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Steel stress monitoring sensor based on elasto-magnetic effect and using magneto-electric laminated composite

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Monitoring of stresses in in-service steel structural components is challenging, but crucial to structural safety and health evaluation. Elasto-magnetic (EM) sensors are promising for stress monitoring of steel structural components, because of their great capabilities for actual stress measurement, noncontact monitoring, and long service life. However, the low sensitivity, low signal-to-noise ratio, slow response, and complicated installation of the EM sensors limit their application flexibility. This paper presents a steel stress monitoring sensor (SSMS) using a magneto-electric (ME) sensing unit to overcome the drawbacks intrinsic in the conventional EM sensors. The ME sensing unit is made of a ME-laminated composite of Terfenol-D magnetostrictive alloy and $0.7Pb\_Mg_{1/3}Nb_{2/3}\_O_3-0.3PbTiO_3$ (PMN-PT) piezoelectric crystal. The theoretical analysis and experimental characterization conducted on the ME sensing unit show high sensitivity, real-time response, and good linearity. Stress monitoring of a steel bar under tension is implemented for the SSMS with a pulse excitation of magnetization. The results demonstrate that the SSMS is feasible for real-time stress monitoring of steel structural components with high sensitivity, fast response, and ease of installation. © *2012 American Institute of Physics*. [doi:10.1063/1.3679420]

Steel structural components are widely used in mechanical and civil engineering structures, and their stress state is essential for structural safety and health evaluation. Elasto-magnetic (EM) sensors have shown promise to meet the requirements of stress monitoring of steel structural components, because they possess distinct advantages of actual stress measurement, noncontact monitoring, and long service life.[1,2]

The EM sensors have been demonstrated to monitor stresses in steel tendons and cables for more than a decade.[3,4] An EM sensor is a cylindrical testing device and consists of a primary excitation coil and a secondary coil. The primary excitation coil provides an excitation magnetic field to magnetize the steel structural component of interest. The stresses exist in the steel structural component and lead to changes in its magnetic permeability. These changes are measured by the secondary coil based on Faraday's law of magnetic induction. In general, the low sensitivity, low signal-to-noise ratio (SNR), slow response, and complicated installation of the EM sensors caused by the secondary coil constrain significantly the engineering applications of the EM sensors. These bottlenecks have called for the necessity of detecting magnetic induction in a real-time, accurate, and simple way.

Magnetoelectric (ME) materials in forms of laminated composites have been a hot research topic for realizing solid-state, power-free ME devices in recent years.[5,6] In this paper, we present a steel stress monitoring sensor (SSMS) by using an ME sensing unit made of an ME laminated composite to take the place of the secondary coil of the conventional EM sensors. Stress monitoring of a steel bar under tension will be implemented with a pulse excitation of magnetization.

The operating principle of the traditional EM sensor originates from the concept of magnetostriction,[7] which demonstrates that the magnetization of ferromagnetic materials leads to the change of shape, as described below.

$$\frac{1}{l}\frac{\partial l}{\partial H}=\frac{1}{4\pi}\frac{\partial B}{\partial \sigma}, \tag{1}$$

where l is the length of the member, H and B are, respectively, magnetic field strength and induction, and σ is stress. Magnetic field parameters can increase or decrease with the application of stress, and the extent of the change is a function of the material itself. This forms the basis of magnetoelastic effect. The stress of the member can be determined by measuring its permeability μ (defined by the ratio of B and H) at various conditions. The measurement is conducted with the secondary coil.[4]

By using the ME sensing unit to take the place of the secondary coil, we present the SSMS system, the principle and structure of which are shown in Fig. 1(a). The SSMS is mainly composed of the magnetic excitation part and the smart ME sensing unit. The ME effect of the laminated composite is utilized, which converts the change of the magnetic field induced by the changes of the magnetic properties of

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the ferromagnetic materials under the action of stress into easily measured electrical signals represented by voltage.[8]

Because of the product effect, the magnetic conversion coefficient can be expressed as[9]

$$\alpha_V = \left(\frac{dV}{dB}\right)_{\text{com}} = K\left(\frac{dV}{dS}\right)_{\text{mags}} \cdot \left(\frac{dS}{dB}\right)_{\text{piezo}}, \qquad (2)$$

where $(\frac{dV}{dS})_{\text{mags}}$ denotes magnetostrictive effect, $(\frac{dS}{dB})_{\text{piezo}}$ represents the piezoelectric effect, and K is determined by the interaction of the component materials and their volume fraction.

