Research and Analysis of Suspension Bridge Cable Force Evaluation Scheme for in-Service Suspension Bridge

Lu Yijun [1, *], Chen Xin [2], Xie Jipeng [1]

[1] Nanjing University of Science and Technology Zijin College, Nanjing 210023, China

[2] Jiangsu Expressway Engineering Maintenance Technology Co., Ltd., Nanjing 211100, China

*Corresponding Author

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Abstract: aiming at the problem of the cable force evaluation of the self-anchored concrete suspension bridge after curing, this paper evaluates the relationship between the cable force before and after maintenance by testing the frequency of the boom and calculating the cable force using the string vibration method; the software calculates the frequency of the boom and compares it with the actual measured frequency on the site to determine the accuracy of the string vibration method to measure the cable force of the boom. Through this test, it provides a reliable and effective cable force test program.

1. Introduction

With the rapid development of china's transportation industry, a large number of highways have been constructed. In order to cross the highway, various large-span bridges have also appeared in large numbers. Long-span suspension bridges are increasingly used in the construction of crossing highways due to their advantages of light weight and strong crossing ability [1]. Among them, the suspension rod is an important part of the suspension bridge structure. As the force transmission member, the suspension rod is complicated in force. The load on the bridge and most of the self-weight load are transmitted from the cable to the tower, which is the key part and weak link of the force. [2]. There have been many bridge damage accidents in china due to bridge cable failure [3].

A large amount of literature has conducted in-depth research on the mechanical behavior of the boom, and has obtained many methods for calculating the cable force of the boom, such as the zero displacement method, the chord vibration method, the minimum bending moment method, and the rigid boom method. Fu jinlong et al. [4] considered that in the construction drawing stage and the bridge inspection stage, the restrained bending energy minimum method can more accurately calculate the suspension cable force of a tied arch bridge, and in the initial setting stage, the suspension cable's cable force is bent. The minimum moment method is applicable; tian zhichang et al. [5] optimized the suspension cable force of the tied arch bridge in the bridged state by the constrained minimum energy method. Liu weinan [6] used genetic algorithm and matlab platform to establish the cable force calculation model and process of tied arch bridge. Sung et al. [7] proposed a cable force calculation method that can achieve the best structural performance using the minimum strain energy theory. Hassan et al. [8] determined the cable force model of the cable-stayed bridge using finite element calculations for the deformation of the main beam and the displacement of the pylon; yu rui et al. [9] used vba as a platform to determine the change in cable force when the boom was replaced an optimization scheme for the replacement of suspension rods of the tied arch bridge was presented.

In summary, the research on the suspension cable force of tied arch bridges at home and abroad is relatively extensive, but it has damage to the suspension rod protective sleeve. How to determine the suspension cable tension after maintenance is less involved. This article will use the self-anchoring method. The suspension rod of the concrete suspension bridge is taken as an object. Through field test and finite element calculation, the cable force test method of the suspension rod

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after curing is obtained.

2. Research Objects and Goals

The test bridge is a separate overpass, the bridge is 160 meters long. The bridge crosses the highway from west to east. This bridge is a double-sided tower-girder self-anchored concrete suspension bridge. The main span is 80m, the side span is 40m, and the mid-span vertical span ratio is 1/5, which is 16m. The total length of the bridge is 40 + 80 + 40 = 160m, the main cable is 22m away from the centre of the bridge, and the distance between the slings is 5m along the bridge. Design load standard: car-over 20, trailer-120. The main beam is a C50 prestressed concrete single box four-chamber box girder. The tower is a “pillar” reinforced concrete structure with a height of 20.6m above the bridge deck and a total height of 28.2m. There are 50 suspension bridges in the whole bridge, using 187-Ø5mm high-strength galvanized steel wire finished cable, standard strength is 1670MPa, double-layer PE protective layer, cold-cast anchor and anchor system. The lower structure of the main bridge: the abutment is a ribbed platform plus a rock-socketed pile, and a rectangular base and a rock-socketed pile under the tower pillar. The bridge structure is shown in Figure 1.

