Zhang et al. Advances in Bridge Engineering (2023) 4:7
https://doi.org/10.1186/s43251-023-00086-1

Advances in
Bridge Engineering

ORIGINAL INNOVATION

Open Access

Elasto-magneto-electric (EME) sensors for force monitoring of prestressing tendons

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Abstract

Stress/force monitoring of prestressing tendons is challenging but crucial to the evaluation of the safety of structures in which they are used. To this end, a smart elasto-magneto-electric (EME) sensor based on elasto-magnetic (EM) and magneto-electric (ME) effects is proposed for noncontact field monitoring of the absolute stress in these steel tendons. In this paper, our research in design, implementation, and application of the EME sensory system for non-destructive monitoring of prestressing tendons is overviewed. The results confirm that the developed EME sensor possesses high repeatability, ease of operation and maintenance, corrosion resistance, and long expected service-life. It is demonstrated that the proposed EME sensory technology is feasible for the stress/force monitoring of prestressing tendons in both new and existing structures and the EME sensory system is reliable and stable.

Keywords: Elasto-magneto-electric (EME) sensor, Prestressing tendon, Structural health monitoring, Stress/force monitoring, Long-term monitoring

1 Introduction

Tendons and cables, in the form of either (i) an individual wire, strand, or bar, or (ii) a group of wires, strands, or bars, are widely employed in various types of civil infrastructure, including buildings and bridges with pre-tensioned and post-tensioned concrete components, as well as pipelines and cable-supported bridges (Darmawan and Stewart 2007; Kim et al. 2019; Zhao et al. 2021). These structures are continuously exposed to various external dynamic loads (e.g., traffic, earthquakes, and possible accidental impacts), as well as environmental conditions that can result in material deterioration, corrosion, and fatigue, and structural health monitoring (SHM) is important for their condition evaluation and assessment (Aktan et al. 2000; Li et al. 2012; Li et al. 2016). Monitoring the absolute stress/force in cables and prestressed tendons is critical to understanding their status, and as such, a subject of much research in SHM (e.g., Oh and Yang 2001; Sim et al. 2014; Li and Ou 2015; Chen et al. 2022). Some researchers have proposed using pressure sensors at the anchorage of the steel cable or attaching strain gauges directly to the outside of the steel tendons to measure stress/force in tendons (Felstead and Lindsell 1981). However, these traditional sensors are difficult to install, maintain, and replace in in-service structures, and their stress measurement is relative (i.e., not the absolute stress/force).

For in-service structures, researchers have proposed methods based on the measured natural frequency of the cables, where the natural frequency is determined from measured accelerations or video of the vibrating cable and used to determine the cable tension (Byeong and Taehyo 2007; Bao et al. 2017). As such, this approach is the most commonly employed to monitor the tension in the cables of in-service cable-stayed and suspension bridges. However, the accuracy of this method is affected by the bending rigidity and boundary condition of the cable; moreover, it is difficult to apply for tendons. The novel vision-based monitoring method realizes noncontact measurements, which utilizes an image-processing technique to monitor the cable force via estimating dynamic characteristics of remote steel cables (Kim et al. 2013; Spencer et al. 2019). But this method is strongly weather dependent and time-consuming (Koch et al. 2014; Jana and Nagarajaiah 2021).

Fiber Bragg grating (FBG) sensors have been actively investigated and employed over the past three decades, with the advantages of high-sensitivity, absolute measurement, immunity to electromagnetism, and resistance to corrosion (Li et al. 2011; Measures and Abrate 2001; Yao et al. 2021). However, the intrinsic fragility limits its application, as the optical fiber can be difficult to install with its extremely small dimension (Yao et al. 2021; Zheng et al. 2018). Thus, for a successful field application of FBG sensor to a harsh construction environment, it is necessary to develop a proper encapsulation technique. However, the presence of the protective coatings or the clamping apparatus of the FBG sensors may significantly affect the strain measurement of the packaged FBG sensors and often results in an underestimation of the strains in the cables (Her and Huang 2011; Sun et al. 2017; Wang and Dai 2019; Chen et al. 2021).As a result, while the FBG sensors might have high accuracy themselves, when they are used to measure cable forces, the accuracy is more closely related to the sensor package and method of deployment. Therefore, the overall accuracy is ranked "medium" for the FBG sensors and interferometer sensors (Yao et al. 2021; Zheng et al. 2018). In addition, the deterioration of the fiber optic sensors and their packages and installation materials should be considered.

