CAAP Quarterly Report

06/30/2023

Project Name: *Easy Deployed Distributed Acoustic Sensing System for Remotely Assessing Potential and Existing Risks to Pipeline Integrity*

Contract Number: *693JK3215002CAAP*

Prime University: *Colorado School of Mines*

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Reporting Period: *[03/31/2023 – 06/30/2023]*

Project Activities for Reporting Period:

During the reporting period, we have been mainly focused on Tasks#3-6, that concentrate on the integrity assessment using DAS for steel pipes. The activities for each task are discussed in the following subsections.

Besides the technical progress that will be discussed later, to ensure a smooth progress during this summer when the two Ph.D. students assigned to this project are both out for internship, we were able to hire 3 other students temporarily for this project, including 1 Ph.D. student and 2 undergraduate students as student helpers. In this period, we organized several intense trainings for these new students. Fortunately, we've made noticeable progress and the overall activities are all on track.

During the past period, we were able to collect data for Task #3 – corrosion detection for a pipe with 3mm corroded depth, Task #5 – infrastructure damage for sparsely supported pipe, and Task #6 – leakage detection at various gas flow rates, leakage sizes, and orientations. Figure 1 is a schematic diagram showing the order of fiber cable connections on the steel pipe. Tap tests were carried out to identify and map the beginning and end of each fiber cable on the steel pipeline.

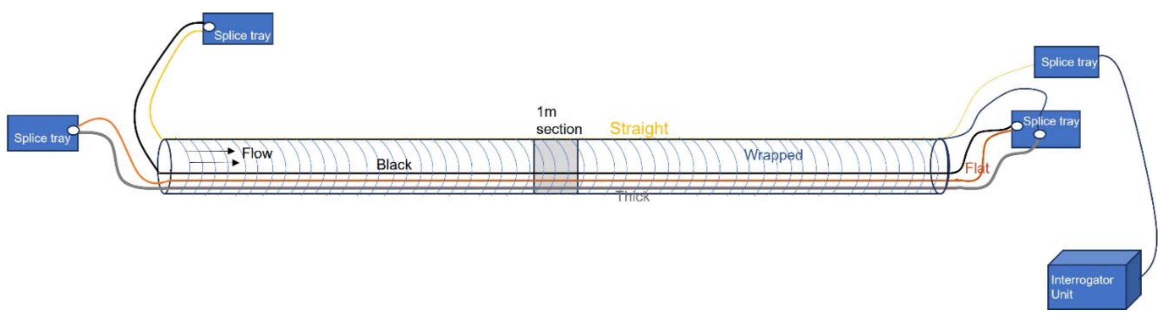

Figure 1. A schematic diagram showing the order of cable connection on the steel pipeline. The two black arrows indicate the direction of flow. Order of looped cable: Straight – Black – Flat – Thick – Wrapped.

Task #3. Detection of Corroded Spots on Pipeline Interior Surface

For this task, we have completed the experiments using a 1-m test section with a 3 mm corrosion depth at 6'clock position, at sparsely supported condition (5 supports). We aim to identify the corrosion-induced inter-surface roughness using DAS. This roughness may generate a stronger local turbulence that could potentially be detectable by the internal cables. Preliminary data analysis, however, has shown only slight variations between the baseline (no corrosion) and measurements taken at a corrosion depth of 3 mm.

Figure 2 provides a visual representation of 0.2 seconds' worth of raw DAS data, illustrating examples from black and flat cable sections.

