Distributed acoustic sensing (DAS) for geomechanics characterization: A concise review

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Abstract. Microseismic/acoustic emission monitoring is a powerful tool for geomechanics characterization. Recent advances in fiber-optic sensing enable the acquisition of broadband seismic wavefields by exploiting the phenomenon of Rayleigh backscattering that occurs naturally in the fiber-optic. This new, relatively inexpensive technology—distributed acoustic sensing (DAS)—repurposes pre-existing fiber-optic cables (e.g., unused telecom cables or so-called dark fiber) or fit-for-purpose cables as dense seismo-acoustic sensor arrays. Recent studies have shown that DAS can be employed to monitor microseismic activities during hydraulic fracturing, quasi-static geomechanical strains induced by well injection, and acoustic emission signatures during laboratory slope failure. In this review, we first briefly describe the measurement principle of DAS. Then, we present a concise overview of the state-of-the-art progress in DAS-based geomechanics studies, with particular emphasis on geomechanical responses associated with hydrofracturing and shallow geohazard triggering. We further discuss the current challenges of this emerging technology, including low signal-to-noise ratio, single-component sensitivity, large data volume, spatial distance uncertainty, and amplitude response complexity. We conclude by suggesting that DAS coupled to dark fiber networks presents a unique opportunity to detect and monitor microseismic/acoustic emission events and that it offers a new possibility to investigate fine-scale geomechanical processes across multi-kilometer distances.

1. Introduction
Microseismicity (MS)/acoustic emission (AE) is a geomechanical response closely related to the deformation and failure processes of geologic materials, which is accompanied by a sudden release of strain energy [1]. Monitoring MS/AE signatures has promise for geomechanics characterization, such as evaluating the stability of underground mines and slopes [2, 3], and estimating hydraulically stimulated fracture networks in unconventional reservoirs [4].

Conventional MS/AE monitoring methods are mostly based on point-wise sensors, which sometimes make it difficult to establish long-term, high-density sensing networks due to budget constraints. Sparsely instrumented measuring points may result in some effective signals not being recorded during restricted monitoring periods. A new technology called distributed acoustic sensing (DAS) offers the opportunity to overcome this dilemma.

DAS is an emerging fiber-optic sensing technology that virtualizes fiber-optic cables into seismo-acoustic sensors [5]. In recent years, DAS has become available for the monitoring of geomechanical responses, including MS activities during hydraulic fracturing [6–9] and AE signatures during laboratory slope failure [10]. In particular, the ultra-low frequency response allows DAS to record
quasi-static deformation during bedrock stimulation [11, 12] and hydraulic fracturing [13–17]. These could provide new insights into geomechanical response processes [18].

In this paper, we first briefly describe the measurement principle of DAS. Then, we provide a concise review of the research on DAS-based geomechanical response monitoring. Finally, the advantages and challenges of DAS technology are summarized.

2. DAS measurement principle

DAS measures dynamic strain fields acting on fiber-optic cables via determining the phase variation of backscattered light in the fiber-optic, using a technique known as phase-sensitive optical time-domain reflectometry (φ-OTDR) [19]. Similar to distributed strain sensing (DSS) [20], a DAS system includes an interrogator unit (IU) connected to a sensing fiber. As shown in Figure 1(a), the DAS IU repeatedly injects narrow coherence laser pulses into the core of the fiber-optic. Rayleigh scattering will be generated at each point along the fiber due to impurities in the doped silica glass core. Some of the Rayleigh scattering light is scattered back in the opposite direction of the pulse, referred to as the Rayleigh Backscatter (RBS) light. As shown in Figure 1(b), for a specified fiber length called gauge length, the phase of RBS delay $\Phi$ of a single pulse along the fast axis is predictable, and the phase delay change $\Delta \Phi$ between two adjacent laser pulses along the slow axis is linearly related to the axial strain caused by the disturbance. The time of RBS flight is used to position the disturbance along the fiber.

![Diagram of DAS measurement principle](image)

**Figure 1.** Measurement principle of DAS based on phase-sensitive optical time-domain reflectometry (φ-OTDR). The inset of (b) is adapted from Lindsey and Martin [21].

3. DAS for geomechanical response monitoring

3.1. Microseismic monitoring

Recent studies have used DAS to monitor microseismic events during hydraulic fracturing. The sensing fiber-optic arrays are typically deployed either inside or outside the casing of monitored wells, and in contrast to conventional geophone arrays, they allow continuous monitoring during stimulation without interfering with downhole operations. Results from field applications have shown that
microseismic events recorded by DAS are in good agreement with geophones [6–9]. DAS systems can detect some microseismic events that cannot be recorded by geophones [7]. However, the signal-to-noise ratio (SNR) of DAS data is lower than that of geophones. To enable automated and real-time detection of microseismic events during hydraulic fracturing, the convolutional neural network (CNN) method was used to analyze DAS data and successfully applied to multiple DAS data sets [22, 23].

Interpreting the location of microseismic events is a critical component of microseismic monitoring [4]. For conventional borehole microseismic surveys, the spatial location information is obtained by three-component geophones. However, DAS systems can only detect strain changes along the length of the fiber-optic, which results in only the distance between the source and receiver be computed using the arrival time difference of P- and S-waves, but not the azimuth information [6, 9]. Consequently, there are some limitations of microseismic events location based on DAS data, but the spatial location can be estimated by geometric methods in a deviated or horizontal well [6] (Figure 2) or with multiple fiber-optic cables.

