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NON-CONTACT STRUCTURAL HEALTH MONITORING OF ROTATING COMPONENTS

Abstract

The article describes a class of diagnostics issues for rotating parts. An indirect method has been applied for the structural health monitoring of critical machine parts, which is based on the detection of the angular position of the rotating parts or defects and precise measurement of the time of their arrival, TOA. The variable reluctance sensor or generator stator is the fixed part of the specific encoder. The subject matter has been illustrated by means of examples.

INTRODUCTION

Rotating blades of fans, compressors and turbines, as well as shafts, toothed gears and elements of roller bearings constitute critical elements of the machine, in which accelerated fatigue wear and an increased risk of critical degradation occur – Fig 1. For the above mentioned elements, it is required to monitor their technical condition in order to provide safe operation of machines.

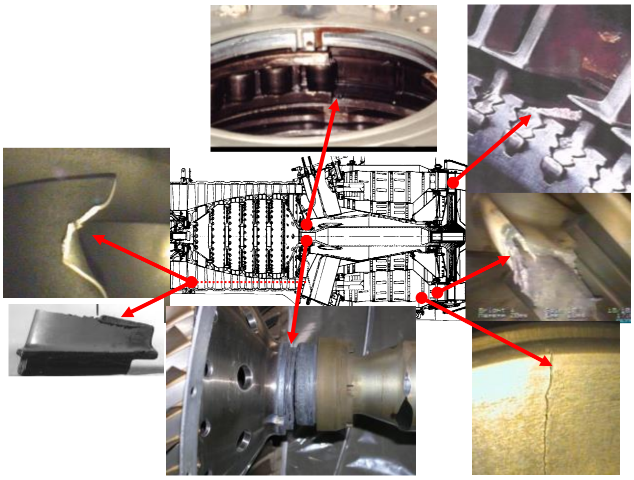


Fig. 1. *Examples of damage to aero-engines [1]*

The paper presents a systematic approach to the class of issues "monitoring of rotating elements", in which economic aspects and optimisation of the measurement chain and data analysis algorithms were taken into account. The discussed issue relates to the rotating elements made of ferromagnetic and paramagnetic alloys. A method of non-contact monitoring of the technical condition of rotating elements (classes of the objects of different geometry, rigidity and load spectrum) as well as many years of experience in its operation in the field and repair conditions were presented.

The strength of the described diagnostic method includes [2]:

- a simple and cheap measurement chain;
- small volume of measurement data which encourages real-time applications (on-line);
- the possibility of comprehensive diagnosing of the rotating machine on the basis of three components of the instantaneous angular velocity (trend, periodic signal, noise and interference) and a dynamic model of the diagnosed object;
- identification of causal relationships: ***unknown processes and technical condition*** → ***transducer transition function*** → ***measurement signal*** → ***measurement data*** → ***diagnostic symptoms*** → ***diagnosis***, including the participation of a human factor (structural, repair and operation errors), which is usually invisible in the NDT classic methods;
- the possibility of using the diagnosis to actively control the fatigue process of critical elements on the basis of additional reliable knowledge describing the following relationships: ***diagnosis*** → ***spectrum of extortion*** → ***technical condition of the machine's critical elements***.

1. MOTIVATION

The material fatigue degradation processes are determined by the type of critical elements, their properties (geometric features and modal properties, material and its heat and mechanical treatment) and actual conditions of their operation. The great unknown, both for the constructor, user, and inspector, includes:

- actual modal properties of critical elements changing during operation;
- actual operating parameters, especially of occasional random events and unusual dynamic loads, e.g. flutter or resonance of the bearing embedded in the vibration damper;
- operation errors - the main operation error of differentiation of the fatigue degradation process of a given element among various users of the same type of machines;
- hidden structural, production and repair errors not detected by the used control methods, e.g. incorrect values of modal characteristics (too weak difference from resonant extortion), local changes of the microstructure (inclusions, hardening/tempering) or hidden micro- or macro-cracks.

The lack of reliable information about actual operation conditions is the main cause, which limits the abilities of the classical non-destructive methods (NDT) to assess the material current health. The prediction of the technical condition based on the NDT results requires support with the use of other test methods, e.g. replica method, condition monitoring of operating parameters (CM), structural health monitoring (SHM), prognostic and health management (PHM). Focusing only on the crack detection or monitoring and analyzing only the operating parameters does not guarantee success of prevention!

The information about the machine actual operation conditions is provided, among others, by the machine vibration spectrum. However, it is not a reliable diagnostic signal for rotating blades, toothed gear teeth and roller bearings' elements – the phase tags of rotating elements. The machine vibration spectrum does not provide information about the health and load of particular phase tags before the occurrence of an emergency situation. A reliable piece of diagnostic information about the phase tags is provided only by the direct measurement of time of their arrival, TOA, to a given angular position, in which the sensor is fixed. The rotating element with rigid or vibrating phase tags and a stationary sensor are an observer of the technical condition not only of individual phase tags (rotating blades, toothed gear teeth, roller bearing elements), but also other elements and machine systems [2 - 4].

The speed monitor has numerous applications in many areas of technology, whether it be for protection of people, machines or manufactured products, to ensure that a plant operates at optimum efficiency, or for speed-dependent switching of system functions in a process. In these applications, temporary averaged rotational speed, determined on the basis of time of the rigid phase tag rotation by a multiple of the angle of 360 degrees, is recorded and analysed. Such a method of measurement and data analysis hides part of the diagnostic symptoms, e.g. rotor misalignment, vibrations, scale errors of the phase tags. Diagnostics symptoms are masked by aliasing [5, 6], as illustrated in the example of a single harmonic:

- the continuous signal in the time domain

$$y(t)=A\sin(\omega t) \tag{1}$$

- the discrete signal in the time domain (after A/D sampling with a frequency f_s, $\omega_s = 2\pi f_s$; k is a discrete time, m is integer)

$$y(k)=A\sin\left(\frac{\omega}{\omega_s}k\right)=A\sin\left(2m\pi\frac{\omega}{\omega_s}k\right) \tag{2}$$

The lost diagnostic symptoms included in the periodic component and noise/interference of instantaneous rotational speed can be efficiently used in non-destructive tests and the machine monitoring systems without incurring additional costs, when:

- measurement chains, data analysis algorithms and diagnostic criteria take into account TOA of some phase tags/rotation;
- phase tag can also include vibrating and rotating elements (flexible phase tags), e.g. compressor or turbine blades.

