Research on A New Type of Excitation Device Applied to Structural Vibration Modal Identification and Structural Vibration Reduction

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Abstract. In order to reduce the frequency of major safety accidents in the bridge construction process, and to realize the real-time monitoring and accurate monitoring of the bridge construction process, a novel excitation device for vibration modal identification and structural vibration reduction is proposed in this paper. The excitation device mainly takes the rotating eccentric mass actuator as the core, uses the centrifugal force of the rotating mechanism to provide internal excitation to the structure, and has the advantages of easy control, low energy consumption, low cost and so on. The research results show that the exciting device has a wide application prospect in structural vibration modal identification and structural vibration reduction, and can effectively reduce the frequency of major safety accidents in the process of bridge construction.

Keywords: New exciting device; Structural vibration identification; Structural vibration reduction.

1. Background Introduction

1.1. Research Background and Significance

With the development trend of large-scale bridges, bridge health assessment is becoming more and more important. In addition, bridge damage monitoring is the basis of bridge health assessment and maintenance management. The dynamic performance test of long-span bridges is an important means of damage detection. From the point of view of damage identification of structural dynamics, the damage or stiffness change of the bridge structure will inevitably lead to the change of the modal parameters of the bridge itself. Therefore, through modal test and analysis, we can carry out long-term monitoring and structural diagnosis of the bridge structure, and to a large extent prevent major safety accidents in the process of bridge construction and use.

At present, the excitation methods used in modal testing of long-span bridges include vehicle jumping method, ground pulsation method, wind vibration method, rocket launch method and so on. Taking the vehicle bumping method as an example, the bridge needs to be closed in modal test and analysis. After the vehicle jumps at a certain point on the structure (usually at the middle or 1/4 span), the required modal frequency and damping ratio are estimated from the after-wave attenuation signal of...
the structure. The deficiency is that the economic cost is high, and it is easy to affect or even change the stiffness of the bridge itself, at the same time, it is easy to be affected by external interference force, which leads to a certain error between the frequency and damping ratio.

As a new type of exciting device, the rotary eccentric mass actuator involved in this project plans to use the centrifugal force of the rotating mechanism to provide internal excitation to the structure, which has the advantages of easy control, low energy consumption and low cost. It has a wide application prospect in structural vibration modal identification and structural vibration reduction.

1.2. Present Situation of Vibration Excitation Device
The function of the actuator is to exert control force on the control object according to the definite control law. In recent years, on the basis of traditional fluid actuator, gas actuator and electrical actuator, many kinds of intelligent actuators have been developed, such as piezoelectric ceramic actuator, piezoelectric film actuator, electrostrictive actuator, magnetostrictive actuator, shape memory alloy actuator, servo actuator and electrorheological fluid actuator.

The application direction of existing actuators is mostly active vibration elimination, for example, Wang Binqing proposed in Active Vibration Elimination Method of Four-Rotor Mechanical Actuator that the main frequency of vibration in ship structure can be effectively suppressed by using actuator. reduce the negative impact of structural vibration. In bridge modal testing, it is not common for actuators to provide excitation.

However, there is also the use of electromagnetic vibration exciter to carry out modal experiments in the laboratory to measure the natural frequency of simple simply supported beams for teaching. This kind of method usually binds the connecting rod directly under the beam, and the excitation process limits the displacement of the bridge, and changes the overall stiffness of the model to a certain extent, which affects the accuracy of modal measurement and can not be used in engineering.

2. Design of Experimental Equipment
2.1. Principle of Exciting Device
The actuator plans to use two eccentric mass blocks at the same height to be connected to the motor through the transmission device to make the mass move in a circle at the same speed and in the opposite direction. In addition, the actuator also uses the generated centrifugal force to excite the bridge (the speed of the motor itself can be adjusted, and the circular frequency of the eccentric mass can be adjusted by different transmission ratios, and then the torque can be adjusted, so that the exciting force of the output can be adjusted). The load imposed by the eccentric mass actuator on the bridge model is a periodic load.

\[ F = 2m e \omega_0^2 \sin \omega_0 t \]

In the formula, \( m \) is the mass of an eccentric mass block, \( e \) is the eccentric distance, and \( F \) is the rotation frequency of the mass block.