Methods based on the elasto-magnetic (EM) effect make use of the relationship between the applied stress and the inherent magnetic properties of the steel members and have attracted significant research interest because they offer a promising alternative to the conventional non-destructive and non-contact stress monitoring sensors (Cappello et al. 2018; Bozorth 1951; Tang et al. 2008; Wang and Wang 2004). The advantages of the EM sensors include noncontact measurement, actual-stress measurement, low cost, corrosion resistance, and long service-life. Commercial implantation of this technology has also been realized (Dong et al. 2016; Duan 2011; Sumitro et al. 2005; Yim et al. 2013; Wang and Wang 2014). All of these approaches use a secondary coil as the detecting unit, which has drawbacks that limit application flexibility, including: high magnetic field requirement, low sensitivity, low signal-to-noise ratio, and slow response of the EM sensors. Moreover, many prestressed tendons are not accessible (e.g., being internal to the structure, sheathed in plastic, or embedded in grout) and are often coated with lubricants, which exacerbates the problems in using the above reference methods for stress/force monitoring.

An elasto-magneto-electric (EME) sensor has been proposed by the authors for stress monitoring of cables and tendons not only with the advantages of the traditional elasto-magnetic sensors, but also with higher sensitivity, faster response, and higher signal-to-noise ratio (Duan et al. 2012; Zhang 2014; Zhang et al. 2014; Duan et al. 2016; Duan et al. 2017). While the theory has been developed and laboratory validation conducted, such EME sensors have yet to be assessed in a field environment. In this paper, the theory, design, and implementation of the EME sensor is first summarized briefly. Then, two example field applications for the force monitoring of prestressing tendons in new and existing structures will be presented. These examples provide a guide for practical engineers to understand this technology are expected to promote further development and applications of EME sensors for intelligent measurement of cable forces.

2 Design and implementation of the EME sensor

2.1 Structure of the EME sensor

The elasto-magneto-electric (EME) sensor is developed based on the elasto-magnetic (EM) and magneto-electric (ME) effects, and it can be used to measure the actual stress of the ferromagnetic items, such as steel cables and tendons. As shown in Fig. 1, the manufactured EME sensor 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 measured member would result in changes in the magnetic properties of the ferromagnetic members 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 on the steel member. For large steel member, after the sensor is installed on the member, expoxy resin is utilized to fill the gap between the member and the sensor. To avoid possible damage and corrosion during construction and sensor's service life, a stainless steel cover is also used to protect the sensor. It is contactless transfer of the stress from the measured member to the EME sensor, with

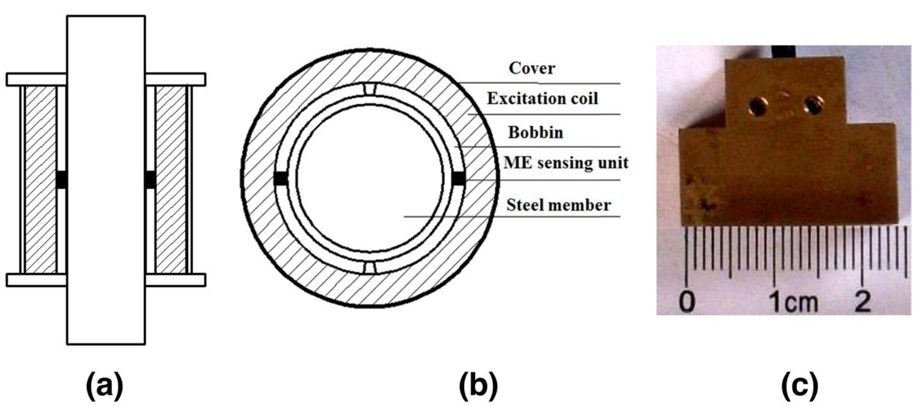

Fig. 1 Structure of an EME sensor: **a** vertical section view, **b** cross-section view, and **c** photo of the ME sensing unit

no glue (as in resistive strain gauges), and no mechanical contact (as in vibrating wire gauges and pressure gauges).