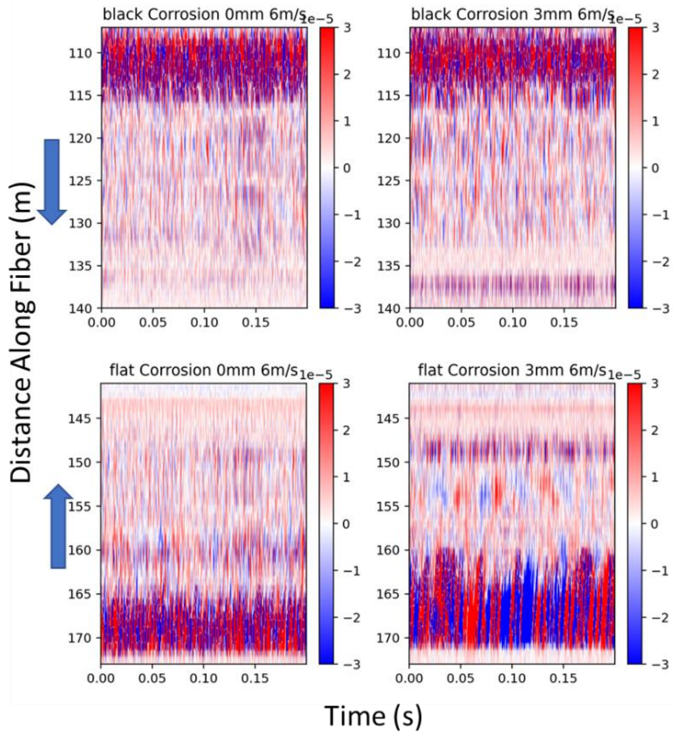

Figure 2. Examples of raw DAS data waveforms from black and flat fiber sections for Task#3. Left column shows the baseline without corrosion, and right column shows measurements with the pipe with 3-mm corroded depth. Blue arrow shows the gas flow direction in the fiber sections.

For a more quantitative comparison, we calculated the average vibration amplitude over an eight-minute period within the frequency range of 100 Hz to 1000 Hz. This amplitude, plotted against fiber distance, is depicted in Figure 3. The measurements were taken at a velocity of 6 m/s, and similar results were obtained at other velocities.

Our results demonstrate that, even after a complete reinstallation of the flow loop to replace a 1-m section in the middle, the DAS measurements within each section are remarkably consistent. This consistency testifies to the repeatability of our experimental setup.

Since 3 mm represents the minimum designed corrosion depth, it's plausible that the internal cables may not be sensitive enough to detect such minor corrosions. In the future, we will enhance our data analysis methods to more effectively extract useful data attributes for corrosion detection. Simultaneously, we will also explore this issue further by assessing deeper corrosion depths, aiming to determine the degree of corrosion that DAS measurements can detect. We are currently preparing another 1-m test section with a target of ~5.8mm corrosion depth. Pictures of the experimental setup and the interior of the corroded test section is given in Figure 4.

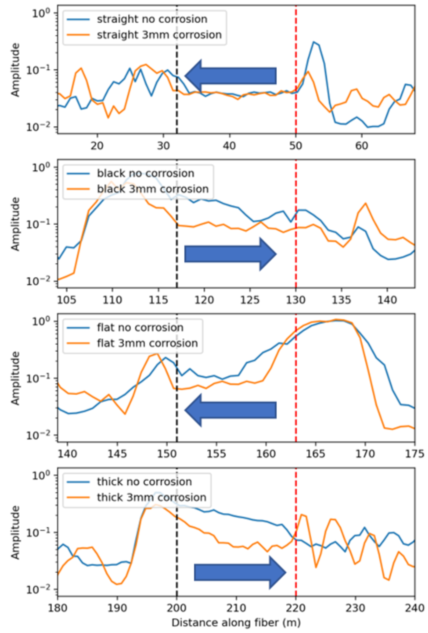

Figure 3. Vibration amplitude comparison at different fiber sections (straight, black, flat, and thick) between the corroded pipe and the baseline. These measurements were taken with a gas flow velocity of 6 m/s, and the data were filtered between 100 Hz and 1000 Hz. The arrow shows the flow direction compared to the fiber distance. Black and red dash lines mark the beginning and end of each section.

