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INTELLIGENT STRESS MONITORING FOR STEEL CABLES USING SMART ELASTO-MAGNETO-ELECTRIC (EME) SENSOR

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ABSTRACT

Monitoring of cable stress of in-service structures is challenging but crucial to the evaluation of structural safety. A smart elasto-magneto-electric (EME) sensor was recently proposed by the authors for stress monitoring of steel cables with obvious superiorities over the traditional elasto-magnetic (EM) sensors. As an innovation part of the EME sensor, the ME sensing unit, made of magneto-electric (ME) laminated composites, displays great potential to be used to design the novel sensor with significant advantages such as small size, large magnetic conversion coefficient, fast response, high magnetic-sensitivity, and low cost. To verify and calibrate the EME sensor as a non-destructive testing (NDT) tool to monitor the cable stress, laboratory test of small components, experiment of the full-scale cable, and factory calibration and in-situ verification for engineering applications were successively carried out. The research results demonstrate that the proposed EME sensor is feasible for stress monitoring of steel cables with high sensitivity, fast response, and ease of installation. The developed EME sensory system has been applied for intelligent stress monitoring for steel cables in the 2nd Jiaojiang Bridge of China.

KEYWORDS

Elasto-magneto-electric (EME) sensor, steel cable, stress monitoring, magneto-electric (ME) laminated composites, intelligent monitoring.

INTRODUCTION

Steel cables are critical members of cable-stayed and suspension bridges. Precisely monitoring of cable stress is important not only in the construction stage, but also in the bridge service life, which provides valuable information for the structural health evaluation As such cables usually contain tens or hundreds of wires or strands sheathed in a plastic protective cover or duct filled by cement grout or grease, invasive stress monitoring methods such as strain-based gauges are inapplicable, or unable to measure the actual stress (not the relative variation of stress). The most common method, vibrating frequency method, is based on the relationship of cable stress and natural vibration frequency. But its measurement accuracy is affected by many factors, for example, the bending rigidity, deflection, boundary condition of the cable, and the effect of cable Poly Ethylene (PE) bushing. Alternatively, the EM effect based method (e.g. Wang *et al.* 1999; Fabo *et al.* 2002; Sumitro *et al.* 2005; Calkins *et al.* 2007), has recently been receiving increasing attention, which takes advantage of the coupling between the elastic and magnetic states of the ferromagnetic material. The steel wires or strands, the main part of the steel cable, are ferromagnetic materials; therefore, the cable stress can be measured using this method. It overcomes the above mentioned disadvantages of the traditional methods while keeps the advantages of normal NDT methods. In the past decades, EM sensors have been developed, fabricated, and tested for the direct stress measurement in steel cables (e.g. Wang *et al.* 1999; Fabo *et al.* 2002; Sumitro *et al.* 2005). EM sensors have shown their superiorities of noncontact measurement, corrosion resistance, actual-stress measurement, low cost, long service-life and so on. Nevertheless, some drawbacks such as the high magnetic field requirement, low sensitivity, low signal-to-noise ratio (SNR) and slow response of the EM sensors, resulted from using a secondary coil as the sensing unit, keep from their engineering applications. The necessity of detecting the induced magnetic induction in an accurate and simple way is now strongly suggested.

A smart EME sensor for stress monitoring of steel cables was recently proposed by the authors for the first time (Duan *et al.* 2011; Zhang *et al.* 2011; Duan *et al.* 2012). The ME sensing unit, one innovation part of the EME sensor, which is made of ME laminated composites, displays great potential to be used to design the novel

magnetic detector with significant advantages such as small size, large magnetic conversion coefficient, fast response, high magnetic-sensitivity, and low cost. To calibrate and verify the EME sensor as an NDT tool to monitor the cable stress, this paper presents the laboratory test of small components, experiment of the full-scale cable, factory calibration for engineering applications, and the in-situ verification in the 2nd Jiaojiang Bridge of China.