For given α_V, V generated by the composite is the function of H. From Eqs. (1) and (2), the dependence of V on the external stress σ under certain H can be deduced for the composite as

$$V = \alpha_V \cdot \frac{4\pi}{l} \cdot \frac{\partial l}{\partial H} \cdot \sigma = \varphi\sigma, \qquad (3)$$

where φ is constant for certain composite and ferromagnetic materials under some magnetic fields.

In previous work,[10] we have applied successfully such a system to test the tension of steel members under sinusoidal excitation. But using short pulse excitation allows us to decrease the current rms level and, thus, the heating, while the current amplitude can be increased to reduce noise and to provide larger magnetic strength. In this study, the pulse excitation of magnetization is applied to the SSMS for stress monitoring of a steel bar.

The proposed ME sensing unit (Fig. 1(b)) was made of an ME laminated composite having a thickness-polarized 0.7Pb_$Mg_{1/3}Nb_{2/3}$_O_3−0.3$PbTiO_3$ (PMN-PT) piezoelectric crystal plate (operating in a d31 mode) sandwiched between two length-magnetized Terfenol-D magnetostrictive alloy plates (operating in a d33 mode). The dimensions of the plates were 12 mm long, 6 mm wide, and 1 mm thick. This type of ME laminated composite possessed the largest known ME effect characterized by a high ME voltage coefficient α_v of 384 mV/Oe.[11,12] In operation, applying an ac magnetic field to the length direction of the ME laminated composite led to magnetostrictive strains along the length direction of the Terfenol-D plates due to the magnetostrictive effect. These magnetostrictive strains resulted in stresses in the sandwiched PMN-PT plate, producing piezoelectric voltages along the thickness direction of the PMN-PT plate due to the piezoelectric effect.[11]

For sensor applications, we carried out the performance tests of the ME sensing unit made of such laminated composites. The ME sensing unit was placed into the primary coil with a preset position for measuring the magnetic induction. A hall probe connected to a Gaussmeter (PEX-045B, Litian Co. Ltd.) was used to provide a reference signal for comparison with the ME sensing unit. A secondary coil was also included in this test setup. The electric apparatus was designed and fabricated, including two parts: the control module, which generated a user-defined pulse current input to the primary coil and the acquisition module, which acquired signals from the secondary coil V_{sec}, ME sensing unit V_{ME}, and hall sensor V_g and conducted proper data processing. Supported by the multifunction Data Acquisition (DAQ) device (USB-6211, NI), including D/A and A/D converters, both modules were connected to the computer and all the inputs and outputs were displayed and processed in the computer with the software Labview. During the tests of the sensing unit only, the steel member was not inserted into the coils.

Fig 2(a) is the typical output waveforms of one cycle for conducting magnetic measurements, including primary voltage V_{input}, discharge current I_{exc}, signal from ME sensing unit V_{ME}, signal from the secondary coil V_{sec}, and output signal of the hall sensor V_g. Using the current I_{exc} in the circuit to represent the magnetic field intensity H and the signal V_{ME} to

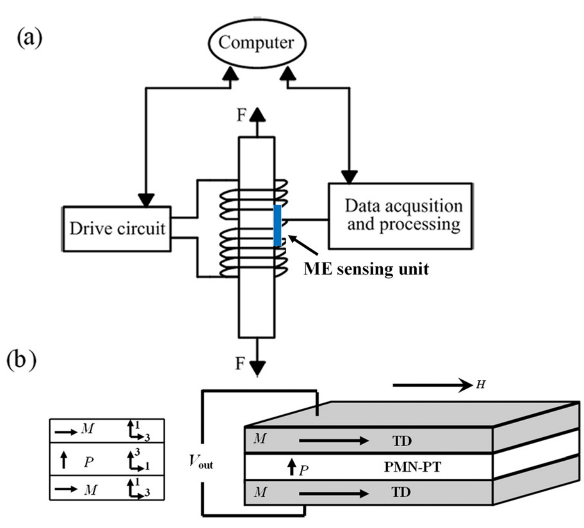

FIG. 1. (Color online) Operating principle and structure of present SSMS: (a) system; and (b) ME sensing unit.

