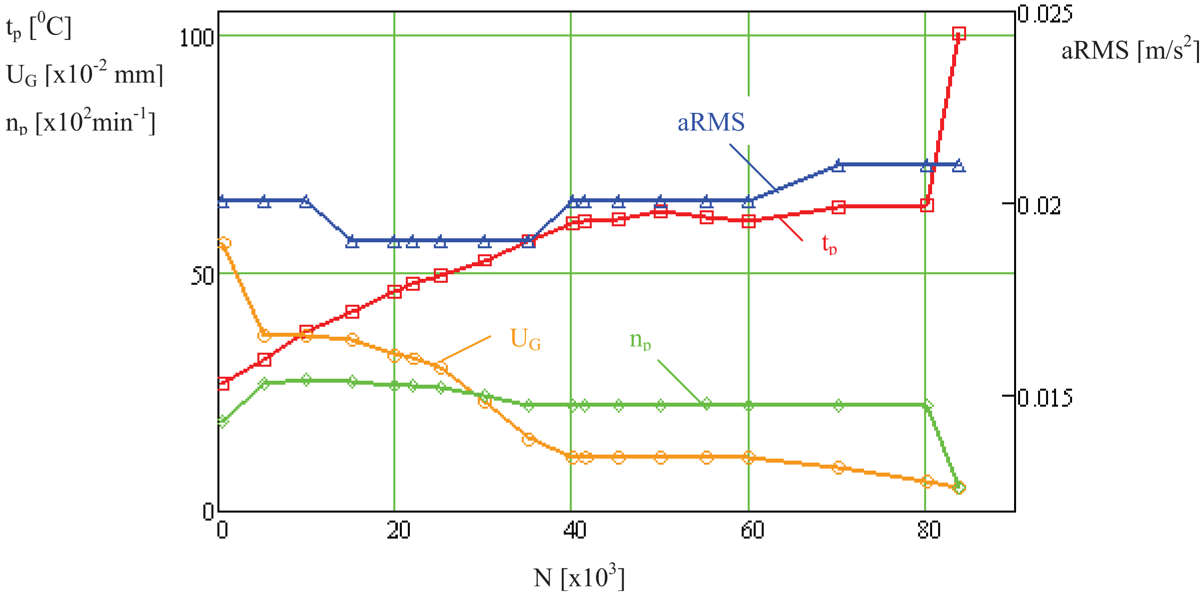


Fig. 5. Time courses of the observed control parameters registered during the pilot fatigue test execution on the stainless-steel sample (unalloyed, fine-grained, weldable steel of S355N type)
t_p – sample's temperature, n_p – sample's rotational speed, U_G – sample's deflection, a – vibration acceleration, aRMS – root-mean-square value of the vibration acceleration, N – cycle number.

3. Physical model of energy processes

A creation of the adequate mathematical model represents one of key execution conditions for a quantitative evaluation of the energy consequences of the sample constructional material's high-cycle fatigue making up the mechanical system's element. Only a set of the differential non - linear equations of partial derivatives delivers the precise movement description of such a system [Cannon, 1973; Cichy, 2001]. The influences of accidental factors were omitted within the elementary, necessitating approach to the issue of modelling processes. Moreover, the physical model of analysed energy processes, possessing the essential dynamic features characterizing an energy streams' flow in unsteady states, was maximally simplified (idealized). Assuming, that the state parameters of dynamic processes change only in relation to the time and that they do not alter their values in relation to the position, the simplest, zero-dimensional model (of the concentrated parameters) was accepted in the initial stage of investigations. It was adjusted, that the zero-dimensional model fulfils the assumed particularity requirements of the real object functioning's mathematical description (a fatigue machine of the Schenck product), for the established modelling purposes - a creation of the diagnostic simulation model of the plain mechanical system. It was additionally adjusted, that a period of the neck creation in the sample, while the spatial stresses state begins affecting, will be neglected.

With regard to the extensiveness and complexity of the energy processes mathematical modelling of the considered mechanical system in unsteady states, the worked out physical model was limited only to the simplified flow of input and output signals among dynamic modules during the fatigue test realization - Fig. 6. Such a model stands for an introduction to the further, wider issue analysis.

