NDE OF MINING ROPES AND CONVEYORS USING MAGNETIC METHODS

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ABSTRACT

Assurance of safe operation and maintenance of vertical and horizontal transportation systems (skip hoists, belt conveyor flights) is a main task for NDT specialists in mining engineering. An active and a passive methods of magnetic non-destructive testing are described in the paper. The active MRT method which uses a strong magnetic field and is a basic method in examination of ferromagnetic ropes is presented. Negative aspects of the MRT method are identified: reduced reliability of examination for compact ropes with surface wire contacts. A proposition of MRT method complementation by means of a passive NDT method – Metal Magnetic Memory (MMM) is also described. In the paper there are presented: theoretical foundations of changes in ferromagnetic remanence under the influence of stresses and operational conditions, a previous scope of the MMM method in ISO 24497, observations of MMM method users from examinations out of the scope of ISO 24497 and results of own research (laboratory and comparative studies) performed on an operational object. It has been pointed out that sensitivity and resolution of contemporary triaxle magnetometers enable to reliably detect magnetic anomalies in magnetic signatures of stranded and compact ropes without the necessity of their magnetization. MRT and MMM methods complement each other. Therefore, it is reasonable to apply both methods in order to increase reliability of examinations.

KEYWORDS: Damage, Mining, Rope, Non-Destructive Testing (NDT), Structural Health Monitoring (SHM), Magnetic testing, Measurement, Signal analysis, Diagnosis

1. INTRODUCTION

Assurance of safe operation and maintenance of vertical and horizontal transportation systems (skip hoists, belt conveyor) is a main task for NDT specialists in mining engineering. Critical elements are steel ropes with different diameters and structures which are accessible directly or through the layer of other material. A basic method of NDT and SHM of ropes (Device Under Testing, DUT) is an active MRT (Magnetic Rope Testing) method [1-6] which is based on artificial, longitudinal magnetization of ropes within the reach of a measuring head and detection of disturbances in a Magnetic Field Line (MFL) in the vicinity of the rope surface by a coil and a Hall sensor. The results of MRT examinations enable detection of Local Faults (LF), changes in Local Magnetic Area (LMA) of ropes, defects such as: fractures of single wires, a set of cracked wires, changes in density of wire structures which are the most frequently observed in steel ropes. From above 80 years MRT method has been a reliable NDT method for classic stranded ropes with point and linear wire contacts. However, a weakness of MRT method is reduced probability of detection (POD) for modern compact ropes with surface wire contacts. Reduced POD concerns detection of internal wire failure which can results from dense structure of external wires and difficult penetration of strong magnetic field into the interior of a compact rope.

A different approach to failure detection is applied in the MMM method [1, 7-15]. The aim of the MMM method is to detect local anomalies without artificial magnetization of a material. The methodology of MMM examinations should enable detection of internal wire failure for compact ropes, providing that:

- special metrological care will be taken including a proper selection of a magnetometer and measuring range, sensitivity and resolution;
- the effect of diagnostic symptom dispersion MMM by following wire layers will be taken into account in algorithms of the measurement signal analysis.

The magnetic and electromagnetic methods are also used in expert systems to Structural Health Monitoring (SHM) of ropes and conveyor belts [16, 17]. In systems that:
• do not require high qualifications of the diagnostic system operator (as opposed to NDT) - expert knowledge is “stitched” in the software;
• they are permanently installed (measuring heads, cabling, local data recorder with network card) in the monitored facility;
• ensure high repeatability of measurement conditions;
• provide continuous and reliable control of the technical condition of supervised DUTs at a remote computer station using modern algorithms for measurement data analysis;
• they automatically detect operating errors DUT (the main cause of accelerated fatigue consumption) and count load cycles (including direction and length of DUT displacements, number of bends, time between load cycles);
• they have verified algorithms for the analysis of the real life curve DUT and forecasting durability, taking into account structural features and real working conditions.

Dynamic development of electronics (analogue and digital sensors, ADC converters, microprocessors, radio and network cards) cause that portable NDT devices have lower power demand and longer working time on one battery charge as well as greater computing possibilities, and investment costs in the SHM system they turn quickly. SHM systems are becoming more and more attractive to the user.