The diagnostic information with atypical encoder, included in new diagnostic symptoms, is determined by the type of the monitored object and dominant degradation processes.

2. ROTATING COMPONENTS

The class of „rotating elements" comprises:

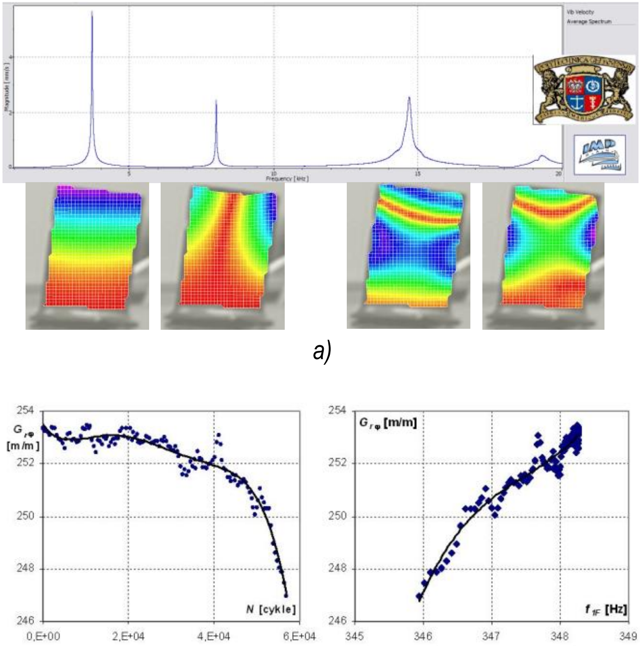
- blades of fans, compressors and turbines,
- discs of fans, compressors and turbines,
- rotators of electric generators and engines,
- gear wheels,
- rolling bearings,
- shafts,
- driving and road wheels.

2.1. Rotor blades

Rotating blades of fans and compressors are elements, that convert mechanical energy (torque and rotational speed) into work of fluid compression (an increase of fluid enthalpy). Turbine blades convert fluid energy (enthalpy of combustion gas, steam, wind or water) into mechanical energy (torque and rotational speed).

The blades are constantly loaded with the quasi-static and dynamic forces and moments, as a result of which, their leaves are subject to quasi-static deformation (deflection and twisting) and vibrations at the frequency of a given mode. The blades have poor damping [2, 7], therefore, they can dangerously vibrate also at the frequency of strong extortion outside the modal frequency. During broadband extortion, the blades vibrate at the same time on several modes. Blades of steam and gas turbines operated in high temperatures are exposed to thermomechanical fatigue (local overheating, creep) [8, 9].

Rotating blades are a broadband, mechanical modal filter, the parameters and properties of which change during changing the scope of the machine operation and the material degradation process (cyclical strengthening, cyclical weakening, propagation of cracking, creeping of turbine blade) [2, 7, 10] – Fig. 2.



a)

b)

Fig. 2. *Compressor blade as a state observer [2]: a) a combo filter (R1 of engine TW3-117); b) symptoms of blade cracking during HCF test (R1 of engine SO-3)*

The rotating and vibrating blades are flexible phase tags. Under the influence of load, the blade changes its leaf tip instantaneous position in relation to its basis. This easily measurable signal TOA and its amplitude, frequency and phase modulation (AM/FM/PM) includes resultant information on [2, 11, 12]:

- current modal properties of the blade (its technical condition),
- the spectrum of mass and aerodynamic extortion,
- vibrations of apparent blades caused changes of the rotor instantaneous angular velocity and alignment errors of the palisade of blades on the shaft and the shaft in the mounted supports
- magneto-mechanical effects.

The characteristic feature of the palisade is uneven distribution of blades in the circuit, with scale errors many times greater than in case of the classic encoder plates. Scale errors are changed during the change of rotor speed.

2.2. Discs

Discs of fans, compressors and turbines transfer mechanical energy between the shaft an rotating blades. Discs of steam and gas turbine scatter also the heat from the blades.

The disc is constantly loaded with the quasi-static and dynamic forces and moments, as a result of which, their leaves are subject to quasi-static deformation and vibrations at the frequency of a given mode.

Fatigue cracking of discs and their failure in extreme cases (Fig. 3.a), are mostly generated by:

- exceeding of acceptable operational parameters for fluid-flow machines (rotational speed, temperature, vibration of rotors),

- resonance effects in grids of blades,
- hidden faults in design.

Monitoring of operational parameters for fluid-flow machines and analyzing of levels and causes for operational exceeding are basic preventive measures for discs [13].

Modal characteristics of discs alter under the influence of cracking, which is useful in diagnostics [14]. When the disc crack is located near the blade mounting seat (Fig. 3.b), modal characteristics of the nearest blades are also changed.

Monitoring of rotating blade vibration by means of measurement and analyses of the time – TOA also enables to diagnose directly some fatigue problems for discs.

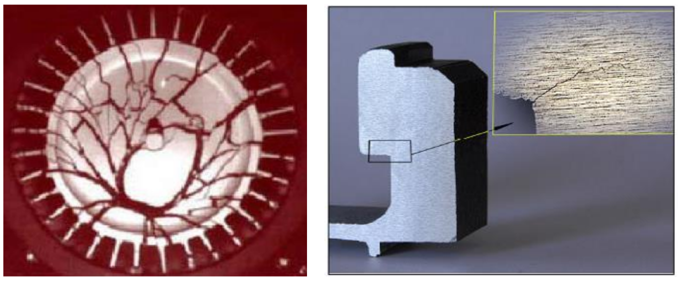

a) b)

Fig. 3. *Illustrations: a) disc failure during destructive tests [15]; b) cracking of the blade mounting seat [16]*

2.3. Toothed gears

The gearbox is a mechanical device capable of transferring torque load from a primary mover (i.e. electric motor, gas, diesel or steam engine) to a rotary output (i.e. compressor, conveyors, mills, paper machines, elevators, screws, agitators), typically with a different relation of angular velocity and torque.

There are two main types of gearboxes, parallel shaft gearboxes and planetary gearboxes. Parallel shaft gearboxes are a collection of simple gear stages. Each gear stage is composed of two shafts, a gear, and a pinion. The planetary box is more complicated than the parallel shaft, because it is composed of three moving components per stage. These components include the planet gear, the planet carrier, and the sun pinion. The ring gear is also part of the planetary box however it is fixed to the gearbox housing [17].

