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An electromagnetic oscillation method for stress measurement of steel strands

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ABSTRACT

A method for stress measurement of steel strands by using electromagnetic oscillation (EMO) circuit only at its both ends, on the basis of magnetic-elastic effect, is proposed in this paper. The basic principle of EMO measurement method is presented, the circuit of EMO is designed, and the experimental system is set up. By stretching the seven-wire steel strand, the stress measurement experiments are carried out. The experimental results indicate that EMO method is an effective approach to measure the stress of steel strands, and it is expected to be used in the stress detection of the existing structures.

1. Introduction

Prestressed concrete is widely applied in modern civil infrastructures, such as bridges and high-rise buildings. Prestressed steel strands embedded in compressive regions of structures enhance the carrying capacity. However, owing to the long-term overloading, serious corrosion and other environmental factors, mechanical prosperities of steel strands decline. Prestress loss is one of the major factors that influence the security of prestressed structures, especially for huge civil infrastructures. It is a potential danger leading to structural failure. Therefore, it is important to detect and evaluate the existing infrastructures' performance periodically.

Methodologies based on acoustic emission (AE) offer an effective solution for structural stress monitoring, for example, acoustic emission testing (AT), ultrasonic testing (UT) and stress wave testing (ST). They are all non-destructive testing (NDT) methods and considered to be feasible and applicable. AT method is able to detect structural integrity by receiving and analyzing acoustic signal going through materials [1]. Some research team made efforts to detect structural cracks and corrosion by this method [2–5]. Peter Lundqvist [6] adopted AT method to detect a beam's prestressing force, and ElBatanouny [7] even succeed in monitoring a whole bridge with this method. UT method is capable of locating and quantifying structural defects. It owns many advantages, such as high speed, high sensibility and low cost. S. Chaki achieved detecting prestressing level by employing this method [8]. Rizzo implemented experimental research on stress measurement of steel strands with UT method [9]. Jiang Xu succeeded in detecting defects of steel strands with ultrasonic lower 400 kHz [10]. Other researchers also tried to detect performance of prestressed structures in laboratory or on real bridges by UT method [11–14]. ST method is also used for stress detection because of the good correspondence between wave speed and stress on the basis of acoustic effect. Research on ST method for detecting stress of steel strands were implemented [15,16]. In addition, studies conducted by Chen [17] and Chaki [8] on stress measurement in prestressed steel strands indicate that measurement error of detecting stress level by UT method can be less than 170 MPa, and be less than 48 MPa by ST method as well. Nevertheless, AT, UT and ST still has technical problems. For example, they are easy to be affected by the mechanical and electrical noise.

In last decades, several new theories based on magneto-elastic effect for materials' stress measurement have been greatly developed [18–25] and applied in the field of aeronautics and astronautics, mechanical engineering, energy sources, building, architecture, and so on. In particular, research and application based on magneto-elastic effect for open long cable structures detection mainly focus on stress detection of cables and steel strands [26]. Zhang et al. [27,28] have implemented experimental research on measuring the stress of short unbonded steel strands based on magneto-elastic effect.

In this paper, an electromagnetic oscillation method for stress measurement of steel strands based on magneto-elastic effect is proposed. Its principle is demonstrated, and the EMO circuit is designed and fabricated. To verify the effectiveness of this method, stress

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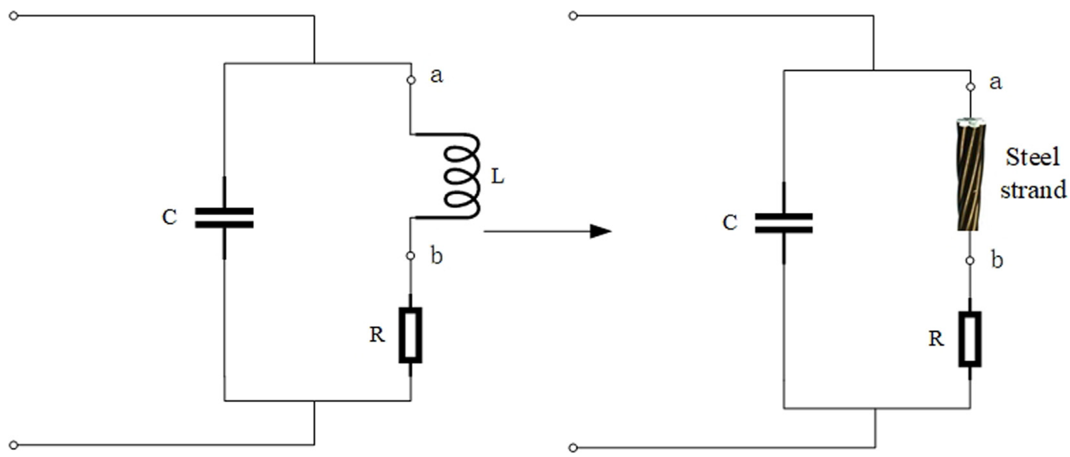

