Magnetic State Observer in NDT and SHM Studies

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Abstract
The article presents the project for the use of magnetic magnetometers in the 0 - 500 Hz band for remote, non-contact monitoring of object operation and assessment of the technical condition of ferromagnetic elements and systems. At the beginning, the theoretical foundations of passive magnetic tests and applied magnetometers (multi channels 3D system) have been presented. Next, selected results of laboratory tests and applied measurement data analysis methods are presented. Then selected results of tests carried out on the real object are presented, among others Kaplan turbine and turbine jet engine. Finally, discussing the results of research, the strengths and weaknesses of the magnetic state observer were pointed out. It has been experimentally demonstrated that a remote magnetic state observer provides qualitative and quantitative diagnostic information that can be used in non-destructive testing (NDT) and structural health monitoring (SHM).

Keywords: fatigue of material, non-destructive testing (NDT), structural health monitoring (SHM), magnetometer, measurement, signal analysis

1. Introduction

During the operation of machines and devices, the wear potential [1] of individual elements and systems. In order to maintain the airworthiness of technical facilities:
- work parameters are monitored;
- service is performed, including non-destructive tests, resulting from the adopted operating system and the results of statistical analysis of adverse events. There are three basic mining systems [2]:
  a) planned prevention with known time between overhauls (TBO) and resources;
  b) technical condition;
  c) the reliability requested.

Most industrial facilities and aircraft engines are operated according to their technical condition or according to planned prevention - useful life period pre-determined by the constructor and manufacturer based of construction assumptions verified during factory and qualification tests. The technical object's lifetime is extended based on:
- values of statistical indicators of operational reliability and safety determined for the population of objects which are also affected by human factors present in the system of design, production, training, operation, renovation and logistic protection [3 - 6];
- new technical and technological possibilities, including modern control and measuring apparatus and diagnostic methods as well as new technologies implemented for the operation, repair and quality control of spare parts production.

Along with increasing the reliability of the diagnosis and the forecast horizon, operational safety increases and operating costs decrease, which was used in the operating system according to technical condition.

Reliable determination of the technical condition of critical elements and forecasting the horizon of their safe operation requires:
- good knowledge of the test object, including construction and material data, which are most often inaccessible to the user and the diagnostician;
- knowledge of the history and effects of real effort;
- proper selection of the state observer [2, 7], based the relationships between the technical condition of the test object and its elements with:
  a) measurable physical and mechanical parameters,
  b) available measurement methods,
  c) costs of prevention;
- basic knowledge of signal theory and algorithms for measuring data pre-processing;
- verified knowledge of experts or knowledge obtained from machine learning, necessary to aggregate the characteristics of measurement signals and to separate estimators and diagnostic criteria (covert relations with degradation of the chemical composition and structure of the material [8, 9]).

The effectiveness of preventive actions, described by increasing the probabilities of diagnosis (POD) and decreasing statistical indicators of faults and failures, is the resultant of:
- the expected diagnostic symptoms (knowledge about the process and accompanying phenomena);
- the choice of observation methods: Electro-Magnetic Interference (EMI), Condition Monitoring (CM), Non-Destructive Testing (NDT), Structural Health Monitoring (SHM), Prognostic and Health Management (PHM);
- the quality of the measurement path, software quality and diagnostic criteria used for numerical analysis.

The article presents the possibility of obtaining new diagnostic information about the current operating conditions of the technical object and the effects of the unknown history of straining ferromagnetic material based on the cheap, Passive Magnetic State Observer (PMSO). The observer combines the functions: control of low-frequency EMI, method of NDT, incomplete observer of CM, method of SHM. Measurement and diagnosis results can be used to reliably predict technical condition in PHM systems. The topic discussed are illustrated by examples of research results on industrial and aviation facilities.