The proposed ME sensing unit is very small, with the size of 23 mm in length, 12 mm in width, and 2 mm in thickness, as illustrated in Fig. 1c. It is made of an ME laminated composite having a thickness-polarized PZT piezoelectric crystal plate sandwiched between two length-magnetized Terfenol-D magnetostrictive alloy plates. This type of ME laminated composite possesses the largest known ME effect characterized by a high ME voltage coefficient as a result of its giant product effect of the magnetostrictive effect and the piezoelectric effect. Such sensing unit can be used to measure both DC and AC magnetic field without an external power supply, and can produce a large output voltage in real time, 2000 times higher than the traditional Hall devices. The structure and design of the ME sensing unit was very simple and each unit consisted of an ME laminated composite packed in a brass housing. Performance tests of the ME sensing unit were conducted before its application (Duan et al. 2011; Duan et al. 2012; Zhang et al. 2011). 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 the measurement of the magnetic field. In addition, the ME sensing unit facilitates the fabrication and operation of the EME sensor. Significant advantages, such as convenience, low cost, small size, large magnetic conversion coefficient, fast response, and high sensitivity, make the ME sensing unit suitable for the design of smart EME sensor.

2.2 Design theory and simulation

Ferromagnetic materials subjected to external stress/force exhibit some amount of changes in their magnetic properties, and the extent of the change is a function of the stress and the material itself, namely EM effect. This EM effect, also referred to as the Villari effect, is the inverse phenomenon of the well-known Joule effect, which can be described as (Bozorth 1951):

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

where l is the length of the member, H and B are respectively magnetic field strength and induction, and σ is stress. It is possible to measure the stress level in ferromagnetic materials by properly establishing the relationship between the magnetic induction and stress.

The ME effect is the polarization P response to an applied magnetic field H (Ryu et al. 2002). The ME conversion coefficient α_v is defined by an induced electrical voltage V in response to an applied magnetic field 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 (Dong et al. 2003; Wang et al. 2008; Zhang et al. 2017). 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. Because of the product effect, the magnetic conversion coefficient can be expressed as (Ryu et al. 2002):

$$\alpha \mathrm{v} = \left(\frac{dV}{dB}\right)\mathrm{com} = K\left(\frac{dV}{dS}\right)\mathrm{mags}\cdot\left(\frac{dS}{dB}\right)\mathrm{piezo} \tag{2}$$

where $\left(\frac{dV}{dS}\right)$mags denotes magnetostrictive effect, $\left(\frac{dS}{dB}\right)$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

$$V = \alpha \mathrm{v}\cdot\frac{4\pi}{l}\cdot\frac{\partial l}{\partial H}\cdot\sigma = \varphi\sigma \tag{3}$$

where ϕ is constant for certain composite and ferromagnetic material under some magnetic field. The ME sensing unit made of such laminated composites converts the change of the magnetic field into easily measured electrical signal represented by voltage, as the function of the ME effect.

In a typical EME sensor, the magnetic field is generated by the magnetic excitation part, and their distribution in the solenoid has been investigated (Zhang 2014). Short pulse excitation is recommended, as it 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. Optimal design of the magnetic excitation part can refer to the transient behavior analysis method of the series RLC circuit, as stated in publications (Wang and Wang 2014; Zhang 2014). Using the ME sensing unit to take the place of the secondary coil as the magnetic detector, the smart EME sensor displays great superiorities.

The influences of surrounding ferromagnetic materials and temperature on magnetization measurement of the steel member have been investigated as well. Researchers reported that the magnetization level of ferromagnetic materials rises with the increase of temperature at lower magnetic field, and vice versa at higher magnetic field (Wang and Wang 2014). The effect from the surrounding strands on the results of the measured strands is refrained, which has been verified in the experiments. In previous work (Zhang 2014; Zhang et al. 2018), both the influences have been overcome using the developed compensation and magnetic shielding technologies.

