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CALIBRATION OF MAGNETIC FIELD SENSOR USED FOR DIAGNOSIS OF STEEL CONSTRUCTION

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We present the results of an investigation into the calibration of a few types of magnetic sensors. This work focused on the diagnosis of large-scale steel construction based on the concept of a passive magnetic field observer. This relatively new method uses observed variations in the magnetic field around steel construction. Due to magneto-mechanical phenomena, the condition of construction material can be estimated and a prognosis of its state of health can be made. To achieve this aim, in addition to an algorithm, one requires a network of magnetic sensors placed near responsive locations in a construction site. These sensors characterize the sensitivity of the magnetic field at the level of the Earth's magnetic field. Considering the long duration of on-line monitoring, the invariability of the sensor parameters becomes an important feature. Magneto-resistive sensors, MR or GMR, and fluxgate type magnetometers were examined. Temperature stability of the sensors appears to play a key role. Both the sensitivity and the sensor offset temperature drift are involved during measurement. To calibrate the temperature, a set of three-axial magneto-resistive sensors was placed in a climatic chamber. In this paper the experiment results are described and a calibration method is proposed. As an example, measurements are presented from a large steel hall under laboratory and real world conditions.

Keywords: magnetic field, sensor calibration, temperature influence

1 INTRODUCTION

Materials that run a high risk of damage due to material fatigue, exceeding maximum stress or plastic deformations have magnetic properties that allow magnetic methods to be used for technical diagnostics. Parallel to the development of active diagnostic magnetic methods [1-3], a group of passive diagnostic methods have been developed [4-6] that have all the advantages of active methods but do not require artificial magnetic field sources, which require the use of complex and costly apparatuses. Furthermore, as it will be shown in this paper, while passive techniques could be applied to construction structure diagnosis, real world objects present some difficulties.

There are some problems that need to be solved to enable the application of passive magnetic methods. The diagnostic symptoms, found in the magnetic field signal during a passive measurement, exist at low levels as a rule. Therefore, the first step is to determine the relevant sensitivity of a sensor. The level of the background magnetic field is often very high in practice [7]. Thus, an ideal sensor is one with a wide measuring range and high sensitivity. In most cases the two requirements are difficult to fulfil simultaneously. Additionally, magnetic sensors need to be either independent of changing environmental conditions or properly process the results to make the measurements reliable.

The relationship between the mechanical, thermal, electrical and magnetic properties of a material have both quantitative and qualitative impacts on the behavior of the magneto-mechanical phenomena. The existing state of magnetization of a tested element is coupled with the effects of its thermal, electrical and mechanical structures.

To successfully use passive magnetic techniques for diagnosis, one must understand what factors will influence the actual measurement and how these factors are related. The next section presents measurements of steel trusses, one located in the laboratory (active experiment) and the other in the roof structure of a real object (passive experiment). Section 3 presents the behavior of different magnetometers under simulated temperature conditions, and Section 4 proposes a temperature sensor calibration. The conclusions are given in Section 5.

2 MAGNETIC FIELD SENSING FOR STEEL CONSTRUCTION STRUCTURES

Experiment on a steel construction structure under laboratory conditions

The test stand consisted of six hydraulic jacks attached to a steel frame, a configuration that allows for the application of force to the investigated steel planar truss structure located within the stand. The experimental truss (part of the construction shown in Fig. 1) was built from General purpose low-carbon steel St3 (PN-EN 10025:2004) typically used in construction engineering.

The truss was loaded using two symmetrically spaced hydraulic jacks. During the experiment, the applied load was gradually increased on the single truss and measurements were taken after load stabilization. Experiments were repeated until damage with maximal load increases for each repetition of 20 kN, 30 kN, 50 kN, and 80 kN. Magnetic sensors were used to identify the magneto-mechanic phenomena and its properties that were linked to the stress changes in the construction.

