Least Squares DAS to geophone transform

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Summary

Distributed acoustic sensing uses optical fibre to measure strain or strain rate along to the fibre direction. The strain rate estimated by distributed acoustic sensing is related to the total displacement of a section of the fibre called gauge length. By using this link between strain rate and displacement we propose a least squares inversion scheme to obtain the particle velocity along the fibre from strain rate in a distributed acoustic sensing system. We test this least squares transformation with data from the Containment and Monitoring Institute Field Research Station in Alberta, Canada. We found that the transformed traces are very similar to a filtered version of the corresponding geophone ones, in particular at early times.

Introduction

Distributed acoustic sensing (DAS) is a seismic monitoring technology that uses optical fibre to obtain the strain, or strain rate, related to the fibre deformation by a passing seismic wave (Daley et al., 2013). A laser pulse probes different sections of the fibre. Some of the laser energy is backscattered and detected by the DAS measuring device called an interrogator. In the absence of any disturbance that can deform the fibre the backscattering is static. When a seismic event deforms a section of the fibre, the backscattering changes for this section and the interrogator can measure the strain from this difference (Hartog, 2018).

The fact that DAS measures strain, or strain rate, and not particle velocity, particle acceleration or pressure like the more usual geophones, accelerometers and hydrophones, creates doubt about applicability of the usual processing techniques and results that can be obtained from this kind of data.

The Containment and Monitoring Institute Field Research Station (CaMI-FRS) is a research facility located in Alberta, Canada, where small volumes of CO_2 are being injected annually into the ground for a 5 year period (Macquet et al., 2019). One of the technologies used to monitor this injection is DAS. There is a 5km loop of straight and helically wounded optical fibre permanently installed that runs inside a trench and two observation wells to record active and passive seismics (Lawton et al., 2017). In this work we develop a least squares DAS to geophone transform based on DAS principles.

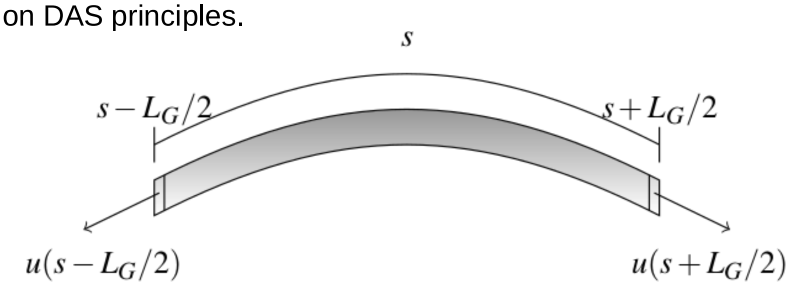

Figure 1: Displacements along a portion of fibre of length L_G, the gauge length, centred around point s. The total dilation or contraction of this fibre portion detected by the interferometer is the difference between the displacements u along the fibre at both ends.

Theory

Figure 1 shows a fibre section around point s of length L_G, the gauge length of the fibre. A DAS system can determine δl, the total change in length of the fibre, using an interrogator unit. Then δl is divided by L_G to obtain the total tangent strain along this fibre portion that is assigned to the middle point s:

$$\varepsilon_f(s) = \frac{\delta l}{L_G} \tag{1}$$

The total change in length δl of this section is related to the difference between the tangential displacements u at both ends of the section:

$$\delta l(s) = u\left(s + \frac{L_G}{2}\right) - u\left(s - \frac{L_G}{2}\right), \tag{2}$$

By replacing this in equation 1 we obtain an expression for the fibre strain in terms of displacement:

$$\varepsilon_f(s) = \frac{1}{L_G}\left[u\left(s + \frac{L_G}{2}\right) - u\left(s - \frac{L_G}{2}\right)\right] \tag{3}$$

Furthermore, as many DAS systems measure strain rate instead of just strain, we can derive in time this last equation:

$$\dot{\varepsilon}_f(s) = \frac{1}{L_G}\left[v\left(s + \frac{L_G}{2}\right) - v\left(s - \frac{L_G}{2}\right)\right], \tag{4}$$

where v is the tangential particle velocity. This tangential particle velocity can be obtained from the general three dimensional particle velocity **v** vector by a projection along the fibre unit tangent vector **t**:

$$v(s) = \vec{\boldsymbol{t}}(s) \cdot \vec{\boldsymbol{v}}(s) \tag{5}$$

After replacing this last expression in equation 4 we obtain the general expression for strain rate in terms of particle velocity:

$$\begin{aligned}\dot{\varepsilon}_f(s) \quad = \quad & \frac{1}{L_G}\left[\vec{\boldsymbol{t}}\left(s + \frac{L_G}{2}\right) \cdot \vec{\boldsymbol{v}}\left(s + \frac{L_G}{2}\right)\right. \\ & \left. -\vec{\boldsymbol{t}}\left(s - \frac{L_G}{2}\right) \cdot \vec{\boldsymbol{v}}\left(s - \frac{L_G}{2}\right)\right]\end{aligned} \tag{6}$$