THEORETICAL BACKGROUND

The effects of applied stress on ferromagnetic magnetization have long been known and extensively studied. The magnetic properties of the ferromagnetic material change with the application of stress, and the extent of the change is a function of the stress and the material itself, namely EM effect (e.g. Bozorth 1951; Chikazumi 1964; Cullity 1972; Jiles 1991). From the view of energy, the magnetic strain energy density for the isotropic magnetostriction material is generally expressed as (e.g. Bozorth 1951; Sumitro *et al.* 2005):

$$E_\sigma = \frac{3}{2}\lambda_{si}\sigma \sin^2\theta \tag{1}$$

where λ_{si} is the bulk magneto-restriction strain that is induced when an un-magnetized material is magnetized to saturation magnetization, σ denotes the applied stress, and θ represents the angle between the magnetization vector and the applied stress. To minimize the magnetic strain energy, the magnetization vector needs to rotate when a uni-axial stress is applied, making magnetization in certain directions easier or more difficult. Keeping other anisotropy constant, the relationship between M and σ in terms of stress related anisotropy is given by (Cullity 1972):

$$M = \frac{M_s{}^2 H}{3\lambda_{si}\sigma} \tag{2}$$

where M_S is the saturation magnetization, and H is the applied magnetic field. And the magnetic induction B is expressed by

$$B = H + 4\pi M \tag{3}$$

Therefore, it is possible to measure the stress level in ferromagnetic materials by properly establishing the relationship between M (or B) and stress. Researchers and engineers have explored the utilization of EM effect in industry, especially in non-destructive evaluation (e.g. Bozorth 1951; Chikazumi 1964; Cullity 1972; Jiles 1991). One of the easiest ways in the experiment to magnetize a material and investigate its magnetic characteristics is in line with the principle of Faraday's law and via two solenoids, a primary coil and a secondary coil, with the investigated material as the core. This also forms the working basis of the EM sensor. However, the use of the secondary coil induces disadvantages in the practical engineering application. The SNR is usually low; the necessity of signal integration, which takes a long time, results in a non-real-time monitoring mode; precise installation of the secondary coil in accordance with the theory assumption is not easy and usually requires skilled technique to guarantee acceptable precision. An alternative way to detect the change of the magnetic property of the tested material is strongly in need.

The ME effect is the polarization P response to an applied magnetic field H (Landau and Lifshitz 1960; Ryu *et al.* 2002). The ME conversion coefficient α_v can usually be expressed as in a simple way:

$$\alpha_V = \frac{dV}{dH} \tag{4}$$

where V is the voltage induced by H. In the past decades, considerable research efforts have been put on the ME effect, and numerous single-phase or multiphase ME materials have been reported (e.g. Rado and Folen 1961; Ryu *et al.* 2002; Dong *et al.* 2003a; Dong *et al.* 2003b). It is noticed that the ME materials in forms of laminated composites have been a hot research topic in recent years in virtue of their stronger ME effect characterized by larger α_v and higher detection sensitivity and thus potential applications in making solid-state, self-powered and smart ME devices (e.g. Dong *et al.* 2003a; Dong *et al.* 2003b; Wang *et al.* 2008; Zhang *et al.* 2009). Using the ME sensing unit made of such laminated composites to take the place of the secondary coil as the magnetic detector, the smart EME sensor displays great superiorities.

SYSTEM STRUCTURE AND WORKING PRINCIPLE

EME Sensory System

The stress monitoring is realized by the EME sensory system (Figure 1), which is designed and fabricated in our laboratory. The system includes mainly three parts: the EME sensor, the regulating module and the remote monitoring module. The EME sensor is used to measure the magnetic signal response to the action of the stress on the tested member, which is detailed in the next sub-session. The regulating module generates a user-defined current input to the primary coil for magnetizing the steel member. It also picks up all the input and output

signals and conducts proper data processing, supported by the multifunction data acquisition (DAQ) device (USB-6211, NI) including D/A and A/D converters. All the signals can be viewed synchronously on the computer by the remote monitoring module in conjunction with LabWIEW virtual instruments technology.

