Damage Investigation in Beam Structures using Fiber Optic Polarimetric Sensors

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1. INTRODUCTION

Fiber Optic Sensors (FOSs) have a lot of advantages over the other sensors, for instance, piezo-electric sensors. FOSs are light weight, insensitive to electromagnetic interference and have small footprint. These sensors can be easily embedded into composite and civil structures for structural health monitoring (SHM). Metal structures do not allow fibers to be embedded, so in this case FOSs are surface mounted. Conventional methods do not allow real-time on-line health monitoring as they are time consuming and require a lot of data processing [1]. FOSS makes such real-time online structural health monitoring very easy and effective. In most of the cases, structural integrity of the structures is very important without being influenced by other sensors. There are a number of NDT methods, such as acoustic emission (AE), ultrasonic scanning, shearography etc., but these classical NDT techniques are not capable of providing online structural health monitoring, because it is very difficult to get real-time data from them [2].

Different types of fiber optic sensing techniques are available for structural health monitoring methods. Extrinsic Fabry-Perot interferometer (EFPI) and Fiber Bragg Grating (FBG) sensors are used for local measurement. Multiplexing allows these techniques for data capture at multiple points. But additional data analysis is needed to relate these values to the structural health. Fiber Optic Polarimetric Sensors (FOPSs) are the best suited for global and dynamic health monitoring. Using FOPSs, both static and dynamic tests can be performed for the global health monitoring of different engineering structures.

A quantitative study, using FOPS, was performed for structural health monitoring and two factors; Static Damage Factor (SDF) and Dynamic Damage Factor (DDF), were proposed [3]. The DDF was a preferred choice as it allowed for testing in-situ. Essentially, structural damage results in a loss of stiffness and hence a change in the modal frequency. The ratio of change in frequency for a damaged structure to an undamaged one is the DDF. However the DDF is not unique and dependent on the damage location, size and number. Thus while indicative and fast, further systematic studies have to be performed to effect practical implemen-
tation. In this paper, a study of the size and location of a single crack on the modal frequencies of beam structures, using FOPS, is presented. A relation between the normalized change in the frequency of the first fundamental mode of different beam structures and relative crack size is established. Some well-designed sets of experiments are performed to verify this relationship.

2. PRINCIPLE

2.1. Crack Analysis by Dynamic Test Using FOPS

A polarization maintaining fiber (Hi-Bi fiber) is used as the sensing fiber in the FOPS method. The Hi-Bi fiber has two axes—fast and slow axis. If linearly polarized light is launched into the Hi-Bi fiber in such a way that its polarization is either along fast axis or slow axis, the Hi-Bi fiber is insensitive to external perturbations. On the other hand, if polarised light equally populates the two axes, the fiber has maximum sensitivity to external changes. As the light traverses the Hi-Bi fiber, the state of polarization of light changes from linear to circular and back to linear over a short distance (called the beat length) within the fiber. Strain on any portion of the fiber causes the beat length to change and hence changes the output state of polarization. The change can be either due to static or dynamic load on the fiber or other changes in environmental conditions. Indeed the entire fiber is sensing. In case of dynamic studies, the strain changes periodically at a rate dependent on the external stimulus. Hence the state of polarization also cycles at the same frequency. Measuring this frequency allows us to measure the dynamic characteristics of the structure.

The schematic of the FOPS set-up for dynamic test is shown in the Figure 1. A half wave plate (polarizer) is used to change the polarization of laser light such that equally populates the two modes in the Hi-Bi fiber. The Hi-Bi fiber is bonded to an aluminium cantilever beam to follow the strain in the beam. The state of polarization of the light emerging from the fiber is analysed via a second polarizer and a detector.

The frequency of the fundamental mode of a cantilever is given as [3].

\[
f_n = \left[ \alpha \frac{(2n-1)\pi}{2} \right]^2 \sqrt{\frac{EI}{A}}
\]  

(1)

From Equation (1), it can be clearly seen that the frequency of fundamental modes depends on the flexural stiffness (EI) of the cantilever. If the cantilever is damaged, the stiffness will reduce and hence, the frequency of fundamental mode reduces.

Theoretically, a crack can be modelled as massless linear spring [4] of stiffness \( K_x \) as shown in Equation (2). The change in the frequency of any fundamental mode is given as [5]:

\[
\frac{\Delta f_n}{f_n} = \sin^2 \left( \frac{n\pi x}{2L} \right) \frac{EI}{K_x L}
\]

(2)

where \( EI \) is the stiffness, \( L \) is the length of the cantilever and \( x \) represents a non-dimensional crack location and it is the function of distance (l) of the crack from the fixed end. The stiffness \( K_x \) of the spring is given as [6]:

\[
K_x = \frac{EI}{(5.346h) \cdot f(a/h)}
\]

(3)

where \( h \) is the height, \( a \) is the size of the crack and the function \( f(a/h) \) is given by:

\[
f(a/h) = 1.8624(a/h)^2 - 3.95(a/h)^3 + 16.375(a/h)^4 \]

\[
-37.226(a/h)^5 + 78.81(a/h)^6 - 126.9(a/h)^7 + 172(a/h)^8 \]

\[
-143.97(a/h)^9 + 66.56(a/h)^{10}
\]

(4)
Figure 2. (a) An aluminium cantilever with a single crack and (b) model of cracked cantilever beam.