For the simply supported beam, the \( r \) order theoretical self-vibration circle frequency is

\[ \omega = \frac{r^2 \pi^2}{l^2} \sqrt{\frac{EIg}{p}}, (r = 1, 2, L, k) \]

Where \( p \) is the uniformly distributed dead weight, \( l \) is the beam span, and \( EI \) is the beam stiffness.

When \( \theta \approx \omega \), the frequency \( \theta \) representing the interference force is approximately equal to the natural frequency. At this time, the beam has the maximum dynamic displacement, that is, the amplitude will tend to infinity (ignoring the damping of the simply supported beam model), from which the solution can be obtained.

\[ n \approx \frac{30\pi r^2}{l^2} \sqrt{\frac{EIg}{p}} \]

When the rotor speed is \( n \), the model and the actuator are in a state of resonance, and the circular frequency of the rotor is the experimental natural frequency of the simply supported beam.
2.2. Parameters of Exciting Device

2.2.1. Quality Parameters of Rotating Parts. When the actuator works, it usually affects the accuracy of the test data because of its own quality, so a main parameter is determined as the overall mass range of the device. In addition, it is hoped to get an obvious experimental phenomenon, that is, resonance, so the magnitude of the exciting force (determined by the quality of the rotor and the speed and eccentricity of the motor) is another main parameter.

Usually, the natural frequency of the large actual bridge model has been determined, which is generally 1Hz; according to the requirements of the project, the volume of the device is as small as possible, so the eccentricity should not be too large, so the magnitude of the exciting force is mainly determined by the quality of the rotor.

According to the amplitude of exciting force provided by the device, the maximum vertical deflection of the bridge model is about 5mm (given by the teacher), from which the rotor mass range is calculated.

For the same bridge, the mid-span deflection $w$ is proportional to the exciting force amplitude $F$ and the dynamic amplification factor $\beta$:

$w \propto F \cdot \beta$

The exciting force $F$ is proportional to the vibration circle frequency $\omega^2$, rotor mass $m$, rotor eccentricity $e$,

$F = \omega^2 \cdot m \cdot e$

Dynamic magnification factor:

$\beta = \frac{1}{\sqrt{(1 - \lambda^2)^2 + (2\zeta\lambda)^2}}$

For every part of the bridge, there is an equivalent stiffness, where the equivalent stiffness is $k_e$, and the relationship between deflection and exciting force is

$w = \frac{F}{k_e} \times \beta$

In the case of static load, the deflection of the primary mass $m_0$ under static load is $w_0$, thus, when

$F = F_1 = m_0g$

$\beta = 1$

$w = w_0$,

It can be analyzed as follows:

$F_{\max} \leq \frac{w_{\max}}{\beta_{\max}} \times F_1 \div w_0$

That is,

$m_{\text{max}} \leq \frac{F_{\max}}{(f_{\max} \times 2\pi \cdot s^{-1})^2 \times e} \leq \frac{w_{\max} \times F_1}{w_0 \times (f_{\max} \times 2\pi \cdot s^{-1})^2 \times e} \times \frac{1}{\beta_{\max}}$

2.2.2. Overall Quality Range of the Device. The maximum value of the overall mass is calculated according to the fact that the influence on the natural frequency of the bridge model is not more than 1% when the overall mass of the device is attached to the bridge.

The force applied to the bridge is removed, and the bridge vibrates freely in the vertical direction by hammering. The displacement-time relationship graph of the midpoint of the bridge is recorded by the laser displacement meter, and the first-order natural frequency of the bridge in free vibration can be calculated by using MATLAB software for fast Fourier transform analysis:

$f_0$
Then the additional mass $M_1$ is added in the middle of the bridge, and the first-order natural frequency of the bridge is measured by the same method.

