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Multiplexed Optical Fibre Strain Sensing by Cross-Correlation of Subcarrier Interferometric Spectra

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Abstract

A novel technique for evaluating strain in multiple long-length sections of optical fibre is described. Sections defined by reflective markers are interrogated with subcarrier interferometry. Path-length changes are monitored using cross-correlation. A resolution of 35μm has been obtained over 5m sensing sections, together with inter-section crosstalk levels below -45dB.

Indexing terms: Optical Fibre Sensors, Cross-Correlation, Subcarrier Interferometry

Introduction: Strain sensing in advanced composite structures has been achieved by interrogating optical fibres in the subcarrier frequency domain.[1-5] Inverse Fourier transformation of frequency domain data supplies a complete time-domain image, but requires both amplitude and phase information over a wide frequency range.[2] Fourier transform methods require interrogation frequencies above 100GHz to achieve spatial resolution suitable for sensors (below 1mm).

Reflective markers in the optical fibre may conveniently define the strain gauge size for use on smart structures. The markers result in nulls in the amplitude and phase spectra obtained from the fibre. The location of amplitude nulls provides sufficient information to evaluate the separation of the markers. Tracking the nulls using a lock-in technique was originally limited to two interfering subcarrier signals.[3] Recent work has extended this technique to interrogate many sensing sections using multiplexing, either in the wavelength[4] or the time domain.[5] We present an alternative technique to track the nulls using cross-correlation of amplitude spectra in the region of the null. Similar resolution to lock-in techniques has been achieved by simpler, commercially available electronic hardware. The presented system has a superior dynamic response to lock-in techniques and is multiplexed in the time domain.[5]

Technique: A null in the amplitude spectrum from two reflectors may be located by searching for the lowest amplitude value in the region of a null. Alternatively, the centroid of the data around the null may be found. Both of these methods give sub-optimum resolution. A null may be more accurately tracked by cross-correlation of a measured spectrum with an earlier reference spectrum. Cross-correlation with the reference is equivalent to detection with a matched filter, which is known to give optimal performance in the presence of white noise.[6]

The spectrum from the unstrained fibre is used as the reference to locate the null in subsequent spectra. A recorded spectrum from a strained fibre is processed by shifting it in discrete frequency steps and cross-correlating it after each shift with the spectrum from the unstrained fibre. The shift with the highest correlation corresponds to the frequency shift of the null from its unstrained position. By subtracting the frequency of the same null in two different spectra[3], the extension x can be related to the frequency shift δf by

$$x = \frac{-\Delta}{1 + \frac{(1+2n)v}{4\Delta\ \delta f}}$$

where n is the order of the null, v is the velocity of light in the fibre and Δ is the unstrained marker separation.

The similarity of the two spectra was quantified using Pearson's correlation coefficient ρ

$$\rho = \frac{\sum_{i=1}^{N} (x_i - m_x)(y_i - m_y)}{\sqrt{\sum_{i=1}^{N} (x_i - m_x)^2 \sum_{i=1}^{N} (y_i - m_y)^2}}$$

where x and y are the N element vectors containing the amplitudes of the two spectra, with mean values m_x and m_y respectively.[7] Pearson's correlation coefficient was used as it compensates for different amplitude spectra. To provide higher accuracy, the centroid of the correlation peak rather than just its highest value is located, as the cross-correlation function is symmetrical about its peak. The spectral compression associated with the shift of the null has no influence on the location of the correlation peak.

Experiment and Results: A single mode fibre was constructed with three broadband TiO_2 reflectors, of approximately 3% reflectivity and a spacing of approximately 5m.[8] A commercial spectrum analyzer with an integrated tracking generator (Marconi Instruments type 2382) was used to interrogate the spectrum of the chosen sensing section. The spectrum was obtained over a frequency range of 5MHz, centred on 348MHz with a resolution bandwidth of 3kHz and a total acquisition time of 2s. Light was launched into the fibre using a Fabry-Perot laser (HP type LST2726, 1300nm, 1mW) and detected by a photodiode receiver (Epitaxx type ERM507FJ-S, bandwidth 1.9GHz). A time-division multiplexing scheme was used to select the chosen fibre section (Fig.1).[5] Different fibre sections were monitored by changing the timing of the control pulses to the switches.

The spectrum of the unstrained fibre was stored in a computer and compared with subsequent spectra from the fibre as the selected sensing section was strained in 1mm steps. The correlation curve produced for a 2mm extension is shown in Fig.2. A cutoff level of 0.9995, below which all data was discarded, was chosen for the calculation of the centroids. The system was found to track the fibre strain well (Fig.3), showing an apparent strain coefficient (optical path length change per actual length change) of 0.76 and an RMS noise equivalent strain level of 35µm.

Crosstalk measurements were performed by straining one fibre section while interrogating an adjacent unstrained section. When a 6mm extension was applied to the second section, there was no measured extension of the first section above the system noise level of 35µm. Taking the system noise level as a worst-case approximation of the detected extension, the crosstalk is below -45dB.

Discussion: Using this system, accurate interrogation is possible with just standard electronic measurement equipment and a time-gated optical communication link. Similar resolution was achieved to lock-in systems of the same bandwidth. The dynamic response and the accuracy of the new system may be controlled by the software and may thus be changed without adapting the hardware. Unlike the integrating feedback loop in the lock-in systems, this system has no memory. Large step changes in length, for example when switching to monitor a different sensing section, are therefore tracked within a single scan.

Conclusions: A new method for interrogating optical path length in multiple sections of an optical fibre has been demonstrated. The system has an RMS noise-equivalent strain of 35µm over 5m sensing sections with a 2 second measurement time and inter-section crosstalk levels better than -45dB. Software controls the dynamic response and the accuracy. Only simple electronics are required to interrogate the subcarrier amplitude response over a narrow frequency range. A dedicated system, using a voltage controlled oscillator and a simple AM demodulator could replace the spectrum analyser to provide a practical low-cost method of multiplexed high-resolution strain sensing.

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Figure Captions

Fig.1 Schematic diagram of the interrogation system

Fig.2 Correlation curve for an extension of 2mm

Fig.3 System performance