The fundamental law of gearing states that the angular velocity ratio between the gears of a gear set must remain constant through the mesh. The velocity ratio *mv* can be expressed by equation (3) with the angular velocity input ω_{in} and the angular velocity output ω_{out} .Parameter mv describes also the relation between the input torque T_{in} and the output torque T_{out}.. It is assumed that the shafts have no inertial properties and so only their stiffness is considered, and mechanical efficiency is near 1.0.

$$mv = \frac{\omega_{out}}{\omega_{in}} \approx \frac{T_{in}}{T_{out}} \tag{3}$$

In the case of dynamics analysis, a more-complex relation must be utilized [18, 19]. An important parameter that must be considered are:

- the inertia of the primary mover, J_1
- the inertia of load device, J_2
- the stiffness of shafts in gearbox, k_1 and k_2
- the gear ratio, n/1.

When the system is compounded the shafts are represented by a single shaft, and a new effective stiffness is calculated by scaling the original values of stiffness with the square of the gear ratio. In the same manner, the inertial behaviour of the system also is adjusted by scaling it with the square of the gear ratio. The reduced stiffness can be calculated by combining stiffness with the following expression.

$$k_{eq} = \frac{n^2 k_1 k_2}{k_1 + n^2 k_2} \tag{4}$$

Every grade of the toothed gear is exposed to resonance vibration being present in the narrow range of rotational speed - Fig. 4. Also clearances and faults in meshing have an influence on resonance parameters.

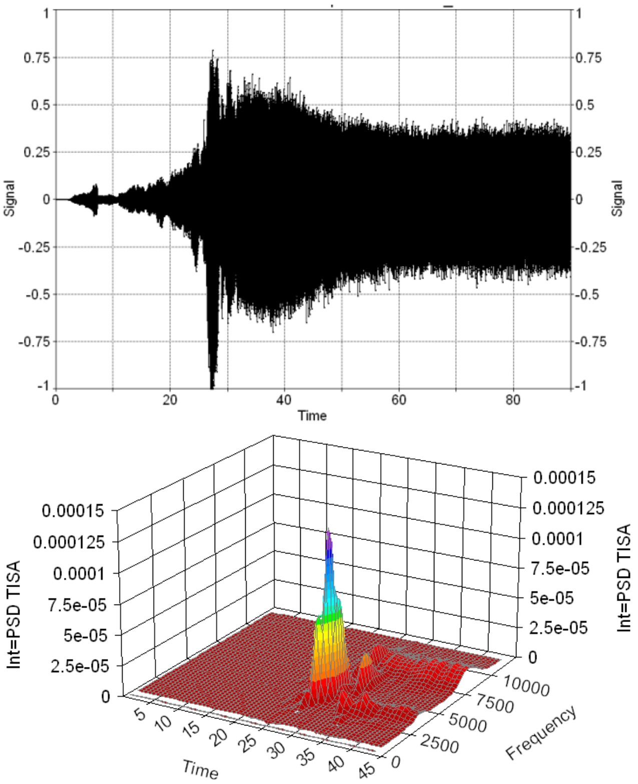


Fig. 4. *The time waveform and time-frequency spectrum (Morlet wavelet analysis) of vibration for gearbox of RR 250-C20R/2(SP) engine during its starting*

The strong load and deflection of teeth occurs only in their gearing zone with the cooperating gear wheel, in the area that is directly difficult to be accessed by the inspector during the gear operation. The indirect symptom of gearing quality includes vibrations and disturbances of the instantaneous angular velocity. In case of the remained scope of the rotational movement, there are teeth in the area of weak centrifugal forces, which do not cause measurable deformation of teeth.

In this scope of rotational movement, teeth are quasi-rigid phase tags of a small scale error comparable to the errors of magnetic and optical encoders. TOA modulation, recorded by the inductive sensor, results from the effect of [2, 4, 17, 20-22]:

- rigidity of meshing teeth and circumferential backlashes,
- tooth chipping,
- stress magnetisation changes of teeth (only for ferromagnetic materials and metastable paramagnetic alloys),
- microstructure changes (surface hardening, plastic deformation)
- errors of the shaft alignment and mounting the gear on the shaft,
- damage to roller bearings,
- instantaneous angular velocity changes, gearbox resonant vibration.

2.4. Rolling bearings

Bearings are devices that allow constrained motion, generally rotational motion. Over time, these devices have evolved to a variety of configurations that are dependent upon their application. The most common bearing used in all industries and aviation is the rolling element bearing. These bearings are chosen due to their low friction and high load capacity.

Bearing fatigue life is determined by a variety of factors including material properties, lubricant properties, speed, load, type, size and number of a rolling element. The actual mode of bearing failure (fatigue, wear, plastic deformation, corrosion, lubrication, faulty installation, incorrect design), which occurs at any particular rotating machine, can have a major influence on the resulting vibration which is measured externally. Fatigue life prediction theories were originally developed in the 1940's. [23].

The theoretical frequencies of the monitored bearing are identified in the machine vibration spectrum on the basis of kinematic properties of the "healthy" bearing and the assumption about ideal conditions of its operation (lack of slippage). The frequencies of the bearing rotating elements are determined on the basis of kinematic relationships (spin speed) and deformation of the immobile track – Fig. 5. The parameters that modulate the time TOA and can be precisely measured by inductive sensor [2].

