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Dynamic Response Measurements of Cantilever Structures Using Distributed Fiber Optic Sensors

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1. Introduction

To enhance the safety of operational nuclear power plants, especially in cases where access to structures like the primary system is restricted due to the radiological environment, there is a need for monitoring technologies that can continuously observe structural conditions and ensure a high level of accuracy. As nuclear reactors age, the loosening of internal structures may lead to increased vibration levels, potentially resulting in displacements that exceed allowable limits. An increase in vibrational displacement of internal structures could surpass the fatigue tolerance between components joined by pins, bolts, or welds, causing detachment and debris generation, which could, in turn, damage the reactor core.

Signals that can be used for monitoring the condition of internal structures in operational nuclear power plants include those from accelerometers installed at the upper and lower sections of the reactor, collected by the LPMS (Loose Part Monitoring System) of the NIMS (Nuclear Steam Supply System Integrity Monitoring System), as well as neutron noise signals from the IVMS (Internal Vibration Monitoring System) and internal neutron detectors installed in fuel assemblies. Although the condition of internal structures can be inferred through analysis of accelerometer signals and internal/external neutron noise signals, the limited sensor installation locations and coverage, along with an insufficient number of sensors, pose challenges for real-time diagnosis and response to the state of internal structures.

When predicting the dynamic behavior of a structure by measuring its acceleration or fluctuation response, minimal sensors may suffice. However, in cases where unexpected dynamic behavior arises due to changes in boundary conditions, multiple sensors may be required to accurately extract this behavior. The installation and maintenance of sensors like accelerometers require space, and considering the installation of cables to transmit signals to preamplifiers or measuring devices, it is difficult to perform condition monitoring using multiple accelerometers in integrated or space-constrained designs.

Distributed fiber optic sensors require minimal installation space and are well-suited for measuring strain or temperature across a broad range. These sensors are extremely thin, flexible, and can be easily attached to structures even in curved areas, making them ideal for measuring the overall response distribution of a structure.

In this study, we conducted a vibration test under boundary conditions similar to a cantilever beam using a steel ruler to extract the dynamic response of the structure using a distributed fiber optic sensor. We also compared this method with the dynamic response extraction method using accelerometers.

2. Methods and Results

The setup for extracting dynamic responses using distributed fiber optic sensor is shown in Figure 1. A distributed fiber optic sensor was attached straightly to the upper surface of a 600mm steel ruler using silicone tape. The strain distribution of the steel ruler was measured using the distributed fiber optic sensor with a minimum length resolution called a gauge pitch(5.2mm). The sensor was attached from the free end at 0 mm to the fixed end at 600 mm, and the steel ruler was bolted to the upper end of a shaker using a jig. The shaker, amplifier, and signal generator used in the test were B&K Type 4809, B&K Type 2718, and Agilent 33500B, respectively. The cantilever beam was subjected to sinusoidal excitation at the first and second resonance frequencies using the signal generator.

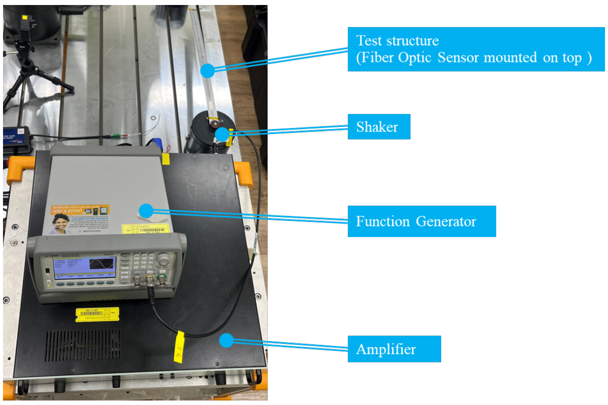


Fig. 1. Test configuration of distributed fiber optic strain measurement

The distributed fiber optic sensing system used was the ODiSI (Optical Distributed Sensor Integrators) system by LUNA Innovations and the sampling frequency was 80 Hz. The dynamic classical beam equation of motion for undamped, free vibration is given by

$$\rho A \frac{\partial^2 w(x,t)}{\partial^2 t^2} + EI_y \frac{\partial^2 w(x,t)}{x^4} = q(x,t) \qquad (1)$$

where ρ is the density, A is the cross-sectional area of the structure, w is the transverse deflection of the beam centerline, E is the elastic modulus, q is transvers load distribution and I_y is the second moment of area for the cross section.

