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Active Noise Cancellation of Drone Propeller Noise through Waveform Approximation and Pitch-Shifting

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ACTIVE NOISE CANCELLATION OF DRONE PROPELLER NOISE THROUGH WAVEFORM APPROXIMATION AND PITCH-SHIFTING

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Under the Direction of Ashwin Ashok, PhD

ABSTRACT

The use of drones introduces the problem of noise pollution due to the audio noise generated from its propeller rotations. To mitigate the noise pollution from drone propellers, this thesis explores a method of using active noise cancellation ANC. This thesis hypothesizes that by analyzing the waveform of the drone propeller noise, an approximated wave function can be produced and used as an *anti-noise* signal that can effectively nullify the drone noise. In order to align the phase of the anti-noise signal to maximize drone noise reduction, this thesis presents a signal pitch-shifting approach, to guide areas of destructive interference to a desired target such as a microphone, at a desired location. Through experimental evaluation using a prototype of the proposed Pitch-Aligned Active Noise Cancellation system PA-ANC, this thesis reveals that the proposed technique can achieve a 43.82% reduction of drone noise.

INDEX WORDS: Active noise cancellation, Drone, Noise pollution, Spectral analysis

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DEDICATION

This thesis is dedicated to my family who have supported me throughout my life and have encouraged me to keep aiming higher and higher in my education.

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LIST OF ABBREVIATIONS

ANC	Active Noise Cancellation
dB	Decibel
FFT	Fast-Fourier Transform
LMS	Least Means Squared
PA-ANC	Phase-Aligned Active Noise Cancellation
UAV	Unmanned Aerial Vehicle

1 INTRODUCTION

Drone technology has become widely integrated into many commercial and industrial applications, and with a large range of cost variation of drones, they have become much more accessible for recreational use. The conveniences that drones present are started to be exploited by many companies where drones can be used as a means on package delivery. In the film industry, drone are being used to obtain footage from angles that would have been difficult to obtain before. Drones have also been used to gather research data in environments where the terrain is difficult to navigate or at high altitudes. While drones have many benefits, drones also present drawbacks such as noise pollution.

1.1 Noise Pollution

Noise pollution can be defined as an abundance on noise that may annoy or harm humans or animals in the surrounding environment. Prolonged exposure to noise pollution can have significant negative impacts to an individual's physical and mental health. Due to rapid urbanization in recent times, urban areas are a hotspot for high amounts of noise pollution. Although noise is regulated in residential areas, in urban environments, noise pollution is highly unregulated and usually the result of poor planning and rapid urban development. Fatigue and hearing loss are common issues caused by noise pollution. With noise pollution already being a prominent issue, the widespread use of drones in these environments further exacerbates this issue. Furthermore, the use of drones are introducing the problem of noise pollution to areas that were not previously affected, such as residential and rural areas.

Large corporations are beginning to incorporate drones as a means to deliver products over large distances. Because these drones must be able to carry heavy loads, more powerful rotors are used which further increase the noise produced. With these delivery drones becoming more abundant, the impact of noise pollution will become much more widespread. According to a NASA study, the noise produced by drones was found to produce a higher negative reaction compared to the noise produced by various land vehicles [11]. It was suggested that people are used to noise produced by automotive vehicles because they heavily rely of these vehicles for transportation, and therefore, tolerate this form of noise. However, drones are a novel source of noise and are not heavily integrated in everyday life, therefore, drone can be seen as an unnecessary source of noise.

In the film industry, the live audio recorded during filming is traditionally used in the final product. However, when using a drone during production, the noise produced by the drone makes it impossible to use the live audio. Instead, the original audio is never used, and audio is dubbed over the video to reproduce the sounds. The majority of commercial drones used for recreational filming are not built with a microphone, as the audio recorded from the drone will always contain the loud buzzing noise from its propellers.

Measures against noise pollution are being implemented in many sources of noise as well as everyday devices in order to mitigate the exposure to noise pollution. Such measures can be referred to as noise cancellation.

1.2 Noise Cancellation

Noise cancellation, or noise control, is the process of attenuating, or reducing, the noise using passive and active methods. Passive noise cancellation involves the use of acoustic insulating or absorbing materials to reduce the ambient noise or noise produced by specific source. Active noise cancellation involves the use a second sound source to produce destructive interference and reduce the overall volume, or amplitude, of the target noise source. Applications of noise cancellation usually implement both active and passive methods in order to maximize the reduction of noise. For example, noise cancelling headphones utilize passive noise cancellation by using sound insulating foam around the earpiece. The residual noise is then reduced further using active noise cancellation. Although noise cancellation techniques are relatively effective at reducing noise, both passive and active noise cancellation have specific uses and limitations. While active noise cancellation performs well against loud, nonlinear noises, such as speech, it performs poorly against low, static noise, such as the vibrations of aircraft engines. Active noise cancellation performs well in low frequency ranges while passive noise cancellation performs well in higher frequency ranges.

