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EME sensors for total stress monitoring of steel cables

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ABSTRACT

In-service total stress monitoring of steel cables is challenging but crucial to the evaluation of structural safety. Traditional invasive stress monitoring methods are inapplicable, or unable to measure the actual stress (not the relative variation of stress). A smart elasto-magneto-electric (EME) sensor recently proposed by the authors for stress monitoring of steel components has shown great promise. In this paper, the theoretical background of the EME sensor was firstly illustrated. Based on this, the structure and working principle of the EME sensor were introduced. To verify and calibrate the EME sensor as a non-destructive testing (NDT) tool to monitor the total stress of steel cables, laboratory test, experiment of the full-scale cable, 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, apart from the advantages of traditional elasto-magnetic (EM) sensor. The developed EME sensory system has been applied for stress monitoring of the steel cables in the Second Jiaojiang Bridge, China.

1. INTRODUCTION

The distinct advantages such as large span, high flexibility, cost-effectiveness and aesthetics make cable-stayed and suspension bridges important forms of modern bridges. Precisely total stress monitoring of steel cables is important not only in the construction stage, but also in the structural service life, which provides valuable information for structural health monitoring (SHM) of these structures. But these components are usually helically wrapped around other steel bars or core materials to make a singular wire rope. Particularly the large steel cable contains hundreds of wires or strands sheathed in a plastic protective cover or duct filled by cement grout or grease. Therefore, invasive stress monitoring methods such as strain-based gauges are inapplicable, or unable to measure the actual stress (not the relative variation of

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stress). Alternatively, the EM effect based method (e.g. Sumitro 2005; Tang 2008), has been receiving increasing attention, with superiorities of noncontact measurement, corrosion resistance, actual-stress measurement, low cost, long service-life and so on. Nevertheless, some drawbacks resulted from using a secondary coil as the sensing unit, keep from their engineering applications.

A smart EME sensor for stress monitoring of steel cables was proposed by the authors for the first time (Duan 2011, 2012). The EME sensor uses the ME sensing unit made of laminated composites to take the place of the secondary coil as the magnetic detector. The application of the developed EME sensory system for intelligent stress monitoring for steel cables in the Second Jiaojiang Bridge are introduced in this article.

2. WORKING PRINCIPLE OF EME SENSORS

2.1 Theoretical Background

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. From the view of energy, the general expression of the magnetic strain energy density for the isotropic magnetostriction materials is (Bozorth 1951):

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

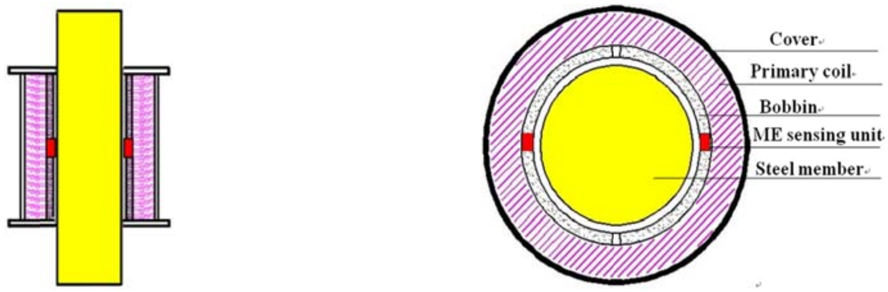
where λ_{si} is the bulk magneto-restriction strain that is induced when an un-magnetized material is magnetized to saturation magnetization, σ denotes the applied stress, and θ represents the angle between the magnetization vector and the applied stress. It is possible to measure the stress level in ferromagnetic materials by developing the relationship between magnetic induction and stress.

The traditional EM sensor uses secondary coil to detect the change of the magnetic flux, resulting in problems in the practical engineering application. The low signal-to-noise ratio (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 and principle 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 due to stress is in need.

The ME effect is the polarization *P* response to an applied magnetic field *H* (Landau 1960). It is noticed that the ME materials in forms of laminated composites have been a hot research topic in virtue of their stronger ME effect characterized by larger ME voltage coefficient ($\alpha_V = {dV}/{dH}$, where *V* is the voltage induced by *H*) and higher detection sensitivity, and thus potential applications in making solid-state, self-powered and smart ME devices (Wang 2008; Zhang 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 advantages.

2.2 EME Sensor

As illustrated in Fig. 1, the manufactured EME sensor is mainly composed of a magnetic excitation part and smart ME sensing units. The magnetic excitation part can be served by the 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 of the related area. 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) (b)

Fig. 1 Structure of an EME sensor. (a) Vertical section view, and (b) Cross-section view.

A typical ME sensing unit (Duan 2011) is made of Terfenol-D/PMN-PT/Terfenol-D (TD/PMNT/TD) ME laminated composites. The performance tests showed 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. 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.

The stress monitoring is realized by the EME sensory system designed and fabricated in our laboratory. The system includes mainly three parts: the EME sensor, the signal regulating module (SRM) and the remote monitoring module (RMM). The SRM generates a user-defined current input to the primary coil for magnetizing the tested steel member and related area. It also picks up all the input and output signals and conducts proper data processing. The EME sensor is used to measure the magnetic signal response to the action of the stress on the tested member. All the signals can be viewed synchronously on the computer by the RMM in conjunction with LabWIEW virtual instruments technology.

