Chapter 11
Collapsing Distributed Fiber Sensors to Point Measurements to Boost Signal-to-noise using Custom-designed Fiber Coils

Angel H. Chafino, Serena A. Vu, Reganne M. Watts, Steven R. Anton, Carly M. Donahue, Andrew K. Harter, Nathan T. Maier, and William A. Redford

Abstract After structural failures like those caused from natural events, the ability for search and rescue teams to locate people is essential to saving lives yet one of the most difficult to complete. Distributed Acoustic Sensing (DAS) has emerged as a versatile and innovative technology that uses a pulsed laser to turn a regular fiber optic cable into an array of vibrational sensors that can prove useful for these scenarios. We propose a novel application of DAS to detect ground propagated waves using surface deployed fiber sensors which could prove to be pivotal for search and rescue efforts. However, two main challenges still exist with this technique; coupling the fiber to the medium of interest, and the reduction of unwanted noise which dictates signal-to-noise ratio (SNR). Here we present experimental results testing different fiber sensor designs which can be integrated into fiber and used to improve SNR for surface deployed scenarios. The sensors are based on fiber coils, which both amplify the signal and allow for noise mitigation techniques. We characterize coil geometry effects on SNR values and the effectiveness of various coupling techniques for detecting ground propagated waves in a field environment. A strain gauge coil geometry greatly improved the SNR and implementation of sensor compression allowed for a compact point sensor; this was successfully implemented into a weighted roll-able noise dampening fabric, significantly improving the amplitude of impulse signals.

Keywords Distributed acoustic sensing (DAS) · Fiber optics · Earthquake monitoring · Emergency response · Point sensors

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Kristin B. Zimmerman, PhD (eds.), *Special Topics & Experimental Techniques in Structural Dynamics, 2026, Vol. 5*, Conference Proceedings of the Society for Experimental Mechanics Series, https://doi.org/10.1007/978-8-743-81444-3_11

Introduction

Distributed acoustic sensing (DAS) has rapidly gained popularity in various fields including seismology, structural health monitoring, and disaster response due to the ability to collect large amounts of data from one fiber [1, 2]. While many researchers have used existing underground telecommunication optical fibers for DAS, these fibers may not exist in the desired sensing areas and are limited to their existing installation configurations. Due to its versatility and live imaging capabilities, we believe DAS could play a pivotal role in rapid response rescue scenarios as it would allow for coverage of a large area with the potential of being rapidly deployed with only one single optic fiber cable. Surface deployment of optical fiber is an emerging sensing method as it allows for temporary deployment of an array of sensors and can be done in areas where trenching is infeasible, such as in emergency response scenarios or environmentally protected land. Rapid installation of surface deployed optical fiber has its own challenges due to fiber sensitivity to wind noise and poor coupling of the fiber to the ground. This paper focuses on evaluating various methods of coiling, coupling, and wind reduction for surface deployed fiber optic cables.

Background

The DAS system consists of an interrogator, which is an electrical unit connected to one end of an optical fiber. The interrogator emits a laser pulse down the fiber and measures the phase shift of Rayleigh backscattering to determine the strain rate of the fiber. Strain rate is averaged over gauge lengths and binned into channels, which are equally spaced in the fiber. The gauge length for the interrogator used in this work is 10 meters. Small perturbations in the fiber location due to acoustic signals alter the interaction of the pulse with the fiber and thus the signal that is received [1].

DAS has found wide applicability in the field of geology as a tool for seismology, subsurface structure imaging, fluid pressure sensing, and studying various other underground phenomena [2, 3]. It has also been used to detect hypersonic vehicle entry and bird calls which shows its versatility and desirability among a wide range of disciplines [4, 5].

While it has shown its versatility, there are still challenges to fully apply this system for rapid deployment using surface fiber. DAS is directionally sensitive, or only able to detect disturbances that cause longitudinal strain on the fiber. It is also highly impacted by the quality of coupling to the desired sensing medium and the configuration of the fibers. Various researchers have found that coiled fibers increase the signal-to-noise ratio, making it more advantageous over straight fiber. This coiling allows a standard gauge length of fiber to be collapsed into a single point sensor, increasing its amplitude and decreasing directional sensitivity as it allows for a portion of the fiber to always have longitudinal strain [5, 6, 7, 8].

Traditional surface deployment methods of fiber optic cables for DAS involve unspooling the fiber on the ground and pressing it into the surface by walking over it [9]. While quick to execute, this results in poor coupling with the desired sensing medium. Various methods have been proposed to improve surface deployment methods for distributed sensing arrays, including using soft robotics, towing the cable behind a vehicle, and a roll-able blanket of sensors [10, 11]. However, these methods can be bulky, time-consuming, and often unfeasible for rapid response.

Our goal is to design an adaptable and easily deployable array of fiber optic point sensors. While there has been research in coiling of fiber and its applications, there is a lack of research into rapid deployment techniques and the viability of only using surface deployed fibers. The goal of this study is to evaluate various methods of coiling, coupling, and wind reduction for coiled optical fiber sensors to guide future work on a rapid deployment mechanism.

This paper begins with a discussion of our instrumentation and coil design. Then we discuss data collection and field layouts. Afterwards we discuss the results of the various tests and conclude with a discussion of future improvements to the rapid deployment system.

Methods

Fabrication

All the coil geometries were fabricated using ABS filament printed with an infill of 15% using a grid pattern in order to reach a higher first natural frequency based on previous research [12]. This shifted the first resonance frequency outside of excitation range of our shaker and any frequency of interest to ensure that the printed components did not impart any external behaviors into the coil system.