The article presents selected aspects of magnetic testing of ropes and conveyor belts used in Polish mining, including the problem of reliable diagnosis of compact ropes by MRT and MMM methods.

2. RESEARCH PROBLEMS

Only about 20% of the free rope's cross section is accessible for a visual inspection. In order to also gain information about the remaining 80% of the steel wire rope cross section, magnetic non-destructive test methods have been developed in XX century, among others MRT and MMM. Magnetic methods are also a basic way to control rubber belt conveyors with a steel core – Fig. 1. The quality and reliability of magnetic testing NDT and SHM affects the safety of machine operation which is an impulse for their development along with the dynamic development of microelectronics (sensors, ADCs, microprocessors), computing power of processors and new algorithms of signal analysis.

In the mining industry are ropes with point and linear contact wires – Fig. 1.a), for the evaluation of which more than 80 years is applied active method MRT (MFL) and diagnostic symptoms detection: Local Faults (LF), Loss of Magnetic Area (LMA) and Structural Faults (SF). Newer technology is compact ropes with a surface-like contact of wires and a dense arrangement of external wires - Fig. 1.b) Their construction is conducive to closing the gaps of broken internal wires and the accumulation of ferromagnetic corrosion products inside the rope. In effect symptoms of LF and LMA of MRT method do not reflect the actual health of the rope [2]. To reduce this risk, new types of measuring heads are needed, measuring systems (preferably parallel multichannel measurement with at least 24-bit resolution of ADC transducers) and verified new criteria and algorithms for expert analysis of measurement data.

Fig. 1 Showing section of: a) wire ropes with conventional strands; b) wire ropes with compacted strands; c) „ST” type steelcord belt; d) belt with fleximat mesh

Relationships between the number of broken wires leading to rope breakage and fatigue durability (including the maximum number of rope deflections the speed of cracking wires) are determined by the structural features of the rope - Table 1. In magnetic NDT methods these aspects are often overlooked and the diagnosis is made only on the basis of raw, noisy measurement data (RAW) and simple algorithms for counting the density of LF and LMA damage symptoms on the control length of the rope:

• 6 times the ropes diameter (6d, it is the equivalent to about 1 lay length) or 30 times the rope diameter (30d) according to standard DIN 15020-2;
• 3d, 6d and 30d according to old standard DIN 3088, replaced by DIN EN 13414-1:2009-02.
The durability of ordinary lay ropes is about 50% lower than the lang's lay ropes which is consistent with the theory and results of research carried out by various research teams. In coiled ropes the growth of cracked wires is slower but in the final phase there is an avalanche process. The overlooked of the moment of approaching the inflection point of the curve may result in breaking the rope between successive NDT tests and the user's exposure to financial losses and the risk of an accident. A different course of the process of increasing fatigue of ordinary lay ropes and lang's lay ropes, present simultaneously in rotation-resistant ropes requires:

- precise location of broken wires and using additional diagnostic criteria in NDT and SHM;
- knowledge of the number of cycles of rope deflection;
- developed algorithms for measurement data analysis which in a modern digital magnetic flaw detector should be implemented in on-line mode (with a maximum delay of a few milliseconds) which enables automatic rope marking or automatic taking of pictures in suspect rope zones and then verification of non-destructive testing results and symptoms after its postponement and disentanglement.

Most manufacturers of NDT test equipment do not provide full metrological characteristics of the measuring head/probe and data recorder. As a result, verification of metrological parameters affecting the reliability of diagnosis lies with the user.

Discrete signals $u_{\text{mes}}(k) = u_{\text{sensor}}(k) + \text{noise}(k)$ from MRT and MMM sensors loaded with the input impedance of the measuring path, they also contain:

- colourful noise generated by the elements of the measuring path $\epsilon_n(k)$;
- possible impulse interference $\epsilon_i(k)$ generated by strong sources of electromagnetic radiation located near the DUT, eg. high-power AC and DC motors, waveform converters, welders, transformers;
- continuous discretization noise $\epsilon_d(k)$;
- possible aliases $\epsilon_a(k)$ from measured continuous signal multiplied spectra during discretization in ADC transducers (with faulty construction of the recorder input system and failure to satisfy the Nyquist condition).

