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Efficient design of Fiber Optic Polarimetric Sensors for crack location and sizing

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ABSTRACT

The Fiber Optic Polarimetric Sensor (FOPS) is an attractive tool for damage monitoring in structures. However the system is not capable of identifying damage location and crack size, which would further assist in the assessment of the severity of damage. Also, the output signal from FOPS is very noisy because of the fact that the whole fiber is sensitive and picks up unwanted signals from its surroundings. In the current work, a new design of FOPS has been put forward for structural health monitoring (SHM). It has been shown that in this new design, only the central part of FOPS is sensitive keeping the “leading-in” and “leading-out” parts insensitive, allowing SHM using FOPS sensitive only to the region of interest. This design is then implemented to locate and estimate the size of a crack in a cantilever. Unlike previous studies, the current approach considers second vibrational mode along with the first vibrational mode to get better understanding of the damage size and location. In this paper, the location and sizing of a crack in a cantilever beam are studied theoretically and verified experimentally.

1. Introduction

Over past years, a number of techniques have already been proposed, utilizing different concepts and techniques, for structural health monitoring (SHM) of different engineering structures. Every technique has its own advantages and disadvantages. Acoustic emission, vibration testing, shearography, sonics are some of the classical methods that have been reported so far. These techniques are efficient but real time monitoring is not possible with them [1–4]. Also, a professional set of skills is required to get the data from these techniques. Fiber Optic Sensor (FOS) technologies are very simple and advantageous for SHM purposes. Among all the FOS, Fiber Bragg grating (FBG) sensors had been the main technique for both research and commercial implementation. It has already been shown that FBG sensors can be used to find out structural damages such as delamination in composite laminates as well as cracks in metallic structures [5,6]. FBG sensors have also been used for the real time monitoring of the curing process of composite materials [7]. Besides FBG, people have also been curious about the potential of Fiber Optic Polarimetric Sensor (FOPS), because it permits real time non-destructive health monitoring of engineering structures. Also, FOPS is very easy to install in any sort of structure. Standard high birefringent (Hi-Bi) fibers are used in this technology. A configuration of Hi-Bi fibers was presented as Sagnac interferometer which worked as temperature and strain independent torsion sensor [8]. A simple and effective design of fiber-optic polarimetric twist/torsion sensor was also presented [9]. Though FOPS has already been studied applying dynamic and static tests for global SHM of different structures [10–12], it could not be used for local and long distance SHM applications. This is because of the limitations of the FOPS system. The output signal from FOPS is noisy as it picks up disturbances readily. When the fiber is embedded into structures for health monitoring, there is always some parts of fiber which will be outside the structure. In the case of FOPS, this extra fiber picks up spurious signals from its surroundings, since the whole fiber used acts as a sensor. These unwanted signals interfere with the actual signal leading to inaccurate measurements. That is why it is essential that the length of sensor be kept short so as to reduce spurious signals arising from perturbations of the optical fiber that is outside the region of interest. As a result, SHM tests could not be performed effectively at long distances.

Other mechanical parameters such as pressure, strain, twist, etc. can also be measured using FOPS [1–4,13]. FOPS makes real-time SHM fast and effective [10–12]. For SHM, FOPS can either be embedded or surface mounted without disturbing the structural integrity of the structure. The dynamic test involves monitoring changes in the fundamental frequencies (or flexural stiffness) of

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the structure. If the material is damaged, its stiffness decreases and so do the fundamental frequencies. In previous studies [10], only the frequency of first fundamental mode was considered for dynamic health monitoring of different structures. A Dynamic Damage Factor (DDF) was proposed which provided information on the global health of the structure. The value of DDF decreased with increased damage in the structure. Experimentally, it was observed that the effect of the size of a single crack on the damage factor is higher than that of number of cracks of same size [1,10]. These inferences are not sufficient to predict the actual state of damage in a structure. It gives almost no information about the actual intensity of damage in a structure. Hence, the information given by the FOPS method is still incomplete and in need of further investigation.

Considering everything stated earlier, though FOPS provides significant information for SHM of engineering structures, it is still noisy and does not provide any information of damage size and location. In this paper, we present a new FOPS design comprising of three parts; the “lead-in” part, the “active part” and the “lead-out” part [14]. Of the three parts, only the active part is made sensitive to the structural variations while the rest of the two parts are kept insensitive. It has already been stated that with former FOPS design, the length of sensor needs to be made as short as feasible to minimize external disturbances. In field applications long fibers are usually required. The new FOPS design abolishes this restriction and provides us with a very stable output signal even with a very long fiber (50 m or more). With this design, the health of any specific part of a big structure could be monitored from long distances using a long lead-in and lead-out fibers while confining the active-fiber to region of interest. With this new FOPS design, long Hi-Bi fibers can be used making long distance SHM possible with FOPS.

