THE REFERENCE SIGNAL FOR MMM EXPERT SYSTEMS

SYGNAŁ REFERENCYJNY DLA SYSTEMÓW EKSPERCKICH MPM

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Abstract: The first step of a methodological approach to the validation of the metal magnetic memory (MMM) method in non-destructive testing (NDT) applications and in systems used for the diagnosis of early stages of material fatigue in mechanical constructions (SHM, PHM) has been presented in the paper. The study is focused on the properties of the external natural source of magnetisation of the object under MMM examination and the impact of its components. The precise data of the Earth’s geomagnetism measurements (from ground stations and satellites) and the revised model of the Earth’s magnetism can be applied in order to calibrate high sensitive magnetic field sensors, validate measurement results and extend the functional capacity of the MMM method.

Keywords: magnetic field, magneto-mechanical effects, structural health monitoring

Streszczenie: W artykule przedstawiono pierwszy krok metodycznego podejścia do wuiarygodnienia metody magneckiej pamięci metalu (MPM) w aplikacjach badań nieniszczących i systemach diagnozowania wczesnej fazy zmęczenia materiału konstrukcji mechanicznych. Uwagę skupiono na właściwościach zewnętrznego naturalnego źródła magnesowania materiału badanego elementu i wpływ jego składowych na wyniki badań MPM. Wskazano możliwość wykorzystania precyzyjnych danych z pomiarów geomagnetyzmu Ziemi (ze stacji naziemnych i satelitów) oraz zweryfikowanego modelu magnetyzmu Ziemi do wzorcowania wysokoczułych czujników pola magnetycznego, weryfikacji wyników pomiarów i rozszerzenia możliwości funkcjonalnych metody MPM.

Słowa kluczowe: pole magnetyczne, efekty magneto-mechaniczne, systemy monitorowania stanu technicznego
1. Introduction

Magneto-mechanical effects resulting from a lattice-spin coupling are more and more often used to diagnose critical structural elements, that are made of ferromagnetic and paramagnetic materials. In non-destructive testing (NDT) and systems to monitor early fatigue symptoms (SHM, PHM) following processes are used [1-5]:

- reversible paraprocesses (Joule'a effect, Villari effect and derivative phenomena),
- irreversible paraprocesses (ΔE effect, Metal Magnetic Memory (MMM) which is an equivalent for Natural Remanent Magnetization (NRM) in geophysics).

Diagnostic information not only about the level of dislocation’s concentration (1st phase of fatigue followed by micro and macro cracks) and cracks but also about changes of internal stresses and the history of maximal material effort can be obtained by means of non contact measuring of magnetization level and distribution. Fig. 1. These features of a passive observer with use of magneto-mechanical phenomena are a base for Metal Magnetic Memory method [6-11].

Interpretation of results for MMM method (research without artificial magnetization of metal) is difficult. Main problems are as follows:

- **natural magnetization signal** – weak Earth’s magnetic field, its intensity and components are dependant on a place and time of performed research (validation of a passive method in different laboratories with use of defect patterns);
- **magnetization of polycrystalline structure with different defects** – shortage of systematized knowledge on magnetic features of constructional steel, simplified models of magnetization without periodical components and noise of Earth’s magnetic field;
- **reference signal** – differential measurements applied in geophysical research (increasing sensitivity of measurements) are not always able to use during measurements performed in interiors with strong ferromagnetic objects (i.e. palisade of compressor/turbine blade).

A proposal to support MMM method by means of data from numerical models of Earth’s magnetism, the INTERMAGNET database and NOAA/SWPC space alerts is presented in the paper.

2. The diagnostic signal in the metal magnetic memory method

The metal magnetic memory method uses the impact of the weak magnetic field of the Earth $B_m$ and electromagnetic noise $\varepsilon_m$ (of the external natural magnetic field $B_i$) to observe the changes in the local magnetic, electric and mechanical properties of the polycrystalline material (mapped among others by orthogonal components of the magnetic permeability $\mu = [\mu_1, \mu_\perp, \mu_n]$, electric conductivity $\rho = [\rho_1, \rho_\perp, \rho_n]$ and Young’s modulus $E = [E_1, E_\perp, E_n]$) of the component under examination) – transmittance $G$. The value to measure is magnetic field $B_p$ in close by the monitoring object, Fig. 2, whose value results from the local structural anisotropy of the material $S$ and distance $\Delta r$ between the object and magnetic sensor.
Reversal stress magnetization $\Delta B = f(\sigma)$ (piezomagnetic sensor, EMAT, MsS, ET)

Irreversible stress magnetization $\Delta B(\sigma=0)$ (MMM diagnostic)