We coiled a single-mode optical fiber from Thorlabs (SMF-28-100), which has an operating wavelength of 1260 to 1625nm, around the geometries presented in Figure 1. This fiber has a 900μm diameter jacket and a minimum bend radius of 3.75cm for long-term storage. The radius for all curves used in the coil designs is 4cm to satisfy this requirement and prevent the fiber from experiencing unnecessary strain. Additionally, the wall thickness of these designs are 1cm thick. We spliced all coiled sensors as a continuous fiber to enable the evaluation of all sensors simultaneously, if desired.

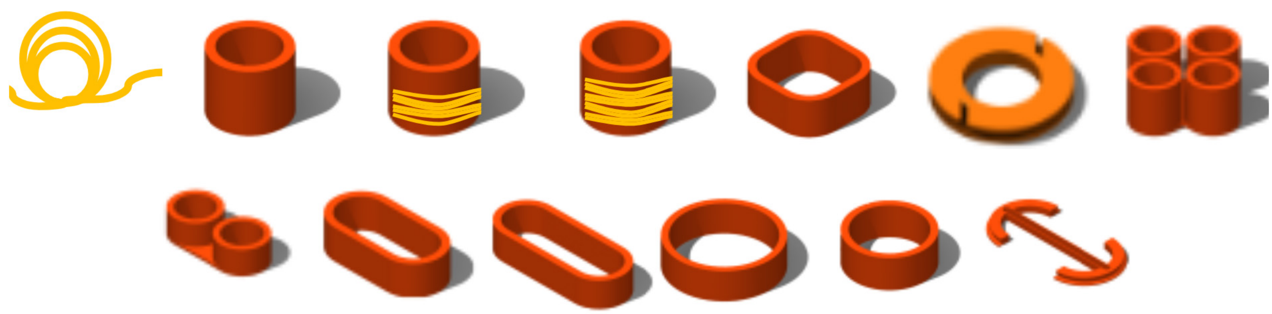

Fig. 1 Top row left to right: plain coil, standard disk, two gauge, three gauge, rounded square, layering disk. Bottom row left to right: infinity, 1 to 2 aspect ratio, 1 to 2.5 aspect ratio, 2x diameter, 1x diameter, low frequency.

Additionally, we used the Finite Element Analysis (FEA) package in SolidWorks to design a coil geometry that combined the aspect ratio and layering disk designs and could be excited by the frequencies supplied by the shaker. We hoped that the vibrations and mode shapes would increase the strain in the fiber and therefore the signal we were detecting. The resulting design and first natural frequency is shown in Figure 2. The accuracy between the FEA model and the environment was not of high concern, and so the analysis was done using a free-free boundary condition when designing for the lowest frequency. This design was printed with 100% infill to best simulate the finite element model. It is understandable that once printed and placed on the ground the fidelity of the model to the actual component will vary. However, we believed that a small exploration of this concept would still prove valuable.

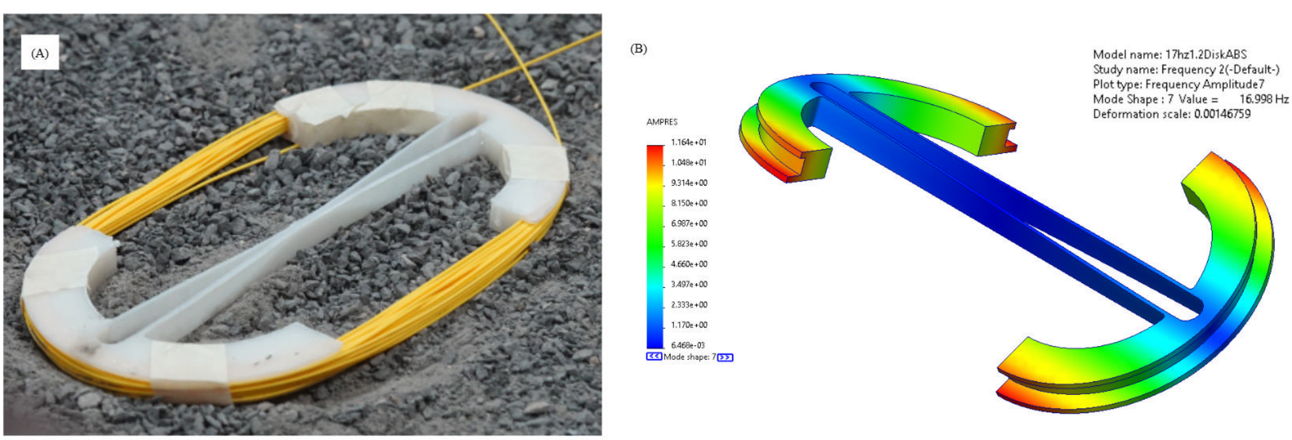

Fig. 2 (A) The fabricated coil design and (B) the finite element analysis showing the 7th mode within those being excited by the shaker.

Taking inspiration from geophone covers and other wind dampening mechanism, we 3D printed a 4 prong basket shape that could easily be placed on top of the coil without disturbing its boundary conditions to the ground. The material is easily hot glued onto the basket which has a minimal area to ensure that the basket itself is not inducing any dampening. As shown in Figure 3, we evaluated four different materials: a quilted fabric, felt, rubber, and an acoustic foam.

We also looked at a high density foam (0.048 g/cm^3) and a low density foam (0.029 g/cm^3) cover with weighted edges and a divot to completely encase the coil, shown in Figure 4.

For coupling methods, we tested a 25lb weight, a 50lb weight, a stake, and covering the coil with a small shovelful of sand. The stake was designed to be modular with the layering coil disk. This was done so we could use the same sensor for each test and only modify the coupling mechanism. These methods are shown in Figure 5.