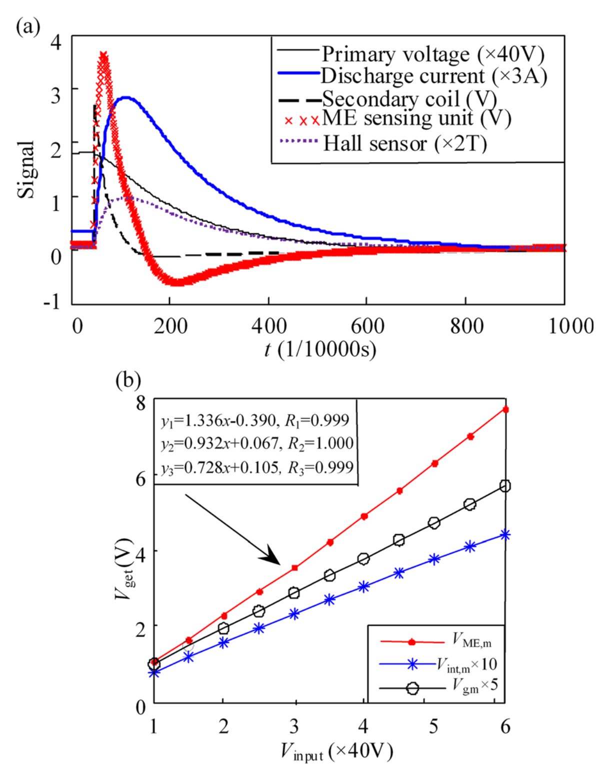

FIG. 2. (Color online) Calibration of ME sensing unit: (a) typical acquired waveforms for conducting magnetic measurements; (b) the measured maximum values of V_{ME}, V_{int}, V_g as a function of V_{input}.

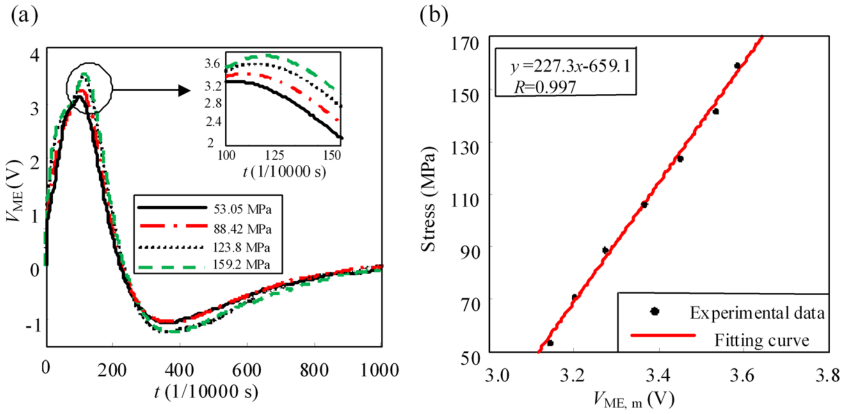

FIG. 3. (Color online) Tension test results of SSMS: (a) time-history of V_{ME} for different stresses and (b) the relationship between the stress and $V_{ME,\ m}$.

represent the magnetic flux density, the magnetization curve can be obtained. Figure 2(b) plots the measured maximum values of V_{ME}, V_{int} (integration of V_{sec}), and V_g as a function of the initial value of V_{input}. It is suggested that there is a good linearity between the output signals of the ME sensing unit and the magnetic induction, and thus, it can be used to measure the magnetic induction, with smaller size, more convenience of installation, and higher sensitivity.

The measurements reported here were performed on cylindrical steel bars of 12 mm in diameter and 800 mm in length. A complete description of the specimens and the experimental apparatus were given previously.[10] The tension-testing machine (CSS5200, SANS) was used to exert different levels of stress to the steel bars. The SSMS was fixed on the middle part of the specimen.

Figure 3(a) shows the acquired signal from the ME sensing unit V_{ME} with several different stress levels. It is found that the response time for stress monitoring, the time for completing one test for a certain stress level, is less than 0.1 s. Figure 3(b) plots the relationship between the steel stress and $V_{ME,\ m}$ (the maximum value of V_{ME}). Each data point is obtained by averaging the results of ten tests, with a relative deviation of no larger than 1%. The linear regression equation of the stress (in MPa) and $V_{ME,m}$ (in voltage) is $y = 227.3x$-659.1, with the correlation coefficient $R = 0.997$ and the repeating error of less than 0.15%. Therefore, as a power-free sensing unit, the ME sensing unit is able to output signals up to several volts, making our proposed SSMS a feasible and reliable steel stress sensor with high sensitivity, fast response, real-time sensing mode, and ease of installation.

We have presented a novel steel stress monitoring sensor (SSMS) by using a ME sensing unit made of a ME laminated composite to take the place of the secondary coil of the traditional EM sensor for the first time. The working principle and structure of the present SSMS have been elaborated. The characterization experiments were first conducted on the ME sensing unit, showing much higher sensitivity, real-time response, and good linearity characteristics for induction measurement. The tension tests were then conducted for the present SSMS using pulse excitation to detect the stress of a steel bar. We find that the present ME sensing unit–based SSMS, using pulse magnetization, is feasible and practical for real-time and precise stress monitoring of steel structural components, with high sensitivity and ease of installation.

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