For better design and application of the EME sensor, Zhang et al. (2014) has developed and verified a model for numerical simulation taking into account the EM coupling effect and ME coupling effect. This model is able to approximate the magnetization changes that a steel structural component undergoes when subjected to excitation magnetic field and external stress, and as well as to simulate the induced ME voltages of the ME sensing unit located in the magnetization area. An improved Jiles-Atherton (J-A) model is used in the simulation of the EME sensor. For placement optimization of the ME sensing unit, the finite element analysis software ANSYS is used to simulate the magnetic field topography and to investigate the influence of model parameters on the magnetic field. The ME coupling effect and the ME voltage coefficient is obtained based on the equivalent circuit method. The experimental results of a full-scale experiment with a large engineering steel cable agree well with the simulation results using this model (Zhang 2014).

2.3 EME sensory system

The EME sensory system for intelligent stress monitoring includes mainly three parts: the EME sensors, the signal regulating module (SRM) and the remote monitoring module (RMM). The EME sensor is used to measure the magnetic signal response to the action of the stress on the tested member. The SRM 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 monitor by the RMM in conjunction with LabVIEW virtual instruments technology. The stress monitoring of multiple structural members can be conducted under control. The program is set according to the demands, which could achieve intelligent control of the monitoring parameters. Configurations, including set-point, data averaging, different alarm settings, and so on, can be set according to the demands, which could achieve intelligent control of the monitoring parameters.

Numerous laboratory tests have been conducted on various steel components of different materials, such as steel bars, steel wire, and steel strands to verify the capability of the EME sensors as a non-destructive testing (NDT) tool to monitor the actual stress using the developed EME sensory system (Duan et al. 2011; Zhang 2014; Duan et al. 2016; Duan et al. 2017). In the following part, typical engineering applications for the force monitoring of prestressing tendons both in new and existing structures will be presented.

3 Engineering applications

3.1 Monitoring for the prestressing tendons of a new bridge

The bridge is one of the important freeways around city located in Quanzhou City of China, with the main bridge three-column portal-framed type tower, as shown in Fig. 2. Its construction was started from December 31, 2009 and completed on June 24, 2014. The bridge has an overall length of 12.45 km, consisting of nine sections. Among them,

Fig. 2 The bridge in Quanzhou City

the northern approach bridge in the deep-water area is designed to carry eight traffic lanes, and its superstructure is of reinforced concrete box girder.

The cross section of the girder is of a single box with double chamber, with a larger width of 20.05 m, as depicted in Fig. 3a. The technology of pre-cast segmental construction and posttensioning to provide large capacity external tendons was adopted in this approach bridge, which was a new challenging construction technology. The actual force and deformation of girders are different during the lifting process and service life.

Figure 3b depicts the used external prestressing tendons of this girder, each consisting of 27 filled epoxy-coated steel strands, for which the strain gauge method is not applicable. EME sensors were used to control tensile stress of external prestressing tendons during construction and to monitor their actual stress performance during the service life of the bridge. Enough steel strands were selected to monitor based on their structure and mechanical characteristics. For instance, three steel strands are monitored corresponding to the strand holes of anchorage as shown in Fig. 3c and d. For this bridge, 51 EME sensors for tendon force monitoring are installed on the northern approach bridge in the deep-water area.

In this study, the monitoring results by the EME sensors at span N119-N120 of the northern approach bridge in the deep-water area within 31 months from July 22, 2015 to January 30, 2018, are selected to discuss. The tendons and EME sensors are generally symmetrically located on the left chamber and the right chamber. Measurements of the tendon force was carried out every 2 h. Figures 4 and 5 illustrate the monitoring strand force and temperature separately. The force of all the tendons did not exceed 160 kN, with variations of each tendon less than 15 kN during the 31-month monitoring period. Several peaks of tendon force occurred, which may be caused by heavy traffic loads. It is clear that the tendon behaviors are within the design limit. Comparison of the tendon (#1, #2 and #3) forces measured at the left chamber with the ones (#4, #5 and #6) at the right chamber of girder shows that during the monitoring period the forces of left

