



The Smart Bridge—Condition Monitoring for Military Bridges

Anand Asundi

Abstract | Online Condition Monitoring has emerged as an attractive alternative to the traditional approach of preventive maintenance. This is especially so in the civil and structural industry, where it is finding widespread application in the health monitoring of bridges and other vital infrastructures that have been converted into ‘intelligent’ systems through the incorporation of computer-linked sensors. The potential of smart structure technology to yield operational benefits, such as near-instantaneous damage detection and quantification of residual load capacity, in military bridges exposed to enemy fire, is enormous and constitutes a true combat-multiplier. This paper presents a study done using fiber optic polarimetric sensors on the SM-1 Launched Bridge.

1 Introduction

The preventive maintenance of mobile bridges and structures has long centered on traditional methods of Non-Destructive Evaluation (NDE) for the early detection of potentially catastrophic faults such as stress cracks and corrosion-induced fractures. Such methods include visual inspections and dye-penetrant tests which require a degree of experience to obtain results that are still subjective in interpretation. Further, such tests are invariably time-consuming and tedious to perform. They also require the structure to be setup in a position which allows the technician to reach otherwise inaccessible portions of the structure like the underside cross beams and bottom trusses. Hence the need for predictive maintenance and the need for adaptive or smart structures.^{1,2}

For peacetime maintenance, these pre-inspection procedures are a minor hassle. However, for operational on-field applications such pre-requisites, are unacceptable due to time, manpower and equipment constraints. Nevertheless, on-field condition monitoring of military assault bridges and other mobile structures are just as, if not more, important due to the high likelihood of the structures’ exposure to weapon effects, which will undoubtedly result in a compromised level of safety and load-bearing performance.

This paper presents the defense initiative to jointly develop an online condition monitoring system for military bridges and structures with the Nanyang Technological University. Christened the “Smart Bridge”, the project aims to develop an intelligent structure capable of providing near-instantaneous feedback on its current structural integrity through the use of embedded sensors linked to an AI-based neural network program. The Finite Element Method (FEM) is employed to analyze the acquired sensor data, and translate these into a coherent approximate of the structure’s bending profile, which is then fed into the neural network algorithm for interpretation into usable information on the structure’s health. This paper reports on the Fiber Optic Polarimetric Sensor (FOPS) implementation and parameters affecting the performance of the sensor.

2 Fiber Optic Sensors

Fiber Optic Sensors are among the preferred sensing material in smart structure applications due to their immunity to electro-magnetic interference, small size, lightweight and compatibility with the host material. In addition, remote sensing is easily accomplished where the test specimen with the sensing fiber is placed in a harsh environment and the sensed information transmitted by optical

Director, Centre for Optical and Laser Engineering, School of Mechanical & Aerospace Engineering, Nanyang Technological University, Singapore.
masundi@ntu.edu.sg

fibers to a remote site for evaluation. Development in fiber optics owes much to the communication industry. Their use as sensors is however, still under study, primarily because communication fibers were designed for the information-carrying beam traversing the fiber to be transmitted undistorted over large distances. On the other hand, as sensors, it is necessary that the external loading influence the transmitted beam which can then be traced back to cause. As such, the sensing part of the fiber is but a small portion of fiber length with the rest still being used to transmit the distorted signal to the processor. An excellent review of fiber optic sensor types and their application in smart sensing is given by Selvarajan and Asundi.³ Basically fiber optic sensors can be classified according to the light modulation mechanisms. Intensity sensors are the most rugged but the least sensitive, as they rely purely on the light intensity and can generally distinguish on/off characteristics only. Interferometric sensors are at the other end of the spectrum providing high sensitivity but with difficult handling characteristics. For smart structure applications, sensors in between these two extremes would be most suitable.

While the cradle to grave health monitoring approach is a longer-term programme, one of the near-term programme with more immediate applications is the on-line Structural Health monitoring. Two avenues are being explored, mimicking nature. The first is a global warning system, where in the entire structural component is monitored. In this the goal is to provide an overall health status of the component. This is similar to our human response of rise in body temperature due to illness. The second is more specific testing, in which quantitative values are analyzed at different locations and the damage then completely identified with respect to size, location and severity. Of course this stage requires longer examination, but it is envisaged that this could be accomplished without significant downtime. This would provide conclusive evidence as to whether the structure needs to be “hospitalized” for a complete check-up, repair or removal from service.

The fiber optic sensor to be evaluated can be categorized as global and local. Of the different global sensors, a Fiber Optic Polarimetric Sensor (FOPS) offers the best choice. For local sensing, Extrinsic Fabry-Perot Interferometric (EFPI) sensor or the Fiber Bragg Grating (FBG) strain sensor are the available choices. The principles of these sensors have been demonstrated as regard strain and temperature measurement. The FOPS^{4,5} provides greater sensitivity and longer sensing

range for global health monitoring of the structures than the Fiber Optics Curvature Sensor (FOCS).⁶ However, the demodulation system is a bit complex.

3 Fiber Optic Polarimetric Sensor (FOPS)

High birefringence is introduced into the optical fiber core by pre-stressing it using strain-inducing elements in the cladding. This birefringence causes the orthogonally polarized components of light launched into this fiber to travel with different velocities. This prevents the transfer of optical energy from one mode to the other, thus maintaining the State of Polarization (SOP) of the light coming out of the optical fiber. When the fiber is stretched, the differential phase delay $\Delta\phi$ due to an external perturbation applied to the fiber of length “ L ” is given by

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

where β is the fiber birefringence.

