Multicomponent imaging with distributed acoustic sensing

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SUMMARY

The usage of Distributed Acoustic Sensing (DAS) in geophysics is rapidly gaining popularity due to its dense spatial sampling and low operation cost, and given that the optical fiber is easily accessible. In the borehole environment, optical fibers for DAS are often readily available as a part of other sensing tools, such as for temperature and pressure. Although DAS provides single axial strain measurement along the fiber, the entire strain tensor can also be recovered through a combination of purposefully-designed optical fibers. Such reconstruction uses multiple strain projections acquired by manipulating the geometry of the optical fiber. Similarly, using the same approach the reconstruction of the displacement vector is possible. The availability of the entire strain tensor opens the possibility for accurate elastic wavefield extrapolation, thus avoiding the generation of nonphysical wave modes that contaminate migrated images. This technology also enables high-quality estimation of reservoir properties, and accurate elastic parameter estimation.

INTRODUCTION

DAS acquires strain along an optical fiber coupled to the ground, which represents the projection of the surrounding strain tensor corresponding to the position of the optical fiber. As shown by Lim and Sava (2016), it is possible to reconstruct six components of the strain tensor by using multiple strain projections measured from a combination of a helical and straight optical fibers or a single chirping (variable wrapping angle) helical optical fiber. The working principle of this method requires exploiting of consecutive measurements within a given spatial window to perform the strain reconstruction. Although the reconstruction results are promising, the method suffers a drawback from the assumption associated with the spatial window that it should be significantly larger than the seismic wavelength of interest. Implementing this method to short seismic wavelength applications such as microseismic is rather difficult.

Lim and Sava (2017) overcome this limitation by proposing a new configuration that allows the reconstruction of the entire strain tensor without the need to group consecutive measurements. They use a setup of with five equally spaced constant pitch angle helical optical fibers and a straight optical fiber to obtain multiple strain projections that sufficiently describe the surrounding strain tensor for the reconstruction. The pitch angle is measured between the tangent vector and the orthogonal direction of the DAS cable. Using six different strain projections, one can reconstruct the entire strain tensor at a given location. This configuration limits the engineering complexity required to build a multi-fiber cable, thus making such data acquisition feasible.

The stress tensor can be obtained from the reconstructed strain tensor if the material properties surrounding the optical fiber are known or estimated accurately. The stress and displacement data can be used for accurate elastic wavefield extrapolation, as shown by Ravasi and Curtis (2013). Conventional methods of elastic wavefield extrapolation using only displacement data (i.e., when stress data are not readily available) are heuristic schemes that do not satisfy the representation theorem. Hence, multicomponent DAS measurements can provide recovery of all information for exact wavefield extrapolation in models of arbitrary complexity. We demonstrate the potential application of multicomponent DAS data with the TTI Marmousi II model adapted from Yan and Sava (2009) and Rocha et al. (2017).

METHODOLOGY

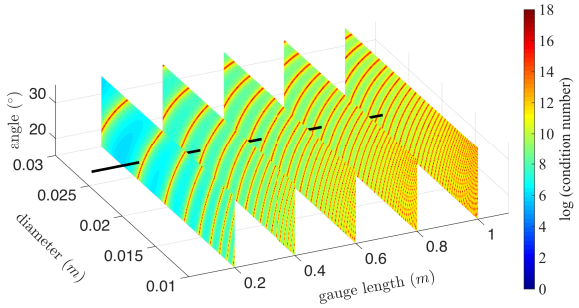
To obtain the stress data for the wavefield extrapolation, we use the DAS configuration of five equally spaced helical optical fibers and a straight optical fiber proposed by Lim and Sava (2017) to perform the reconstruction of the strain tensor. The equally spaced helical fibers provide sufficient azimuthal sampling of the surrounding strain tensor. However, the reconstruction is only possible with the additional straight optical fiber to constrain the inversion. Assuming an accurate estimation of the Earth's surface material properties surrounding the optical fiber, we obtain the stress tensor from the reconstructed strain tensor through conventional stress-strain relations. As suggested by Lim and Sava (2017), we perform a parameter space search to select our optimal cable configuration using the associated condition number defined from the Gram matrix $\mathbf{L}^\intercal\mathbf{L}$ where the operator $\mathbf{L}$ is a cascade of operators

