Design of By-Pass Excitation Cable Force Sensor

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Abstract. With the continuous progress of bridge technology and the requirements for bridge aesthetics, cable technology is increasingly widely used in long-span bridges. Due to the long-term environment of alternating stress, corrosion and wind-induced vibration, it is easy to cause local fatigue and damage of the cables, which endangers the safety of the entire bridge structure. The sleeve cable force sensor based on magnetic flux method is widely used in practical engineering among many measurement methods. Existing sleeve cable force sensors need to be installed at the beginning of construction, so it is difficult to reinstall them in the follow-up, and its long-term performance is also difficult to evaluate and measure online. To solve this problem, this paper introduces the design of a kind of magnetic flux cable force sensor with by-pass excitation, and presents its measuring principle and design structure. The designed by-pass excitation cable force sensor is expected to solve the problem of the existing sleeve sensor.

1. Introduction
As the bearing member of various large buildings and structures, steel cables are the most important part of the whole structure, and the stress status plays an extremely important role in the overall structure safety [1, 2]. Real-time measurement of cable force is the main means to judge whether the bridge structure is safe. At present, many measurement methods such as vibrating string, fiber optic strain, pressure gauge and magnetic flux have been developed [3-7] to realize long-term monitoring and measurement of cable force. Among them, the cable force sensor based on magnetic flux method is widely used in practical engineering due to its excellent sensing performance and long-term working stability [8-10]. The existing magnetic flux cable force sensors are all designed in a sleeve type, that is, both the excitation coil and the induction coil are wound and nested on the same insulating hollow sleeve, the tested cable passes through the sleeve, and the excitation magnetic field directly magnetizes the tested cable, and its magnetization characteristics are obtained from the measuring coil for measurement and analysis [11]. The sensor has simple structure, uniform magnetic field, good linearity and accurate measurement result. However, due to the sleeve design, it needs to be installed at the beginning of bridge construction. Once completed, it is difficult to carry out follow-up installation. In addition, for long-term service bridges, it is difficult to disassemble and calibrate the measurement performance of sensors after long-term operation. Therefore, there is an urgent need for a kind of high-precision sensor that can be applied to the field installation at a later stage, to install the cable force monitoring system for the built bridge, and to carry out field measurement and calibration for the existing sensor.
This paper introduces the measurement principle and design structure of a kind of bypass cable force sensor with double bypass excitation.

2. Principle of magnetic flux cable force measurement

The ferromagnetic materials will be magnetized in the magnetic field, and when it is subjected to mechanical force, strain is generated internally, resulting in the change of permeability $\mu$. Permeability $\mu$ is the ratio of magnetic flux density $B$ to magnetic field intensity $H$. In the presence of stress, the permeability will change, and the relationship between the change value and the stress can be expressed as:

$$\Delta \mu = -2\lambda_m \left( \frac{\mu_i}{B_m} \right)^2 \sigma$$

(1)

$\Delta \mu$ is the permeability variation, $\lambda_m$ is the magnetostriction coefficient in the state of magnetization saturation, $\mu_i$ is the permeability without external force, $B_m$ is the magnetic induction intensity in the state of magnetization saturation, $\sigma$ is the stress generated inside a component. From formula (1):

$$\sigma = -\frac{B^2}{2\lambda_m \mu_i} \Delta \mu$$

(2)

As can be seen from formula (2), $\Delta \mu$ is proportional to $\sigma$, and the stress value can be calculated by measuring $\Delta \mu$. Since it is difficult to measure the permeability directly, the magnetization characteristics of ferromagnetic materials can be studied by using the principle of electromagnetic induction. That is, the alternating magnetic field is generated around the material by the excitation coils, and induced electromotive force generated by inductive measurement of the measuring coil is used to calculate the variation of permeability [12]:

$$\Delta \mu = \frac{\Delta B}{\Delta H} = \mu_0 \left[ 1 + \frac{S_0}{S_f} \left( \frac{V_{out}}{V_0} - 1 \right) \right]$$

(3)

Among them, $S_0$ is the total cross-sectional area of the coil, $S_f$ is the cross-sectional area of the cable under test, $V_{out}$ is the average output voltage after integrating the induced voltage with time, and $V_0$ is the output voltage when the cable is unloaded. The integral voltage is measured by experiment, and the permeability variation can be calculated from formula (3), and then the stress value can be obtained from formula (2).

3. Design of bypass excitation sensor

![Figure 1. 15.2 mm steel cable for test](image)
In this paper, the system designed for the Φ15.2 mm prestressed steel cable, which is the most widely used prestressed steel cable specification. The cable consists of seven steel wires, including six side wires and one middle wire. The diameter of side wires is 5.025 mm and the diameter of middle wire is 5.15 mm (Figure 1).

In order to facilitate subsequent disassembly and assembly, it is necessary to change the excitation mode of the sleeve type. Compared with sleeve sensors, bypass excitation has lower relative efficiency due to the problems of air reluctance and magnetic leakage. Four excitation coils are used to increase the magnetization intensity, and more turns are designed to facilitate the magnetization. Because the number of measuring coil is less, it can be manually wound on site.

The sensor is mainly composed of bypass core, cover plate and excitation coil arranged on the bypass core. The 3D structure of the designed sensor is shown in Figure 2.

![Figure 2. The 3D structure of the designed sensor](image)

3.1 Bypass core
Bypass core is used to connect and fix the measured steel cable, and as the core of the excitation coil, it is the key part of the magnetic circuit. The bypass core is processed with pure electrical iron to ensure good magnetic conductivity. Φ15.6 mm installation space is designed for Φ15.2 mm measured steel cables to ensure a certain system error margin. At the same time, excessive gap leading to excessive magnetoresistance should be avoided. The structure of bypass core is shown in Figure 3(a).

3.2 Cover plate
The cover plates are used to fix the iron core and conduct magnetic conduction as part of the magnetic circuit in the system. The system adopts double bypass excitation mode, requiring two cover plates with the same structure design. To ensure good magnetic conductivity, the cover plates are processed with pure electrical iron. The structure of cover plate is shown in Figure 3(b).

3.3 Insulated coil tube
The insulated coil tube is nested on the bypass core, and is made of insulating epoxy resin material. It can be wound separately in advance, and then installed and wiring during field measurement. The structure of insulated coil tube is shown in Figure 3(c).

3.4 Sensor assembly
The sensor is arranged on both sides of the cable in a symmetrical structure. About 1600 turns of high strength enameled wire of Φ0.6 mm is wound around the coil tube. When the sensor is assembled on the cable, magnetorheological grease is used to reduce the magnetoresistance introduced by air between the bypass core and the cable. The structure of sensor assembly is shown in Figure 4.
Figure 3. The design of key components

(a) bypass core  (b) cover plate  (c) insulated coil tube

Figure 4. The structure of sensor assembly

It is necessary to ensure that the magnetic field generated by the four coils of the sensor is in the same direction when passing through the cable. Figure 5 shows the wiring method of sensor coil. Figure 6 shows the sensor and its installation.
Figure 5. Wiring method of sensor coil

Figure 6. Sensor and its installation

4. Conclusion
This paper introduces the structural design of a magnetic flux cable force sensor with bypass excitation. The sensor adopts the bypass structure, which is convenient for installation at the measurement field, and can solve the problem that the sleeve sensor cannot be installed in the follow-up. It is expected to effectively calibrate the existing sleeve sensor in service and solve the problem of on-site calibration.

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