The premise behind global health monitoring system is that there is a change in stiffness associated with damage of the structure. Thus, relating the change in stiffness to the phase change under similar loading conditions, allows one to simply monitor the damage growth over the entire structure.

Figure 1(a) is the schematic of compact plug and play Fiber Optic Polarimetric Sensor, designed and developed at NTU, while Fig. 1(b) shows the actual system. It is made of two modules—an illumination module and a detection module. The detection module could be modified for dynamic measurement through the use of a single detector. The response of this system for specimens with different size cracks enables the determination of a Damage Factor,⁶ which is the ratio of the stiffness of the damaged material to that for an undamaged material. Asundi and Ma⁶ proposed the concept of Damage Factor to describe the extent of degradation of the stiffness of the structure. Both the Static Damage Factor (SDF) and the Dynamic Damage Factor (DDF) was proposed with the DDF providing reliable and consistent values with minimal loading constraints. This damage factor variation is shown in Table 1 for different amounts of damage. Also shown in Table 1 is a Dynamic Damage Factor that was recorded of a specimen, which was dynamically loaded. The dynamic damage factor that was determined by the same FOPS shows a trend similar to that of the static damage factor. This, thus, testifies the fact that the sensor could be used for live loading as well.

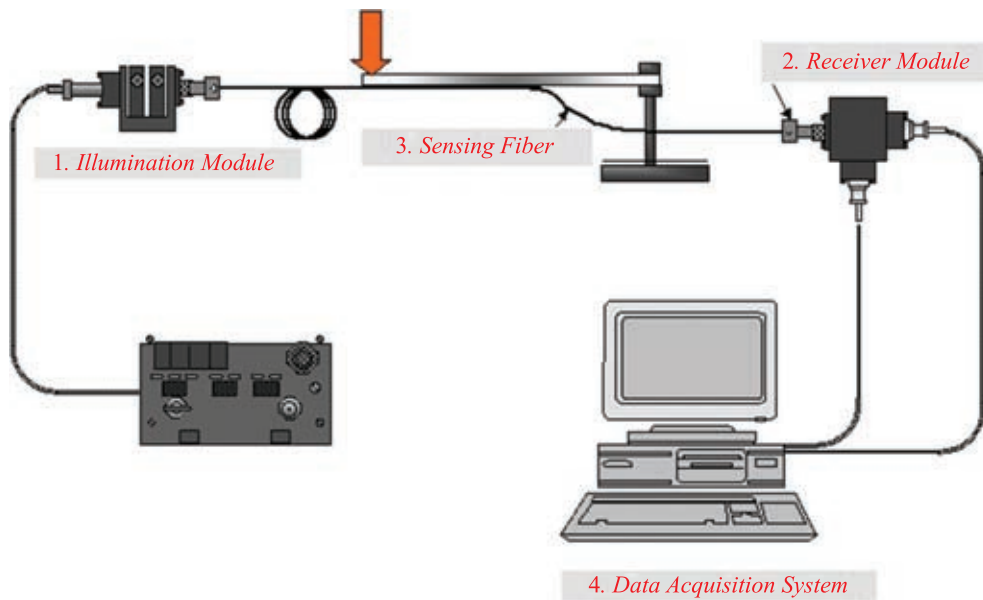


Figure 1(a): Schematic of the FOPS system.

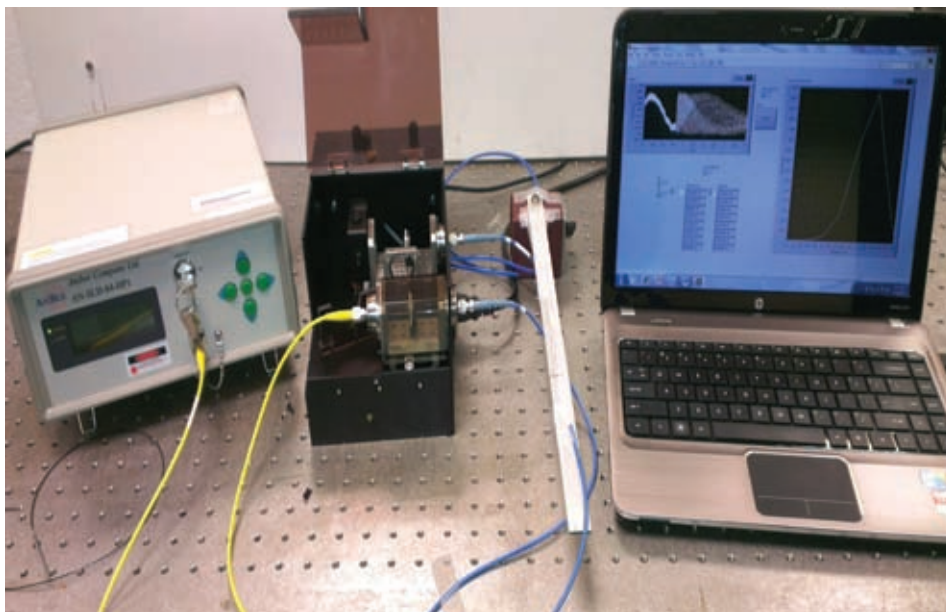


Figure 1(b): Actual compact FOPS system.