1.3 Problem Statement and Thesis Contribution

As drones become more abundant, the level of noise pollution is further increased to being dangerous. Many attempts at noise cancellation have proved to be effective, such as altering the propeller shapes, reducing the weight of the body of the drone[1], and implementing active noise cancellation techniques[1][3]. However, such methods can be expensive to implement or can negatively impact the performance of the drone.

This thesis hypothesizes that it is possible to actively cancel the drone noise using an external *anti-noise* signal. In this regard, this thesis proposes Pitch-Aligned Active Noise Cancellation (PA-ANC) approach, which aims to efficiently reduce the noise produced by a drone's propellers without affecting the performance on the drone itself. In order to align the anti-noise signal to the drone noise signal, the PA-ANC system takes advantage of the principle of beats, the oscillations in amplitude as a result of two signals of different frequencies. The oscillations in amplitude due to beats are a result of oscillations in the phase between the two signals over time. By manipulating the dominant frequency or pitch of the anti-noise, the PA-

ANC system can determine when the phase between the anti-noise and drone noise signals is exactly 180°, which correlates to a maximum reduction in noise.

The key contributions of this thesis include the frequency domain analysis of drone propeller noise, dominant spectral frequency estimation, and exploration and development of the use of pitch-shifting as a form of phase alignment. The rest of this thesis document will describe these contributions made towards the analysis of drone noise and the noise reduction in detail.

2 RELATED WORKS

Active noise cancellation, or active noise control (ANC), is a widely explored method of noise reduction in various fields and applications. Despite this, ANC technology has only recently begun to be integrated into drones. The following works explore a variety of applications of ANC systems, design considerations, and implementations of ANC for drone technologies.

2.1 Noise Cancellation Techniques in Everyday Technologies

ANC is process of using an anti-noise signal to reduce the effect of a target noise signal. Therefore, ANC is essentially a signal estimation problem. While ANC systems are relatively effective at reducing the strength of noise, it is nearly impossible to completely reduce noise to silence only using ANC. Certain characteristics of the noise, such as its spectral frequencies, can have a significant impact on the design of an ANC system. Furthermore, the acoustic paths and the transfer functions between different components of an ANC system can limit the performance of system and can severely affect the effectiveness of the noise reduction. Milani et al., in the paper *On Maximum Achievable Noise Reduction in ANC Systems*, analyzed the performance of different ANC system configurations from the perspective of the maximum achievable noise reduction. Feed-forward, feedback and hybrid configurations using the causal Wiener filtering algorithms were compared. It was found that feed-forward configurations performed far better than feedback configurations. Hybrid configurations marginally outperformed feed-forward configurations achieving a maximum level of noise reduction of 56.46 dB [7].

Although the goal of an ANC system is to reduce a target noise as much as possible, many ANC implementations do not take into account that human hearing have non-uniform sensitivity to different frequencies. This means that any residual noise after the noise reduction may still have a large negative impact if its frequencies are within a certain range that are sensitive to human hearing. In the paper *Psychoacoustic Active Noise Control Based on Delayless Subband Adaptive Filtering*, Bao et al. implemented an ANC system that incorporated weighted noise. In this implementation, the noise was divided into subbands and processed using the Filtered-Error Least Means Squared algorithm in parallel. Each of the subbands of frequencies can be processed with different weights according the human ear's sensitivities to each subband. The filtered subbands are then combined to produce an anti-noise signal which is then played through a loudspeaker to cancel the target noise. This implementation was able to reduce the human-perceived loudness of residual noise by 46% compared to traditional ANC systems [10].

ANC technology has been widely adapted to many applications such as noise-cancelling headphones, mobile devices, as well as vehicle noise reduction. While traditional ANC techniques are relatively effective in these applications, each application presents certain challenges that require additional components to achieve a more effective result.

