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A Parallel Wire Cable Tension Testing Method Based on a Permanent Magnetizer

Youwei LIU and Xinjun WU [1]
School of Mechanical Science & Engineering, Huazhong University of Science and Technology, Wuhan 430074, China

Abstract. Obtaining the cable tension accurately is important to the structural safety. Among different cable tension testing methods, the method of testing stress under the excitation of constant magnetic field is not affected by the boundary condition of the cable and avoids the affection of eddy current. Through analyzing the structural features of parallel wire cable, a cable tension testing method is presented based on the principle of testing stress under the excitation of constant magnetic field. An experiment setup is carried out to verify the feasibility of the method.

Keywords. Parallel wire cable, cable tension, constant magnetic field

1. Introduction

The cable is one of the commonly used components on bridges, dome structures and so on. The tension of the cable can affect the safety of the structures, so measuring the cable tension is of great significance. Presently, there are four often-used cable tension testing methods: the lift-off method, the pressure sensor method, the vibration method and the magnetic method. The lift-off method is low in efficiency and hard to be used in the built bridge. For the pressure sensor method, the tension information can be obtained directly, while it is necessary to embed pressure sensors inside the cable which increases the cost. For the vibration method, the natural frequency is used to characterize tension. A linear theory of free vibration of suspended cables is presented [1]. However, the result of vibration method can be easily influenced by the boundary conditions of the cable. The magnetic method is based on the effect of stress on magnetic parameters. It has unique advantages such as low cost, no pollution and free from the influence of the boundary conditions. The metal magnetic memory (MMM) technique is the most representative passive magnetic method. Doubov uses the normal and tangential magnet flux density to judge the stress distribution and find the stress concentration [2]. Magnetizing windings and sensing coils are used in several magnetoelastic methods to monitor the steel forces [3-4]. Coils are usually employed to excite and receive magnet signals in above research, which brings the influence of eddy current. In order to overcome this shortage, the principle of testing stress under the excitation of constant magnetic field was proposed. Permanent magnets are employed to magnetize steel wire and Hall elements are used to measure the magnetic flux density at different lift-offs [5]. According to the measured data, the inner magnetic flux density and magnetic field intensity are obtained by using

[1] Corresponding Author, Xinjun WU, Huazhong University of Science and Technology, Wuhan 430074, China; E-mail: xinjunwu@hust.edu.cn

the interpolation method and magnetic boundary conditions, and then the steel wire stress can be deduced. For the parallel wire cable (PWC), because there's high density polyethylene (HDPE) layer surrounding the steel wires, it is difficult to magnetize the PWC and measure the magnetic field for magnetic testing.

In this paper, a cable tension testing method based on the theory of testing stress under the excitation of constant magnetic field is carried out. In the method, Gauss' law is applied to establish the relationship between stress and a feature parameter at a large lift-off from the cable surface. Finally, an experiment is carried out to verify this method.

2. Principle

The principle of the PWC tension testing method proposed in this paper is shown in Figure 1. First of all, when an axial stress is applied to the cable, it can be assumed that the axial stress in the steel is uniformly distributed. Then, circumferentially uniform constant magnetic excitation is employed to the cable to produce an axially-varying magnetic field. The axial magnetic flux density B_{fer}^{z} inside the steel is uniformly distributed in a cross section. Also, since the axial component B_{fer}^{z} is far higher than the radial component B_{fer}^{r} in the steel, B_{fer}^{z} equals to the magnetic flux density B_{fer} in the cable. Based on these conditions, further derivation is developed.

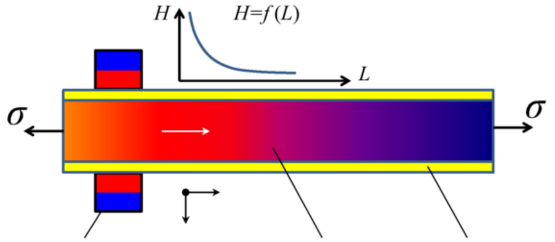


Figure 1. The principle of testing parallel wire cable tension based on a permanent magnetizer

According to the J-A-M model[6], B_{fer} is function of H and σ, which can be written as

$$B_{fer} = F_1(H, \sigma) \tag{1}$$

Under the excitation of the constant magnetic field, H is only the function of the axial position L. So,

$$B_{fer} = F_2(L, \sigma) \tag{2}$$

when L is determined, B_{fer} is only relative to σ, which means it can characterize σ. However, it is unable to measure B_{fer} inside the cable. Also, because of the HDPE layer surrounding the steel wires, the lift-off is large and previous extrapolating method may not be feasible any more. Thus, it is necessary to find a new feature parameter for the cable tension testing under constant magnetic field excitation at large lift-off.

Figure 2 shows how Gauss's law is applied for analyzing. The bundle composing all steel wires in the cable is simplified into a cylinder of diameter *d*. The axial position of the cylinder is *L* away from the permanent magnet and the height of the cylinder is *ΔL*.