Our rapid deployment design was inspired by seismic land streamers which are arrays of geophones towed behind a vehicle. We also took elements from our coil geometry studies and coupling/wind tests to build our land streamer shown in

Fig. 3 (A) The rubber basket, (B) the quilt basket, (C), the acoustic foam basket, (D) the felt basket, and (E) an underside view showing the 3D printed base for each of the baskets.

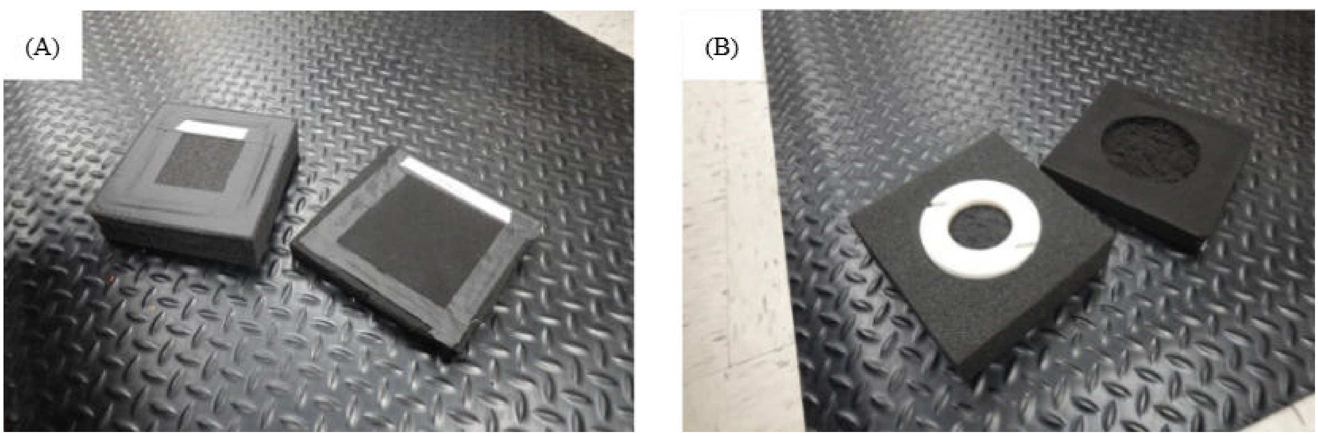

Fig. 4 (A) Top view of the two foams with low density on the left and high density on the right. (B) Bottom view of the two foams with a disk inside low density on the left and high density on the right.

Figure 6. The body of the land streamer was made from an acoustic deadening fabric cut into 7in wide strips and then pieced together into a 21ft long strip. We glued six layering disk coils to the bottom and taped four 3oz weights around each coil to help couple it to the ground. To deploy the streamer, one end was rolled up so a bundle was created that could quickly be rolled out on the field.

Indoor Testing Environment

To minimize external noise sources, we conducted individual coil SNR tests in a 10m by 0.53m wooden box filled with basalt sand shown in Figure 7. Previous work had found that the box has a resonance at 30Hz which greatly impacted the response of the fibers within. In order to ensure that comparisons can be made between different coil geometries, a particular interest is set on frequencies lower than 30Hz and all coil geometries are placed in the same location to mitigate areas of nodes and anti-nodes within the box.

We used a shaker located at one end of the box to generate a step sine wave in the frequency range of 15 to 40 Hz. The shaker was controlled as an open loop using TiePie to supply 10-second steps in 1Hz increments to achieve steady state. Smaller step increments were not considered due to time constraints.

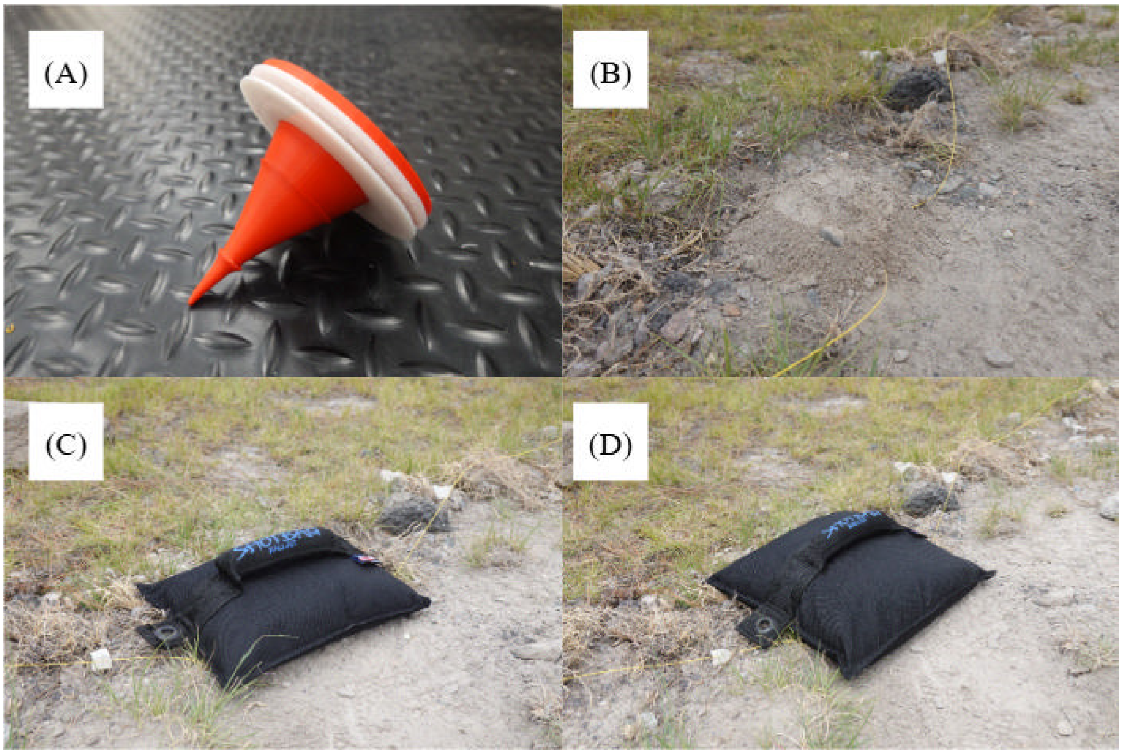

Fig. 5 (A) The modular stake design, (B) adding medium to simulate buried conditions, (C) the 25lb shot bag, and (D) the 50lb shot bag.