We are interested primarily in DAS installed in vertical seismic profiles (VSP). In this survey configuration, the fibre is installed vertically. This means that the only non zero component of the tangent vector **t** is $t_z = 1$. Using this, the expression for strain rate in DAS VSP reduces to:

$$\dot{\varepsilon}_f(s) = \frac{1}{L_G}\left[v_z\left(s + \frac{L_G}{2}\right) - v_z\left(s - \frac{L_G}{2}\right)\right], \tag{7}$$

where v z is the vertical particle velocity. This expression is also used in Hall et al. (2020) to transform particle velocity to strain rate data.

The next step is to assemble a linear system of equations by considering every fibre portion of length L_G where DAS measured the strain rate. We suppose that DAS measured at points s_i, with $i = 1, \ldots, M$, along the fibre, for some integer M. We also assume that the distance between consecutive points s_i is Δs and that the gauge length $L_G = N\Delta s$ for some integer N. With this in mind, equation 7 is discretized in the following way:

$$\dot{\varepsilon}_f(s_i) = \frac{1}{L_G}\left[v_z\left(s_{i+\frac{N}{2}}\right) - v_z\left(s_{i-\frac{N}{2}}\right)\right] \tag{8}$$

Notice that additional points s_j with $j = 1 - N/2, \ldots, 0$ and s_k with $k = M + 1, \ldots, M + N/2$ are needed for this equation at the first and last points along the fibre. Finally, all discretized equations are assembled in a linear system:

$$\begin{bmatrix} \dot{\varepsilon}_f(s_1) \\ \vdots \\ \dot{\varepsilon}_f(s_i) \\ \vdots \\ \dot{\varepsilon}_f(s_M) \end{bmatrix} = G \begin{bmatrix} v_z(s_{1-\frac{N}{2}}) \\ \vdots \\ v_z(s_i) \\ \vdots \\ v_z(s_{M+\frac{N}{2}}) \end{bmatrix} \tag{9}$$

where

$$G = \frac{1}{L_G}\begin{bmatrix} -1 & 0 & \cdots & 1 & 0 & \cdots & 0 \\ 0 & -1 & 0 & \cdots & 1 & \cdots & 0 \\ \vdots & & & \ddots & & & \vdots \\ 0 & \cdots & 0 & -1 & 0 & \cdots & 1 \end{bmatrix} \tag{10}$$

The linear system of equation 9 follows the common pattern where the measured data, strain rate, depends linearly on the model parameters, the vertical particle velocity. This system is usually written as:

$$\vec{\boldsymbol{d}} = G\vec{\boldsymbol{m}}, \tag{11}$$

where **d** is the vector of strain rates and **m** are the vertical particle velocities. In order to regularize the solution of this system we expand it as:

$$\begin{bmatrix} G \\ \varepsilon R \end{bmatrix} \vec{\boldsymbol{m}} = \begin{bmatrix} \vec{\boldsymbol{d}} \\ \vec{\boldsymbol{0}} \end{bmatrix}; \tag{12}$$

where operator R is the identity operator if we want to obtain the smallest model, or is the derivative operator if we want to obtain the flattest model (Aster et al., 2019), and ε is the regularization weight. We solve this system by using the conjugate gradient least squares method (Aster et al., 2019) with Claerbout's conjugate gradient iteration step (Claerbout, 2008).

Results

We tested the least squares DAS to geophone transform on DAS data from CaMI-FRS. The top part of Figure 2 shows a DAS gather from one of the wells. The gauge length is 10m and the output trace spacing is 0.25m (Gordon, 2019). The source was an IVI EnviroVibe located on the surface close to the wellhead with a linear sweep of 10 to 150Hz.

The middle and bottom parts of the Figure 2 show two inversion results, the smallest and the flattest, result of the two different regularization operators in equation 12.

The shape of the first arrival changes in both inversions from a front lobed wavelet to a more zero phased one. Although less noticeable, the shape of the upgoing events also changes, for example just above 0.1s and 220m. However, downgoing events seem to be unchanged.