Table 1: Static and dynamic damage factors.

Crack number (length mm)	Load for phase change of 2π (g)	Static damage factor	Dynamic damage factor
0	366.5	1	1
1(30 mm)	336.2	0.92	0.96
2 (30 mm each)	308.2	0.84	0.86
14 (20 mm each)	271.4	0.74	0.83

4 Research Methodology

A 1:10 model of the actual bridge was fabricated as shown in Fig. 2(a) (top view) and Fig. 2(b) (bottom view). The FOPS was bonded over the entire length of the bridge. A software interface was developed to give the sensor sensitivities and the damage status of bridge immediately after data acquisition. If the tested damage factor exceeded a preset value, the LED indicator will give a warning. Specimens were progressively loaded in a three point bending arrangement through Instron 5565

universal testing machine, and the data analyzed to determine the sensor sensitivity (i.e. the damage factor). Damage was simulated by removing individual trusses which were supposed to provide part of the structural stiffness. The experimental results showed small variations in the sensor sensitivity with removal of individual trusses.

To further evaluate the parameters affecting the quality of acquired signals from a FOPS system, a study was done to evaluate the effect of

- Strength of impact
- Location of impact
- Type of support
- Bonding method
- Mounting location
- Type of FOPS
- Damage quantification and location.

Two FOPS mounting patterns were derived based on accessibility considerations for initial testing to determine their effect on the FOPS response to impact-induced vibration. In addition, two fiber bonding methods were used for each mounting pattern—tape and epoxy—yielding a total of four distinct FOPS mounting configurations. Each mounting configuration was applied on a separate bridge model, and each model had both HiBi and LoBi FOPs mounted in the assigned configuration. Figure 3 shows different configurations used in the initial test series:

Each of these FOPS configurations was tested using the setup shown in Fig. 4, for the different variables such as fiber type, location and bonding method, etc. For every unique mounting and setup configuration, three different strengths of impact—high, medium and low, were applied at

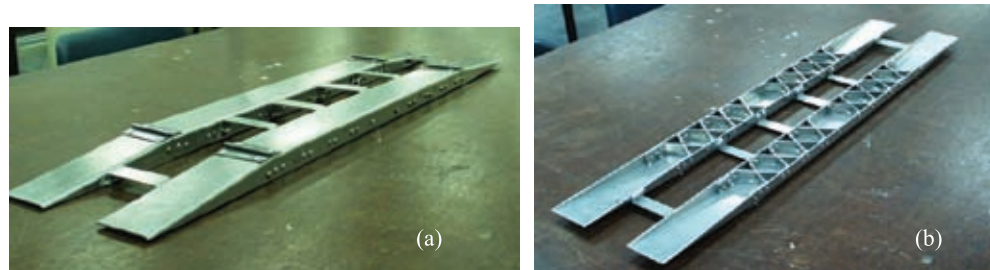


Figure 2: Scale model of the attack bridge (a) right side up and (b) lower part of bridge.




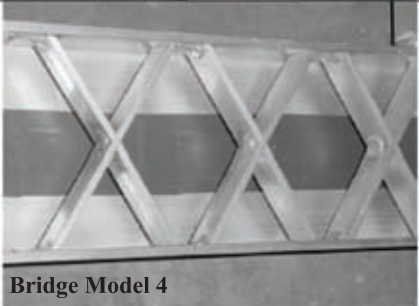
Model Nos.	FOPS on Side	FOPS on Underside
1 & 2 (FOPs bonded with epoxy)	 Bridge Model 1	 Bridge Model 2
3 & 4 (FOPs bonded with duct tape)	 Bridge Model 3	 Bridge Model 4

Figure 3: Configuration used in test setup.

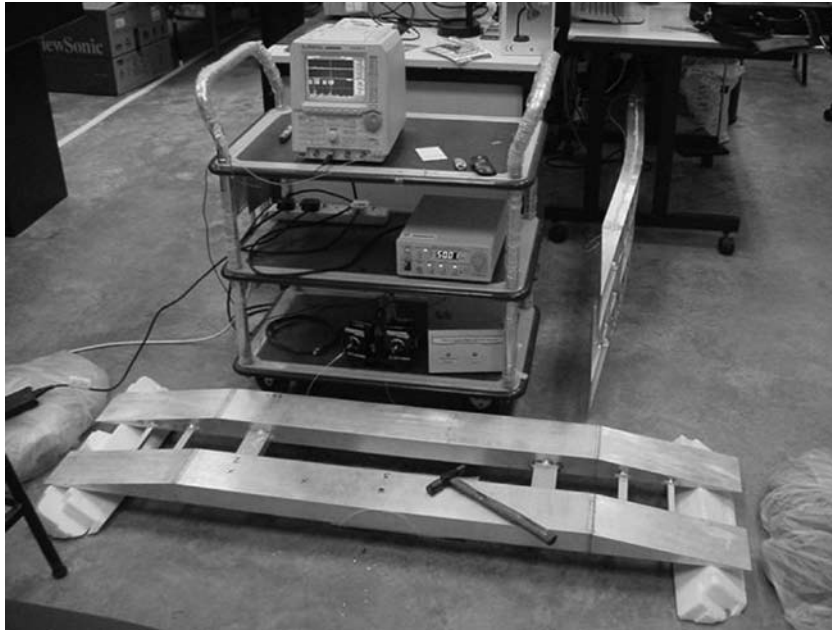


Figure 4: Fiber Optic Polarimetric Sensor test on model of SM-1 Launch Bridge.

