3D DELAMINATION PATCH DETECTION IN LAMINATE COMPOSITES WITH AN NOVEL NDE TECHNIQUE

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Abstract
Interferometric type fiber optic sensors have advantages of high sensitivity and can be employed to measure very small measurand. In this paper, a 3×3 coupler based demodulation using software approach is introduced and its advantages are presented. Based on this technique, mechanical tests are performed and the sensing arm of the interferometer is embedded along the neutral plane of the laminate. A quasi-impulse loading is applied and the total elongation of the embedded optical fiber is measured as a function of load position. When a delamination is present, the shift of neutral axis position can be clearly reflected in the fiber integral strain versus load position plot. Experimental results demonstrate the feasibility of detecting both the size and location of delamination patch with the proposed technique.

1 Introduction
Interferometric type fiber optic sensors have advantages of high sensitivity and can be employed to measure very small measurand. In real applications, proper signal processing technique is needed to provide automatic linearized and real-time output of the measurand signal. All of currently proposed demodulating techniques have to use one of the following techniques for signal recovery [1]:

1) Scanning the wavelength of the laser source;
2) Using PZT (piezo-actuator) as phase servo-actuators to control the OPD (optical path difference) to maintain the orthogonal condition;
3) Developing an optical frequency (wavelength) shifters (eg., in-fiber acousto-optic frequency shifters) to achieve heterodyne phase detection;
4) Using 3×3 or 4×4 coupler to let the outputs have a relative phase difference of 120° or 90°.

Comparing to the first three techniques, 3×3 coupler based demodulation possesses high resolution over a large dynamic range, good environmental stability and polarization insensitivity, and is thus very useful in practice.

Brown et al. [2] demonstrated a demodulation technique to recover the phase signal from the measurand through complicated calculation. This technique can be realized by both hardware and software approaches. One method is using operating circuit. Although this method provides real-time signal processing, it needs a number of complicated circuits and leads to large errors. The other method is using commercially available software to perform the demodulation [2]. By using this technique, not only complicated operating circuits are omitted, but also a high demodulating resolution is achieved. Moreover, by using software for demodulating operation, one can obtain the waveforms of intermediate steps and analyse the errors and their causes.

The paper introduces a technique utilizing software to demodulate the signal. Based on this technique, mechanical tests are performed and the sensing arm of the interferometer is embedded along the neutral plane of the laminate. A quasi-impulse loading is applied and the total elongation of the embedded optical fiber is measured as a function of load position. When a delamination is present, the shift of neutral axis position can be clearly reflected in the fiber integral strain versus load position plot. Experimental results demonstrate the feasibility of detecting both the size and location of delamination patch with the proposed technique.

2 The Principle of the Signal Demodulation

The schematic diagram of a Mach-Zehnder interferometer terminated with a 3×3 coupler is shown in Figure 1. It consists of a 2×2 coupler at the input and a 3×3 coupler at the output. The excitation was applied to the sensing arm of the interferometer. In an ideal 3×3 coupler, where there is an equal amount of light splitting into each arm, the outputs have the same magnitude and a relative phase difference of 120°. Mathematically, the outputs of the interferometer, i.e. the measured light intensities, can be expressed as:

$$f_n(t) = B + C\cos[\phi(t) - (n-1)\frac{2}{3}\pi] \tag{1}$$

where n is a labeling index having value 1, 2, or 3. Φ(t) is the optical phase difference between the legs of the interferometer, C is the fringe contract, and B is a central value around which the output will vary with amplitude C.

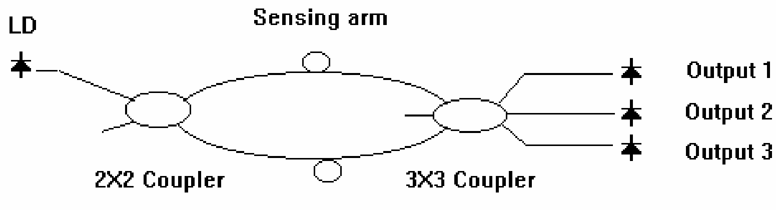

Figure 1. Fiber optic M-Z interferometer based on 3×3 coupler

Our objective is to measure the phase change Φ(t). In Equation (1), C, B and Φ(t) are all unknowns. By measuring all the three outputs f1(t), f2(t) and f3(t) from the coupler, three equations are available at each time t for the three unknowns, and specifically for Φ(t), to be obtained. With this approach, a much higher resolution than conventional fringe counting can be obtained.

