

## PHYSICAL MODEL OF ENERGY-RELATED PROCESSES IN A ROTATING MECHANICAL SYSTEM FOR THE PURPOSES OF DIAGNOSIS OF TRANSMISSION SHAFTS

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### Abstract

*In the present article, selected problems connected with identification of slowly changing energy-related processes accompanying high cyclic fatigue of construction materials of simple mechanical systems, with special consideration of transmission shafts, are mentioned for diagnostic purposes. The article also presents physical models of object and processes that in a simplified way reflect mechanical energy transmission from transmission engine to ship propeller.*

**Keywords:** *modelling of energy-related processes, rotating mechanical system, transmission shaft, technical diagnostics, acoustic emission*

### 1. Introduction

Main danger for reliability and durability of rotating motive unit is the loss of stability of its mechanical system. It means that operation of such system is accompanied with a resonance phenomena<sup>1</sup>, in which amplitudes of transverse oscillations (flexural), longitudinal or torsion ones reach very high values. Increased, cyclic elastic distortions of construction material of elements correspond with equally high amplitudes of periodically changing inner stress. These are the reason for the mechanical fatigue, whose boundary states are described by fatigue graphs „stress- cycle number”, so called Wöhler's graphs<sup>2</sup> – pic. 1. They illustrate mutual fatigue dependance from corresponding strength of construction material, which is usually reflected by the number of fatigue cycles, but also number of rotations, number of hours of operation, process, evolutions performed etc. After exceeding

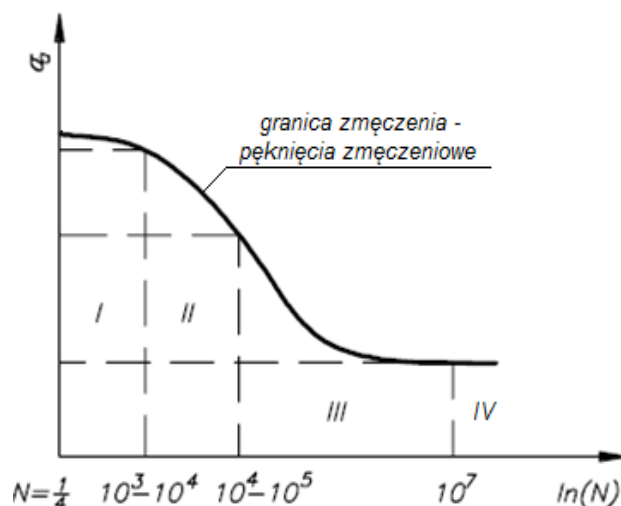
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<sup>1</sup> Mechanical resonance phenomenon is observed when frequency of oscillations of the system or any random construction element of the system is equal or is a multiple of frequency of periodically changing forces and moments forcing the oscillations (global or local resonance).

<sup>2</sup> Named in such a way since 1936 in honour of a prominent German railway engineer August Wöhler (1819-1914), who was doing research on the phenomenon of fatigue of axles of carriages wheels and in 1870 formulated so called Wöhler's law: “Material can be subjected to a damage as a result of cyclic changes of stress, with each of them being lower than static durability. Stress' amplitude has a crucial impact on the damage of the integrity of the material. Maximum stress result in such a way that the higher its value the lower the stress amplitude conducting to a fatigue damage”.

the boundary number of cycles  $N$ , for which fatigue strength was defined with amplitude of cycle of variable stresses  $\sigma_a$ , initiation of a structural fracture occurs.

Additional consequence of the loss of stability of rotating mechanical system is the increase of the amount of dispersed kinetic energy to force the oscillations.



