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Miniature, multiplexed fibre-grating-array sensor for the interrogation of localised strain patterns during crack growth studies upon hybrid laminate panels

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ABSTRACT

As part of a project to optimise hybrid laminates for resistance to fatigue failure, arrays of fibre Bragg gratings are being used to monitor small-scale strain perturbations in composite materials. A remote multiplexed sensing system with 40 remote sensing sites using fibre optic technology, has been developed to monitor the strain field developed across the composite lamina of a hybrid laminate in the vicinity of a fatigue crack. Developed primarily for fatigue-critical aerospace applications, i.e. fuselage and lower wing skins, the hybrid laminates are orthotropic materials having lower density and higher strength than a simple alloy monolith without reinforcement. Fatigue crack growth in hybrid laminates is a complex process that involves a combination of delamination and fibre bridging. The fibre optic system has been applied to the problem of characterising delamination zone development about a fatigue crack, initiated at a through-thickness fastener hole.

Keywords: fibre Bragg grating, multiplexed interrogation, hybrid laminate, strain profile

INTRODUCTION

Optical fibre sensors based on in-fibre Bragg gratings have been researched for many potential applications in material and structural monitoring[1,2]. They are particularly well suited for use in carbon fibre composite materials because of their small size and unobtrusive nature. A major attraction is that they permit the combining of a tiny sensing element (the grating in the fibre core) with a very thin, flexible and strong communications/telemetry link (the polymer clad glass fibre itself). The uniform cylindrical nature of the fibre greatly reduces the problem of stress concentration points that would occur if attempts were to be made to embed conventional electrical (i.e. resistive) strain gauges, with their associated wire leads and bonding pads. Finally, the passive and non-electrical nature of the fibre and grating avoid any problems with corrosion, electromagnetic interference, earth-loops, etc.

Fibre Bragg gratings have been widely used to sense strain and temperature, since both parameters change the peak reflective wavelength of the grating[3]. Extensive research has been undertaken into Bragg grating sensors at the University of Southampton, to benefit from their advantages as fibre sensors. We have previously demonstrated a wavelength tracking system using an acousto-optic tunable filter (AOTF) and a lock-in feedback loop[4]. Gratings in an array have been monitored with high accuracy in real-time, by both sequential and simultaneous methods[5]. We have also used gratings to measure both strain and temperature, simultaneously, at a single point[6].

Further to this work, closely spaced arrays of embedded gratings are being used to map strain fields in composite materials. Strain fields may also be mapped using a distributed grating sensor[7]. Distributed sensors measure a continuous profile of a measurand by measuring the Bragg wavelength as a function of distance. We previously demonstrated a distributed grating sensor capable of interrogating non-monotonic wavelength profiles. Low-coherence interferometry selected the distance

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1. It is to our great regret that Daniel Guerrier died recently in Italy. His contribution to the project as both a friend and colleague was invaluable. He will be fondly remembered by all who worked with him.
2. Keith Trundle is now with GEC, Southampton, UK.

under interrogation and a tunable optical filter measured the wavelength. A novel configuration using a commercial optical coherence domain reflectometer has been presented[7].

Whereas the above advantages have been appreciated, and indeed realised in practice for the monitoring of working structures (e.g. marine vessels, aircraft and civil structures, such as bridges), they have so far not found extensive use for materials testing. We have been successful in constructing a multiplexed grating interrogation system for addressing serial arrays of in-fibre gratings, based on the broadband source / acousto-optic tunable filter approach, and have used it to interrogate a closely-spaced two-dimensional array of Bragg grating sensors embedded in a composite test piece. It has already been reported that gratings can be incorporated in carbon fibre materials without significantly degrading their strength. These gratings therefore offer an ideal way of monitoring the condition of hybrid laminates.

Hybrid laminates are advanced aerospace materials consisting of bonded layers of aluminium alloy and fibre reinforced plastic (FRP). Development of hybrid laminates has progressed steadily since aramid reinforced aluminium laminate (ARALL) was first reported[8]. These developments include (a) the utilisation of alternative FRPs[9] and (b) reduction of post-cure residual stresses arising from thermal mismatch, either by a process of plastic straining or by incorporating buffering FRP layers with an intermediate coefficient of thermal expansion[10].

The response of the hybrid laminate to fatigue cracking about fastener holes is of particular design interest. The response of the material is well documented, although characteristic variations can be attributed to certain forms of FRP, i. e. glass fibre as compared with carbon fibre reinforced plastics. The behaviour is typically one of fatigue cracking confined to the alloy laminae, and delamination between the composite and alloy layers[11,12]. Although there is a deterioration in the integrity of the FRP laminae in the vicinity of the fatigue crack, there is a tendency for the reinforcing carbon fibre to 'bridge' the crack flanks[13], hence improving the resistance to fatigue crack growth (FCG) by restraining the opening displacement across the crack in the aluminium alloy layer[14].

