Cable Tension Sensor Based on Magneto-elastic Effect

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ABSTRACT:
This article introduces a sensor based on magneto-elastic effect in order to measure the axial tension of steel cable. We explained the basic principle of the sensor in detail, designed and analyzed the magnetic circuit structure with single magnetic loop. We propose a kind of device based on the pulse magnetization circuit of the steel cable and present the experiment results .Our results indicate that the system is in accordance with theory and it is stable and reliable. The device is battery-powered, small, cheap and portable.

Keywords: magneto-elastic effect，cable tension，sensor

1. INTRODUCTION

A lot of steel cable were used in the process of modern engineering. Many engineering establishments use directly the cable tension to load weights, so the tension of measuring the cable accurately concerns the harmony that security and construction control. Meanwhile, the state of guy cable is an important sign in normal running of bridge after building up. The purpose of strength monitors is not merely offering the basis to the security assessment of the guy cable, but to analyze accurately girder and the internal tension of the tower. So, we need measure accurately the tension of oblique guy cable.

Three kinds of measuring cable tension are usually used at home and abroad at present, the manometer measurement, the pressure transducer measurement and the frequency measurement. The first and second are suitable for measuring the tension of drawing oblique guy cables, and difficult to drawn cables. So, the frequency law is the main way in measuring the tension of drawn cable online. At present, it is nearly only choice to measure the cable of finished constructing in frequency law. Several years ago, the new method to measure the tension of cable based on magneto-elastic effect was put forward , this way can directly measure the tension of cable, and the device is fast dynamic response , long service time and cheap price. The results does not receive environmental factors such as wind, vibration and superficial antiseptic layer of steel cable. Compared with traditional frequency law, this kind of method of testing is more simple and more convenient, more visual. This method in overseas already had the relative reports and applied in the actual project examples, but in domestic we very little saw the relative material and the report.

But theoretical system of this method is not ripe, and the key technology on the choice and infection factors of its excitation magnetic design, magnetic circuit structure, parameter, and excision magnetic field is needed study deeply.

2. THE PRINCIPLE OF CABLE TENSION SENSOR

We know through magneto elastic effect that the size and form can change when the ferromagnetic in degaussing status is magnetized. Utilizing the way of magneto-elastic effect we can change magnetism (the electric energy in fact) into the mechanical energy. On the contrary, we can change the mechanical energy into to magnetism (the electric energy in fact). The cable tension sensor realizes measure tension based on magneto-elastic effect. When the cable receives the axial tension, the change of axial form results in the magnetization intensity changing. According to Joule effect:

$$\varepsilon = \frac{\Delta l}{l} = \frac{3\lambda_s M_S}{2K_u} \Delta M \sin^2\theta_0 \cos\theta_0 \qquad (2.1)$$

In this formula, ε is axial strain, λ_s is the constant of axial strain, M_S is the saturation magnetization,

K_u is the constant of uniaxial anisotropy, ΔM is the change of magnetization, θ_0 is the angle between magnetic field and the easy magnetization axis.

According to Hook’s law of material mechanics:

$$\varepsilon = \frac{\Delta l}{l} = \frac{P}{EA} \qquad （2.2）$$

P is the tension, E is the elastic modulus of the material, A is the cross section area.

According to the magnetization law of ferromagnetic materials,

$$\Delta M = \Delta\left[\left(\mu - \mu_0\right)H\right] \qquad (2.3)$$

μ is the permeability of ferromagnetic materials, H is the strength of magnetic field. When H is not change:

$$\Delta M = \Delta \mu H \qquad (2.4)$$

Substituting （2）、（4）into (1):

$$P = EA\frac{3\lambda_s M_S}{2K_u}\Delta \mu H \sin^2\theta_0 \cos\theta_0 \qquad (2.5)$$

So, we know that cable tension is proportional to the change of permeability.

The magnetization of a material is typically described by the relationship between the magnetic field strength and the flux density, and for any material can be expressed by the general constitutive equation:

$$\bar{B} = \mu \bar{H} \qquad (2.6)$$

Fig.1 shows a typical magnetization curve for ferromagnetic material. It is evident that the permeability, μ, is not a constant, but is dependent on the field strength, H. μ is not the slope of the magnetization curve, but simply represents the ratio $\frac{B}{H}$.