$$\mathbf{L} = \mathbf{WAG}. \tag{1}$$

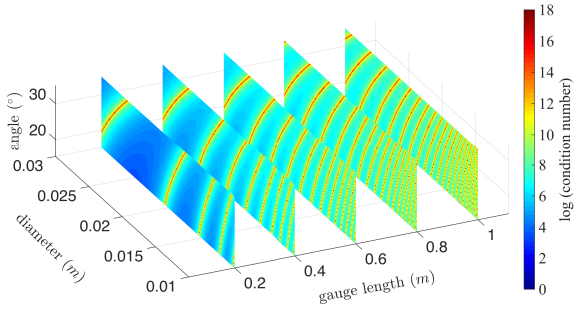
$\mathbf{G}$ is the transformation matrix that captures the geometric information of the optical fiber to project the strain tensor onto the optical fiber direction. $\mathbf{A}$ is a banded matrix characterizing the gauge length, and $\mathbf{W}$ is a windowing matrix that sets the channel spacing between consecutive average strain measurement. In the proposed multicomponent DAS configuration by Lim and Sava (2017), every row of the operator $\mathbf{L}$ is responsible for an individual DAS measurement of the respective optical fibers. Using measurements $\mathbf{d}$ from the individual optical fibers, we reconstruct the strain tensor $\mathbf{m}$ in a least-squares sense as

$$\mathbf{m} = \left(\mathbf{L}^\intercal\mathbf{L}\right)^{-1}\mathbf{L}^\intercal\mathbf{d}, \tag{2}$$

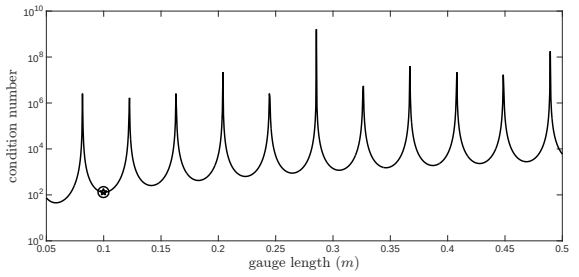
An example of the parameter space scan is shown in Figure 1a where we seek parameter combinations with the lowest condition number. A low condition number



(a)



(b)



(c)

Figure 1: (a) Condition number of the Gram matrix to reconstruct the strain tensor using optical fiber parameters of pitch angle from 15° to 35° and diameter from 0.01 m to 0.03 m. These slices are specifically scanned for but not limited to gauge lengths at every 0.2 m to 1.0 m. (b) Condition number of Gram matrix to reconstruct displacement vectors using the same parameters as (a). (c) The line in (a) where the condition number is a function of gauge lengths with 0.1 m marked.

implies that the reconstruction of the strain tensor using the associated design parameters is feasible. To narrow the search in the gauge length space, we can set the geometry design parameters such as the diameter at 1 in and the pitch angle at 20°. Since the gauge length is a DAS interrogator parameter, it does not change the configuration geometry. The line in Figure 1a represents the defined diameter and pitch angle parameters, and the graph in Figure 1c shows the corresponding condition numbers as a function of gauge lengths. The high condition numbers refer to DAS measurements that do not contain azimuthal information when the gauge length is

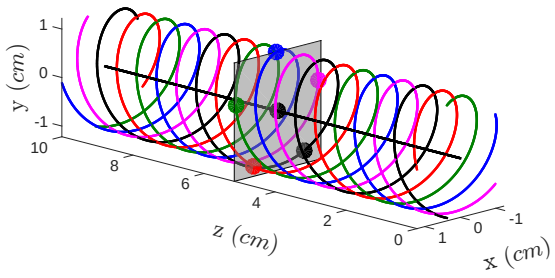


Figure 2: Illustration of five equally spaced helical optical fibers and a straight optical fiber using selected design parameters from Figure 1c. The dots represent measurement at the same level along the cable indicated by the horizontal plane.

equal to a multiple of the helix lead which is the axial advance of a helix for a complete 360° turn. This high condition number phenomenon further highlights the need for careful selection of design parameters to ensure accurate strain tensor reconstruction. Figure 2 shows an illustration of the optical fiber configuration using the design parameters marked in Figure 1c.