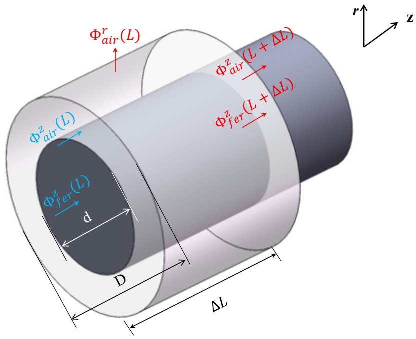


Figure 2. Gauss' law for magnetism at the unit length *ΔL*

As is shown in Figure 2, the magnetic flux passing through the base of the cylinder consists of the magnetic flux inside the ferromagnetic area denoted as Φ^z_{fer} and outside the ferromagnetic area denoted as Φ^z_{air}. The magnetic flux passing through the side of the cylinder is denoted as Φ^r_{air}. According to Gauss' law for magnetism, the net magnetic flux passing through the cylinder surface is always zero. Then the derivation can be:

$$\Phi^z_{fer}(L) + \Phi^z_{air}(L) = \Phi^r_{air}(L) + \Phi^z_{fer}(L + \Delta L) + \Phi^z_{air}(L + \Delta L) \tag{3}$$

Since $\Delta L \to 0$, B^z_{fer} is uniformly distributed in the cross section and B^z_{air} and B^r_{air} varies with the radial and axial position, these flux expressions can be written as:

$$\Phi^z_{fer}(L) = B^z_{fer}(L) \cdot \pi d^2/4 \tag{4}$$

$$\Phi^z_{air}(L) = \int_{d/2}^{D/2} B^z_{air}(L, r) \cdot 2\pi r dr \tag{5}$$

$$\Phi^r_{air}(L) = B^r_{air}(L, D/2) \cdot \pi D \cdot \Delta L \tag{6}$$

$$\Phi^z_{fer}(L + \Delta L) = B^z_{fer}(L + \Delta L) \cdot \pi d^2/4 \tag{7}$$

$$\Phi^z_{air}(L + \Delta L) = \int_{d/2}^{D/2} B^z_{air}(L + \Delta L, r) \cdot 2\pi r dr \tag{8}$$

So, Eq. (3) can be rewritten as

$$B^r_{air}(L, D/2) \cdot \pi D \cdot \Delta L = [B^z_{fer}(L) - B^z_{fer}(L + \Delta L)] \cdot \pi d^2/4 + \int_{d/2}^{D/2} [B^z_{air}(L, r) - B^z_{air}(L + \Delta L, r)] \cdot 2\pi r dr \tag{9}$$

Since B^z_{air} and its gradient is far smaller than these of B^z_{fer}, the second term on the right side of Eq. (9) can be ignored, then there is

$$B_{air}^{r}(L,D/2)=(d^{2}/4D)\cdot[B_{fer}^{z}(L)-B_{fer}^{z}(L+\Delta L)]/\Delta L=(d^{2}/4D)\,\partial B_{fer}^{z}/\partial L \quad (10)$$

It is obvious in Eq. (10) that the radial magnetic flux density B_{air}^{r} at certain axial position and D is proportional to the derivative of B_{fer}^{z} on L at that axial position. A certain D is equivalent to a certain lift-off from the outer surface of HDPE layer. Combined with the approximation that $B_{fer} = B_{fer}^{z}$ and Eq. (2), if the lift-off is fixed to l_0, for example, there is

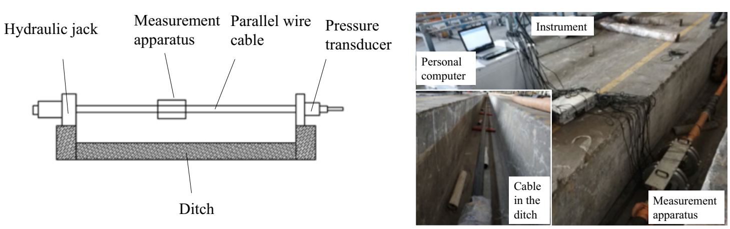
$$B_{air}^{r}(L, lift-off = l_0) = F_4(L, \sigma) \quad (11)$$

It means that B_{air}^{r} at certain lift-off l_0 is function of axial position L and stress σ. Different L determined different linearity between B_{air}^{r} and σ. If we find proper L and lift-off, it can be feasible to use B_{air}^{r} to characterize σ. Therefore, it is possible to get the stress information by measuring B_{air}^{r} at a large lift-off.

3. Experiment verification

3.1. Experiment setup

In order to verify the above cable tension testing method, a PWC tension testing experiment setup is built as is shown in Figure 3.



(a) Diagram of the experiment setup (b) the experiment setup site photo

Figure 3. Diagram and photo of the experiment setup

The whole experiment is carried out on one PWC of type LZM7-85 with an external diameter of 87 mm. It consists of 85 steel wires and HDPE layer surrounding them. Steel wire diameter is 7 mm. The cable is put in a ditch and is tensioned by hydraulic jack at one end. At the other end, a pressure transducer is installed to measure the axial tension of the cable. A measurement apparatus based on the above principle is set up on the PWC.