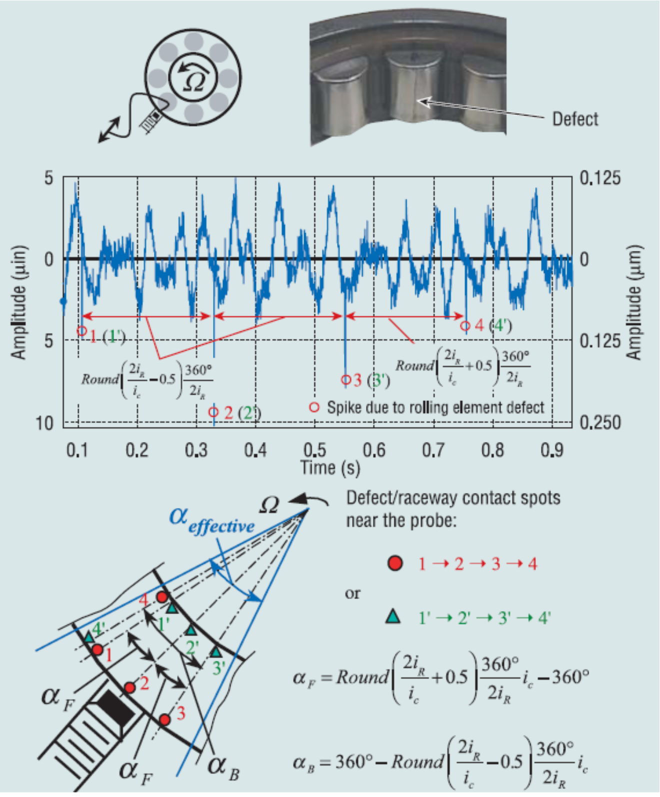


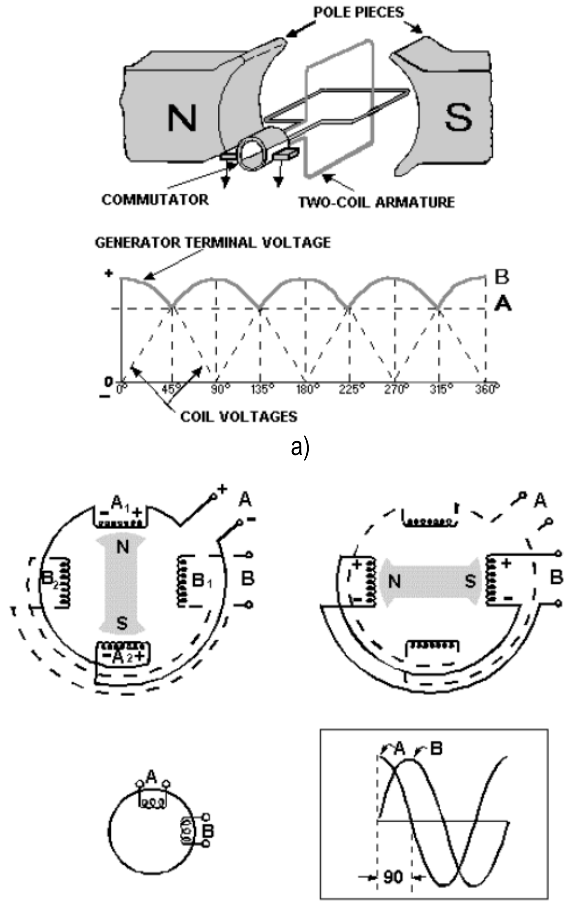
***Fig. 5.** Rolling element defect signal detected by REBAM probe at 720 rpm with 1379 kPa load, after removing i_{ORBPX} and $2i_{ORBPX}$ components along with corresponding defect contact locations near the probe [24]*

2.5. DC and AC generators

Generators are devices that transform mechanical energy into electrical energy. There are two types of generators, one is direct current generator (DC) and other is alternating current generator (AC). Whatever may be the type of generators, it always converts rotational speed and torque to electrical power based on same fundamental principle of Faraday's laws of electromagnetic induction, which are described by relation (5)

$$emf(t) = -\frac{d\Phi}{dt} = -\frac{d\Phi}{d\alpha}\frac{d\alpha}{dt} = -\frac{d(B\cdot A)}{d\alpha}\omega \qquad (5)$$

Emf is the dynamic inducted electromotive force, *A* is the cross section area, *B* is the magnetic induction, *Φ* is the magnetic flux. This *emf* causes a current to flow if the conductor circuit is closed. The main difference between a DC generator and AC generator lies in the manner in which the rotating coil is connected to the external circuit containing the load. As a result, shape of *emf*(*t*) is different for DC and AC generator – Fig. 6.



a)

b)

***Fig. 6.** Theoretical voltage signals for [25]: a) DC generators; b) AC double-phase generators*

The behavior of the generator is mimicked by using an angular velocity-to-torque relationship. For simulations of normal operation, the relationship can be represented by a simple linear relation (5). In the case of intricate events — such as starting and braking events — a more-complex relation must be utilized [25]. Important parameters that must be considered are:

- the inertia of the generator
- winding configuration
- type of armature core,
- magnetic field system (number of pole and pole-pitch, commutator pitch).

AC and DC generators are atypical encoders, which can be used to monitor the kinematic system of a machine. Generators have quasi-rigid phase tags of a small scale error comparable to the errors of classic encoders. Scale errors are not constant and alter under the influence of:

- changes in generator loading;

- changes in generator health (e.g. bearings, rotor alignment, magnetic field asymmetry caused by e.g. overheating, commutator sparking level.

2.6. Shafts and wheels

Shafts are machine elements, that transfer torque between two rotating elements or components. Shafts can be also loaded by bending moments. [18, 26].

Driving and road wheels are the most important parts of wheeled vehicles (locomotives, carriages, trams), that in cooperation with rails enable translational motion of wheeled vehicles. Wheels are exposed to a negative influence of Hertz stresses, sliding friction and local overheating [27].

Clearances of wheel ring or shaft, ring and one-block road wheel cracking threaten safety of traffic. Therefore, periodical checks of their health are required. Above mentioned faults result in discontinuity of material magnetic and electromagnetic properties (anomalies) - Fig. 7, which is used in non-destructive testing (NDT). An appearance of a local anomaly can be also useful as a diagnostic signal in structural health monitoring (SHM) systems, that are based on measurements of TOA time or electromagnetic impedance [28, 29].