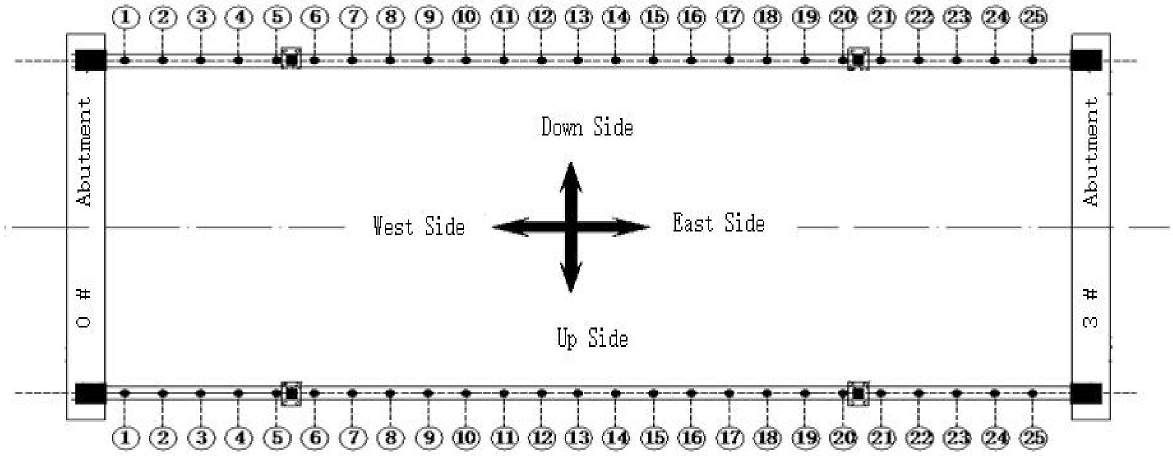

Fig.1 Schematic Plan of the Suspension Bridge

The bridge started operation in 2006. Periodic inspection found that the PE protective layer of the boom was damaged. After comprehensive consideration, the damaged boom sheath was cut with a thickness of 3mm rubber to a size of 33cm × 9m and wrapped. The density of the rubber it is 1270kg / m3. This protective measure is undoubtedly beneficial to increase the durability of the boom, but because it changes the mass of the length of the boom unit, it also changes the free vibration frequency of the boom. There will be some impact. For this reason, this experiment mainly explores the following issues:

1) Study the effect of the addition of rubber sleeves on the frequency of the boom and the cable force of the boom calculated from this frequency.

2) Theoretically discuss the accuracy of detecting cable force using the string vibration theory in this project.

3) Use the finite element software to check the measured frequencies of the front and rear booms.

3. Experiment Content and Principle

3.1 Cable Test of Front Suspension Boom

For the detection of the internal force of a bridge, the commonly used detection method is the vibration method, that is, the cable is instantaneously excited, the vibration frequency of the cable is measured with a vibration sensor, and the internal force of the cable is calculated by a theoretical formula. In this test, the laser vibrometer PDV100 (pictures of field force testing with the laser vibrometer in Figures 2 and 3, and Figure 4 is the spectrum analysis of the vibration signal of the laser vibrometer) were used to detect the cable force of the boom. The collected data and analysis of the test data, so as to obtain the vibration frequency of each order of the cable.

Fig.2 Ld Boom Cable Force Test   Figure 3 Pdv100 Laser Vibration Meter

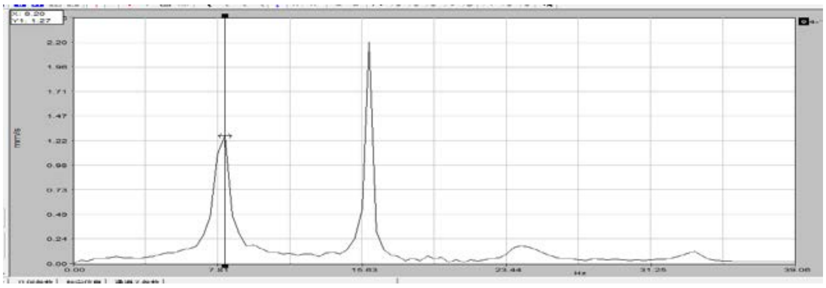

Fig.4 Spectrum Analysis of Vibration Signal of Laser Vibrometer

After measuring the natural frequency of the boom, the cable force of the cable is calculated according to the following formula.

$$\boldsymbol{F_n} = \frac{4\boldsymbol{mL}^2 \boldsymbol{f_n}^2}{\boldsymbol{n}^2} - \frac{\pi^2 \boldsymbol{EI}}{\boldsymbol{L}^2} \quad (1)$$

Where: F_n is the cable force of the boom calculated from the nth order frequency;

m is the mass per unit length of the boom;

L is the length of the boom;

f_n is the n-th order natural frequency of the boom;

n is the order of the natural frequency taken.