We shall now describe the composite panels, the grating arrangement, the interrogation system architecture, the addressing method, the test procedure and the results in more detail.

MULTIPLEXED BRAGG GRATING SENSOR

The AOTF based grating tracking system for the measurement of strain, developed at Southampton University[4], has been extended to include a facility for interrogating arrays of small, discrete, fibre Bragg grating sensors (Figure 1). The main objective of the current programme has been to prove and develop new techniques for materials research, particularly for the evaluation of composite materials for aerospace applications. The grating arrays are used as embedded strain sensors within test panels of the composite material. The gratings are used to study the strain field in the region near to the propagating crack.

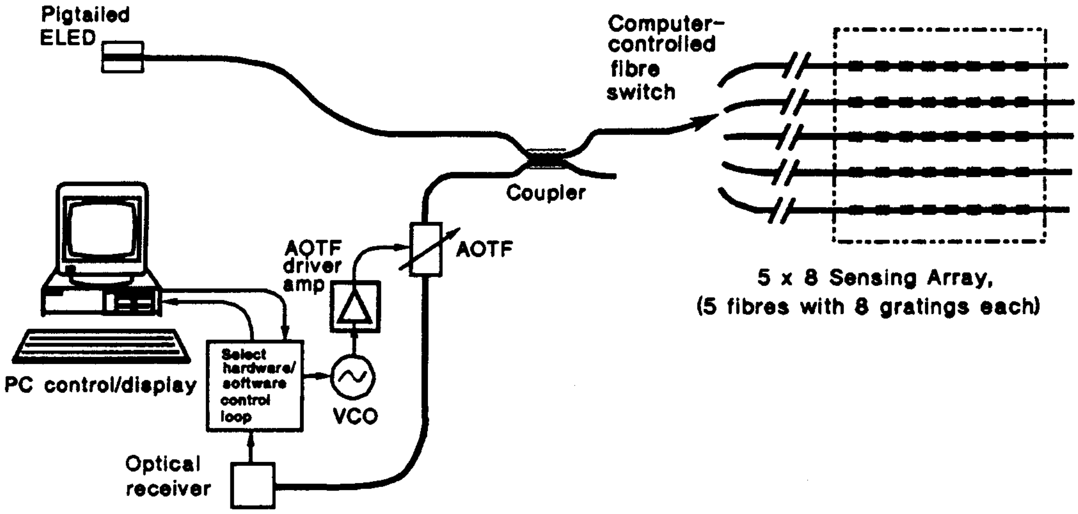


Figure 1. Schematic arrangement of the fibre optic interrogation system using computer controlled AOTF filter and optical fibre polling switch.

The test panels for the reported experiments have five lines of embedded fibre sensors, with each line having eight small, fibre Bragg gratings, ranging in length from 0.5 to 2.0 mm. The gratings in each line have 8 different peak reflective wavelengths written using a phase mask, such that there is fixed wavelength separation between them. All gratings were written in the 1520 to 1580 nm region using the same phase mask pattern to write each line of gratings, so each sensor line is ostensibly identical. Individual lines of fibres can be interrogated in turn using a computer controlled monomode (DICOM Inc.) fibre switch. An additional line of fibre from the switch can be attached to a temperature stabilised, reference grating which can be used to monitor, and correct for, wavelength drift due to thermal effects in the AOTF.

Typical trials involve cyclically loading a test panel with a small, central hole, which acts as a stress concentrator and also simulates a fastener hole. A notch at the side of the hole is used to initiate crack growth. The strain field is recorded at intervals during the trial by interrogating each individual grating in each embedded fibre in turn, with the results being logged automatically. Each trial has an approximate duration of one week.

In future, it is expected that the technique will be extended to include up to sixteen gratings in each sensor line.

INTERROGATION TECHNIQUE

Light from a broadband source (1550 nm ELED) illuminates all the gratings in a selected line (each having different Bragg wavelengths) via the coupler and the computer controlled switch. The reflected light is filtered by an AOTF and detected by a transimpedance receiver.

The fibre-pigtailed AOTF acts as an electrically-tuneable, frequency-agile narrow band optical filter. Its centre wavelength depends on the RF frequency applied to its electrical input by a voltage-controlled oscillator (VCO).