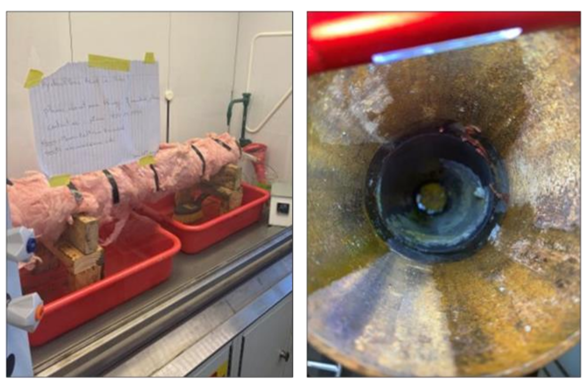

Figure 4. A picture of the experimental setup for corrosion preparation (left) and the interior of the corroded test section (right).

Task #4. Detection of Dent/Deformation on Pipeline

In this reporting period, we have been working with the Machine Shop at Colorado School of Mines on creating the dent on the 1-m test section. The effort is ongoing. At the same time, we are consulting the other departments at Mines, such as EMI (The Excavation Engineering and Earth Mechanics Institute), to help us with creating the dent. We are hoping to get this done in the next reporting period.

Task #5. Detection of Infrastructure Damage

During this reporting period, we finished the experiments for infrastructure damage under the sparsely supported condition. In the base case, 5 supports were distributed evenly along the 21m steel pipeline. The second support from the inlet was removed to simulate the scenario of support damage, resulting in a total of 4 supports for the damaged support condition.

Every infrastructure possesses its own unique resonant frequencies, which are determined by the structure's elastic properties and various boundary conditions such as support, surrounding materials, and more. For our task, the removal of one support from the pipeline is likely to alter the boundary conditions of the structure. This alteration could provoke changes in both the frequency and amplitude of the structure's resonant vibration modes.

To extract these resonant frequencies, we carried out spectrum analysis using the Fourier transform. The collected DAS data were divided into 10-second sections, with a Fourier transform performed on each channel. We then averaged the spectra over eight-minute intervals during each experiment. The resulting amplitude spectrum, when plotted against the fiber distance, can be seen in Figure 5.

As shown in Figure 5, the steel pipe vibrates at discrete resonant frequencies with an interval of approximately 120 Hz as the gas flows. These are illustrated by the vertical line-like patterns in the colormap plots. Each resonant frequency, characterized by alternating sections of higher and lower amplitude along the pipe, can be effectively explained by the theory of standing waves. For a standalone pipeline, the frequency and amplitude of each resonant mode, especially the higher frequency ones, are closely associated with the boundary condition of the pipe. In this experiment, we altered the boundary condition by removing one of the weight-bearing supports of the steel pipe, which in turn changed the resonant vibration patterns. A comparison of the left and right subplots in Figure 5 reveals that the vibration pattern is fairly consistent between the two cases. However, a detailed analysis shows that the frequency and amplitude of several resonant modes have changed after reducing the number of supports from five to four. As shown in Figure 6, the resonant mode at around 700 Hz exhibits two adjacent frequency peaks. After the removal of the support, these two frequency peaks merged into one. We also observed a slight frequency shift in several vibration modes. For instance, the peak at 583 Hz shifted to 585 Hz following the removal of the support.

All cables are able to detect these changes at a gas rate of 6 m/s, although the noise floor of the internal cables (black, flat, and thick) is higher than that of the external one (straight), likely due to flow-cable interaction. Owing to its geometry, the flat cable demonstrates the highest noise level in this case. The frequency spectrum from the flat cable also reveals minor frequency peaks, probably linked to the flow-induced cable resonant vibration.

At a higher gas rate, the signal-to-noise levels of the internal cables are further reduced. Nevertheless, we can still identify the frequency changes of resonant modes in the internal cables at the highest gas rate (18 m/s). However, at the lowest gas rate (2 m/s), very little pipe vibration can be detected by any of the cables, rendering the measurements unsuitable for identifying infrastructure damage.

