Multiplexed Fibre-Optic System for Both Local and Spatially-Averaged Strain Monitoring

H Geiger[a], M G Xu[a], M A Longstaff-Tyrell[a], J P Dakin[a], N C Eaton[b], P J Chivers[c]

[a] Optical Fibre Group, Department of Electronics & Computer Science, University of Southampton, Southampton SO17 1BJ, UK; Email: hg@orc.soton.ac.uk

[b] Consultant to Westland Aerospace, 16 Kings Road, East Cowes PO32 6SE, UK

[c] Westland Aerospace, East Cowes PO32 6RH, UK

Abstract

An optical fibre sensor system to interrogate point sensors (Bragg gratings) and optical path length between point sensors is discussed. The paper describes interrogation schemes capable of measurement resolutions better than 100 microstrain based on simple optics, telecommunications electronics and sophisticated signal processing.

1 Introduction

Sensor systems are an essential component of smart structures in order to provide information to the control system.[1] To control smart structures effectively, the sensor provides information (strain, temperature etc) in both a localised and a spatially-averaged manner. The ideal optical fibre sensor would be a *distributed* sensor,[2] but this is still difficult to achieve with a realistic level of hardware. We present an approach combining both point sensors and long gauge-length sensors in a *multiplexed* sensor system, providing information almost as valuable as a distributed sensor system.

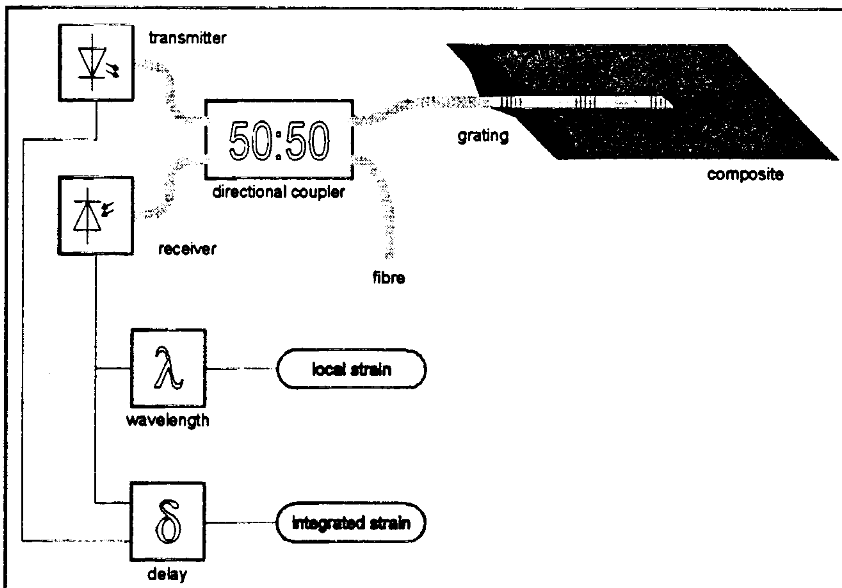

Fig 1: Multiplexed sensor system to resolve local and spatially-averaged strain

Our sensing system (Fig 1) combines Bragg gratings[3] to interrogate points with an *Optical Time Domain Reflectometry* (OTDR) system to interrogate the distance between the gratings. The mechanical and thermal environment **around** the gratings changes the reflected wavelength, and the environment **between** the gratings changes the time delay between the reflected signals. The fibre-optic probe is mechanically small (≈ 150 μm outer diameter) and of continuously cylindrical shape. It can be embedded in both civil structures and composites and does not degrade the mechanical properties of the structure.[4]

Development of this system has concentrated on two aspects: a system to monitor the wavelength of multiple gratings (short gauge-length sensor) and a precision OTDR to monitor the optical path length between these sensors (long gauge-length sensor).

2 SHORT GAUGE-LENGTH SENSOR

Various schemes to detect small wavelength shifts of Bragg gratings have been developed. These include the filter-edge demodulation method where the edge of a filter or a wavelength-division coupler is used to convert wavelength changes to amplitude variations,[5,6] interferometric approaches,[7,8] the use of frequency-locked grating pairs,[9] and laser-sensor concepts where the grating sensor determines the lasing frequency.[10]

However, all above methods have limitations when it is desired to interrogate the wavelength of many gratings in a frequency-agile manner. In this paper we present advances on our method of constructing an interrogating system for fibre Bragg grating sensors using an *acousto-optic tunable filter* (AOTF).[11]

2.1 Grating Interrogation Scheme

Operation of our dedicated interrogation system (Fig 2) is similar to the system we proposed earlier[11]: A grating is illuminated with a broadband source, thereby filtering the light at the Bragg wavelength λ_p. This band-filtered light is then coupled through the acousto-optic tunable filter onto a suitable photodiode.

