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Experimental study on natural frequency measurement of underwater structure with fiber optic sensor

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Abstract. An equivalent single pier model of a typical deep water bridge was investigated in this study. A rod made of aluminum was used to simulate a bridge pier and a mass was attached to the top of the rod to simulate the superstructure of the bridge. An initial displacement of 5cm was applied to the top of the rod and then released to produce free vibration. Fiber Bragg grating (FBG) sensor was used to measure the dynamic strain of the rod under different water depth conditions. The feasibility of fiber optic sensor applied in underwater structures monitoring is discussed. The natural frequency of the underwater structure can be obtained by Fourier transformation of the dynamic strain. The experimental results show that the FBG sensor can realize the measurement of dynamic strain and natural frequencies of underwater structures under different water depths.

1. Introduction

Safety monitoring of cross-sea bridges, offshore platforms, underwater oil and gas pipelines, especially under seismic loading, is an important task. It is difficult to monitor the dynamic behavior of these structures due to the coupling vibration of liquid-solid interaction under earthquake. The traditional electric sensors are hard to monitor the dynamic behavior of the underwater structures [1]. Fiber optic sensors have good potential in this area due to the advantages of waterproof, corrosion resistance and anti-electromagnetic interference. It is superior to conventional sensors in the monitoring of underwater structures in harsh environment. The layouts of the fiber optic sensors are very flexible and can easily achieve the single point or distributed monitoring.

In recent years, fiber optic sensing technology has been receiving increasing attention for the measurement of dynamic performance of structures. A. Cusano et al. [2] described the measurement of static and dynamic strain with fiber Bragg grating (FBG) sensors. J. Carlos et al. [3] used FBG sensors

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to measure the temperature and dynamic strain of cantilever beam. L. Sun et al. [4] discussed the feasibility and advantages of dynamic measurement of FBG sensor. J. Frieden et al. [5] employed an embedded FBG sensor to measure the internal strain in a composite structure under dynamic loading. P. Antunes et al. [6] carried out dynamic monitoring of two tall and slender steel towers with FBG sensors. Minardo et al. [7] described an experimental analysis of a 1m cantilever beam based on the Brillouin distributed dynamic strain measurement method. I. Toccafondo et al. [8] conducted a dynamic strain measurement experiment with hybrid fiber.

Although the application of fiber optic sensors for dynamic measurement has made some progress, there is no relevant report on the measurement of dynamic performance of underwater structures. The change of natural frequencies, modes and damping can show the dynamic characteristics of a structure. The natural frequency, especially the first natural frequency is considered as the important parameter to determine the structural response. In this paper, an experimental model was established and fiber Bragg grating sensing system was applied to measure the natural frequency of the underwater structure. The feasibility of fiber optic sensor applied in underwater structures monitoring is discussed.

2. **Methodology**

The FBG sensor is a sensing type fiber optic sensor and part of the optical fiber is the sensing area. The relationship between the wavelength λ_{B} of reflection peak and the period Λ of fiber grating is:

$$\lambda_{\mathrm{B}} = 2n_{eff}\Lambda \tag{1}$$

Where n_{eff} is the effective refractive index of the fiber.

According to equation (1), the wavelength of FBG sensor depends on the effective refractive index and grating period of the fiber. Any physical process that changes these two parameters will cause the wavelength shift of the FBG sensor. By detecting the wavelength shift of the FBG sensor, the measured parameters can be obtained. Strain and temperature are two major parameters that can significantly change the wavelength of the FBG sensor. When the grating is affected by external strain, the stretching of the grating will lead to the change of the grating period and the photo-elastic effect will lead to the change in refractive index. When the grating is subjected to the change of the external temperature, the grating period will change because of the thermal expansion of the material and the refractive index will change with the temperature. These changes will eventually lead to the shift of Bragg wavelength. The relationship between wavelength shift, strain and temperature is:

$$\Delta\lambda_B = \lambda_B(1-p_e)\varepsilon_x + \lambda_B(\alpha+\xi)\Delta\mathrm{T} \tag{2}$$

Where $\Delta\lambda_B$ is the wavelength shift caused by temperature and strain, λ_B is the wavelength of Bragg, ε_x is strain, $\Delta\mathrm{T}$ is temperature variation, α and $\xi$are the thermal expansion coefficient and thermo-optic coefficient of the fiber, respectively. $p_e$is the coefficient of the strain-optic of the fiber.