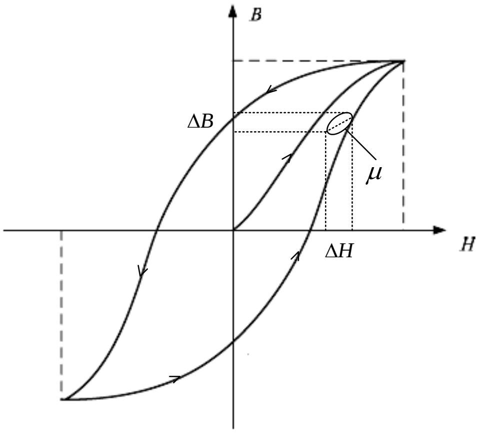

Figure 1 Magnetic curve of ferromagnetic material

One of easiest ways to magnetize a material and study its magnetic characteristics can be carried out using the principle of magnetic induction and two solenoids a primary coil and a secondary coil with the material whose magnetic characteristics are to be investigated as the core. If a DC current is applied across the primary coil it produces a magnetic field (H) and the magnetic flux density (B) within the specimen. If we are able to determine the ($\frac{B}{H}$) ratio within the coils, the permeability at that bias condition can be determined. The direct measurement of magnetic flux or flux density is difficult. An easiest way is to measure the induced terminal voltage across a pickup or a secondary coil wrapped around the specimen also. If an AC excitation is applied across terminals of the primary coil a time varying magnetic field is set up and an emf is induced in the secondary coil due to rate of change of flux linkage through the pickup coil accordance to Faraday’s law:

$$V_{ind}(t) = -N\frac{d\Phi}{dt} \qquad (2.7)$$

In the testing procedure, the specimen may not completely fill the surface enclosure of the coils. Therefore, the total flux consists of flux through air and through specimen. The induced voltage can be written :

$$V_{ind} = -N\frac{d}{dt}\left[\mu_0\int_{S_{\mu 0}} H(\rho,\varphi,t)ds + \int_{S_\mu} B(\rho,\varphi,t)ds\right] \qquad (2.8)$$

Where, $S_{\mu 0}$ and S_μ are surface areas of the coils occupied by air and the specimen, respectively, μ_0 is the permeability of air. If the induced voltage is integrated with respect to time, the resultant time averaged output is

$$\begin{aligned} V_{out} &= -\frac{1}{T}\int_{t1}^{t2} V_{ind}(t)dt \\ &= \frac{N}{T}\left[\mu_0\int_{S_{\mu 00}} \Delta H(\rho,\varphi,t)ds + \int_{S_\mu} \Delta B(\rho,\varphi,t)ds\right] \end{aligned} \qquad (2.9)$$

Where ΔH and ΔB are the change of the magnetic field intensity and magnetic flux density in the interval ($t_1 - t_2$), respectively. If the spacing between each turns is very small, the magnetic field within the coil is almost uniform. As a result may be simplified

$$V_{out} = \frac{N}{T}\left[\mu_0 \left(S_0 - S_f\right)\Delta H + S_f \Delta B\right] \qquad (2.10)$$

Where S_0 is the area of the entire cross-section of the coil, and S_f is the cross-section of the specimen. The integration of the time varying output voltage is first performed without the specimen. It is shown that

$$V_0 = \frac{N}{T}\mu_0 S_0 \Delta H \qquad (2.11)$$

By taking the equation (10) and (11), we can find the permeability from the following equation:

$$\mu = \frac{\Delta B}{\Delta H} = \mu_0 \left[1 + \frac{S_0}{S_f}\left(\frac{V_{out}}{V_0} - 1\right)\right] \qquad (2.12)$$

From the equation (12), we know that the permeability through the secondary coil is direct ratio with the integration of the output voltage.

The last, we know that we can get the expression of cable tension through the equation (5) and (12) in the sane magnetization.

$$P = EA\frac{3\lambda_s M_S}{2K_u}\mu_0 H \sin^2\theta_0 \cos\theta_0 \left[1 + \frac{S_0}{S_f}\left(\frac{V_{out}}{V_0} - 1\right)\right] \qquad (2.13)$$

3. DESIGN THE STRUCTURE OF THE MAGNETIC CIRCUIT

The main shortcoming of magneto-elastic sensor in the structure is that the present magnetic structure is a sleeve model, it uses cable as the core of the excitation coil and measuring coil, so sensors are difficult to be fixed when they are used measuring cable of built-up construction, the field winding machine is only used. Not only technological difficulty is high, limited by the working environment, but the precision measurement is low. This restrain the application of the magneto-elastic sensor greatly. In order to solve the above problems, we do not use the cable as the core of coil but as one part of conducting the magnetic field and permeability. And the iron core of the coil is made of the Model U silicon steel sheet that the most permeability is very high(show at Fig.2). Hereby, the sensor can be designed to the independent probe form. At the field, we can fix the probe expediently on the testing cable.