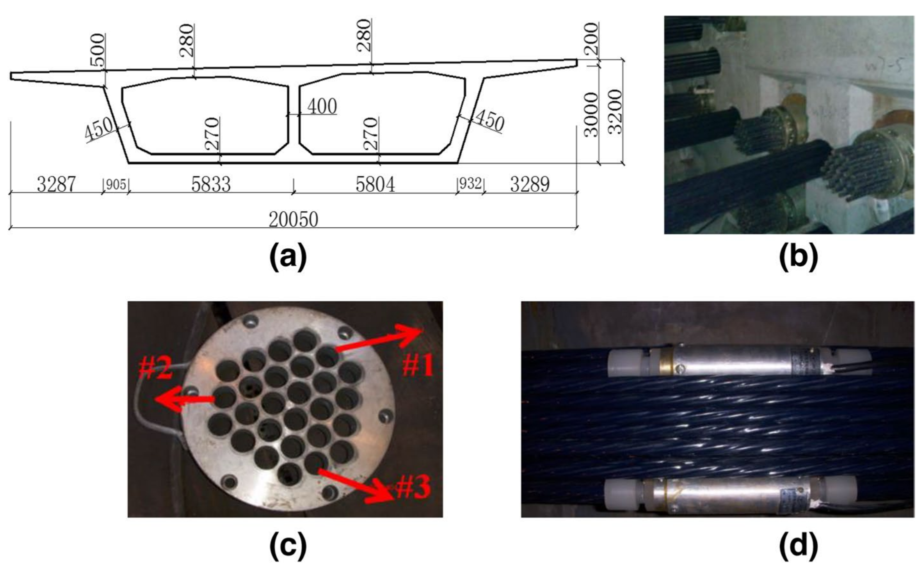

Fig. 3 Monitoring of the steel strands in the bridge (unit: mm): **a** representative cross section of the girder, **b** external prestressing strands, **c** layout of monitoring points, and **d** EME sensors during the construction

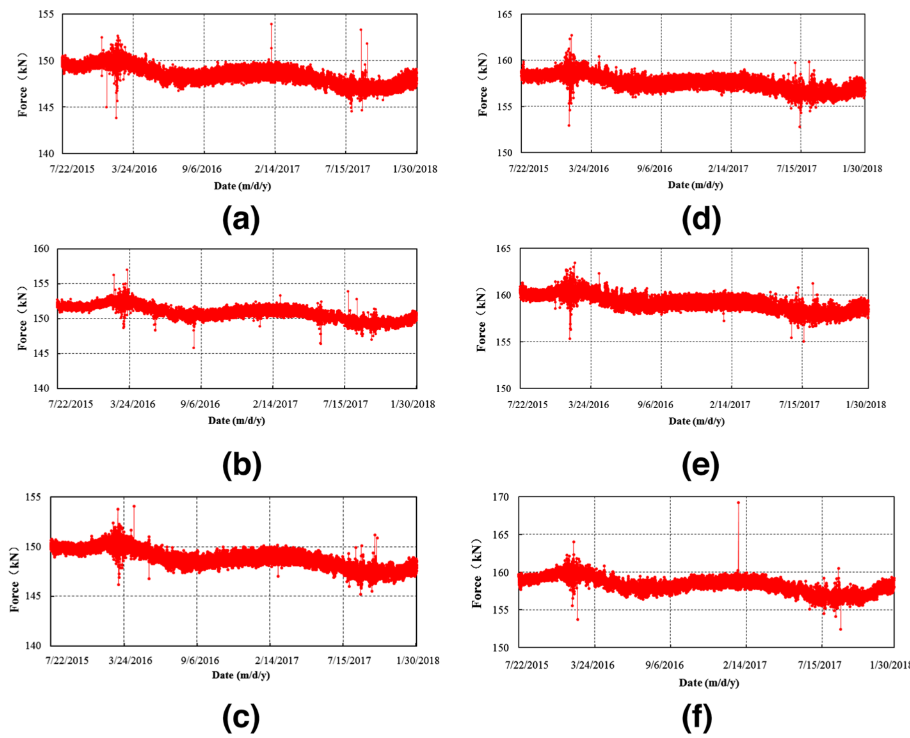

Fig. 4 Monitored force of tendons in different locations (from July 22, 2015 to January 30, 2018): **a** #1 tendon, **b** #2 tendon and **c** #3 tendon at the left chamber of the girder; and **d** #4 tendon, **e** #5 tendon and **f** #6 tendon at the right chamber of the girder