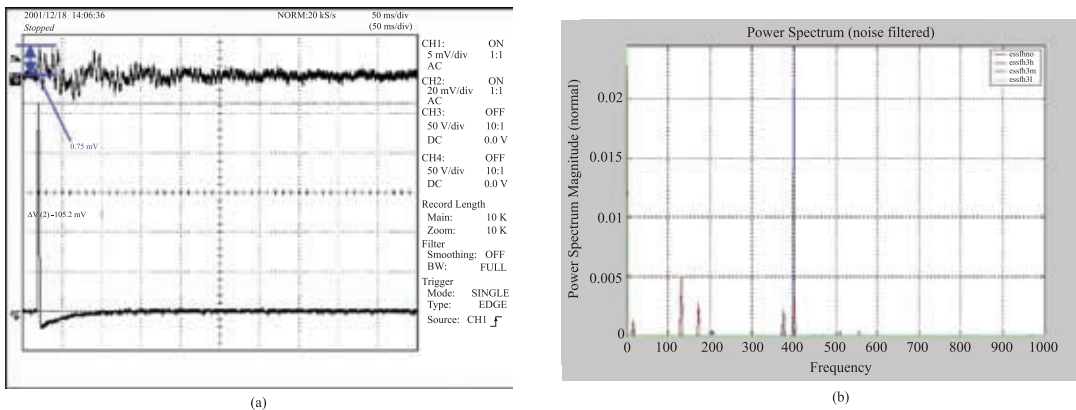


Figure 5: (a) Timebase waveform of signal acquired by epoxy-bonded, side-mounted HiBi FOPS in response to medium impact to mid-span of bridge model supported on foam. (b) Frequency power spectra of timebase waveforms after FFT and noise-filtering.

each impact location with an instrumented hammer to ensure consistency of impact strength. Each impact test was repeated thrice and the average reading recorded. Fast Fourier Transform was used to convert the acquired raw time base waveforms to the frequency domain to obtain the frequency power spectrums. These frequency spectrums were also noise-filtered to isolate the bridge models' vibration responses as acquired by the FOPS from ambient noise. Figure 5(a) shows a typical raw time base waveform registered by the epoxy-bonded, side-mounted HiBi FOPS in response to a medium impact to the mid-span of bridge model 1, while supported on foam blocks. Figure 5(b) shows the

corresponding frequency power spectrum used to analyze the FOPS response. From the experimental methodology described earlier, a total of 144 frequency power spectrums, representing the signal acquisition performances of the HiBi and LoBi FOPS under different test and setup configurations were obtained for analyses and comparison. The results will be discussed in terms of the various parameters listed in the following sub-sections.

5 Results and Discussions

The amount of data obtained from the experiments described in the earlier section is too voluminous to present in totality, and hence only

representative excerpts are included for each sub-section to aid in elucidation of the findings. Results in this section were drawn solely from observations of the frequency peak positions and their power spectrum magnitudes without using any signal processing techniques.

5.1 Effect of strength of impact

The magnitude of the impact force imparted to the bridge model to induce vibration excitation was found to have no effect on the degree of shift of the frequency spectrum peaks of that particular setup configuration. Hence, with all other parameters being equal, the strength of impact affects only the magnitude of the frequency peaks. Figure 6 shows the superimposed frequency power spectra of three different impact magnitudes (High—Blue, Medium—Red, Low—Green) at the midspan registered by the HiBi FOPS of bridge model 1 while supported on foam blocks. The high impact force used was 5 N, the medium impact 3 N and the low impact 1 N. Similar results were obtained for all the other setup configurations—including those for LoBi FOPS. Thus, it was concluded that the impact strength does not have any influence on the HiBi or LoBi FOPS performance—save to make the frequency peaks more prominent in larger structures for easier identification.

5.2 Effect of location of impact

It was observed that the location of impact has a substantial influence on the position of the peaks of the acquired frequency power spectra. For impacts in the same direction but at different locations

(e.g. impacts vertically perpendicular to the top deck at the mid-span, quarter-span and ramp ends of the bridge model), the resulting frequency spectra display peaks at largely similar frequencies with the peak magnitudes increasing as the location of impact approaches the mid-span. For impacts in different directions, however, the peaks occur at significantly different frequencies within the monitored range of 1000 Hz despite all other parameters remaining constant. For example, a lateral impact to the sidewall of bridge model 1 at the mid-span produced the HiBi FOPS-acquired frequency spectrum shown in Figure 7. Comparing this spectrum with that of Figure 6, it is apparent that a substantially different set of frequencies have been excited to an observable extent.

