Impact Response of a Cantilever Beam Measured by Optical Fiber Sensors

Shiuh-Chuan Her[1] and Hsi-Wen Hou[2]
Department of Mechanical Engineering
Yuan Ze University
Tao Yuan, Taiwan
[1] e-mail:mesch@saturn.yzu.edu.tw
[2] e-mail:s945120@mail.yzu.edu.tw

***Abstract*—Mach-Zehnder interferometric technology combined with optical fiber sensor allows the direct measurement of the impact response of a cantilever beam. The difference in the optical path due to the strain induces a relative phase shift in the Mach-Zehnder interferometer. A 3 × 3 coupler is used to demodulate the phase shift of the Mach-Zehnder interferometer. Experimental results show that the optical fiber sensor is capable of measuring the dynamic strain of a cantilever beam impacted by a hammer. The impact responses measured by the optical fiber sensor are in good agreement with the strain gauge. The proposed optical fiber sensor is simple, inexpensive and easy to implement; moreover, it is highly reliable and accurate.**

Keywords- optical fiber sensor; Mach-Zehnder interferometer; dynamic strain; 3 × 3 coupler.

I. INTRODUCTION

Optical fiber sensors have attracted a great deal of attention in recent years due to their advantages over conventional sensors such as flexibility, embeddability, multiplexity, small size and immunity to electrical or magnetic interference. Optical fibers based on Fabry–P´erot interferometer (FFPI) have been utilized to measure electrical current [1] and the multiplexed interferometric current sensors have also been reported [2]. In this study, Mach-Zehnder optical fiber interferometric sensor is employed to measure the dynamic response of a cantilever beam subjected to impact. The method developed by Brown et al. [3] for demodulation of the phase shift is adopted. The demodulation scheme utilizes a 3 × 3 coupler to reconstruct the signal of interest. The experimental test results are validated with the strain gauge. In Section II, the Mach-Zehnder interferometer is briefly described. In Section III, the methodology of phase shift demodulation is discussed. In Section IV, the experimental test results for a cantilever beam are presented to demonstrate the feasibility of the proposed method.

II. MACH-ZEHNDER INTERFEROMETER

Mach-Zehnder interferometer consists of two 2 × 2 couplers at the input and output. The excitation is applied to the sensing fiber, resulting in an optical path difference between the reference and sensing fibers. The light intensity of the output of Mach-Zehnder interferometer can be expressed as [4]:

$$I = 2A^2(1+\cos\Delta\phi) \tag{1}$$

$$\Delta\phi = \frac{2\pi n_0}{\lambda}\left\{1-\frac{n_0}{2}\left[(1-\nu_f)p_{12}-\nu_f p_{11}\right]\right\}\int_{L_f}\varepsilon_f dx$$

where $\Delta\phi$ is the optical phase shift; n_0 is the refractive index of the optical fiber; λ is the optical wavelength, ν_f is the Poisson's ratio; p_{11} and p_{12} are the Pockel's constants; L_f and ε_f are the bonding length and strain of the optical fiber, respectively. Since the terms in front of the integral sign of (1) are constants for any given optical fiber system, the total optical phase shift $\Delta\phi$ is proportional to the integral of the optical fiber strain. By measuring the total optical phase shift, the integral of the optical fiber strain can be easily obtained as follows:

$$\int_{L_f}\varepsilon_f dx = \frac{\Delta\phi}{\frac{2\pi n_0}{\lambda}\left\{1-\frac{n_0}{2}\left[(1-\nu_f)p_{12}-\nu_f p_{11}\right]\right\}} \tag{2}$$

The integral of the strain in (2) denotes the change of the length of the sensing fiber which is surface bonded onto the host structure. The average strain of the optical fiber for optical phase shift $\Delta\phi$ is:

$$\varepsilon_{avg} = \frac{\int_{L_f}\varepsilon_f dx}{L_f} = \frac{\lambda\Delta\phi}{2L_f\pi n_0\left\{1-\frac{n_0}{2}\left[(1-\nu_f)p_{12}-\nu_f p_{11}\right]\right\}} \tag{3}$$

Thus, once the phase shift $\Delta\phi$ of the Mach-Zehnder interferometer is demodulated, the strain of the host structure can be determined by utilizing (3).