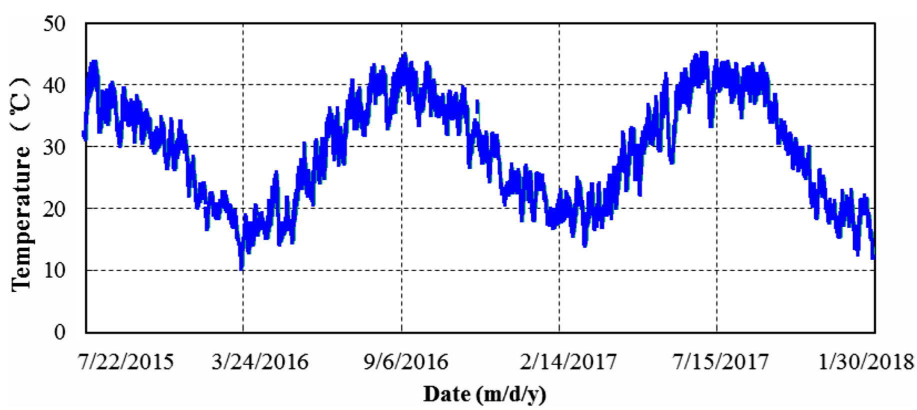

Fig. 5 Monitored temperature of the girder (from July 22, 2015 to January 30, 2018)

chamber and right chamber points did not vary more than 20 kN from each other, which is a relatively uniform distribution. This uniformity indicates that the girder of this part is performing well. From the comparison of Figs. 4 and 5, the tendon force showed no close relationship with the temperature. This reflects that the thermal expansion effect of the tendon in this design is not very apparent.

3.2 Monitoring for the suspenders of the existing bridge

The bridge is a reinforced concrete arch bridge located in Mianyang City of China. The overall length of the main bridge is 260 m, with a center-span of 185 m and two side-spans of 37.5 m. The main span is a half-through reinforced concrete arch bridge. During the repair and rehabilitation of the bridge in 2000, all the suspenders were replaced due to severe corrosion of the steel wires and anchorage devices. And a structural health monitoring system was also built to acquire the behaviors and performance of the bridge under real loadings and environmental conditions. Real-time knowledge of the actual force of the suspenders provides valuable information on distribution of forces during the operating lifetime and occurrence of isolated events such traffic overloads.

The typical suspender adopted in this bridge now is composed of 30 seven-wire steel strands sheathed in a seamless steel tube of 6-mm-diameter. This seven-wire steel strand is composed of six helical wires twisted around a central straight wire, with the nominal external diameter of 15.24 mm. The ultimate tensile strength of this strand is 1860 MPa, the yield strength is 1488 MPa, and Young's modulus is 1.95×10^5 MPa. The steel tube is filled with micro-expansion cement mort. Anchorages at both ends are plugged with concrete. Accordingly, unlike the common cables in the bridge, there is no regular

