Laboratory Testing of Low Frequency Strain Measured by Distributed Acoustic Sensing
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Summary
Recent field experiments have demonstrated that distributed acoustic sensing (DAS) can be used to record strain in fiber optic cable at mHz frequencies. However, the effect of fiber optic cable construction on strain transfer has not been evaluated. The laboratory experiments presented here were designed to mimic fiber optic cable cemented into a borehole that intersects bedrock fractures. Hydraulic stress on the fracture is expected to stretch the cemented borehole which can be sensed by DAS. In the laboratory, we cemented five different fiber optic cable constructions into a pipe and then strained the pipe periodically using stepper motors. Strain was measured with DAS. The magnitude of strain measured by DAS varied by about a factor of two. These results are very preliminary, but demonstrate the importance of cable construction on the interpretation of low-frequency strain measurements.

Introduction
Distributed Acoustic Sensing (DAS) has become an established method for measurement of seismic and acoustic vibrations of interest to petroleum applications (Li et al., 2015). Most of the testing and application has been related to frequencies greater than 1 Hz. Very recently, however, low frequency response of DAS has gained attention due to relevance for monitoring hydraulic stimulation of unconventional oil and gas reservoirs (Jin and Roy, 2017) and for determining hydraulic connectivity in geothermal reservoirs (Becker et al., 2017a; Becker et al., 2017b; Becker et al., 2018).

Because the native measurement of DAS is strain rate, sensitivity is greater at high frequencies. Consequently, measurement at very low frequencies pushes the signal to noise limitations of the instrument, though improvements to DAS instruments based on engineered fibers (not tested during this study) are expected to improve the low frequency response.

If the objective is to measure strain in a formation, it is important that the DAS fiber optic cable be coupled mechanically to the formation. This has been accomplished in some experiments using temporary solutions (Becker et al., 2017b; Daley et al., 2015) but in practice the fiber optic cable is more likely to be cemented into the well. This can be done outside a production casing or in a dedicated slimhole. Cement should provide a continuous transfer of strain from the formation to the fiber optic cable. However, strain must also be transferred from the cement to the fiber optic glass itself. This strain transfer is often inefficient as downhole cables are generally designed to limit strain on the fiber to prevent damage. In addition, structures that are designed to prevent fluids from contacting the fiber glass also limit strain transfer. Fiber in metal tube (FIMT) constructions are typically used where the fiber is contained within a continuous stainless steel tube. Sometimes double walled tubes are used. A hydrogen savaging gel may surround the fiber to prevent glass darkening.

We report laboratory experiments that were designed to evaluate the influence of cable construction on low frequency strain measurements by DAS. This work was motivated by field tests that showed strains measured in different cables produced different strain magnitudes (Becker et al., 2018). We tested five different cable designs in a “core” consisting of a PVC pipe filled with Class G cement. These tests were performed a week before this writing so results are preliminary.

Method
A laboratory experiment was designed to mimic, as closely as practical, strain measurement on fiber optic cable embedded in a cemented borehole. Fiber optic cables were cemented into a 5 cm diameter clear PVC pipe and strained using a bracket operated by a stepper motor (Figure 1). A standard Class G borehole cement was used and the inside of the PVC pipe was scored with a wire brush to ensure bonding. Fibers were centered about a 5 cm diameter circle within the PVC using plastic centralizers.

Strain was accomplished using a pair of specially machined aluminum brackets affixed to the PVC pipe with a pair of shaft clamps separated by 8 cm. The brackets were strained using a pair of computer controlled stepper motors rated at 547 N force, each. Strain was also measured using a DVRT strain meter with 10 nm resolution (Lord Sensing, NANO-G-DVRT-0.5). The strain meters were mounted on a separate, outer pair of brackets clamped onto the PVC pipe (Figure 1). The entire apparatus was placed on rollers for frictionless mounting.

Strain was accomplished by instructing the stepper motor to move a certain number of moves forward (expansion) or backward (contraction). Programming resulted in an approximately sinusoidal displacement from the initial position. The amplitude and period were varied in repeat experiments, but only the 1 minute period test is presented here for brevity.

Five fiber optic cable designs were tested in the lab to quantify strain transfer through the cable construction to the
Optical fiber. All measurements were made on single-mode fiber.

1. 900 μm OD tight buffered 9/125 μm singlemode fiber: This fiber was selected as a baseline as the polymer buffering is directly coated on the optical fiber. This construction was selected over a bare 250 μm coated fiber to provide a degree of robustness during the cementing process; however, we expect the results to be similar between the two fiber constructions.

2. 1/8" double stainless-steel tube with encapsulation: This cable is a common design for downhole and industrial installations. Two 50/125 μm multimode and two 9/125 μm singlemode fibers are incorporated into a gel filled fiber in metal tube (FIMT). HDPE encapsulation brings the overall OD to ¼”.

3. 5.5 mm four-channel tactical: This all-dielectric tight-buffered cable contains two 50/125 μm multimode and two 9/125 μm singlemode fibers, aramid strength members, and a polyurethane jacket. This cable construction is commonly used for surface or shallow direct burial applications.