It can be seen from the equation (2) that when the$\Delta\mathrm{T}$ =0, then $\Delta\lambda_B = \lambda_B(1-p_e)\varepsilon_x$. The strain is proportional to the wavelength shift. Therefore, by compensating the temperature effect, the wavelength shift is linear with the strain. The strain of the structure can be obtained by measured the wavelength shift of the FBG sensor.

3. Experimental equipment

In this paper, FBG sensors were used to measure the dynamic strain of the underwater structure under different water depths. The natural frequency of the underwater structure can be obtained by Fourier transformation of the dynamic strain.

The central wavelengths of the FBG sensors were measured by a four channel demodulation system SI425-500 which was made by Micron Optics Corporation, as shown in Fig. 1. The device is an integrated swept laser source and adjustable optical filter demodulation module. The instrument has a scan frequency of 250 Hz and a wavelength resolution of 1 pm. The operating wavelength range is from1510nm to 1590nm.

Figure1. FBG demodulation system

4. Experimental program

In this paper, an equivalent single pier model of a typical bridge was studied and a mass was attached to the top of the model to simulate the superstructure of the bridge. The model is shown in Fig.2(a). The pier was simulated by an aluminum rod, the elastic modulus was 69Gpa, the diameter of the rod was 15.8mm, and the length of the rod was 1.3m. The bottom of the rod was fixed to the base and a mass of 0.5 kg was applied to the top. Since the rod will produce maximum strain at the bottom of the rod during the vibration, a FBG sensor was arranged at the bottom of the rod to measure the dynamic strain of the rod during vibration.

(a) Waterless model (b) Half water level model (c) Full water level model

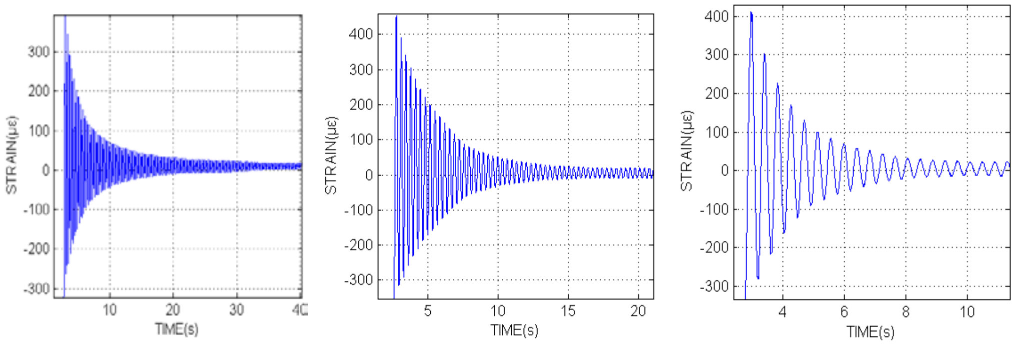
Figure 2. Experimental models

In order to explore the influence of water depth on the natural frequency of the structure, the water level was gradually added to the half water level and the full water level, which was 0.5m and 1m respectively, as shown in Fig. 2 (b) and Fig.2 (c). The radius of the water area was 0.68 m. The initial displacement of 5 cm was applied to the top of the rod, and the rod was vibrated after being released.

The dynamic strain of the rod was measured by FBG demodulator.

5. Experimental results

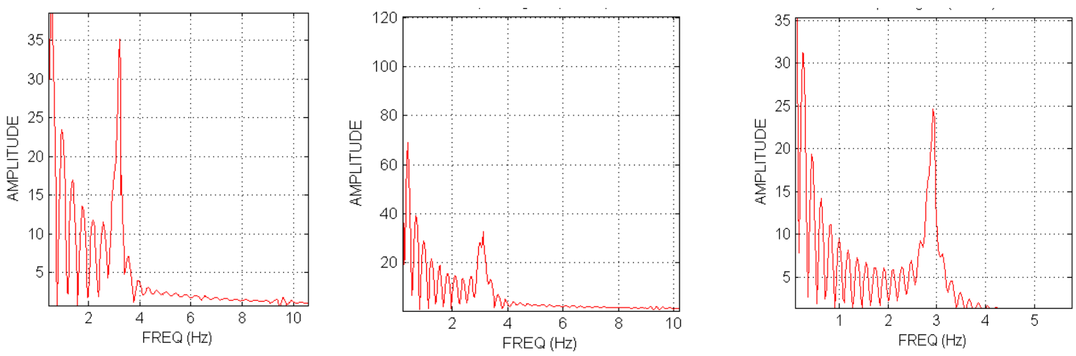
The test results of dynamic strain at the bottom end of the rod under the condition of waterless state, half water level and full water level are shown in Fig.3. As can be seen from these graphs, the strain of the rod decreases gradually with time. The rod is affected by damping with the increase of water depth and reaches the equilibrium state more quickly. When the water depth increases from the waterless state to the half water level state, the maximum dynamic strain at the bottom end of the structure increases significantly, from 361$\mu\varepsilon$ to 463$\mu\varepsilon$, and the variation range reach to 28.2%. When the water depth increases from half water level to full water level, the maximum dynamic strain at the bottom end of the structure decreases due to the effect of damping, which is 403$\mu\varepsilon$.