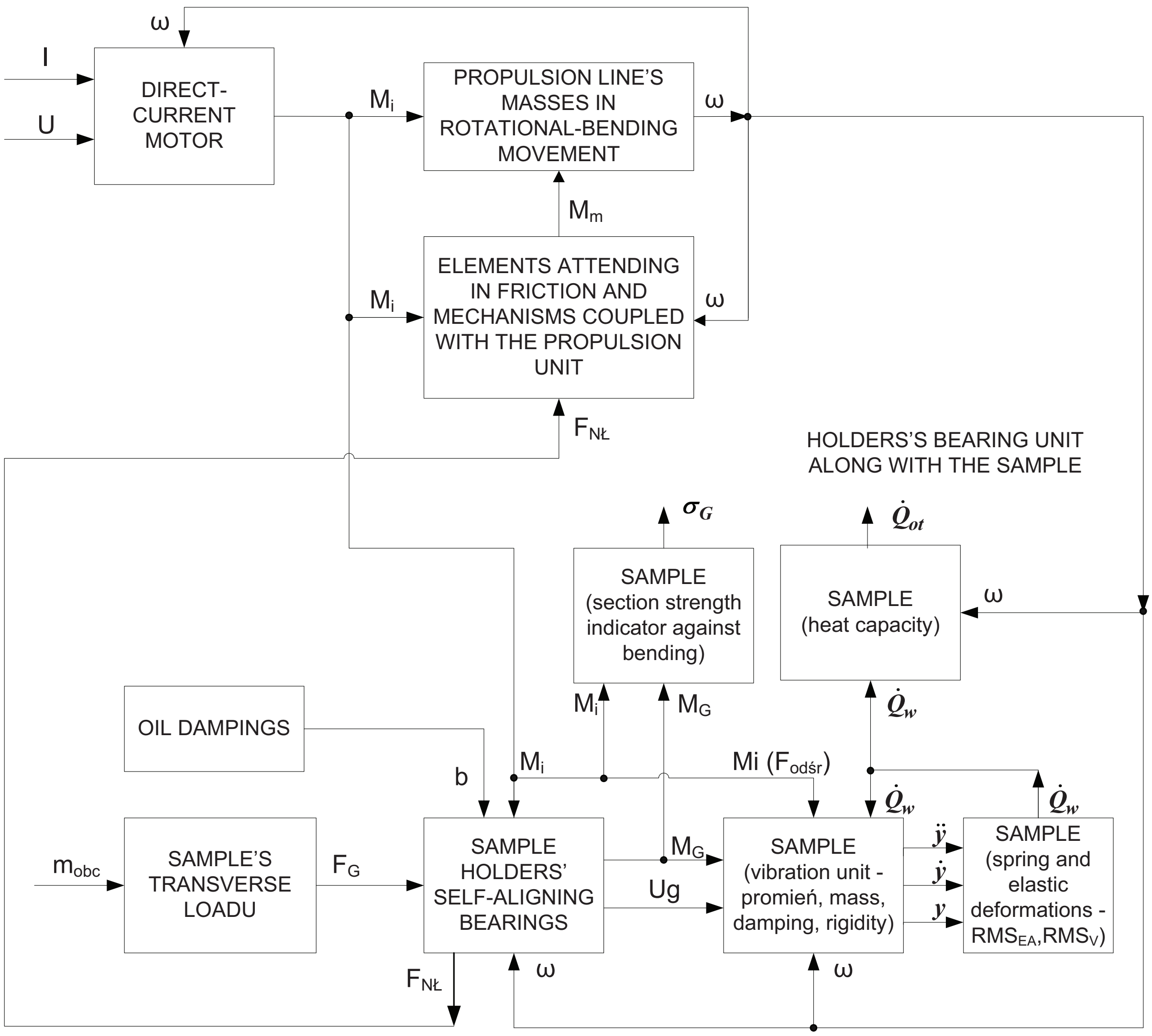


Fig. 6. Physical model of the energy processes worked out within the mechanical system of the Schenck fatigue machine

b – damping coefficient, F_G – loading force, $F_{odśr}$ – centrifugal force, $F_{NŁ}$ – trust forces in bearings, I, U – respectively: current intensity and voltage, k – rigidity coefficient, m_{obc} – loading mass, M_i – driving torque developed on the engine shaft, M_m – torque of the mechanical losses, M_G – bending moment, Ug – deflection, ω – angular speed, σ_G – amplitude of the changeable deflection stresses, $\dot{Q}_w, \dot{Q}_{ot}$ - heat flux, respectively: released and convected to external environment, $y, \dot{y}, \ddot{y}$ - respectively: vibration displacement velocity and acceleration.

In the next modelling stage one should to execute a classification of the distinguished dynamic modules on inertial and inertialess ones as well as to accept assumptions simplifying equations of the process's state. Time constants of the energy processes worked out during the system's unsteady working states will constitute the basis of the conducted considerations, with special regard of masses' inertia in a rotational movement (kinetic energy accumulation and dissipation) as well as transportation inertia of the released heat from the studied material sample (internal energy accumulation).

4. Conclusions and final remarks

The conception introduced within this scientific study concerns a diagnostic application of the energy investigations of the slow-changeable unsteady processes that go with the high-cycle fatigue of materials and constructions of the plain mechanical systems. It represents for an introduction to elaborate a diagnostic method of their technical state evaluation in real operating conditions. There is foreseen, that the method will supplement a lacking link of the existing diagnosing systems of the marine engines and propulsions.

The presented physical model of the energy processes worked out within the Schenck fatigue machine stands for an initial stage of these processes' mathematical modeling for the qualitative and quantitative identification of the developing fatigue defects' impact on time courses of the observed unsteady process's state variables.

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