The results of the above experiments to investigate the effects of impact strength and location corroborate the assumption that the FOPS acquire a global frequency spectrum derived from amalgamated modal frequencies. Since different modes are excited to different degrees depending on the direction of the dominant vibration excitation, a change in impact direction will result in distinct frequency spectra being acquired by the FOPS. If the direction of impact is maintained but the location changed (e.g. from mid-span to ramp), then similar frequency peaks with differing magnitudes will be recorded by the FOPS. If only the impact magnitude is varied, then the FOPS-acquired frequency spectra will be identical except for the magnitude of the peaks which will all vary in almost the same proportion across the spectrum.

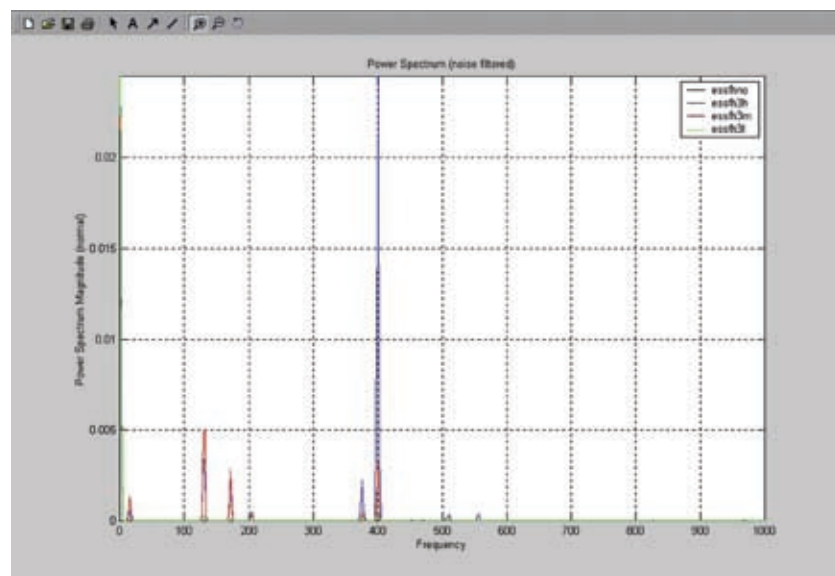


Figure 6: Effect of Magnitude of Impact Excitation High—Blue; Medium—Red; Low—Green.

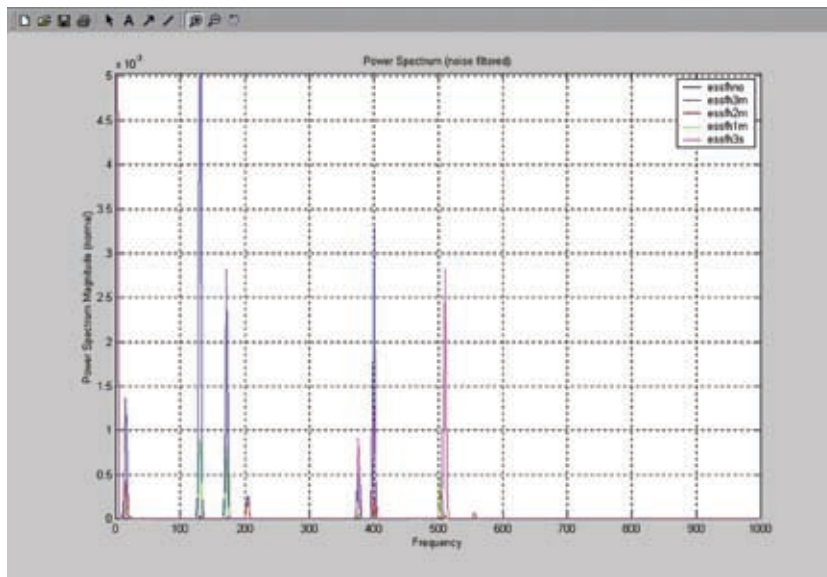


Figure 7: Epoxy-bonded, side-mounted HiBi FOPS-acquired frequency spectra for different location and direction of impact on foam supported model.

5.3 Effect of type of support

Obviously, the condition of the ground on which the bridge rests may vary considerably—from hard compacted soil to soft sand and even mud. These varied ground conditions affect the natural frequency and vibration response of the bridge due to the different degrees of damping imparted on the structure. Hence, to simulate the extremes of the ground support conditions, two different types of support were selected for investigation—soil support for high damping conditions and foam support for low damping. It was observed that the soil support cases usually yielded fewer and smaller peaks than those supported on foam. The peaks of the frequencies registered by the soil support cases were usually of the order of 100 to 5 times lower in magnitude than the foam-supported ones. This is directly attributable to the higher damping of the soil. Further, an average of 3 common peaks (at ~510 Hz, ~205 Hz and ~16 Hz) can usually be found for both soil and foam support cases when the impacts are at the Mid- and Quarter-spans. This is true for both HiBi and LoBi FOPSs, but the HiBi peaks are usually more prominent and easier to distinguish. Impacts on the ramp do not produce distinguishable common peaks. The worst cases whereby common peaks between soil and foam support cannot be found are those with the FOPSs mounted on the underside and with impacts to the ramp. This can be attributed to the contact between the underside-mounted FOPSs and the supports during the impact. Figure 8 shows the superimposed frequency spectra acquired by the HiBi FOPS on