(a) Waterless state (b) Half water level state (c) Full water level state

Figure 3. Dynamic strain under different water depths

With Fourier transform, the spectrum of the structure in three states can be obtained. The results are shown in Fig.4. The first order natural frequency of the three states can be obtained, which are 3.207 Hz, 3.033 Hz and 2.961 Hz respectively. With the increase of water depth, the natural frequency of the structure decreases. The natural frequency of half water level state and full water level state decrease by 5.4% and 7.6% respectively compared with that of waterless state.



(a) Waterless state (b) Half water level state (c) Full water level state

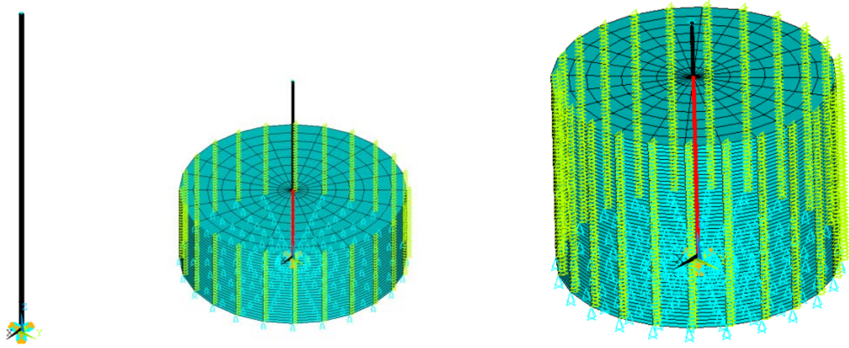
Figure 4. Spectrums of structure under different water depths

6. Analysis and discussion

In order to verify the experimental results, the numerical simulation was performed. The finite element models were established by ANSYS. The Solid 45 element was chose to simulate the rod. The

MASS21 unit with a mass of 0.5kg was applied to the top of the rod, and the bottom of the rod was fixed.

FLUID30 element was employed to simulate the water. The FLUID30 unit is a three-dimensional acoustic fluid unit, the FLUID30 (PRESENT) element and the FLUID30 (ABSENT) element are defined as the fluid unit in contact with the structure directly and non-direct contact one respectively. FSI label was used to distinguish the interface between the fluid and structure. The boundary condition of zero pressure was applied to the periphery of the water. The calculation model is shown in Fig.5.



(a) Waterless state model (b) Half water level state model (c) Full water level state model

Figure 5. ANSYS models

The first order natural frequency of waterless state, half water level state and full water level state are 3.297 Hz, 3.013 Hz and 2.922 Hz respectively. The first order natural frequency of half water level state and full water level state decrease by8.6% and 11.3% respectively compared with that of waterless state. Compared the experimental results with the calculated results, it can be seen that the experimental results are close to the calculated results, and the trend is the same. With the increase of water depth, the natural frequency of the structure has a decreasing trend, which is consistent with the existing research conclusions.

7. Conclusions

An underwater experimental model was established and fiber Bragg grating sensing system was applied to measure dynamic stain of the structure. The feasibility of fiber optic sensing technology applied in underwater structure monitoring was verified by the dynamic strain test of structure under different water depth conditions. The frequency-domain curves of the structure were obtained by Fourier transform of the dynamic strain measurement results. The results show that the FBG sensor can measure the natural frequencies of underwater structure very well, and the measured results are close to the calculated values.

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