Fig. 6 One of the coils attached to the bottom of the land streamer

Fig. 7 The 10m long wooden box used as an indoor testing environment

Outdoor Testing Environment

For outdoor testing, we used a large field located on laboratory campus, shown in Figure 8. We dug a trench 6in deep and buried 100m of tactical optic fiber to serve as a reference for our rapid deployment measurements. This is largely informed from previous research showing that the best coupled fibers are those that are buried underground, as it allows for a more direct measurement of the ground strain and reduces the wind noise. We wanted to compare the best known coupling and wind reduction method to our rapid deployment designs. Existing fibers that are underground and used for DAS are generally in conduit reducing its coupling with the ground. We then deployed a single coil on the fiber to perform our coupling methods on to make the assumption that manufacturing variations had no impact on the response of the coil.

We used a PCB 086D20 modal sledgehammer to generate our impulses. The medium tip was selected to excite frequencies between 0 to 300Hz. To avoid damaging the modal hammer and creating a hole from repeated impacts, an aluminum block was placed to take the impact at the 2m, 5m, and 10m distances away from the surface deployed coil. Three impacts were captured at each location, using a proprietary Matlab script and a National Instruments USB-4431 to make sure analyzed impacts were between 9,000 and 11,000 Newtons. For the coupling methods, we only tested impacts that were perpendicular to the fiber while the land streamer had impacts both perpendicular to and parallel to the fiber. The interrogator recorded the entire testing session of 9 impacts, and the data from the impulse collection was used to obtain a 4 second range of where the impulse from the hammer occurred.

Results and Discussion

Indoor Testing

Coil SNR

To calculate the SNR for the various coil geometries, we took a 5 second sample of the signal at each excited frequency and a 5 second snippet of noise at the same frequency. We then used Equation 1:

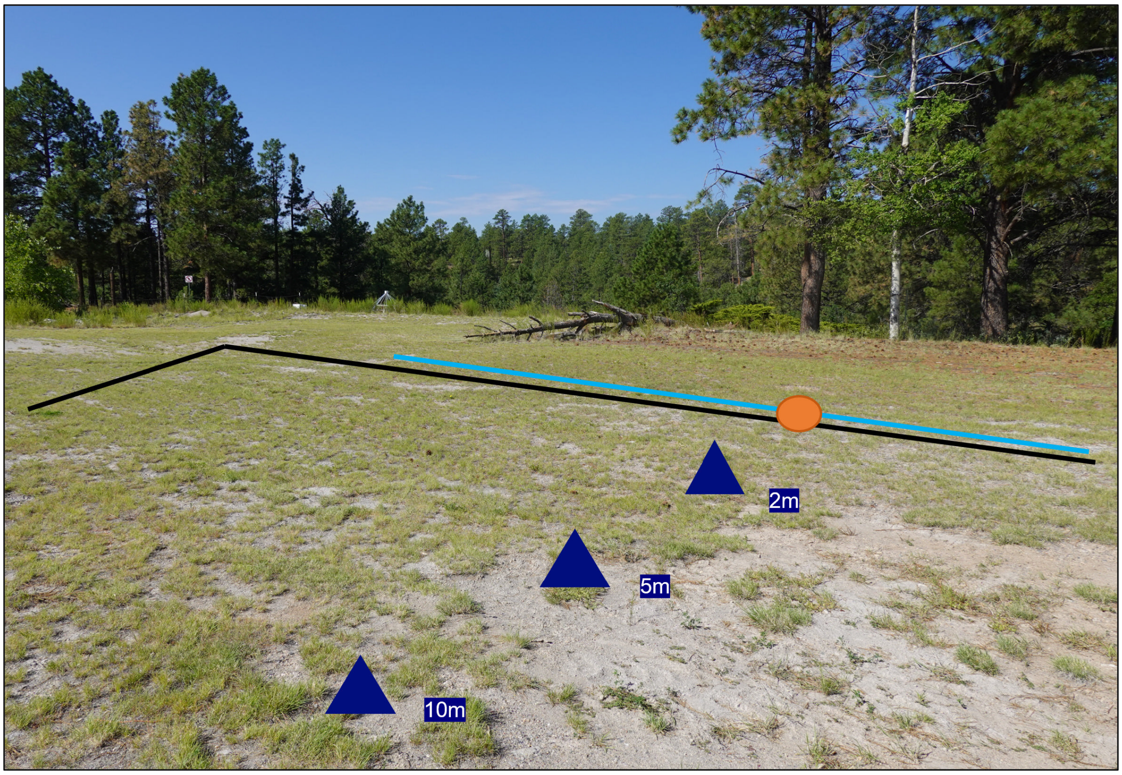

Fig. 8 A ground view of the outdoor testing environment. Triangles represent the location of perpendicular to the fiber impulse locations (2, 5 and 10 meters) while the circle represents the sensor used to test the coupling methods and wind mitigation.

$$SNR = 10\log_{10}\frac{A_S}{A_N} \tag{1}$$

where A_s is the mean amplitude of the signal at the given frequency and A_N is the mean amplitude of the noise at the same frequency.

