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Application of Inclinometer in Arch Bridge Dynamic Deflection Measurement

Xianlong He*[1], Xueshan Yang[2], Lizhen Zhao[3]
[1,2]Key Laboratory of Earthquake Engineering and Engineering Vibration, Institute of Engineering Mechanics, CEA, Harbin 150080, China, Ph:+8613784772917;
[3]Institute of Disaster Prevention Science and Technology, HeBei Shanhe, 065201, China, Ph:+8613785626623.
Corresponding author, e-mail: hxl4128@163.com*[1], 524245186@qq.com[2], hxl120626@163.com[3]

Abstract

Dynamic deflection measurement is an important component to the bridge loading experiment or health monitoring. Using high-precision inclinometers to test the dynamic deflection is a good method for High-Speed Railway Bridge deflection measurement in this paper, we develop a kind of precision inclinometer which comprehensives the Capacitive sensor technology and the Servo sensor technology and has been called QY inclinometer. We also derive a new theory to calculate deflection based on inclination. Using eleven QY inclinometers and three Cable-Displacement sensors, we have done a comparison dynamic deflection measurement experiment on an arch bridge. Test results indicate: using inclinometers to measure dynamic deflection can achieve the same accuracy with Cable-Displacement sensor which can achieve 0.1 mm accuracy. Therefore, this experiment has proved Using high-precision inclinometers to measure dynamic deflection of bridge can satisfy the dynamic deflection measurement request of high-speed railway bridge. Comparing with other methods of dynamic deflection measurement, using high-precision inclinometers to measure dynamic deflection is very easy to operate, and also do not need find a static reference point.

Keywords: *arch bridge, dynamic deflection, inclinometer, cable-displacement sensor, measure deflection*

1. Introduction

As we know, dynamic deflection measurement is very important for the operational safety and structural damage assessment of High-Speed Railway Bridge [1-3], because the dynamic deflection has close relationship with the live-load capacity of span and high-speed train derailment [3]. There have several methods to detect dynamic deflection of bridge, mainly including: using cable-displacement sensor to measure, using high accuracy GPS receiver device to measure, using laser device to measure [4]. It is an easy operation and low cost and high accuracy method to test dynamic deflection by cable-displacement sensor, but this method needs find a static place to install the sensor, can’t been used to measure such bridge which cross upon the river or canyon[5]. High precision GPS receiver can been used to test the dynamic deflection of bridge, but its accuracy can only reach cm level [1, 6], only been used to measure the deflection of cable-stayed and suspension bridge which have long span and significant deflection changed. Using laser device to measure deflection also needs a static place to install the device, so it can’t test such spans that cross river or canyon [7].

As we know, prestressed concrete box beam bridges and steel truss arch beam bridges are the main part of High-Speed Railway. Such bridges have large stiffness and strong ability to resist deformation and can meet the requirements of High-Speed Railway. It maybe has slight dynamic deflection for some short span of such bridges when High-Speed train runs across. Therefore, the precision of GPS receiver is not enough for dynamic deflection measurement of High-Speed Railway Bridge. Many High-Speed Railway Bridges cross river or canyon. Therefore, using cable-displacement sensor or laser device to measure dynamic deflection of such High-Speed Railway Bridge is very difficult, because there are not static place near the bridge to install these devices. There has another shortage of these methods that can only test one point’s dynamic deflection at the same time [8-10]. Therefore, it is a significance

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research to develop a new dynamic deflection measurement method for the High-Speed Railway Bridge [11-14].

In this paper, we develop a new dynamic deflection measurement method which basing high-precision inclinometers to test all position's dynamic deflection of bridges [5]-[6]. Based on this method, we have used QY inclinometers to test the dynamic deflection of on arch bridge successfully.

2. The Principle of QY Inclinometer

QY inclinometer includes the technology of electric capacity displace sensor and electromagnetism feedback sensor, as shown in Figure 1. We use the technology of electromagnetism feedback to changed the damping coefficient of pendulum and develop a differential motion electric capacity displace sensor to response the displacement of pendulum.

Figure 1. QY Inclinometer

The principle of QY inclinometer has shown in Figure 2 and 3.