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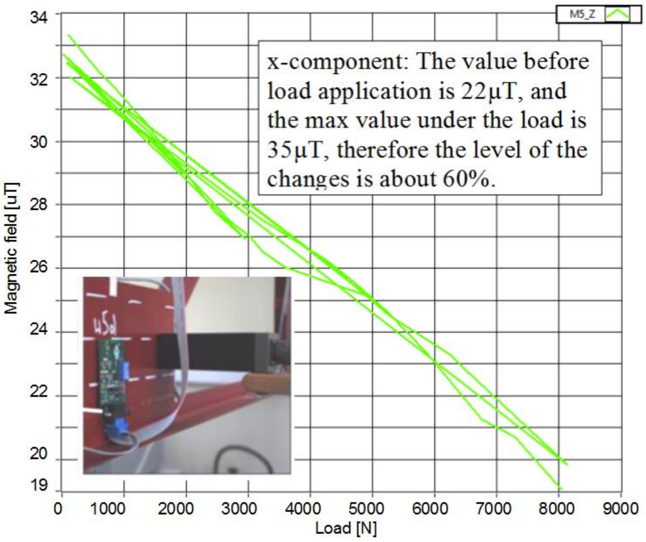

Fig. 1. Laboratory magnetic field measurements

During the experiment two types of three axial magnetometers were used: the APS-536 fluxgate type magnetometer and a low cost MRA-based magnetometer.

To compare their readings at the center joint of the truss (the steel plate connecting the three members), the two magnetometers were placed close to each other (Fig. 1), shifted by 5 cm. In the analyzed joint, five different members come together, some of them were compressed and some were tensioned so that the state of the stress in the plate had a complex nature that was very difficult to analyze.

During the experiment, both sensors showed changes in the magnetic field that were identified as the Villary effect. The recorded changes in the magnetic field were Δx=13 μT, Δy = 0.9 μT, and Δz= 18 μT for the fluxgate sensor, and Δx = 20 μT, Δy = 0.9 μT, and Δz= 14 μT for the MEMS sensor. The base level of the intensity of the magnetic field under no load was 0.22 μT in the x-direction. Truss loading to 0.35 μT increased this value by 60%. In the y-direction the increase was 62% and in the z-direction (the vertical direction) there was a 225% increase. The measurements in the x- and y-directions were well correlated with the stress changes in the joint, showing large variations during the load increase. Figure. 1 shows the results for the x-direction of the fluxgate sensor.

The change in the magnetic field appeared to be well correlated to the change of stress in the structure, especially in the characteristic direction. Both fluxgate magnetometers and the ones based on MRA transducers appear to be appropriate for registering the magneto-mechanical effects.

Table 1. Set of investigated sensors.

Specification of	**FluxGate APS 536**	**Grad-03-500L Bartington**	**ST Microelectronic LSM303**	**HMC5893 Honeywell**
Sensitivity	10V/Gauss	10μT/V	1 mG/bit	1mG (100nT) / bit
Measurment range	±1 Gauss	± 1 Gauss / 100μT	±4 Gauss	+-8 G (800uT)
Level of noise	< 3 x 10-7G RMS/Hz½	10 to 20pTrms/√Hz at 1Hz		
Frequency operation	DC 400 Hz (-3 dB)	>2kHz	75 Hz	220Hz
Power supply	±15V DC	±12VDC min, ±15VDC max	5-12 V DC	5-12 V DC
Signal output	Analog - voltage	Analog – voltage to analogue correction unit	digital	digital
Connector	Bendix 10 pin connector P/N PT02A-12-10S	Amphenol 62GB-51T14-12P	CAN/USB interfaces	USB interfaces

Experiment on a steel construction structure under real world conditions

The pitched roof of the Warsaw Waterworks hall was chosen as a real object on which to mount a monitoring system. The roof structure consists of eight interconnected roof girders in the form of flat trusses. The system was equipped with, among other things, magnetic field transducers. These sensors are of our own design, built using MRA transducers. The magnetic transducers were connected to a CAN bus system. Each sensor had its own address assigning it to the appropriate point.

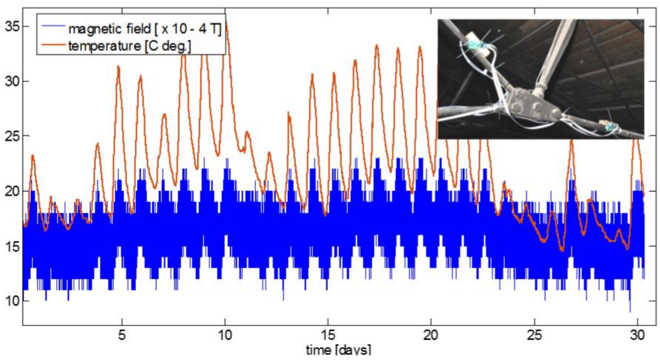

Fig. 2. Real object magnetic field and temperature measurements

The sensor's task was to observe magneto-mechanical phenomena around the steel roof structure. As it turned out, however, the dominant factor determining the sensor readings of the magnetic field was the change in the temperature.