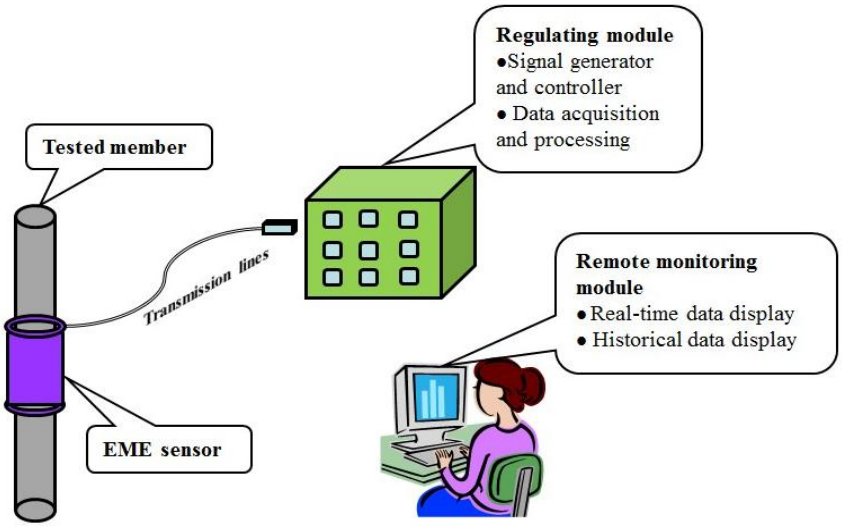
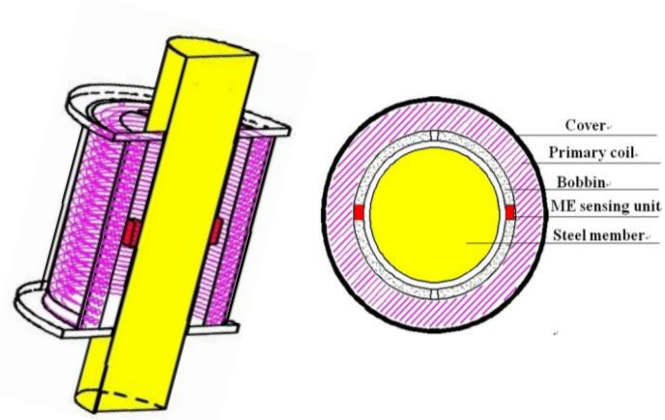


Figure 1. Schematic illustration of the operation principle and structure of EME sensory system

EME Sensor

The manufactured EME sensor (Figure 2) is mainly composed of a magnetic excitation part and a smart ME sensing unit, mounted on an aluminum-alloy bobbin and sealed with an insulating material. The magnetic excitation part can be served by the common magnetic coil wound on the bobbin. The smart ME sensing unit(s) is/are inserted in the pre-set slot of the bobbin. Due to the EM coupling effect, the action of the stress on the steel member would result in changes in the magnetic properties of the ferromagnetic materials and thus in the distribution of magnetic field. The ME sensing unit converts the change of the magnetic field into easily measured electrical signal represented by voltage, as the function of the ME coupling effect. A wedge-shaped fixing device is designed to fix the position of the sensor in case of vibration. Furthermore, after the sensor is installed on the strand, silicon sealant is utilized to fill the gap between the member and the sensor. In order to avoid possible damage and corrosion during construction and sensors' service life, a stainless steel cover is also used to protect the sensor.

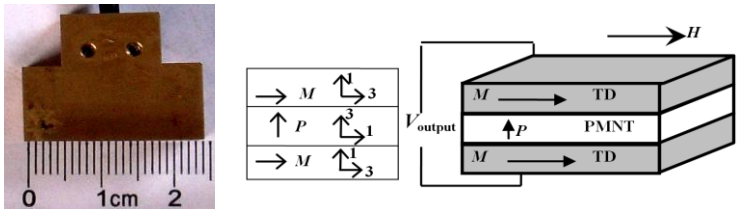


(a) Longitudinal section (b) Horizontal section

Figure 2. Structure of an EME sensor

The photograph and working principle of a typical ME sensing unit is shown in Figure 3, with the dimension of 23 mm long, 12 mm wide, and 2 mm thick. It was made of Terfenol-D/PMN-PT/Terfenol-D (TD/PMNT/TD) ME laminated composites (e.g. Dong *et al.* 2003a; Wang *et al.* 2008; Duan *et al.* 2012). Under the action of an external magnetic field, mechanical stains arise in the sandwiched Terfenol-D plates (operating in a d33 mode) due to a magnetostriction effect. These strains are transferred to the PMNT plate (operating in a d31 mode) where they produce an electric signal owing to the piezoelectric effect. Such sensing units can be used to

measure both direct current (DC) and alternating current (AC) magnetic fields without an external power supply, and can produce a large output voltage in real time, 2000 times higher than the traditional Hall devices.
To calibrate the ME sensing unit, performance tests of the ME sensing unit were conducted in the early stage (Duan *et al.* 2011; Zhang *et al.* 2011; Duan *et al.* 2012). It was observed that the peak voltage output from the ME sensing unit exhibited good linearity with the peak input voltage both in pulse excitation and sinusoidal excitation at a certain excitation frequency. The ME sensing unit has higher response than the Gaussmeter, and higher accuracy than secondary coil in measurement of the magnetic field. In addition, the ME sensing unit facilitates the fabrication and operation of the sensor.