III. DEMODULATION OF PHASE SHIFT

To demodulate phase shift $\Delta\phi$ of the Mach-Zehnder interferometer, a 3 × 3 coupler is employed. It consists of a 1

× 2 coupler at the input and a 3 × 3 coupler at the output. The two outputs of the 1 × 2 coupler comprise the reference fiber and sensing fiber of the Mach-Zehnder interferometer. The sensing fiber is surface bonded onto the host structure. Mechanical or thermal loadings applied to the host structure, leads to an optical path difference between the two fibers. The difference in the optical path induces a relative phase shift in the Mach-Zehnder interferometer. The two optical signals are guided into two of the three inputs of a 3 × 3 coupler, where they interfere with one another. The methodology developed by Brown *et al.* [3] for demodulation of the phase shift is adopted.

IV. EXPERIMENTAL RESULTS

A cantilever beam impacted by a hammer is conducted in the experimental test. The beam of length L = 220 mm, width b = 20 mm, thickness h = 1 mm is made of copper with elastic modulus E = 120 GPa, density ρ = 8740 kg/m^3. An optical fiber is surface bonded to the middle of the cantilever beam as the sensing fiber of the Mach-Zehnder interferometer. The bonding length is L_f = 60 mm in this work. A schematic drawing showing the cantilever beam with optical fiber sensor is presented in Figure 1. The material properties for the optical fiber are: elastic modulus E_f = 72 GPa, Poisson's ratio ν_f = 0.17, index of refraction n_0 = 1.45, pockel's constants p_{11} = 0.12, p_{12} = 0.27, radius r_f = 62.5 μm. An electric resistance strain gauge is adhered to the cantilever beam near the optical fiber. The optical fiber sensing system is a Mach-Zehnder interferometer with a 3 × 3 coupler operating at the wavelength of λ = 1,547.28 nm. Figure 1 shows the signals of the three outputs of the 3 × 3 coupler. Substituting the three output signals of the 3 × 3 coupler as shown in Figure 2 into the Matlab software, performs the phase shift demodulation. The result of the demodulated phase shift is presented in Figure 3. Substituting the phase shift $\Delta\phi(t)$ from Figure 3 into (3), it leads to the determination of the dynamic strain of the cantilever beam. The dynamic strains obtained by the optical fiber sensor are compared with the results of the strain gauge as shown in Figure 4. Good agreement is achieved between these two sensors. The dynamic strain measured by the optical fiber sensor exhibits smooth and continuous oscillation, while a small perturbation and discontinuity appears at the peak of the oscillatory strain for the strain gauge. This demonstrates that the optical fiber sensor is more reliable and accurate compared with the strain gauge.