2. Research objects

Two groups of technical objects will be considered - presented in the Table 1, with different: design features, operating conditions, material degradation processes and magnetic properties. Their main features are expected high reliability and operational safety. In the general case, the material of the test object is exposed to a complex state of stress and deformation caused by external forces which generates complex three-dimensional (3D) states of stress and strain and material fatigue: Low Cycle Fatigue (LCF), High Cycle Fatigue (HCF), Very High Cycles Fatigue (VHCF), Thermo-Mechanical Fatigue (TMF), with negative impact [8]:
- erosion,
- corrosion,
- foreign matter,
- pulsation of air, steam or water flow,
- rotor imbalance and misalignment,
- dynamics of transient and short-term resonance impacts.

3. Theoretical basis for diagnosing DUT

The complex process of effort, material degradation and risk of emergency damage to critical elements can be described by simple Multiple Input, Single Output (MISO) model including:
- geometric features of Device Under Testing (DUT),
- mechanical properties of the DUT material and its surroundings,
### Table 1. Specificity of DUT

<table>
<thead>
<tr>
<th>DUT</th>
<th>Example</th>
<th>Specific speed</th>
<th>Casing</th>
<th>Internal components</th>
</tr>
</thead>
<tbody>
<tr>
<td>Industrial</td>
<td>Water, steam and gas turbine</td>
<td>Low to medium (up to 3000 rpm)</td>
<td>Ferromagnetic</td>
<td>Ferromagnetic, few paramagnetic</td>
</tr>
<tr>
<td>Gears</td>
<td></td>
<td></td>
<td></td>
<td>Ferromagnetic</td>
</tr>
<tr>
<td>Kinematic system</td>
<td></td>
<td></td>
<td></td>
<td>Ferromagnetic</td>
</tr>
<tr>
<td>Transformer</td>
<td></td>
<td></td>
<td>Soft ferromagnetic</td>
<td>Paramagnetic winding, soft ferromagnetic core, ( \mathbf{B} = f(I_{load}) )</td>
</tr>
<tr>
<td>AC and DC generator</td>
<td></td>
<td>Low to medium (up to 3000 rpm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air</td>
<td>Aircraft (airplanes, helicopters)</td>
<td></td>
<td>Paramagnetic (composite or aluminium alloys)</td>
<td>Paramagnetic, few ferromagnetic</td>
</tr>
<tr>
<td>Turbine engine</td>
<td>High (up to 40000 rpm)</td>
<td></td>
<td>Paramagnetic</td>
<td>Paramagnetic, few ferromagnetic</td>
</tr>
<tr>
<td>Gears</td>
<td>Low, medium and high</td>
<td></td>
<td>Paramagnetic</td>
<td>Ferromagnetic or paramagnetic</td>
</tr>
<tr>
<td>Kinematic system</td>
<td></td>
<td></td>
<td></td>
<td>Paramagnetic, few ferromagnetic</td>
</tr>
<tr>
<td>Landing gear</td>
<td></td>
<td></td>
<td>Ferromagnetic or</td>
<td>Ferromagnetic</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>paramagnetic</td>
<td></td>
</tr>
</tbody>
</table>

- the actual load spectrum and severity of adverse phenomena (e.g.: erosion, corrosion, human errors),
- design working conditions and accepted strength criteria.

Most of the above data is unknown to the DUT user and diagnostician - the object being diagnosed is a "black box". The implicit influence of input signals, however, changes the technical condition and energy status of DUT material, including:

- **operational stress** \( \sigma_e \) (aperiodic component \( \sigma_a \) and dynamic component \( \sigma_d \)), which in general are generated by external forces \( F_z \): centrifugal force \( F_r \), force of gravity \( F_g \), bending moment \( M_g \) and torque \( M_s \) and apparent strength - the force of inertia \( F_g \). The state of operational stress at a given point of the critical element is described by the relation (1).

\[
\begin{bmatrix} F_B \\ F_g \\ F_r \\ M_g \\ M_s \end{bmatrix} \rightarrow \sigma_e = \begin{bmatrix} \sigma_x & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_y & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_z \end{bmatrix}
\]

- **residual stress** \( \sigma_{rp} \) deliberately introduced into the surface material of the critical element at the production stage to increase fatigue strength.
- **residual stress** \( \sigma_{rh} \) induced in the material of the critical element by the history of its operation, also occurring when the machine is at a standstill
- **total state of material stress** \( \sigma_T \)

\[
\sigma_T = \sigma_e + \sigma_{rp} + \sigma_{rh}
\]