(a) Photograph (b) Working principle

Figure 3.Schematic illustration of the ME sensing unit (The arrows designate the directions of the magnetization (*M*) and polarization (*P*), respectively)

EXPERIMENTAL INVESTIGATIONS

Laboratory Test of Small Components

Using the developed EME sensory system, numerous laboratory verification tests on various small steel components of different materials, such as steel bars, steel wire, and strands have been conducted. As an example, the tests on cylindrical steel bars of 12 mm in diameter and 800 mm in length were fully studied. As given in Figure 4, the steel bar was stressed axially by the tension testing machine step by step. For comparison and calibration, the secondary coil and Hall probe connected to a Gaussmeter (PEX-045B, Litian Co. Ltd.) were also implemented for the sensing of the magnetic signal. The sensing results under both sinusoidal excitation and pulse excitation were investigated. A more detailed description of the specimens and the experimental apparatus and calibrating process has been given previously (Duan *et al.* 2011; Duan *et al.* 2012). Here only the results are discussed.

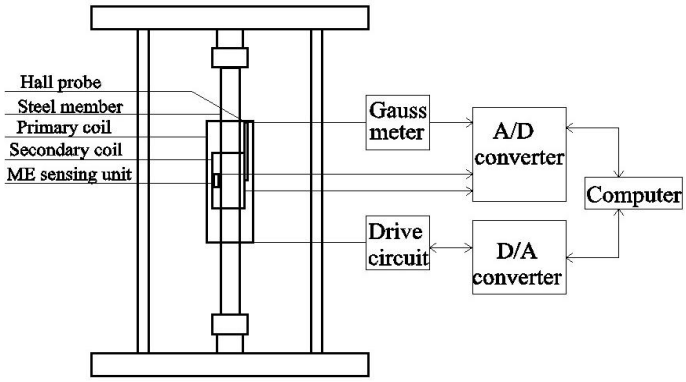
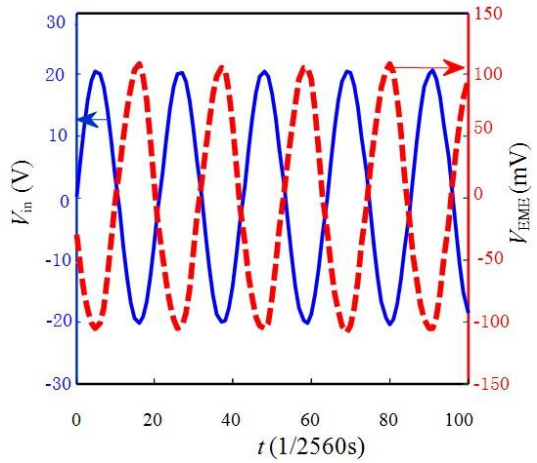


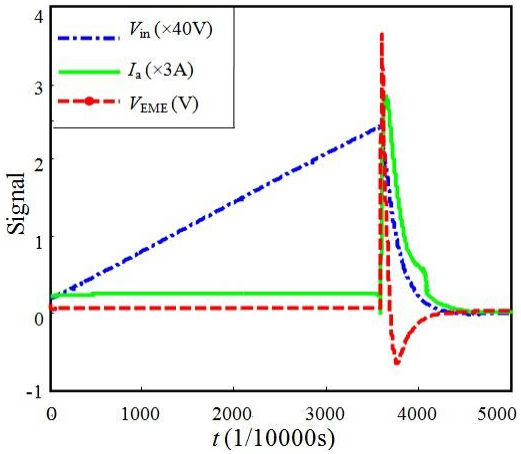
Figure 4. Schematic diagram of the laboratory experimental setup