Modern hearing aids implement some level of noise reduction in order to filter background noises. While this is effective on the noise received from its microphone, noise leakage can have a significant negative impact on the overall noise reduction. In [6], Serizel et al. proposed an ANC system that aimed to reduce the noise caused by secondary acoustic paths and noise leakage in hearing aids. Such factors are not taking into account in standard noise reduction implementations in hearing aids, however, the impact of these noise sources are non-negligible. The proposed system uses both a noise reduction algorithm and ANC in a cascading scheme to increase the noise reduction effect. A Filtered-x Multichannel Wiener Filter is implemented in parallel to the cascading scheme and combined to make a more robust noise reduction algorithm. When compared to a Multichannel Wiener Filter in a classic noise reduction framework without ANC, the proposed system performed the best at reducing background noise.

In the system proposed in [4], Sahib et al. implemented an ANC system that aimed to reduce the noise produce by the tire/road interactions in eco-friendly cars. This system needed to adapt to nonlinearities introduced through system actuators and sensors, the noise source, and acoustic propagation paths. Because each of the four tires of the vehicle was treated as an individual source of noise, a multichannel filtering approach was needed to quickly and accurately produce an effective anti-noise signal. The paper evaluated and highlighted certain aspects of the system design that must be considered in order to produce an effective adaptive ANC system. Such aspects include the tonality of the noise, and the bandwidth of the spectral frequencies of the noise signal.

Further system design considerations can be derived from [5]. Lifei aimed to reduce the noise experienced within a driver's cab. It was observed that acoustic frequencies above 800 Hz propagated through the air, while frequencies below 400 Hz propagated though the structure of the vehicle. While passive noise control techniques are widely implemented in vehicles, passive techniques perform poorly against low frequency noise. Lifei focused on reducing the lower frequency noise that could not be reduced through passive techniques by implementing an ANC system utilizing a Radial Basis function Neural Network that focused on the 100-500 Hz range of frequencies. This system was able to achieve a 30 dB reduction in noise.

While many ANC systems require additional components, such as loudspeakers, to be installed, [8] takes advantage of a mobile phone's preexisting hardware. Kottayi et al. proposed a system to reduce the noise in a small zone around mobile device. It was found that background noise is generally 500 Hz or below and that the effectiveness of an ANC system depended on if the noise freely propagated thought the air or within a confined space.

In [9], Liang et al. aimed to reduce the noise produce by transformers in urban environments. The constant noise produced by these transformers have a large negative effect on the surround residents, therefore, noise reduction must be highly considered. It was found that transformers produced harmonic frequencies 100 Hz, which is classified as low frequency noise. Using the LMS filtering algorithm, Liang et al. were able to achieve a large level of noise reduction. However, it was found that if either the step size or filter order in the LMS algorithm exceeded the other, the level noise reduction quickly decreases.

2.2 Passive Noise Control and Hardware-based Attenuation in Drone Technology

Passive noise control involves the use of sound insulating or absorbing materials to reduce the noise being produced. In manned aerial vehicles, such as airplanes and helicopters, the structure of the aircraft is altered and contains such vibration absorbing materials in order to reduce the vibrations and noise experienced by the passengers. However, in unmanned aerial vehicles (UAV), such material have little effect in noise attenuation to observers and can have a significant impact in performance. Instead of reducing overall noise through the use of these materials, the noise can be redirected such that the level of noise that reaches the observer is minimized. In [17], Mohamud et al. aimed to reduce the noise emitted by a drone’s propellers by forming shrouds composed of sound insulating foam as well as aluminum to reflect the noise back towards the drone. In this method, the level of noise was measure from different angles of the drone. It was found that the sound insulating foam performed the best at reducing the noise emitted from the propellers, especially from the front of the drone. Dotterel, a company specializes in noise reduction in UAVs, also developed such a method similar to this. This method involves the use of a lightweight material arranged in a cone around each of the propellers of the drone. The noise produced by the propellers bounce off this material and is redirected upwards, greatly reducing the level noise that reaches the observers on the ground without significantly affecting the performance of the drone [13].

While many UAVs used for industrial and military purposes used fuel in order to provide power to the propellers, the majority of recreational UAVs used electrical power in order to operate the propellers. In the study of UAV noise by [12], it was found that electrically powered UAVs produced less noise compared to fuel powered UAVs. The engine used to convert the fuel to power produced vibrations that significantly increased the amount of overall noise produced by the UAV. While the electrically powered UAV produced less noise, electricity has a lower power density than fuel, thus these UAVs cannot operate for long periods of time.