Pic. 1. Complete<sup>3</sup> Wöhler's graph with identified range of a fatigue durability [Kocańda & Szala, 1985]: I - quasi-static; II - low-cycle; III - high-cycle; IV - unlimited fatigue durability

Exploitation experience of various types of rotating transmission units reveal that irrespective of the field of its applying and usage, the primary reasons of deterioration of dynamic state of a mechanical system, which result in excessive increase of flexural<sup>4</sup> oscillations amplitude, usually belong to following factors:

- wear or ageing of construction material of foundation of elements transmitting rotational moment (corrosion of steel washers, ageing of rubber dampers and washers made of chemohardenable material, especially with the influence of high temperatures, as well as chemically active products f.i. lubricating or propulsive oil),
- wear or ageing of construction material of elastic coupling or elastic bond between transmission lines and auxiliary installations,
- subsidence of carrying construction of the foundation, as a result of static strain or impact load (f.i. during landing of the airbus as well as during the collision, running a ship aground, colliding the shore or any other obstruction of a ship),
- permanent deformations of means of transport frame, inside of which transmission system had been built-up (f.i. the hull, as a result of weakening of its construction structure),
- static distortion of transmission shafts as a consequence of prolonged usage downtime,

<sup>3</sup> On the complete Wöhler's graph, start of the coordinate system corresponds to  $\frac{1}{4}$  of a cycle, assuming that the damaging stress for this part of the cycle is equal to durability at static stress.

<sup>4</sup> Excluding the constraints of transmission engine and operating machine. However, in practical exploitation the measurements of torsion oscillations are made on transmission units with pistone engine and only if they are specially adjusted for this purpose. Low control susceptibility of serial parts in this area considerably lowers the credibility of obtained measurements' results. In contrast, the measurements of longitudinal oscillations are made mainly on ship units with screw propeller, where main sources of constraints are periodically changing pressure of a screw propeller, flexural oscillations of a hull and periodically changing gas and mass forces of transmission engine, which acting on the crankshaft's bearings are contributing to the deformation of cranks and the movement of bearings along the axle of the crankshaft.

- contamination, losses of a material (unwelding) as a result of tribological use, corrosion or erosion of rotating elements, which results in uneven distribution of masses in rotary motion of the system.

Their consequences are usually the following states of exploitation incapability of rotating transmission unit:

- loss of concentricity or flexure of the cranks lines,
- dislocations of centres of gravity of rotating elements on the transmission line regarding the lines of its rotary motion (statically or dynamically unbalanced centrifugal force).

In both cases, there is increase in strain in bearings, couplings and cogged bonds in the unit, which contributes to tribological wear as well as assembly backlashes. Their observable symptom is the increase in flexural oscillations amplitude, generated in specific construction centres of a mechanical system, with all the above mentioned fatigue effects.

Analysis of fatigue damages in rotating mechanical units of a complex construction revealed that almost 50% of a general number was caused by wrong location of operating machines, which resulted in flexure or dislocation or cranks lines axles [3]. Most vulnerable construction element in such cases are crank shafts, whose fatigue flexures usually contribute to immobilization of the entire transmission unit. Moreover, fatigue state in case of dislocation of crystalline structure caused by amplitude of cyclically changing stresses, is „remembered” by the construction material of the crankshafts and despite the facts that the original reasons for oscillations constraints are eliminated (by f.i. setting the axles of the cranks lines), still there is no spontaneous restoration of its durability properties. Fatigue state of crankshafts is also reflected by the balance of energy transformed by the rotating mechanical unit. It is thus possible to observe the degradation (evolution) of their microstructure, based on the variables of state of energy-related processes in the entire system, which are directly measurable diagnostic symptoms of cranshafts fatigue during usage (during movement).

## 2. Current research status

Energy-related processes realised in rotating mechanical systems are the subject of scientific research in numerous national and international research facilities dealing with exploitative diagnostics of combustion transmission systems applied in: energy sector, ship building industry and air transportation [5]. Special attention in the conducted research is put to analysis of the process of mechanical energy transmission in the system subjected to slow degradation of construction elements of main subassemblies. Prof. Czesław Cempel from Poznan University of Technology is renowned for his achievements in this area [11], for conducting research on vibro-acoustics of machines and bringing up a question of fatigue durability of crucial machine elements with applying energy-related methods and for formulating the energy processor model. Elaboration of energy-related theories was the research of prof. Henryk Kaźmierczak, who in empirical way confirmed the validity of energy-related methods in the description of the process of material fatigue. However, still there is lack of studies approaching a question of material fatigue and slow changing processes for transmission shafts subjected to loss of concentricity.