- **total state of material strain** including elastic \( \varepsilon_s \) and plastic \( \varepsilon_p \) deformations
\[\sigma_T \rightarrow \varepsilon_s + \varepsilon_p = \begin{bmatrix} \varepsilon_x & \gamma_{xy} & \gamma_{xz} \\ \gamma_{yx} & \varepsilon_y & \gamma_{yz} \\ \gamma_{zx} & \gamma_{zy} & \varepsilon_z \end{bmatrix} \]

- **magnetization** \( M \) which has an induced component \( M_i \) by operational extortion and the residual component \( M_r \) present in the material after the extinction disappears, as described in equation (4).

\[ M = M_i + M_r \] (4)

### 3.1. Magnetization

Magnetization - a directly immeasurable parameter describing the distribution of the magnetic field inside the ferromagnetic or metastable paramagnetic DUT, including [10-14]:
- object geometry (demagnetization tensor);
- initial magnetic properties of the material resulting from the chemical composition and physical structure of the material containing: non-metallic inclusions and structural defects as well as stress state \( \sigma_i, \sigma_{ii}, \sigma_{iii} \) respectively on the nano, micro and macro scale (the size of the iron atom in the allotrophic alpha version \( Fe_\alpha \) is 290 pm);
- unknown operation history and current DUT operating conditions,
- magneto-mechanical effects including magneto-mechanical damping (influence of internal friction and internal energy loss on heat dissipation);

was used for remote non-contact diagnostics of a technical object by means of a PMOS.

Magnetization can be accomplished by 3 independent variables [10]:
- **external magnetic field** with intensity \( H \), which has been used in recording devices and magnetic information carriers for over 100 years;
- **stress state** \( \sigma_{ij} \), which is used in applications based on magneto-mechanical effects i.e. the metal magnetic method;
- **temperature changes** \( \Delta T \), which is used, among others, for thermomagnetic and geophysical treatment.

The non-linear effect of these variables on the magnetization is described in relation (5)

\[ M = M_i + M_r = f(H, \sigma_{ij}, \Delta T) = (1 + k_H)(1 + k_\sigma)(1 + k_{\Delta T})M_0 \] (5)

where: \( M_0 \) - initial magnetization of the element; \( k_H = k_H(t) \), \( k_\sigma = k_\sigma(t) \), \( k_{\Delta T} = k_{\Delta T}(t) \) - influence functions described by the physical properties of the material, among others: magnetic permeability \( \mu_m \), linear magnetostriction \( \lambda_i \) (longitudinal and transverse), coercivity\( H_c \), electric resistivity \( \rho_e \), coefficient of thermal expansion \( \alpha_T \), thermal conductivity coefficient \( \lambda_T \).

Equation (5) can be presented in a simplified additive form (6) after ignoring the effects of multiple internal couplings in the material.

\[ M = M_i + M_r \approx M_0 + \Delta M_H(t) + \Delta M_\sigma(t) + \Delta M_{\Delta T}(t) \] (6)

Magnetization occurs only in DUT material, which prevents its direct observation by non-destructive methods [15]. For remote evaluation of parameters and magnetization distribution \( M = M(x, y, x, t) \) in DUT uses the definition of a magnetic field with equivalent magnetic field strength \( H_{eq} \) in a material medium with magnetic permeability \( \mu_m(H_{eq}) \) and (Figure 1) [12 - 13]:
- magnetic field features:
a) magnetic field lines tangent to the magnetic induction vector $\mathbf{B}$ they create closed contours.
b) magnetic field lines penetrate the border separating two media with different magnetic properties (e.g. ferromagnetic DUT - air gap - paramagnetic fuselage-air between DUT and magnetometer) bending on the border;
- boundary conditions on the border of two media with different magnetic properties, described by the relations resulting from Gauss's law and Amper's law.