The reliable detection of magnetic anomalies by means of the MRT and MMM methods requires separation of the signal $u_{\text{sensor}}(k)$ on the above components, including:

- expected spectral properties of detected magnetic anomalies which are dependent on the shape, size and position of the defect in the ferromagnetic and the progressive speed of the DUT during measurements (for a given distance from the DUT, the wavelength of the given anomaly is unchanged);
- spectrum of coloured noise determined during periodic control of the measurement path with statistical methods, e.g. Allan deviation;

### Table 1 Fatigue life of 6x47NWS-FC ropes with a diameter of 52 mm [18]

<table>
<thead>
<tr>
<th>Rope construction</th>
<th>Number of cycles for the first wire break, $N_0$</th>
<th>The number of wire breaks on the length of 4.77 m during the last inspection before breaking the rope</th>
<th>Number of fatigue cycles until the last inspection, $N_i$</th>
<th>Number of fatigue cycles to break the rope, $N$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Langs lay</td>
<td>23000</td>
<td>65</td>
<td>34570</td>
<td>34594</td>
</tr>
<tr>
<td>Ordinary lay</td>
<td>7000</td>
<td>206</td>
<td>14320</td>
<td>15108</td>
</tr>
</tbody>
</table>
signal-to-noise-ratio level (SNR) determined for standard laboratory signals and magnetic anomaly patterns in the DUT.

3. THEORETICAL BASES OF MAGNETIC METHODS NDT AND SHM

Magnetic studies of ferromagnetic objects (among others MRT and MMM methods) are based on: basic relations with magnetism described by equations (1) - (3) and the principle of deflection of the magnetic field lines at the boundary of two centres with different magnetic permeability’s described by equations (4) and (5) for the components of normal and tangential vectors \( B \) and \( H \) relative to the boundary surface.

\[
\begin{align*}
B &= \mu_0 (H + M) \quad (1) \\
M &= M_i + M_r \quad (2) \\
\mathcal{R} &= \frac{l}{\mu A} \quad (3) \\
B_{1n} &= B_{2n} \quad \frac{H_{1n}}{H_{2n}} = \frac{\mu_2}{\mu_1} \quad (4) \\
\frac{B_{1t}}{B_{2t}} &= \frac{\mu_1}{\mu_2} \quad H_{1t} = H_{2t} \quad (5)
\end{align*}
\]

Where: \( B \) is a magnetic induction, \( H \) is the intensity of magnetic field, \( M \) is the magnetization of material, \( \mu_0 = 4\pi \times 10^{-7} \ (H/m) \) is the permeability of magnetic vacuum, \( \mu = \mu_r \mu_0 \) is the relative permeability of the material (dimensionless), \( \mathcal{R} \) is the reluctance of a magnetically uniform element, \( l \) is the length of the magnetic path in meters, \( A \) is the cross-sectional area of the circuit in square meters.

The magnetization of the material (unmeasurable directly) contains two components:
- \( M_i \) is magnetization induced by an external magnetic field, directed in accordance with the vector of the forcing field and disappearing after its removal;
- \( M_r \) is residual magnetization recorded and saved in the non-linear ferromagnetic material through the history of its operation and the operation of the external magnetic field.

For ferromagnetic (strongly non-linear material) there is no definite relationship between \( H \) and \( M \). Magnetization also depends on the history of changes in magnetic field strength (magnetic hysteresis) which is consciously used in NDT and SHM.