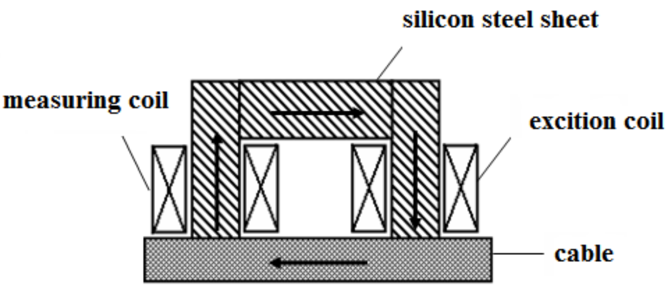

Figure 2 Magnetic circuit structure of the sensor

In order to reduce the magnetic flux leakage, the end of the probe should keep in touch with the outside of the cable for reducing the air gap. The cross-section area S_f of the silicon steel sheet should be little more larger than the cross-section area S_0 of cable in order to flux permeability easily passing the cable and reduce the magnetic flux leakage. In the testing, the axial length of the steel core L_S should be little more longer than the length of the single section for reducing the mutual inductance of the excitation coil and measuring coil and produce a symmetrical magnetic field in the axial direction of the cable. At the same time we should think about the adequate space that we can fix the framework of the coil on the steel core.

For being as accurate as possible to receive induce magnetic field, the secondary coil should be only one layer and the diameter of the coil is very important. So, the vertical length of the core should be longer than the measuring coil.

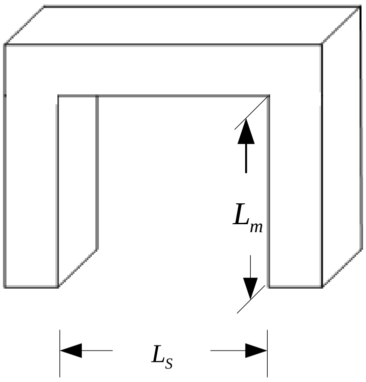

Figure 3 Shape diagram of silicon steel sheet

4. A PULSED MAGNETIZATION CIRCUIT

According to the direct ratio between the integral of the output voltage of the measuring coil and the permeability, we designed a kind of pulsed magnetization circuit. The circuit is divided into the charged-up capacitor, the discharged circuit, the integral circuit and the signal adjusted circuit. The device instead of measuring the reversal permeability measures the incremental permeability in the saturation zone of the material. A 9V battery is used to charge up a capacitor to a user set voltage (dependent on current requirement) is then discharged through the primary coil. The output of the secondary coil is the input to an analog integrator circuit with a gating control to switch the integration process off and on at user defined set points. This allows the measurement of the incremental permeability in the optimal range for maximum sensitivity and linearity. The effect of the operating point has a strong influence on the slope of the permeability stress curve and the dependence is similar to those obtained in the reversal permeability measurements. It is therefore important to optimize point for a given sensor material combination and fix that operating point for all other measurements. Once an operating point in terns of the high and low current are established the results were found to be independent of the maximum current through the circuit, and duration of the current pulse. The measurement accuracy and resolution is determined by the ratio of the number of turns in the primary and secondary coil and the resolution of the voltage measurement device. Since it is important to quantify the diameter of the secondary coil as precisely as possible it is possible to have one layer of wires in the secondary coil (0.2mm diameter wire, 100 turns).

5. PULLING EXPERIMENT

The steel wires of 10 mm diameter are experimented in room temperature 25℃on the pull machine of the maximum pull 200KN (resolution is 0.02kN) as the experiment object. The range of the experiments is from 0KN to 50KN. The discharged frequency of the capacitor is 100Hz and the old rolling orientated silicon steel sheets as the core. They are easier magnetized than the hot and has better permeability and low iron-loss and the characteristic of magneto elastic effect. This is favorable to improving the sensor sensitivity.

