Design and deployment of a prototype multicomponent Distributed Acoustic Sensing loop array
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SUMMARY

In 2016-2017 a range of analyses and applications of a geometrical model of fibre-optic (DAS) data for arbitrary fibre shapes was described. Amongst those applications was a multicomponent estimation scheme based on a careful accounting, and combined usage, of the varying fibre directions associated with a shaped cable layout. In 2018 a prototype shaped DAS fibre array was buried at the Containment and Monitoring Institute Field Research Station in Newell County AB to put some of these ideas and their feasibility to the test. The loop was illuminated from several directions, and shot records were analyzed to assess if directional sensitivity is sufficient to permit multiple components of strain to be estimated simultaneously. By picking a P-wave arrival and comparing it to an analytic model, we conclude with a cautious “yes”. The size of the loop (roughly 10m on a side) was chosen to accommodate standard DAS gauge lengths; at this size, horizontal but not vertical strain rate components were sensed. Future designs for gauge lengths on the order of 2m will permit 6-component estimation.

INTRODUCTION

In 2016-2017 a geometric model was set up to support analyses of the directionality properties of Distributed Acoustic Sensing (DAS) fibre-optic seismic systems (Innanen, 2017b; Eaid and Innanen, 2018; Eaid et al., 2018). One of the applications of the model was a framework for multicomponent sensing with shaped fibres (Innanen, 2017a). Within this framework, it was evident that given

1. Free rein to set up well-coupled DAS fibres in arbitrary shapes;
2. Gauge lengths of order ≪ 1m,

the DAS signal at each of a relatively dense set of channel locations could be transformed into 6 traces, one for each independent component of strain or strain rate. However, current DAS interrogator technology, and the practicalities of field deployment, make assumptions (1) and (2) unrealistic. In 2018, during a large seismic experiment (Hall et al., 2019; Spackman and Lawton, 2019), a project was undertaken to assess practical multicomponent DAS sensing by designing and deploying a prototype sensor, in the form of a shaped loop of DAS fibre. Since it was to actually be buried, and field tested with an actual interrogator (with its gauge length / SNR restrictions), it was an opportunity to see how the approach of Innanen (2017a) managed given realistic limitations on (1)-(2). The multi-directional DAS loop was surveyed and buried at the Containment and Monitoring Institute Field Research Station (CaMI-FRS) in Newell County Alberta. After roughly 1 month for the ground to settle, the loop was illuminated alongside surface 3C calibration geophones. The partners in this were CaMI-FRS, Lawrence Berkeley National Labs (who supplied the helical-wound fibre), and Halliburton, who supplied and operated the DAS interrogator hardware, and provided the resulting raw data.

DAS seismic sensing applications (e.g., Mestayer et al., 2011; Daley et al., 2013; Mateeva et al., 2013, 2014) continue to proliferate. Although not all of its original promise, especially in 4D sensing in deepwater wells (Chalenski et al., 2016), has been realized, the low cost of deployment has led to its use in many unconventional reservoir settings. Research both in academia and industry have been active in interrogator improvements, fibre hardware improvements (Yu et al., 2018; Willis et al., 2018), and in processing improvements (Hardeman-Vooy et al., 2018). Applications have also widened considerably (e.g., Huot et al., 2018). DAS fibres respond proportionally to longitudinal strain or strain rate in the direction of the fibre axis only. This directionality has been a point of concern throughout the lifespan of the technology (e.g., Mateeva et al., 2014; Kuvshinov, 2016). Absent the complicating issue of ground-to-cladding-to-fibre coupling, the DAS measurement assigned to an output point can be thought of as projections of the point-wise tensor strain (or strain rate) onto a fibre along its local axial/tangential direction, followed by a weighted averaging over the gauge length centred on the output point. So, with reasonable accuracy, one can think of a DAS fibre as a “pointable” sensor, which will capture a portion of the strain tensor in whatever direction it is laid – provided the fibre interval so laid out exceeds the gauge length. Assuming this is so, multicomponent sensing, by virtue of a fibre which has been shaped to occupy a range of independent directions, becomes possible (Innanen, 2016, 2017a; Ning and Sava, 2018). This has to date only been discussed theoretically; the possibility of a practical, deployable multicomponent DAS sensing array remains an open question.