Figure 1. Electromagnetic interference (EMI) issue: measurement and imaging of 50 Hz magnetic field near the transformer and interpretation of results: a) the field penetrates the walls of the transformation station building (remote diagnostics are possible); b) **diagnosis** - changes in magnetic field parameters are caused by: 1) a change in the transformer load or / and 2) a change in its technical condition (health) or / and 3) a change in shielding parameters or / and 4) the effect of external disturbances.

The magnetization process is described by the formula (7), where $\alpha_{ij}$ is the medium magnetization tensor.

$$
\begin{bmatrix}
M_x \\
M_y \\
M_z
\end{bmatrix} =
\begin{bmatrix}
\alpha_{xx} & \alpha_{xy} & \alpha_{xz} \\
\alpha_{yx} & \alpha_{yy} & \alpha_{yz} \\
\alpha_{zx} & \alpha_{zy} & \alpha_{zz}
\end{bmatrix}
\begin{bmatrix}
H_x \\
H_y \\
H_z
\end{bmatrix}
$$

In general case $\mathbf{M}$ and $\mathbf{H}$ have different directions. For paramagnetic and diamagnetic, vectors $\mathbf{M}$ and $\mathbf{H}$ are parallel. For ferromagnetic, there is no unambiguous relationship between $\mathbf{M}$ and $\mathbf{H}$ – magnetization depends on history of field strength changes and magnetic hysteresis. As a result, $\alpha_{ij} \neq \alpha_{ji}$ and the ferromagnetic stores magnetic information. The parameters of recording and resistance of magnetic information stored in the ferromagnetic describe two variables. These are (Figure 2) [16]:
- loop squareness

$$
S = \frac{M_r}{M_s}
$$

- remanent squareness

$$
S^* = 1 - \frac{M_r}{H_c} \frac{1}{\left. \frac{dM_r}{dH} \right|_{H=H_c}}
$$

where: $H_c$ - coercivity; $M_r$ - saturation remanence; $M_s$ - the medium saturation magnetization; 
$\left. \frac{dM_r}{dH} \right|_{H=H_c}$ - magnetic susceptibility of the material for $H = H_c$. 
The hysteresis loop field of $\mathbf{M}(\mathbf{H})$ and coercivity reflect the effect of internal friction of the material.

![Hysteresis Loop](image)

Figure 2. Showing hysteresis loop for ferromagnetic material used on carriers magnetic ($\chi_r$ - reversible magnetic susceptibility along a minor loop) [16] and magnetic wire recording (V. Poulsen, 1898)

When magnetizing only via an external magnetic field $\mathbf{M}(\mathbf{H}_{\text{ext}})$, it is assumed:
- invariability of the chemical composition and microstructure of the material,
- negligible small impact of changes in stress and mechanical strain on the magnetization process of the material,
- negligible small impact of changes in material temperature during the magnetization cycle.

Stress inducted magnetization $\mathbf{M}(\sigma_{ij})$, resulting from accidental impact:
- stress state,
- magneto-mechanical effects,
- internal friction and energy losses,
- changes in chemical composition and microstructure,
has different properties than $\mathbf{M}(\mathbf{H}_{\text{ext}})$. Especially, when stresses and deformations of the material are generated in the material in the presence of a weak Earth's magnetic field [18-25]. Without the user's knowledge, valuable magnetic information about the history of unknown material strain and progressive material degradation $D = D(t)$ is stored in the ferromagnetic material, which can be used to [2, 23]:
- diagnosing technical condition of DUT,
- monitoring the quality of operation, service and renovation,
- support for the accident investigation process.