Figure 3. Oscilloscope traces showing the frequencies of first fundamental mode of the cantilever with crack location is 2 cm and crack size is (a) no crack, (b) 3 mm, (c) 6 mm, (d) 8.5 mm.
As the ratio $a/h$ is small, higher orders of $a/h$ can be neglected. Hence Equation (4) reduces to:

$$f(a/h) \approx 1.8624(a/h)^2$$

(5)

From Equations (2) and (3) we have:

$$\frac{\Delta f_n}{f_n} = \sin^2 \left( \frac{n \pi x}{2L} \right) \frac{5.346 \cdot h \cdot f(a/h)}{L}$$

(6)

Equation (6) suggests that the change in natural frequency depends both on the location and size of the crack. Equations (5) and (6) suggest that $\Delta f_n/f_n$ is a quadratic function of $a/h$. For other beam structures the form of $x$ in Equation (6) changes, but the form of equation remains the same.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1. Experimental Verification of Single Crack Theory by FOPS

An experiment was performed on an aluminium cantilever, size 268 x 19 x 3.2 mm$^3$ to test the validity of this approach. A short impact force generates the vibration modes in the specimen which is detected by the fiber, Figure 2. A crack was sawed at different locations with different lengths to simulate various levels and severity of damage. The frequency of first mode was recorded for each test on undamaged and damaged specimens. Figure 3 shows the oscilloscope traces showing the first fundamental frequencies (F1 cursor) with a fixed crack location at 2 cm from the fixed end of the cantilever, but with different crack sizes. F2 cursor is not used in this experiment.

Figure 4 shows the relative change in the frequency ($\Delta f_1/f_1$) of first fundamental mode with relative crack size (ratio of the crack size $a$ to the total height $h$ of the cantilever beam) at different crack locations. For small $(a/h)$ values, Equations (5) and (6) indicate that the quantity $\Delta f_n/f_n$ is a quadratic function of $(a/h)$. From Figure 5, it can be seen that the distribution of the functions $\Delta f_1/f_1$ is quadratic and has the form $A(a/h)^2 + B(a/h) + C$, the coefficient $B$ and $C$ are very small in comparison to coefficient $A$. Hence, the term $(a/h)$ and constant $C$ can be neglected. The presence of coefficients $B$ and $C$ could be because of the experimental errors such as variations in boundary condition, the resolution of oscilloscope. Hence it can be inferred that the function $\Delta f_1/f_1$ follows the relation established in Equations (5) and (6).

For different crack sizes, the change in the frequency of first fundamental mode ($\Delta f_1$) of a cantilever has been plotted against the relative crack location ($l/L$) from the fixed end of the cantilever in Figure 6. Clearly from Figure 6, the change in the modal frequency ($\Delta f_1$) is larger when crack is closer to the fixed end. This is since the strain is highest at the fixed end and any damage at the fixed end would induce larger changes in stiffness and hence higher changes in the frequency mode.

![Figure 4. Relative change in the first fundamental frequency ($\Delta f_1/f_1$) with relative crack size $(a/h)$ at different crack locations for a cantilever.](image-url)
One very important observation is that the ranges of values of $\Delta f_1$ in Figure 6 corresponding to different crack sizes, do not overlap, indicating no crack size discrepancy. A specific value of $\Delta f_1$ belongs to a particular crack size most of the times. In other words, the value of $\Delta f_1$ gives us an indication of the crack size. This information could further be used with Figure 5 to calculate the approximate crack location.

As stated earlier, Equation (6) preserves its form for other
beam structures. An experiment was performed for a beam fixed at both the ends. The size of the beam was $370 \times 19 \times 3.2 \text{ mm}^3$. The distance of crack was measured from the midpoint of the beam. Again from Figure 6, the relative change in the frequency ($\Delta f_1/f_1$) follows the same relationship with relative crack length. From Figure 7, the value of $\Delta f_1$ is higher when the crack is close to the mid-point of the beam and decreases as the crack moves towards the fixed ends of the beam. Once again this suggests that stiffness changes are larger at points with greater strain. In this case, however, the values of $\Delta f_1$ for different crack sizes overlap indicating some ambiguity in crack location determination.

4. CONCLUSION

Experimental results show that the relative change in the frequency of fundamental mode of beam structures follows a pattern established by spring theory of a single crack. Also, the values of the change in frequency of first mode ($\Delta f_1$) give very important information about the crack size and location. In fact by looking at the values of $\Delta f_1$, the size and location of the crack can be determined without ambiguity in most cases. The study shows that the FOPS method has great potential in the field of SHM.

REFERENCES