3.2 Cable Test

Increase protection for broken booms. A thin layer of rubber is evenly wrapped on the outside of the boom, and a reflective sheet is directly attached to the protective rubber sleeve. When measuring the vibration of the boom, the common vibration of the rubber sleeve is included. The change is no longer the original 24.2kg / m. After measurement, the converted unit length mass of the rubber jacket is 0.84kg / m. This unit length mass should be added to the boom. The theoretical calculation is as follows:

Assume that there is no change in the constraint conditions before and after the rubber sleeve is added, and the actual cable force does not change. According to the string vibration formula, it is easy to obtain:

$$\frac{4m_1 L^2 f_{n1}^2}{n^2} = F_n = \frac{4m_2 L^2 f_{n2}^2}{n^2} \quad (2)$$

Where: F_n is the cable force of the boom calculated from the nth order frequency;

m_i is the mass per unit length of the boom;

L is the length of the boom;

f_{ni} is the n-th order natural frequency of the boom;

n is the order of the natural frequency taken.

Available: $\frac{f_{n2}^2}{f_{n1}^2} = \frac{m_1}{m_2}$

Bring in m_1 = 24.2kg / m, m_2 = (24.2 + 0.84) kg / m

$\frac{f_{n2}^2}{f_{n1}^2} = \frac{m_1}{m_2} = 0.966$ It can be seen that if the cable force calculation correction is not performed for the unit mass of the boom, a cable force calculation deviation of 3.4% will be caused.

Therefore, when theoretically calculating the cable force of the boom after protection, the mass per unit length of the boom needs to be corrected. The mass of the boom after correction is 25.04 kg / m. The cable force of the boom after protection is calculated based on the corrected unit length mass.

3.3 Cable Force Test after Adding Ferrules

Because there is no adhesive bond between the protective rubber layer and the original boom, it is not clear whether the protective rubber layer and the boom vibrate together during the test, and the impact on the test results needs to be demonstrated. A ferrule is added outside the rubber sleeve at the measuring point, and the rubber sleeve is clamped to be tightly combined with the original suspension rod. The reflective sheet is attached to the ferrule during vibration measurement. The arrangement of the ferrules is shown in Figure 5.

Fig.5 Arranging a Ferrule on the Rubber Sleeve

3.4 Finite Element Software Calculation

Table 1 Finite Element Calculation Parameters

Name	Specifications	Poisson's ratio	Modulus of elasticity	Density
Boom	187-Ø5mmWire rope	0.28	200GPa	7.85t/m3
Main cable	13-91-Ø5mmCable Stock	0.28	200GPa	7.85t/m3
rubber	3mm	0.47	0.79MPa	1.27t/m3
Cable tower	2mx2.8m- Reinforced concrete column	0.23	37GPa	2.6t/m3
Bridge structure	22m- Single box four room reinforced concrete box girder	0.23	37GPa	2.6t/m3

The finite element software is used to calculate the frequency of the boom in the three cases of protection before, after protection, and the addition of a hoop. Compare the calculated frequency of the software with the actual frequency measured on site to verify the accuracy of the results. The calculation parameters are shown in Table 1:

4. Boom Cable Force Test Results

Figure 6 is a comparison diagram of the measured cable force distribution of the boom in three cases before protection, after protection, and after the addition of a hoop. The test boom is an up-and-outer bar. The cable number is the same as the plan view of the boom. The measured vibration frequency of each boom is a first-order frequency.