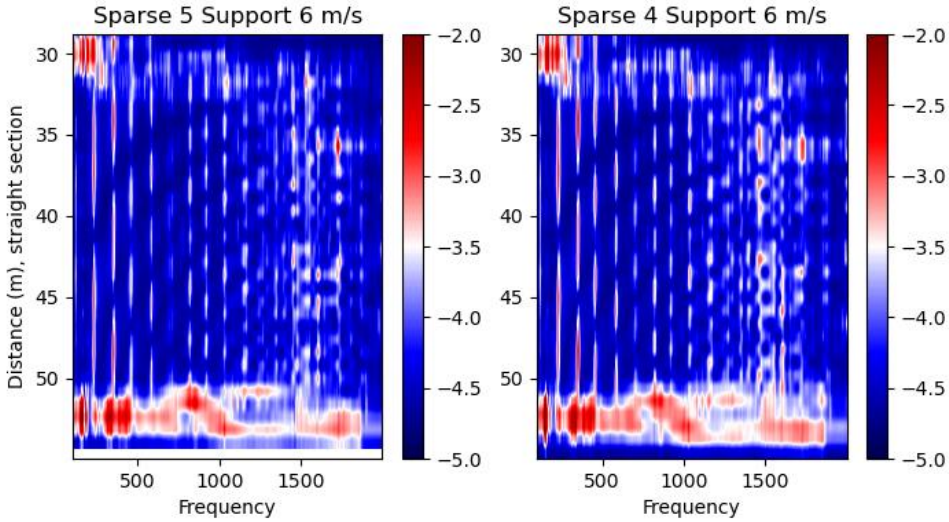

Figure 5. Frequency Spectrum of the straight fiber section with gas flow rate at 6 m/s. Vertical axis is the distance along the fiber/pipe, horizontal axis is frequency. Warmer color indicates higher amplitude at a certain frequency/location. The color is in log scale.

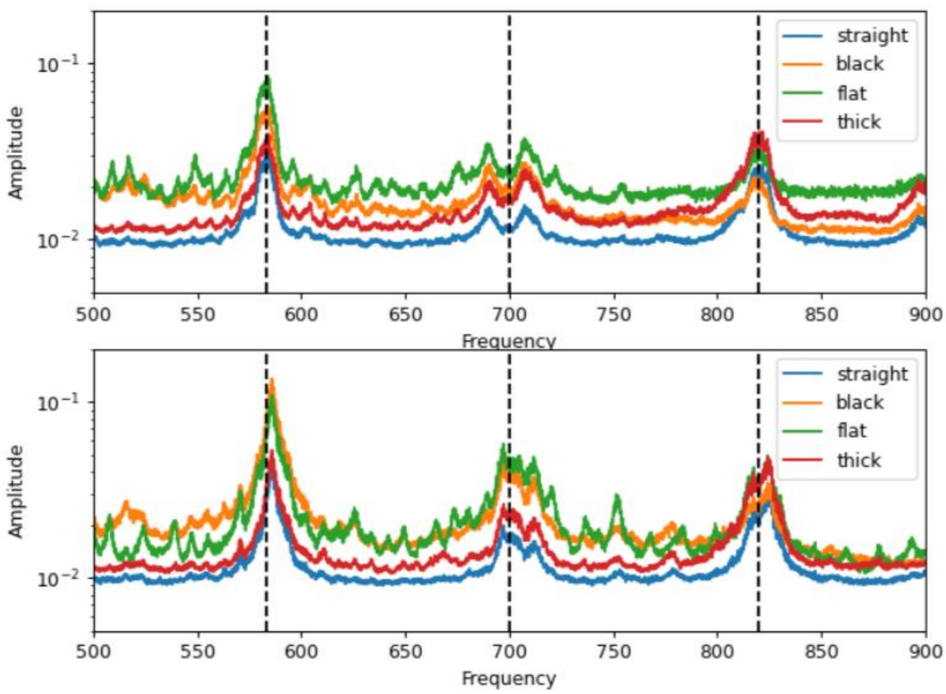

Figure 6. Averaged frequency spectrum of each fiber section, zoomed in between 500 Hz and 900 Hz. Top panel shows measurements with 5 supports, while the bottom panel shows those with 4 supports that simulates a scenario with a damaged support. Dashed line marked the estimated resonant frequency of three vibration modes.