We also can perform similar reconstruction for the three-component displacement vector given that we obtain the displacement projections along the optical fiber through accurate conversion from the native strain projection measurements, such as integration or through relationships presented by Mikumo and Aki (1964); Langston et al. (2006); Langston (2007). Applying the same parameter scanning method suggested by Lim and Sava (2017), we utilize the displacement projection matrix instead of the strain projection matrix. By fixing the same design parameters ranges as for the strain reconstruction, the corresponding condition number plot is shown in Figure 1b. Unlike the strain tensor where there are six number of unknowns corresponding to the six components, the three-component displacement has a broader range of design parameter combinations for the reconstruction. It is worth noting that the design parameters that are optimal for the strain tensor reconstruction are also optimal for the displacement vector reconstruction. However, the reverse is not true.

Upon obtaining both the stress tensor and the displacement vector, we perform wavefield extrapolation using the surface integral of the representation theorem (Aki and Richards, 2002) by assuming that both stress and displacement on the surface are due to the body force within the volume. Aforementioned is similar to the formulation shown by Ravasi and Curtis (2013) as

$$\mathbf{V} \approx -\oint_{\partial\Omega} ds \left(\underline{\boldsymbol{\sigma}} * \mathbf{G}^{\mathbf{f}} + \mathbf{u} * \mathbf{G}^{\underline{\mathbf{h}}}\right) \cdot \mathbf{n} \qquad (3)$$

where $\mathbf{V}$ denotes the extrapolated displacement wavefield, $\underline{\boldsymbol{\sigma}}$ and $\mathbf{u}$ are the measured stress tensor and displacement vector respectively. The wavefield extrapola-

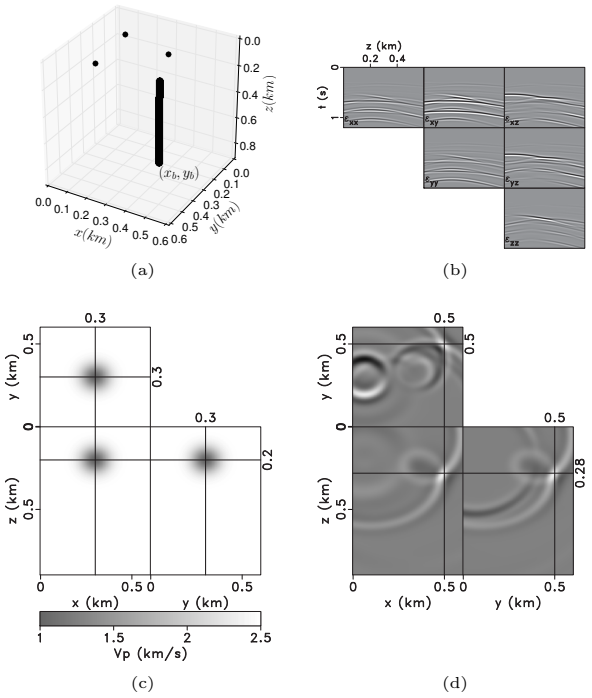


Figure 3: (a) Schematic representation of a DAS experiment depicting the source (dot) and receiver (line) locations. (b) The ideal strain tensor that we would like to reconstruct from DAS measurements. (c) The P-wave velocity model containing a low velocity Gaussian anomaly designed to produce wavefield triplications. The S-wave velocity is half of the P-wave velocity. (d) A snapshot of the vertical displacement wavefield.

tion uses both the stress tensor data $\underline{\boldsymbol{\sigma}}$ as a dipole source in the wavefield propagator $\mathbf{G^f}$, and the displacement vector $\mathbf{u}$ as a quadrupole source in the wavefield propagator $\mathbf{G^{\underline{h}}}$. The integral is implied by simultaneously injecting at the surface $\partial\Omega$ which is defined by all the receiver locations. The vector $\mathbf{n}$ is normal to surface $\partial\Omega$. Conventionally, such extrapolation method is impossible as the stress tensor data are not available. Therefore, in instances where only displacement data are available, we perform the heuristic extrapolation method given as

$$\mathbf{V} \approx -\oint_{\partial\Omega} ds\, \mathbf{u} * \mathbf{G^f} \tag{4}$$

where we propagate the measured displacement vector $\mathbf{u}$ as a dipole source in the wavefield propagator $\mathbf{G^f}$ to obtain the extrapolated displacement wavefield $\mathbf{V}$.