Figure 5 shows the performance of the EME sensor under sinusoidal excitation of magnetization and pulse excitation. It can be seen that the EME sensor exhibits almost a synchronization response with the input excitation with the lag time less than 0.5ms, which is partly due to the hysteresis lag. The tested results under the two excitation modes are compared in the Figure 6. There is a good linearity between V_{EME} and stress for the tension range in the experiment, with the correlation coefficient of linear regression exceeding 0.99 and the repeating error of the sensor less than 0.15% in both of the results. The excellent results give the confidence in the basic validity of the ME sensing unit based EME sensor. So it can be designed for real-time and precise stress monitoring of steel structural components, with high sensitivity and easy installation.
Considering large steel member or some special material may require large charge voltage, technique for pulse excitation is investigated. The power loss and output efficiency can be obtained from the time history of Voltage and Current. Use of short pulses for excitation allows us to decrease the current rms level and thus the heating, while the current amplitude can even be increased, which is shown to reduce signal noise and provide larger

magnetic strength. Therefore, short pulses for magnetic excitation are preferred and employed in our later experiment.

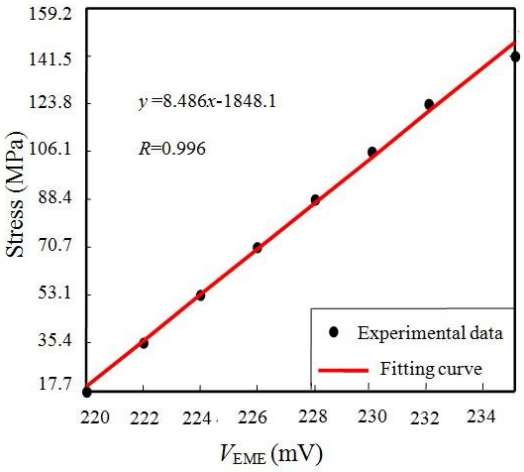


(a) Sinusoidal excitation of magnetization with the peak-to-peak value of input voltage 41.0 V and the frequency 120.0 Hz



(b) Pulse excitation of magnetization with the peak of input voltage 100V. (V_{in} is the input voltage, I_a the monitored current in the primary coil, V_{EME} the output from the EME sensor.)

Figure 5. The performances of the EME sensor under different excitation modes



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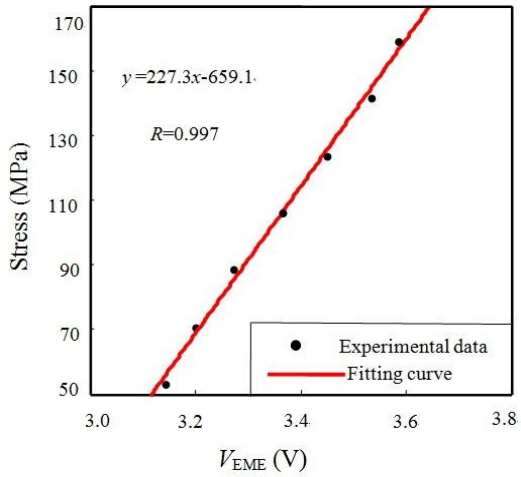


(b) Pulse excitation of magnetization with the peak of input voltage 100V

Figure 6. Results of the laboratory tests on small components under different excitation modes

Full-Scale Experiment

To verify the capability of the EME sensory system for other steel structures, especially for the large-diameter steel cable, a full-scale experiment was carried out on the steel cable PES(C)7-151, manufactured in conformity with the Chinese National Standard (GB/T 18365-2001), a most common steel cable used in the bridge. Its nominal breaking load is 9124kN. As shown in Figure 7, the microcomputer-controlled electro-hydraulic servo multi-function testing machine (YAW-10000F, Hangzhou POPWIL Electromechanical Control Engineering Co., Ltd.) acted as the loading setup, which can monitor the stress and displacement for providing a reference for the stress monitoring. The fixtures at both ends of the cable were specially designed for facilitating acting load and assuring the steel cable in straight tensions. The EME sensor was mounted at the middle of the steel cable.

The output signal V_{EME} from the EME sensor with different stress levels is obtained, as shown in Figure 8. It is found that V_{EME} has distinctive features with the different stresses and the inserted plot enlarging one section of the curves makes this clearer. For stable magnetization and precise results in this experiment, the measurements were conducted 15 times for each level and the results were averaged. As seen from Figure 9, the normalized magnetic character X_{EME} varies with the increasing stress level in a good linearity through its operating range, which also indicates that the large steel cable has good magnetic reaction with stress. It is demonstrated that the

present EME sensor is feasible for real-time and precise stress monitoring of full-scale steel structural components used in the engineering.