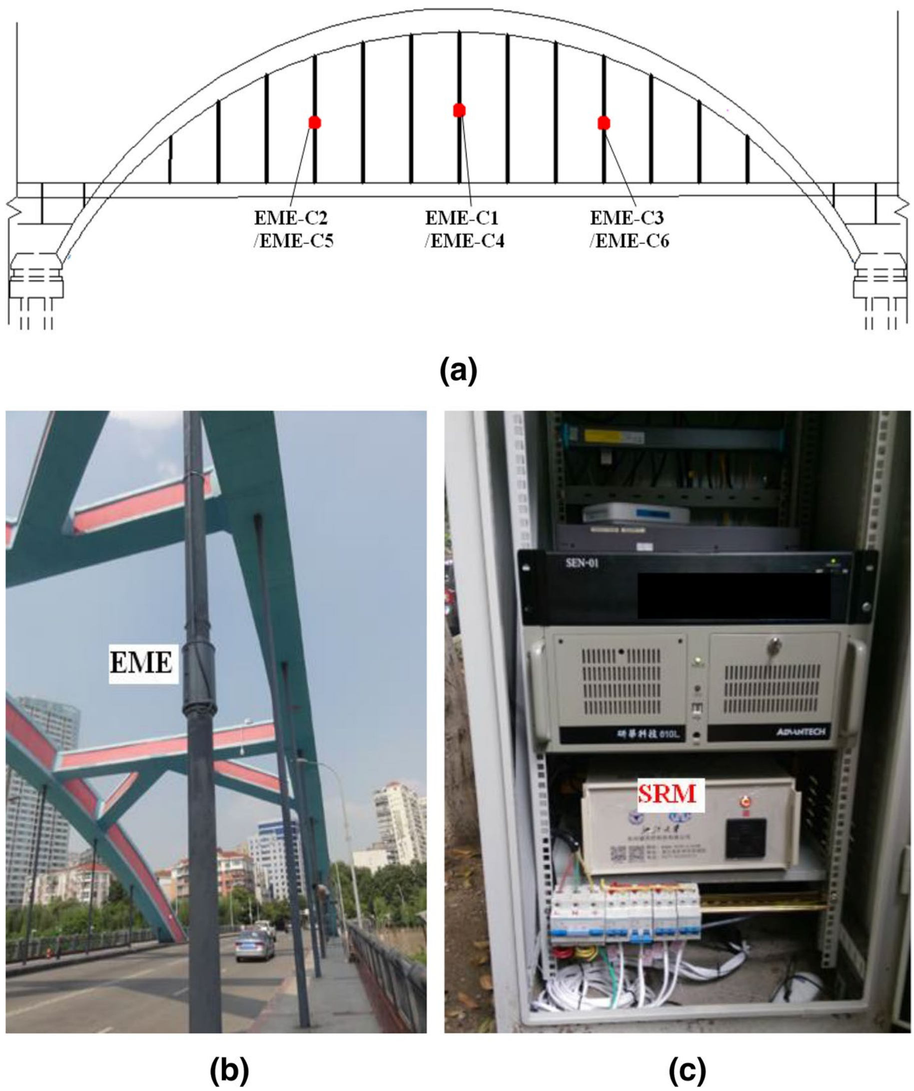

Fig. 6 EME sensors and SRM for long-term monitoring in the arch bridge: **a** Layout of EME sensors, **b** installed EME sensor, and **c** SRM

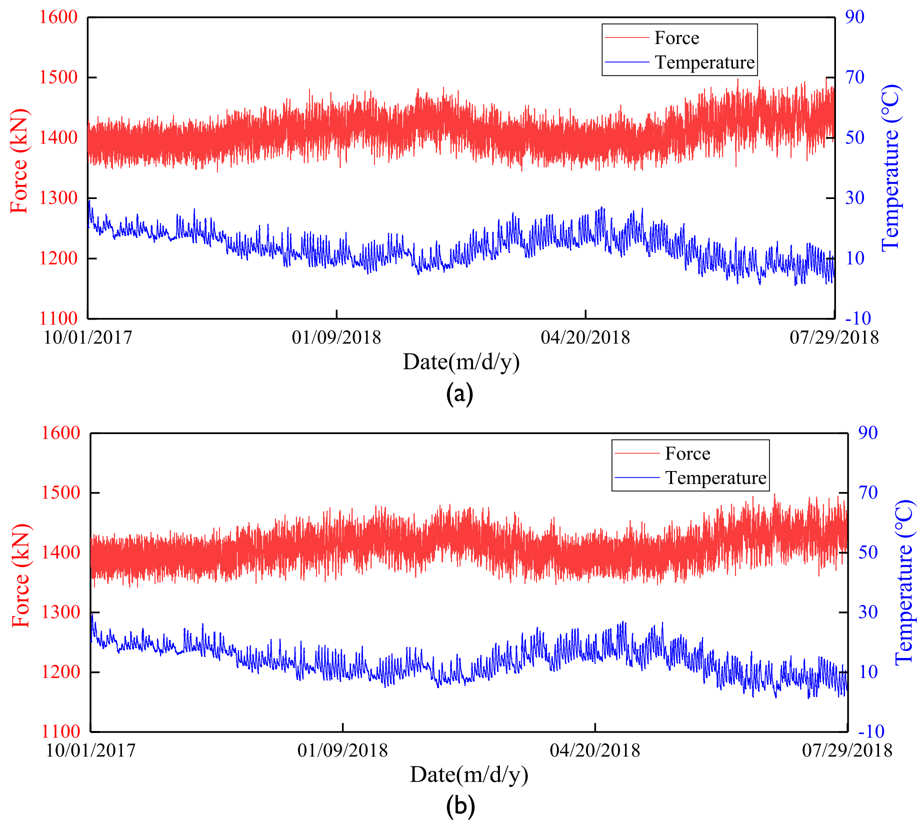

Fig. 7 The monitored result (from October 1, 2017 to July 29, 2018): **a** for the suspender C1, and **b** for the suspender C4

