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A novel bridge curve mode measurement technique based on fog

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ABSTRACT

In order to achieve the rapid measurement of bridge structure curve mode and locate accurately the maximum deflection, a continuous curve mode measurement method based on fiber optic gyro (FOG) sensing technology is studied. According to the characteristics when FOG-based continuous curve mode measurement used for the bridge, the measurement method premises are analyzed, the trajectory calculating formula of continuous curve mode is derived. In addition, some revising and calibration methods for the testing results and integration way for the measurement device are put forward. The application in a scale model bridge and an actual bridge showed that the testing results of FOG-based continuous curve mode were close to the traditional way by dial indicator and total station, had the same change trend and can be used for correctly locating the bridge maximum deflection position.

1. Introduction

The bridge structure curve mode is an important and intuitive safety inspection index, which can deduce the structure internal force change [1]. At present, level is the main way for curve mode measurement which needs to establish a surveying control network and consumes a long testing period. Other ways such as connected pipe, GPS and inclinometer have some shortcomings in high implementation cost, long testing time and relatively low testing precision [2–5]. All the above existing ways for curve mode measurement base on fitting limited measurement points. The potential structure deflection diseases distributed in the areas without measurement points are likely to be submerged in the fitting process due to limited measurement points. Therefore, the existing ways are not easy to capture the actual maximum deflection position for each bridge span and cannot guarantee the rapid measurement for the large span bridge load test. FOG [6] which can track the continuous trajectory of moving object has been widely used in the military field. The magnitude of meter in positioning accuracy demanded in the long distance inertial navigation field, cannot meet the short distance bridge curve mode measurement accuracy requirement. So far, except several related research in the laboratory [7–9], there is no successful study report about bridge curve mode measurement based on FOG in actual engineering. This paper firstly analyzed the different testing characteristics between bridge curve mode and inertial navigation trajectory when using FOG sensing technology. According to the different characteristics, a bridge continuous curve mode measurement method based on FOG was proposed. Finally, some verification tests were carried out by load test on a scale model bridge and an actual large span suspension bridge.

2. Continuous curve mode measurement method

2.1. Object characteristics and method premises

Comparing to the inertial navigation, the bridge continuous curve mode measurement characteristics and method premise are shown in Table 1.

2.2. Trajectory measurement principle

FOG is sensitive to the angular velocity change of moving object. The angle change of bridge continuous curve mode trajectory can be deduced by integrating the angular velocity. So combined with the distance change between each integral interval, the bridge continuous curve mode can be depicted. The angular velocity change is recorded automatically by FOG. The distance change at each integral interval can be derived from the product of time and linear velocity. As shown in Fig. 1 and Eq. (1), the coordinate change formula of continuous trajectory at each minor integral interval is established.

$$\begin{aligned} \Delta X &= X_{i+1} - X_i = \Delta L \cdot \cos\theta_i = V_i \Delta t \cdot \cos \Omega_i \Delta t \\ \Delta Y &= Y_{i+1} - Y_i = \Delta L \cdot \sin\theta_i = V_i \Delta t \cdot \sin \Omega_i \Delta t \end{aligned} \tag{1}$$

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Table 1
Object characteristics and method premises.

Item	Object characteristics	Method premises
1	The test distance in inertial navigation field is long and test cannot be carried out repeatedly. However, the test distance for bridge is relatively short and the test path can be used repeatedly	The test distance is relatively short and test can be carried out repeatedly in the same path
2	The inertial navigation systems usually run a long period and need high linear velocity. However, the consuming time for bridge curve mode test is relatively short	The drift relative to time and temperature of FOG can be neglected due to short time test period
3	Comparing to the constant bridge structure, there are some randomness effects in inertial navigation trajectory	There are some known bridge boundary conditions for revising the divergent cumulative error

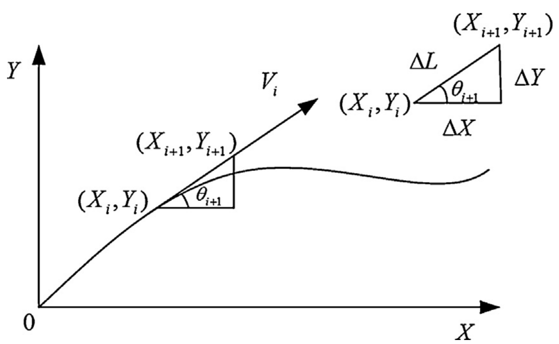

Fig. 1. FOG-based bridge continuous curve mode trajectory measurement principle.