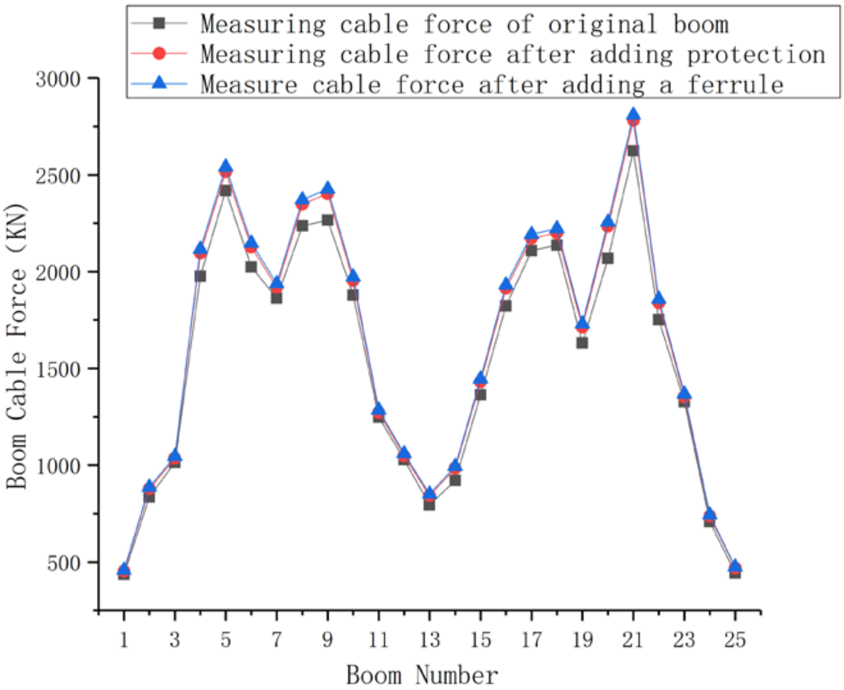

Fig.6 Comparison of Measured Cable Forces Before and after Boom Protection

It can be seen from Figure 6 that the measured cable force of the boom in all three cases is less than the design cable force (6127kN). The measured cable force of the boom near the tower is larger and the cable force distribution is reasonable.

Comparing the cable force of the boom before and after the protection, it was found that after adding the rubber protection layer, the test cable force of the boom increased, increasing between 1% and 5%, which is the same as that of the boom after the rubber layer was added to protect the boom. Increase in mass per unit length. In the comparison of actual boom cable forces, the increase in rubber-protected boom test cable forces requires a 3.2% reduction in the actual cable forces of the inner cable of the boom.

The cable force of the boom before and after the addition of the ferrule is compared, and it is found that the force of the ferrule remains basically the same. From this, it can be seen that whether the clamping by the ferrule has basically no effect on the test cable force. It shows that whether the clamp is clamped with a ferrule, the protective rubber sleeve vibrates synchronously with the original boom. It is correct to regard the protective rubber sleeve as a mass distributed along the length of the boom. However, considering the impact of local vacancies caused by rubber aging, in actual cable force testing, it is still recommended to add a ferrule to ensure that the measurement point vibration is boom vibration.

5. Finite Element Simulation

Using the finite element software, the finite element calculation model of the suspension bridge is established, the nodes are arranged according to the actual conditions of the project, and the vibration frequency of each boom under the actual working conditions is calculated; meanwhile, the difference between the measured frequency of the boom and the calculated frequency of the finite element is compared to Determine the accuracy of the field measured data.

5.1 Finite Element Calculation of Boom Frequency

The longer the length of the boom, the less the frequency of the boom is affected by other factors, and the more accurate the value is. Therefore, a 5 # boom near the pylon is used as an example to compare the protection before, after protection, and after adding a ferrule. The vibration frequency of the boom is calculated in three cases, as shown in Figure 7.