$\Delta B = f(\sigma)$ (piezomagnetic sensor, EMAT, MsS, ET)

Fig. 1 Detect of stress prehistory: a) reversible and irreversible process of stress magnetization [3]; b) identification of blade fatigue risk ($H_p = f(\text{blade number})$) [5]
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Fig. 2 The idea of MMM testing

The health of the object and the fatigue stage of its material (mapped by mechanical and physical local properties) are expressed by the relation:

$$ B_p(S,r + \Delta r,t) = B_e(r,t) \cdot G(\mu, \rho, E, \Delta r,t) = (B_m(r,t) + \varepsilon_m(r,t)) \cdot G(\mu, \rho, E, \Delta r,t) $$  \hspace{1cm} (1)

where: $t$ – measurement time, $r$ – coordinates of the measuring point ($r = (\lambda, \varphi, r)$ in global geocentric (field)/geographical (object) coordinates or $r = (x, y, z)$ in local cartesian coordinates (object/sensor), $r = a + h$ (a = 6371200 m – Earth’s radius, $h$ – WGS-84 ellipsoid altitude), $\mu$, $\rho$, $E$ – magnetic, electric and mechanical properties of the polycrystalline material, $\Delta r < 5$ m.

Material variables $\mu$, $\rho$, $E$ depend among others on the type (grade) and structure of the material, the external magnetic field intensity, applied and residual stresses, material temperature, dislocation density (manufacture quality and events health) and external excitation (level, frequency and historic). Material variables are complex data, which describe nonlinear property of the material. The real parts of $\mu$, $\rho$, $E$ describe reversible sub-processes (i.e. Villary effect); the imaginary part of ones describe irreversible sub-processes (losses) present during electric current flow, technical and stress magnetization (stress-strain cycles) and structure damage (residual stress redistribution, LCF, HCF, VHCF and TMF fatigue).

In order to obtain, by means of the MMM method, a reliable identification of the material health based on signal $B_p$, it is essential to know the magnetic properties (spectrum) of the Earth’s magnetic field $B_m$ and electromagnetic noise $\varepsilon_m$.

3. The earth's magnetic field

The magnetic field $B_m$ at or near the surface of the Earth is a combination of Earth’s magnetic field and fields of external (solar, space) origin [12-15]. The geomagnetic field is a sum of contributions:

$$ B_m(r,t) = B_{core}(r,t) + B_{crust}(r) + B_{disturbance}(r,t) $$  \hspace{1cm} (2)

where $B_{core}$ - the core field generated in Earth’s conducting, fluid outer core (primary geodynamo effect, about 95% $B_{m}$); $B_{crust}$ - the crustal field from Earth’s crust/upper mantle (about 4% $B_{m}$); $B_{disturbance}$ - the combined disturbance field from electrical currents flowing in the upper atmosphere and magnetosphere, which also induce electrical currents in the sea and the ground (secondary geodynamo effect).
The $B_{\text{core}}$ and $B_{\text{crust}}$ are quasi-static (secular variation), whereas $B_{\text{disturbance}}$ is rapidly time-varying (it has periodic and stochastic contributions).

Seven elements are needed to describe the field, generated by a variety of sources, Fig. 3. These are the northerly intensity $X$, the easterly intensity $Y$, the vertical intensity $Z$ (positive downwards) and the following quantities derived from $X$, $Y$, and $Z$: the horizontal intensity $H$, the total intensity $F$, the inclination angle $I$ (measured from the horizontal plane to the field vector, positive downwards), and the declination angle $D$ (measured clockwise from true north to the horizontal component of the field vector).

Components $X$, $Y$, $Z$, $F$ or $H$, $D$, $Z$, $F$ are recorded precisely by ground-based observatories of the Earth's geomagnetism and by low orbit satellites – with an accuracy better than 1 nT (induction) and 0.001 A/m (intensity), averaging values in a minute-period. Geomagnetic measurements are two/three orders of magnitude more accurate than MMM measurements, that are nowadays applied in non destructive testing of elements made of ferritic steel. When results of MMM method are analyzed (which are performed in the frequency band up to 5 Hz), a simplified model of Earth’s is applied and an influence of components $B_{\text{crust}}$ i $B_{\text{disturbance}}$ is excluded. Nevertheless, these components cannot be omitted in structural health monitoring systems (SHM), that are based on high-sensitive sensors of magnetic field and trend analysis.