Temperature inducted magnetization $\mathbf{M}(\Delta T)$ also has different properties than $\mathbf{M}(\mathbf{H}_{\text{ext}})$. The magnetic properties of ferromagnetic and domain structure change strongly as the temperature of the material changes [10, 13]. Local and volumetric changes in material temperature during DUT operation are due to:
- the temperature of the surrounding environment (air, water);
- the amount of energy generated in the material, depending on the speed of deformation changes and microstructure parameters (type, grain size, number of inclusions and defects);
- conditions for energy dissipation in the material and energy reception from the material by the surrounding medium;

3.2. Magneto-mechanical damping

Considering five main contributions to the total energy of a ferromagnet without an external field (exchange energy $W_{ex}$, magnetocrystalline anisotropy energy $W_k$, magneto-elastic or magnetostrictive energy $W_\lambda$, magnetostatic energy $W_m$, energy of magnetic domain walls $W_W$), four main mechanisms of magneto-mechanical damping may be defined [14]:
- Magnetoelastic hysteresis damping ($Q_h^{-1}$)
- Macroeddy-current damping \( (Q_a^{-1}) \)
- Microeddy-current damping \( (Q_u^{-1}) \)
- Damping at magnetic transformations \( (Q_{phT}^{-1}) \) e.g., at Curie and Néel temperatures, spin-flip transitions etc.

Therefore, the total magneto-mechanical damping \( Q_M^{-1} \) in ferromagnets can be considered as a sum of these components:

\[
Q_M^{-1}(\varepsilon, f, T) = Q_h^{-1}(\varepsilon, f, T) + Q_a^{-1}(f, T) + Q_u^{-1}(f, T) + Q_{phT}^{-1} \tag{10}
\]

where, contrary to \( Q_a^{-1} \) and \( Q_u^{-1} \), the hysteretic contribution \( Q_h^{-1} \) depends on the strain amplitude \( \varepsilon \) [14, 23, 24].

### 3.3. Impact of the DUT hull

To remotely monitor the magnetization status of the DUT internal components, it is necessary to consider the shielding impact of the hull for:

- direct current (static) magnetic field (DC),
- alternating current magnetic field (AC).

Since in contrast to electrical fields no isolated magnetic charges (monopoles) exist, magnetic flux lines are always self-contained; they have no beginning and no end. Consequently, there is no such thing as a magnetic insulator (the principle of superconductivity is excluded here) [24, 25]. While electromagnetic fields with frequencies above approx. 1 kHz can be very well shielded by thin metal foil or meshes made of materials with high electrical conductivity (Faraday cage principle), static or low-frequency electromagnetic fields require more effort. If the frequencies are sufficiently low, the electric and magnetic fields must be considered and shielded independently of each other. The big problem with shielding the low-frequency magnetic field is an advantage for the PMSO. Observation of internal DUT processes can be performed remotely in its vicinity.

The shielding effect of a housing depends on the permeability of its material, the form and size of the housing as well as on the thickness of its walls. Analytical calculation provides a solution for only a few forms. For example, the attenuation of DC magnetic field by DUT hull with single layer is described by a formula (11)

\[
A = \frac{H_{\text{out}}}{H_{\text{in}}} \approx \frac{\mu_m}{4} \left( 1 - \frac{R_1}{R_0} \right) \tag{11}
\]

where \( A \) - attenuation @ DC; \( \mu_m = \mu_m(H) \) - permeability value of material; \( R_1 \) - inside radius of the single layer; \( R_0 \) - outside radius of the single layer.

Those results can however be used as reference when estimating the shielding effect of other housings. It is important to note that the value for the permeability of a material used for the purposes of a calculation depends on material composition and level of its damage, shield geometry, and field intensity. Because the characteristics \( \mu_m(H) \) of ferromagnetic is strongly non-linear in the medium and high magnetic field intensities, this ferromagnetic hull not only weakens the field strength generated by internal DUT elements, but also changes the spectrum of the signal. Near the DUT, magnetizing frequency harmonics will also be present, so the level of total harmonic distortion (THD) is a diagnostic symptom.

A strict mathematical analysis of ferromagnetic shielding of AC magnetic field is also very difficult and so the literature gives useful approximate equations for the shielding effectiveness of common box shapes such cylinders, spheres and cubes [28]. For AC magnetic field the
material permeability has a real component \( \mu' \) and an imaginary component \( \mu'' \) and the overall permeability is given by:

\[
\mu_m = \mu'_m - j \cdot \mu''_m
\]  

(12)

The Figure 3 shows frequency characteristics.