DESIGN AND DEPLOYMENT

In collaboration with CaMI, a location nearby the FRS station trailer was selected for the prototype sensor to be deployed (Figure 1). Southwest of the observation well (identifiable as the centre of the star pattern), a twin-square shape is visible. This is the fibre array design in map view.

![Figure 1: Deployment image](image-url)

Optimal DAS responses are often observed in fibres deployed in boreholes, cemented behind casing; sensitivity issues may appear in trenched deployments. However, borehole environments are both expensive and inflexible for early-stage experimentation. So, for practical purposes, our first try at a multicomponent DAS sensor was in a trenched and largely horizontal configuration. A pattern of two squares with their repeated straight segments was chosen because it afforded good lateral directional coverage, and because it was straightforward to survey and excavate. In all analysis in this paper, the two squares are distinguished schematically by the colours green and blue, with the edges of the green square approximately aligned with the cardinal directions and the edges of the blue square aligned with the NE-NW-SE-SW directions. A photograph of some of the detail of the fibre layout at the bottom of the 2m trench, and a diagram of the associated points on the array are included in Figure 2. Around each square both straight (black cable) and helical-wound (blue cable) fibres were deployed, each cable wrapping twice about each square.

According to the least-squares scheme discussed by Innanen (2017a), to create robust and complete tensor strain (or strain-rate) estimates, a fibre must be shaped such that it has intervals in many different orientations, with each of the three coordinate directions represented. Fur-
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1. Gauge length restrictions impose a lower bound (5-10m) on the size of a DAS sensor of the type we contemplate. At this size a loop is not a point sensor of waves traveling at standard seismic velocities and frequencies.

2. The fibre loop sensor we deployed lacks vertical coverage. The fibre occupies 2m vertical intervals as it enters and leaves the trench, but assuming a 5-10m gauge length, the vertical signal will be impure.

Figure 3: Geometrical model of buried DAS fibre loop. Top left: map view; bottom left: easting vs. depth; right panel: reference map view.

All corner and crossover points of the fibre were surveyed with the RTK-GPS system and hand-measured for lateral position and depth (Figure 3). The array was illuminated by 10-150Hz sweeps from the University of Calgary Envirovibe at four different source locations; each sweep was repeated 10 times and stacked to maximize signal. A middle-offset vibe point about 30m from the centre of the fibre array was selected for detailed first analysis.

SIMULATED DATA

The DAS response can be modelled provided an accounting of the fibre geometry, which we collected on deployment as described above (for a full discussion of the geometrical features of the DAS response model, see Innanen, 2017a; Eid and Innanen, 2018). Briefly, a DAS fibre is assumed to describe a piecewise smooth curve within the subsurface. A local orthogonal coordinate system is defined based on the unit tangent \( \mathbf{t} \) (i.e., the axial direction) of the fibre along its arc-length \( s \). The plane normal to \( \mathbf{t} \) is spanned by the normal and binormal unit vectors, \( \mathbf{n} \) and \( \mathbf{b} \). The strain tensor \( \varepsilon \) with components defined in this coordinate system is \( \varepsilon_{\alpha\beta} \). At any point along the fibre, seismic energy might arrive along a raypath which has a characteristic coordinate system of its own, also locally (for heterogeneous media) or globally (for homogeneous media) defined in terms of ray tangent and normal/binormal directions, which we will number 1, 2 and 3, with \( \mathbf{l} \) being the tangent direction. A strain tensor \( \varepsilon \) with components defined in this coordinate system is \( \varepsilon_{\alpha\beta} \). The DAS fibre at the point \( s \) responds proportionally to the longitudinal strain (or strain-rate) projected onto the \( \mathbf{t} \) direction. If we define elastic strain being carried by a seismic wave as \( \varepsilon_{123} \) in the ray coordinate system, when it arrives at \( s \) along the fibre at time \( t \), the response can be directly read from the first \((1)\) component of the tensor