### 3. The issue of modelling of energy - related processes

Identification of energy-related processes realised in rotating mechanical system for diagnostics purposes requires elaboration of physical model of these processes. It means that according to the rules of operation theory, graphical division of considered technical object into functional modules, crucial from the analysed processes point of view, as well as establishing the possible coupling between them with the use of the signals' flow scheme. Each functional module should be considered as a dynamic element of specific quality features (proportional, inertial, integrating etc.), regarding the dynamics of realised energy-related processes and to set the input and output signals. To identify dynamic features of these elements, in the meaning of quantity, it is necessary to determine mathematical relations between input and output signals, as well as to define the set of variables of processes' state. Such activity is called mathematical modelling of processes. It starts with elaborating the mathematical model of processes for particular dynamic elements, and then for the entire mechanical system.

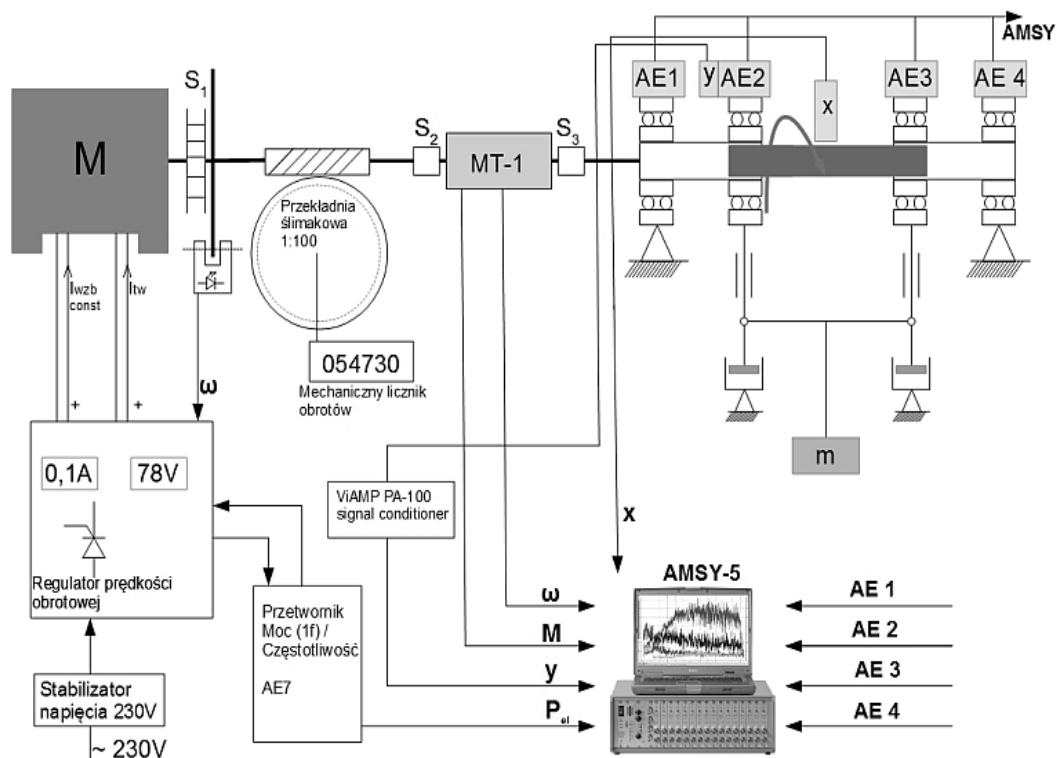
According to the theory of mathematical modelling and methods of planning of experimental research presented for example in the publications [1,9,10], two ways of operation are possible:

1. Starting with theoretical basis of modelling process, assuming specific simplistic assumptions, we formulate the equations linking the input and output signals (so called balance equations), applying basic laws of physics (f.i. the principle of conservation). Elaborated mathematical model should be then verified by tests with comparing adequate results of conducted numerical simulation of processes with results of the same processes run on the real object, after introducing the same constraints. In such a way its adequacy is determined;
2. First, the research on the real object is conducted, based on experiment planned in details. The flow of output signals with specified changes (precisely planned) of input signals are determined. Based on the analysis of regression of both signals, the mathematical relations between them are defined, and subjected to verification, according to the theory of testing of parametric statistical assumptions.

