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2015

Maheshwari, M., Annamdas, V. G. M., Pang, J. H. L., Tjin, S. C., & Asundi, A. K. (2015). Fibre optic sensors for load-displacement measurements and comparisons to piezo sensor based electromechanical admittance signatures. Proceedings of SPIE - Structural Health Monitoring and Inspection of Advanced Materials, Aerospace, and Civil Infrastructure 2015, 9437, 94370V-. doi:10.1117/12.2084039

<https://hdl.handle.net/10356/88739>

<https://doi.org/10.1117/12.2084039>

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Fibre Optic sensors for load-displacement measurements and comparisons to piezo sensor based electromechanical admittance signatures

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ABSTRACT

Structural health monitoring techniques using smart materials are on rise to meet the ever ending demand due to increased construction and manufacturing activities worldwide. The civil-structural components such as slabs, beams and columns and aero-components such as wings are constantly subjected to some or the other forms of external loading. This article thus focuses on condition monitoring due to loading/unloading cycle for a simply supported aluminum beam using multiple smart materials. On the specimen, fibre optic polarimetric sensor (FOPS) and fibre Bragg grating (FBG) sensors were glued. Piezoelectric wafer active sensor (PWAS) was also bonded at the centre of the specimen. FOPS and FBG provided the global and local strain measurements respectively whereas, PWAS predicted boundary condition variations by electromechanical admittance signatures. Thus these multiple smart materials together successfully assessed the condition of structure for loading and unloading tests.

Keywords

Fibre optic polarimetric sensor (FOPS), fibre Bragg grating (FBG), piezoelectric wafer active sensor (PWAS), global-local health monitoring and load monitoring

1. Introduction:

A single structural health monitoring (SHM) technique alone is not enough to interpret complete condition of any structure. In the past, many global and local SHM techniques were implemented to monitor the condition of structures, but no single technique alone could successfully present the complete health assessment^[1]. Thus many researchers proposed the use of more than one SHM technique and the fusion of several smart techniques as adopted in this study could provide a better solution especially as they provided both global and local observations of the specimen^[2-4].

Smart materials are the latest generation elements surpassing the capabilities of traditional structural and functional materials which can achieve an effective alternate to traditional SHM techniques^[5]. Smart materials can be categorised as active or passive. Active smart materials are those materials which possess the capacity to modify their geometrical or material properties under the application of light, heat, electric or magnetic fields, thereby acquiring an inherent capacity to transduce energy whether they are attached to host structure or not^[6, 7]. Piezoelectric materials are very active smart materials as they actuate under electric field and also sense the reactions^[1]. On the other hand although smart but passive materials, like fibre optic sensors (FOS) can only sense the reactions on the structure without ability to actuate^[8-12]. FOS sensors offer a wide number of advantages over traditional sensors. These include immunity to electromagnetic interference, electrically passive, long term stability, light weight, small size, multiplexing capabilities, ease of installation and durability. This article presents the application of both piezoelectric wafer active sensor (PWAS), and passive

FOS, namely, fiber optic polarimetric sensor (FOPS) and fiber Bragg grating (FBG) for monitoring strain and boundary conditions. This article thus focuses on strain measurement due to the loading-unloading cycle on a laboratory specimen for a simply supported boundary condition.

Among the various FOS; FOPS has its unique advantages over the rest^[13, 14]. Such a sensor typically employs a single high birefringence (Hi-Bi) or bow-tie fibre, which is surface mounted on the structure^[11] under investigation. FOPS was used for dynamic SHM of beam structures^[14-17]. Since FOPS is highly sensitive to the perturbations over its entire length, global SHM or a significant length of structure can be monitored. In case of a polarimetric sensor, changes in the state of polarization of the light traveling in a single-mode optical fibre are used to determine the measurand (strain, stress, temperature etc.) imposed on the sensor^[14].

Formation of FBGs was reported more than three decades ago^[18], but intensive study began only after when a controllable and effective method for their fabrication was devised about two decades ago^[19]. In recent years, there have been a number of initiatives towards the development and deployment of FBG sensors for structural engineering^[20-22]. FBGs are suitable for local structural health monitoring or in other words they can be used for only spot strain measurement^[17].

PWAS patches are usually in the shape of circle or square, which do not directly measure physical parameters like stress, strain or temperature etc. PWAS are relatively new compared to FOS. These are usually permanently bonded on the surface or embedded in the host structure which is to be monitored^[23-25]; on the other hand, fibres are usually reusable.