Three magnetic research strategies are used in NDT and SHM:
- Measurement performed during strong magnetization of the DUT material - when: 1) the criterion is met \( M_i \gg M_r \) with simultaneous “erasure” of information about an unknown history of DUT exploitation mapped in the existing component \( M_r \); 2) the expected distribution of the magnetic field lines in the DUT and its vicinity was obtained; 3) the symptoms of discontinuities of structures located perpendicular to the magnetic field lines were strengthened. This high signal-to-noise-ratio (SNR) strategy is used in the active MRT method (method of magnetic flux line adapted for testing ropes).
- Measurements in a weak magnetic field (Earth and surrounding ferromagnetic elements) after a strong pre-magnetization of the DUT material in order to: 1) “delete” the current component imitating an unknown history of DUT exploitation; 2) obtaining the expected reference distribution \( M_r \) with a value often greater than the original value \( M_r \); 3) the use of sensitive vector magnetometers and a lighter measuring head (distribution of MRT head mass on the mass of the magnetizing head and measuring head) for the detection of magnetic anomalies (LF and LMA symptoms from MRT). This strategy is used in the MRT + MMM hybrid method. It is also unknowingly used in the MMM method when tests are performed on the site on which MRT tests were performed earlier. The MRT test technology most often does not provide for the demagnetization of the DUT material after the completion of the tests.
- Measurement in the weak magnetic field of the Earth and surrounding ferromagnetic elements without interfering with the existing value \( M_r \) in order to: 1) detect magnetic anomalies correlated with areas of accelerated degradation of the DUT material (information recorded by stress magnetization and local magnetic non-uniformity of the material); 2) the use of cheap and sensitive vector magnetometers with low power demand (essential for SHM systems and mobile NDT applications).This strategy which requires more attention and effort at the stage of measuring data analysis, is used in the passive MMM method.
3.1. MRT METHOD

In NDT the MRT method is based on a closed magnetic circuit with air gap whose element is the tested part of DUT, moving with the progressive speed \(v\) less than the maximum working speed of the rope \(v_{\text{max}}\) (typically \(v < 4 \text{ m/s} \) and \(v_{\text{max}} \in (10 \text{ m/s}; 20 \text{ m/s})\) and local measurement:

- (near the DUT) the result of the velocity of changes in the normal component of the scatter field \(\frac{dB(t)}{dt}\) and angle of the magnetic field lines \(\frac{d\theta(t)}{dt}\) (changes in the voltage of the measuring coil \(u_{\text{c}}(t)\)) or parameters of the scatter field \(B(t)\) (Hall sensor voltage changes \(u_{\text{H}}(t)\)) and detection of magnetic anomalies in the DUT material;
- parameters of the magnetic flux \(\Phi_{\text{load}}\) of closed magnetic circuit, imaging the reluctance \(R\) of magnetic circuit and indirect reluctance of DUT’s material and its health. A Hall single-axis (1D) sensor placed in the gap between the DUT and the head’s magneto or near the surface of the head’s magnetic core is used for the measurement. Coils are also used to measure reluctance changes.

The air gap between the magnetizing circuit of the measuring head and the DUT:

- weakens the magnetization of the tested material and affects magnetic permeability \(\mu_{\text{m}}(H)\) material yoke (soft ferromagnetic) and DUT (medium ferromagnetic) and slightly modifies the working point of the permanent magnet NdFeB, more strongly - the magnet from AlNiCo;
- reduces the non-linear properties of the magnetic circuit;
- enables optimization of the magnetic circuit work point in order to obtain the maximum sensitivity of LF and LMA symptoms detection;
- changes the amplitude and wavelength (spectrum) of symptoms LF, LMA, SF - must be controlled.

Two groups of coils spaced evenly at different distances from the DUT axes (with \(K\) and \(M\) coils), wound on ferrite cores and connected in series are most commonly used to detect and locate the magnetic field discharge from the DUT. In this configuration of the measuring head:

- only a coarse location of the defect depth is possible (by the signal amplitude) without precise determination of its angular position (on the DUT circuit).
- it is difficult to detect the group of wire failures with different magnetic polarizations, because the signals of disturbance of the magnetic field detected by individual coils of the serial circuit compensate each other and weaken the resultant signal registered by the measurement system.