Parameter k is the stiffness of mechanical spring, defines b as damping coefficient, G is an electric-feedback damping coefficient, $G = BL_1L_2$, BL_1 is mechanical coupling factor, L_2 is the length of pendulum, g is an small electric-feedback damping coefficient which is used to adjust to level of pendulum, θ is the inclination of pendulum, k_c is the sensitivity of electric capacity sensor, X is the displace of electric capacity sensor, R is the resistance of coil. Equation (1) is the motion equation of mass block m .

$$\begin{aligned} & k_1\ddot{\theta} + b\dot{\theta} + k\theta + Gi = -Mg\theta_1 \\ & u_0 = k_c x = k_c L_2 \theta \end{aligned} \tag{1}$$

k_1 is moment of inertia, $k_1 = L_3L_4m$, L_3 is the equivalent length of pendulum, L_4 is the length of the moving center of pendulum to the center of mass block m , θ_1 is the vertical inclination of measuring point, M is the quality of QY Inclinometer. Solving Equation (1), we can get Equation (2):

$$\begin{aligned} & \frac{u_0}{\theta_1} = -B_1 \times \frac{1}{(\frac{s^2}{n^2} + \frac{2D}{n}s + 1)} \\ & B_1 = \frac{k_c L_2 Mg}{n^2 k_1} \end{aligned} \tag{2}$$

s is operator. n is the inherent circular frequency of pendulum, $n=\sqrt{\dfrac{k}{k_1}}$. D is the damping coefficient which calculated from b and G , $D=\dfrac{G^2}{2k_1 nR}$.

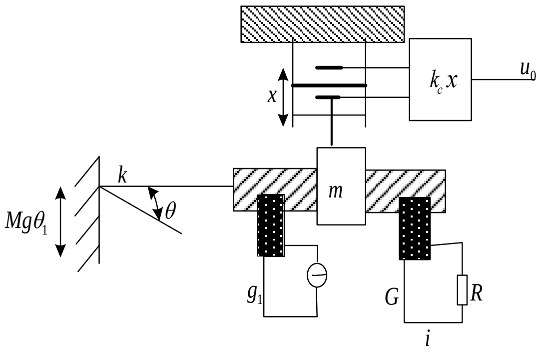

Figure 2. The Structure Principle of QY Inclinometer

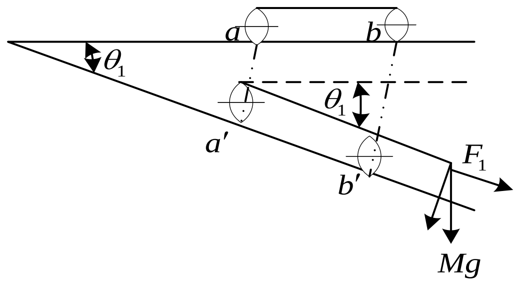

Figure 3. The Force Balance of YQ Inclinometer

If $D<1$ and $s^2 << n^2$, we can get the sensitivity of sensor, just like Equation (3).

$$\frac{u_0}{\theta_1}=-B_1 \tag{3}$$

3. The Theory of Deflection Calculation from Inclination

We define the length of one span of bridge is L meter, and install N_1 inclinometers on this span.

So we can get N_1 position's inclination data and define them as Matrix (4):

$$Q=\begin{bmatrix} q_1 & q_2 & \cdots & q_{N_1} \end{bmatrix} \tag{4}$$

q_i is the i position's inclination data.

We define the static deflection function as:

$$\begin{aligned} y(x) &= c+\sum_{i=1}^{N} f_i(x) \\ f_i(x) &= a_i\sin(w_i x)+b_i\cos(w_i x) \end{aligned} \tag{5}$$

x is any position of the beam. $f_i(x)$ is defined as the i modal function of the beam. w_i is defined as the i modal frequency, a_i and b_i are coefficients of function $f_i(x)$. c is the corrected coefficient of deflection.

As we know, there have not deflection changed near piers. So we can calculate the following equations:

$$\left.\begin{aligned} \sum_{i=1}^{N} b_i &= -c \\ \sum_{i=1}^{N} a_i \sin(w_i l) + \sum_{i=1}^{N} b_i \cos(w_i l) &= c \end{aligned}\right\} \tag{6}$$

Defining the inclination function of beam as $p(x)$, and getting the following equation:

$$p(x) = \frac{\partial y(x)}{\partial x} = \sum_{i=1}^{N} a_i w_i \cos(w_i x) - \sum_{i=1}^{N} b_i w_i \sin(w_i x) \tag{7}$$

If we discrete parameter x, we can get the following equation:

$$p(x_j) = \sum_{i=1}^{N} a_i w_i \cos(w_i x_j) - \sum_{i=1}^{N} b_i w_i \sin(w_i x_j) \tag{8}$$