4. Model of the earth’s magnetic field

A very convenient way of representing geomagnetic fields is to expand the scalar magnetic potential $V$ into spherical harmonic function [12, 13, 15]. In geocentric spherical coordinates (longitude $\lambda$, latitude $\varphi^\prime$, radius $r$) it can be written as the negative spatial gradient of a scalar potential.

$$B_m(l, \varphi^\prime, r, t) = -\nabla V(\lambda, \varphi^\prime, r, t)$$

$$V(\lambda, \varphi^\prime, r, t) = a \sum_{n=0}^{N} \sum_{m=-n}^{n} \left( g_n^m(t) \cos(m\lambda) + h_n^m(t) \sin(m\lambda) \right) \frac{a}{r} P_n^m(\sin \varphi^\prime)$$

where $N$ is the degree of the numerical model, $a = 6371200$ m is the geomagnetic reference radius, $g_n^m(t)$ and $h_n^m(t)$ are the time-dependent Gauss coefficients of
degree \( n \) and order \( m \) describing the Earth’s main magnetic field. \( P^m_n(\mu) \) are the Schmidt semi-normalized associated Legendre functions.

Such a model can then be evaluated at any desired localisation to provide the magnetic field vector, its direction or the anomaly of the total intensity of the field. Verified models of Earth’s magnetism enable to obtain an accurate reference signal \( (B_{m,\text{ref}} = B_m \pm 5 \text{ nT}) \) for MMM expert analysis, Fig. 4.

\[ \begin{align*}
  \text{Fig. 4 The SHM expert system based on MMM data (} & \alpha, \beta, \gamma, h - \text{the MMM sensor position in local coordinates relates to the object surface; MMM G2 sensor (MEMS) includes 3 channels of magnetometer (} B_x, B_y, B_z \text{) and 3 channels of accelerometer (} a_x, a_y, a_z \text{); } B_{m,\text{ref}} - \text{estimator of } B_m \text{ near the object surface; } a(t) = [a_x(t), a_y(t), a_z(t)] - \text{signal of object deformation and vibration} \end{align*} \]

5. **B_{core} - Verified models**

Determination of the expected value for \( B_{core} \) is based on free of charge low degree models, i.e. the International Geomagnetic Reference Field IGRF-11 (degree 13, 195 Gauss coefficients) [16, 17] or the World Magnetic Model WMM-2010 (order 12, 168 Gauss coefficients) [15, 18]. The source code is in the public domain and not licensed or under copyright.

The IGRF is generally revised every five years by a group of modellers associated with the International Association of Geomagnetism and Aeronomy (IAGA). The WMM is a joint product of the United States’ National Geospatial-Intelligence Agency (NGA) and the United Kingdom’s Defence Geographic Centre (DGC). The WMM was developed jointly by the National Geophysical Data Center (NGDC, Boulder CO, USA) and the British Geological Survey (BGS, Edinburgh, Scotland). The WMM is updated every five years.

The WMM-2010 is the standard model used by the U.S. Department of Defense, the U.K. Ministry of Defence, the North Atlantic Treaty Organization (NATO) and
the International Hydrographic Organization (IHO), for navigation, attitude and heading referencing systems using the geomagnetic field. It is also used widely in civilian navigation and heading systems. The WMM-2010 is valid for the period 1 January 2010 through 31 December 2014 between altitudes of 1 kilometer below the surface to 850 kilometers above the surface of the Earth. The accuracy requirements for the WMM are detailed in the military specification MIL-W-89500 (Defense Mapping Agency, 1993). In summary, the requirement is that the global root mean square (RMS) difference between the WMM and the observed magnetic field at sea level should be within 1° for $D$ and $I$, within 140 nT for $X$ and $Y$, within 200 nT for $H$ and $Z$ and within 280 nT for $F$ for the entire 5-year lifetime of the model.

The data and charts produced from IGRF and WMM models characterize only the long-wavelength portion of the Earth’s internal magnetic field (waveband of 2500 km), which is primarily generated in the Earth’s fluid core – Fig. 5.

Fig. 5 Result of WMM-2010 model (epoch 2010.0) for: a) total intensity; b) annual change of total intensity
The portions of the geomagnetic field generated by the Earth’s crust and upper mantle, and by the ionosphere and magnetosphere, are largely unrepresented in the $B_{\text{core}}$ models. Consequently, a magnetic sensor may observe spatial and temporal magnetic anomalies (typically of magnitude 200 nT, but often much larger until some thousand nT) when referenced to the models. In particular, certain local, regional, and temporal magnetic declination anomalies can exceed 10 degrees.