In *Methods for attenuation of unmanned aerial vehicle noise*, Miljković explores aspects of unmanned aerial vehicle noise and various methods of noise reduction in propeller technology. The tips of the propellers have a significant impact on the level of noise produce by the propellers. The shape of the blades controlled the formation of air vortices above the wingtips which were found to be a source of noise produced by the propellers. By altering the shape of the tips of the propeller blades, the airflow around the blades can reduce the formation of these vortices and reduction the noise produced by the propellers. The number of propeller blades was also found contribute the noise produced. Traditionally, drone propellers are composed of two blades. However, the same amount of lift produced by two-bladed propellers can be replicated by propellers will a smaller diameter but larger number of blades. The reduction in the diameter of the propeller correlates to a slower wingtip speed. The speed of the wingtips are proportional to the noise produced by the propeller, therefore, as the diameter of the propeller decreases, the amount of noise produced also decreases [1][14].

2.3 Active Noise Cancellation in Drone Technology

In [1], Miljković also explored ANC methods applied to propellers. In one explored ANC method, he used an array of 12 single-channel speakers arranged in a circle surrounding a single propeller. Each of the 12 speakers plays the same synthesized waveform at a 30-degree phase shift from the previous speaker in the array. In this setup, the noise produced by the propeller is cancelled as the propeller wings pass in front of each speaker. Another explored method of ANC is the use of a synchrophaser. A synchrophaser is a device used to synchronize the rotational speed and phases of a multi-propeller setup. In this method, the synchrophaser was implemented in a four engine C-130 aircraft with two propellers and was used to alter the phase of the second propeller relative to the first propeller. The noise produced by the second propeller cancels the noise from the first propeller. This setup was able to achieve a 3-5 dB reduction in noise. In this last explored ANC method, Miljković describes a method patented by RotoSub® technology which is implemented for computer cooling fans, but a similar approach can be potentially implemented for drone propellers as well. By switching on and off the electricity flowing through a coil within the propeller frame, the magnetic fields produced interacts with magnets placed inside the tips of fan blades. These brief interactions with the magnetic fields creates slight modulations is the rotational movements of the blades, and thus, creates an anti-noise signal. Because this anti-noise signal originates from the target noise source itself, the speed and phase of the signal exactly matches the target.

In the paper *Acoustic Sensing from a Multi-Rotor Drone*, Wang et al. implemented a drone noise reduction method through spatial filtering a target sound enhancement. In this method a multi-microphone setup was implemented in order to localize and isolate the noise produced by the drone propellers. By determining the direction in which the noise is produced relative to a microphone, the resulting filter is further enhanced by being directionally aware. The spatial frequencies of both stationary and nonstationary drone noise were analyzed and measured against a normal frequency distribution using the kurtosis measurement. By combining both the direction of the noise as well as its spatial characteristics, a filter can be produced. This filter can be used while recording live recordings in order to reduce the noise and leave target sounds intact [2].

In [3], Kang et al. developed a hybrid approach to drone noise reduction through both ANC and spectral subtraction. In this method, a drone is equipped with two microphones. One microphone captures the target sound signals, such as speech, as well as the noise from the drone and its propellers. The other microphone captures only the drone noise signal. To reduce noise, first, ANC is applied by emitting an inversed signal of the drone only noise signal. This will reduce the drone noise to a certain degree. This interference is then captured and processed using a spectral subtraction filtering method to further reduce the drone's noise. The ANC method is applied first, because spectral subtraction methods tend to produce better results when the power of the frequencies within the frequency spectrum is weaker. While the effect of noise reduction in this method is observable in the real world, the effect of the spectral subtraction filtering is done programmatically and is not observable in the real world. This method was able to produce a reduced noise signal with a 67.5% similarity to the original target noise signal.

3 EXPLORATION OF ACOUSTIC NOISE FROM DRONES

Acoustic noise can be defined as the propagation of pressure waves through a medium, such as air. Acoustic signals are comprised of many complex characteristics that have significant impacts of the interactions of noise cancellation systems. During preliminary research, these characteristics were analyzed to better comprehend the design requirements for a noise cancellation system.

