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The Optics of Distributed Vibration Sensing

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SUMMARY

In distributed vibration sensing (DVS) - also known as distributed acoustic sensing (DAS) technology, an optical fibre is deployed in the borehole to be surveyed and is used to detect seismic waves originating from a source outside the well. Although the EAGE and SEG literature describes the results of using DVS for borehole seismic applications, essentially nothing has been written about the underlying optical technology in the geophysics technical literature. This paper therefore outlines the main methods that are probably used by the main participants in the DVS activity, insofar as this can be deduced from publications in the field of fibre optics and the patent literature.

Introduction

The subject of distributed vibration sensing (DVS), also known as distributed acoustic sensing (DAS), using optical fibres has appeared in the geophysics literature in the last year or two (Barberan et al. 2012, Madsen et al. 2012, Mestayer et al. 2011, Mestayer et al. 2012, Miller et al. 2012), with contributions from oil companies, service companies and developers of instrumentation.

In the DVS (DAS) technology, an optical fibre is deployed in the borehole to be surveyed and is used to detect seismic waves originating from a source outside the well. Although the available references describe the *results* of using DVS for *inter alia* borehole seismic applications, essentially nothing has been written about the *underlying optical technology* in the geophysics technical literature. The purpose of this paper is, therefore, to outline the main methods that are probably used by the main participants in the DVS activity, insofar as this can be deduced from publications in the field of fibre optics and the patent literature.

Optical time-domain reflectometry (OTDR)

OTDR forms the basis for essentially all DVS systems used in borehole experiments. It was initially developed as a means of assessing the length dependence of losses (Barnoski and Jensen 1976) and other properties (Gold and Hartog 1982) of optical fibres. Its basic principle is that a short pulse (the probe pulse) of light is launched into an optical fibre. As the probe pulse travels along the fibre, it scatters, at each elemental section of fibre, a small amount of its energy in all directions. A small fraction of this light is recaptured by the waveguide in the return direction. A weak signal is thus received back at the launching end and generally has the form of an exponential decay as a result of the attenuation of the probe as it travels to the scattering point and back. Local variations of the backscatter waveform provide information on the optical fibre, at a location determined by the round-trip transit time from launching end to point of interest.

This process is similar to that of launching a tube wave down a borehole and observing reflections at discontinuities in the properties of the hole, the difference being that the light scatters from a myriad of microscopic (many times smaller than the wavelength) imperfections throughout the glass forming the fibre. This type of scattering is known as Rayleigh scattering and is the basis of DVS systems.

When the probe pulse has a wide spectrum, the light scattered within the section of fibre it occupies at any time (the resolution cell) is incoherent. In this case, there is no predictable phase relationship between the scattering occurring in the separate parts of the resolution cell, and the detector measures the total power scattered within the cone of acceptance of the optical fibre. Incoherent OTDRs allow loss distributions to be measured, but are not sufficiently sensitive for DVS applications, even when variants, such as polarisation analysis of the backscattered light, are considered.

At the other extreme, in a coherent OTDR (COTDR), the probe pulse is narrowband and is coherent throughout the resolution cell. In this case, there is a stable, although random, phase relationship between the contributions to the scattering signal from all parts of the resolution cell. This continues as long as the fibre is undistributed and the frequency of the laser is stable. The resultant signal is random in amplitude (Healey 1987) and, although not formally analysed, also in phase. These systems suffer from fading of the received wave, which occurs when the summation of backscattered electric fields from the different parts of a resolution cell sum to a very small total as a result of their phase relationships.

Amplitude-based DVS systems

In a COTDR, the total intensity is backscattered along the fibre, and a signal with a jagged appearance is obtained. However, the signal is extremely sensitive to disturbance (Juarez et al. 2005, Shatalin et al. 1998, Taylor and Lee 1993). A change in length of a few tens of nanometres over a resolution cell will be sufficient to substantially alter the signal level locally. These systems have been used in intrusion detection, for example. However, the response to a disturbance, such as strain in the fibre, is highly nonlinear, and the response also suffers from a second form of fading in which the derivative of intensity versus strain is small, even though the intensity of the scattered wave is sufficient to provide a reasonable signal-to-noise ratio. In spite of these difficulties, it is possible to classify a number of intrusion signals reliably. It is not known if this approach is used in borehole seismic applications.