6. $B_{\text{crust}}$ - Verified models

Subtracting the appropriate IGFR or WMM from the observatory spline function (trend) gives the $B_{\text{crust}}$ part of the internal field that is not represented by the $B_{\text{core}}$ models. $B_{\text{crust}}$ has spatial variations on the order of meters to thousands of kilometers and cannot be fully modeled with low degree spherical harmonic models. On land, spatial anomalies are produced by mountain ranges, ore deposits, ground struck by lightning, geological faults, and cultural features such as trains, planes, vehicles, railroad tracks, power lines, etc. The corresponding deviations are usually smaller at sea. In ocean areas these anomalies occur most frequently along continental margins, near seamounts, and near ocean ridges, trenches, and fault zones, particularly those of volcanic origin. The rock magnetization resulting in $B_{\text{crust}}$ may be either induced (by the core field) or remnant or a combination of both.

A convenient way of representing local magnetic anomaly is to expand the scalar magnetic potential into spherical functions. The free of charge NGDC-720 and EMM-2010 models (products of U.S. the National Geophysical Data Center, NGDC) [19] provides such an expansion for the crustal field from spherical harmonic degree 16 to 720 (516 736 Gauss coefficients), corresponding to the waveband of 2 500 km to 56 km. The models were compiled from satellite, marine, aeromagnetic and ground magnetic surveys. The degree 720 cut-off corresponds to an angular wavelength of 30 arc minutes, providing a 15 arc minute model resolution – Fig. 6. The models are produced at 5-year intervals. To meet increasing demand for accurate geomagnetic referencing, NGDC produces the High Definition Geomagnetic Model (HDGM) [20] which accounts for long-wavelength crustal magnetic anomalies. HDGM significantly reduces geomagnetic referencing errors. The HDGM model includes main field, secular variation and crustal field to degree 720 (similar in properties NGDC-720 and EMM-2010 models) but it is updated annually. The HDGM is available for purchase from NGDC.
Fig. 6 Influence degree of numerical model on $\mathbf{B}_{\text{crust}}$ field component detection

7. B-disturbance Component

The regular variations of the magnetic field are related to rotation and/or orbital movements of the Earth, Sun and Moon [12, 14]. The most prominent is the diurnal variation or solar daily variation, having an magnitude of the order of $10^{-1}$ to $100$ nT. Solar radiation ionizes the higher atmosphere during the daylight hours, and the gravitational forces of the Sun and the Moon force the ionospheric layers in a tidal motion. So the ionized gas in the ionosphere moves in the magnetic field of the Earth, creating electric currents which are seen as daily variations in magnetic
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recordings. There are two well-known periodic variations, the solar daily variation and the lunar daily variation – Fig. 7. The lunar tides are of course not fixed to the solar day, so the lunar magnetic effect, which is small, a few nT, depending on time and latitude, can be separated only statistically from the solar effect having an amplitude up to 100 nT during summer times. The regular solar daily variation is also a function of the time of the year, solar activity, and the geomagnetic latitude.

Fig. 7 Detect of regular and stochastic components of $B_{\text{disturbance}}$ during 3 days observation (source: BEL Belsk, Poland)

The irregular variation of the ionospheric and magnetospheric fields (and $B_{\text{disturbance}}$ near the Earth’s surface) occur at time scale mostly ranging from seconds to hours are related to Sun activity and space magnetic impulse – magnitude variation up to 1000 nT and more during a magnetic storm [21]. On a longer time scale (days to years), the large-scale magnetic field of the external ring current (approximately represented by the $D_s$ index) will give perhaps 1000 nT during and after a magnetic storm.

In order to identify periodic components $B_{\text{disturbance}}$ data from local geomag-netism observatory (available in INTERMAGNET net [22]) and from developed analysis algorithm are used. In order to identify a stochastic component (the Sun activity and magnetic impulses from the Universe) converted satellite-data (NOAA/SWPC alerts [23]) are applied – Fig. 8.
8. Conclusions

The measuring data from the INTERMAGNET network and the forecasts of the space activity, provided for example by the NOAA/SWPC, and the numerical verified models of $B_{core}$, $B_{crust}$ and $B_{disturbance}$ fields have been proposed to generate reference signal and identify new MMM symptoms (for NDT, SHM and PHM applications), as well as for the systematic/periodic calibration of the magnetic field sensors, taking the...
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time of the testing and the location of the monitoring object into consideration.
The geomagnetic data $B_{m,ref}$ are a reliable base for the verification of the MMM measurement results in terms of considering unknown (for MMM users) geomagnetic phenomena, such as regular variations of the magnetic field, irregular magnetic pulses and storms or solar activity.
The National Geophysical Data Center (U.S.) is the repository and distribution center for free of charge geomagnetic models (IGRF-11, WMM-2010, NGDC-720) and data.

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9. References


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