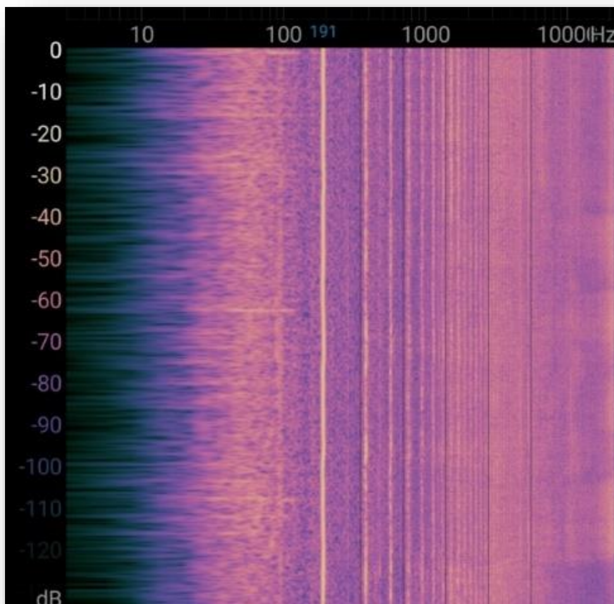

Figure 3.1 Spectrogram of Propeller Noise (obtained using the Spectroid application[18])

3.1 Spectral Frequencies

By mapping the spectral frequencies of the drone propeller noise over time, the dominant and harmonic frequencies can be determined. In order to determine the spectral frequencies of the drone propeller noise, the drone propeller was mounted to a stand and operated at its maximum speed setting. Using the Spectroid application [18], the drone propeller noise signal was recorded through the use of a mobile device's microphone, which was located approximately three feet away from the propeller. The noise was recorded over a length of ten seconds. The Spectroid application is able to display the spectral frequencies of the real time noise signal and determine the frequency with the largest amplitude, which is the dominant frequency of the noise signal. Figure 3.1 depicts the frequency spectrum of a ten second recording of the drone propeller noise. In this recording, the dominant frequency is 196 Hz, and its harmonic frequencies are multiples of 196. The strength of the harmonic frequencies relative to the dominant frequency as well as the number of harmonic frequencies are characteristics closely related to the waveform of the noise. A single frequency noise is composed of a simple sinusoid wave. When multiple sinusoid waves of varying frequencies and amplitudes are compounded, harmonic frequencies are produced. These compounding waves also contribute to the waveform of the noise as well.

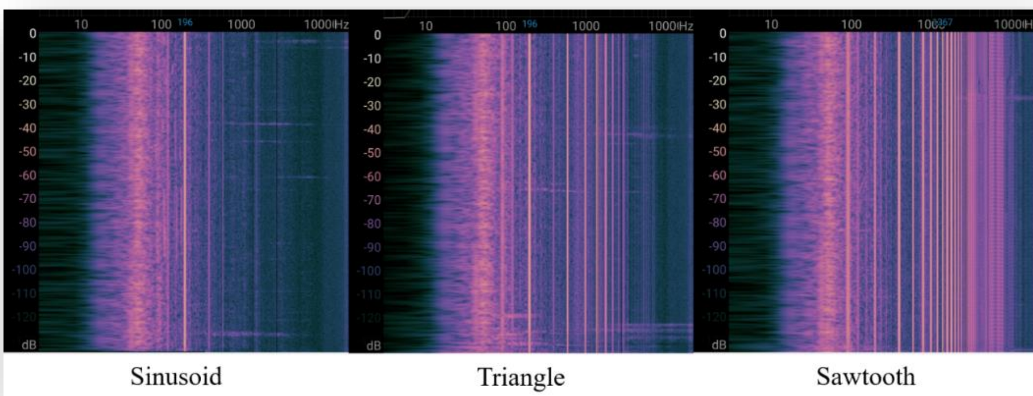

Figure 3.2 Spectral frequencies of sinusoid, triangle, and sawtooth waves

In Figure 3.2, the spectral frequencies of a sinusoid, triangle and sawtooth waveform playing a 196 Hz tone are shown. The sinusoid waveform generates a single dominant frequency at 196 Hz. The triangle waveform has a dominant frequency at 196 Hz as well as harmonic frequencies that are multiples of 196. However, there is a quick falloff in strength as the harmonic frequencies increase. A sawtooth waveform also has a dominant frequency at 196 Hz as well as harmonic frequencies being multiples of 196, however, the falloff in strength of each of the harmonic frequencies is much slower.