We repeated this process for each frequency that was excited. We then calculated the mean SNR below 30 Hz, which was the first resonant frequency of the box, and the mean SNR above 30 Hz, which included the box resonant frequency. As shown in Figure 9, we compared the SNRs for each of our coil geometries. All of the geometries performed better than a plain coil looped without any base geometry both above and below the box resonance. The coils generally followed the same trends even above the box resonance, however particular emphasis will be taken for those below this region where the box is well characterized.

When comparing the usage of having multiple gauges, the two and three gauge coils provide a marginal SNR increase when compared to the standard and plain coils. We did not find the increase in SNR to be significant enough to justify taking the time and manufacturing effort to spool the larger amount of fiber onto one coil. Interestingly, it was also found that layering the fibers on top of each other did not negatively impact the SNR of the coils which allows us to design more compact sensors which are easier to rapidly deploy without greatly affecting the response, when compared to the standard single layer coils.

For the aspect ratio geometries inspired by strain gauges, we observed an increase in SNR both above and below the box resonance when compared to the plain coil. However, there was not a substantial difference between the 1:2 and 1:2.5 designs likely due to only an inch being added to the longitudinal sides. These findings held up with previous research that used fiber as a strain gauge and supports the principle of the fiber having higher response to longitudinal strain. The low frequency design did not perform better than the regular aspect ratio however, it did produce a smaller standard deviation in the mean SNR both above and below the first box resonance frequency.

When comparing the standard and plain coils to the 1.5x diameter and 2x diameter (where 8cm is 1x diameter), we see significant variations above and below the box resonance. The 1.5x diameter has a smaller standard deviation both above and below the box resonance. When only looking at the SNR below the box resonance, the 1.5x diameter has a greater mean

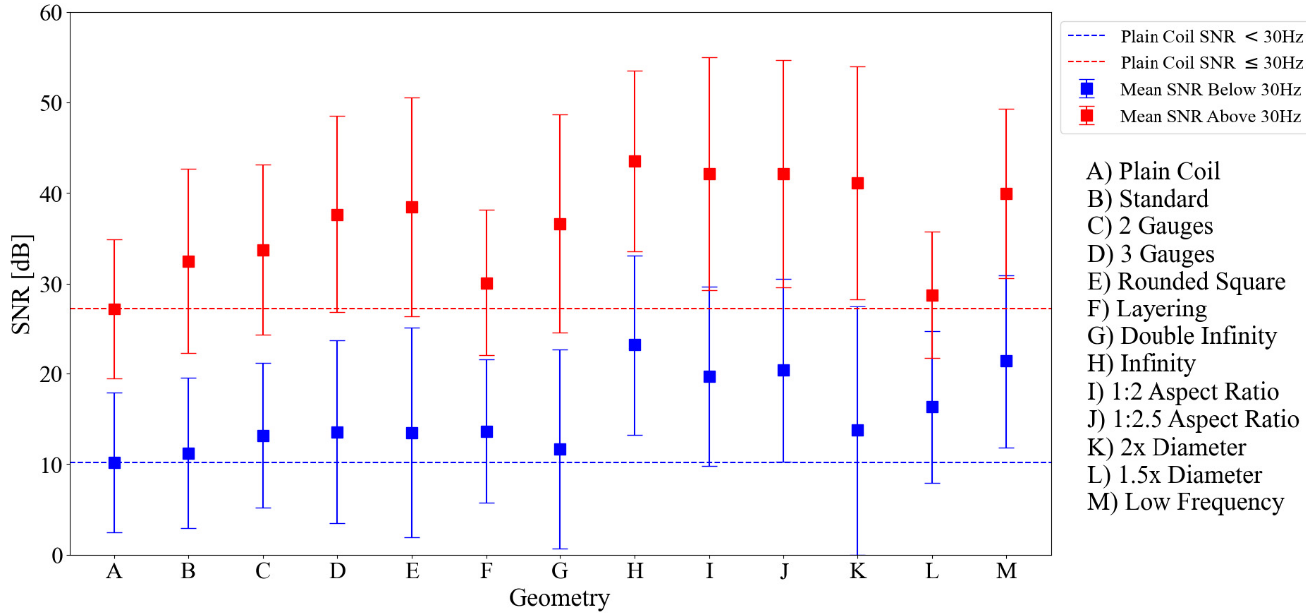

Fig. 9 A Plot of all calculated SNRs for the various coil designs. The boxes are separated into two data sets corresponding to responses above or below the box resonance of 30Hz. The bars represent one standard deviation of the mean amplitude.

SNR than the 2x, while the converse is true for SNR above the box resonance. We expected to observe an increase in the SNR as the diameter got larger. However, only a small sample of diameters were tested, so trends, plateau, or correlations are indiscernible and require more testing to characterize.

We create novel coil geometries to explore the idea of having coils with longitudinal sections at different angles in an attempt to increase the signal by having more fiber in regions that will be responsive to a perpendicular wave. The infinity has the highest mean SNR both above and below the box resonance frequency. The rounded square has a slightly larger SNR than the double infinity. This suggests that utilizing a variety of angles in the sensor can positive impact the sensor's ability to detect impacts.

Outdoor Testing

Coupling Methods

From the output of the modal sledgehammer, we found that the magnitude of the force input and the amplitude of the signal recorded by the coil have a highly nonlinear relationship. We averaged all three impulse time series recorded by the coil at each impact distance (2, 5, and 10m) from the coil. The results of this averaging are shown in Figure 10. Due to fluctuations in the noise floor and an uncontrolled environment, we couldn't calculate the signal to noise ratio for the different coupling methods.