NUMERICAL EXAMPLE

Following the method presented by Lim and Sava (2017), we illustrate an example of the 3D strain tensor reconstruction from axial strain measurements using the optical fiber configuration discussed before using synthetic examples of a complex wavefield. The complex wavefields exhibit triplications caused by a velocity model containing a low-velocity Gaussian anomaly, as shown in Figure 3c. We use smaller than usual gauge lengths such as 0.1 m which are possible using specially designed optical fibers, as indicated by Farhadiroushan et al. (2016). Lim and Sava (2017) demonstrate the use of a more conventional fiber system with a gauge length of 1.0 m. The condition numbers for the gauge length of 0.1 m marked in Figure 1c corresponds to a low value.

Our numerical setup mimics a simultaneous source experiment with three sources indicated by the dots and the straight line of receivers at coordinates (x_b, y_b) in Figure 3a. Figure 3b, shown in a tensor layout, represents our target strain reconstruction observed along the receivers. The horizontal and vertical axes of the individual panels represent the distance along optical fiber and time, respectively. We perform the reconstruction by adding random noise with 10% of the maximum amplitude of the data and in the data frequency band. When the signal is weak, the noise overwhelms the signal. Using a gauge length of 0.1 m, we can reconstruct the strain tensor as shown in Figure 4a. The difference plot in Figure 4b shows no signal leakage and only contain primarily random noise.

In the example using the modified TTI Marmousi II model (Bourgeois et al., 1991; Yan and Sava, 2009; Rocha et al., 2017), we assume the deployment of a multicomponent DAS system to reconstruct the entire strain tensor and the displacement vector. We also assume that the properties of the Earth's surface material are known to perform strain to stress conversion. We adopt the energy imaging condition by Rocha et al. (2017) to produce a single elastic image without wave-mode decomposition. Figure 5a shows the single shot image obtained through heuristic wavefield extrapolation using displacement data only. The nonphysical waves present themselves as events cross-cutting the geological reflectors, especially in the shallow section. The cross-cutting is further highlighted in the zoomed section in the shal-

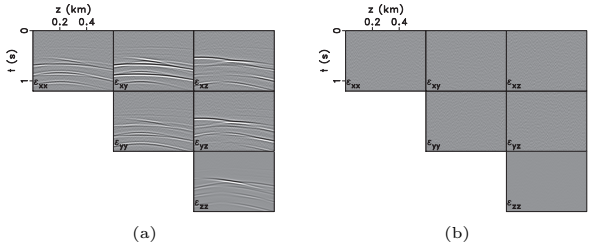


Figure 4: (a) Strain tensor reconstructed from data containing random noise with 10% of the maximum data amplitude and band-limited to the data band with five equally spaced helical optical fibers and a straight optical fiber using a gauge length of 0.1 m. Panel (b) is the difference between the ideal strain tensor in Figure 3b and the reconstructed tensor in (a).