The interrogation system allows two modes of interrogation: a scan mode and a lock-in mode. In the scan mode, the feedback loop has not yet been enabled and the personal computer (PC) tunes the VCO (in open loop mode), and hence the AOTF, over the wavelength range of interest. The power reflected from the gratings is recorded as a function of VCO voltage. The recorded signal is a correlation between the spectra of the gratings and the instantaneous spectrum of the AOTF in the wavelength domain.

In lock-in mode, the system tracks the wavelength of a particular grating using the feedback loop. The PC initiates a frequency-shift keying (FSK) of the RF drive signal to the AOTF by driving the VCO with a square wave (in addition to its

DC bias signal). This toggles the centre wavelength of the AOTF between two wavelengths within the bandwidth of a selected grating. When the selected optical power at these two wavelengths is not equal, the detected optical signal is amplitude-modulated at the toggling frequency. Multiplying the detected signal by the toggling signal generates an error signal proportional to the difference between the mean AOTF wavelength and the grating wavelength. This error signal is integrated to tune and control the mean AOTF wavelength to match the grating wavelength. By counting cycles of the AOTF drive signal over integer multiples of the toggling period, the mean AOTF frequency can be measured. The mean frequency gives an accurate measurement of changes in the grating wavelength.

Because of the frequency-out nature of the measurement, the measurement resolution automatically improves when the gating time of the counter is increased. This measurement period determines the system response, and is software controlled to optimise the system for either fast or slow measurements with the same system.

During typical operation, the system initially scans the wavelength range of interest to identify the gratings and then tracks the wavelength of a selected grating.

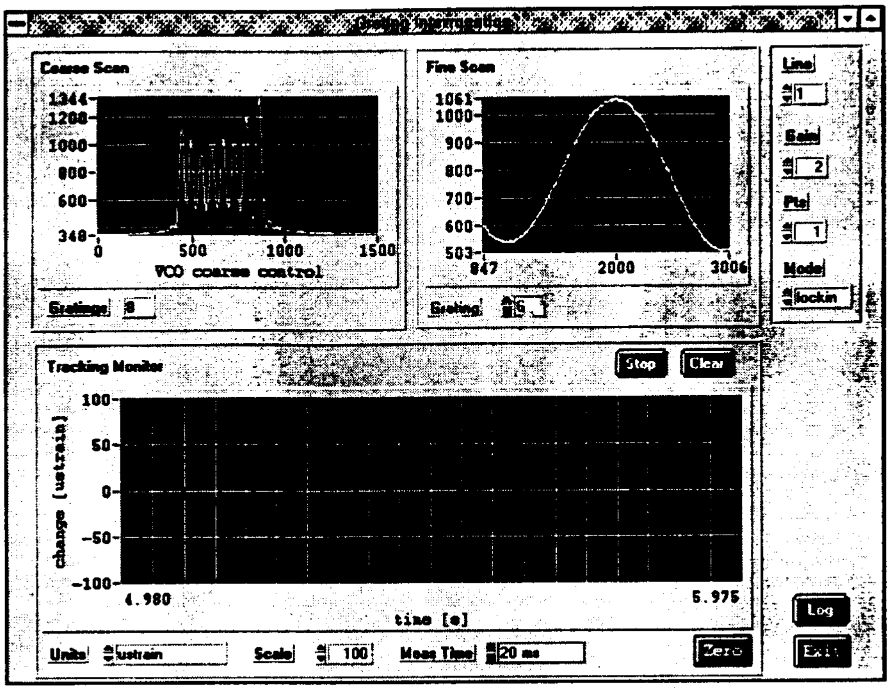
In common with many other optical filters, AOTFs are temperature sensitive. Therefore the AOTF must either be temperature stabilised or the temperature must be monitored, with the PC compensating for any temperature changes. The AOTF temperature could be monitored by a conventional temperature sensor, but we have chosen to do this by interrogating a constant wavelength reference, in the form of a stress free in-fibre Bragg grating (reference grating) at constant temperature.

With good wavelength referencing, the ultimate accuracy of the frequency measurement is determined by the accuracy of the measurement period. This period is derived from a quartz oscillator, which in the current system has an error of 10^{-9}/s.

SYSTEM OPERATION

In 'interactive' mode, after scanning the spectrum, the PC displays the recorded data (Figure 2). This consists of a 'coarse scan' to pass relatively slowly through the broadband spectrum of the source and cover all the gratings, then a 'fine scan' across the narrow band spectrum associated with a single grating, is done to more closely define the return signal from that grating and provide 'initial settings' data for future lock-in mode operation.