#### 3.1. Physical model of research object

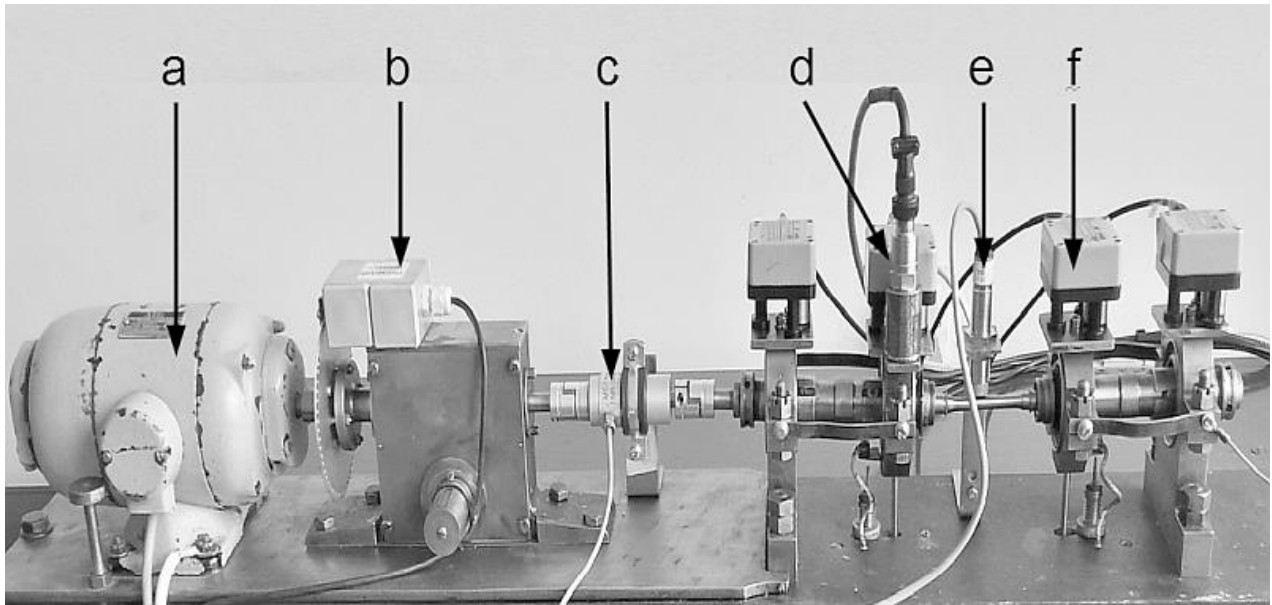
In order to model the real conditions of ship transmission system, it was necessary to build a simplified physical model in specific scale, in which crucial construction and functional features of real object are maintained. For this purpose a sustaining machine of SCHENCK company was applied, originally designed to conduct research on determination of construction material fatigue threshold with two-sided bending-pic.2. Characteristic feature is the lack of power reception at the end of the transmission line. Main advantage of the machine is even stress on the sample with pure torsion-bending momentum, what can reflect the operation of transmission shaft in the conditions of loss of concentricity of cranks lines. Similarly, in the fullsize transmission system, rotational velocity of Schenck's is being stabilized - by supplying the electric motor with thyristor controller. During the operation of the physical model the following measurement signals are noted: rotational velocity and rotational momentum at the measurement point, oscillations and acoustic emission acceleration (generated from bearings centre), bending of the transmission crankshaft, voltage and current intensity of motor engine, thermograms of bearings centres together with transmission crankshaft. Measurement of mechanical losses in the analysed physical model was realised with electronic torque meter MT-1, with measuring scope of  $\pm 1\text{Nm}$ . In this device, a tensometric measurement of momentum on the torsion crank with digital transmission of data from the susceptible element to the stator via contactless electromagnetic feedback was used. Simultaneously, the measurement of