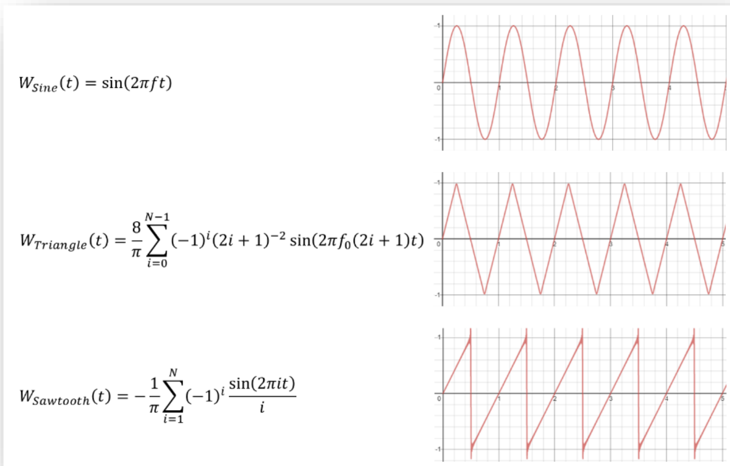

Figure 3.3 Equations used to approximate triangle and sawtooth waves

Although these waveforms have a single dominant frequency at 196 Hz, the observable loudness and noise are much different. These differences can be explained using the formulas that approximate these waveforms, as shown in Figure 3.3. Triangle waveforms are approximated using a compound of sinusoid waves. These frequencies are multiples of the dominant frequency and the amplitude, which correlates to the strength of the signal, of each compounded sinusoid wave is proportional to the inverse squared of the amplitude of the dominant frequency. The inverse squared relationship is the cause of the quick falloff in strength of the harmonic frequencies. Sawtooth waves are similar to triangle wave in that it is composed of compounded sinusoid waves, however, each harmonic frequency has an inverse of the amplitude of the dominant frequency. This characteristic explains the slow falloff of the harmonic frequencies. These approximations also contribute to the loudness of the noise as well. The number of harmonic frequencies as well as the falloff in strength correlates to the loudness of the overall noise. Each harmonic frequency can be considered its own noise source with a certain loudness, and the compounding of these noise sources will increase the overall loudness of the noise. Therefore, a noise signal with many harmonic frequencies is observably louder that a noise signal with few harmonic frequencies but the same falloff rate. Sawtooth waves must use a nearly infinite amount of harmonic frequencies in order to approximate its waveform, while triangle waves can be closely approximated with few harmonic frequencies. This explains why sawtooth waves are louder than triangle waves despite having the same maximum amplitude. To confirm this, a loudness of a triangle wave and sawtooth wave of 196 Hz and same amplitudes were compared. The triangle wave was observed to have a loudness of 97 dB, while the sawtooth wave was observed to have 111 dB.

The spectral frequencies of drone propeller noise are very similar to that of a triangle wave. Using this information, it is possible to generate anti-noise signals using triangle waveforms in order to target certain frequencies. This process is known as spectral subtraction. Spectral subtraction is able to reduce the strength of certain frequencies while ignoring other frequencies. This is useful for applications where a background noise needs to be reduced but a target noise, such as speech, can be preserved.

3.2 Interference Patterns

Acoustic pressure waves from different source can be superimposed and interact. Acoustic noise is the propagation of periodic high and low pressure. When the noise from different sources interact, these high and low pressures are compounded. This is referred to as constructive and destructive interference. When similar pressures (high + high pressures or low +

low pressures) interact, the resulting pressure becomes more intense than its individual components. This is constructive interference. During destructive interference, areas of differing pressures (low + high pressures) interact, and the resulting pressure is less intense than either of its original components. ANC utilizes destructive interference to cancel sound. The anti-noise signal used to cancel sound is generally an inverse of the target sound. The areas of high and low pressure in the target noise correlates to the areas of low and high pressure in the anti-noise signal, respectively. Another key component of ANC is the phase of the anti-noise signal.

3.3 Phase of Acoustic Noise

The phase between two or more noise signals is the alignment of each signal with respect to the corresponding points. In osculating signals, such as sinusoid waves, these corresponding points are the peaks of each wavelength. The phase determines whether two signal experience constructive or destructive interference. In order to achieve destructive interference, the phase between two signals must be 180°. In order to achieve this, the polarity of one of the signals is inverted. However, small delays in a signal can also affect the phase between signals as well. ANC system aim to minimize or eliminate delays and latency in order to minimize changes in phase when emitting the anti-noise signal.

