LOW-FREQUENCY INTENSITY VECTORS AND WIND NOISE REDUCTION

USING A COHERENCE-BASED METHOD

by

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ABSTRACT

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A method has been developed to cancel out wind noise from outdoor recordings using coherence as the filter. Many tests have been performed and analyzed to show the usefulness of this method. A coherence-based PAGE method has been developed to correct the magnitude of the intensity during analysis of outdoor recordings. Continual analysis is being performed to further test and develop this method.
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Chapter 1

Introduction

1.1 Background

In the field of acoustics, outdoor recordings are often needed in order to analyze real life data. A few examples of outdoor recordings are at rocket launches, near wind turbines, and near airplanes taking off. These types of outdoor recordings have a tendency to record a large amount of wind noise. There are a few ways to reduce this wind noise, one of which is by adding a wind screen to protect the microphones from the contaminating wind noise. This helps reduce the wind noise but in certain scenarios such as near wind turbines, where large amounts of wind are necessary for them to work, a wind screen is not sufficient to cancel out the large amounts of contaminating wind noise. A coherence-based method has been developed to reduce wind noise in outdoor recordings. This method uses the coherence between two microphones to filter out excess wind noise. Outdoor field tests have been performed to test the usefulness of this coherence-based method in reducing wind noise and a continued analysis of these and similar tests is being used to check the validity of the coherence-based phase and amplitude gradient estimation (PAGE) method.
1.2 Theory

1.2.1 Coherence Method

The wind noise at any given microphone will be slightly different than at the next microphone. To filter out this wind noise, a coherence analysis is done between the recorded signals of two microphones separated by a certain distance. The process to do this is as follows. First the auto-spectrum for each microphone is found using a Fourier transform. The two auto-spectra are then compared to find the cross spectrum. We are then able to use a transfer function to find the coherence and as we multiply the coherence by the original auto-spectrum of the focus signal, we can find the coherent output power which shows us the original signal with a portion of the incoherent noise.

![Diagram of dual channel spectrum averaging process](image)

**Figure 1.1** Explanation of the analysis process used to find the coherent output power. The Fourier transform is taken of the two channels, a and b, to find the auto-spectrum of each. These auto-spectra are then compared to find the cross spectrum. The auto-spectra and cross spectrum are then analyzed to find the coherence and then the coherent output power.
1.2 Theory

The equation for the coherent output power is

\[ \gamma^2 = \frac{|G_{ij}(f)|^2}{G_{ii}(f)G_{jj}(f)} \]  

(1.1)

Where \( G_{ii} \) and \( G_{jj} \) are the two auto spectra and \( G_{ij} \) is the cross spectra of the two. Figure 1.1 [4] shows a diagram of the process of obtaining the coherence and coherent output powers. Further explanation of the coherence process can be found in Mylan Cook’s master’s thesis [3].

1.2.2 Coherence-Based PAGE Method

After some initial tests, this coherence-based method was then added as an addition to the PAGE method. The PAGE method as explained by Thomas, Christensen, [5],

\[ \text{Microphones} \]

\[ \text{Sound Source} \]

Figure 1.2 The intensity measurements created using the PAGE method analysis is shown. With the use of multiple microphones the position of the sound source can be found. This is done by finding the intensity at each microphone and following them backwards to where they meet. This shows where the sound source is located.
and Gee [1] is a new way of calculating the position of a sound source. This method was developed at Brigham Young University and originally published in 2015. The PAGE method uses the phase and amplitude gradients to estimate the position of the sound source. The updated version of the PAGE method sometimes referred to as a Coherence-Based PAGE method or CPAGE method allows the coherence to be taken into account so that a more accurate magnitude can be found and the wind noise filtered out of the analysis. A simple explanation of how the PAGE method works is shown in figure 1.2. With the use of a multiple microphone array the position of the sound source can be found. This is accomplished by finding the intensity at each microphone using the phase and amplitude gradients and then following the intensity vectors back to where they meet. This position is where the sound source is located.
Chapter 2

Methods

2.1 Microphone Set Up

The set up of each individual microphone was the same throughout each the tests mentioned in this paper. We worked to find level ground for these tests so that the microphones would all be on the same plane. For each microphone there was a ground plate which allowed for a harder ground surface, weather protection, and a consistent set up for each of the wind screens and microphones. Each microphone, after being carefully calibrated, was inverted and placed on the ground plate using a three-pronged microphone holder which securely and safely connects it to the ground plate. Over the microphones was placed a wind screen which was also attached to the ground plate to hold it in place. The wind screens were created and tested specifically to protect the microphone and its cable connection from the elements and especially from the wind. These wind screens greatly reduced the noise we recorded from the wind, but they are not perfect wind noise protection which shows the need we had for the coherence-based wind reduction method explained in section 1.2.1. For each test, the data was recorded in time segments of 10 minutes. During most of the tests we
Figure 2.1 Microphone setup for one of these initial tests to see how the coherence is correlated to the separation distance between the microphones.

also recorded the weather data using a Kestrel weather meter. This data included the wind speed and direction as well as many other weather factors, such as the humidity and temperature, that could influence our results.