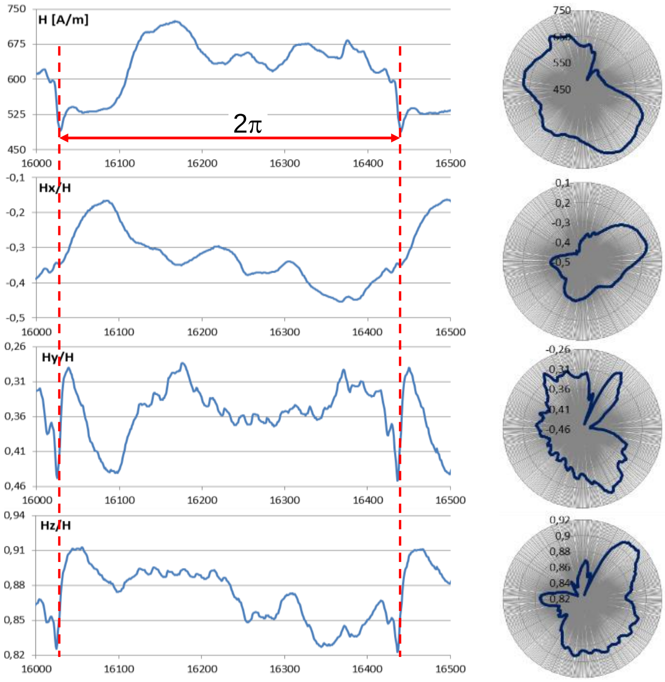


Fig. 7. Magnetic field anomalies registered by means of the 3D magnetometer from the distance of about 5 cm from a cracked shaft of a lift machine [30].

3. MEASURING METHODS

The instantaneous speed of the rotor and TOA of phase tags can be measured by frequency (by counting clock pulses between impulses generated by rotating phase tags).

3.1. The tip timing method

The time measurement of the rotating and vibrating phase tags is implemented in the diagnostic systems based on the tip timing method (TTM) – Fig. 8. The TTM is based on the definition of angular velocity, precise measurement and analysis of the *TOA* each phase tag, without the requirement of its rigidity and accuracy of the angular position on the circuit. The conditions required in standard rotational speed measurement chains with the use of encoders.

In order to observe the phase tags, inductive sensor with a known frequency response (time constant and phase delay) can be used. Its working principle is described by the equation (5). Depending on the required TOA measurement resolution, resulting from the limit amplitude of the phase tag vibrations and maximum rotational speed, the clock frequency of 10 - 250 MHz is used.

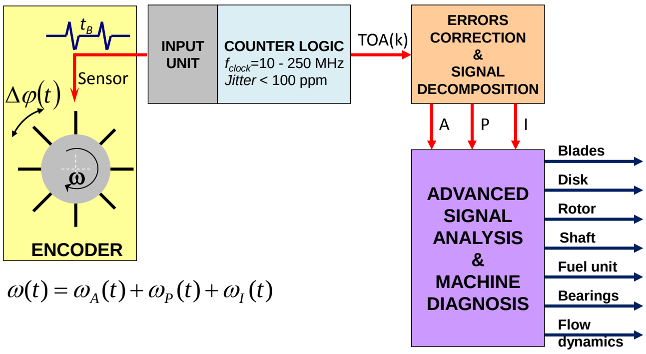


Fig. 8. The idea and block diagram of the TTM method with single variable reluctance sensor and time resolution of counter logic up to 4 ns [2]

The measured time TOA_m includes three variables, which represent the monitored object (a dominant component of a signal), noise and interferences in the measuring section and the resultant jitter of oscillators.

$$TOA_m(k) \approx \frac{1+\zeta_\theta(k)}{1+\zeta_\omega(k)} TOA_{avg}(k) \qquad (6)$$

Jitter ζ_θ is a resultant effect of real and apparent changes in the position of the phase tags, including the applied sensor and the tested object type.

Jitter ζ_ω reflects the effect of disorders of the rotating element instantaneous angular velocity (errors of assembly and the impact of control signals).

The time TOA_{avg} is average instantaneous angular velocity of the ideal rigid inertial element (without errors of alignment, oscillation and interference impact), whose dynamics of changes (time constant) between successive positions of the phase tags results from:

- the value of the moment of inertia of the kinematic layout rotating elements brought to the axis of rotation of the phase tags;
- amplitude of the control signal or disorders, e.g. the torque difference of the compressor and turbine in the aircraft engine, or fluctuation of the frictional moment in the bearing.

Signal TOA_m is subject to decomposition into components, including individual channels of the phase tags after prior transformation of equation (6) to the additive form (7)

$$TOA_m(k) = A(k) + P(k) + I(k) \qquad (7)$$

where *A(k)* is aperiodic part (trend), *P(k)* is oscillating part, *I*(k) is noise/weak oscillating component. Assignment of $TOA_m(k)$ signal components to *P*(*k*) or *I*(*k*) is taken into consideration in the formula (8) describing Taylor-series expansion and a real resolution of a measurement section. For the clock frequency $f_{clock} \leq 250$ MHz Taylor series expansion can be limited to $m = 4$ [31].

$$\frac{1}{1+\zeta_\omega} = \sum_{i=0}^{m} c_i(\zeta_\omega)^i \qquad (8)$$

Next the TOA_m signal components are identified, analysed and classified by numerical methods [2, 11, 12, 32].

3.2. FAM-C and FDM-A methods

Measurements of an instantaneous frequency of voltage signals from AC or DC generators (a specific encoder with quasi-constant phase markers) are applied in AFIT to diagnose kinematic and power transmission systems in different machines. Depending on the used rotational speed signal source, the method is marked as FAM and FDM (F..M - frequency modulation of: A – alternating current generator, D – direct current generator) [4].

A measured quantity is TOA time, that is determined between subsequent exceeding of AC or DC generator voltage signals through the reference level (zero for AC generator or $U_{dc}(\omega)$ for DC generator). Measurements are made:

- in stationary states of machine rotational speed,
- for loaded generators (a minimum influence of complex state observer health on diagnostic symptoms).

Input system comprises optoinsulation, that protects counter section from destruction. Depending on the required TOA measurement resolution, the clock frequency of 1 - 33 MHz is used.