Only a few measuring heads for MRT rope testing enable disconnection of the serial circuit and parallel measurement of signals from each coil [4]. Multi-channel measurement systems are used to diagnose conveyor belts. For this DUT containing several dozens of parallel ropes in rubber a measuring head is used in which each subsequent ropes outside the group. The coefficient and influence of individual ropes on the induced signal depend on the spatial characteristics of the measurement system (coil geometry, yoke spacing and geometry), distance of measurement, distance between ropes and rope diameter.

Signals \(u_{c1}(t)\) and \(u_{c2}(t)\) induced in coil assemblies (closer and further away from the axis of the rope, without being loaded by the input circuit of the measuring path), describe the formulas (6) and (7):

\[
u_{c1}(t) = \sum_{i=1}^{M} \left( -k_{1,i} \frac{dB_i(t)}{dt} - A_i \cos[\theta_i(t)] + k_{2,i} \frac{d\theta_i(t)}{dt} B_i(t)A_i \sin[\theta_i(t)] \right)
\]

\[
u_{c2}(t) = \sum_{i=1}^{N} \left( -k_{1,j} \frac{dB_j(t)}{dt} - A_j \cos[\theta_j(t)] + k_{2,j} \frac{d\theta_j(t)}{dt} B_j(t)A_j \sin[\theta_j(t)] \right)
\]

where \(k_1\) and \(k_2\) are the constructional parameters of the coils and the distance of the rope from the coils. The distribution of the magnetic field near the group of ropes in the conveyor belt and changes and within a given coil, they are the resultant of adding the influence of the ropes of a given group and the weaker influence of the subsequent ropes outside the group. The coefficient and influence of individual ropes on the induced signal depend on the spatial characteristics of the measurement system (coil geometry, yoke spacing and geometry), distance of measurement, distance between ropes and rope diameter.

Signal from a single-axis Hall magnetometer is proportional to the magnetization of the DUT which can be described by a low-order polynomial (8) in the sensor’s working range.
\[ u_{Hall}(t) = a_0 + \sum_{k=1}^{m} (a_k \cdot B_{load}^k) \propto b_0 + \sum_{k=1}^{m} (b_k \cdot M_{DUT}^k) \propto \]

(8)

### 3.2. MMM METHOD

MMM is a passive method of NDT and SHM which uses the fundamentals of physics from magnetism. According to the theory of magnetism, each ferromagnetic object in the magnetic field is induction magnetized \( M(x, y, z, t) \) and has a non-zero residual magnetization \( M_r(x, u, z, t) \). The effect is the source of magnetic anomalies \( \Delta B_{DUT} \) (has its magnetic signature) near the DUT. The heterogeneity of the structure of the DUT material, including:

- increased dislocation density in the wire break zone;
- local changes in the shape of wires (corrosion, plastic deformation, clashes);
- stress.

they are a source of additional magnetic anomalies \( \Delta B_{anomaly} \) imposed on the magnetic signature of the object and the induction of an external magnetic field DUT. Both components of the magnetic field disturbances are detectable by passive magnetic methods - Fig. 2. Magnetic anomaly of different wavelengths are determined from the formula (9) taking into account the Nyquist criterion during the discretization of the measurement signal.

\[ \Delta B_{anomaly} = \Delta B_{measure} - \Delta B_{expected} \]

(9)

![Fig. 2 Detection of magnetic anomalies: a) on the surface of the transformer sheet using the MagEye microscope (depiction of magnetic domains near the line of laser scribing recorded by the insulator layer using the MOKE method) [19]; b) broken rope wire using a ferromagnetic powder (passive MPI NDT) [20]; c) permanent magnet with a magnetic camera type MagCam MiniCube3D (with 12.7x12.7 mm working array and 0.1mm spatial resolution, 16384 microscopic magnetic field sensors on one single chip) [21]]
technical condition of the material (chemical composition, microstructure and level of degradation) \( D(t) \) – the main objective of NDT and SHM research.