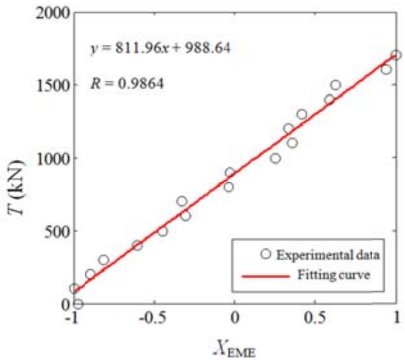
Numerous laboratory tests have been conducted on various steel components of different materials, such as steel bars, steel wire, strands and prestressing tendons to verify the capability of the EME sensors (Duan 2011, 2012; Zhang 2014). In this work, the intelligent stress monitoring for steel cables in the Second Jiaojiang Bridge of China using the developed EME sensory system is introduced.

3. IN-SERVICE STRESS MONITORING FOR STEEL CABLES

3.1 Full-scale Experiment

To verify the capability of the EME sensory system for the large-diameter steel cable, a full-scale experiment (Duan 2016) was firstly carried out on the steel cable PES(C)7-151. Fig. 2(a) shows the experimental setup. As seen from Fig. 2(b), the normalized magnetic signal X_{EME} varies with the increasing force levels T in a good linearity through its operating range with the linear regression equation y = 811.96 x + 988.64 and a correlation coefficient of R = 0.9864. This also indicates that the large steel cable has good magnetic reaction with tensile force.

(a)



(b)

Fig. 2 The full-scale experiment on large steel cables. (a) Experimental setup, and (b) Experimental result.

3.2 Factory Calibration

In order to utilize EME sensor technology in field application, the factory calibration for engineering applications was carried out in the cable factory. The calibrated steel cables were the ones to be deployed in the actual bridge, labeled with A8-3, A8-4, J8-3, and J8-4, respectively. 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 shown in Fig. 3. It can be concluded that different cables of the same material can be calibrated using the same equation, without the need of calibrating each cable separately. The results can be directly employed in the following in-situ measurement.

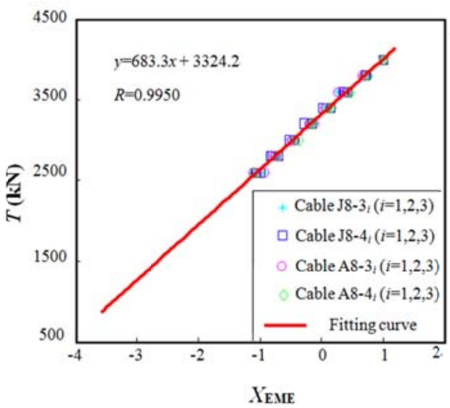


Fig. 3 Results of factory calibration for the typical steel cable PES(C)7-151.

3.3 In-situ Verification in the Second Jiaojiang Bridge

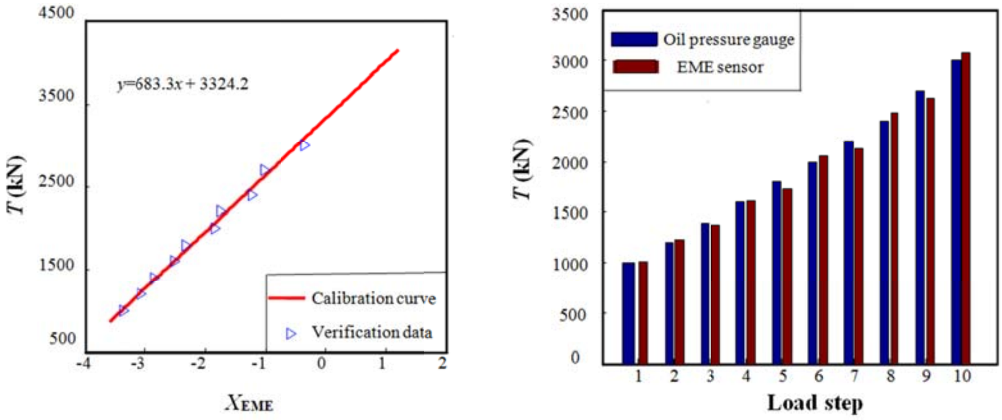
As shown in Fig. 4(a), the Second Jiaojiang Bridge is a twin-tower dual-cable-plane cable-stayed bridge of symmetrical geometry, which is an important highway and city bridge in Taizhou city of China. The EME sensors were manufactured in our laboratory, shipped to cable factory for calibration, and then 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 was carried out, using the developed EME sensory system based on previous factory calibration. Fig. 4(b) shows the EME sensor during the construction, Fig. 4(c) is the finished one performing the role of long-term monitoring, and Fig. 4(d) shows the SRM used in this engineering.

(d)

(a) (b) (c)

Fig. 4 Stress monitoring in the Second Jiaojiang Bridge. (a) The Second Jiaojiang Bridge, (b) EME sensor during the construction, (c) EME sensor for long-term monitoring, and (d) The signal regulating module (SRM).

Fig. 5(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. Fig. 5(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%. 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 fluctuation less than 1%. So the EME sensor with such kind of accuracy, linearity and repeatability, is suitable for the long-term stress monitoring of steel structures.



(a) (b)

Fig. 5 The results of in-situ verification. (a) Calibration curve and verification data, and (b) The compared results of EME sensors with the oil pressure gauge.

5. CONCLUSIONS

A smart EME sensor for in-service total stress monitoring of steel structures was proposed by the authors using the ME sensing unit as the magnetic field detector. By observing the results of the full-scale experiment, factory calibration, and in-situ verification, 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. The application in the second Jiaojiang Bridge of China is the first time that the EME sensory system is deployed for 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.

6. ACKNOWLEDGMENTS

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