Simulation through software is used to investigate the feasibility of this demodulation technique [3]. The results show that the demodulation technique can efficiently recover the input signal even the three outputs of the interferometer are not ideally symmetric (Figure 2).

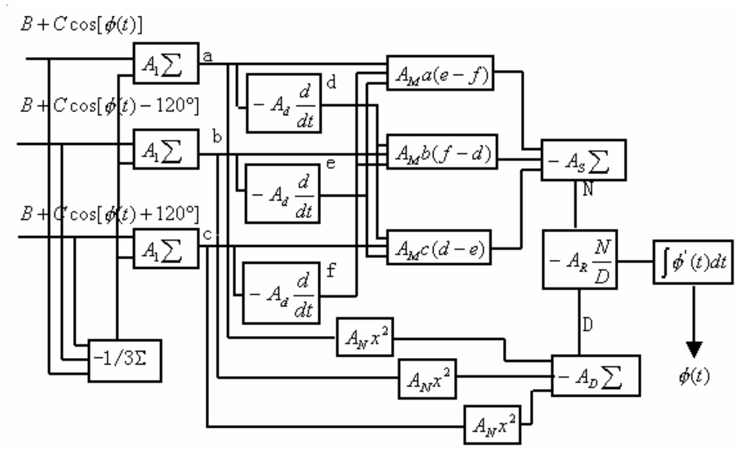

Figure 2. The diagram of the software demodulator

3 Application in Delamination Detection in FRP Composite Material

FRP (Fiber reinforced polymer) Composites are widely used in aircraft and aerospace industry due to its high strength and stiffness relative to weight. It is also applied in civil construction area, such as strengthening and upgrading of structurally inadequate or damaged structures. FRP composites are commonly produced by curing under high temperature and pressure after lay-up of multiple plies of carbon fiber sheet. For FRP composites, delaminations are often caused by low energy impact [4]. The delamination will continue to grow under cyclic loading and eventually leads to the fracture of the whole structure [5].

Since the delamination is invisible and often in the form of a patch (i.e. the delamination spans across only part of the plate’s width) rather than a through-width crack, it is difficult to detect visually and thus increases the failure probability of primary structures without warning. With the increasing use of composite materials in various engineering structures, it is of growing importance to develop reliable and effective nondestructive evaluation methods to assess and monitor the mechanical serviceability and safety of in service composite structures. The determination of the extent and location of delamination in critical composite structural components is most critical for the assurance of structural integrity.

The non-destructive evaluation (NDE) of delamination or debonding in structural members has been studied very extensively in the literature, which includes popular techniques such as ultrasonics and radiography. However, these techniques require expensive instrumentation and are not very efficient due to their point sensing methods [6, 7]. In 1980’s, fiber-optic based techniques for delamination detection have been developed by many investigations [8~11]. The advantage of these techniques include invulnerability to electromagnetic interference, compatibility with in-service operation, real-time response to damage, high resolution, good durability, low loss for remote signal transmission and ability for the sensor to be embedded within composite structures. Among all different kinds of fiber-optic sensors, interferometric optical fiber sensor has the highest sensitivity and thus can be employed to measure very small delamination. Moreover, the technique has the advantage over traditional point sensing methods since the damage state at any section along the fiber can be determined through only one interferometer instead of large numbers of point sensors [11]. In this paper, a 3 × 3 coupler based Mach-Zehnder interferometer was utilized for the experiment investigation and the results of the test showed that the interferometer could efficiently locate the delamination zone in composites.

The composite specimen in this paper was made by hand lay-up of 24 plies of carbon fiber sheet with the same fiber orientation. The material parameters are given in Table 1. After 12 plies have been laid, optical fibers are placed on the carbon fiber sheets. Another 12 plies were then laid above the fiber. The geometry of specimen is 300 mm×35 mm×3 mm. Since in reality, the delamination often occurs below the surface of a laminate as a patch rather than a through crack, this paper focuses on experimental feasibility of detecting closed delamination patches using the 3×3 coupler based interferometric technique. For ease of specimen preparation, the delamination is assumed to be formed on one side of the plate and penetrate only through part of the width. To introduce artificial delamination patches, a thin Teflon sheet (0.1mm thickness) of specified width was placed between selected layers of lamina. Releasing oil was applied on the surfaces of the sheet. After the composite laminate hardens, the sheet was pulled out from the side to introduce a delamination patch of known location and size.