In MMM method the measurement is carried out in an open magnetic circuit by a 1D, 2D or 3D vector magnetometer, so measurement results are also influenced by the shape of the DUT and its position relative to the external homogeneous magnetic field of the Earth which takes into account the demagnetization coefficient \( N \). Magnetization of material \( \mathbf{M} \) describes the equation:

\[
\mathbf{M} = \mathbf{M}(H, T, \sigma, N, D, t)
\]  

(10)

The parameters of the Earth's magnetic field (in which the DUT is located) depend on its geographical location (latitude and longitude and altitude above the sea level) which means that the symptoms of the diagnostic defect have different parameters (amplitude and spatial distribution) → diagnostic criteria must be defined for a given DUT location. The amplitude and spatial resolution of the magnetic signature of the DUT and structure defects are very sensitive to the change of the distance and position of the magnetometer with respect to the DUT (exponential function with a power factor between 2.0 and 3.0).

Magnetisation of the DUT in a weak magnetic field (Earth’s and surrounding elements) describes the implicit function of several variables which makes it difficult to quantitatively and qualitatively analyse the results of MMM research on the basis of only data from magnetometers → not every magnetic anomaly present in the results of the MMM research is caused by structural defects. Therefore in the MMM research methodology, additional assumptions overlooked in the ISO24497 standard should be accepted:

- a fixed or known position of a vector magnetometer or matrix of vector magnetometers with respect to the DUT surface;
- known location of DUTs and magnetometers in relation to the Earth's magnetic field and other ferromagnetic objects (verified models of the Earth's magnetic field [28] and measurement data from low-cost three-axis accelerometers and gyroscopes made in MEMS technology are helpful).

which significantly limits the number of variables and makes it possible to objectively verify the results of the MMM research. Only in the working range of a very sensitive magnetometer used in MMM research its signal (voltage, less often the current or frequency depending on the type of magnetometer) is proportional to the magnetic induction or the magnetic field intensity \( \mathbf{B} \) near the DUT. In addition to the operating range indicated by the manufacturer in the catalogue data, saturation or deflection of the characteristics of the magnet sensitive element occurs and the measurement data are unreliable. A recorded MMM signal describes the equation:

\[
u_m = \begin{cases} f(B) & \text{for } B \in (B_{\text{min}}; B_{\text{max}}) \\ \text{out of range} & \text{for } B \notin (B_{\text{min}}; B_{\text{max}}) \end{cases}
\]  

(11)

For measurement data obtained from 3D magnetometers it is possible to determine:

- the amplitude of the vector \( \mathbf{B} \) (or \( \mathbf{H} \), for measurement in the air \( \mathbf{B} = \mu_0 \mathbf{H} \)), \( B = \sqrt{B_x^2 + B_y^2 + B_z^2} \);  
- vector projections \( \{B_{xy}, B_{xz}, B_{yz}\} \) of vector \( \mathbf{B} \) on the orthogonal plane of the magnetometer coordinate system;  
- the inclination angles, deviations and deviations of the vector.

Reliable detection of a real magnetic anomaly is possible. To isolate the symptoms of magnetic anomaly it is necessary to differentiate the analogue signal before discretizing the signal or determining the gradient of the scaled, discrete measurement data sampled at a frequency \( f_s \).

4. OBJECT AND AIM OF R&D

Magnetic tests were carried out on various types of ropes and belt conveyors with steel cord used in mining industry. The main objective of the research was the detection and identification of magnetic anomalies (structural defects) with different wavelengths using the MRT and MMM methods.

Measurement signals from sensors and magnetic anomaly signatures are amplitude modulated and frequency by the instantaneous progressive and transverse velocity of the DUT as well as constructional features and magnetization of the DUT. The frequency spectrum of a given magnetic anomaly depends on the instantaneous speed of the DUT. To reliably identify weak symptoms of a magnetic anomaly is necessary:

- reliable measurement data that meets the Nyquist criterion;  
- identification of noise parameters and initial filtration of measurement signals;
5. MEASUREMENTS

The MRT tests were carried out using: GM heads with permanent magnets (adapted to geometric features of the DUT) and MD121 recorder from Zawada [4, 29]. The measuring heads are equipped with two coil circuits spaced evenly and a Hall sensor. The MMM tests were carried out using various analogue and digital magnetometers, among others:

- SpinMeter3D (3-axis TMR magnetometer probe) from MicroMagnetics [30];
- magnetic ruler AMI305-16AR (including 16 3-axis MI AMI305 digital compass) from Aichi [31];
- 3-axis TMR magnetometer FXOS8700 by NXP [32];
- a prototype module with three magnetometers XEN1210 (1-axis Q-Hall magnetometer) from Sensixs [33].