By applying the boundary conditions of the cantilever beam to the above equation, the resonance frequencies can be obtained, and the normalized mode shapes of the cantilever beam are shown in Figure 2.

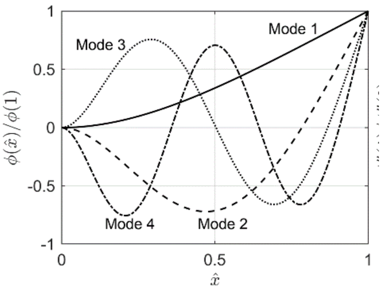
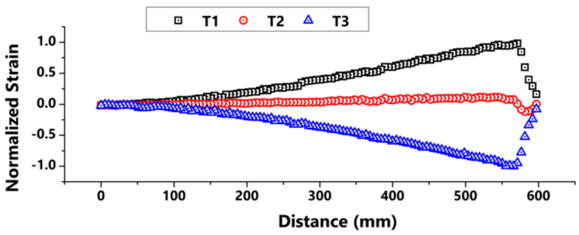


Fig. 2. Normalized mode shapes of a cantilever beam [1]

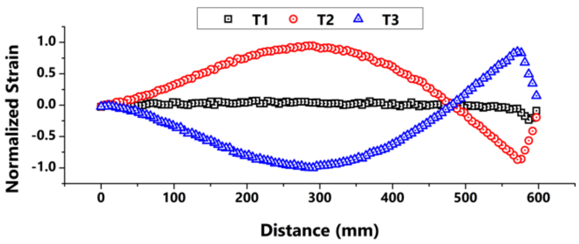
(a)



(b)

Fig. 3. 1st mode shape(2.61Hz) and strain distribution (a: transverse deflection from the test, b: strain distribution)

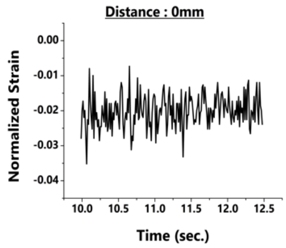
(a)



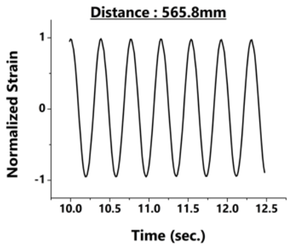
(b)

Fig. 4. 2nd mode shape(15.7Hz) and strain distribution (a: transverse deflection from the test, b: strain distribution)

The test results confirm that the mode shapes calculated using classical theory match the experimental results, as shown in Figures 3(a) and 4(a). Figures 3(b) and 4(b) show the strain distribution measured by the fiber optic sensor in the first and second modes, respectively. The strain distributions reveal that the shape of the transverse deflection in Figures 3(a) and 4(b) is opposite to strain distributions. This is because the strain is proportional to the curvature when bending occurs in the beam.



(a)



(b)

Fig. 5. Time series of strain signals (a: distance at 0mm, b: distance at 565.8mm)

Figure 5 presents the time series strain signals at two points on the distributed fiber optic sensor. A clear sinusoidal signal was observed at the point close to the fixed end at 565.8 mm, but at the 0 mm point, near the free end, where the curvature change was minimal, the strain appeared as noise, and a sinusoidal signal could not be discerned in the time series.

In the case of mode testing using accelerometers, the mass of the accelerometer can affect the dynamic characteristics of the structure. Reducing the mass of the sensor results in lower sensitivity at low frequencies, making it vulnerable to low-frequency noise. Additionally, the placement and number of sensors are restricted, making it difficult to adapt to changes in boundary conditions. In contrast, the distributed fiber optic sensor used in this experiment is equivalent to having approximately 114 strain measuring points on a single optic fiber, making it well-suited for closely monitoring the low-frequency behavior of structures.

3. Conclusions

In this study, we measured the strain at the resonant mode shapes of a cantilever-type structure using the distributed fiber optic sensor. The densely located measuring points in the sensor provided a comprehensive view of the strain distribution of the structure, and in regions with significant strain variation, a clear sinusoidal signal was observed in the time series. The use of distributed fiber optic sensors is expected to overcome the challenges associated with installing accelerometers, such as space constraints, cable installation, and low-frequency sensitivity issues. Moreover, these sensors can be attached to large structures like reactors, making them useful for diagnosing structural defects.

Acknowledgement

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