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Scanned Measurements and Averaging: Characterizing the Spatiotemporal Output of a Speaker (and Resulting Acoustic Wave Propagation)

Introduction:

Sound waves are a cornerstone of many engineering fields, including acoustics, audio engineering, and SONAR technology, where understanding wave propagation is critical for optimizing performance and design. These waves travel through a medium like air as pressure fluctuations, with their behavior influenced by factors such as frequency, temperature, and density (Acoustic Wave 1.1). This knowledge is vital for applications ranging from designing better sound systems to improving underwater navigation tools (Staelin 23).

The goal of this experiment was to analyze the spatial and temporal propagation of a 5 kHz acoustic wave generated by a speaker, with a specific focus on its speed, amplitude distribution, and attenuation over distance. Using a CNC-controlled scanning stage and a microphone, measurements were systematically collected across predefined points in a scanning area. Noise was reduced through time-domain averaging, which enhances the signal-to-noise ratio (SNR) by minimizing random variations (Prawda 1).

This experiment serves as a practical demonstration of concepts like wave propagation, noise reduction, and signal processing. The findings can have direct applications in audio engineering and signal optimization, providing a framework for accurately measuring acoustic phenomena in noisy environments. In many practical scenarios, accurately capturing and analyzing sound wave propagation is essential for improving device performance and addressing real-world challenges. For instance, in noisy environments, such as industrial plants or urban settings, background noise can obscure critical sound wave details, making precise measurements challenging. Understanding sound wave behavior is not only crucial for designing high-fidelity audio systems but also for applications like non-invasive medical imaging, noise pollution control, and optimizing communication systems in complex acoustic environments. By examining the propagation, attenuation, and reflection of sound waves, engineers can design systems that are more efficient, resilient, and adaptable to varying conditions. This experiment provides a controlled environment to explore these phenomena, allowing us to apply theoretical principles to real-world scenarios while also gaining insights into methods for improving signal quality and measurement accuracy.

Results:

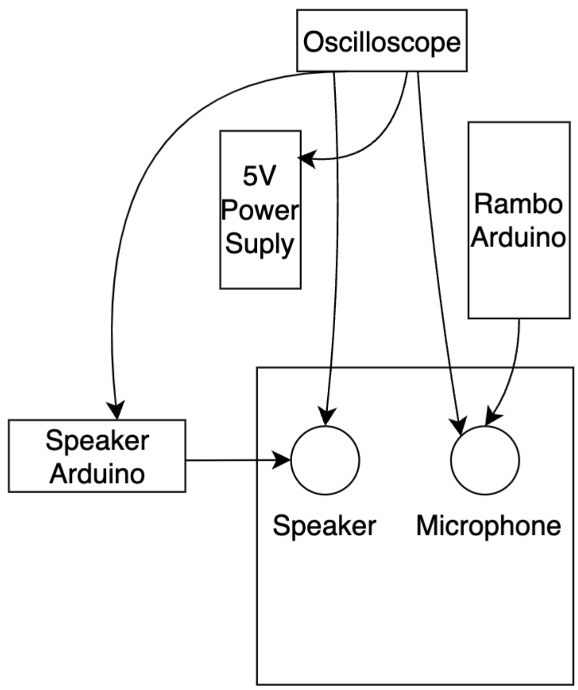

Figure 1: Schematic diagram of the experimental setup showing the CNC-controlled scanning stage with a microphone positioned at various points relative to the speaker. The Arduino system controls the stage movement along the x- and y-axes, allowing for systematic data capture of the 5 kHz acoustic wave generated by the speaker. This configuration enables precise spatiotemporal analysis of wave propagation in the defined scanning area.

The data for this experiment were collected using a CNC-controlled scanning stage, equipped with a microphone to measure the 5 kHz acoustic wave emitted by the speaker, which enabled precise measurements of sound wave propagation across various points in the scanning area. This setup allowed for systematic data acquisition along the x- and y-axes, with the microphone capturing the 5 kHz acoustic wave generated by the speaker at each position. As illustrated in the schematic in **Figure 1** above, the scanning stage facilitated repeated measurements across a defined spatial grid. The data gathered includes the time delay of the sound wave's arrival at each position along the x-axis, with the results displayed in a plot of position versus time delay in **Figure 2** below. Error bars were added to account for measurement uncertainties in both time and position, with time uncertainties arising primarily from random noise and position uncertainties stemming from minor inaccuracies in the scanning stage.