Figure 2 shows the waveforms of the 30 days of measurements. Clearly the passive magnetic method under real conditions presents some difficulties. Solutions to these difficulties will be proposed in the following sections.

3 ENVIRONMENTAL EXPERIMENT

To investigate the significant influence of temperature on the magnetic measurements, an experiment was performed in an environmental chamber that allowed parameters such as temperature and humidity to be controlled. The study involved four different probes (Table 1), which represent two groups of sensors, fluxgate and magneto resistive.

The experimental results for three selected sensors are presented in Figs. 3 and 4.

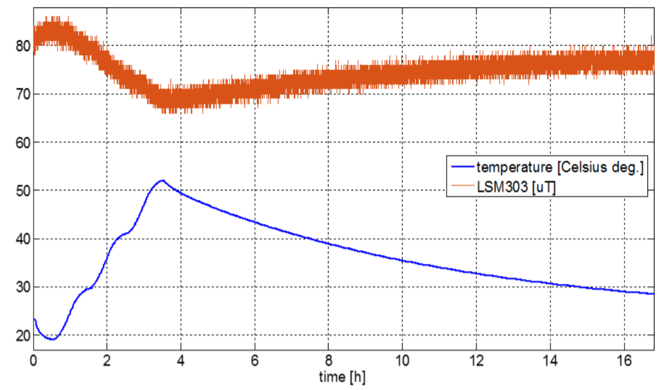

Fig. 3. Measurements in the climatic chamber – MRA based sensor

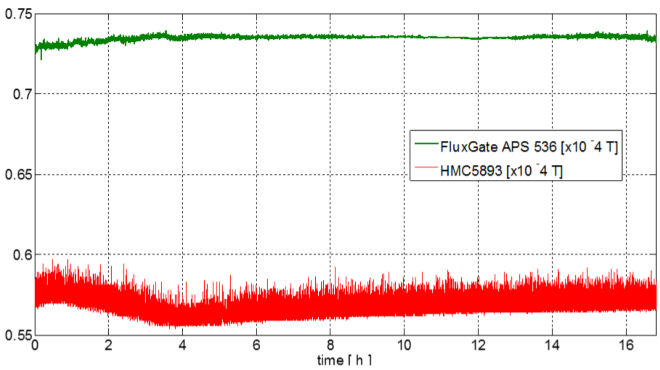

Fig. 4. Measurements in the climatic chamber – Fluxgate and MRA based sensors

The results indicate that the type of sensor has a decisive influence on its susceptibility to temperature. The least sensitive to temperature changes was the fluxgate sensor, whose level changes were at the level of magneto-mechanical effects; however, even the best sensors need temperature calibration.

4 SIGNAL PROCESSING

Magnetometric sensor calibration is a subject discussed in multiple scientific communities. In the literature, many examples can be found where the authors describe new approaches for sensor calibration [8–22]. In all cases, the fundamental relationship used can be described in vector form as follows

$$\sqrt{\mathbf{B}_E' \cdot \mathbf{B}_E} = |\mathbf{B}_E| = const \tag{1}$$

This relationship of the magnetic vector module is invariant regardless of the angular orientation of the sensor that measures the vector. The measurement model of the field is described by the following relation

$$\mathbf{B}_E = \mathbf{S}(\mathbf{B}_M + \mathbf{B}_0) \tag{2}$$

where $\mathbf{B}_E$ is the vector magnetic field measured by the sensor, $\mathbf{B}_M$ is the field value registered by the sensor, $\mathbf{S}$ is the sensitivity matrix that also describes the major misalignment of the sensor measurement axis and the rotation of the sensor coordinate system relative to the reference coordinate system, and $\mathbf{B}_0$ is a constant value applied to the recorded measurement. Multiple authors use this model, together with equation (1), as a basis to determine calibration algorithms. However, there are no publications that have addressed the described problem of sensor temperature calibration. A similar model can be used to describe the influence of temperature

$$\mathbf{B}_E = \mathbf{S}(T)\big(\mathbf{B}_M(T) + \mathbf{B}_0(T)\big) \tag{3}$$

where

$$\mathbf{S}(T) = \begin{bmatrix} S_x(T) & 0 & 0 \\ 0 & S_y(T) & 0 \\ 0 & 0 & S_z(T) \end{bmatrix}$$

$$\mathbf{B}_0(T) = \begin{bmatrix} B_{0x}(T) \\ B_{0y}(T) \\ B_{0z}(T) \end{bmatrix}$$

and for $i = x,y,z$

$$S_i(T) = s_0^i + s_1^i T + s_2^i T^2 + s_3^i T^3$$
$$B_i(T) = b_0^i + b_1^i T + b_2^i T^2 + b_3^i T^3$$