The measurement apparatus includes the permanent magnetizer and the magnetic field measuring element is shown in Figure 4. The material of permanent magnet is NdFeB and its grade is N52. Five permanent magnetizers are attached circumferentially uniformly on the cable. 16 rows of Hall element sensors distribute from 55 mm to 580 mm away from the magnetizer to measure the field. The Hall element sensors' model is HAL1823 from Micronas. A row of sensors measure B_{air}^{r} at 4 different lift-offs, which are 1.5 mm, 3 mm, 4.5 mm, and 6 mm away from the outer surface of the cable.

The breaking load of the cable is 5460.11 kN, and during the experiment, the biggest tension applied to the cable is 50% of the breaking load. Six different tensions are applied to the cable in the experiment, which are 34%, 36%, 38%, 40%, 42% and 46% of the breaking load.

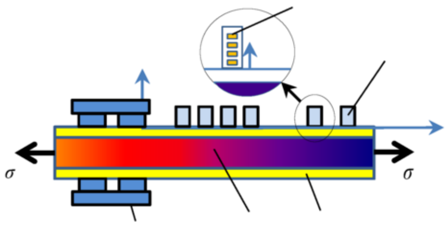


Figure 4. Diagram of the permanent magnetizer and the magnetic field measuring element

3.2. Experiment result

Since the cable's cross-sectional area can be seen as the same at any axial position, the cable tension is always proportional to the stress. Also, the tension of the cable can be seen as the same along the whole cable as well as the stress. Thus, the relationship between B_{air}^{r} and the cable stress can be extended to that between B_{air}^{r} and the cable tension. What is analyzed below is the B_{air}^{r}-tension relationship.

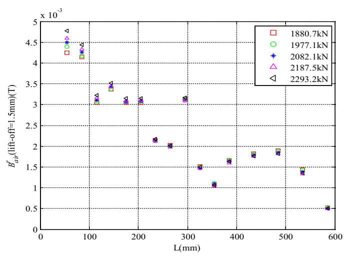
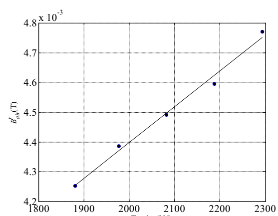
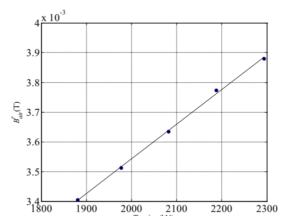


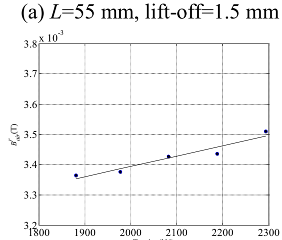
Figure 5. B_{air}^{r}(lift-ff=1.5mm)-L relationship



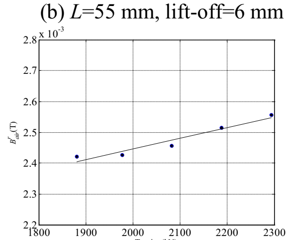
(a) L=55 mm, lift-off=1.5 mm



(b) L=55 mm, lift-off=6 mm



(c) L=145 mm, lift-off=1.5 mm



(d) L=145 mm, lift-off=6 mm

Figure 6. B_{air}^{r}-Tension relationship at different L and lift-offs

Figure 5 shows the B_{air}^{r}-L distribution at 1.5 mm lift-off from the surface of the HDPE layer under different tensions. It can be found that B_{air}^{r} varies with cable tension and the variation trend is different at different L. Use the data under the first 5 tension to do the linear regression analysis. The goodness of fit of the four conditions in Figure 6 are respectively R_a^2=0.9903, R_b^2=0.9987, R_c^2=0.9306 and R_d^2=0.9451. It shows that B_{air}^{r}(L=55mm) has a better linearity with cable tension than B_{air}^{r}(L=145mm). The linearity varies notably with the axial position L, which agrees with the above derivation.

From the above analysis, B_{air}^{r} (L=55mm,lift-off=6mm),which has the best linear relationship with cable tension T, can be used to fit the cable tension and the equation of linear regression is $B_{air}^{r}=1.2\times10^{-6}T+0.00199$. Use the function to extrapolate another tension on the cable being experimented. The extrapolation result is 2547.9kN while the true value is 2498.6kN. The relative error of linear regression is 1.97%.

4. Conclusion

A parallel wire cable tension testing method based on a permanent magnetizer is studied. Permanent magnetizer is used to produce an axial-varying magnetic field on the cable and a principle is presented to characterize cable stress. Based on the J-A-M model and the field spatial distribution feature, a stress-characterizing parameter B_{air}^{r} is derived using Gauss's law. To verify the method, an experiment setup is built. The experiment result shows that B_{air}^{r}(L=55mm,lift-off=6mm) has the best linearity with cable tension. The best goodness of fit can be 0.9987, and the best error of linear regression analysis is less than 2%. The result indicates that the cable tension testing method is correct and it is feasible to use B_{air}^{r} to characterize cable tension.

5. Acknowledgement

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