\[
\varepsilon_{\alpha\beta}(s,t) = R(s)\varepsilon_{123}(s,t)R^{-1}(s),
\]

where \( R(s) \) is the \( s \)-dependent rotation matrix from the 123 system into the tnb system (Innanen, 2017a). The datum at a given time \( t \) and arc-length \( s \) is then \( d(s,t) = \varepsilon_{1}(s,t) \); or, if the interrogator response is proportional to strain rate, \( d(s,t) = \dot{\varepsilon}_{1}(s,t) \). We incorporate gauge length by integrating this point strain definition over fibre intervals, normally with a Gaussian window. Each channel location thus represents a mean strain computed over half a gauge length on either side.

The DAS data after pre-processing is stored as shot records with traces separated by a constant channel spacing and characterized by a fixed gauge length (we use 1.02m and 10m respectively to match with the field experiment discussed below). DAS output is directly in terms of arc-length along the fibre. Therefore, the horizontal axis of the shot record is an unwrapped version of the fibre segments we have been considering so far (Figures 4-5).

Figure 4: Fibre shape and its appearance when “unwrapped” (edges of the green square labelled as an example).

Choosing a causal wavelet and assuming a P-wave with first strain positive in the direction of propagation, propagating in a homogeneous medium velocity \( V_p=500\text{m/s} \), the shot record in Figure 5 is produced. Overlain on the figure is the schematic diagram of the unwrapped fibre. We observe that with the P-wave moving slowly in the near surface, and at standard seismic frequencies, the loop does not respond as a point sensor; specifically, approximately piece-wise linear moveout should be expected across the length of the fibre. If lower frequency waveforms are used, or if the signal is filtered to pass only wavelengths much greater than the \( \approx 10\text{m} \) scale of the loop, this pattern will diminish. The amplitudes in the synthetic responses (e.g., the shot record in Figure 5) are dominated by the directionality of the fibre. Geometric spreading is a second order influence.

To put the amplitude variations into their geometric context, consider two parts of the shot record. In Figure 6, a yellow box is drawn around the response from one of the edges of the blue square in the loop. With a P-wave is incident on this segment from the red source point, the ray intersects the fibre obliquely, and thus its strain, which is longitudinal...
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![Synthetic shot record on DAS fibre loop with field geometry. Overlain is the unwrapped fibre loop with each segment labelled.](image1)

![Oblique segment of the loop array highlighted.](image2)

![Broadside segment of the loop array highlighted.](image3)

and aligned with the ray, will be largely aligned with the fibre, producing a high-amplitude response. In contrast, in Figure 7, the ray carries the longitudinal strain of the P-wave across a segment of the fibre to which it is almost perpendicular. This is the direction of the lowest sensitivity of the fibre and so the response (again indicated with a yellow box) is almost zero.

![Directionality: Oblique = strong Broadside = weak](image4)

Polarity reversals appear in the simulated data by virtue of the tangent vector \( \mathbf{t} \), which is locally parallel to the fibre and oriented away from the interrogator. Accounting for geometry in this way, if two antiparallel segments of the fibre see the same strain, one will register it as positive and the other as negative. This polarity is convenient to maintain, but it will not tend to match what is seen in DAS data. We can either suppress the polarity in the analytical model or add it to the data; if the component of \( \mathbf{t} \) aligned with the source-fibre unit vector is positive/negative, we multiply the modeled or the measured axial strain estimate by +1/-1. In the following, we alter the data in pre-processing.