Unidirectional carbon fiber/epoxy prepreg		
E11=235GPa	E22=8.6GPa	E33=8.6GPa
v12=0.011	v13=0.011	v23=0.4
G12=5.07GPa	G13=5.07GPa	G23=3.07GPa

Table 1. Material properties of the CFRP laminae

In this paper, the optical fiber is embedded inside the composite along the neutral plane of the section. This way, the global bending effect is theoretically zero for any loading configuration. In reality, the fiber cannot be placed exactly along the neutral plane, but the distance from it is expected to be very small. As a result, the sensor output should be small when the member is not delaminated. Since real delaminations will never occur symmetrically about the neutral axis, its presence will lead to a shift of the neutral plane. The integral strain along the optical fiber should change accordingly. This change in integral strain is expected to be quite significant in comparison to the reference value when there is no delamination. The presence of the delamination can hence be easily observed from the test results.

A schematic of the delamination sensing principle is illustrated in Figure 3, which shows a beam member under arbitrary support conditions and an all-fiber Mach-Zehnder interferometer. In order to improve the signal/noise ratio, a quasi-impulse loading was applied along the CFRP laminates at discrete points that were 10 mm apart. To apply a quasi-impulse loading, an instrumented impact hammer with load cell (B&K 8202+8200) was employed. The strain of the composite specimen under the loading is obtained with the 3×3 coupler based Mach-Zehnder interferometric system. Based on the measured phase change, the change in length can be calculated. With the system, a displacement resolution of 1 nanometer under a dynamic loading can be achieved.

4 Test Results and Discussions

Elastically supported boundary condition is considered during the test. For each load position, the test was repeated three times. The average variation of the testing result is about 7% and the repeatability of the test method is therefore considered satisfactory.

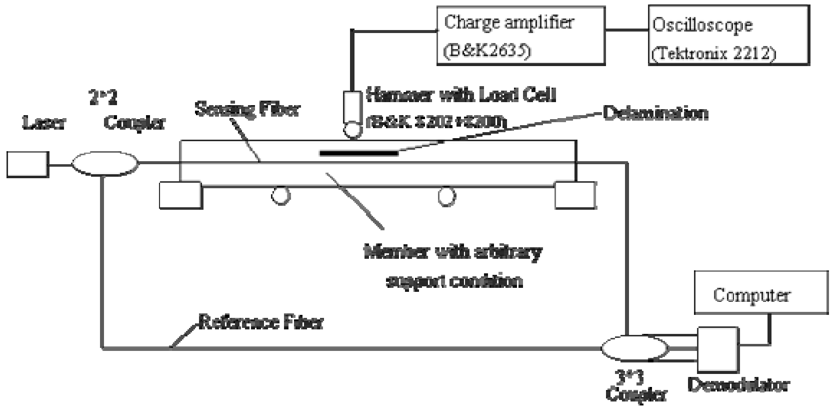

Figure 3. Schematic of the measuring system

The geometry and the fiber location of the specimen is shown in figure 4. An artificial delamination patch, 100mm 17mm 0.1mm, was made between 18th and 19th layer of lamina (f=h/2 in Figure 4). The fiber was embedded at 20mm from one side of the plate, along the mid-plane of the member (Figure 4). The quasi-impulse loading was applied along a longitudinal line above the delamination patch (Figure 4). In the test, 30 points are equally marked along the length of the plate and the loading was applied along the plate at discrete points that were 10 mm apart from point 4 to point 24. The outputs from the interferometer and the corresponding results are shown in Figure 5 and Figure 6. The arrowed line denoted by W shows the actual extent of the delamination patch.