2. THEORY

2.1 Fiber Optic Polarimetric Sensors (FOPS)

The typical schematic of FOPS is shown in the Fig 1(a). In FOPS, polarization maintaining (PM) or high birefringence (Hi-Bi) fibres like, bow-tie fibres are used. The Hi-Bi fibre has fixed fast and slow axes throughout its length. Therefore, the light coming out of these Hi-Bi fibres has fixed state of polarization. When a longitudinal force is applied along the core of the fibre, the length of the core changes which means the length of the birefringent medium traversed by the light changes. As a result, the polarization of the light coming out of the fibre changes^[26]. Polarized light has two orthogonally polarized modes. In normal medium both the components (fast and slow) travel with the same velocity, therefore, there is no phase difference between both the components. But in a birefringent medium, fast component (having direction of polarization along fast axis) moves faster than the slow component (having direction of polarization along slow axis). This difference in velocities introduces an additional phase between both the components. In case of Hi-Bi fibre, this additional phase is given by

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

Where, L is the length of the fibre and $\Delta\beta (= \beta_{fast} - \beta_{slow})$ is difference in propagation constant between two orthogonally polarized modes which travel along fast and slow axes respectively. $\Delta\beta$ is called the 'birefringence' of the fibre. From equation (1) it is clear that there are two factors which can cause change in the additional phase; one is the change in the length (or axial strain) of the fibre and another is birefringence ($\Delta\beta$). If longitudinal strain is produced in the Hi-Bi fibre continuously, the phase of the light coming out of the fibre changes sinusoidally^[26]. Since the light finally passes through an analyzer, as shown in the schematic diagram (Figure 1(a)), the intensity (or voltage V) measured by the photo detector also changes sinusoidally. In static loading test as conducted in present experiment with FOPS, a normalized output parameter called state of polarization (SOP) is calculated, which is given by:

$$SOP = \frac{V - V_{av}}{V_R} \quad (2)$$

Where, $V_{av} = (V_{max} + V_{min})/2$ is the average photodiode voltage and $V_R = (V_{max} - V_{min})/2$ is the range of the variation of the photodiode voltage. Following photodiode voltage V , SOP also changes sinusoidally. The cycle

of SOP variation depends on the beat length ($L_b = 2\pi/\Delta\beta$) of the Hi-Bi fibre used. A phase change of 2π in SOP cycle means a change of L_b in the length of Hi-Bi fiber used as FOPS. This fact can be used to calculate total strain in the specimen.

2.2 PWAS patches

The basic concept of this electromagnetic admittance (EMA) based SHM approach is that the presence of damage/load on the host structure will affect its mechanical impedance. Therefore, the presence of damage/load will also affect the admittance (inverse of impedance) of the PWAS patch which can be directly measured by an electrical analyzer, such as the Agilent's LCR (inductance -L, capacitance -C, and resistance -R measuring) meter as shown in Figure 1(b). This imposes an alternative voltage signal of 1 volt rms to the bonded PWAS patch (Figure 2) over the user specified frequency range. The change in extracted admittance signature is an indication of structural loading change or boundary condition change or a damage^[23]. The admittance signature comprising of peaks is a function of the stiffness, mass and damping of the host structure, the properties of PWAS patch and the additive glue with which it is bonded^[23, 28]. In principle, the EMA based SHM technique is similar to the conventional global vibration techniques. The major difference is only with respect to the frequency range employed. The frequency is typically <400 kHz for EMA based SHM and is <100 Hz for the global vibration technique. The peaks are proportional to the natural frequencies of the host structure and shifting of these peaks indicates changes in natural frequencies of the structure. The change in the frequencies arises due to crack/load in the structure. The technique has several advantages over the conventional load/stress/strain measurement based techniques, as it does not warrant any complex analytical/numerical modelling of the structure under monitoring. It employs low-cost and low-power PWAS patches, which can be non-intrusively bonded to the structure and can be interrogated without removal of finishes. One-dimensional approach to model PWAS-structure interaction has already been proposed^[29]. This is based on the piezoelectric effect of imparting mechanical strain when subjected to an electric field and the converse piezoelectric effect of generating electric charges in response to a mechanical strain. The admittance of the PWAS sensor is expressed as

$$Y(\omega) = j\omega \frac{w_a l_a}{h_a} \left(\bar{\epsilon}_{33}^T - d_{31}^2 \bar{Y}^E \right) + \left(\frac{Z(\omega)}{Z(\omega) + Z_a(\omega)} \right) d_{31}^2 \bar{Y}^E \left(\frac{\tan \kappa l_a}{\kappa l_a} \right) \quad (3a)$$