Task #6. Detection of Leakage

After Tasks #3 and 5, we conducted experiments for leakage detection using a 1-m test section with 1-in. holes at three different positions (top, side, and bottom), such that we can simulate the leakage at different orientations. A picture of the facility is shown in Figure 7a. Combined with reducers with three different sizes (Figure 7d), we can simulate four leakage sizes, namely ¼-in, ½-in, ¾-in, and 1-in. Five gas flow rates, 2, 6, 10, 14, 18 m/s, were tested.

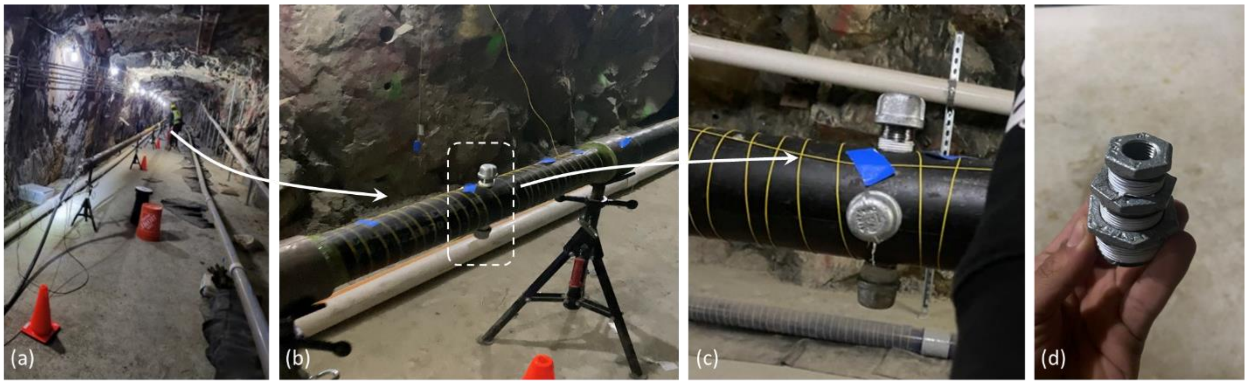

Figure 7. (a) A picture of the facility; (b) 1-m test section for leakage detection; (c) holes with caps on the 1-m test section; (d) reducers for hole size control

Because the experiments involving leakage tasks have recently been concluded, only a limited amount of data visualization and fiber mapping has been conducted so far. Figure 8 presents a 0.2-second snapshot of the raw DAS data where different sections can be distinctly identified and mapped. Tap tests were conducted to identify the beginning and end of each cable section in the pipeline. The straight fiber starts at around 30 m and ends at around 59 m away from the interrogator; black fiber is from 117 to 140 m; flat fiber is from 153 to 174 m, thick fiber is from 200 to 229 m, and wrapped yellow fiber is from 230 to 490 m away from the interrogator. Distances not represented include locations on the fibers that are not on the steel pipeline and are loose and carefully laid on the ground or wrapped around the splicing tray. The begging and end of each fiber cables are indicated as black and red lines in Figure 8. In this study, we aim to detect high-frequency noise generated by the leakage point, consequent to the gas flowing from this point into the atmosphere. We plan to conduct a more comprehensive data analysis and, based on these findings, further adjustments to the experiments might be undertaken.