So we need solve 3N number parameters. We define function:

$$z(a_1, a_2, \cdots, a_N, w_1, w_2, \cdots, w_N, b_1, b_2, \cdots, b_N) = \sum_{j=1}^{N_1} (p(x_j) - q_j)^2 \tag{9}$$

According the rule of least square method, we can get N sets of following equations:

$$\left.\begin{aligned} \frac{\partial z}{\partial a_i} &= 0 \\ \frac{\partial z}{\partial w_i} &= 0 \\ \frac{\partial z}{\partial b_i} &= 0 \end{aligned}\right\} i = 1, 2, \cdots N \tag{10}$$

Expanding Equation (10), we can get N sets of following equations:

$$\left.\begin{aligned} &(\sum_{j=1}^{N_1} \sum_{t=1}^{N} (a_t w_t \cos(w_t x_j) - b_t w_t \sin(w_t x_j) - q_j) w_i \cos(w_i x_j) = 0 \\ &(\sum_{j=1}^{N_1} \sum_{t=1}^{N} (a_t w_t \cos(w_t x_j) - b_t w_t \sin(w_t x_j) - q_j)(a_i \cos(w_i x_j) - b_i \sin(w_i x_j) - \\ &\quad a_i w_i x_j \sin(w_i x_j) + b_i w_i x_j \cos(w_i x_j)) = 0 \\ &(\sum_{j=1}^{N_1} \sum_{t=1}^{N} (a_t w_t \cos(w_t x_j) - b_t w_t \sin(w_t x_j) - q_j) w_i \sin(w_i x_j) = 0 \end{aligned}\right\} \tag{11}$$

As we know, all model functions are orthogonal functions. So we can also define $(f_1(x), f_2(x), \cdots, f_N(x))$ are orthogonal functions, and get N-1 sets of following equations:

$$\int_0^l (a_i \sin(w_i x) + b_i \cos(w_i x))(a_t \sin(w_t x) + b_t \cos(w_t x)) dx = \begin{cases} 0 & i \neq t \\ k_i & i = t \end{cases} \tag{12}$$

If $N_1 \geq 3N$, we can solve parameters $[a_1, b_1, w_1, \cdots, a_N, b_N, w_N]$ from Equation (11) and (12), then we can solve parameter c from equation (6). So we solve all parameters of static deflection function $y(x)$.

If we define all parameters have changed following time, we can get the dynamic deflection function:

$$
\begin{aligned}
y(x,t) &= c_t + \sum_{i=1}^{N} f_i(x,t) \\
f_i(x,t) &= a_i(t) \times (\sin(w_i x) + b_i(t) \times \cos(w_i x)
\end{aligned}
\tag{13}
$$

4. Application in Arch Bridge

We have used QY inclinometer and other sensors to test dynamic deflection of HUANGHE River High-Speed Railway bridges. This bridge has 1360meters long and 23 spans. We have chosen a 100 meter long arch bridge to test. Its shape is shown as Figure 5.

Figure 5. The Picture of Arch Bridge which We Test

We have used eleven QY inclinometers to test this bridge. The position of installing QY inclinometers are shown as Figure 6.

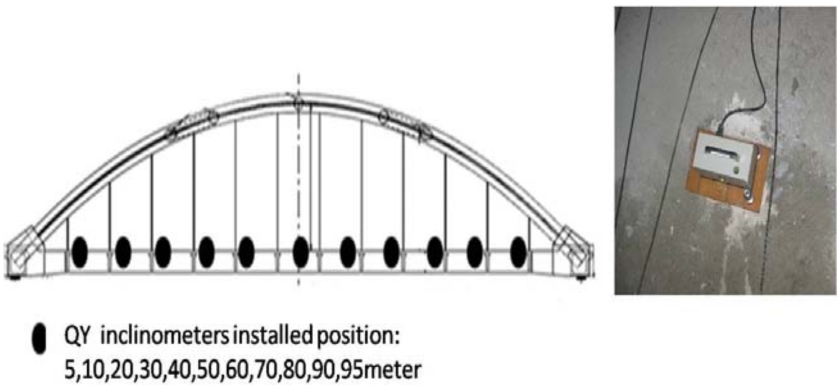

Figure 6. Installing Positions of QY Inclinometers

At the same time, we have installed three Cable-Displacement sensors near 25 and 50 and 75 meter long to test the dynamic deflection of this bridge. QY inclinometers have been installed in the right side of box beam. We used the same train running across with different speed as dynamic loads. The test results are shown in table one to table three, and Figure 7 to Figure 9.