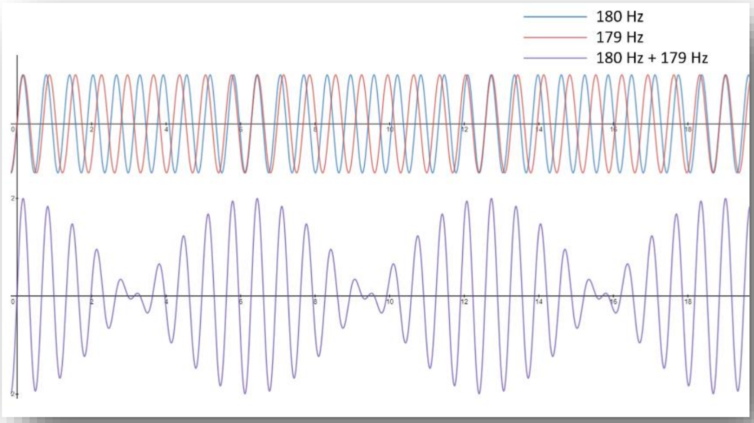

Figure 3.4 The interference pattern between signals of differing frequencies

While two signals with the same frequency while not experience changes in phase over time, when two signals have differing frequencies, the phase between the two signals will change over time. These changes in phase over time can be observed as oscillations in maximum amplitude over time. These oscillations are referred to as beats, the difference between the two frequencies are referred to as the beat frequency. In Figure 3.4, two sinusoid waves of differing frequencies are superimposed, and the resulting wave experiences periodic points of total destructive interference.

Acoustic noise signals propagate in three-dimensional space in all directions, therefore, the interference between two signals can also be mapped in three-dimensional space. In Figure 3.5, the interference pattern between two signals of the same frequency is mapped in two-dimensional space. The cyan areas represent the destructive interference in which the noise signals are completely cancelled out. These areas also represent points in which the two signals have a phase of 180°. There are other regions in the mapping where the noise signals are not cancelled. This is due to the speed of sound affecting the time it takes an acoustic noise signal to reach a location. This creates a delay which misaligns the phase of the signals. Because sinusoid signals are periodic, the delay can realign the phase such that the peak of one signal is superimposed on the next peak of the other signal. In Figure 3.6, the interference pattern of two signals with differing frequencies is mapped. When two signals have differing frequencies, the phase between the signals change over time. Because the rate in which the signal repeats is different between the signals, the superposition of the signals changes over time as the difference between wavelengths cause the phase to drift over time. In oscillating waves, the changes in phase will also oscillate, the signals will experience repeating periods of constructive and destructive interference.

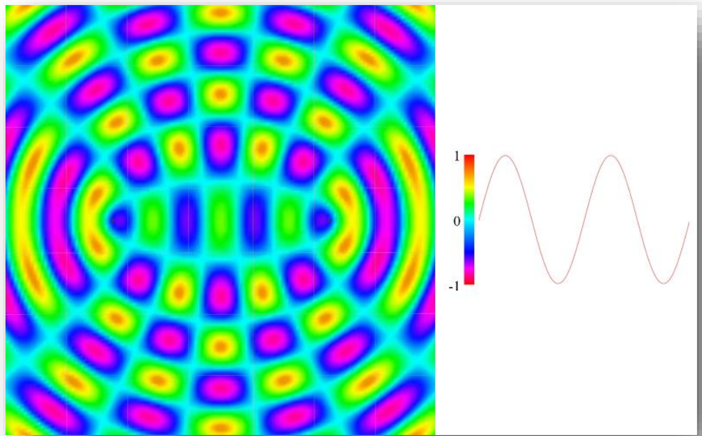

Figure 3.5 2D mapping of interference between signals with the same frequency

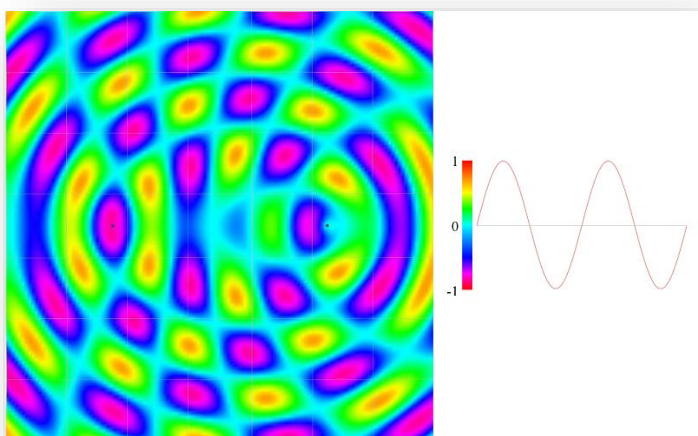

Figure 3.6 2D mapping of the interference between 2 signals of differing frequencies

Methods for aligning phases rely on compensating for latency in an ANC system. However, the phase between oscillating signals can also be aligned if the signals have differing frequencies. Because phase alignment between signal of differing frequencies changes periodically over time, a phase of 180° can be predicted.