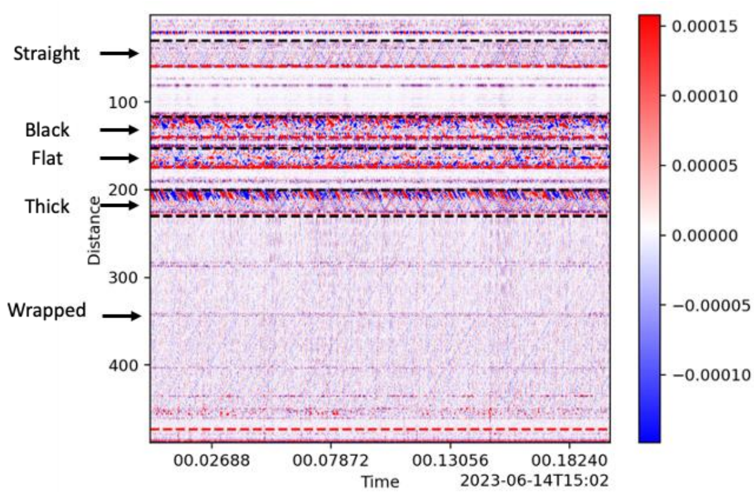

Figure 8. Raw DAS data recorded during the leakage experiment. The flow rate is 18 m/s, and with a 1' leakage point at the bottom. Black and red dashed lines are each fiber section's beginning and end points, prospectively.

Project Financial Activities Incurred during the Reporting Period:

The following table summarizes the financial activities and the corresponding expenses during the reporting period. Also shown are the budget for the 2nd year and the total expenses in the 2nd year so far. Please note that the actual amount for the expenses might be slightly different from the numbers in the final financial report, since some of the expenses occurring in late of the quarter may not be included in the university's financial system that we use for managing the funds and expenses by the time the report is submitted. Normally, it takes several business days for an expense to be shown in the system after its occurrence.

Items\Budget and Expenses		Budget for Year 2	Total Expenses in Year 2 So Far	Expenses During Reporting Period
1	Faculty Salaries and Wages including Fringe Benefits	$28,510	$20,760	$20,760
2	Student Salaries	$65,920	$40,170	$17,115
3	Graduate Student Tuition	$46,260	$23,516	$510
4	Experimental Expenses (experimental work supplies, services, maintenance, cables, etc.)	$27,000	$10,658	$5,471
5	Travel	$3,000	$875	$875
6	Indirect Costs (51.5%)	$64,703	$36,803	$22,259
Total		**$235,392**	**$132,783**	**$66,990**

Project Activities with Cost Share Partners:

The cost shares are the AY efforts of the PI and co-PIs. Activities are the same as above.

Project Activities with External Partners:

No external partners.

Potential Project Risks:

The two Ph.D. students assigned to this project both go for an internship this summer. To ensure smooth progress, we hired 1 Ph.D. and 2 Undergraduate students temporarily to support the experiments during the summer months. Since the students are new to this project and have limited prior experience doing experiments or processing data, it takes time for them to catch up on the project. This could delay the project timeline.

Future Project Work:

In the next 30 days, we will: 1) continue the data analysis for Task#6.2; 2) modify the facility for Task#2; 3) continue Task#4; 4) continue corroding the 1-m test section with a deeper depth.

In the next 60-90 days, we will: 1) conduct experiments for Task#3.6 with a deeper corroded test section, as well as the corresponding data analysis; 2) continue data analysis for Task#6.2 and redo the experiments as needed; 3) conduct experiments for Task#4.2 once the dent is ready; 4) continue modifying the facility for Task#2.

Potential Impacts to Pipeline Safety:

Tasks#1 and #2 can potentially help identify and characterize the possible liquid accumulation in a gas gathering or transmission pipeline using DAS, while Tasks#3-6 will potentially help detect the internally corroded surface, deformation, infrastructure damage, and leakage in a gas pipeline.