Model 1 for both soil and foam support cases. Recalling the working principle of the FOPS, the LoBi FOPS's more sedate response to the above dynamic stimulation may be explained by the lower frequency of SOP change resulting from its much longer beat length as compared to the HiBi FOPS6. This would account for the more heavily damped profile of the LoBi FOPS waveform, as its SOP change (and corresponding intensity change of the measured light component) would become even less pronounced as the structure's vibration deflection damps out. In fact, since the LoBi FOPS's beat length is over 50 m (compared with a maximum deflection of 2–3 mm for the dynamically-excited structure), the SOP of the light propagating within the LoBi FOPS would change only by a few degrees. In contrast, the HiBi FOPS with its extremely short beat length would cause its propagated light to undergo at least several 360° cycles of SOP change. Hence, even as damping reduces the deflection amplitude, the light intensity of the measured component would still vary across the full intensity range as long as the propagated light continues to undergo full 360° SOP changes.

5.4 Effect of FOPS bonding method

It was observed that the epoxy-bonded FOPS generally yielded higher peaks in the frequency spectrum than the tape-bonded FOPS. However, the range of frequencies registered is comparable with epoxy bonding sometimes yielding more peaks and vice-versa. The tape-bonded FOPS also tends to produce a greater number of smaller peaks

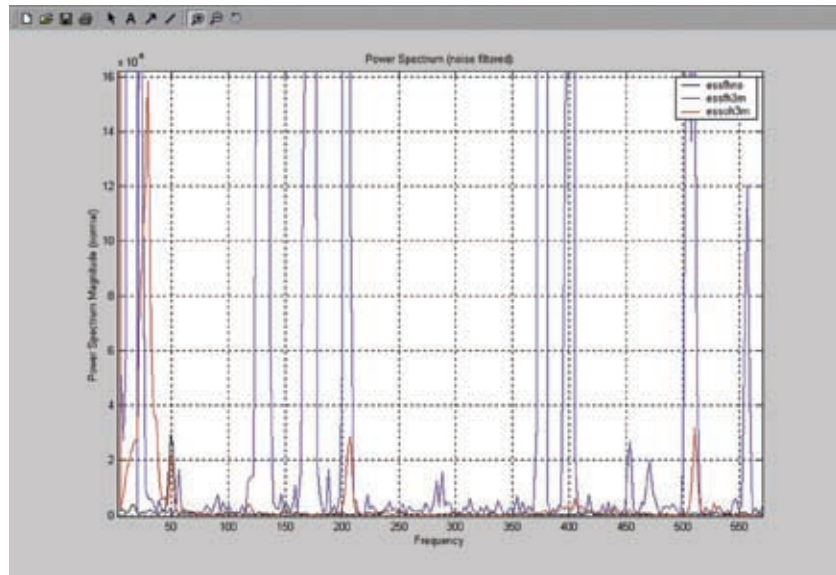


Figure 8: Frequency spectra acquired by HiBi FOPS on Model 1 for foam (red) and soil support (blue) cases.

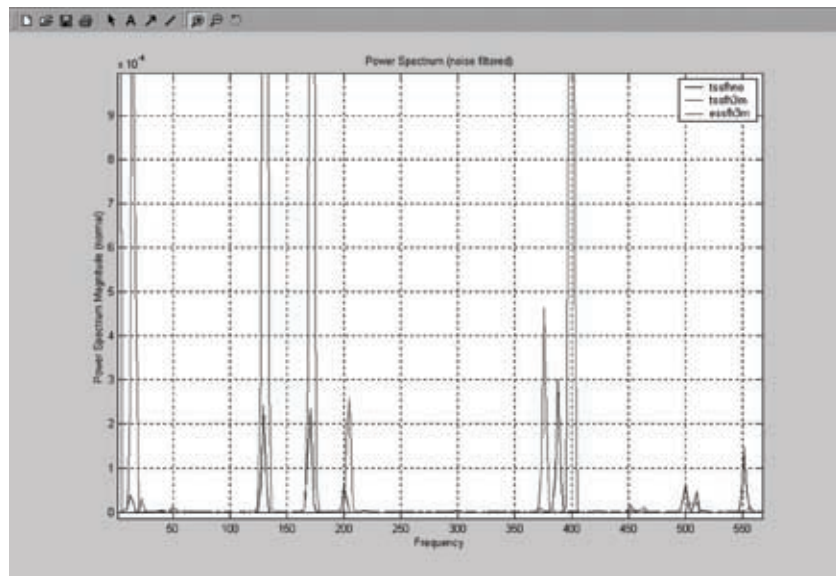


Figure 9: Comparison of frequency spectra acquired by side-mounted epoxy- and tape-bonded HiBi FOPS on foam supported models.

compared to the epoxy-bonded FOPS. These numerous small peaks may not be the modal frequencies of the model, but ‘noise’ due to the vibration, albeit small, of the FOPS against the metal surface of the model, which the tape-bonding method cannot fully prevent. Figure 9 shows the frequency spectra acquired by HiBi FOPSs bonded to the sidewalls of Models 1 and 3 using epoxy and tape respectively. Hence, the tighter the adhesion, the clearer will be the signal acquired by the FOPS.