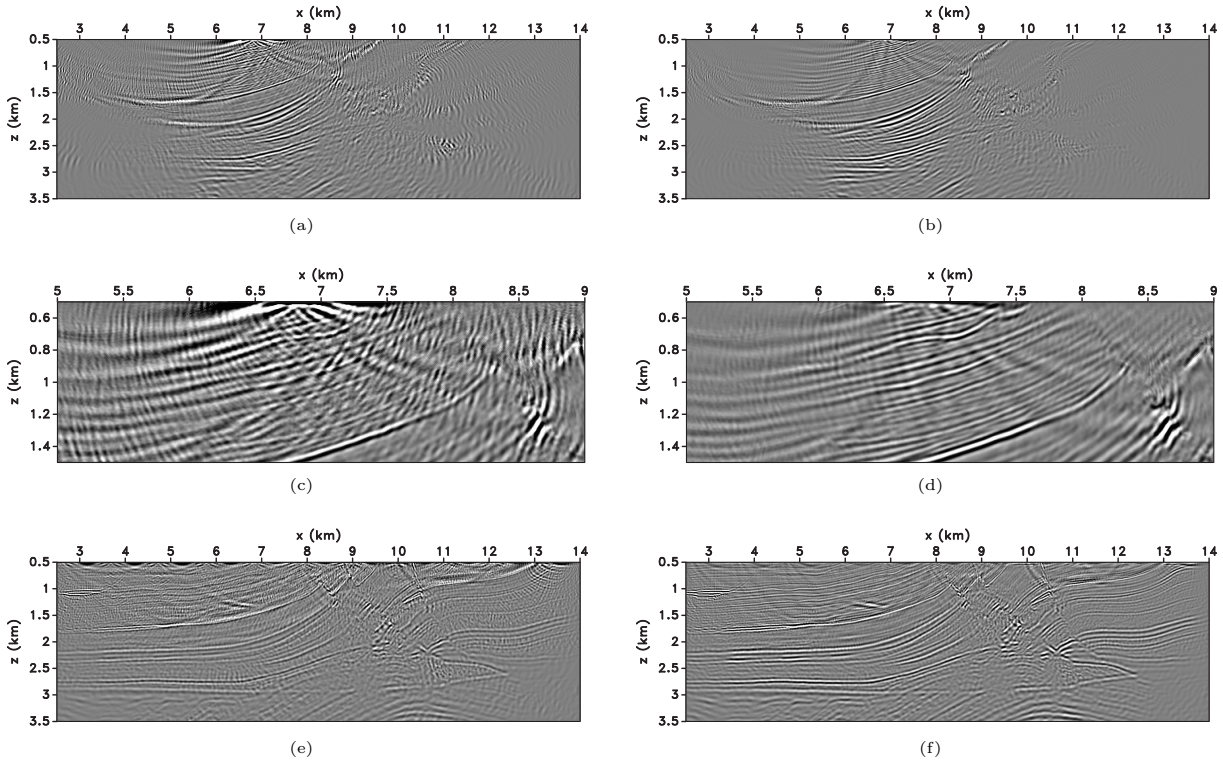


Figure 5: Images obtained using the energy imaging condition from the Marmousi II experiment: (a) **single shot** image using the exact and (b) heuristic wavefield extrapolation. The energy image in panel (c) and (d) is the zoom section of the respective panels in (a) and (b). The **stacked** images in panel use (e) the exact and (f) heuristic wavefield extrapolation.

low region as illustrated in Figure 5c. However, Figure 5b shows an improved single shot image obtained using exact wavefield extrapolation and the corresponding zoomed section in Figure 5d. The same observation holds for the image obtained by stacking multiple shots. Although the cross-cutting in Figure 5a appears less severe after stacking in Figure 5e, the geological reflectors are not as coherent comparing to Figure 5f. Extrapolating with both stress and displacement eliminates the non-physical waves, reduce the uncertainty associated with the cross-cutting artifacts in the final image.

CONCLUSION

We demonstrate the possibility of accurate reconstruction of the strain tensor using distributed acoustic sensing data by measuring strain projections along several optical fibers opens the possibility for accurate elastic wavefield extrapolation. This requires optical fiber system that is purposefully built to access diverse projections of the strain tensor. The design parameters mentioned in this paper serve as an example of how one parameterizes a multicomponent DAS acquisition system with five equally spaced helical optical fibers, together with a straight optical fiber. From our analysis, a shorter gauge length plays a significant role in the accuracy of the strain tensor reconstruction in the presence of noise. Systems with short gauge length are possible with specially-engineered optical fiber together with rapidly evolving DAS interrogator technology. Even using current technology, increasing the diameter of our multi-fiber configuration when the dimension of the fiber is not restricted, such as for surface seismic acquisition, allows the use of larger gauge lengths. However, as seen in our analysis, careful selection of the design parameters through parameter scanning is necessary to ensure accurate reconstruction. The more accurate wavefields lead to a higher quality image without the presence of nonphysical waves in the elastic medium, which supports reservoir characterization in complex geological structures. The technique discussed in this paper applies to elastic models characterized by arbitrary anisotropy and heterogeneity.

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