Having triggered the 'scan' mode, and thereby invoking a 'coarse scan' to identify individual gratings according to their peak wavelength, the user selects a grating and starts the 'lock-in' mode. The fine scan of the chosen grating then identifies the points on the slope of the spectrum that will result in the highest sensitivity to wavelength changes. The system uses the wavelength difference between these points to set the frequency deviation of the FSK in the lock-in mode.



Gratings: 8

Grating: 6

Line: 1

Gain: 2

Pts: 1

Mode: lockin

Units: ustrain

Scale: 100

Meas Time: 20 ms

Figure 2. Interrogation system 'interactive' mode software interface.

Once in lock-in mode, the counter measures the mean AOTF frequency over a measurement period (field labelled 'Meas time' in Figure 2) set by the user. The measured frequency is displayed and a graph of frequency change against time may be plotted in real time. In Figure 2, the mean AOTF frequency is plotted as its equivalent strain.

MULTIPLEXING SCHEMES

Our technique is well suited to tracking the wavelength of multiple gratings, owing to the large tuning range and frequency-agile behaviour of the AOTF. The current interrogation system, shown in Figure 1, is only constructed to lock onto and track a single grating at any time, but may switch to lock onto many more gratings in turn. When used in this 'polling then lock-in' mode, the switching time between gratings is currently 50 ms.

Since the AOTF may be driven by multiple RF frequencies, an extended scheme may in future interrogate multiple gratings using a separate feedback loop for each grating[2]. It is then important that the modulating signals for the FSK drive signal in the different feedback loops should have low cross-correlation to avoid crosstalk.

CALIBRATION

The system requires calibration to relate grating wavelength changes to actual strain values. Since the system had originally been configured for use with 1300 nm gratings, a dead-weight technique was employed to re-calibrate the system for use at 1550 nm. The change in mean AOTF frequency due to the applied load was recorded and used to calculate a nominal engineering strain. Assuming linear elastic behaviour, the elastic modulus was then used to calculate the expected strain. We found that a constant conversion factor of 1.24 was required to calibrate the nominal strain over the stress range examined, Figure 3. This correction probably arose because the system had been set up originally to interrogate gratings of different wavelengths.

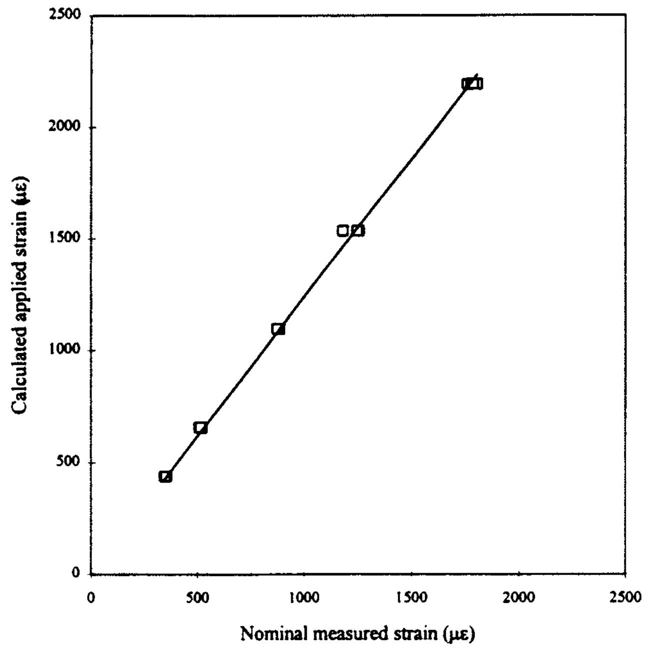


Figure 3. Calibration curve generated using a dead weight procedure.

EXPERIMENTAL RESULTS AND DISCUSSIONS

FCG studies were performed upon M(T) specimens[15], fabricated from four carbon fibre reinforced plastic (CFRP) plies of 0.5 mm total thickness, sandwiched between 0.48 mm thick 8090 Aluminium-Lithium alloy skins. All panels were unidirectional, with all the carbon fibres aligned along the long (i.e. loading) axis, and the aluminium alloy aligned in its original rolling direction. A series of five fibre optic sensor lines, each containing eight gratings of different wavelength, were embedded 5 mm apart in the centre of the carbon fibre plies, and were aligned in a direction parallel to the ply (See Figures 1 and 6).