The first step is to omit the effect of the misalignment of the sensor axis. This assumes that both the constant value and the sensitivity can be described using a third degree polynomial. Using (1), a full calibration equation can be written, which could in turn be used to determine the desired coefficients. However, due to the significant complexity and high degree of the resulting equation, we use a different approach.

Experimental measurements were carried out in a climate chamber in which the test sensors were placed in fixed locations and positions. It can therefore be assumed that the magnetic field inside the chamber remained intact. Comparing the derivatives of the temperature on the left and right sides of equation (3) results in an equation of the following form

$$0=\frac{\mathrm{d}}{\mathrm{d}T}\mathbf{S}(T)\left(\mathbf{B}_M(T)+\mathbf{B}_0(T)\right) \tag{4}$$

The matrix $\mathbf{S}(T)$ is a diagonal vector equation that can be written in the form of three independent scalar equations for each of the three axes. After applying a transformation equation for the x-axis, the equation can be written in the following form

$$\frac{\mathrm{d}}{\mathrm{d}T}\begin{pmatrix}(s_0^x+s_1^xT+s_2^xT^2+s_3^xT^3)B_M^x+(s_0^x+s_1^xT\\ +s_2^xT^2+s_3^xT^3)(b_0^x+b_1^xT+b_2^xT^2+b_3^xT^3)\end{pmatrix}=0\,. \tag{5}$$

Transforming the above equation to determine the minimum number of independent coefficients, we obtain

$$\begin{aligned}&u_1^x\left(2B_M^xT+\frac{\mathrm{d}B_M^x}{\mathrm{d}T}T^2\right)+u_2^x\left(B_M^x+\frac{\mathrm{d}B_M^x}{\mathrm{d}T}T\right)+u_3^xT^5+\\&u_4^xT^4+u_5^xT^3+u_6^xT^2+u_7^xT+u_8^x\frac{\mathrm{d}B_M^x}{\mathrm{d}T}+u_9^x=\\&=-\left(3B_M^xT^2+\frac{\mathrm{d}B_M^x}{\mathrm{d}T}T^3\right)\end{aligned}\quad, \tag{6}$$

where

$$u_1^x=\frac{s_2^x}{s_3^x},\quad u_2^x=\frac{s_1^x}{s_3^x},\ u_3^x=6b_3^x$$
$$u_4^x=5(b_2^x+b_3^xu_1^x),\quad u_5^x=4(b_1^x+b_2^xu_1^x+b_3^xu_2^x)\,,$$
$$u_6^x=3(b_0^x+b_1^xu_1^x+b_2^xu_2^x+b_3^xu_8^x)\,,$$
$$u_7^x=2(b_0^xu_1^x+b_1^xu_2^x+b_2^xu_8^x)\,,$$
$$u_8^x=\frac{s_0^x}{s_3^x},\quad u_9^x=b_1^xu_8^x+b_0^xu_2^x\,.$$

The above equations offers some very interesting conclusions. The identification of the factors u_1^x through u_9^x do not allow for the determination of the relationship of a particular sensitivity. It is impossible to determine the absolute values of these coefficients, but knowing even one of them, for example s_0^x, allows to determine the others. They can also be set using other methods that determine the sensitivity $S_i(T)$, for a given temperature; then the auxiliary formula (3) can be used to determine the appropriate values of the polynomial sensitivity.

The second observation is that a valuable opportunity exists to determine the fixed value (offset) of the coefficients. This is a very interesting feature because all the previous algorithms assumed that the sensor experienced angular displacements, requiring further measurements. This often involved the use of appropriate mechanical instrumentation and sometimes undermined the main condition for the stability of the magnetic field, (1). In this case, it is apparent that even if the detector is stationary, it is possible to determine all the components of the offset.