Phase-based approaches

As noted above, the phase of the OTDR signal when probed with a coherent source is a function of the random disposition of the scattering elements within the resolution cell. However, disturbing a region of the fibre has two effects: locally, it alters the phase of the backscatter in an unpredictable manner, but it also alters the phase of all subsequent sections of the fibre completely linearly with respect to strain. Thus, by subtracting the phase of the light backscattered from two separate regions of the fibre, a quasi-linear signal is obtained. Phase-based DVS schemes must provide some form of interference process to sense the phase difference between the scattering originating in two different parts of the fibre. In the first two examples provided below, this reference is provided by interfering two versions of the backscatter signal with each other; in the third example, the backscatter is interfered with an external reference, similar to a one-dimensional holography process.

The earliest differential phase DVS system (Dakin and Lamb 1990) used a pair of pulses of slightly different frequency (f_1 and f_2) and duration τ, launched some time ΔT (typically 100 to 200 ns) (Figure 1). This is often achieved using an acousto-optic modulator (AOM) that simultaneously modulates the intensity of the light passing through it and shifts the frequency under electronic control. The separation of these pulses results in two backscatter waveforms which mix at the detector to produce a signal at their beat frequency $\Delta f = |f_1 - f_2|$, in addition to the baseband signal attributable to each of the probes individually. The component at the beat frequency results from backscatter from the first pulse at location z_1 mixing with that from the second pulse from location z_2, with $z_1 - z_2 = \Delta z = \Delta T.c/(2.N_1)$ where c is the speed of light in vacuum, and N_1 is the group refractive index of the fibre. Thus it contains a component of the random phase of each of the regions occupied by the two-probe pulse plus a term relating to the optical path between the two regions—the latter phase term is a linear function of fibre strain. The overall linearity of the system is proportional to $\Delta T/\tau$ and, with the right parameters, is sufficient for applications in geophysics such as stacking and correlation for frequency-swept sources. The technique was enhanced (Russell et al. 2008) by the addition of a number of features, such as wavelength diversity (to overcome fading) and optical amplification.

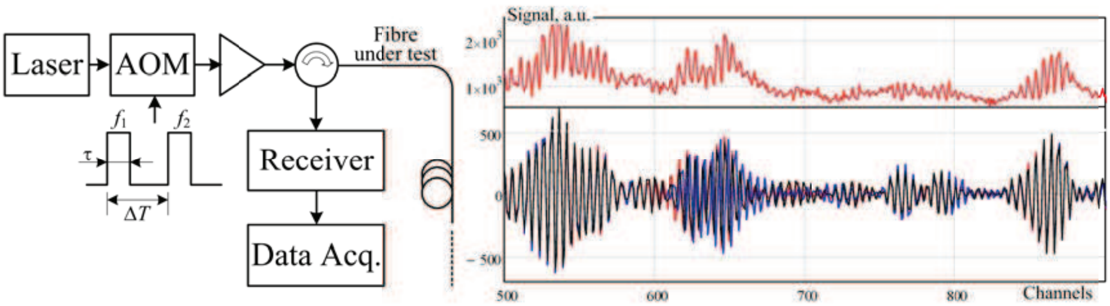

__Figure 1__ Schematic arrangement of a dual-pulse DVS system (left). A typical trace is shown as acquired (top right) for Δf = 60 MHz. Successive backscatter traces are shown (bottom right) after band-pass filtering. Note that a disturbance occurs in the second division, affecting the local signal.

A second approach (Figure 2), attributable to Posey et al. (2000), involves launching a single pulse, but comparing the relative phase of the backscatter from two locations in the fibre in an interferometer immediately prior to the optical detectors. On returning to the launching end, the signal is split into two paths of dissimilar length, and on recombining, the coupler allocates the optical energy to the output ports according to their phase relationship. The 3 × 3 coupler provides a nominal 120° phase shift between each of the outputs, and so by monitoring these outputs, the phase can be recovered. Farhadiroushan et al. (2010) later proposed a modified version of this approach, in particular using a fibre Michelson interferometer, rather than the Mach-Zehnder fibre interferometer (MZI) that is shown in Figure 2.