Figure 7. Photograph of the experimental setup for the full-scale experiment

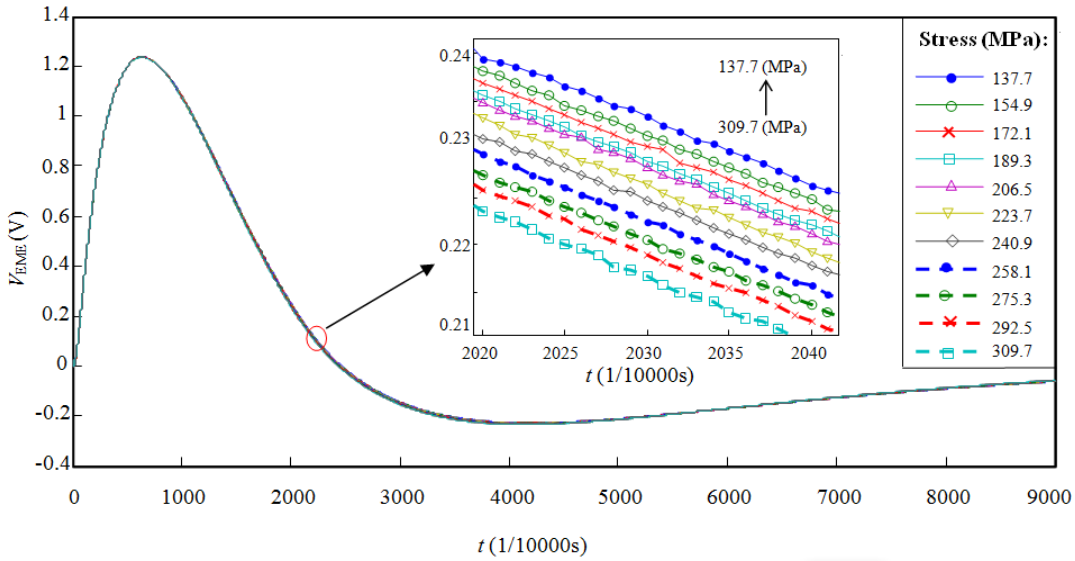


Figure 8. The output signal V_{EME} from the EME sensor under different stress levels

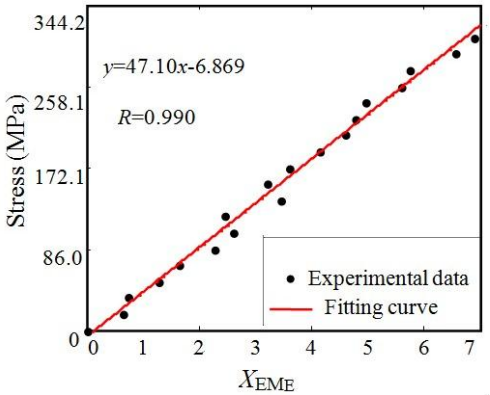
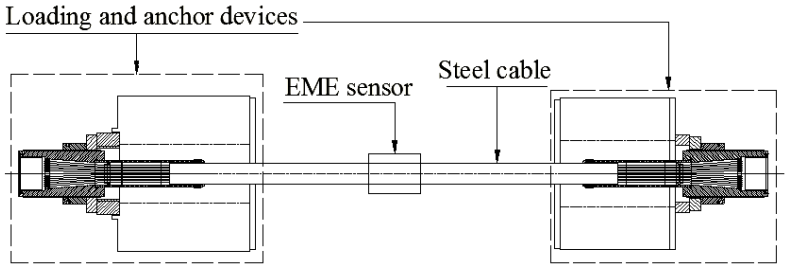


Figure 9. Results of the full-scale experiment on large steel cables

ENGINEERING APPLICATION

Factory Calibration

In order to utilize EME sensor technology in field application, the factory calibration for engineering applications was first carried out in the cable factory-Chongqing Wan Qiao Co. Limited, China. The calibrated steel cables were the ones to be deployed in the 2nd Jiaojiang Bridge of China, labeled with A8-3, A8-4, J8-3, and J8-4, respectively. They are of the same type as used in the full-scale experiment, namely steel cable PES(C)7-151. The pump hydraulic prestressing system (ZB10/320_4/800B, Liuzhou OVM Co. Ltd.) with a pressure gauge was used to stretch the steel cable to the necessary tensile load, as shown in Figure 10. The EME sensor was mounted at the same location on the steel cable as to be installed in the bridge site. The loading and measuring process were conducted three times for each steel cable.