![Figure 3. Magnetic permeability of ferromagnetic steel with initial (low frequency) permeability \( \mu_{m,0}' = 300 \), and a relaxation frequency \( f_m = 1 \, kHz \): a) without influence of diluted component; b) with influence of diluted component [27]

The equations which describes the real component of \( \mu_m(f) \) characteristic is:

\[
\mu'_m = \left( \frac{\mu'_{m,0} - 1}{1 + (f/f_m)^2} \right) + 1
\]  

(13)

At high frequencies this equation is asymptotic to unity, and this is typical of many magnetic materials especially ferrites. Some workers have measured a higher asymptote for steel, and so the above equation needs to be modified to:

\[
\mu'_m = \left( \frac{\mu'_{m,0} - \mu_{\infty}'}{1 + (f/f_m)^2} \right) + \mu_{\infty}'
\]  

(14)

where \( \mu_{\infty}' \) is the high frequency permeability. For instance, Bowler measured \( \mu_{\infty}' = 78 \) on his steel sample [29].

The loss component shows a resonant characteristic with an amplitude equal to that of the real component at the frequency \( f_m \). Its equation is:

\[
\mu''_m = \frac{\mu''_{m,0}(f/f_m)}{1 + (f/f_m)^2}
\]  

(15)

4. Passive magnetic state observer

Having basic theoretical knowledge of magnetism, the research task boils down to:
- selection of the measuring path and its calibration;
- measuring the existing magnetic field near the DUT;
- identification of magnetic anomalies and their sources using measurement data processing algorithms, the basic design features of DUT and the expected signal spectrum;
- determining the current working conditions of the DUT and its health using statistical standards and diagnostic criteria;
- analysis of trends in estimators to predict the technical condition of DUT.
The reliability of diagnosis and prognosis increases as the diagnostician and software learn new capabilities of the diagnostic method.

4.1. Metrological path – capabilities

Magnetic field measurements and analysis are widely used in various applications which results in an increasing market demand for mass-produced magnetometers: magneto-resistive (AMR, GMR, TMR), magneto-induction (MI) and Hall (Hall, Q-Hall) and low their price. Only very high sensitivity (with fT and pT resolution) and low-noise scalar (cesium, rubidium) and vector magnetometers (SQUID, fluxgate) used, among others in geophysics, geology, satellite technology, medicine (magnetoencephalography, magnetocardiography), aerial and marine reconnaissance, detection of unexploded ordnance (UXO), have a price several times higher than other sensors of physical size. The e-compass magnetometers using in smartphones with < 150 nT sensitivity (the Earth magnetic field is about 50000 nT) cost lower than 5 Euro. In the 21st century, there are no technical and technological limitations for the design of applications based on magnetic field measurements from some fT to several T, with divided into subrange or dynamic change in gain. Unfortunately, the dynamic development of the analogue and digital magnetometers market is not reflected in the area of NDT and SHM systems. Only approx. 0.04% of magnetometers produced goes to the NDT and SHM applications, despite the growing share of magnetometers in production quality control systems and car monitoring systems. The price of mass-produced magnetometers and their datasheets are a reference point to solutions offered by manufacturers of NDT and SHM applications and prototyping.

4.2. Measuring track

Three types of digital magnetometers (MI, TMR, RTD-fluxgate) [30 - 35] with operating data rate (ODR) up to 500 Hz were used in the study. The spectrum of the measured signal contains aliases – weakness of cheap magnetometers (e-compasses), which after considering aliases in data analysis [2] is the strength of PMOS. The limitation of the upper frequency of observation depends on the type of magnetometer and its sensitivity.

4.3. Data analysis (numerical post-processing)

The raw measurement data $B_m(k)$ and its components are described by the relation (16)

$$B_m(k) = \frac{B_p(k) + noise(k)}{Result \ of \ a \ measurement} = \frac{B_{p,LPF}(k) + B_{p,BPF}(k) + B_{p,HPF}(k) + noise(k)}{Analyzed \ signal \ components}$$

(16)

where: $B_{p,LPF}(k)$ are low-frequency components (process trends), $B_{p,BPF}(k)$ are band components resulting from DUT design features and observed processes; $B_{p,HPF}(k)$ are high-frequency components; $noise(k)$ - colorful noise whose spectrum contains components: $1/f$, $1/f^2$, ..., $1/f^n$ and white noise. 