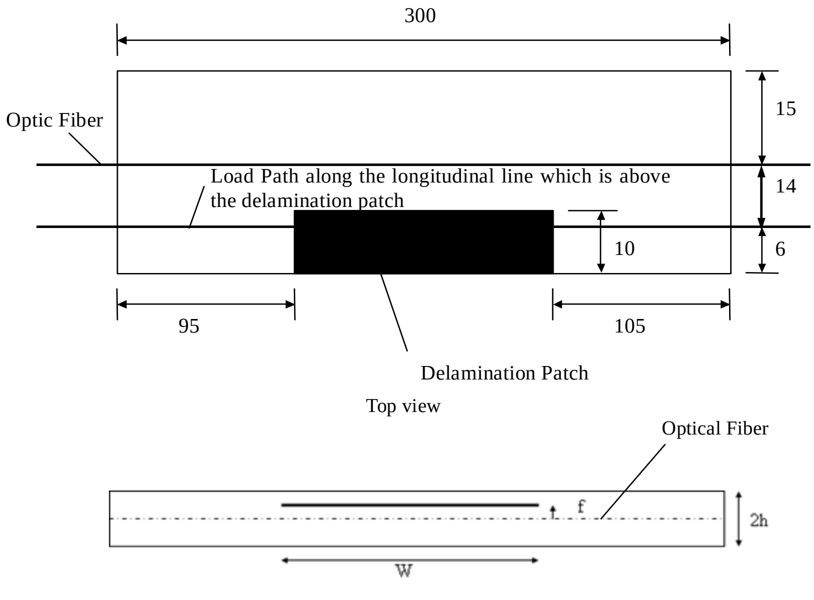

Figure 4. The geometry of the composite plate with 0.1mm delamination patch

Figure 5 is the output of interferometer for the elastically supported plate when loading applied along a longitudinal line above the delamination patch. It shows that for point 4 ~8, and point 19 ~ 24 where it is outside the delamination patch, there are only slight vibrations but zero integral strain values from the interferometer. However, once the delamination patch is reached (point 9~18), the integral strain value become none-zero and a clear peak appears at each loading point. The curve in Figure 5 shows an ascendant drift due to air currents, vibrations and temperature fluctuations. Since the loading time is very short compared to the period of the drift, the signal due to the impulse can be easily identified from the background drift.

Figure 6 is the normalized integral strain curve versus loading position for Figure 5. It shows that the magnitude of the integral strain exhibits a sudden increase when the loading reaches the two edges of the delamination and the extent and location (along the longitudinal direction) of the delamintion patch can be easily identified from the sudden increase of the integral strain value (point 9 ~ 18 in Figure 6). The test results show that if loading is applied above the delamination area, it is possible to detect the delamination patches even if the optic fiber is away from the delamination zone.

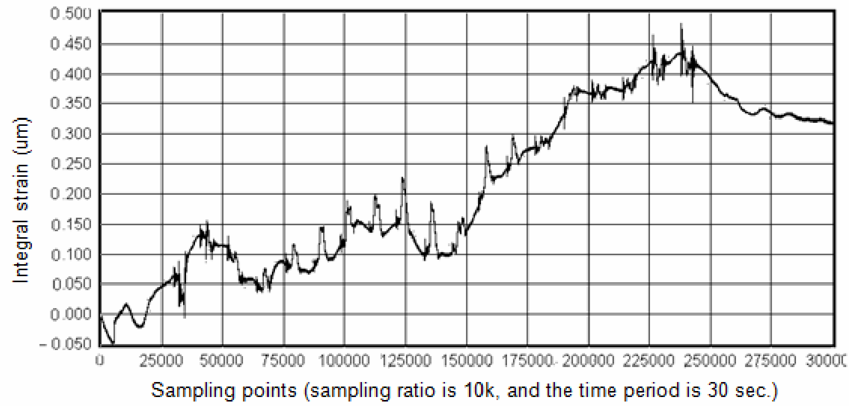

Figure 5. The output of interferometer for an elastically supported plate with 0.1mm delamination patch when loading tapping through the top of the delaminated area