$$Y(\omega) = G + jB \quad (3b)$$

where Z_a and Z are the mechanical impedances of the PWAS patch and the host structure, respectively; j is the imaginary unit; ω is the angular frequency of the driving voltage; w_a , l_a and h_a are the width, length and thickness of the PWAS patch, respectively; $\bar{Y}^E = Y^E(1 + j\eta)$ is the complex Young's modulus of the PWAS material at zero electric field; d_{31} is the piezoelectric constant; $\bar{\epsilon}_{33}^T = \epsilon_{33}^T(1 - j\delta)$ is the complex dielectric constant; η and δ denote the mechanical loss factor and the dielectric loss factor of the PWAS material, respectively; κ is the wave number which is related to the angular frequency of excitation ω by $\kappa = \omega \sqrt{\rho / \bar{Y}^E}$; and ρ is the material density of the structure. G is real component of admittance, i.e. conductance and B is imaginary component of admittance, i.e. susceptance. Equation (3) indicates that the admittance of PWAS patch is directly related to the mechanical impedance of the host structure. Therefore, any change in the admittance signatures is the indication of a change in the structural integrity. The signature comprises of conductance and susceptance both.

During the last decade, the EMA technique has demonstrated its potential to be an efficient and cost-effective SHM technique for a wide variety of engineering structures. LCR meter facilitates the wired communication in-out of PWAS. The patch is bonded to the specimen as shown in Figure 3. The setup of wired communication is as shown in Figure 1(b), which is a global and local monitoring system.

Figure 1: Schematic diagram of (a) FOPS, (b) LCR- wired PZT Impedance communication and (c) FBG.

2.3 Fiber Bragg Grating (FBG)

A Bragg grating is a periodic structure of refractive index, fabricated by exposing a photo sensitised fibre to an ultraviolet light through a phase mask. When light from a broad band source interacts with the grating, a single wavelength, known as the Bragg wavelength is reflected back whereas the rest of the signal is transmitted. The Bragg wavelength λ_B depends on the grating period of the FBG, that is

$$\lambda_B = 2\Lambda n_{eff} \quad (4)$$

Where, n_{eff} is the effective refractive index of the mode propagating along the fiber and Λ is the grating period of the FBG. The grating period varies with longitudinal strain imposed on the fiber and hence, longitudinal strain shifts the Bragg wavelength through expansion or contraction of the grating periodicity^[27]. The strain is calculated by:

$$\varepsilon = \frac{\Delta \lambda_B}{\alpha} \quad (5)$$

Where, $\Delta \lambda_B$ is the change in the Bragg wavelength of FBG and α is the wavelength-strain sensitive factor and its value is $0.67 \mu\epsilon^{-1}\text{pm}$ for 850 nm. The schematic of FBG experimental setup is as shown in Figure 1(c), which is a local monitoring system.

3. Experimental Results and Discussions

A simply supported aluminum beam was put under loading/unloading test as shown in the Figure 2. FOPS, PWAS patch and FBG were bonded to the bottom surface of the specimen. FBG and PWAS were kept at the centre point of the specimen and FOPS covers 160 mm length of the central region of the specimen as shown in the Figure 3. The dimensions of the specimen and the spacing between the boundaries are also shown in Figures 2 and 3. The test was carried out first by FOPS to calculate global strain, next by PWAS to access the global

situation then by FBG to measure the local strain at the centre of the specimen. The following sections present the results and discussions of these tests.

Figure 2: Specimen with simply supported boundary condition under loading/unloading test.

Figure 3: Lay-out of FOPS, FBG and PWAS on the specimen.

3.1 FOPS

In this experiment, a Hi-Bi fibre with beat length of 2.8 mm was used. Specimen was placed on simple supports as shown in Figure 2. The FOPS (Hi-Bi fibre) was at the bottom side of the aluminum beam and the load was applied at mid-point of the beam. Loading bent the beam and thus, the longitudinal strain was produced in the in the beam/FOPS. As a result, the phase of the light and hence the polarisation of light coming out of the fibre changed. The light finally passes through an analyser, as shown in the schematic diagram (Figure 1(a)); the intensity changes sinusoidally. The intensity of light impinging on the photodiode was recorded in mV for no load condition through DAQ system. Then, the load was kept on increasing (loading) and the corresponding voltage values were recorded. In the same-way, the load at the centre of specimen was reduced in same steps (unloading process) and voltage readings were recorded once again.

