Distributed Optical Fibre Sensors

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This paper presents a summary review of the field of distributed optical fibre sensors. The basic principles are outlined and the direction of recent development in the field is indicated. The verbal presentation will be illustrated with slides showing some recent engineering applications. No attempt has been made to cover all of the developments in this extensive field. Instead, a brief overview is given, with a more comprehensive list of references and bibliography included for further reading.

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The Advantages of Distributed Operation

The commercial viability of optical fibre sensors in the real world depends greatly on their intended application. The cost of the optical interrogation terminal, relative to conventional electronic systems, will often render a non-multiplexed sensor uneconomic, except where there are other over-riding factors which favour the optical fibre approach. With multiplexed or distributed sensors, however, the economic equation becomes more dependent on the cost of the passive optical cabling network, an area where optical fibres are becoming ever more competitive, compared to electrical systems, and where the non-interactive nature and small size of the optical cable confers real advantages.

Principles and Applications of Distributed Sensors

The majority of distributed sensors are based on the concept of optical-time-domain-reflectometry, (OTDR), or analogous methods, involving either a different form of optical processing (eg optical-frequency-domain-reflectometry, OFDR), or inelastic scattering processes in the fibre (eg Raman scattering OTDR). The basic (Rayleigh-Scattering) OTDR instrument has been widely used as an instrument for the interrogation of fibre integrity, since its invention by Barnowski et al. Its mode of application can be changed to interrogate a number of distributed or multiplexed sensors, where the scattering or the attenuation of the fibre is modified by the physical quantity to be measured.

examples:

(a)The temperature of liquid-filled fibres, where the scattering coefficient is changed [Hartog & Payne (1982)].

(b) Cable microbending losses [Oscroft 1987, Fibre cable is commercial product from Herga Electric, U.K.].

(c) Ionising radiation, detected from the increased fibre attenuation [Gaebler & Braunig (1983)].

(d) The temperature of polymer-clad silica fibres, where the fibre N.A. is reduced by spillage of cryogenic liquids [Pinchbeck & Kitchen (1985)]

Historically, the first paper to suggest distributed sensing of **external** parameters, using Rayleigh OTDR in fibres, was by Rogers (1980), who envisaged its use for sensing the state of polarisation of light (POTDR) from different parts of a continuous fibre .

The Raman OTDR [Dakin(1985 a & b)] is the first inelastic scattering method to find real use in engineering applications. (This method has since been developed as a commercial product by Hartog of York VSOP) The linear-scattering OTDR methods have the advantage of relative simplicity and inherent linearity. The linear Raman scattering method, however, has the disadvantage of a relatively small scattering cross-section, and considerable signal averaging is necessary to extract a low-noise thermal signature of the fibre. Methods which rely on a non-linear scattering mechanism [eg. Raman amplification (Farries & Rogers 1984)] offer the potential of enhanced sensitivity, but are vulnerable to problems arising from the non-linear power dependence of the signal on the pump power. This may lead to problems in calibration if the pump power changes.

Several recent inelastic-scattering OTDR papers have examined the application of Stimulated Brillouin scattering to distributed measurement [eg: Culverhouse et al (1989)]. The scattering cross section is significantly greater than that of Raman scattering, but there are two main disadvantages. Firstly, the distance resolution is limited to several tens of metres, because of the time delay in the creation of the optically-induced acoustic wave. Secondly, the Brillouin lines tend to be relatively narrow, and are situated very close to the central, elastic, Rayleigh scattering peak. Thus, extremely narrow-band filters (or more-complex coherent optical detection methods) must be used to separate out the Brillouin signals.

The linear, inelastic, scattering mechanism having the greatest potential for a strong OTDR signal return is that of fluorescence. Using a fibre with a fluorescent core material, excited by a laser pulse on a suitable absorption line, [Dakin (1984)] the fluorescent signal return may be much higher than for a Rayleigh scattered signal, albeit at a price of higher fibre attenuation. However, unfortunately all the glass fibre dopants which have a high fluorescent quantum efficiency also appear to have a long fluorescent lifetime, and hence the spatial resolution would be poor. This is not expected to be so for organic dyes in polymer materials [Dakin (1987)]. However, in this medium, the high fibre attenuation and the high modal dispersion are likely to preclude operation over more than a few tens of metres.

One of the most attractive future applications of distributed sensors will be in the area of chemical sensing. The major difficulties are in achieving reliable, reproduceable, reversible and stable operation in real-world environments. Lieberman et al (1989) have published early work on distributed oxygen sensors containing fluorescent dopants in a polymer optical cladding. The technique shows great promise for chemical sensing using the fluorescent dye as an indicator, provided the likely sensitivity to temperature, water vapour, surface contamination etc can be solved. Blyler et al (1988) have published similar results on the detection of ammonia.

Another application area of distributed sensors is in the detection and location of mechanical disturbance or intrusion. The Rayleigh OTDR method, in conjunction with a pressure-sensitive cable, is one of the simplest methods. However, interferometric methods should be capable of more sensitive detection of small disturbances. The method of Franks et al (1986) utilises the mode mixing between orthoganally-polarised co-propagating modes in a polarisation-maintaining (Hi-Bi) fibre to locate the disturbance. The method of Dakin, Pearce et al (1987) uses a fibre Sagnac interferometer arrangement, with counter-propagating light energy, to locate disturbances causing a relative phase change between the propagating light beams.

It is unfortunately not possible, in the short space available here, to do justice to all the methods suggested for distributed sensors. New methods are evolving rapidly, and there is still a great deal of scope for imaginative research and for down-to-Earth engineering application. Popular directions of current research are on Brillouin scattering systems, on systems monitoring beat-length in Hi-Bi fibres [Parvaneh et al (1990), this conference], and on coherence multiplexed schemes [egs: Kotrotsios & Parriaux (1989); Chen et al (1990), this conference]. The references below should provide a more extensive background for the interested reader.

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