The relative error between the two is:

$$e_1 = \frac{f_1 - f_0}{f_0} \times 100\%$$

Gradually increase the mass weight (with 200g as the loading order), and use the same method to measure the first-order natural frequency of the bridge until the relative error is more than 1%.

$$e_n = \frac{f_n - f_0}{f_0} \times 100\% \geq 1\%$$

Take the last additional mass $M_{n-1}$, that is, the maximum value of the total quality theory.

2.3. Control Mode of the Device

The vibration exciter consists of a stepper motor, a variable speed gear, a bevel gear, a pair of rotors, a transmission rod, a 3D printed base and a bracket. In the experiment, the vibration exciter is placed in the middle of the bridge model span, and after the output of the stepper motor changes the speed and expands the torque through the variable speed gear, it drives the transmission rod and the bevel gears at both ends to rotate, and the two pairs of bevel gears at the end of the transmission rod rotate 90 degrees in the direction of rotation. Drive a pair of rotors to rotate at a fixed frequency. According to the working principle of the experimental device, the exciter will provide a sinusoidal exciting force in the vertical direction.

The matching driver of the stepper motor is a part that converts the electric pulse signal into the angular displacement of the stepper motor. After receiving a pulse signal from the stepper driver, the stepper motor can be set to turn to a fixed angle, that is, the step angle.

The matching controller of the stepper motor is a component that can send out uniform pulse signals. The pulse signal sent by the controller is input into the stepper motor driver and converted into a strong current signal to drive the motor rotation.

PC terminal controller supporting software, the use of personal computer to set the stepper motor controller unit time pulse number, accurate control of motor speed.

The stepper motor driver and the controller power supply can convert the AC power supply into the power supply needed by the driver and controller.

3. Experiment

3.1. Experimental Principle

The actuator is placed in the middle of the bridge model, and the first-order symmetrical vertical bending frequency of the model is measured by the way of single point excitation in the middle of the span.

When the actuator is excited in the middle of the bridge span, the bridge model can be simplified to a forced vibration model with single degree of freedom. $M$ is the equivalent mass of the bridge and $k$ is the equivalent stiffness of the bridge.

Through the setting of the stepper motor controller at the end of the computer, the rotor speed is changed. When the bridge is forced to vibrate, the mid-span deflection is affected by both the frequency and amplitude of the exciting force at the same time. By calculating the structural dynamics, the displacement amplitude of the forced vibration model with single degree of freedom is simplified:

$$B = \frac{F_0}{k} \sqrt{(1 - \lambda^2)^2 + (2\xi\lambda)^2}$$

Among them,
\( F_0 = 2m\omega^2 \) is the amplitude of exciting force, 

\( k \) is the equivalent stiffness, 

\( \lambda \) is the ratio of the natural frequency \( \omega_0 \) to the excitation frequency \( \omega \), and \( \xi \) is the damping ratio.

When the exciting force frequency \( \omega \) increases, the exciting force amplitude \( F_0 \) increases. In order to find the relationship between the amplitude of the forced vibration displacement and the exciting frequency of the bridge, the influence of the change of the exciting force on the displacement amplitude is removed.

Make \( B_0 = F_0 / k \), take the dynamic magnification factor:

\[
\beta = \frac{B}{B_0} = \frac{1}{\sqrt{(1-\lambda^2)^2 + (2\xi\lambda)^2}}
\]

Making the relationship between the dynamic amplification factor \( \beta \) and the frequency ratio \( \lambda \) and the damping ratio \( \xi \), as shown in the following figure, the frequency influence characteristics of the system can be obtained intuitively. When the resonance occurs, that is, \( \lambda \) is close to 1, the dynamic amplification factor reaches the peak, and the change of damping ratio has little effect on the position of the peak. Therefore, through the measured values of the deflection in the bridge span under different excitation frequencies, the dynamic amplification factor corresponding to each frequency can be calculated. When the dynamic amplification factor reaches the peak, the bridge resonates. At this time, the frequency of the exciting force frequency can be regarded as the first-order symmetrical vertical bending frequency of the bridge.

![Figure 1. Vibration exciter device diagram](image1)

![Figure 2. System frequency response curve](image2)
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