As this is a static loading test, SOP was calculated using equation (2) and then SOP was plotted for loading and unloading processes as shown in figure 4(a). SOP varied sinusoidally during loading and unloading processes. Figure 4(a) shows that both, loading curve and unloading curve follow the same pattern. Since the beat length of the Hi-Bi fibre used here in this experiment is 2.8 mm, one complete cycle of SOP variation corresponds to 2.8 mm increment in the fibre length. The total length of the Hi-Bi was 16 cm (Figure 3). The cycle of SOP variation in Figure 4(a) could be segmented to calculate the total longitudinal strain in 16 cm length due to a particular load. Thus FOPS can be used to calculate the total strain over a certain length. The total strain for loading and unloading processes in 16 cm length at different load values is shown in the Figure 4(b). Figure 4(b) provides a global (or atleast in the range of 16 cm length of Hi-Bi fiber) estimation of longitudinal strain, but it cannot predict any condition of the structure other than strain variations. Therefore, PWAS patch was used to get further information about the loading/unloading condition of the specimen.

Figure 4: FOPS results for loading and unloading tests (a) Variation of SOP (b) Average strain.

3.2 PWAS

EMA signatures were obtained at each loading state for the frequency range from 10 Hz to 150 KHz at a frequency sweep step of 0.25 KHz. The loading started from 0 (no load), then a loading hanger of 130 gms was hanged and then again the load was increased till 1930 gms in the steps of 200 gms. In the final step the load was increased by 500 gms to make it 2430 gms. Similar steps were considered in the unloading process by removing the loads one by one. Figure 5 shows twelve conductance and susceptance signatures obtained during 12 steps of loading. It was observed that for conductance and susceptance both, peaks were more 'active and consistent' at higher frequencies (say > 70 KHz) compared to peaks at lower frequencies (say < 70 KHz). Here 'active' means that the peaks in the loaded signatures are relatively taller and are shifting compared to healthy state (at 0 gm) signature whereas 'consistent' means that the peaks shift are consistently and proportionally with the load increment.

Thus narrow active frequency ranges, which are greater than 70 KHz were considered for closer study to predict the behaviour of the specimen. Figures 6(a)-6(c) show a clear up-ward or down-ward shifting of peaks or both from 0 to 2430 gms (e.g., peaks at frequencies 70.25 KHz, 72.5 KHz and 74.75 KHz). However it can be noted that signature taken at 0 gm is different from signature cluster taken between 130-1930 gms which is also different from the signature taken at 2430 gm. i.e. signatures taken at 0 and 2430 gms did not have similar peaks to the peaks at 130 - 1930 gms. The signatures change when specimen is loaded. These changes are due to sudden change in boundary condition. Probably, attaching the hanger (130 gm) at the centre might have slightly changed the boundary conditions which are not observed either by naked eye or by FOPS. However, for every step from 130 gms to 1930 gms (i.e. 130 gm, 330 gm, 530 gm, 730 gm, 930 gm, 1130 gm, 1330 gm, 1530 gm, 1730 gm and 1930 gm) signatures shifted gradually. The signature taken at 2430 shifted by larger magnitude than its predecessor signatures because the increment was of 500 gms, which could have impacted the boundary conditions more. Thus the enlarged view at 70 - 75 KHz presented three boundary conditions and twelve loading variations, i.e. at 0 gm, 130-1930 gms and 2430 gms. Thus EMA signatures were effective in reflecting the changes in boundary conditions through twelve loading steps.

Figure 7 shows twelve conductance and susceptance signatures obtained during 12 steps in unloading process. Figure 8 (a) shows another frequency range (80 - 85 KHz) which depicts three peaks; two peaks (at about 80 KHz and 84 KHz) continuously shifted in anti-clock wise direction, whereas peak at 81.75 KHz decreased continuously in magnitude as load increased. Figure 8 (b) shows close up view of signatures in the range of 110 - 122 KHz, which presents completely different observations, i.e. there was decrease in the magnitude of peaks with increasing load. In general, increase in peak magnitudes in some frequency range and decrease in some other frequency range is a commonly observed phenomena in any EMA signature^[30]. Peaks and valleys co-exist in signatures. If peaks increase, valleys will decrease or vice versa^[3]. Thus in Figure 7, peaks mostly increased except in the frequency range 110 - 122 KHz. Overall, the EMA signatures were able to predict the change in boundary condition during the loading process.

This experiment shows that the PWAS based EMA signatures were able to clearly differentiate between “loading” and “unloading” processes because Figure 6 and Figure 8 are almost opposite in behaviour. Such information could not be obtained by FOPS, which merely gave total strain.