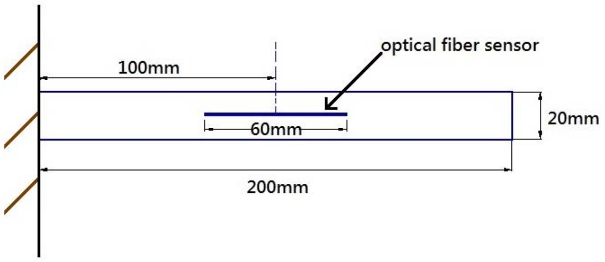

Figure 1. Cantilever beam with surface bonded optical fiber sensor

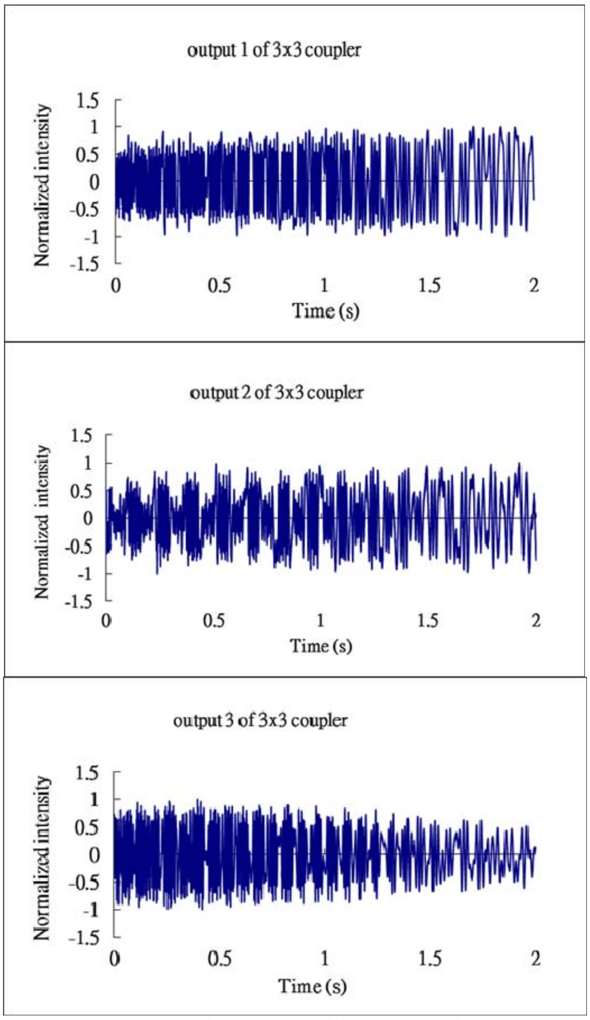

Figure 2. Three outputs of the 3 × 3 coupler

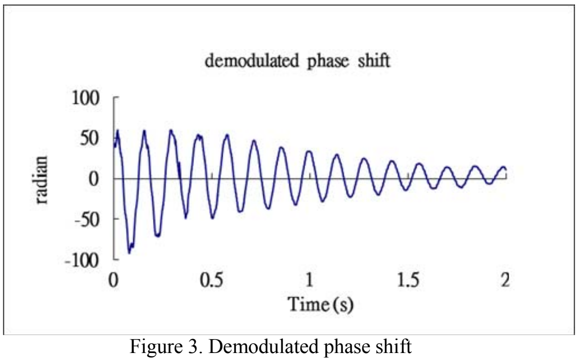

Figure 3. Demodulated phase shift

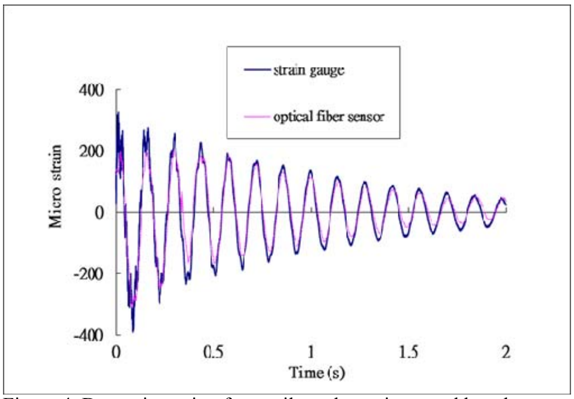

Figure 4. Dynamic strain of a cantilever beam impacted by a hammer

V. CONCLUSIONS

The dynamic strain of a cantilever beam subjected to impact by a hammer is determined using the optical fiber sensor. Mach-Zehnder interferometric technique is employed to measure the impact response. The impact responses measured by the optical fiber sensor are validated with the strain gauge. Good agreement is achieved between these two sensors. The proposed optical fiber sensor is simple, inexpensive and easy to implement. Moreover, its capability of measuring the impact responses with high reliable and accurate results demonstrates the novelty of present study.

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