rotational velocity is being conducted. Temperature measurement is conducted with the use of thermal imaging camera NEC Thermo Gear G30, together with an adapter triggering the shutter, enabling the regular and repeatable registration of thermograms. The time of thermogram realization is registered by AMSY-5 in the form of time indicator. Bending of the transmission crank is measured with inductive displacement sensor of type IGA 005GU, with detection range of 0-5mm. The bending is registered in the form of proportional voltage signal. To measure the acceleration of oscillations, a piezoelectric accelerometer was applied of type ICP601A01, together with conditioner PA1000.



*Pic. 2. Physical model of rotating transmission system: M – electric motor 0,25kW; MT-1 – momentum meter; AE1-AE4 – active sensors of acoustic emission; y – accelerometer ; x – bending sensor; S<sub>1</sub>-S<sub>3</sub> – flexible coupling*

Acquisition of measurement signals is realised with the use of AMSY-5 recorder. Its main advantage is the possibility of simultaneous registration of all the analysed physical values, which are characterised by energy-related state of rotating transmission system, apart from acoustic emission (sensors AE 1- 4). Arrangement of sensors and system's shaft line on a laboratory stand are shown in pic.4 .



*Pic. 4. View of the shaft line in a laboratory stand: a – electric motor DC 0,25kW; c – MT-1 torque meter; d – accelerometer; e – bending sensor; f – acoustic emission sensor*

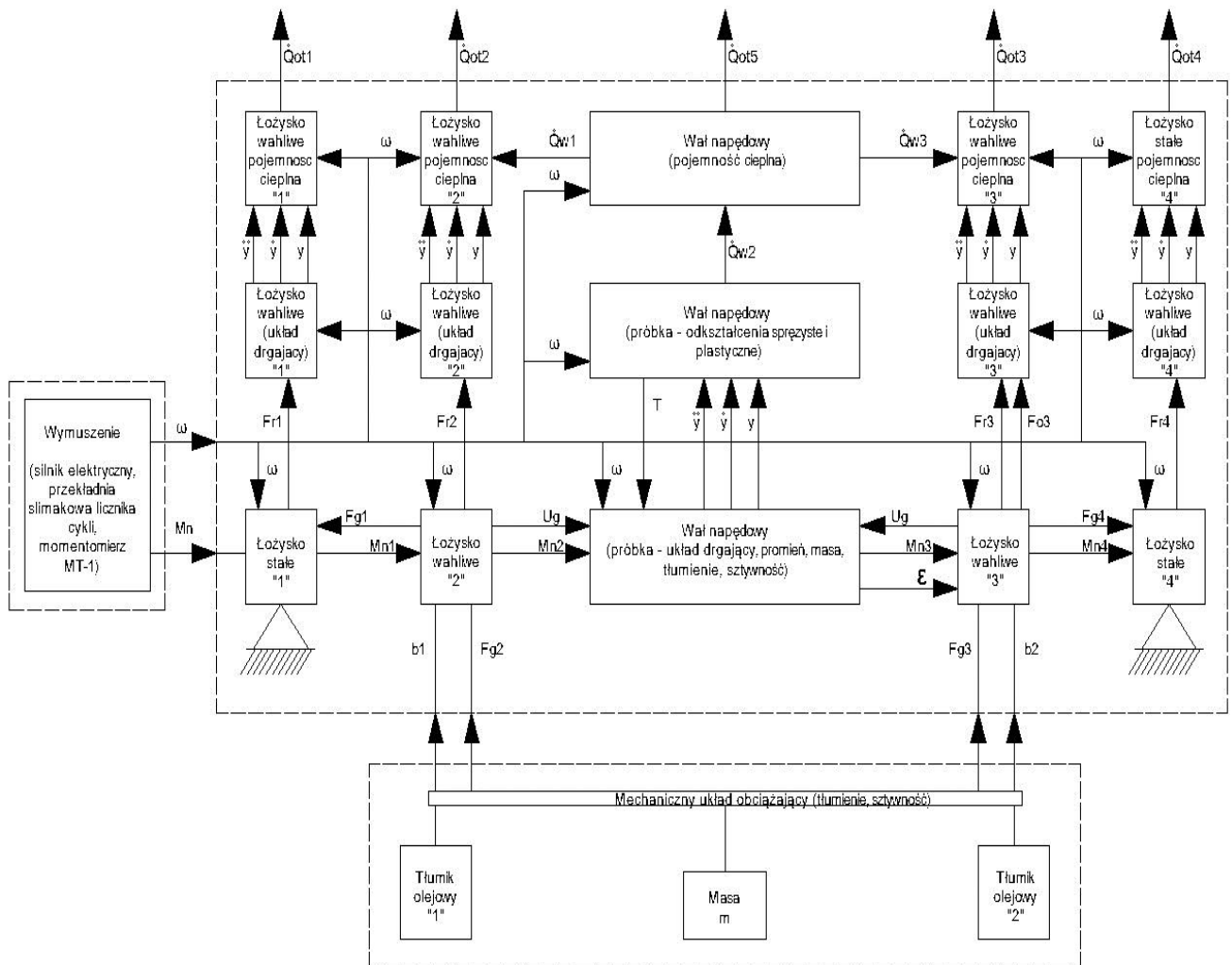
### 3.2. Physical model of realised processes