A further analysis was carried-out to verify the observation obtained in Figure 6 and Figure 8 using Root Mean Square Deviation (RMSD) index. There are few pattern recognition techniques such as ‘signature assurance criteria’ and ‘adaptive template matching’ to quantify changes in signatures^[31] in addition to the RMSD indices^[2, 32], which is used to compare the signatures of two different states. However, RMSD has been widely accepted and used for estimation of amount of variation between any two signatures. It is defined as

$$\text{RMSD-k (\%)} = \sqrt{\frac{\sum_{i=1}^N (y_i^k - x_i^k)^2}{\sum_{i=1}^N x_i^2}} \times 100 \quad (9)$$

Where, y_i^k and x_i^k ($i = 1, 2, 3 \dots N$) are signatures obtained from the PWAS bonded to the structure before (at no load) and after the loading (kth) is incurred, respectively. Where $i = 1, 2, 3 \dots N$ indicates the frequencies where the value of admittance was collected. The RMSD is a comparable index of initial signature with later stage signatures ($k = 1, 2, 3 \dots$). In the present study the RMSD index was adopted to evaluate the signatures obtained from the ‘PWAS-specimen’ system.

Figure 9 shows the RMSD indices for loading and unloading process for both conductance (RMSD_C) and susceptance (RMSD_S) signatures from the specimen in the considered frequency range of 10 – 150 KHz with a sweep step of 0.25 KHz. In figure 9, the radial axis from centre to circumference (i.e. 0 to 45) indicates the RMSD axis and the circular axis shows the loading and unloading stages. The circular axis is divided into two halves; one for twelve loading steps and another for twelve unloading steps. From figure 9, it can be observed that the average RMSD values in loading process are smaller than that in unloading process which indicates that the boundary conditions were altered during these processes. During the loading process in the beginning, a hanger was first hanged at the centre of the beam (Figure 2), which might have caused slight changes in boundary conditions. This is reflected in the right side of the Figure 9 at load step 2. From load steps 2 to 11 i.e. from 130 gm to 1930 gm, there was steady increment as indicated in Figure 9. Again at final load step 12 (at 2430 gm), there was a jump in RMSD index because the magnitude increase of 500 gms compared to 200 gms. During the unloading process, extra care was taken not to disturb the boundary conditions and therefore, the RMSD indices were steadier. Thus both RMSD and the signatures (Figures 6 and 8) show same predictions about change in boundary conditions during initial loading step (step 2) of hanger and final loading step (step 12) of 500 gms increase, whereas these sudden changes in boundary conditions were unapparent during unloading process because of the extra care taken during unloading process.

Figure 5: Admittance Signature response of wired-communication system during central loading on the specimen

Figure 6: Conductance Signature response of wired-communication system during central loading on the specimen in the frequency range indicating (a) increase (b) increase and decrease (c) decrease.

Figure 7: Admittance Signature response of wired-communication system during central unloading on the specimen.

Figure 8: Conductance Signature response of wired-communication system during central unloading on the specimen in the frequency range indicating (a) decrease (d) decrease-increase.

Figure 9: RMSD indices for loading and unloading.

3.3 FBG sensors

Previous methods FOPS and PWAS gave information related to global (or total) strain and boundary conditions respectively, but FBG sensors measured the local strain at the centre. The local strain, obtained by FBG is plotted in Figure 10 for both loading and unloading processes. Figure 10 shows some hysteresis, but there was no hysteresis in case of FOPS (Figure 4(b)).

Figure 10: Local strain measurements obtained from loading-unloading at the centre of specimen using FBG sensor.

4. Conclusions

This article focused on measurement of strain (global and local) and EMA signature due to loading-unloading cycle on a laboratory specimen for simply supported aluminum beam using multiple smart materials viz., FOPS, FBG and PWAS. This study demonstrated the efficiency of FOPS and FBG for measuring global and local strain, respectively. Though FOPS successfully measured the total strain over the placed length, it did not differentiate between loading and unloading processes. Furthermore, PWAS demonstrated the effectiveness of EMA signatures to assess the global condition of the specimen as to how loading/unloading affects its boundary conditions. If the EMA signatures are analyzed in narrower frequency range rather than wider range, the difference between loading signatures and unloading signatures is apparent or in other words, considering the

narrow frequency ranges, if loading signatures result in upward shifts, unloading signatures will result in downward shifts and vice versa. Thus, both FOPS and PWAS are able to present the global condition of the specimen in their own way. FOPS measured global strain quantitatively, but it could not differentiate between loading and unloading processes; on the other hand, PWAS discriminated the loading and unloading processes, but it only presented a qualitative case. However all these multiple smart materials together successfully assessed the condition of structure. Different smart materials have their own advantages and the fusion of such methods is essential for effective SHM.

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