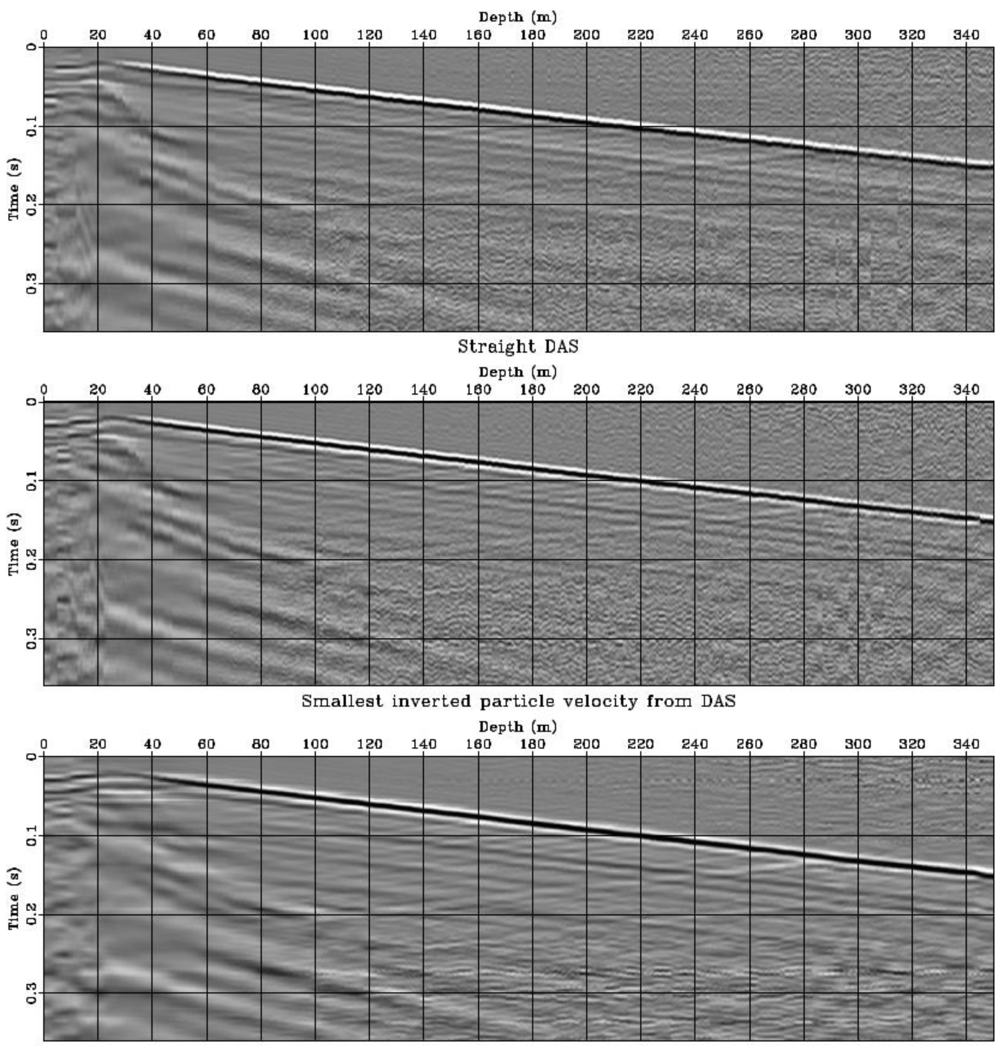

Figure 2: The top part is a straight fibre DAS vertical seismic profile shot gather from the Containment and Monitoring Institute Field Research Station (CaMI-FRS). The middle shows the vertical particle velocity inverted from the DAS data using the identity operator as regularization operator to obtain the smallest

particle velocity model. The bottom part is the same inversion but using a derivative regularization operator to recover the flattest particle velocity model.

Figure 3 exhibits the corresponding vertical geophone data. In the observation well the geophones are installed from 191m to 306m depth every 5m. The left part is the original shot gather. The inverted gathers from Figure 2 do not look very similar to this gather. However, the right part shows a filtered version, with a 50Hz low cut filter, that is more similar to the inverted DAS gathers.