4. FIMT with steel wire armor/armored steel tube: This rugged design is commonly used for distributed sensing applications and contains two 50/125 μm multimode and two 9/125 μm singlemode fibers within a gel filled FIMT surrounded by stainless steel armor wires. The cable is then encapsulated with HDPE bringing the overall OD to 4.2 mm.

5. Specialty strain and acoustic sensing cable: This design incorporates a single 9/125 μm singlemode optical fiber into a small diameter FIMT filled with a coupling resin to maximize strain transfer from the FIMT to the fiber when compared to a typical gel filled FIMT design. The FIMT is then encapsulated with a polyamine outer sheath. Overall diameter is 3.2 mm.

Dynamic strain rate was measured using a Silixa iDAS™ system. Sampling rate was 1 kHz and a strain measurement is reported every 25 cm. The measurement gauge length was 10 m. The gauge length, consequently, was much larger than the zone of strain in the core. Simulations have shown that 90% of the strain is confined to a zone about 3 times the core diameter from the strain locus (Becker et al., 2018). The additional cable was stabilized so it moved with the displacement of the core. Consequently, only strain in the core between the two shaft clamps was measured by the DAS. The five cables were spliced in series into a single length to allow simultaneous measurements to be made on all cables. Additional fiber was added between the tested cables to isolate each tested cable so that there was no overlap between strain measurements in each section of measured cable. Cable mapping was conducted using tap tests to identify the DAS channel locations in each cable.

Results

A dependence of strain on cable design is clearly visible in the DAS response. Figure 2 shows the amplitude of strain rate in response to the periodic stress imposed by the stepper motors. The ordinate scale should be considered arbitrary in this plot as strain rate has not been converted to strain. However, the relative responses will hold also for strain.

The cable constructions associated with measured DAS channels are indicated by numbers 1-5 in Figure 2. These numbers correspond to the cable constructions enumerated in Methods. The strain response in Cable 1 was about twice the response of Cable 2, for example. Cable 1 is considered...
the most accurate measurement of strain in the cement core due to its small diameter and because the glass fiber is directly buffered in flexible polymer material. Cable 3 turned out to be nearly as sensitive to strain. This “tactical” cable is a tight-buffered construction with the fibers and aramid jacketed with a flexible polyurethane, although the jacket is thicker and overall construction is much larger diameter than Cable 1. Cables 5, 2, and 4 all produced similar strain responses. Poor responses from Cables 2 and 4 were expected as both are gel-filled fiber in metal tube (FIMT) constructions. Surprisingly, the specialty strain-sensing FIMT cable (Cable 5) did not perform significantly better than standard gel filled FIMT constructions. The fiber in Cable 5 is coupled to the tube using a special resin rather than gel, which is designed in enhance strain transfer.

Conclusions

The reader should be cautioned that these results are incomplete and preliminary. The tests were conducted the week prior to the submission of this abstract. Consequently, we are not yet prepared to report a comparison of DVRT and DAS strain measurements or the effect of strain oscillation period (strain rate) on strain measurement.

The preliminary results do make it clear that cable design has a profound impact on DAS dynamic strain sensing. For the cable designs tested, strain sensitivity varied by a factor of two. The most reasonable cable design for downhole DAS applications (Cable 2) measured about half the strain magnitude as the simple (near bare) fiber construction (Cable 1). The dependence on cable design may not be noticed in seismic sensing because higher frequency strains create greater drag between the fiber and its protective tubing. At low frequencies, the fiber may have time to slip within the protective tubing. We believe we may have observed this in previous low-frequency laboratory experiments (Becker et al., 2017a).

These tests were designed to mimic localized strain induced by a fracture undergoing hydraulic (normal) stress on the fracture surfaces. In a real borehole, the blocks of rocks on either side of the fracture would be expected to move in opposite directions, and distribute displacement over many meters of borehole. We could not replicate this effect in our laboratory experiments. In addition, fiber is typically “overstuffed” into tubing to prevent damaging strains during deployment and to compensate for the thermal expansion coefficient difference between glass fibers and steel. This extra fiber length (EFL) obviously leads to some reduction in sensitivity but is difficult to assess in a short section of cable.

Likewise, seismic strains are propagated over a longer section of cable which creates greater drag between fiber and the protective tubing. Strains at fractures are applied very locally which may induce greater slip of fiber in the protective tubing. We apply strain very locally in these laboratory experiments but cannot distribute this displacement as there is only about a half meter of cemented core on either side of the strained section. Consequently, there may be greater slip of fiber in tube in these laboratory experiments than would be observed in the field.

Distributed dynamic strain sensing at very low frequencies is a new application of DAS and, consequently, begs further testing and research. The laboratory experiments described here suggest that strain sensitivity can be impaired by protective cable structures such as gel-filled metal tubing. These structures are critical for protection of the fiber, however, and cannot be avoided. Strain measurements will need to be calibrated for particular fiber optic cable constructions for any highly quantitative dynamic strain sensing applications.

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