FIELD DATA

The raw shot record from the 30m offset source is plotted in Figure 8. Overlain are two event interpretations, and a label emphasizing the lack of polarity reversals as discussed above. The simulated data we devised were built for P-wave arrivals on the assumption that the first-arrival amplitudes would be the easiest to evaluate for directivity. The moveout patterns are suggestive that a P arrival is first, followed by S-wave energy and surface wave energy. The directivity patterns predicted in the simulated data are largely present in the field data. This is the primary conclusion of our experiment (compare Figures 5 and 8):

![Shot records produced by stacking of 10 sweeps at 30m offset source point. Event interpretations and lack of polarity are indicated.](image5)

To quantitatively assess the match between the analytic and measured data, some processing was carried out (most of this is only to allow the assessment to take place, and would not be required for multicomponent estimation). First, to accentuate the P-wave, a mute after the first arrival was applied. Second, to match the simulated data, a directional polarity change based on the relative directions of the fibre loop was included in the field data. The size of the loop required correction. As mentioned, the 10×10m loop size was decided based on gauge length considerations. A complication of these choices is that a seismic wave will not see this loop, even approximately, as a point sensor. This is clear in the moveout patterns in the synthetics and real data. This can be corrected for (or managed) in one of several ways:

1. By treating the loop as a sensor for low-frequencies only. The dominant frequency of the P-wave arrival in Figures 8 is close to 100Hz; if the P-wave is travelling at \( n \times 100\text{m/s} \), its dominant wavelength is roughly \( n \) metres. To appear as a point sensor, our loop would have to be several times smaller than this. The wave velocity must exceed 1000m/s by several times for this to be true, which is unrealistic in the near surface. However, at 10Hz, waves moving at \( n \times 100\text{m/s} \) have wavelengths on the order of 10×100m, which is much larger than the sensor footprint for most realistic velocities. So, the large loop we buried can be treated as a point sensor for data filtered to pass frequencies near 10Hz but not those near 100Hz.

2. By accepting that the loop is not a point sensor, and defining some internal processing to correct for its spatial distribution.

Since we are focusing on a single mode P-wave arrival, the second option is much the most straightforward, and we adopt it here. (We emphasize that as standard available gauge lengths drop to order 10m from 100m, these steps stop being necessary.) Our approach was to determine flattening velocities, and corrections, for the moveout along the segments of the fibre loop. After the correction, the amplitudes in a time slice through the muted/polarity-altered data approximate the strains carried by the same point on the P-wave wavefront, projected in a range of different directions. In Figure 9a, the field data after the full correction regimen are plotted; the first amplitudes of the simulated data with the same processing are plotted in Figure 9b. A time slice through the arriving P-wave allows a more complete comparison to be made between the measured and the predicted amplitudes and directivity patterns. In Figure 10a, the raw measured amplitudes are
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Figure 9: Processed first breaks. (a) Field data; (b) synthetics. White dashed lines reference match between synthetic and measured data.

Figure 10: Shot record time slice: field data (black) vs synthetic (red).

Although the absolute amplitudes between the field and synthetic data do not match precisely, both the leading order directionality trends in the amplitudes, and the smooth obliquity changes, are apparent in the field data. The most remarkable feature of the comparison is the close match between predicted and measured amplitudes for the first two amplitude “bumps” (120-210m), followed by the persistent discrepancy for the second two amplitude bumps (220-290m). Our current interpretation is that this persistent discrepancy is real, and is suggestive that the wave arriving is not a pure P-wave mode.