(a) Schematic diagram of the experimental setup

(b) Photograph of the experimental setup

Figure 10. Factory calibration for engineering applications

Figure 11 shows the measured results of the EME sensor for the three loading processes of one single cable J8-4. The abscissas X_{EME} are the normalized results from the sensors. The results on the relationship between the normalized signal and stress for the three times are almost coincident. The little deviation may be caused by the temperature variation (within 5℃) during the tests. The influence of the cable sheath in heat transmission and temperature homogenization has been investigated by many researchers (e.g. Chen 2000; Fabo *et al.* 2002; Lloyd *et al.* 2003; Singh *et al.* 2004). It is reported that the calibration curve of the EM characteristics of the cable shifts in a parallel way with temperature fluctuation.

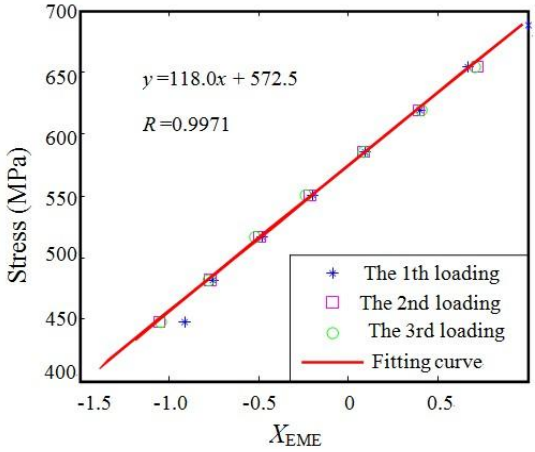


Figure 11. Results of factory calibration for the typical single cable (J8-4) of three times loading

The calibration results are averaged across the four steel cables to obtain a unified calibration curve for the tested type of steel cable PES(C)7-151, as is shown in Figure 12. From the calibration results, it can be concluded that: (i) the three times of calibration results of the EME sensor show good repeatability. It is observed that measurement results are in good agreement with the cable stress calculated based on the pressure gauge results, with the max fitting relative error of the full measuring range 0.0245. (ii) As indicated in Figure 12, different cables of the same material can be calibrated using the same equation, without the need of calibrating each cable separately. And the results can be directly employed in the following in-situ stress measurement. (iii) Changes of EM characteristics of the tested steel cable with time were also observed from the different measurement time and it is confirmed that long-time stability of the EM characteristics is high with 1% fluctuation. So the EME sensor with such kind of accuracy, linearity and repeatability, is suitable for the cable stress monitoring of cable-stayed and suspension bridges not only in construction, but also for long-term health monitoring.

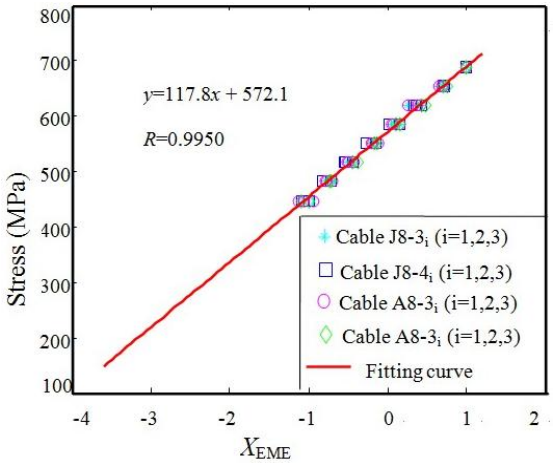
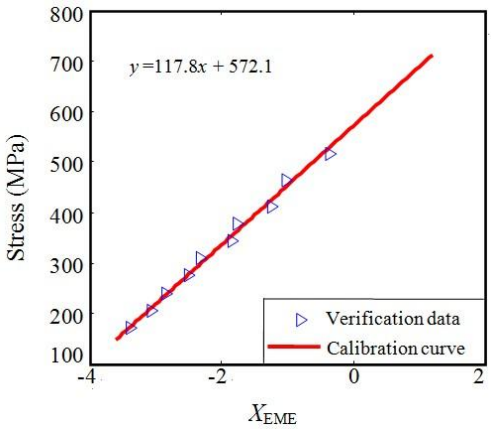