5.5 Effect of FOPS mounting location

Varying the mounting location of the FOPS is analogous to varying the impact location. This is corroborated by the results, which show that the frequency spectra acquired by the side-mounted and bottom-mounted HiBi FOPSs differ significantly, as can be seen from Figure 10. The reason for this is the same as that for the variation in impact location: different modal frequencies are acquired by the fibers according to their mounting orientation. Hence, a FOPS mounted on a vertical

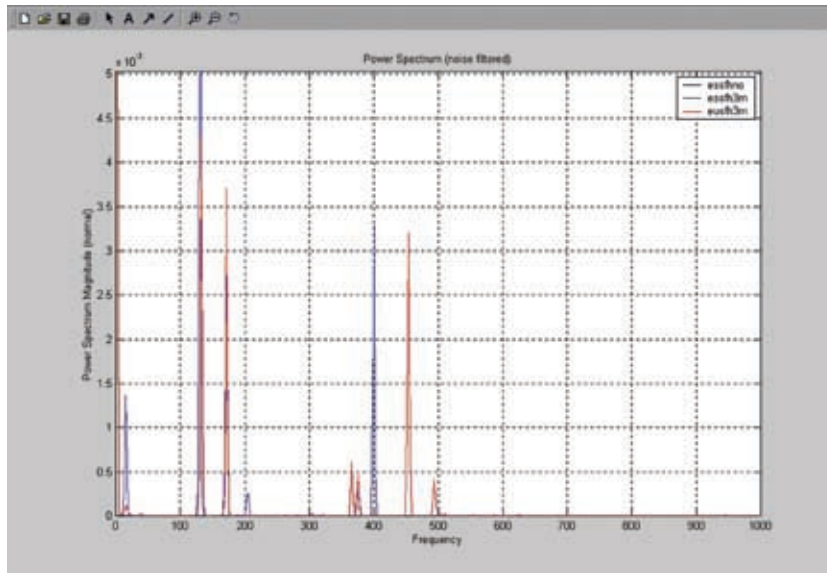


Figure 10: Frequency spectra acquired by HiBi FOPS mounted at different locations.

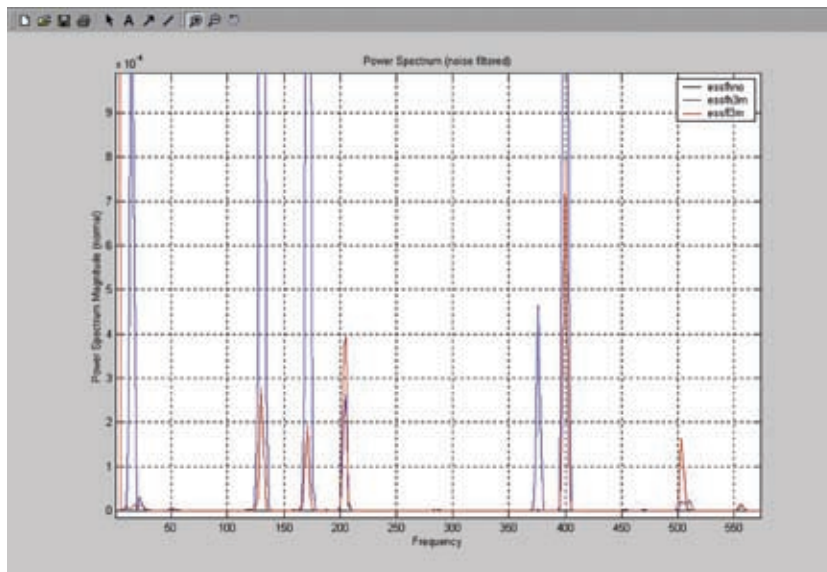


Figure 11: Frequency spectra acquired by epoxy-bonded, side-mounted HiBi (Blue) and LoBi (Red) FOPSs for Model 1 supported on foam blocks.

surface would acquire certain modal frequencies more clearly than another mounted on a horizontal surface and vice-versa.

5.6 Effect of type of FOPS

In all of the tests, it was observed that the HiBi FOPS generally yielded higher peaks than the LoBi FOPS for the same test configuration. As mentioned earlier, this is because of the working principle of the two types of polarimetric sensors, which pre-disposes the HiBi FOPS to acquiring

dynamic signals such as this impact-induced vibration excitation. However, despite the difference in frequency peak magnitudes, the main frequencies registered by both FOPSs are generally similar. Frequencies which appear to be only acquired by the HiBi FOPS are actually also acquired by the LoBi FOPS, albeit at much lower magnitudes that may not be readily distinguishable without greater signal amplification. Figure 11 shows the contrast in frequency peak magnitudes acquired by the HiBi and LoBi FOPS.

6 Effect of Parameters on Damage Quantification & Location

To deploy the FOPS as a structural health monitoring sensor, a damage quantification system capable of interpreting the power spectrum frequency peak shifts arising from structural changes/damages is required. Such a system was based on the earlier works of Asundi et al.,⁶ and is based on the following formula for dynamic signals:

$$DDF = \sqrt{\frac{w_1 \left(\frac{f_{1,damaged}}{f_{1,undamaged}} \right)^2 + w_2 \left(\frac{f_{2,damaged}}{f_{2,undamaged}} \right)^2 + \dots + w_n \left(\frac{f_{n,damaged}}{f_{n,undamaged}} \right)^2}{n}} \leq 1$$

where DDF stands for Dynamic Damage Factor, f_i are the frequencies of the power spectrum peaks, w_i are the weighting factors for each selected frequency and n is the number of frequencies selected for the computation. The derivation of the DDF formula is beyond the scope of this paper and will not be presented, but it should be noted that the DDF provides a proxy indication of the prevailing flexural stiffness of the structure. A DDF of 1.0 indicates that the structure is intact with no degradation in flexural stiffness. Structural changes due to damage will result in a shift of the frequency peaks to a lower range, resulting in a lower DDF.