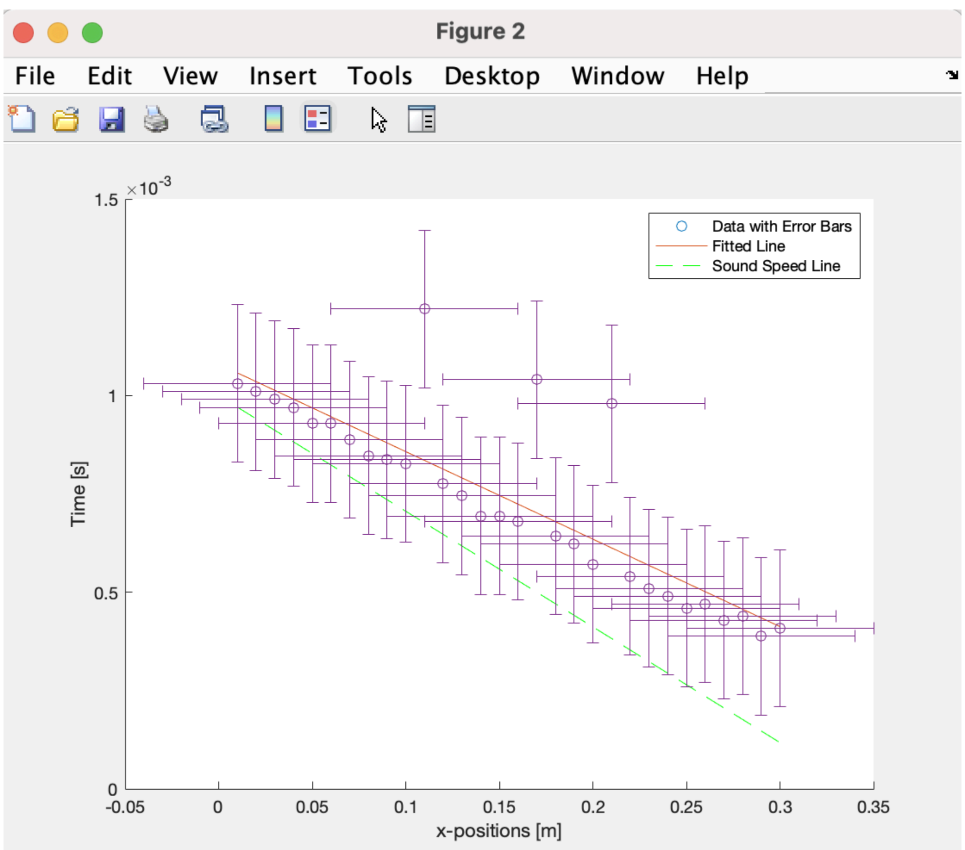

Figure 2: Plot of position (x-axis) versus time delay (y-axis) for sound pulse arrival, with error bars representing uncertainties in both measurements. The red line denotes the experimental best fit, while the green dashed line represents the theoretical time delay for sound traveling at 340 m/s. The slope of the fitted line provides an estimate of the experimentally determined speed of sound, which is compared to the theoretical value.

Additionally, a color plot was created to visualize the normalized amplitude of the sound field over time and position, as shown in **Figure 3** below. This plot illustrates the change in amplitude across the x-axis over time, normalized by each position's maximum amplitude, providing a clear visual representation of the sound wave's progression through space. **Figure 4** below provides a spatial snapshot of the sound field distribution at a specific time *t*= 2 ms) across the scanning area, offering insights into the wave's spatial amplitude pattern within the scanning grid. This figure allows us to observe variations in sound intensity along both the x- and y-axes, showing how the acoustic wave propagates in two dimensions.