The experiments is done repeatedly five times in the same condition, the output voltages were shown at Tab

1. The repeatability errors of measurement are according to Bessel formula:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \bar{y})^2}{n-1}} \qquad （5.1）$$

y_i is the result of every measurement, $\bar{y}$ is the average value, n is the measurement tine.

The results of the repeatability error are low than 0.015V, then that can prove the repeatability of the system is reliable. Linear regression fitting curve with the average value and the relative pull value(Fig5.), the square of correlation coefficient is 0.9993, this shows that the pull force is linear with permeability. This system is suitable to measure cable tension.

Tab 5.1 Contrast of cable tension and output voltage of sensor

pull force（KN）	1	2	3	4	5	average	error σ （V）
0	2.122	2.114	2.125	2.144	2.121	2.125	0.01
5	2.338	2.323	2.336	2.345	2.331	2.335	0.007
10	2.549	2.552	2.539	2.541	2.534	2.543	0.007
15	2.756	2.742	2.732	2.759	2.764	2.751	0.012
20	2.951	2.964	2.948	2.966	2.977	2.961	0.01
25	3.172	3.185	3.189	3.174	3.173	3.179	0.007
30	3.398	3.390	3.381	3.377	3.386	3.386	0.007
35	3.516	3.529	3.536	3.511	3.538	3.526	0.011
40	3.745	3.756	3.731	3.734	3.771	3.747	0.015
45	3.952	3.968	3.979	3.987	3.985	3.974	0.012
50	4.172	4.195	4.171	4.182	4.198	4.184	0.011

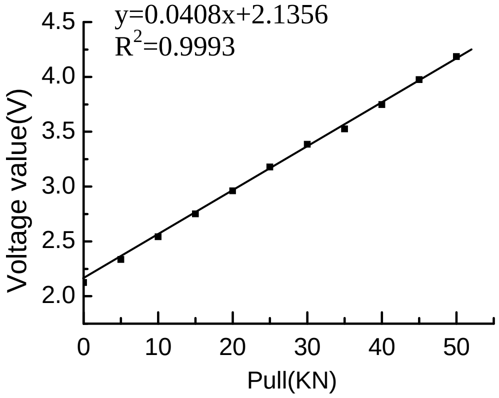

Figure 5 Curve fitting of experiments

One of the major concern in all measurement system involves the effect of temperature sensitivity of the system and the permeability measurements are no exception. They are strongly influenced by the temperature at which the measurements are made. The tends of the functional relationship of permeability changes with tension indicate that while the permeability changes as a function of temperature , the slope of the permeability tension curve do not change. This is advantageous in terms of developing a compensation scheme. Thus it is possible to carry out the temperature calibration at zero tension and extrapolate the results for temperature compensation at any other temperature.

6. CONCLUSION REMARKS

We know that the cable tension is proportional to the permeability based on magneto-elastic effect, and the cable tension sensor is researched according to that. The magnetic circuit of the sensor was analyzed and a pulsed magnetization circuit was designed. The simulation experiments were done on the pull machine for calibrating the sensors. The results indicate that the repeatability errors of the system is lower than 0.015V, the square of correlation coefficient is 0.9993.

REFERENCES:

[1] Sumitro.(2001).True-stress measurement of PC steels by EM sensor. J. of Pre-stressed Concrete Japan (Japan Prestressed Concrete Engineering Association)**43:6**, 99-103.
[2]Chen, Z., Wang, M.L., Okamoto, T., and Sumitro.(2000). A new magneto-elastic stress/corrosion sensor for cables in cable-stayed bridges using measurement of anhysteretic curve.2nd Workshop on ATUEDM **144:7**, 11-13.
[3]Wang, M.L., and Chen, Z(2000).Magneto-elastic permeability measurement for stress monitoring in 0steel tendons and cables. Proc. of the SPIE 7th Annual Symposium on Smart Structures and Materials, Health Monitoring of the Highway Transportation Infrastructure **399:5**, 492-500.
[4] S.Sumitro, A. Jarosevic & M.L. Wang (2002). Elasto-Magnetic Sensor Utilization on Steel Cable Stress Measurement. The First fib Congress, Concrete Structures in the 21th Century, Osaka, 79-86.
[5] Kvasnica B and Fabo(1996).Highly precise non-contact instrumentation for measurement of mechanical stress in low carbon steel wires. Meas.SciTech, 763-767.
[6]Tian Min Bo(2001). Magnetic material. Tsinghua University press.
[7]Lin Qi Rong(1987). Principle of magnetic circuit design .China Machine Press.