Table 1. The Max Measurement Deflection of Two Systems at 25 meter Long

Train-speed（km/h）	inclinometer D1	Cable-Displacement D2	(D1-D2)/D2
5	3.78mm	3.69mm	2.5%
60	3.67mm	3.73mm	-1.7%
120	3.86mm	3.75mm	2.9%

Table 2. The Max Measurement Deflection of Two Systems at 50 meter Long

Train-speed（km/h）	inclinometer D1	Cable-Displacement D2	(D1-D2)/D2
5	3.28mm	3.49mm	-6.1%
60	3.39mm	3.56mm	-4.7%
120	3.69mm	3.55mm	3.9%

Table 3. The Max Measurement Deflection of Two Systems at 75 meter Long

Train-speed（km/h）	inclinometer D1	Cable-Displacement D2	(D1-D2)/D2
5	3.52mm	3.67mm	-4.1%
60	3.57mm	3.78mm	-5.6%
120	3.65mm	3.82mm	-4.5%

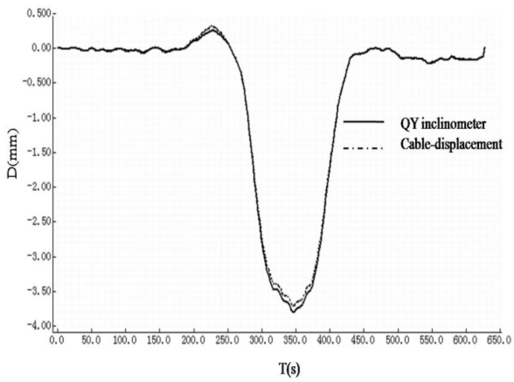

Figure 7. The Dynamic Deflection Curve of 25 meter Point when Train Runs Across with 5Km/h speed

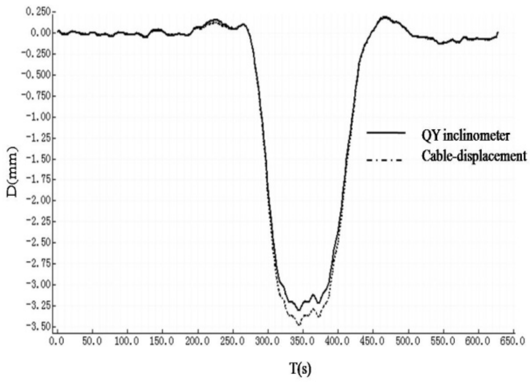

Figure 8. The Dynamic Deflection Curve of 50 meter Point when Train Runs Across with 5Km/h Speed

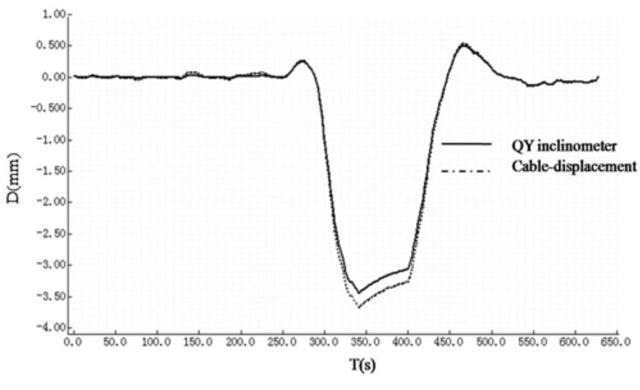

Figure 9. The Dynamic Deflection Curve of 75 meter Point when Train Runs Across with 5Km/h Speed

Comparing with cable-displacement sensor, test results of using QY inclinometer to test dynamic deflection have smaller than 7 percent errors, and also have similar dynamic deflection curves.

5. Conclusion

According inclination to calculate dynamic deflection of High-Speed Railway Bridge is a good measurement method. We have developed a new kind of precision inclinometer and a new theory to fast calculate dynamic deflection from dynamic inclination data, and have used eleven inclinometers to test the dynamic deflection of one arch bridge which is a part of HUANGHE River High-Speed Railway Bridge with a same train running across with different speed as the dynamic loads. Comparing with test results of cable-displacement sensors, we can get some conclusion: using eleven inclinometers to test dynamic deflection of arch bridges has smaller than 7% error; and can get similar dynamic deflection curves, and can achieve a precision of 0.1mm.

Using inclinometers to measure or monitor dynamic deflection of bridges is a good and easy operation method, because inclinometers can be installed into box beam or on the deck of bridge, and do not need a static reference point.

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