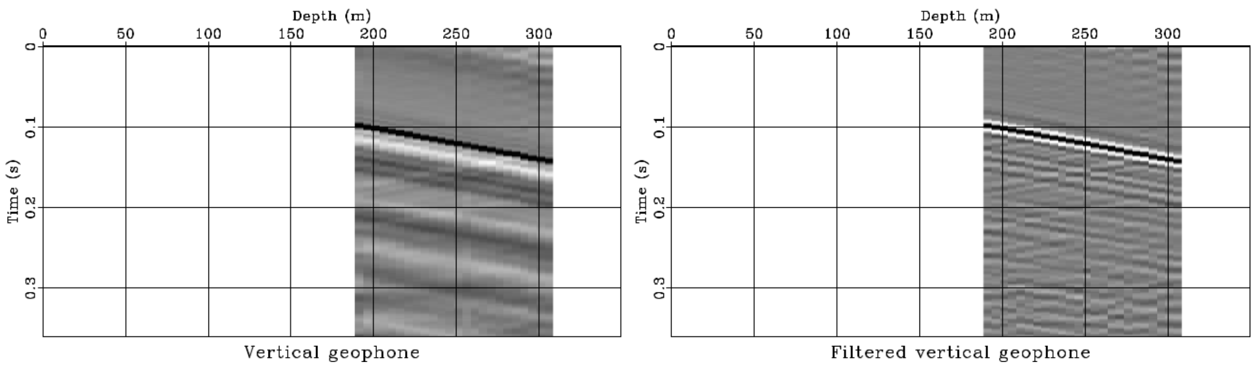

Figure 3: Vertical geophone shot gather corresponding the the DAS shot gather of Figure 2. Geophones are installed in the observation well from 191m to 306m depth every 5m. The left is the original data and the right is a 50Hz low cut filtered version.

Figure 4 shows selected traces from the vertical geophone, DAS and inverted datasets. The geophone traces are at 191m depth. After depth registration the equivalent DAS traces are at 211m along the fibre. The first trace is the geophone trace while the second is the DAS one. Notice the difference in the first arrival character and the overall higher frequency content of the DAS trace.

The next group of traces is from the least squares inversion technique described earlier. The third trace is the result with no regularization. The noise before the first break has been amplified, the first arrival looks similar to the geophone one and it seems like a noisy version of the geophone trace, at least before 0.2s. The fourth trace is the inversion result regularized to obtain the smallest model. It has less noise before the first break and a first arrival similar to the geophone one. However, the rest of the trace has little resemblance to the geophone trace. The fifth trace comes from the inversion regularized to obtain the flattest solution. It has similar characteristics to the smallest inverted model.

The sixth trace is a filtered version of the geophone trace. Specifically, the band below 50Hz is suppressed. This version of the geophone trace is more akin to the regularized inversion results in traces four and five.

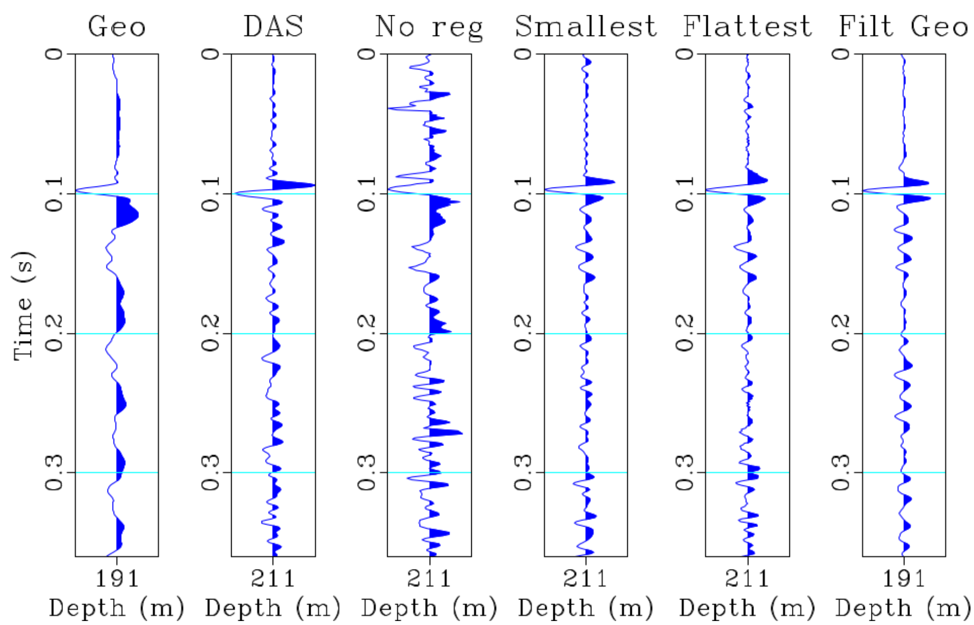

Figure 4: Selected traces from the vertical geophone, DAS and inverted datasets. Geophone traces are at 191m depth in the well while DAS traces are at 211m depth along the fibre. From left to right, the first trace is the geophone response. The second is the DAS response. The third is the inverted geophone response from the DAS data without using regularization. The fourth solves for the smallest model while the five solves for the flattest one. The sixth trace is the high frequency part of the geophone response.

Conclusions

The least squares DAS to geophone transformation presented is based on a linear operator that follows a published description of the DAS inner workings (Hartog, 2018). However, there are many details that are proprietary and are not being included in the linear operator. For example, the patent Mahmoud et al. (2010) uses visibility factors to calculate a better acoustic perturbation. DAS aspects not modelled can be difficult to invert.

The least squares DAS to geophone transformation was able to invert the early times and the high frequency part of the geophone trace.

Regularization is fundamental in the least squares transformation. Without it the noise before first arrivals was amplified.

Acknowledgements

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