Both the 25lb and 50lb weights substantially increased the SNR when compared to the plain coil, especially at the 10m impact distance where there are still prominent peaks in the data. Both the stake and scoop of sand did not increase the amplitude and the impacts were indiscernible from the noise at the further distances. This suggests that weighing down the coils helps them couple to the ground and allows them to detect signals from farther away.

Wind Reduction Methods

To control the wind noise source, we placed an industrial fan approximately 1.5m away from the uncovered coil. We then compared the mean amplitude of 5s of noise taken after the last hit was produced. In Figure 11, the values were then normalized by the uncovered coil so values <1 indicate a reduction in noise while the values >1 indicate an increase in noise floor.

The basket materials that show promise for wind reduction were the acoustic foam and the felt as they all had smaller mean noise values and error bars than the uncovered coil. The quilt material performed similarly to the plain coil while the rubber had a slightly higher mean noise than the plain coil.

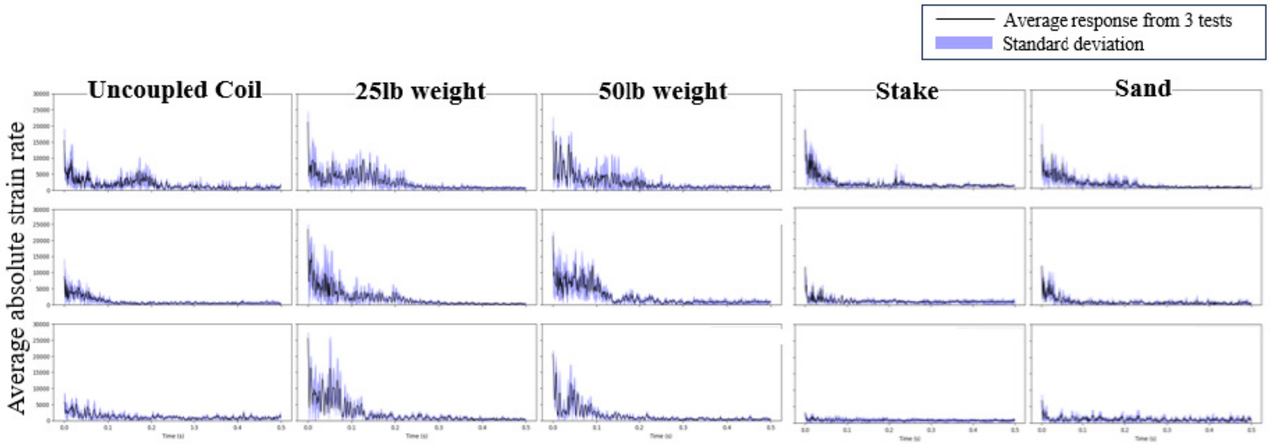

Fig. 10 A series of plots showing the average response of the coil and the standard deviation for 0.5 seconds after the impulse at 2m, 5m, and 10m.

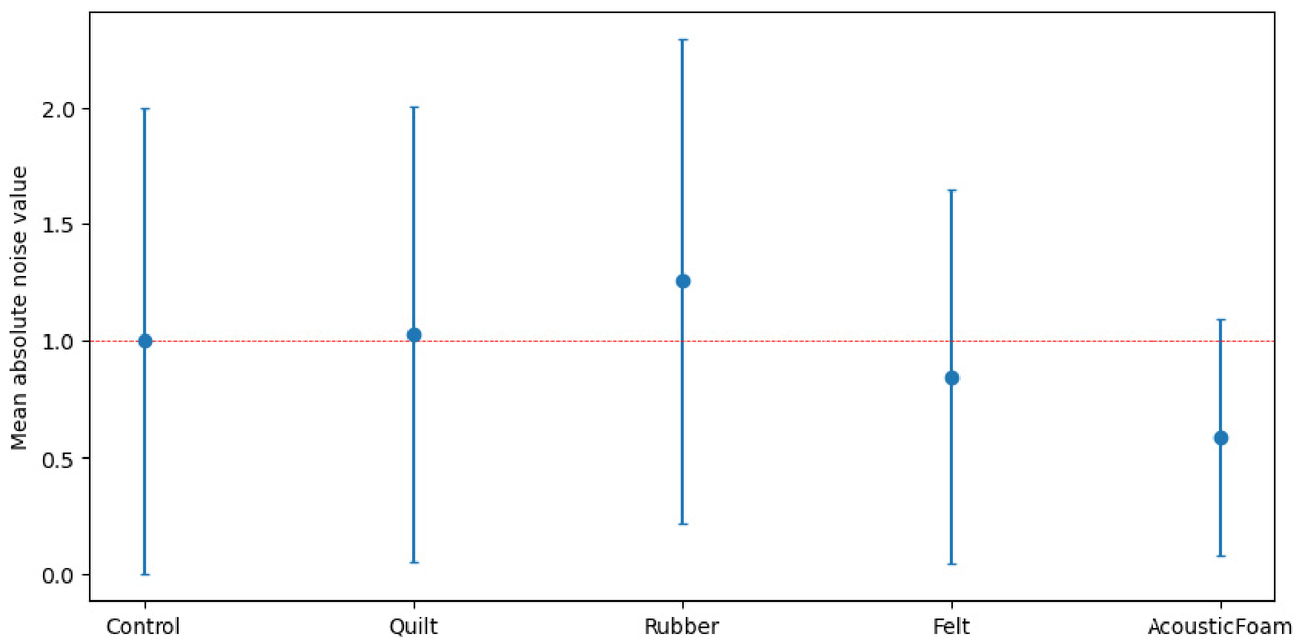

Fig. 11 A comparison of the normalized noise values for the various basket coverings. The error bars representing one standard deviation of the mean.