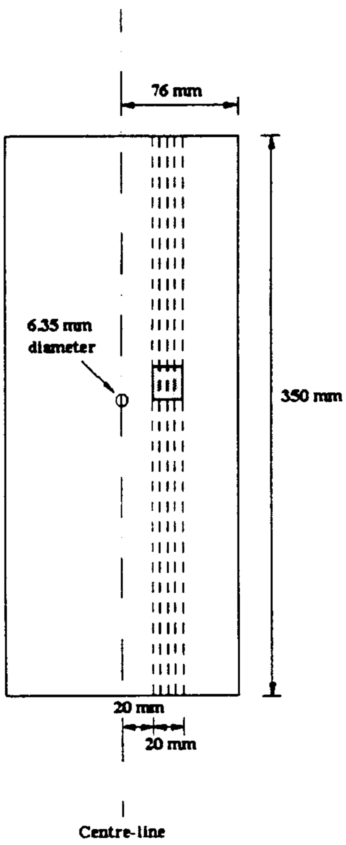


Figure 4. Middle Tension, M(T), panel configuration with embedded optical fibres (broken lines). The shaded box represents the area over which gratings are distributed.

The pattern of eight gratings was distributed over an axial fibre length of 20 mm. Each was produced by traversing a 100 mW UV beam, at a rate of 50 µm/s, across a phase mask held lightly against each fibre. In order to optimise the glass / epoxy bond, the stripped length was treated with hexamethydisilazane immediately prior to embedding between prepreg plies. The series of five lines, embedded at 5 mm intervals, was located such that the array of forty gratings occupied a 20 x 20 mm square area (shaded area in Figure 4) immediately adjacent to the expected path of crack propagation.

FCG studies were performed upon the M(T) specimen type using a servo-hydraulic system. The sample was cyclically loaded, using a sinusoidal waveform, at a frequency of 10 Hz. Crack length and load-line displacement were logged continuously using pulsed direct current potential drop (DCPD) and a clip gauge methods respectively. A direct visual measurement of crack length was made independently using a travelling microscope. A 'dry' ultrasonic C-scanner was used to provide a record of internal delamination zone development.

The interrogation system was configured to track individual gratings for a period 1.1 seconds, and sampled at a frequency of approximately 200 Hz, thereby allowing the strain to be tracked continuously. Figure 5 shows results when optimised for a sinusoidal external excitation of 10 Hz.

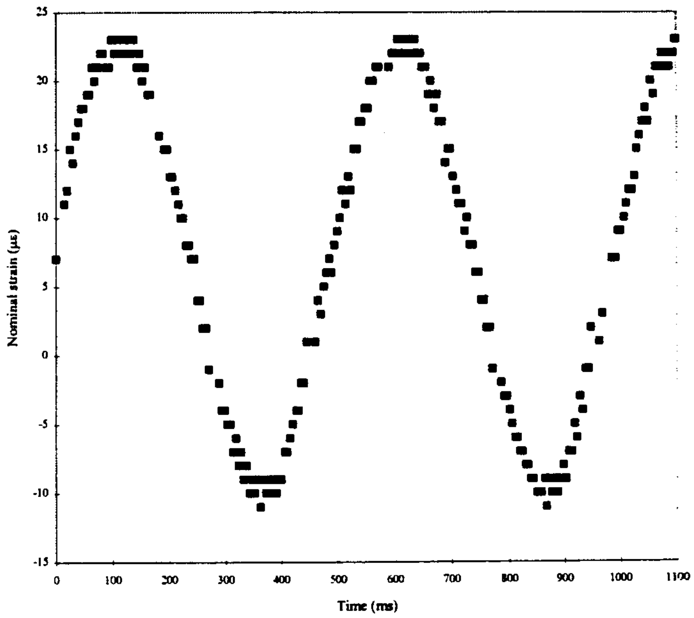


Figure 5. Measured strain in sample (prior to calibration) when stressed at a cyclic frequency of 2 Hz.

In 'logging' mode, data for the fatigue crack growth studies were recorded at intervals of 100 seconds. The logging process involved continuously switching the fibre selection switch between measurement lines, scanning each line to assess peak wavelengths, followed by sequential lock-in and tracking of individual gratings. To monitor the entire grid required a total period of approximately 90 seconds. Compared to the complete fatigue crack growth test duration of typically 7 days, this 90 second scan time generated an essentially instantaneous record of strain across the 20 x 20 mm square area over which the gratings were distributed.

For the purposes of our present fatigue crack growth investigation a continuous record of strain was not required, instead maxima and minima were stored and used to calculate the strain amplitude.

CONCLUSIONS

We have demonstrated an interrogation system for the tracking of multiple fibre gratings which provides a convenient frequency output. Static and dynamic changes have been tracked in surface-mounted and embedded gratings. The system may operate with transmissive and reflective optical configurations. Gratings at different wavelengths may be situated either along one fibre or along different fibres.

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