Further, this new design of FOPS is implemented to present our data on an aluminum cantilever. This structure is considered for study because there are lots of important structures like wings of an aircraft, blades of wind turbines, small foot bridges, etc. that experience stresses similar to that of a cantilever. In the present work, the effect of damage on the frequency of the second mode is explored for the first time by the FOPS method. The effect of a crack on both the first and the second fundamental frequencies of a cantilever is analyzed. A relation between the relative size of a crack in a cantilever and change in the frequencies of fundamental modes is established [15–17]. This relation has been verified experimentally in this paper. It has also been shown that for the crack near to the fixed end of the cantilever, the frequency of the second mode is more sensitive than the first one. It means that the second fundamental mode can be used more effectively for the determination of crack location. A methodology has been proposed which shows that the FOPS technology can be used for the investigation of crack location and crack size along with the global health monitoring.

2. Theory

In the Fiber Optic Polarimetric Sensor, a polarization maintaining fiber (or Hi-Bi fiber) is used. In such fibers, light propagates down the fiber along two mutually orthogonal polarization axes known as the fast axis and the slow axis. The component along the fast axis moves faster than the component along the slow axis. This difference in velocities introduces a phase between the components given as follows [10]:

$$\phi = \Delta\beta L \qquad (1)$$

where L is the length of the fiber and $\Delta\beta$ $(=\beta_{fast}-\beta_{slow})$ is difference in propagation constant between two orthogonally polarized modes, which travel along the fast and the slow axes. $\Delta\beta$ is called the birefringence of the fiber. Hence clearly, there are two factors which can cause a change in the additional phase (ϕ): one is the length (or axial strain) of the fiber and another is birefringence ($\Delta\beta$). The length of Hi-Bi fiber, required to create a phase change of 2π, is called the beat length of the fiber. In the present work, a Hi-Bi fiber with a beat length of 1.2 mm is used. Whenever there is a force or pressure on the specimen structure embedded with FOPS, the longitudinal strain is produced in Hi-Bi fiber and hence the distance traveled by the light in the birefringent medium of fiber changes leading to a change in the phase and hence in the polarization of light.

2.1. Layout of the new design of FOPS for a stable output signal

In the conventional FOPS system, linearly polarized light with its direction of polarization at 45° with the slow (or fast) axis is sent into the fiber. Half-wave plate is used to set this angle. This angle is kept at 45° because in this case the components of electric field vector, along fast and slow axes, are equal in amplitude which makes the Hi-Bi fiber the most sensitive. However, it also makes the polarization of light at the output to be highly prone to unwanted disturbances, and therefore an unstable intensity of the signal at the output. If the direction of polarization of the light is kept along any of the two (slow or fast) axes, the sensor is not sensitive at all and output light will be linearly polarized in the same direction as it was at the entrance end of the fiber.

With this understanding, we designed an FOPS with three parts; the lead-in fiber part, active fiber part and lead-out fiber part, as shown in Fig. 1. Linearly polarized laser light is launched into the lead-in fiber with electric vector along either the fast or slow axis, making this fiber insensitive to external perturbations and we get the same linearly polarized light at the output of the lead-in fiber. The lead-in fiber is spliced at an angle of 45° with the active fiber. Light then enters the active fiber with electric vector at 45° with fast (or slow) axis, making it very sensitive to external perturbations. The amplitudes of the fast and slow components are equal in length in the active fiber. Since the exact length of the active fiber is not known, the phase change introduced by the active fiber cannot be known. Hence, at the output of the active fiber, the polarization state of the light is unknown. The active part is further spliced with the lead-out fiber at an angle of 45°, which essentially align the fast and slow axes of the lead-in and the lead-out fibers. As the lead-in fiber is insensitive and does not change the polarization of light, a stable polarization mode is likely to be induced in the lead-out fiber [14]. As the light enters the lead-out fiber, the fast and slow components are redistributed and do not have the equal amplitudes anymore. The exact length of lead-out part is not known and hence we get unknown state of polarization at the output of the lead-out fiber once again, as shown in Fig. 1. The analyzer, at the exit end of the lead-out fiber, is kept along the fast (or slow) axis of the lead-out fiber. In polarization maintaining fibers, the phase difference between the fast and slow components changes continuously which decides the state of polarization at a particular point, but their amplitudes remain the same at all the time. Since the analyzer is along the fast axis, it selects the fast component from the lead-out fiber only. Essentially, the phase difference introduced by the lead-out fiber is not taken into account, as only one component (fast in this case) is considered by aligning the analyzer along the fast axis of the lead-out fiber. Hence, the light after passing through the analyzer will be independent of changes in the polarization of light made by the lead-out fiber. Thus this design keeps the lead-in and the lead-out parts of the sensor insensitive while maintaining the active part to be sensitive to structural stress.