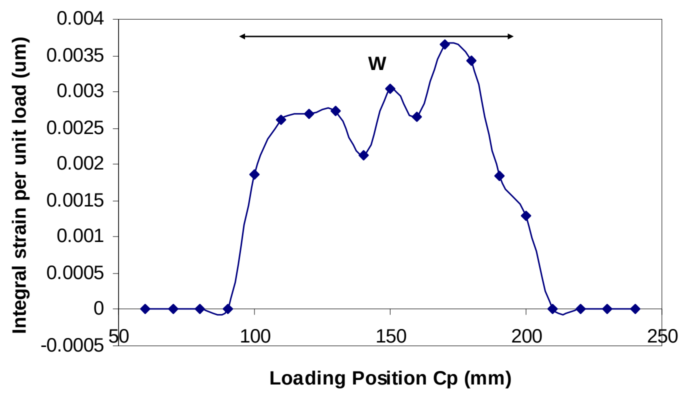

Figure 6. Normalized integral strain curve versus loading position for elastically supported plate with loading tapping through the top of the delaminated area (0.1mm delamination patch)

5 Conclusion

A 3×3 coupler can be utilized for signal demodulation of fiber optic interferometric sensors without modulating the laser source and the arm length of the interferometer. However, signal processing of this method is relatively complicated. In this paper, a demodulation technique using commercially available software is proposed. The technique can accurately perform signal demodulation and analyse the performance of the system.

To demonstrate the technique, experiments are carried out on CFRP plates with delamination patches. Based on the results, several guidelines for delamination detection can be proposed. The experimental results show that for elastically supported plate, the output of the interferometer is equal to zero when loading is applied at the undelaminated region, however, once the delamination zone is reached, the magnitude of the integral strain exhibits a sudden increase and the extent and location (along the longitudinal direction) of the delamintion patch can be easily identified from the sudden increase of the integral strain value. The techniques can be applied for rapid and distributed detection of delamination or debonding in composites and are applicable as long as loading can be applied to at least one surface of the structure.

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References

[1] Liu K.X., Measures R. M. Singnal processing techniques for interferometric fiber-optic strain sensors. *J. of Intell. Meter. Syst. and Struct.*, **Vol.3**, pp.432-461(1992).

[2] Brown A. D., Cameron B. C., Keolian M.R., Gardner L.D., Garrett L. S. A symmetric 3×3 coupler based demodulator for fiber optic interferometric sensors. *SPIE*, **Vol.1584**, pp. 328-335 (1991),.

[3] Yi J., Lou Y.M., Wang H.W. Software demodulation for 3×3 coupler based fiber optic interferometer. *Acta Photonica Sinica*, **Vol.27(2)**, pp. 152～155(1998).

[4] Choi H.Y. and Chang F. K. Model for predicting damage in graphite/epoxy laminated composites resulting from low-velocity point impact. *Journal of Composite Materials*, **Vol.26**, pp. 2134-2169 (1992).

[5] Geubelle P. H. and Baylor J. S. Impact-induced delamination of composites: a 2D simulation. *Composites Part B: Engineering*, **Vol.29(5)**, pp.589-602 (1998).

[6] Khuri-Yakub B.T., Degertekin F.L. and Pei J. Dry contact ultrasonic sensors for structural monitoring. *Structural Health Monitoring: current status and perspectives,* Fu-Kuo Chang (editor), USA, pp. 481-491 (1997).

[7] Lahiri J., Siddalingaiah D.L., Kamaraguru P.P. and Reddy K.S. Non-destructive evaluation of delaminations and voids in axi-symmetric CFRP shells: part A scope and limitation of X-ray radiography. *non-destructive testing 92.* C. Hallai and Kulcsar P. (Ed.), Elsevier, New York, pp. 625-631 (1992).

[8] Hofer B. Fiber Optic Damage Detection in Composite Structures. *Composites,* **Vol.18(4)**, pp. 309-316(1987).

[9] Elvin N., Leung C.K.Y., Sudarshanam V. S. and Ezekiel S. A Novel Fiber Optic Delamination Detection Scheme: Theoretical and Experimental Feasibility Studies. *Journal of Intelligent Material, Systems & Structures*, **Vol.10(4)**, pp. 314-321(1990).

[10] Xu Y., Leung C. K.Y., Yang Z. L., Tong P., and Lee S.K.L. A new fiber optic based method for delamination detection in composites. *Structural Health Monitoring*, **Vol.2(3)**, pp. 205-223(2003).
[11] Claus R. O. Optical fiber instrumentation and applications. *Proceedings of SPIE -- Smart Materials, Structures, and Integrated Systems,* Alex Hariz, Vijay K. Varadan, Olaf Reinhold (editors), **Vol. 3241** , pp. 20-24(1997).