The measured TOA signal is described by means of the equation (6), and TOA signal in the TTM method likewise. For the encoder with quasi-rigid phase tags the dominant component of TOA fluctuation is rotary jitter ζ_ω. Therefore, the measurement data analyses is based on instantaneous frequency of signals (9) and their FM/PM demodulation. A principle of f_m signal demodulation is illustrated in Fig. 9.

$$f_m(k)=\frac{1}{TOA_m(k)}\approx\frac{1+\zeta_\omega(k)}{1+\zeta_\theta(k)}f_{avg}(k) \qquad (9)$$

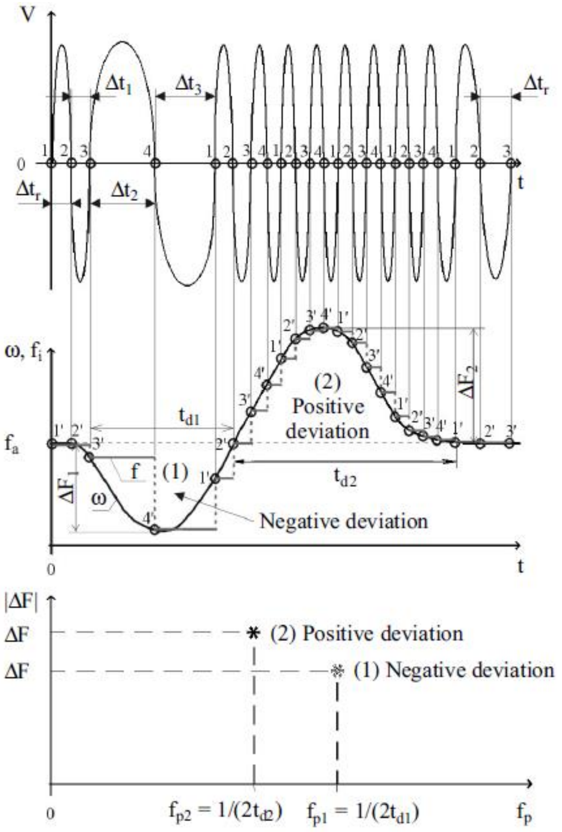


Fig. 9. A signal from AC one-phase generator and FM/PM demodulation method of TOA signal [20]

The frequency of any AC generator in hertz (Hz), which is the number of cycles per second, is related to the number of poles and the speed of rotation, as expressed by the equation (10)

$$f_{AC}=\frac{n}{120}p \qquad (10)$$

where p is the number of poles, n is the speed of rotation in revolutions per minute (rpm), and 120 is a constant to allow for the conversion of minutes to seconds and from poles to pairs of poles [20].

An average frequency for DC generator is zero. In the voltage signal of DC generator are weak periodical components, that represent characteristics of the generator and the diagnosed object (disturbances in the instantaneous rotary speed). Diagnostic symptoms are generated by [4, 20, 25]:

- groove pulsation (an influence of changes in reluctance, generated by rotary motion of a toothed rotor),
- pole pulsation (modulation of a signal amplitude by stator poles and changes in reluctance between rotors and stators),
- commutator pulsation (an influence of cooperation between brushes and commutators, sparking under brushes and generator loading with reference to the neutral axis location).

4. RESULTS

Possibilities of non-contact diagnosing for rotary objects by means of TOA signal are presented on examples selected from different machine operation.

4.1. Monitoring of compressor blades

The TTM method has been used in the Polish Armed Forces to diagnose the compressor rotating blades of the SO-3 type engines since 1993 (SNDŁ-1b/SPŁ-2b diagnostic system). Since 1997, this method has been also used in the repair workshop (CTM-PER/SPŁ-2b diagnostic system) [2, 33]. The time measurement resolution of both diagnostic systems is 100 ns. The monitored 1st stage blades of the axial compressor have an uncorrected structural error – too weak frequency difference of the 1st mode from the resonant extortion in take-off and maximum continuous range of the engine speed.

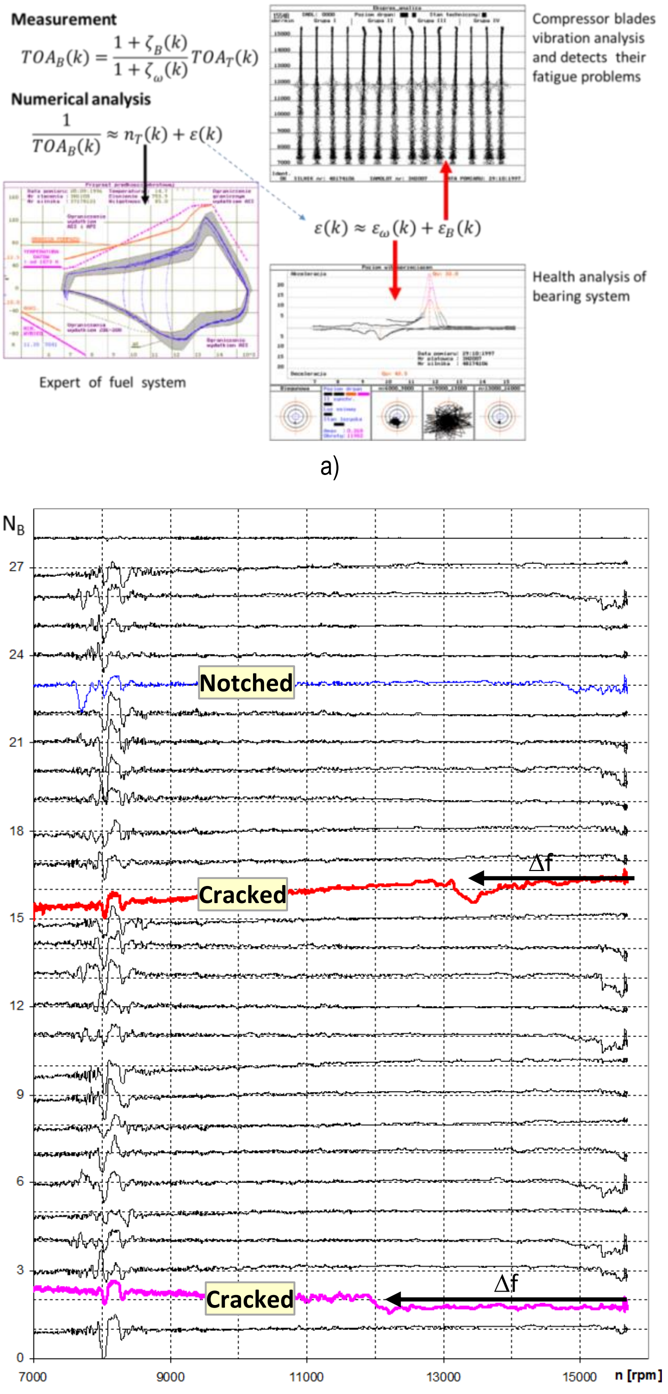
The whole information included in TOA is currently used to comprehensively diagnose the SO-3 type engines and control the material fatigue process – Fig. 10. For more than 20 years of operation, very high effectiveness of the TTM method has been demonstrated in diagnosing both technical problems (excessive vibrations and cracking of blades, the impact of regulation quality on the vibration spectrum of blades and the rotor), and human errors (production, repair, and operation), including: the possibility of the engine comprehensive monitoring, technical condition monitoring, and cracking of blades, as well as active controlling of the material fatigue process [2, 31].