When comparing the two weighted foam squares, low density foam had a higher mean noise and a higher standard deviation than the high density foam as seen in Figure 12. One possible reason for this increase is that this foam block was approximately an inch taller than the high density foam block which would make it less aerodynamic, possibly introducing more wind noise into the system.

Land Streamer Deployment

The land streamer was able to clearly detect impacts at all three distances, as shown in Figure 13. While they is more noise than the ground fiber, the impacts are still prominent among the spectra. Due to the prominence of the peaks at 10m, we believe the streamer could clearly detect impacts even further away.

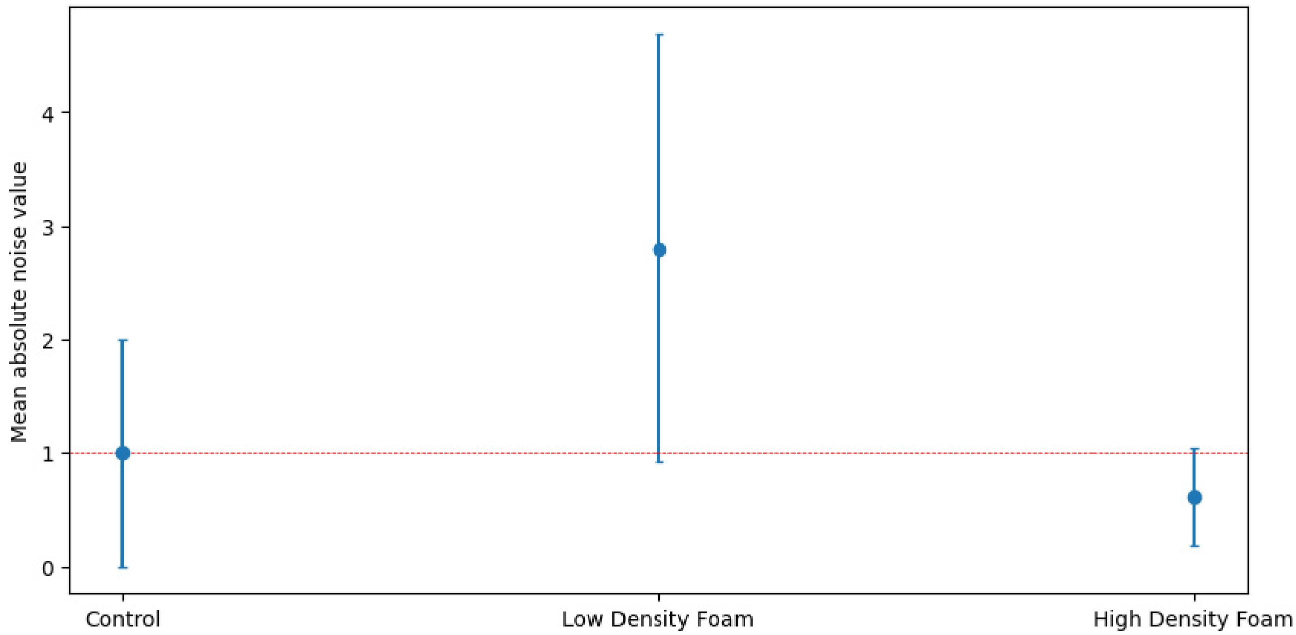

Fig. 12 A comparison of the normalized noise values for low and high density foam blocks as wind reduction methods. The error bars represent one standard deviation from the mean.

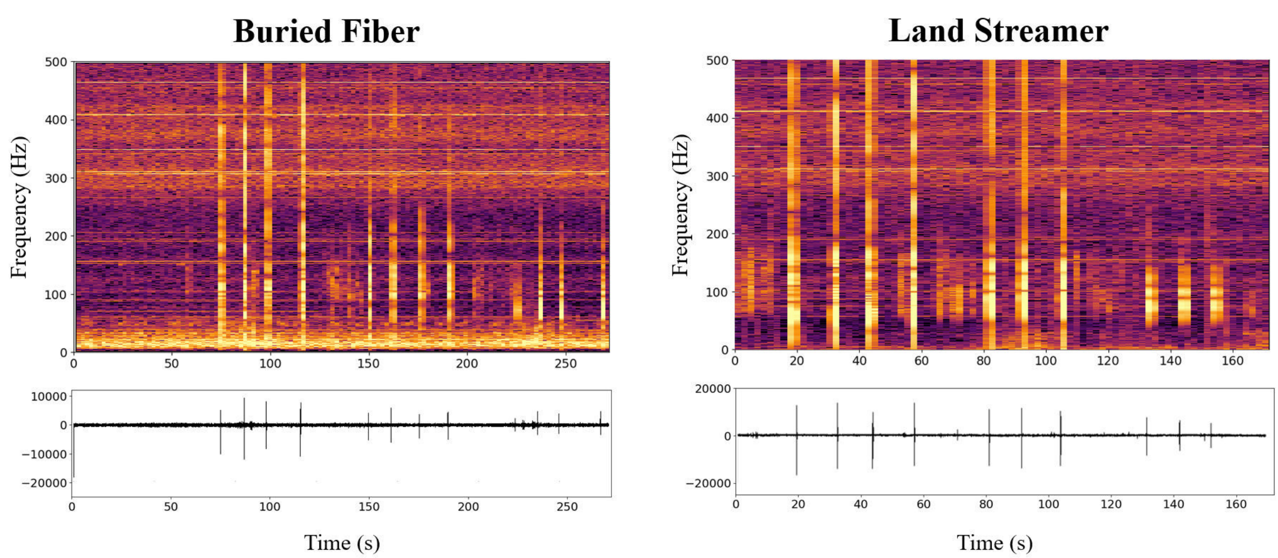

Fig. 13 A comparison of the waterfall plots for the land streamer and buried fiber. The first group of impacts are at 2m, the second group are at 5m, and the last group are at 10m.

