Intragrating strain sensing using a chirped FBG and an integration method

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Abstract — Localised strain measurements of a notched aluminium specimen, in which intensity reflection spectra from a chirped fibre Bragg grating (FBG) were processed using an integration method, were in agreement with a finite element method calculation.

I. INTRODUCTION

Fibre Bragg gratings sensors (FBGs) \cite{1} are now in widespread use for the measurement of strain and temperature, or both, in a wide range of application areas. Furthermore, FBGs offer the very considerable advantage that it is straightforward to multiplex a significant number of FBGs of different wavelengths, along a single fibre, to obtain point readings at a number of locations \cite{2}. This is ideal for situations in which information on measurands is required at multiple locations over a large region or distance.

Intragrating sensing, on the other hand, is the process of obtaining a continuous profile of strain or temperature within a single fibre Bragg grating \cite{2-4}. This can be accomplished by applying appropriate transforms to complex phase and amplitude spectra through the use of specialised equipment \cite{5-6}. Techniques for intragrating sensing based on conventional FBGs have had varying degree of success \cite{2-4}. One way to overcome problems associated with conventional FBGs is to use chirped fibre Bragg gratings (CFBGs). The chirp rate within the CFBG will affect its performance including the precision and spatial resolution. Chirped gratings enable non-monotonic field profiles and peak localised strain and temperature to be measured and also increase the spatial resolution of the measurement \cite{2}. Prior work on determining intragrating temperature profiles using a hypothesis profile and employing transfer matrix or Fourier grating models require the shape of the temperature profile to be conjectured and programmed \cite{7-8}. Recently, we applied an integration method to operate only on a chirped fibre Bragg grating (CFBG) without the requirement for prior knowledge of the shape of a hypothesis temperature profile \cite{9}. In the method, which has been used to analyse a temperature hot-spot \cite{9} and a temperature step \cite{10}, the known chirp of the grating provides the means to associate each wavelength in the FBG spectrum with a location along the sensor \cite{9}.

Much of the interest in intragrating strain sensing relates to applications such as crack detection or identifying conditions within a structure prior to the occurrence of structural failure. The use of strain sensors, particularly those based on fibre Bragg gratings, involves the detection of changes in the strain field, in which sensors have to be arranged carefully within a structure in locations where structural degradation is anticipated.

This paper reports on the use of a CFBG that was bonded to an aluminium test specimen containing two thin rectangular notches; this specimen was subjected to a range of longitudinal stresses. From the CFBG reflection spectra the strain distribution was deduced using our integration method \cite{9}. The use of finite element method (FEM) modelling confirmed the strain profiles determined.

II. METHODOLOGY

The CFBGs used in this investigation were fabricated in stripped hydrogen-loaded Corning SMF-28 telecommunications fibre with a linear chirped phase mask using a scanning FBG fabrication system. The phase mask had a centre pitch of $A = 1.0665 \mu$m and chirp rate of $(dN/dz) = 12.6 \text{ nm/cm}$. A piezo phase mask shaker was used to flatten the average refractive index at the ends of the apodised sensors, which have lengths of 15 mm. The sensors were annealed at 330 °C for 150 s to prevent subsequent shift in the spectra due to out-diffusion of H$_2$ and were calibrated for temperature and strain. The reflected spectra, $R(\lambda)$, were normalised to 14.6 dB above an average measured reflection spectrum of an FC/PC connector, through a 3 dB, 1550 nm ETEK 70070002 coupler \cite{8}.

Aluminium specimens of rectangular cross-section having approximate dimensions of 350 mm $\times$ 12 mm $\times$ 6 mm containing a machined notch at the centre of the specimen were used as shown in Fig. 1(a). The pair of rectangular (with a circular tip) notches of dimensions (width 1 mm, depth 3 mm) generated a strain gradient along the axial direction of the specimen. The notch shape was selected for its close resemblance to a crack in a structure. A shallow slot of 0.5 mm in diameter machined on the surface (along the centre of the axial direction) of the specimen was used to embed each sensor at the geometrical centre of the notch using Locite

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Fixmaster (97483). The epoxy was allowed to cure for 4 days at room temperature; a small tension was applied to the fibre to prevent it from curving during the curing period.

Fig. 1(b) shows a schematic of the mechanical and optical arrangements; the latter being similar to that used previously [8-10]. The CFBG sensor was monitored in reflection using an Er3+ dual-band broadband (EBS-7210) light source via a 3-dB 1550 nm coupler. The reference and disturbed spectra were measured using an OSA with a resolution of 0.05 nm and saved on a computer. The specimen was subjected to a range of controlled static tensile loads using a materials testing machine. The load was displacement controlled by means of the supporting frame attached to the actuator shaft of the machine, allowing the applied load and the displacement to be electronically measured. As axial tensile forces ranging from 0.5 kN to 8.0 kN in steps of 0.5 kN were applied, reflection spectra from the CFBG sensor were recorded. For each applied load 50 repeat spectral measurements were obtained to provide an average suitable for analysis.

(a)

(b)

Fig. 1. Schematic diagram of (a) the aluminium specimen and (b) the experimental system for applying tensile load to a specimen.

The surface strain distribution along the specimen was calculated using numerical structural FEM analysis employing FEMAP/NASTRAN software. A 2-D model, based on the linear elasticity theory of solid mechanics was chosen to simulate the strain distribution along the specimen subjected to an axial tensile force. Only one quarter of the specimen was modelled because of the symmetry of the problem along the two directions. The mesh consisted of 6407 grid points (nodes) and 5976 rectangular elements.

III. RESULTS AND DISCUSSIONS

Fig. 2 shows an example of averaged reflected spectra obtained at various tensile loads. The spectra have characteristic dips and humps around the shape induced strain gradients. As expected, the local Bragg wavelengths around the notch shift to longer wavelengths and the grating chirp becomes nonlinear. The occurrence of two dips and humps suggests that there are two regions of peak strain on either side of the notch centre. The modified peak reflectance is approaching 80%, which justifies the use of gratings with low reflectance for measurements involving large gradients [8].

Fig. 2. Reflection spectra from the CFBG subjected to various tensile forces.

Fig. 3 shows the extracted strain profile as a function of position along the grating, obtained using the integration of difference technique, for various loads. A strain error of approximately 170 μɛ along the sensor length is estimated, the limiting factor being mainly the fluctuations in the applied load. The strain profiles obtained for each repeat measurement at a particular applied force were highly repeatable, with two regions of high strain being evident.

Fig. 3. The deduced strain profile as a function of position along the CFBG during load application.

Fig. 4 shows the extracted and the FEM simulated strain profiles around the notch at an applied force of 1.0 kN. There is good correlation between the measured and simulated curves. However, closer inspection shows that the experimental strain evaluated by the sensor is approximately 100 μɛ lower than that predicted by FEM calculations with the deviation being greater at the notch centre. This discrepancy is most likely to be due to incomplete transfer of
surface strain within the specimen through the 3-layers (host/adhesive/fibre) to the fibre core.

Fig. 4. The extracted and the FEM modelled strain profiles around the notch centre for the CFBG at an applied force of 1.0 kN.

IV. CONCLUSION

The measurement of a localised strain distribution with a CFBG, involving processing of power reflection spectra only and without the need for an initial strain distribution hypothesis, has been presented. The results compare favourably with a FEM simulation, although some discrepancies were noted. An intragrating sensor of this type is expected to find many applications in the area of structural health monitoring.

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