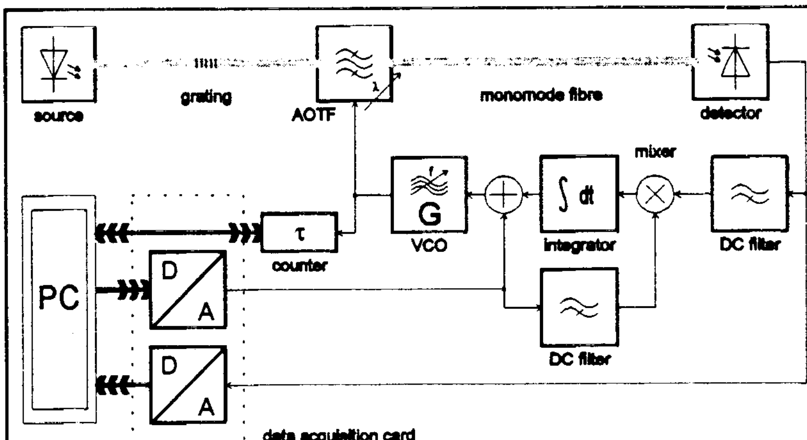

Fig 2: Grating interrogation system, here for one grating in transverse mode

An AOTF is a narrow-band optical bandpass filter whose centre wavelength λ_{AOTF} depends on an applied RF frequency.[12] By sweeping the RF frequency, the detector records the spectrum of the source filtered at λ_p. This is similar to the function of an optical spectrum analyser.

The PC generates a square wave with DC offset, toggling a *voltage-controlled oscillator* (VCO) between two RF frequencies. The VCO then toggles the AOTF between two optical wavelengths.[13] When the modulating square wave is mixed with the resulting AC signal from the detector, an error signal occurs if the mean AOTF wavelength does not correspond to λ_p. The sign of the error signal indicates whether the mean wavelength is above or below λ_p. If the error signal is integrated and added to the square wave, the mean AOTF wavelength is locked to λ_p. The mean RF frequency measured by the counter hence indicates the Bragg wavelength.

2.2 Modes of Operation

The circuit can operate in two different modes:

1) *scan mode*: Here the feedback circuitry is not connected and hence the PC can scan the AOTF. From the detector signal the PC can identify the VCO voltage corresponding to the grating wavelength λ_p.
2) *lock-in mode*: In this mode the PC sets the DC offset of the VCO voltage so that the AOTF wavelength is within the grating bandwidth. Then the feedback is closed and the circuit locks onto the Bragg wavelength and tracks it.

The system has scope for interrogating multiple gratings at different wavelengths either (i) simultaneously using the scan mode or (ii) in time-division multiplexing using the lock-in mode. The AOTF can also be driven by the VCOs of multiple feedback circuits in lock-in mode to track multiple gratings simultaneously.

The VCO and the frequency counter have been built and tested in scan mode with a quartz filter simulating the optical system. The software interface for the scan mode has also been developed. Computed results based on earlier measurements[11] predict a scale factor of -98 Hz/$\mu\varepsilon$[†].

3 Long Gauge-Length Sensor

Our precision *Optical Time Domain Reflectometry (OTDR)* system uses hardware already developed for telecommunications. Such an OTDR should form a suitable basis for practical sensing systems. It allows monitoring the range of reflective markers on optical fibres,[14,15] which can then be related to strain or temperature of the fibre.[16]

To enhance the range resolution of conventional OTDR, our system design uses a modified **electrically** coherent receiver[‡] (*correlator*) to detect the reflections from the fibre. Conventional OTDR uses a delay in the correlator that can only be switched in discrete steps, usually in multiples of the pulse duration. We report a method to improve range resolution by sweeping the delay continuously. We use the triangular shape of the autocorrelation function of a pulse to measure the time delay (ie optical range) of reflected signals more accurately.

3.1 Theoretical Background

An OTDR measures the reflections from an optical fibre[17] to characterise attenuation and reflective points along the fibre. Optical pulses of length τ and periodicity T (Fig 3, top left) are sent into the fibre and the returned power is monitored by an electrically coherent receiver. The output of the coherent receiver is the crosscorrelation between transmitted pulse and received signal.

If there is only one reflective point on the fibre, the output of the coherent receiver is approximately proportional to the autocorrelation of the transmitted signal (Fig 3, bottom left). If two or more pulses are received (eg from multiple reflections) the OTDR response has the form of a crosscorrelation (Fig 3, bottom right) between the two upper traces in Fig 3.