As it was underlined in the introduction of the following article, most significant condition to conduct the quantitative evaluation of energy-related consequences of fatigue of transmission crankshaft in the rotating mechanical system is to build the adequate mathematical model of realised physical processes. In the first stage of building of such model, it is necessary to elaborate the physical model of the process, proposition of which is presented in the pic. 5. Such model in a simplified way reflects the flow of energy streams from the engine to bearings centres and transmission crankshaft (the sample), as well as the energy dispersed in the system in the form of infrared radiation, mechanical oscillations and declining elastic waves (acoustic emission). Energy stream from the power source is transformed only into dissipated energy. This part of the energy, which is internally dissipated, being accumulated and is contributing to destruction of the machine - in this case break of the sample.

Original reason for dissipation of energy in the considered mechanical system is the loss of concentricity of transmission line, what results in oscillations, increased friction in the bearings, as well as deformations of crystalline lattice of transmission crankshaft.

In the proposed physical model of considered transmission and transformation of energy processes, numerous simplistic assumptions are taken into account, which enable to formulate balance equations of mathematical model:

- all the elements of rotating system are made of identical and homogenous linear and elastic material;
- the influence of bearings centres is not having an impact on the moment of inertia of the system;
- specific heat of transmission crankshaft is constant;
- the mass of sensors located on the bearings' covers are not taken into account;
- stresses in the entire cross section of the fatigue sample are identical.



Pic. 5. Physical model of energy-related processes realised in the considered physical model:  $b$  – suppression coefficient,  $Fr$  – radial forces,  $Fg$  – load forces,  $Fo$  – axial forces,  $\omega$  – angular velocity,  $Mn$  – momentum,  $Ug$  – bending of the sample,  $m$  – load mass,  $y$  – acceleration, velocity and dislocation of oscillations;  $Q$  – heat stream emitted to the surroundings

#### 4. FINAL REMARKS AND CONCLUSIONS

The concept of physical model of rotating transmission system, which is presented in the article, is the base for the balancing of energy-related processes. It gives the possibility to formulate the equations of mathematical model and to conduct the experiments of numerical simulation of considered processes in the condition of the loss of concentricity of the line of transmission shafts. It will enable to elaborate the diagnostic model of analysed system, assumed to be applied in real objects.

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