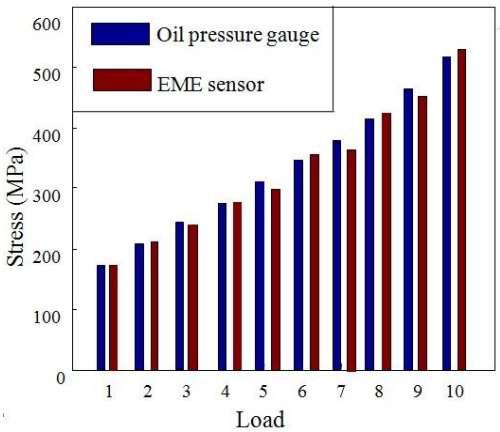
Figure 12. Results of factory calibration for the typical steel cable PES(C)7-151 in engineering applications

In-Situ Verification

Based on the previous calibration, one developed EME sensor monitoring system has been applied to monitor in-situ cable stress in the 2nd Jiaojiang Bridge of China. All the cables are made of cold drawn, low-relaxation and high-strength steel wire. The EME sensors were manufactured in our laboratory, shipped to cable factory for calibration, and then to the bridge construction site attached together with the cable. During the tensioning process of the steel cables on the bridge, the in-situ verification of the sensors for steel cable labeled with A8-3 and J8-3 was carried out. The cables were pulled up to 4000 kN under stepwise loading below the yielding strength.



(a) Calibration cure and verification data



(b) The compared results of EME sensors with the oil pressure gauge

Figure 13. The results of in-situ tests

Figure 13(a) plots the calibration curve and the verification data of the EME sensor using the in-situ tested results. The verification data are plotted using the EME sensor output as the abscissas and using the oil pressure gauge results as the ordinates. It is seen that the verification data are located very closely to factory calibration curve. Figure 13(b) shows a histogram for comparing the in-situ measuring results by the oil pressure gauge and by the calibration curve of EME sensor. It is observed that the two sets of results are in good agreement, with relative errors less than 2%.

Therefore, it is verified that the developed EME sensory technology is reliable for stress monitoring. The structural health condition can be assessed from the field-retrieved actual stress data by utilizing EME sensory technology. In Figure 14, the bridge is under construction with the EME sensors performing the role of stress monitoring. This is the first time that EME sensory system is deployed for intelligent stress monitoring for steel cables on an actual bridge.

Figure 14. Intelligent stress monitoring for steel cables of the 2nd Jiaojiang Bridge under construction using the EME sensors

CONCLUSIONS/OUTLOOK

From the study of the EME stress monitoring technique, the conclusions can be summarized as follows:

(1) Structural health monitoring of the cable-stayed and suspension bridges is the strong need to guarantee their normal operation or timely effective remedy. Steel cables are critical members of cable-stayed and suspension bridges; precisely monitoring of cable stress is very important not only in the bridge construction stage, but also in the bridge service life, which provides valuable information for the structural health evaluation.

(2) A smart EME sensor for stress monitoring of steel cables was recently proposed by the authors using the ME sensing unit as the magnetic field detector. The ME sensing unit displays great potential to be used to design the novel sensor surpassing the traditional magnetic detectors in their small size, large magnetic conversion coefficient, fast response, high magnetic-sensitivity, and low cost.

(3) By observing the results of laboratory test of small components, experiment of the full-scale cable, and factory calibration for engineering applications, it is confirmed that EME sensor is feasible for stress monitoring of steel cables with high sensitivity, fast response, and ease of installation, apart from the advantages of traditional EM sensor. It is also found that steel cables have good EM characteristics.

(4) The application in 2nd Jiaojiang Bridge of China is the first time that the EME sensor monitoring system is deployed for intelligent stress monitoring of steel cables on the actual bridge. It is a reliable, accurate, easy-to-operate system to measure actual stress of steel members and generally applicable to many structural monitoring situations, even when other methods are inapplicable.

(5) Owing to the use of ME sensing unit as the magnetic field detector measuring the direct magnetic change rather than the secondary coil measuring the average flux change of a certain length along the tested member, the EME sensor can be applied to detect the local stress or damage of members of different section shapes. Furthermore, it is also indicated that the EME sensor has great potential in steel related structures, especially in the stress or corrosion inspection of pre- or post-stressing and other steel under concrete cover, which is a particularly difficult NDE problem.

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