The factors of equation (6) are less than the number of physical factors that describe the temperature dependence of the coefficients in the set derived from equation (6). This means that some factors are redundant and are a linear combination of the others. The maximum possible number of factors that can be determined from the equation is seven (four offsets and three sensitivity relationships), while the number of designated coefficients is nine. This is clearly demonstrated when trying to determine the offset of the coefficients. They can be determined from the auxiliary equations of (6), and written in the form of a matrix

$$\begin{bmatrix}0&0&0&6u_1^x\\0&0&5u_1^x&5u_2^x\\0&4u_1^x&4u_2^x&4u_3^x\\3u_1^x&3u_2^x&3u_3^x&3u_9^x\end{bmatrix}\begin{bmatrix}b_0^x\\b_1^x\\b_2^x\\b_3^x\end{bmatrix}=\begin{bmatrix}u_4^x\\u_5^x\\u_6^x\\u_7^x\end{bmatrix} \tag{7}$$

and

$$\begin{bmatrix}0&0&0&6u_1^x\\0&0&5u_1^x&5u_2^x\\2u_2^x&2u_3^x&2u_9^x&0\\u_3^x&u_9^x&0&0\end{bmatrix}\begin{bmatrix}b_0^x\\b_1^x\\b_2^x\\b_3^x\end{bmatrix}=\begin{bmatrix}u_4^x\\u_5^x\\u_6^x\\u_{10}^x\end{bmatrix} \tag{8}$$

Designating a relationship that would reduce the number of coefficients is virtually impossible. The needed coefficients can be determined if we describe the sensitivity using a first-degree polynomial and the offset using a first- or second-degree polynomial. In this case, Equation 6 reduces to the form

$$u_1^x\left(B_M^x+\frac{\mathrm{d}B_M^x}{\mathrm{d}T}T\right)+u_2^xT^2+u_3^xT+u_4^x=-\frac{\mathrm{d}B_M^x}{\mathrm{d}T} \tag{9}$$

where

$$\begin{aligned}&\frac{s_1^x}{s_0^x}=u_1^x,\quad u_2^x=3b_2^xu_1^x\\&u_3^x=\left(2b_1^xu_1^x+2b_2^x\right)\,,\\&u_4^x=b_1^x+b_0^xu_1^x\,.\end{aligned} \tag{9}$$

Now there is a real possibility to determine the sought after coefficients; however, it is impossible to accurately determine the coefficients of sensitivity. Only the relationship between the coefficients can be determined, which is still advantageous.

N measurements at different temperatures that can be determined by *N* equations (9), can be written in matrix form as

$$\begin{bmatrix}c_1^1&c_2^1&c_3^1&1\\c_1^2&c_2^2&c_3^2&1\\&\vdots&&\\c_1^N&c_2^N&c_3^N&1\end{bmatrix}\begin{bmatrix}u_1^x\\u_2^x\\u_3^x\\u_4^x\end{bmatrix}=\begin{bmatrix}d_1^x\\d_2^x\\\vdots\\d_N^x\end{bmatrix} \tag{10}$$

where

$$c_2^i = T(i)^2, \quad c_3^i = T(i), \quad d_i^j = -\frac{\mathrm{d}B_M^j}{\mathrm{d}T}(i)$$

Equation (10) can be solved using a variety of methods in Matlab. Simulations indicate that this method is sensitive to noise measurements and the value of temperature derivative of magnetic field. This derivative is needed for the estimation, and during its assignment, it is necessary to take into account the high-order polynomial approximations. Otherwise, the solution obtained may vary significantly from the expected results.

5 CONCLUSIONS

Passive magnetic methods are considered to be among the most promising and modern techniques of the XXI century. Compared to active methods, they have many advantages. They do not require an artificial magnetic field source; therefore, they can be used not only for diagnostic tests but also continuously, for example in condition monitoring. Such an approach poses problems with changing environmental conditions, which instantaneously influence the measurements. This paper concludes that temperature variation could be an issue.

The main challenge of passive magnetic methods results from the low values of the magnetic field level, as well as the magnetic variations. This implies another problem, which is subscalability for many different physical external conditions and the internal behavior of materials in objects in low magnetic fields.

The results led to an improvement in the existing measuring and post processing approach for passive magnetic methods and a reduction in the risk of omissions of valuable diagnostic information. The presented examples demonstrate the possibility for optimizing sensor choice and for developing a calibration procedure to analyze specific classes of problems.

The issues discussed here indicate that it is possible to use a passive diagnostic magnetic method using an object's own magnetic field change to provide new opportunities to detect early stages of damage in construction objects (*eg* exhibition halls, warehouse halls, bridges, and viaducts).

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