It is apparent from the above formula that the judicious selection of frequencies (and their respective weighting factors) for use in the DDF computation is essential for accuracy. However, since the frequencies acquired depend on the mounting and setup configuration of the FOPS, the discussed parameters must be considered along with the target area of measurement. For instance, if coverage of the sidewalls is desired, then the FOPS should be mounted onto a surface of similar orientation—preferably on the surface of interest itself. Moreover, to ensure that the FOPS acquires the relevant vibration signals optimally, finite element analysis and experimental modal analysis should be performed a priori for the structure of interest to determine its mode shapes before fiber routing. The knowledge of modal behavior structure will allow the FOPS to be mounted on the surfaces of prime relevance in order to acquire the appropriate modal frequencies to be constituted in the final amalgamated signal output. However, should manipulation of the FOPS mounting location prove to be impractical for accessibility reasons, the location of impact excitation delivery may be adjusted to compensate for the shortcoming in coverage. Apart from the above considerations of optimal signal acquisition,

the basic factors such as type of FOPS, impact magnitude, support condition/degree of damping, method and length of bonding should all be observed to achieve signal clarity.

It is known that the higher-order modes contain spatial information, which may be used to achieve damage location by the FOPS if the sensor can be set to acquire the correct modal frequencies. Since these frequencies are more prominent

at certain locations of the structure according to its mode shape, it follows that the FOPS mounting location can be chosen to allow for triangulation of the damages to be achieved. This, however, will possibly require more than one FOPS to be deployed on the structure.

7 Conclusion

The novelty of the FOPS as a global structural health monitoring sensor has necessitated the development of the new signal acquisition and interpretation techniques presented here to achieve performance reliability. These results concerning the effect of the various setup and testing parameters on the quality of FOPS-acquired signals constitute part of a larger study to determine the feasibility of using FOPSs in the global structural health monitoring role. The main conclusion from this feasibility study is that the FOPS is capable of providing an instantaneous indication of structural health based on flexural stiffness (in terms of DDF), much as body temperature or heart rate is used by physicians to gauge a patient's state of health. Its reliability in this role as a structural 'vital signs' monitoring system, however, is contingent on several factors—including those presented in this paper. While many issues concerning the correlation of the FOPS-acquired data with structural health remain, it is hoped that the research results presented in this paper have served to illuminate further the performance parameters of the FOPS, and the factors which anyone exploring their use in structural health monitoring must consider.

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Prof. Anand Asundi (安顺泰) graduated from the Indian Institute of Technology, Bombay with a B.Tech (Civil Engg.) and a M.Tech (Aeronautical Engg.). Subsequently he received his Ph.D. from the State University of New York at Stony Brook. Following a research fellowship at Virginia Tech., he was with the University of Hong Kong from 1983 to 1996 as Professor in the Department of Mechanical Engineering. He is currently Professor and Director of the Centre for Optical and Laser Engineering in the School of Mechanical and Aerospace Engineering at the Nanyang Technological University in Singapore. His teaching area is in Optical Engineering with research interests in Computational Optical Metrology, Photomechanics, 3D imaging, measurement and display and Fiber Optics Sensors. He has numerous patents, has published extensively and presented invited seminars/talks at various institutions and at international conferences. He is Editor of Optics and Lasers in Engineering and Fellow of SPIE, the International Society of Optical Engineers and the Institution of Engineers, Singapore. He is founding chair of the Optics and Photonics Society of Singapore, Asian Committee on Experimental Mechanics and the Asia Pacific Committee on Smart Materials and Nanotechnology. He has organized numerous conferences and served on the Membership, Scholarship/Awards and Presidential Asian Advisory committees of SPIE and its the Board of Directors.

Following a research fellowship at Virginia Tech., he was with the University of Hong Kong from 1983 to 1996 as Professor in the Department of Mechanical Engineering. He is currently Professor and Director of the Centre for Optical and Laser Engineering in the School of Mechanical and Aerospace Engineering at the Nanyang Technological University in Singapore. His teaching area is in Optical Engineering with research interests in Computational Optical Metrology, Photomechanics, 3D imaging, measurement and display and Fiber Optics Sensors. He has numerous patents, has published extensively and presented invited seminars/talks at various institutions and at international conferences. He is Editor of Optics and Lasers in Engineering and Fellow of SPIE, the International Society of Optical Engineers and the Institution of Engineers, Singapore. He is founding chair of the Optics and Photonics Society of Singapore, Asian Committee on Experimental Mechanics and the Asia Pacific Committee on Smart Materials and Nanotechnology. He has organized numerous conferences and served on the Membership, Scholarship/Awards and Presidential Asian Advisory committees of SPIE and its the Board of Directors.