Only knowledge of the real frequency characteristics of the magnetometer as well as dynamic properties and noise level of the measuring path enables:
- reliable observation of dynamic phenomena occurring on the DUT with frequencies higher than the sampling frequency, which the authors used in the passive magnetic state observer;
- reliable DUT diagnosis based on a typical diagnostic criterion: the detected magnetic anomaly must be greater by min. 2 times (3dB) relative to the noise level.

As the noise level decreases, it increases exponentially:
- likelihood of reliable diagnosis (POD) and DUT status prognosis;
- the distance from which the diagnostic symptoms are detected, among others:
  a) single magnetic anomalies,
  b) groups of cyclical anomalies generated e.g. by gear teeth or compressor and turbine blades
  b) average level of anomaly generated by DUT (in total)
  b) technical condition of DUT ferromagnetic elements (internal and external).
Signal decomposition is implemented numerically using a software prototype and generally known algorithms among others: numerical filtration, FFT analysis, wavelet analysis, demodulation of amplitude modulation (AM) and frequency modulation, 3D analysis of vector components.

5. Results
Examples of PMOS capabilities in the area of EMI, CM, NDT and SHM as well as failure state tests are illustrated in Figure 4 – Figure 9. The obtained research results showed the possibility of extending the functionality of the Metal Magnetic Memory (MMM) method [15, 23] and the need to correct substantive errors in the standard ISO-24497 [36].

Figure 4. Impact of observation distance on the distribution of the magnetic field near the R1 working blade of a SO-3 engine compressor - a simple test enables the optimal selection of the PMSO measuring range and the type of magnetometer as well as the coefficients of the influence of DUT components on the $B_p$ signal

Figure 5. Cold start of SO-3 turbine engine ($n_{max} \approx 2000 \text{ rpm}$): remote measurement of instantaneous rotational speed from $0 \rightarrow n_{max} \rightarrow 0$ and identification of the technical condition of the middle support by MI PMOS, measuring distance up to 1.0 m from the engine, sensitivity of PMOS about 1 nT, ODR = 250 Hz [37]
Main parts:
- Rotor blades: 4 \( f_B = 4.0 f_T \)
- Adjustable diffuser blades
- Turbine shaft (horizontally, \( f_T \))
- Angular gear
- Generator shaft (vertical, \( f_B \))
- AC generator

Working medium: water

Synchronization with the 50 Hz power grid

Figure 6. Magnetic field disturbances near the Kaplan turbine - possible remote monitoring of turbine operation parameters and technical condition of its components by PMOS [38]

Figure 7. Magnetic field near the gear wheel from the gearbox of the Mi-24 helicopter after an emergency landing - the visible effect of overloading the group of teeth (without cracks) and the PMOS distance on averaging of magnetic anomalies generated by teeth and diagnostic symptoms [38]
Figure 8. Monitoring of laser clean rust (ablation) by low-cost PMSO [39]

Figure 9. Comparative studies of MRT and PMSO (MMM) methods in the diagnosis of mining ropes – the synthetic aperture of the magnetometer array provides better signal-to-noise ratio (SNR) than the Magnetic Rope Testing (MRT) method - active magnetic state observer (Magnetic Flux Leakage, MFL) using in NDT [40]

Conclusion

The theoretical foundations of the passive magnetic state observer are presented. Possible functions of PMSO have been experimentally verified for:
- non-contact monitoring of electromagnetic interference near the DUT,
- non-contact condition monitoring of DUT,
- nondestructive testing – most reliable then metal magnetic memory method,
- non-contact structural health monitoring,
- failure cause analysis,
- prognostic and health management.

Further research work will be focused on increasing the measurement capabilities up to 25 kHz in the pT range, improving research methodologies and verifying diagnostic symptoms on dynamic objects.
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