where $V_i\Delta t$ and $\Omega_i\Delta t$ respectively represent the distance and angular change at each integral internal. The sensing principle of continuous curve mode tested by FOG mainly uses the above function relationship, in which dependent variable is the unknown deformation and independent variables contain angular velocity, linear velocity and time interval. The starting point for the bridge curve mode measurement usually can be determined, namely, initial coordinate X_i and Y_i are known. Therefore, according to the real-time output V_i and Ω_i, the next step coordinate at Δt time interval can be deduced, which provides a theoretical basis for the calculation method and device design of bridge continuous curve mode based on FOG.

2.3. Revising and calibration

The result revising mainly aims at the global continuous curve mode. The main purpose is to facilitate the test result more close to the actual value by adjusting the interior and exterior influence factors. The interior factors contain FOG initial angular which easily leads to the global divergent of curve mode, and FOG scale factor which may lead to the amplification of cumulative integral error. The exterior influence factors are derived from engineering environment, such as rutted road, driving vibration and so on. The testing application environment determines that there are some known relatively fixed points, such as abutments, piers and so on, which can be used as boundary constrain conditions to revise the original testing results. Based on multiple back and forth measurements, according to filtering smoothing algorithm, the 'short wave' derived from the exterior influences can be eliminated from the 'long wave' which represents the bridge structure deflection.

The result calibration mainly aims at the local deflection of interest in the continuous curve mode. The main purpose is to improve the deflection testing accuracy by applying a proposed calibration coefficient K as shown in Eq. (2).

$$K = \frac{D_{m2} - D_{m1}}{h_s} \tag{2}$$

where h_s represents the thickness of standard cushion, D_{m1} and D_{m2}, respectively represent the deformation values before and after putting standard cushion at the location of interest.

2.4. Device integration

As shown in Fig. 2, continuous curve mode measuring system needs to be attached to a moving carrier to finish the test. Angular velocity change is recorded by FOG. The moving distance is recorded by linear velocity sensor. Position sensor finishes the positioning reflection for the boundary revising points. By integrating the above modules, a moving measuring carrier can finish the continuous curve mode testing for different types of bridge.

3. Measurement experiments

3.1. Scale model bridge

A scale model cable-stayed bridge with 1:40 reduced-scale, 9.7 m main span, 3.46 m tower height, 0.55 m deck width and 56 cables is shown in Fig. 3. By using the measurement device as shown in Fig. 4, the bridge continuous curve mode tests were carried out. Firstly, a reference continuous curve mode with no loading was recorded. Then in the middle span, 30 kg weight was used to simulate loading. Besides the continuous curve mode measurement, the deflection values relative to reference state at 1/4 span,

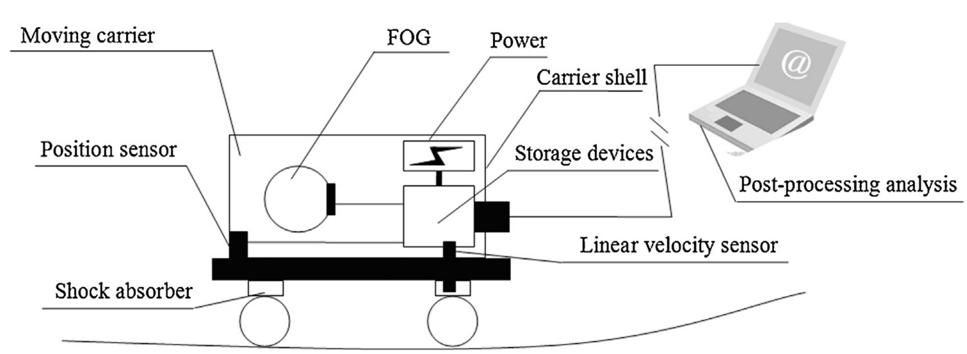

Fig. 2. Movement carrier of continuous curve mode measurement.