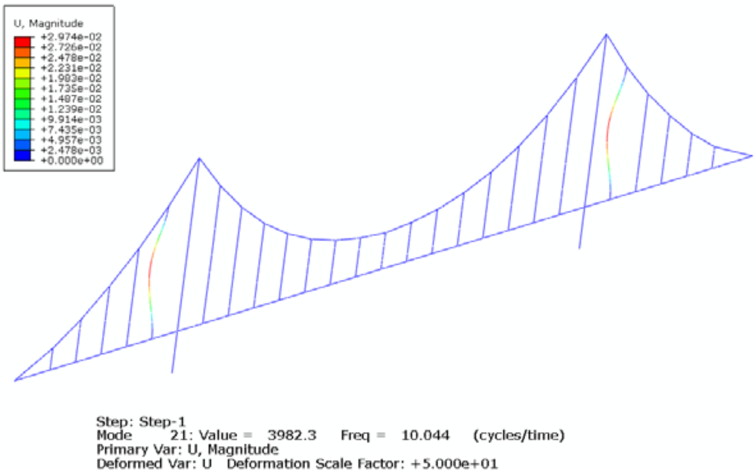

Fig.7 (a) Fem Calculation Frequency of the Original No. 5 Boom

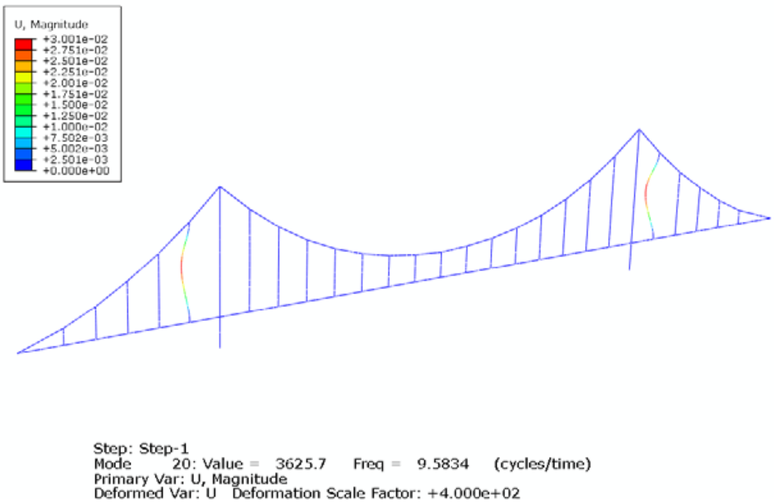

Fig.7 (b) Fem Calculation Frequency of Rubber Boom 5 after Rubber

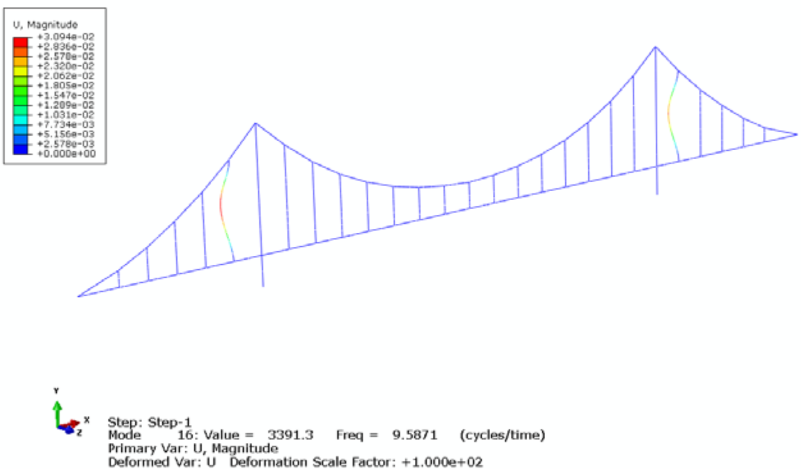

Fig.7 (c) Fem Calculation Frequency of Boom 5 with Ferrule

It can be seen from Figures 7 (a) and (b) that the original FEM calculation frequency of the No. 5 boom is 10.044, the calculated frequency after rubber protection is 9.5843, and the calculated frequency of the boom after rubber protection is reduced by 4.57%, the main reason After the protection of the rubber layer is increased, due to the presence of the rubber layer, the vibration of the boom is converted to the damped vibration in a weakly damped state. The theoretical calculation formula of the vibration frequency of the boom is [10]:

$$\omega_d = \sqrt{\omega_n^2 - \alpha^2} = \omega_n \sqrt{1 - \left(\frac{\alpha}{\omega_n}\right)^2} = \omega_n \sqrt{1 - \xi^2} \tag{3}$$

Where is the natural original frequency of undamped free vibration.

It can be seen from formula (3) that under weak damping vibration, the vibration frequency of the boom will decrease, and the vibration period will be extended accordingly.

As shown in Figure 7 (c), the calculated frequency of the boom with the added hoop is 9.5871, which is basically the same as the calculated frequency of the boom with rubber added, indicating that adding the hoop has no effect on the calculated frequency of the boom. The added rubber layer is vibrated together with the boom, and the two are considered as a whole.

5.2 Boom Frequency Comparison

The vibration frequency of the boom measured by the field instrument is compared with the frequency of the boom calculated by the finite element method, as shown in FIG. 8.