MULTICOMPONENT STRAIN ESTIMATION

Six independent components of tensor strain within DAS fibre reconstruction windows can in principle be determined collectively within the loop. In this section we examine the use of that formulation to carry out multicomponent sensing with the buried array. Let the right handed coordinate system involving the directions west, north, and depth be labelled W, N and D respectively. A strain tensor evaluated in this coordinate system has components

$$\mathbf{e} = \begin{bmatrix} e_{WW} & e_{WN} & e_{WD} \\ e_{NW} & e_{NN} & e_{ND} \\ e_{DW} & e_{DN} & e_{DD} \end{bmatrix}.$$  

(2)

Innanen (2017b) provided a formula for determining these data from a set of directional DAS data $d_1 = e_{rr}(S_1)$, $d_2 = e_{rr}(S_2)$, ...; the issue at hand is that the prototype sensor we deployed has no coverage in the depth direction, which means the available data will not constrain $e_{WD}$, $e_{ND}$ or $e_{DD}$ in the 6C tensor above. To proceed, we invoke a reduced version of the full 2017 inversion formula:

$$\begin{bmatrix} \hat{e}_{WW} \\ \hat{e}_{WN} \\ \hat{e}_{WD} \end{bmatrix} \approx (\mathbf{L}^T \mathbf{L} + \alpha \mathbf{I})^{-1} \mathbf{L}^T \begin{bmatrix} e_{rr}(S_1) \\ ... \\ e_{rr}(S_N) \end{bmatrix},$$  

(3)

where

$$\mathbf{L} = \begin{bmatrix} \lambda_{WW}^1 & 2\lambda_{WN}^1 & \lambda_{WN}^1 \\ \lambda_{WN}^1 & 2\lambda_{NN}^1 & \lambda_{NN}^1 \\ \lambda_{WD}^1 & 2\lambda_{DN}^1 & \lambda_{DN}^1 \end{bmatrix},$$  

(4)

and where $\lambda_{ij}^k = (\hat{t}(s_k)_i \cdot \hat{t}(s_k)_j)$, with i and j ranging over W and N values. The instantaneous profiles plotted in Figure 10 permit us to carry out an estimation of the instantaneous components of strain excluding depth. In the synthetic case, in which a pure P-wave traveling from the north was assumed, the “right answer” is

$$\mathbf{e} = \begin{bmatrix} e_{WW} & e_{WN} & e_{WD} \\ e_{NW} & e_{NN} & e_{ND} \\ e_{DW} & e_{DN} & e_{DD} \end{bmatrix} = \begin{bmatrix} 0 & 1 & e_{WD} \\ 0 & 0 & e_{ND} \\ 0 & 0 & e_{DD} \end{bmatrix},$$  

(5)

This is more or less captured in the synthetic data:

$$\mathbf{e}_{\text{synth}} = \begin{bmatrix} 0.13 & 0.03 & e_{WD} \\ 0 & 0.74 & e_{ND} \\ 0 & 0 & e_{DD} \end{bmatrix};$$  

(6)

the leakage of P-wave strain into the NW and WW components is a measure of the error introduced by the gauge length averaging along the straight segments. The field data have patterns on the second square which do not match our synthesized P-wave, so we should not expect to see the strain estimate recreating equation (5). There is no reason to expect that coupling in one part of the backfilled trench will be consistently different from that of another part (and there are parts of these loops that lie very close to one another and must have essentially identical coupling properties). We conclude that the response seen by the fibre loop is real, and reflects not a problem with the sensor but rather a deviation of the elastic distortion on the fibre away from the assumed pure P-wave. The strain we estimate is

$$\mathbf{e}_{\text{field}} = \begin{bmatrix} 0.04 & 0.11 & e_{WD} \\ 0 & 0.26 & e_{ND} \\ 0 & 0 & e_{DD} \end{bmatrix};$$  

(7)

i.e., much of the strain component distribution of a P-wave coming from the north, but mixed with other modes.

CONCLUSIONS

In 2016-2017 a geometrical model of DAS data for arbitrary fibre shapes was published, of which multicomponent sensing was an application. A prototype shaped DAS fibre array was buried to put these ideas and their feasibility to the test. Field shot records were analyzed to assess whether commonly available directional sensitivity is sufficient to permit multiple components of strain to be estimated. By picking and modelling a P-wave arrival, we conclude with a cautious yes. Future versions with depth as well as lateral components will be straightforward as gauge lengths of order 1-2m become available.

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