INVITED

2442

STRUCTURAL MONITORING WORK AT SOUTHAMPTON UNIVERSITY USING FIBRE GRATING SENSORS

J.P.Dakin, M.Volanthen, M. Mowlem, L. Dokos
Optoelectronics Research Centre, University of Southampton, SO17 1BJ, England. jpd@orc.soton.ac.uk

Abstract

A review of distributed and multiplexed sensor technology and applications, based on fibre gratings, is given. This is followed by more specific details of work undertaken at the University of Southampton. The paper includes a short discussion of the problems that must be avoided in order to construct viable systems for engineering requirements.

Review: Fibre Bragg grating sensors are narrowband reflective filters, which are formed by periodic variations of refractive index in the core of an optical fibre, written using UV light. They allow sensor encoding as peak reflected wavelength and have been used to measure many physical parameters including strain, temperature and pressure. They are readily multiplexed, hence enabling the spatial distribution of a measurand to be sampled. Simultaneous measurement of several parameters is facilitated by linear regression.

More recent techniques have provided continuous distributed spatial information in (multiplexed) long Bragg gratings, with resolution below 1mm.

Multiplexed interrogation can be achieved using any of the following approaches, usually by monitoring light reflected from sensor arrays:-

a) Broadband source and a spectrum analyser
b) A scanned optical source and a fixed detector
c) An active grating system (e.g. Distributed Feed Back (DFB) lasers) and a spectrum analyser.

Grating sensors are most commonly multiplexed in the wavelength domain, but the time domain (propagation delays) and the coherence domain (matching white-light interferometers) are also used. Using an optical switch to select fibre lines can also increase sensor numbers.

Recent research on fibre grating sensors has concentrated on the production of either low-cost, compact, or high-accuracy interrogation systems. A number of solutions have been published.

Active (lasing) grating systems offer greater resolution, as the optical intensity is orders of magnitude higher. Care must be taken however to avoid of self-heating effects.

Several sensor systems have been devised to measure the average strain in long sections of fibre between reflective markers, Bragg gratings offer an easy means of forming an array of reflective markers in a fibre.

Sensing of grating wavelength (and hence measurand) is now possible as a function of position. Such distributed sensors provide a high-resolution measurement with no dead-zones.

Work at the University of Southampton:

Grating Fabrication: On-line grating fabrication during the pulling of fibres has been demonstrated. This holographic technique (utilising converging UV beams from a 20ns-duration excimer laser pulse) not only gives advantages in cost and speed of production but also provides a dramatic improvement in the mechanical strength of gratings, as the pristine nature of the outer silica surface is not degraded.

Long fibre gratings for distributed sensing are also fabricated in a sophisticated inscription system, capable of making gratings with any desired pre-programmed wavelength chirp up to 1m in length.

Multiplexed addressing: Our techniques for interrogating gratings use an acousto-optic tuneable filter, or AOTF. This has a typical bandwidth of 0.5 to 3nm, a wavelength range of over an octave, and is frequency-agile, with a typical reaction time of 10 μs. Centre wavelength and transmission are regulated by RF frequency and amplitude respectively. It can also be driven simultaneously at more than one RF frequency, to give several independently tuneable passbands.

Two methods of tracking grating wavelengths have been developed using an AOTF. The first uses a broadband source to illuminate the sensor array and places the AOTF before the detector. By dithering the wavelength of the AOTF, its peak transmission wavelength is locked on to track the wavelength of a grating giving $0.18\mu\varepsilon/\sqrt{Hz}$ accuracy with early versions. Simultaneous closed-loop interrogation of gratings has also been demonstrated using this interrogation arrangement and different FSK dither frequencies for each grating. The crosstalk was measured to be below the system noise floor.

The second interrogation system, consists of a precision narrow band tuneable source. Grating wavelengths are calculated from the amplitude of the reflected light at a number of strategically chosen wavelengths, resulting in a sample frequency of 5kHz (for a single grating) and the ability to track a large number of gratings virtually simultaneously with a resolution of $0.1\mu\varepsilon/\sqrt{Hz}$.

Strain monitoring experiments utilising paired sensors, either co-located but having different sensitivities to temperature and strain, or located opposite each other and equidistant from a beams neutral axis, have allowed the determination of temperature and strain. The first method exploits the differing variation of photoelastic and the thermo-optic coefficients with wavelength.

The first interrogation system configuration has recently been used in a series of routine tests for monitoring of destructive fatigue cracks in CARRAL, as part of an evaluation for aerospace applications. Gratings within the CFRP layer (when measured relative to a reference to calibrate for AOTF drift) measured a strain field that correlated well with the observed spread of the crack and resulting delaminations in the panel.