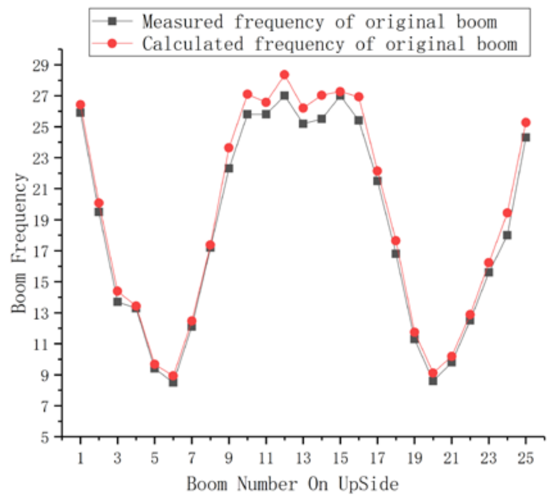

Fig.8 (a) Comparison of the Measured Frequency and the Finite Element Calculation Frequency of the Original Boom on the Upside

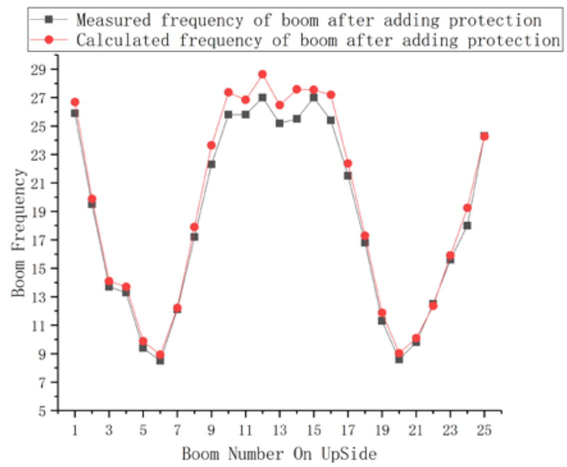

Fig.8 (b) Comparison of Measured Frequency and Finite Element Calculation Frequency of Boom after Adding Protection on the Upside

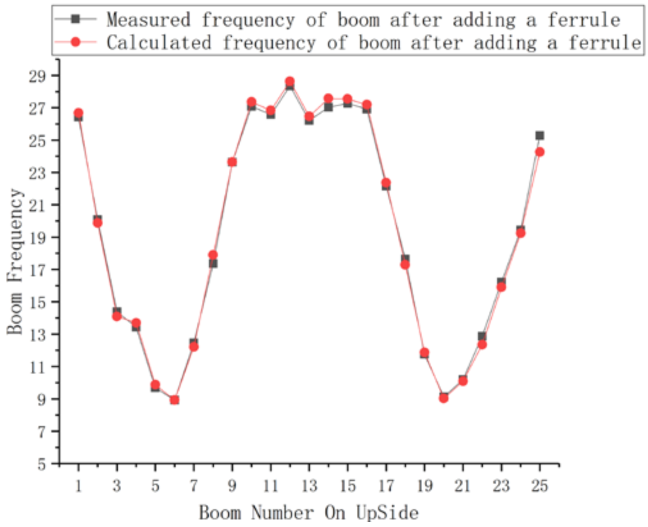

Fig.8 (c) Comparison of the Measured Frequency of the Boom and the Calculated Frequency of the Finite Element after Adding a Ferrule on the Upside

It can be seen that in three cases, the measured frequency of the boom is basically consistent with the calculated frequency, indicating that the accuracy of the measured frequency of the boom is high and the measurement results are accurate. There are deviations in the frequency of individual short booms. This is mainly due to the short boom and the short calculated length of the boom. When measuring the boom frequency, it is greatly affected by other factors.

6. Conclusion

Most of the calculated cable forces of the boom before and after the maintenance have different degrees of change, mainly due to the mass change caused by the wrapped rubber. In the future testing, we should pay attention to the correction of the results when referring to the rubber quality when calculating the cable force.

The actual measurement results show that the current protective rubber sleeve is synchronized with the original boom. The test results before and after the addition of the clamp are basically the same. However, considering the impact of local voiding after the aging of the rubber, it is still recommended to increase the clamp to ensure that the vibration of the measuring point Boom vibration.

Through the finite element calculation, the measured vibration frequency of the boom is consistent with the calculated vibration frequency, which verifies that the string vibration method is correct and accurate for testing the cable force of the boom.

In summary, through this test, a reliable and effective cable force test scheme is provided for the boom that is protected by adding a protective cover.

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