6. RESULTS

During the laboratory tests, the following were verified: 1) metrological parameters of MRT and MMM measuring systems; 2) magnetic signatures and defects; 3) new data analysis algorithms. The measurements were carried out on ropes testing stations at different speeds of the measuring head relative to the DUT and on the 1D scanner with the advancing speed up to 0.1 m/s (with a spatial resolution not worse than 0.02 mm). The sample results are illustrated in Fig. 3 and Fig. 4.

![Fig. 3](image-url)

Fig. 3 The impact of the probe’s distance from the DUT (belt with steel cord, d=2.7 mm, pitch=10 mm) on the diagnostic symptoms of a single defect (numerical simulation in Autodesk Inventor and Comsol Multiphysics):

a) the belt is OK, b) the belt with cord defect; c) h = 0 mm; d) h=50 mm
Fig. 4 Testing of the conveyor belt with the rope failure patterns of the magnetometers matrix: a) RAW data of the magnetic induction amplitude (zeroing of magnetometers to the existing magnetic field before starting the measurement, 'B' - beginning of belt motion, 'E' - end of belt motion, $f_s = 66.7$ Hz); b) detection of rope damages with a statistical estimate determined by the TKEO transform from the IF estimator, level POD > 0.9

The passive experiment were carried out on conveyor belts and ropes operated in mining industry. Comparative studies of the MRT and MMM methods were carried out on the compact line DF34LR (16/6/6/6/1) with a nominal diameter of 42 mm and the rope stroke length 262 mm, operated on the Bzie1 lifting machine. On the rope there were symptoms of accelerated fatigue consumption generated by the cooperation of the rope with the drum of the winding machine. Symptom of a strong magnetic anomaly and plastic deformation of the rope was observed every 1 turn of the drum. On the measurement data from real objects the new algorithms of measurement data analysis of the MRT and MMM methods were also verified. The sample results are shown in Fig. 5.
Fig. 5 Comparative NDT study of compacted wire rope (MRT and extended MMM methods): a) measure path - MRT, MMM and IMU heads close the DUT (compacted rope); b) RAW data of B_y component; c) results of comparative tests MRT and MMM estimators [2]; d) results of 3D magnetometer (without offset) and 3D accelerometer of IMU head - oscillation of the rope (y_{DUT} = 1 m/s, f_{MMM} = 1066 Hz (equivalent), f_{IMU} = 200 Hz); ground vibration have a neglected effect on the MMM head; e) analysis of magnetic anomalies A and B with line of magnetometers horizontally (B_y - tangent to the rope, B_x - radial, B_z - along the rope, #1 and #16 – respectively magnetometer number 1 and 16)

7. CONCLUSIONS

Based on the conducted tests, it was confirmed:

- the advantage of both magnetic NDT methods - low cost of non-destructive testing and the ability to quickly detect: cracks, clashes, plastic deformation and corrosion;
- the effectiveness of the MMM method for diagnosing ropes and transmission belts with a steel cord;
- new diagnostic symptoms of MRT and MMM methods determined by the tested algorithms of extended MRT and MMM data analysis.

For diagnosing compact ropes it is advisable to use the NDT / SHM hybrid method - simultaneous MRT and MMM measurement with min. 24-bit resolution of ADC transducers or:

- oversampling - using cheaper and faster 16-bit converters and decimation improving the signal-to-noise ratio (SNR);
- parallel measurement of the matrix of sensors with low sampling frequency.

It is possible to further increase the POD of the MMM method by:

- precise monitoring of the position of the rope (transversal and torsional movements) with respect to the matrix of 3D magnetometers;
- application of "sensor fusion" technology - inclusion of measurement data from accelerometers and gyroscopes (made in MEMS technology) to control the current position of the measuring head.

REFERENCES

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