Figure 14 shows the mean amplitude for the impacts tangential (along the fiber) and normal (perpendicular to the fiber) for the buried fiber and the land streamer. The land streamer has a similar amplitude for impacts in both directions, showing that we were able to reduce the directionality of the fiber and make a more omnidirectional sensor. We also noted that, despite rolling and unrolling the land streamer several times, there were no fractures in the fiber showing promise for future rapid deployment designs using this method.

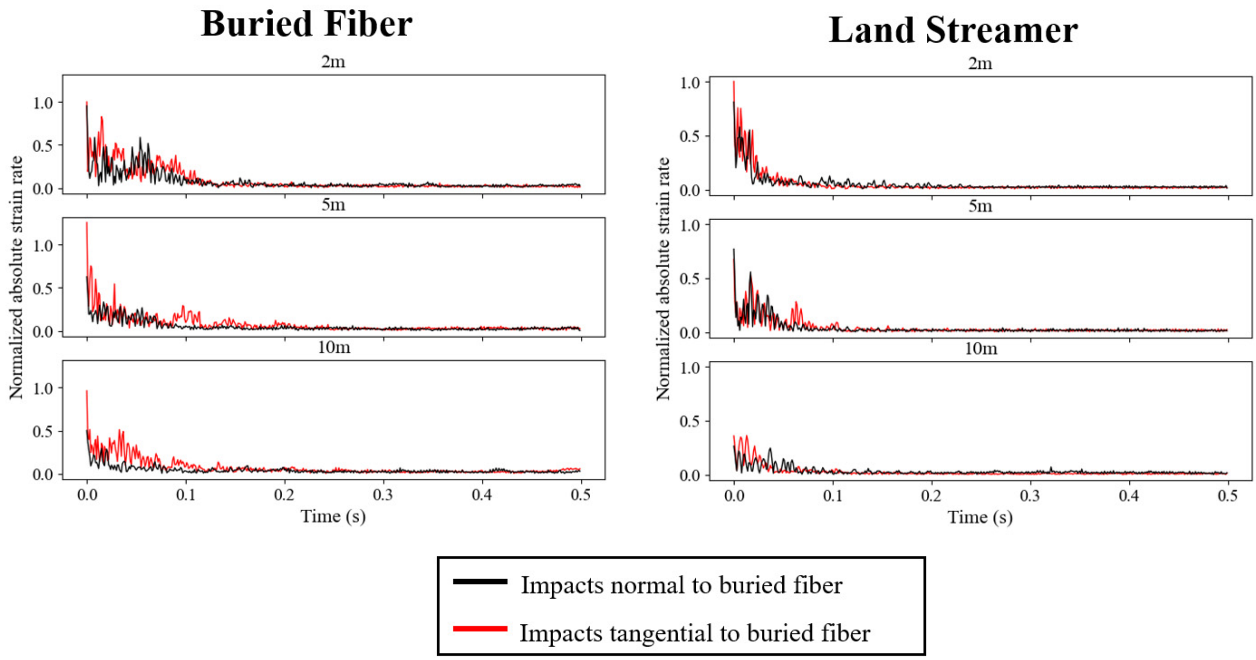

Fig. 14 A comparison between the average amplitude of the land streamer and the buried fiber at the given distances.

Conclusion

Design Recommendations

From the various experimental results, we have several design recommendations regarding future fiber optic point sensor coiling geometries. One of the most appealing is that layering fibers does not have a significant impact on SNR. This implies that smaller compact coils can be created and implemented into rapid deployment methods. We believe this is applicable to any coiling geometry and thus could be combined with the most responsive geometry, if layering can be integrated into the design. Although fiber is inherently directional, this can be used advantageously to create more sensitive coils by forming long longitudinal sections. This is particularly supported by the aspect ratio and infinity geometries, as these contained long sections of fiber that could still be compressed to a point sensor and sense ground propagated waves. This can be used both for directionality if the source direction is known or omnidirectional sensing by ensuring symmetry of the longitudinal sections like that of the infinity and double infinity. Additionally, it is clear that weighing down the coils leads to an observable improvement in the amplitude of the signal as both the 25lb weight and the 50lb weight improved the signal at all distances.

Rapid Deployment Feasibility

We were able to easily manufacture the land streamer and meet all of the design requirements. Our design showed significant reduction in the noise floor of the fiber, especially when compared to a plain coil, while also improving the response at larger distances. We were able to easily roll and unroll the land streamer without damaging the fiber, showing promise for future designs that involve unrolling long strings of fiber point sensors.

Future Work and Experimental Recommendations

Future work should be done to better optimize the coiling geometry, looking into more complex simulations and optimization algorithms based on the findings presented here. Additionally, more thorough laboratory studies should be done on the wind reduction methods in order to confidently quantify the response of various materials.

Acknowledgments This research was funded by Los Alamos National Laboratory (LANL) through the Engineering Institute's Los Alamos Dynamics Summer School. The Engineering Institute is a research and education collaboration between LANL and the University of California San Diego's Jacobs School of Engineering. This collaboration seeks to promote multidisciplinary engineering research that develops and integrates advanced predictive modeling, novel sensing systems, and new developments in information technology to address LANL mission relevant problems. The authors also thank Jason Martinez for providing 3D printers and guidance throughout the project.

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