relationship between the strains of the steel wires and the external steel tube. Methods such as using strain gages or FBG sensors are impossible for invasive monitoring in this case. The developed EME sensory technology enables one to measure directly the actual force of suspenders. For the main span, six suspenders were selected to monitor using EME sensors (marked in red), as depicted in Fig. 6a. Figure 6b shows the EME sensor installed performing the role of long-term monitoring. There is no adverse effect to the suspender's mechanical properties or integrity. The SRM used in this engineering is shown in Fig. 6c.

EME sensory system for this bridge was established in August, 2017. The force and temperature of the six suspenders were automatically and continuously collected. Figure 7 shows the typical monitored results using EME sensors (EME-C1, and EME-C4) from October 1, 2017 to July 29, 2018. Measurements of the force and temperature were carried out every half an hour. The force of all the monitored suspenders did not exceed 1600 kN, with changes of each tendon less than 180 kN, which is below the design limit. The similarity of the two figures reveals that the two corresponding central suspenders perform in the close way. Similar monitored data and working states were yielded from other suspenders. No particular event has occurred on these suspenders in the past year. It is noticed that the force of suspenders varies in a slight opposite phase with the temperature. It also suggests that the thermal effect should be taken care of in the design of suspender arch bridge.

4 Conclusions

This article proposed a novel EME sensory technology for stress/force monitoring of prestressing tendons based on the EM effect of the ferromagnetic materials and the ME sensing unit. The design, implementation, and application of the developed EME sensor and sensory system are presented. The main contributions and findings are as follows:

(1) SHM of the civil infrastructure is a strong need to guarantee their normal operation or timely effective remedy and retrofit. Actual stress/force monitoring of the prestressing tendons is very important not only in the construction stage, but also in the service life of the structures.
(2) The research results demonstrate that the proposed EME sensor is feasible for stress/force monitoring of prestressing tendons not only with the superiorities of the traditional EM sensors such as noncontact monitoring, actual-stress measurement, low cost, corrosion resistance and long expected service-life, but also with higher sensitivity, faster response and higher Signal-to-noise Ratio (SNR).
(3) It is concluded that the EME sensory technology can realize long-term SHM both for existing and new structures in a reliable, stable, and easy-to-operate way. The long-term on-line monitoring of the prestressing tendons on these structures is in progress. Furthermore, for standard and health development of the EME sensory system, the code and guide for the sensor manufacturers and users are being compiled.

Abbreviations

EME	Elasto-magneto-electric
EM	Elasto-magnetic
ME	Magneto-electric
SHM	Structural health monitoring
OFBG	Optical Fiber Bragg grating
FBG	Fiber Bragg grating
J-A	Jiles-Atherton
SRM	Signal regulating module
RMM	Remote monitoring module
DAQ	Multifunction data acquisition
NDT	Non-destructive testing

Acknowledgements
The support of Monitoring and Control Hangzhou Co., Ltd. and CCCC Highway Consultants CO., Ltd. is greatly appreciated.

Authors' contributions
RZ conducted the design of the EME sensory system and drafted the paper. YFD proposed the conceptualization and guided the implementation of the EME sensory system and revised the paper. XYH performed the engineering application and data processing. WW participated in the design of the EME sensory system. YZ and LX offered practical advice. All authors read and approved the final manuscript.

Funding
The authors disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: The work described in this paper was jointly supported by the National Key R&D Program of China (2018YFE0125400, 2019YFE0112600), the Zhejiang Provincial Natural Science Foundation of China (LGG21E080004, LGG20E080004, LHZ23E080003), the National Natural Science Foundation of China (U1709216, 51608478).

Availability of data and materials
The datasets used and analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests
The authors declare that they have no competing interests.

Received: 16 January 2023 Accepted: 13 March 2023
Published online: 03 April 2023

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