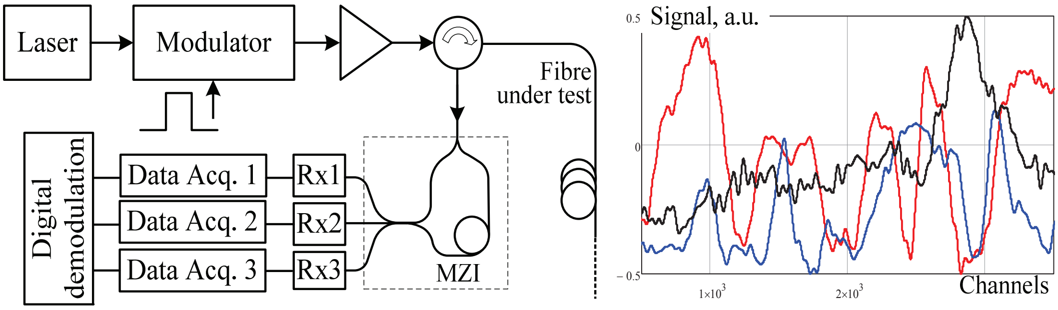

Figure 2 *Schematic arrangement and specimen signals for DVS system with interferometric phase demodulation.*

In the approach disclosed by Hartog and Kader (2012), the optical phase is first converted to the electrical domain using a coherent detection receiver, in which the backscatter signal is mixed at the optical receiver with a local oscillator tapped directly from the laser (Figure 3). Since the local oscillator is much stronger than the backscatter signal, the electrical current from the photodiodes at the receiver can usually be made sufficiently large that it dominates the thermal noise of the preamplifier, resulting in so-called shot-noise-limited performance. In this approach, the phase differentiation is carried out in the digital domain after acquisition, which, *inter alia*, allows the differentiation interval (i.e., the spatial resolution of the system) to be determined during processing rather than at acquisition time or when the equipment is manufactured.

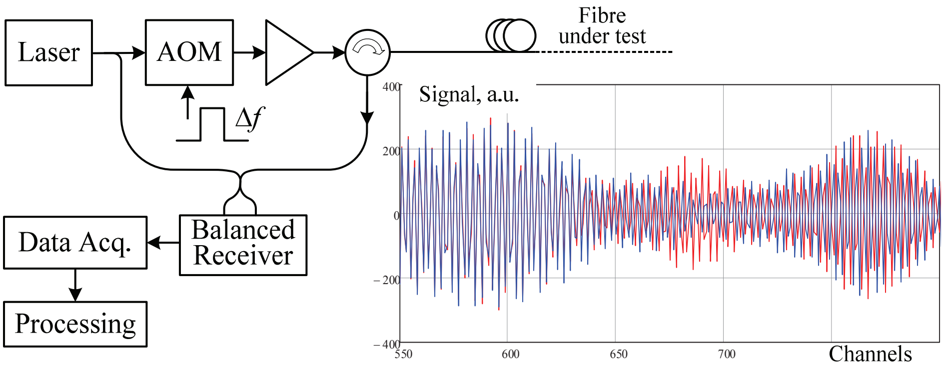

Figure 3 *Schematic arrangement and specimen signals DVS system with coherent optical detection.*

Discussion

At least three methods have been put forward for measuring, with some degree of linearity, DVS signals on optical fibres. All suffer from a reduction of linearity where the entire fibre is insonified, thus altering the intrinsic phase of the zones where the phase is sensed, with the linear contribution coming from the section of fibre between these zones. They also suffer from amplitude fading, but this can be alleviated very effectively with diversity, for example, probing the fibre simultaneously or on successive pulses with signals that have statistically independent fading characteristics.

Each of these approaches has demonstrated ability to acquire seismic signals in borehole applications, and there is insufficient data to allow a definitive determination of their relative merits. In addition, it is likely that instrumentation manufacturers will choose approaches that best match their particular competencies, and their choices are thus dictated as much by objective benefits as by their own strengths. It is not known which of these techniques is actually used by industry participants, because this has not been disclosed. Yet another approach, based on low-coherence interferometry (Sikora and Healey 2008) is not used in this context to our knowledge.

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