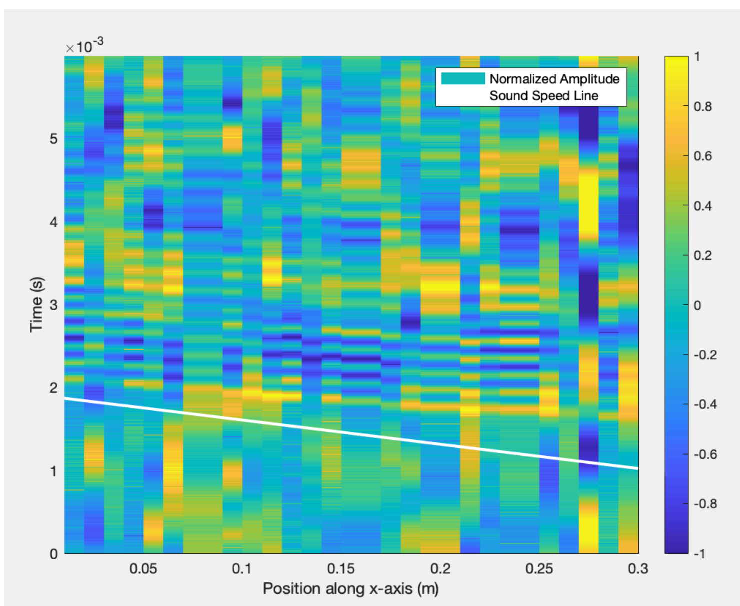

Figure 3: Visualization of the normalized amplitude of the sound field over time and position along the x-axis. The x-axis represents the position along the scanning stage, while the y-axis shows the time. The color scale indicates the normalized amplitude of the signal at each position, with each x position normalized by its maximum absolute amplitude. The white line

represents the theoretical travel time of sound at a speed of 340 m/s, providing a reference for the expected speed of sound in air.

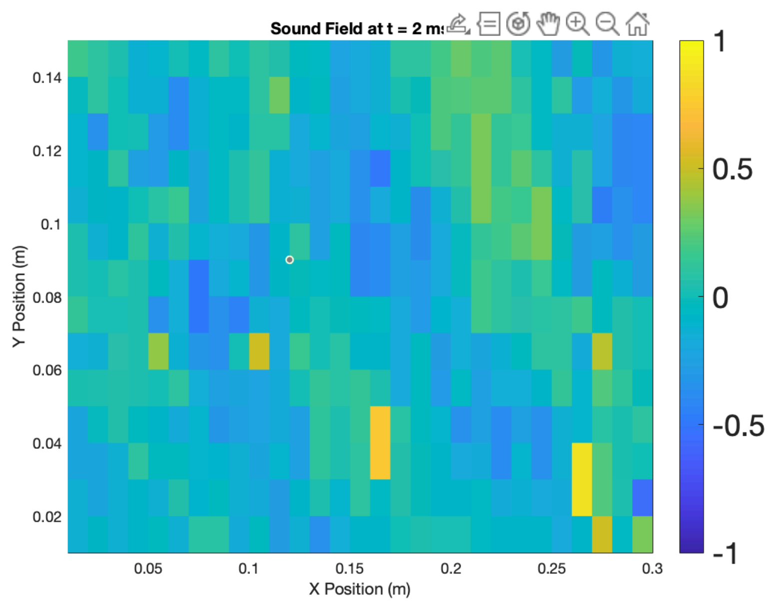

Figure 4: Sound field distribution at t = 2 ms across the scanning area. The x-axis represents the position along the x-axis of the scanning system, and the y-axis shows the position along the y-axis. The color scale indicates the normalized amplitude of the sound signal, with higher values shown in warmer colors. This plot visualizes the spatial variation in the sound field at a specific time point, providing insights into the amplitude distribution within the scanning region.

For the scanning process, there was a critical 1.1-second pause between individual charging cycles. With a total of 450 positions scanned 64 times each, the total time required for data collection was approximately 8.8 hours. This demonstrates the time-intensive nature of averaging techniques, which significantly improve data clarity but at the cost of efficiency.

Discussion

The experimental results highlight the behavior of the 5 kHz acoustic wave as it propagates across the scanning area. In the **Figure 2**'s position versus time delay plot, the linear relationship between position and time delay is consistent with the theoretical speed of sound in air. The slope of the line of best fit for the experimental data provides an estimated sound speed of 243.75 m/s. While this value deviates from the expected theoretical speed of 340 m/s, the discrepancy may be attributed to several factors, including environmental conditions (e.g., temperature or humidity variations), random noise in the measurements, and potential calibration errors in the equipment.The estimated speed of sound has an error margin of approximately 20%, which accounts for uncertainties in distance and time measurements.The inclusion of error bars highlights these uncertainties and emphasizes the importance of precise calibration and environmental control.