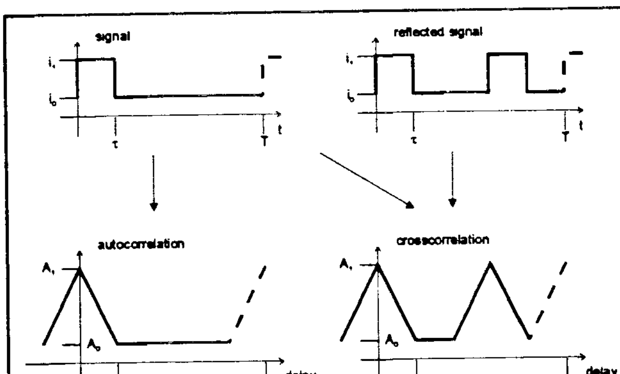

Fig 3: Correlation of a pulse of length τ with itself (*autocorrelation*) and with two similar pulses (*crosscorrelation*)

For many sensor systems a typical OTDR spatial resolution of 1-10 m is sufficient, but there is a need to monitor each reflective point with a range accuracy below 1 mm. Our current technique overcomes this problem by interrogating the slopes of the correlation peak.[††] These slopes (bottom of Fig 3) are normally not used because receivers of OTDRs do not allow a continuous sweep of the output.

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† microstrain

‡ *matched filter* or *correlation detector*, to be distinguished from **optically** coherent (ie interferometric) receivers, as used eg in *coherent OTDR*

†† UK patent application 9407077.8

3.2 OTDR Interrogation Scheme

In the system in Fig 4, a digital signal intensity-modulates a 780 nm CD-type laser and is received by a fast silicon photodiode. Integrated circuits for fast telecommunication links support the electro-optic design.[18]

A PC controls the high-resolution delay system and acquires the output from the coherent receiver. Hence any receiver output can be converted to the corresponding delay, and only data from the regions of interest (ie the slopes of the peaks) need to be acquired.

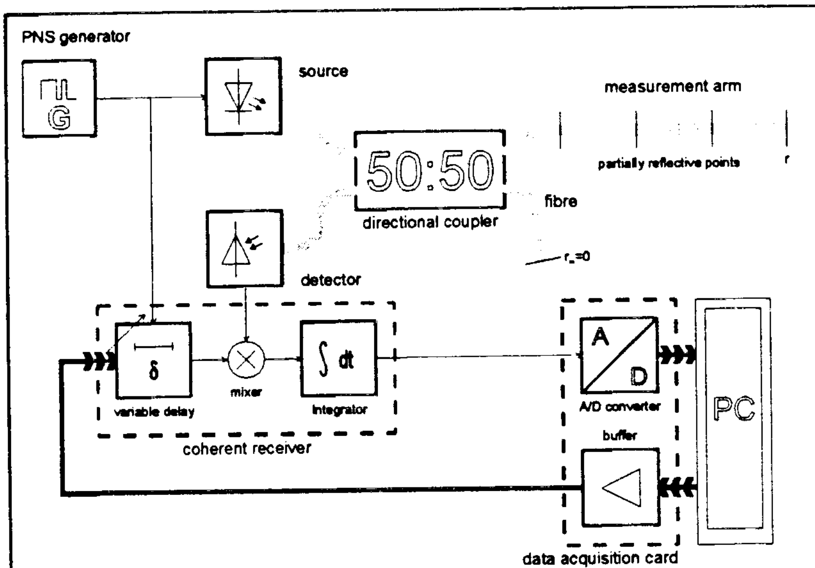

Fig 4: Computer-controlled OTDR system using high-resolution variable delay

The PC varies the delay over the region of interest whilst acquiring the receiver output. Then it detects the peaks in the receiver output and curve-fits a line to either slope of every received peak. The delay corresponding to the intercept of each peak's slopes is the time delay from that particular reflection.

Use of a *pseudo-random binary sequence (PRBS)* improves the duty cycle and hence the signal-to-noise ratio.[19] Because the technique relies solely on delay information, it is insensitive to both amplitude and polarisation changes. In other approaches, amplitude changes may either limit the performance[20] or force the use of more complex coding schemes.[21,22] Radial strain in the optical fibre could cause problems in polarisation-based systems.

This system shows, as an example, a reflection from 12.183685 m range with a standard deviation of 440 μm (≈ 36 ppm) within a measurement time of 1 sec.

4 Conclusions

We have presented a general concept combining point sensors with long-gauge length sensors to produce a versatile monitoring system for short and long gauge lengths.

As a short gauge-length sensor we discussed a Bragg grating interrogation scheme capable of addressing multiple gratings. The long gauge-length sensor described is a precision OTDR system monitoring the difference between multiple reflective points.

Both schemes have demonstrated high accuracy and should be suitable for monitoring both static and dynamic signals. Each approach uses a simple optical setup and sophisticated signal processing to achieve a robust sensor system.

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