2.2 Wind Noise Reduction Test Set Up

We started out by performing three field tests in one dimension to see how this coherence-based method works to reduce wind noise. The set up for these recordings, shown in figure 2.1, involved three or four microphones positioned in a straight line
2.2 Wind Noise Reduction Test Set Up

Figure 2.2 Diagram of the microphone setup used to take data for intensity measurements.

with separation distances of 6, 8, and 10 feet between consecutive microphones. This allowed for an analysis to be done at distances of 6, 8, 10, 14, 18, and 24 feet. These three tests were done in various locations around Provo, Utah in order to see how the location of the tests, mostly focusing on ambient noises, impacted our results. The first two tests we did were surrounded by contaminating noise sources such as busy roads, construction, trains, and airplanes flying overhead. The third test we were able to do in a quieter area west of Utah Lake and south of Eagle Mountain in a large open valley. This location allowed for a better analysis without excess contaminating noise. The main issue with these contaminating noises is that they were still coherent between all the microphones and so the filter used would not help to filter these noises out of the analysis. This third location was used for further testing.
2.3 Intensity Measurements

After an analysis of the first few tests showed promising results, the next step was moving on to two dimensional tests to see how well the PAGE method works in a larger scale setup and eventually to see how the CPAGE method works to correct the magnitude of the sound levels at lower frequencies. The set up for these intensity measurements, shown in figures 2.2 and 2.3, have a triangle probe with a microphone in the center. This setup, on a smaller scale, has been shown to work well for the PAGE method [1] in previous tests done by its developers. The radius of the microphone probe was 10 feet, which is the minimum separation distance explained further.
in section 3.1, with triangle side lengths of 17.3 feet. The uncertainty in the positioning of each microphone is ±1 inch based on human error. This set up was the same between each recording, and we used the same subwoofer as the main sound source. The location of the subwoofer in relation to the probe varied between set ups. The location we determined to use for these recordings was west of Utah Lake and south of Eagle Mountain in a large open valley.
Chapter 3

Results

3.1 Wind Noise Reduction Analysis

The recordings described in section 2.2 showed promising results. Though the results were similar, the last few recordings taken near Utah Lake had the least amount of contaminating noise from other sound sources and therefore showed the clearest picture of the coherence. One of these sets of data shown in figure 3.1 shows clearly the correlation between the separation distance between two microphones and the coherence between those microphones. A similar connection was made by F. D. Shields [2] who showed through a different set up and analysis that there is a connection between the separation distance of each sensor pair and how similar the recorded pressure signals are when working with wind noise.

Looking at the coherence between the microphone sets as shown in figure 3.1, we can see that the coherence of microphones with a separation distance of 6 to 8 feet is in the range of 0.5 and higher. This coherence is quite high compared to the coherence of those microphones with separation distances of 10 feet to 24 feet. A drop of 0.5 in the coherence is shown between 6 and 10 feet. This shows that there is some
Figure 3.1 Results showing relation between coherence and separation distance. Shown is the coherence between each microphone set given by frequency. The top two lines are at a separation distance of 6’ and 8’ where the lower lines are at a separation distance of 10’ or more. This shows the conclusion that 10’ is a sufficient separation distance between each set of microphones to reduce the coherence significantly. This allows the coherence to be used to filter out wind noise.

correlation between the coherence and the separation distance as explained above. Based off these results, we decided that 10 feet would be a large enough separation distance for us to achieve a significant decrease in the coherence which then allows us to filter out the incoherent noise. This 10 foot seperation distance is also small enough to be realistic.

In figure 3.2 we see the auto-spectrum with its coherent output powers from the coherence calculations between microphone 1 and each of the other three microphones. The blue line shows the original auto-spectrum. One notable point in this analysis is how the sound level of the acoustic signal stays essentially the same between the original signal and filtered signals. The acoustic signal shown is from a subwoofer sending out a 45 Hz frequency. The sound levels at each of the peaks in this acoustic
3.1 Wind Noise Reduction Analysis

signal are still spot on with the original. This is because the acoustic signal is coherent between each microphone and is therefore not reduced while the wind noise is not coherent between each microphone and therefore is reduced using this method. This shows that using the coherence as a filter does not reduce the actual acoustic recording we are looking at, but simply helps to decrease the wind noise in the recording. In Figure 3.2, the wind noise is reduced by anywhere between 5 to 30 dB depending on what frequency is analyzed.