4.2. Monitoring of gas turbine blades

The TOA time measurement was applied to monitor rotating blades of the gas turbines. Therefore, in the Air Force Institute of Technology, a high-temperature inductive sensor (to 1.400 K) was developed, and a multi-channel measurement chain (on-board computer) with a time resolution of 5 ns was tested on the SO-3 and RD-33 type aircraft engines [31, 34].

4.3. Monitoring of steam turbine blades

In order to monitor the rotating blades of the steam turbine's low-pressure part, modernised high-temperature inductive sensors and the multi-channel measurement chain with a resolution of 10 ns were used. The measurement of vibrations of rotating blades from a distance of 10 mm has been implemented for more than 3 years on the 370 MW turbine [31, 34] – Fig. 11.



a)

b)

Fig 10. Illustrated [31]: a) comprehensive SHM of the aero-engine using a single variable reluctance sensor and TTM (compressor blades are phase tags, $\zeta_B = \zeta_\theta$); b) non-contact detection of cracked blades during engine operation

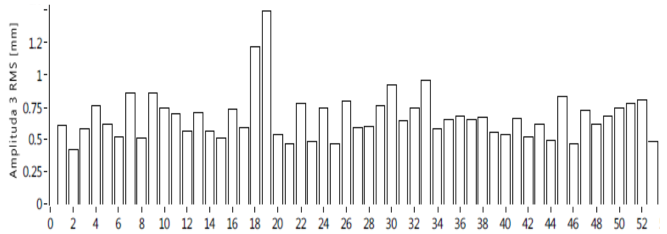
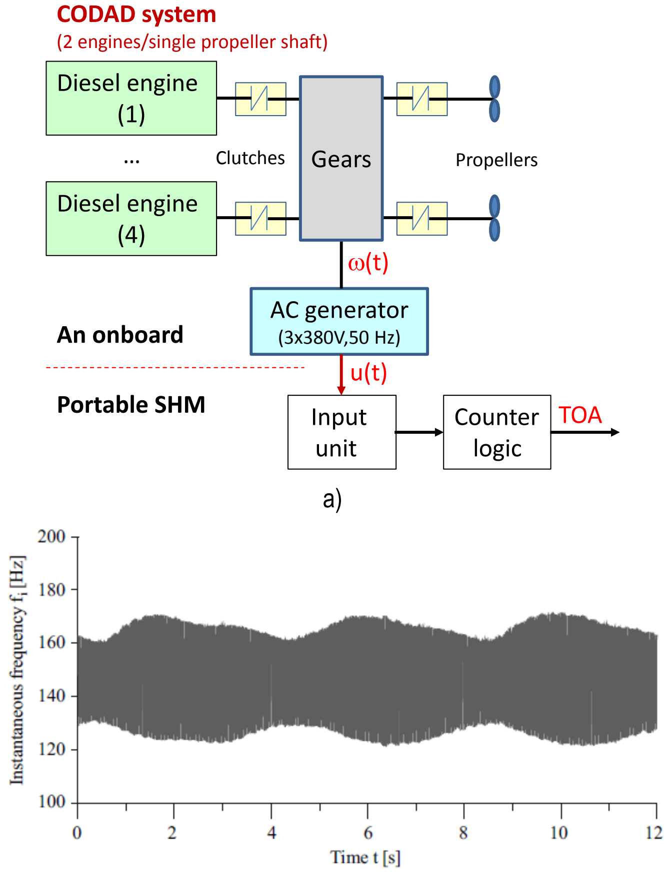


Fig. 11. Amplitude of 1st mode of LP turbine blades type ND-37 for n = 3000 rpm [34]

4.4. Monitoring of kinematic layout

In order to monitor the kinematic layout of the rotating machine, a multipolar inductive sensor – DC or AC generator, included in the machine, was applied. Such an observer of the condition has been used in Poland for more than 20 years, among others, to diagnose the MiG-29 aircraft main gear, to bear the SO-3 type engine and the kinematic layout of Mi-24 helicopters [4]. Signal from AC and DC generators are also used to monitor other machines, i.e. drive systems in sea ferries – Fig. 12.



a)

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Fig. 12. Application of FAM-C method in diagnosing of drive systems in sea ferries[ ]: a) the model of the drive system; b) fluctuation of AC generator frequency generated by the sea state and changes in torque of marine screw propeller (loads)

CONCLUSION

For over 20 years of operation of the TOA measurement and inductive sensors (variable reluctance, AC and DC generator), the following elements have been demonstrated:

- very high efficiency of the non-contact diagnostics of rotating elements (among others, excessive vibration and cracking of blades, the impact of regulation quality on the vibration spectrum of blades and the rotor, alignment errors), and human errors (production, repair, and operation) affecting the durability and reliability of rotating elements;
- the possibility of comprehensive monitoring of the rotating machine and active controlling of the material fatigue process. For the compressor blades of the SO-3 type engines, the statistical average time between cracks was extended by more than 1500%.