Impact experiments also indicate that this system is also suitable for the measurement of hypervelocity impact damage for spacecraft applications and for low velocity impact damage with impact energy as low as 0.6Joules.

Bragg Gratings as distance markers: We have recently used gratings to measure the average strain in long sections of fibre between reflective markers using the LIDAR (Light Detecting And Ranging) concept, i.e. an optical-time-domain sensor system monitoring light reflected back from a series of markers in a fibre.

We have also proposed using a novel sub-carrier fibre grating sensor (SFG), a widely spaced periodic array of reflective Bragg gratings which is resonant at a series of RF eigenfrequencies, the value of which is determined by the spacing of the reflectors.

Sensing in the coherence domain: Sensing pairs of matched-wavelength gratings, each with different spatial separations were interrogated using a scanning Michelson interferometer. When its path imbalance approximated the separation of the gratings, a burst of interference fringes was observed. Each burst can contain several hundred fringes, allowing accurate processing. The grating wavelengths are derived from the fringe-passing frequency and the path imbalance from the peak of the fringe envelope. By combining this method with WDM and TDM, very large numbers of grating pairs may be interrogated.

Distributed interrogation: Distributed grating sensors have many advantages, including high spatial resolution (~0.5mm) and no dead-zones. We have demonstrated a novel, broadband interrogation system for distributed measurement of long-length grating sensors, capable of measuring arbitrary strain fields over several tens of cms to high spatial resolution. Our most comprehensive demonstration was that of measuring the spectral and spatial dimensions of two co-located (in terms of optical distance) gratings

Active (Lasing) Grating Sensors: Our preferred system uses DFB fibre lasers. These are formed by a grating, with an internal phase, step in written in a short (typically 50mm) highly-Er^+-doped section of fibre. When pumped by a suitable laser diode (980 or 1480nm) output in the 1550nm region is obtained. This output is effected by a number of measurands (c.f. Bragg gratings). Use of birefringent fibres allows the simultaneous generation of two lasing outputs from each laser, giving the possibility of heterodyning the outputs to give an RF difference-signal output (typically up to 1.2GHz). Such a high radio frequency can be measured with great precision. In addition, the absolute wavelength of each lasing output can be measured to allow linear regression to be used for the simultaneous determination of temperature and strain.

Design considerations: Gratings offer substantial advantages over conventional electrical sensors (e.g. resistive strain gauges), in that they are essentially immune to many of the problems associated with these (E.g.: E-M interference, lightning strikes, earth-loops, corrosion, electrolytes etc.) Particular attention must, however, be paid to the following aspects:

Spectral overlap of gratings: If gratings in a multiplexed system have overlapping spectra, then there will be crosstalk. Additional care is needed if all the gratings are in line in a single fibre, as problems arising from spectral shadowing (i.e. filtering effects of the light passing twice through any gratings which are nearer to the interrogation system than the grating it is desired to interrogate) may occur. If the reflection of the gratings is high effects due to multiple reflections may also become significant.

Sidebands in the measured gratings, the interrogation filter or the tuneable light source: The effects of sidebands in any of the measured gratings, in a tuneable filter (e.g. AOTF, Fabry-Perot, etc.) or tuneable source used to interrogate a grating array will lead to measurement errors, if the sidebands overlap the response from an adjacent grating.

Changes in grating spectrum: Non uniform measurand fields result in the narrowband reflective spectrum of the grating being lost. The spectrum will broaden and may become significantly asymmetrical and irregular. This will increase the possibility of crosstalk and may lead to severe errors if the peak reflective wavelength is measured. Centroid measurement will give a better measure of the true mean level of strain in the grating.

Wavelength dependent optical components: Broad spectral gradients may give small errors (which may be removed by calibration under some circumstances) in absolute wavelength. However any temporal variation in gradient will result in inaccuracy.

Sharper wavelength dependencies are not uncommon in a number of optical components, and are often susceptible to large variation due to various noise sources. However careful optical design and high manufacture standards can dramatically reduce the effect of a number of these phenomena.

Polarisation-dependent changes: Fibre Bragg gratings are inherently birefringent (ie. their properties vary with polarisation state of incident light), partly due to the mode of their creation (UV illumination from one side) and also due to any birefringence in the fibre in which they are written. Additional birefringence can be induced if transverse deformation occurs (often occurs when mounting in a composite). A number of optical components are unfortunately polarisation sensitive or selective (including most standard fibre, when coiled or bent) which can result in significant measurement inaccuracy due to polarisation effects. Polarisation scrambling has been used to reduce this effect.