![Figure 2. DAS allows localizing microseismic events in horizontal wells [6].](image)

3.2. Low-frequency DAS monitoring

The characteristics of fractures provide a proxy for studying the hydrodynamic behavior in rock masses [24, 25]. Downhole geophysics can only depict fracture networks at low spatial resolution. Recent studies have shown that low-frequency DAS data at the millihertz level could provide critical information about the geometry of stimulated fractures [12, 17]. Fluid injection and pumping in the rock mass can lead to the opening and closing of fractures and the generation of new fractures; changes in hydraulic stress result in small dynamic deformations surrounding the stimulated fracture zone. These geomechanical responses can be recorded by DAS cables mechanically coupled to the formation.

In the hydraulic tests at the Mirror Lake Fractured Rock Hydrology site, the displacement profiles obtained by low-frequency DAS can indicate the location of the fractures in the bedrock (Figure 3), which corresponded well with the previous results [11]. Therefore, this approach is feasible for understanding the hydraulic connectivity in bedrock systems.

In the hydraulic fracturing of unconventional reservoirs, low-frequency DAS was used to constrain the fracture geometry [17]. To relate low-frequency DAS patterns to fracture geometries, the relative positions of fibers and fractures, and fracture interactions, several forward models have been proposed to qualitatively interpret low-frequency DAS data [15, 16, 18], and a Green’s function-based algorithm has been used to quantitatively invert fracture geometry [13, 14].
3.3. Acoustic emission monitoring of slope failure

MS/AE monitoring is also a promising tool for early warning of slope failure. In a laboratory experiment, DAS was used to record AE signals during the failure process of a model slope [10]. The experiment showed that all deformation stages of the landslide both left a different signature in DAS and the piezoelectric sensor (AE energy rate; Figure 4). The monitoring results of the two sensors were similar in terms of trends, but there were differences due to distinct sensing principles and installation methods.

4. Advantages and challenges

4.1. Advantages

(1) Large-aperture and fine-sampling acquisition and broadband frequency response. DAS enables the acquisition of spatially dense seismic data over tens of kilometers of fiber-optic cables with meter-scale spatial resolution and provides an exceptional broadband frequency response from millihertz to
tens of kilohertz [5]. Thus, the DAS array can provide more detailed seismic signals than standard geophones.

1) Repeatable acquisition. The small-diameter fiber-optic cable is not intrusive. Once DAS cables are deployed, they provide non-intrusive, continuous, and real-time data collection. This is particularly helpful for long-term dynamic data acquisition, such as microseismic sensing and time-lapse vertical seismic profiling.

2) Dark fiber measurements. DAS can use pre-existing cables for data acquisition. There is a vast number of fiber-optic cables in urban areas and within infrastructures. DAS can establish an unprecedented monitoring network leveraging dark fibers.

3) Low cost over long periods and large areas. High-density arrays have become a widely used tool for geophysicists. The advantages of large aperture, fine sampling, and repeatable acquisition can reduce costs under tight budgets.

4) Strong environmental adaptability. Because fiber-optic cables are resistant to high pressure, high temperature, and corrosion, they can be installed in most environments. DAS systems can work in highly deviated wells, ultra-deep wells, high-temperature and high-pressure wells, small-diameter wells, and other special wells where conventional instruments cannot be deployed.

4.2. Challenges

1) Low SNR. Currently, DAS has a low SNR compared to geophones. This limits the ability of DAS to detect weak signals. Recent developments have shown that the SNR of DAS systems can be improved by reducing the background noise level or by using engineered cables.

2) Single-component sensitivity. Common fiber-optic cables can only monitor axial strains without broadside sensitivity. Some specially designed cables can provide broadside sensitivity [26] and multi-component sensing capability [27], but more field applications are needed to test their performance.

3) Large data volume. A drawback of distributed and high sampling rates is the large amount of data. A DAS array consisting of 12,000 channels sampled at 500 Hz generated 128 TB of raw data over a 3-month acquisition [28]. This size of data volume requires careful consideration of data storage, sharing, and processing, limiting the application of the DAS technology.

4) Uncertainty in spatial distance. DAS uses the time of RBS flight to position disturbances along the cable. The distance obtained is the length of the fiber-optic rather than the actual spatial length. There are some discrepancies between the two lengths because fiber-optic cables are not an ideally straight and have a considerable number of redundant segments.

5) Complexity of amplitude response. Previous research has shown that the type of fiber-optic cable [29], installation procedures [12, 30–32], and optical interferometry setups [33] can influence the amplitude response of a DAS system. Recently, Lindsey et al. showed that DAS amplitudes could be calibrated utilizing a broadband seismometer [34]. However, the transfer function needs a recalibration under different monitoring conditions, and there is presently no unified standard to calibrate DAS amplitudes.

5. Conclusions

DAS shows promise for measuring low-frequency strains and MS/AE signals induced by changes in geomechanical states, offering several advantages over conventional instruments. While further applications of DAS to geomechanics characterization are still limited by low SNR, single-component sensitivity, spatial distance uncertainty, and amplitude response complexity, the DAS technology is improving rapidly through newly designed cables and IUs. Moreover, the correlation between DAS recordings and geomechanical behavior is not yet fully understood. To accurately describe geomechanical responses with DAS, much field as well as laboratory research remains.

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