![Microphone 1 Autospectrum and Coherent Output Powers](image)

**Figure 3.2** Results showing auto-spectrum before and after coherence filter is applied. The auto-spectrum is given by the top line and the coherent output powers are shown in the three lower lines. One noticeable feature is the acoustic signal shown by a peak in the sound level. The coherence-based filter does not affect the sound level of the acoustic signal as this signal will be coherent between all microphones. The acoustic signal shown is from a subwoofer sending out a 45 Hz frequency.
Chapter 3 Results

3.2 Coherence-Based PAGE Method

3.2.1 Analysis of Direction

Through an analysis of the first few tests we did with the triangle probe setup, we were able to determine the direction of the sound source. We have been unable to complete our analysis of all the field tests we did to test this, but the analysis of one of the tests that has been analyzed is shown below. As a part of this analysis we have compared the finite difference p-p or traditional method with the original PAGE method and two altered PAGE methods. The coherence-based method is called the CPAGE method in the figures below. In figure 3.3 we are looking at each of these four methods at a frequency of 100 Hz. The small red box is a representation of where the loud speaker was at during the test, and each small circle is one of the microphones. The arrow shows the intensity vector including the direction and magnitude of the sound recorded. As we can see, in figure 3.3 the traditional method is not working as accurately as the arrow is not pointed at the box representing the speaker. On the other hand, each of the PAGE methods are working wonderfully to find the direction.

In figure 3.3 we see an overview of all the frequencies from 0 to 275 Hz. At each frequency we can see what direction the sound is believed to be coming from based on the different methods. All of the PAGE methods show the same direction at each frequency. The loud speaker we used for this test has a lower limit of about 35 Hz. These are the lowest frequencies the speaker can produce, therefore the speaker is not able to produce an acoustic signal below 35 Hz and neither method is able to calculate where the speaker is located. In figure 3.4 we can see how the PAGE methods converge on the green line which shows the actual direction of the speaker. This convergence happens near the 35 Hz line and the PAGE methods do a very good
3.2 Coherence-Based PAGE Method

Figure 3.3 PAGE and traditional method results at 100 Hz. The direction and magnitude of the intensity vector is shown for each of the PAGE methods and the traditional p-p method. The PAGE methods show promising results in finding the direction of the sound source, while the traditional method has a harder time with accuracy. The square is the subwoofer and the three circles show the microphone array. The arrow shows the direction and magnitude of the sound source.

job of determining the direction from there on up to very high frequencies. In figure 3.4 it shows that it is still working at 275 Hz. The traditional method only works for a small range of frequencies. This limits its abilities to find this direction quite dramatically as we have been using large separation distances for these tests.

3.2.2 Analysis of Intensity

In figure 3.5 we are looking at similar results, but at a frequency of 3000 Hz which is nearing a separation distance of 30 wavelengths apart. We can see how the CPAGE method shows a reduction of the magnitude portion of the intensity vector. This is what we were expecting to see when the coherence of the wind noise is low at certain frequencies.
Figure 3.4 Intensity direction calculated using PAGE and traditional p-p methods. The focus is on lower frequencies show in the range from 0 to 275 Hz. The green, straight line near the bottom shows the actual position of the subwoofer. The PAGE method shown by the dotted line calculates the intensity direction to a near perfection once it has passed the lower limit of the subwoofer’s range which is at approximately 35 Hz. The traditional line shown in blue is accurate between 35 and 75 Hz.

Figure 3.5 Intensity magnitude correction by using the coherence-based PAGE method. Similar to figure 3.3 this one shows the direction and magnitude at 3000 Hz. In a comparison of the CPAGE graph with the PAGE and cohPAGE methods which do not take into account the coherency, the intensity magnitude has been altered due to the reduced wind noise using the coherence-based filter.
Chapter 4

Conclusions and Future Work

4.1 Conclusions

The results explained in chapter 3 show that a separation distance of 10 feet is significant enough to filter out a large amount of contaminating wind noise. They also lead us to believe that the coherence-based PAGE method is working well to filter out excess incoherent noise from the subwoofer recordings.

4.2 Future Work

Along with the tests explained above, we were able to collect data from a Falcon 9 launch at the Vandenburg Air force Base as well as data located near the two wind turbines at the Camp Williams Base. The set up for the microphone array was the same as the two dimensional triangle array explained in section 2.3. Each of these two tests brings a new challenge as they bring a third dimension into the analysis. We have not been able to fully analyze this data and so the next step in analyzing the coherence-based PAGE method used on low-frequency wind noise will
be to analyze the rest of the data we have obtained and comparing the results to see what consistencies and inconsistencies exist.
Bibliography