Fig. 1. Parallel resonant circuit and the steel strand.

detection by electromagnetic oscillation loading on two ends of steel strand is implemented in laboratory. The measuring accuracy and error of this method is also analyzed in this paper. Experimental results and analysis indicate that compared to the existing measurement method for short steel strands, the EMO method has superior advantage for steel strands of real length in practice, and this method can be adopted in pre-stressed infrastructures after construction.

2. Principle of EMO method

2.1. Modeling of EMO method

According to the electrical theory, a steel strand in low-frequency circuit can be modeled as a single conductance including three parts: resistance, capacitance and inductance. The variation of the inductance is much greater than that of other two parameters when the steel strand is stretched, so the steel strand can be modeled as an inductor.

To measure the inductance value, a parallel resonant circuit is employed. The both ends of a steel strand are linked to the circuit between point a and point b, as illustrated in Fig. 1. In this circuit, the steel strand can be equivalent to the inductor L. Because the variation of the inductance leads to the change of resonant frequency in the single steel strand, we can detect stress's alteration and measure its value by measuring the frequency indirectly with this measurement circuit.

2.2. Theoretical analysis and derivations

Based on this model, an EMO circuit is designed for realizing parallel-resonance (detailed in Section 3). The resonant frequency is defined as:

$$f = \frac{1}{2\pi\sqrt{LC}} \tag{1}$$

According to the electromagnetic theory [29], the inductance of a steel strand is related to its magnetic permeability and length. Hence, its inductance can also be formulated as:

$$L = P(\mu,l) \tag{2}$$

where P is a function that has two input parameters, magnetic permeability μ and length l。

According to the constitutive relation of linear material, we have:

$$\sigma = E\varepsilon = E\frac{\Delta l}{l_0} \tag{3}$$

where E is the elastic modulus, and ε is the strain, and l_0 is the material initial length.

Therefore, the formula that reflects the relationship between length variation and stress can be defined as:

$$\Delta l = g(\sigma) \tag{4}$$

where $g(\gamma)$ is a function including the stress parameter σ.

Meanwhile, the steel strand's magnetic permeability will change along with stress [26], thus the relationship between variation of magnetic permeability and stress can be formulated as:

$$\Delta\mu = h(\sigma) \tag{5}$$

where $h(\sigma)$ is a function including the same stress parameter σ.

With the derivation above, because stress causes variation of magnetic permeability and length, formula (2) can be transformed as:

$$L = P(\mu_i + \Delta\mu, l_0 + \Delta l) = P(\mu_i + h(\sigma), l_0 + g(\sigma)) \tag{6}$$

where μ_i is the initial magnetic permeability. Then incorporation (6) into (1), we have:

$$f = \frac{1}{2\pi\sqrt{C\cdot P(\mu_i + h(\sigma), l_0 + g(\sigma))}} \tag{7}$$

According to the Eq. (7), there is an explicit relationship between frequency and stress, and we assume their relationship as:

$$\sigma = Q(f) \tag{8}$$

we can Taylor expand equation (8):

$$\sigma = Q(0) + Q'(0)(f) + \frac{Q''(0)}{2!}(f)^2 + ... \tag{9}$$

where $Q(0)$, $Q'(0)$, $Q''(0)$ and so on are all constants.

To simplify the equation, the items after $Q''(0)$ can be ignored. Finally, we get:

$$\sigma \approx Q(0) + Q'(0)(f) + \frac{Q''(0)}{2!}(f)^2 \tag{10}$$

According to Eq. (10), the qualitative relationship between frequency and stress indicates that the value of stress can be calculated from the frequency measured by the EMO circuit.

3. Experimental study

3.1. Sensor design

According to the EMO method and experimental requirements, an EMO sensor is designed and fabricated. Its core circuit mainly composes of two parts: a voltage controlled oscillator MC1648 and a parallel resonant circuit consisting of the inductor L and capacitor C, as shown in Fig. 2.