REFERENCE

1. Witos M., Zieja M., Kozdra J., *Non-Contact Structural Health Monitoring of Rotating Components Using Inductive Sensor and Time of Arrival Signal*. 21st Int. Workshop on Electromagnetic Nondestructive Evaluation, Sep. 25-28, Lisbon.
2. Witos M., *Increasing the Durability of Turbine Engines Through Active Diagnostics and Control*. Research Works of Air Force Institute of Technology, 2011, 29, p. 1-324, (pol.), DOI: 10.13140/RG.2.1.4341.4560.
3. Szczepankowski A., *How to diagnose the maintenance status of a turbojet engine with the method of analysing the rotational-speed phase display*. PhD thesis, ITWL Warszawa, 1999.
4. Gebura A., *The Inspection of the Technical Condition of Bearing Kinematic Pairs and Selected Gear Parts of the Power Unit*. Wydawnictwo ITWL, Warszawa 2014, (pol.).
5. Zieliński T. P., *Cyfrowe przetwarzanie sygnałów. Od teorii do zastosowań*. WKiŁ 2012.
6. Bilinskis I., *Digital Alias-free Signal Processing*. Wiley 2007.
7. Hanson M. P., *Effect of blade-root fit and lubrication on vibration characteristics of ball-root-type axial-flow-compressor blades*. NACA Research Memorandum, RM No E50C17, Washington 1950.
8. Dobrzański J., *Materials science interpretation of the life of steels for power plants*. Open Access Library, Vol 3 2011 (pol.).
9. Shaniavski A. A., *Modeling of fatigue cracking of metals. Synergetics for aviation*. Publishing House of Scientific and Technical Literature “Monography”, Ufa 2007.
10. Witoś M., *On the modal analysis of a cracking compressor blade*. Research Works of AFIT, 2008, Issue 23, p. 21-36.
11. Zielinski M., Ziller G., *Noncontact Crack Detection on Compressor Rotor Blades to Prevent Further Damage after HCF-Failure*. RTO-MP-AVT-121, RTO/NATO 2005.
12. Knappett D., Garcia J., *Blade tip timing and strain gauge correlation on compressor blades*. Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering 2008, Vol. 222, No 4/2008, p. 497-506.
13. Romeyn A., *Additional Analysis of Left Engine Failure VH-LQH*, ATSB Transport Safety Investigation Report, ATSB 2006.
14. Wang W., *Spin Test Monitoring Using Blade Tip Timing Measurement*. AIAC14 Fourteenth Australian International Aerospace Congress/7th DSTO Int. Conference on Health & Usage Monitoring (HUMS 2011), Feb. 28 – March 3, 2011, Melbourne.
15. http://www.testdevices.com
16. Witos M. et al., *Diagnozowanie zmęczenia materiału przy pomocy efektu magnetycznej pamięci metalu*. X Warsztaty Techniczne PALANGA 2009, DOI: 10.13140/RG.2.1.2002.9284.
17. Sheng S., Veers P., *Wind Turbine Drivetrain Condition Monitoring – An overview*. NREL/CP-5000-50698, 2011.
18. Sanjib Chowdhury M. E., *Effect of Shaft Vibration on the Dynamics of Gear and Belt Drivers*. PhD thesis, The Ohio State University 2010.
19. Lohrengel A. et al., *Modelowanie zjawisk dynamicznych w przekładniach zębatych, z wykorzystaniem metody elementów sztywnych*. Górnictwo i geologia 2011, T. 6, Issue 3, p. 115-126.
20. Gębura A., PhD thesis (pol.), DOI: 10.13140/RG.2.1.3745.2006.
21. Roskosz M. Witoś M. Zieja M., *Examination of Technical Gear with the Help of Magnetic Passive Observer Status*. 11th European Conference on Non-Destructive Testing, The -e-Journal of Nondestructive Testing, 2014-12, www.ndt.net.
22. http://www.zkz.net.pl/pl/izba-pomiarow
23. Zaretsky E. V., *Rolling Bearing Life Prediction, Theory, and Application*. NASA/TP-2013-215305, Glenn Research Center, Cleveland, Ohio 2013.
24. Bently D. E., Goldman P., Yu J. J., *Rolling Element Bearing Defect Detection and Diagnosing Using REBAM® Probe*. ORBIT 2001, 2Q01, p. 12-25.
25. Bhatia A., *AC Generator and Motors*. Course NoE03-008, Continuing Education and Development, Inc.
26. Perkowski W., *Analiza drgań wału doprowadzającego napęd do przekładni ogonowej śmigłowca ultralekkiego*. Prace Instytutu Lotnictwa 2011, Vol 213, s. 148-160.
27. http://www.transportszynowy.pl
28. Żurek Z. H., Duka P., *RLC Circuits for Material Testing and NDT*. Institute of Electrical Drives & Machines KOMEL 2015.
29. Żurek Z. H. et al., *Hochpräzise Induktive Digital Wandler LDC 1000 zur Erfassung der Ermüdung des Radsatz-Stahles*. 14. Int. Schienenfahrzeugtagung mit begleitender Fachausstellung Dresden, 23.- 25. Sep. 2015, DOI: 10.13140/RG.2.1.3924.5284.
30. Iwaniec M., Witoś M., Żokowski M., *Monitorowanie stanu technicznego wału maszyny wyciągowej*. VIII Międzynarodowa Konferencja Bezpieczeństwo Pracy Urządzeń Transportowych w Górnictwie, Ustroń, 7-9.11.2012, DOI: 10.13140/RG.2.1.1159.8562.
31. Wachłaczenko M., Witos M. *Structural Health Monitoring of Compressor and Turbine Blades with the Use of Variable Reluctance Sensor and Tip Timing Method*. 19th WCNDT 2016 World Conference on Non-Destructive Testing, 13-17 June in Munich, DGZfP-Proceedings BB158.
32. Barnett J. T., *Zero-Crossing Rates of Some Non-Gaussian Processes with Application to Detection and Estimation*. Thesis report Ph-D 96-10, University of Maryland 1996.
33. Szczepanik R., Witoś M., *Komputerowy system diagnozowania silników odrzutowych bazujący na dyskretno-fazowej metodzie pomiaru drgań łopatek*. Zeszyty Naukowe Instytutu Lotnictwa, 1998, Nr 152/1/1998, p. 135-149.
34. Przysowa R., Rokicki E., *Inductive sensors for blade tip timing in gas turbines*. Conference of RTO AVT-229 Test Cell and Controls Instrumentations and EHM Technologies for Military Air, Land and Sea Turbine Engines, Rzeszów 20-25th April 2015.
35. Gębura A., *Possibilities of FAM-C method in diagnosing power plants*. Polish Maritime Research 2003, 2(36), p. 14-19.

BEZDOTYKOWE MONITOROWANIE STANU TECHNICZNEGO WIRUJĄCYCH ELEMENTÓW

Streszczenie

Artykuł opisuje klasę zagadnień diagnostycznych dotyczących wirujących elementów. Do monitorowania ich stanu technicznego zastosowano pośrednią metodę, bazującą na detekcji położenia kątowego wirujących elementów lub defektów i precyzyjnym czasie pomiaru ich przybycia, TOA. Czujnik reluktancyjny lub stator prądnicy są składową specyficznego enkodera. Omawianą tematykę zobrazowano przykładami.

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