Figure 3 consists of a color plot of normalized amplitude over time and position that provides further insight into the sound wave's spatial characteristics. The clear visual of peaks and troughs in the amplitude over time demonstrates the effectiveness of time-domain averaging in enhancing signal clarity. This averaging method reduces random noise, allowing a more accurate representation of the sound wave. The white line, which represents the theoretical speed of sound, closely parallels the peaks in the normalized amplitude, confirming that the experimental setup successfully captured the wave's expected behavior.

In the spatial amplitude distribution at t=2, shown in **Figure 4**, the data show the amplitude's decay with increasing distance from the speaker, which aligns with theoretical expectations. This highlights the inverse relationship between distance and sound intensity, validating the propagation patterns observed in the time-delay plots. The ability to visualize these variations underscores the scanning stage's accuracy in capturing both one-dimensional and two-dimensional wave behaviors.

Regarding the spatial resolution, the calculated ratio of step size (d=0.01m)to wavelength (λ=0.0686 m) is approximately 0.1458, satisfying the Nyquist sampling criterion, which requires at least two samples per wavelength for accurate reconstruction. This correction ensures clarity in resolving wave features without aliasing artifacts.

In conclusion, the experiment demonstrates that precise measurements of sound wave propagation can be achieved using a controlled scanning stage and averaging techniques. The findings validate the effectiveness of noise reduction strategies, such as time-domain averaging, in improving the signal-to-noise ratio, which is crucial in environments prone to random fluctuations. However, further refinements, including the use of servomotors for positional feedback and enhanced calibration methods, could reduce errors and enhance the reliability of future measurements. These insights provide valuable contributions to acoustic studies and practical applications in fields like audio engineering and signal processing.

References:

[1] Staelin, Davi. "Electromagnetics and Applications." *MIT OpenCourseWare*, MIT OpenCourseWare, 2009, ocw.mit.edu/courses/6-013-electromagnetics-and-applications-spring-2009/.

[2] Prawda, Karolina, et al. "Calibrating the Sabine and Eyring Formulas." *Pubs.Aip.Org*, 2022, https://pubs.aip.org/asa/jasa/article/152/2/1158/2838408/Calibrating-the-Sabine-and-Eyring-formulas

[3] "Acoustic Wave." *Acoustic Wave - an Overview | ScienceDirect Topics*, www.sciencedirect.com/topics/physics-and-astronomy/acoustic-wave#:~:text=In%20subject%20area%3A%20Physics%20and,%2C%20fluid%2C%20or%20biological%20medium. Accessed 20 Nov. 2024.

Peer Review (Kaitlyn Shrihavong)

Introduction

1. References:
   - Make sure references (e.g., "MIT OpenCourseWare" and "ScienceDirect Topics") are properly cited with specific details like publication years or article titles, using a consistent citation format (APA, IEEE, etc.). You could just cite it with '[1]' since you have numbered each source in your reference list.
2. Clarity and Precision:
   - You may prefer to remove phrases like "we aim to" or "through this approach" for a stronger, more scientific tone. *EXAMPLE*: *"This experiment aims to address this challenge..." Changed to: "This experiment investigates..."*

Results

1. Experimental Setup Description:
   - Add specific details about the scanning area's dimensions, to give readers a better sense of the experiment's scale.
2. Error Bars and Uncertainties:
   - Describe how the error bars account for uncertainties in both time and position, and any limitations in the scanning stage's positional accuracy.

Discussion

1. Detailed Error Analysis:
   - Provide a more comprehensive error analysis, possibly mention potential sources such as the scanning stage's accuracy, microphone sensitivity, and any other

factors.

2. Vagueness Around "Uncertainties"

    - You mention "measurement uncertainties" without specifying what these uncertainties are and how they were quantified. For instance: Error bars are mentioned but not explained in terms of their origin. Are these from instrumental precision, human error, or something else?
    - Suggestion: Discuss how uncertainties were measured or calculated.

3. Increased Precision in Language

    - The use of phrases like "demonstrates the effectiveness" or "clear visual" is somewhat vague and could be made more precise. Instead of just saying the averaging "demonstrates the effectiveness," explain how it does so with evidence.
    - For example, "The time-domain averaging method significantly reduced random noise, as evidenced by the reduction in amplitude fluctuations in the normalized amplitude plot (Figure 2)."