3.4 Waveform Filtering

In traditional ANC systems, the input noise signal is inverted and used as the anti-noise signal. While this method is effective at reducing the overall noise, it affects all sources of noise equally. In applications of ANC where the goal is preserving a target noise while reducing ambient noise, the input noise signal must be preprocessed or analyzed before an anti-noise signal can be produced. Many implementations of ANC system incorporate a sophisticated filtering algorithm in order to target certain spectral frequencies. In order to successfully implement these filtering techniques, the hardware used must be able to handle such computationally expensive tasks.

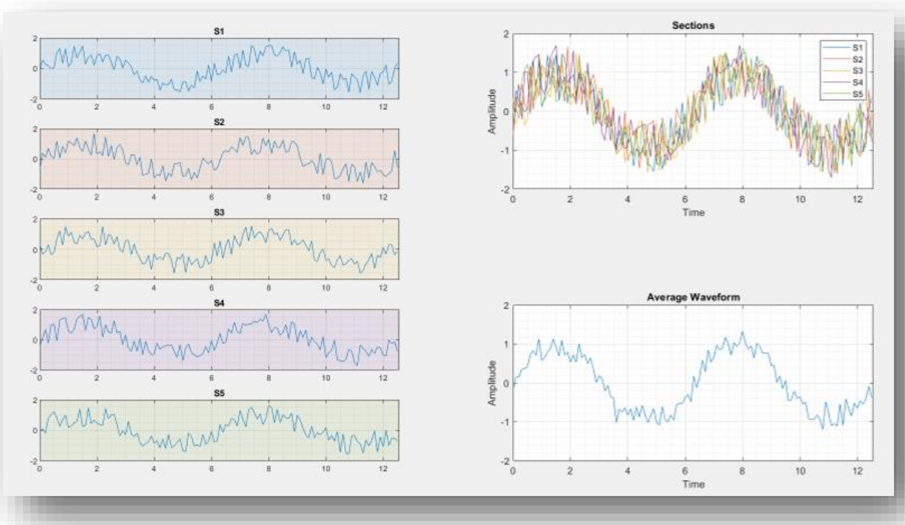

Figure 3.7 The averaged waveform is produced through from the original noise signal

The noise produced by a propeller, when the drone is stationary, is composed of highly repetitive waveform patterns. In order to use these waveform patterns, the errors in the signal (due to data noise) must be removed. Waveform averaging can take advantage of the repetitive nature of the propeller noise to filter out the noise data while obtaining the noise signal produced solely by the propeller. By superimposing the individual waveforms of a signal into a single wavelength, the corresponding individual points of data can be averaged. The nonrepetitive data, such as speech and ambient sounds, have a negligible impact on the average. The repetitive data produced by the drone propellers will converge to a single waveform that will represent the true waveform of the propeller noise. This is due the waveform of the propeller noise being present in the entirety of the noise signal. Once the averaged waveform is produced, it can be used as an anti-noise signal. Figure 3.7 illustrates this process. The colored sections represent the wavelengths of the original input noise signal. Superimposing these sections of data reveals the true nature of the waveform of the propeller noise.

This signal will contain the spectral frequencies of the propeller noise, therefore, it will only target frequencies similar to that of the propeller noise, leaving target noises unaffected. This process of waveform averaging is relatively computationally inexpensive and can also be parallelized to further increase computation speed. Also due to the repetitive nature of the propeller noise, the averaged waveform does not need to be continuously updated in order to accurately reduce the propeller noise. This averaged waveform will only need to be updated when the drone's propellers changes the nature of its noise, or over a long period of time to avoid error due to phase drifting.

3.5 Preliminary Exploration and Experimentation

Traditionally, ANC systems will use the unfiltered inverted noise signal as the anti-noise signal to cancel the sound. In order to test the effectiveness of the traditional technique, the drone propeller noise was recorded, inverted, and emitted from a loudspeaker. When the noise produced by the drone propeller and the anti-noise signal emitted from the loudspeaker interacted, the superimposed signals were aligned such that the high pressure areas of one signal overlapped the low pressure areas of the other signal, creating destructive interference and reducing the strength of the resulting noise signals. The interference between the propeller noise and the anti-noise signal was able to achieve a reduction of 27.64%. However, this technique also achieved a 14.46% increase in noise as well. This was due to the lack of phase alignment techniques needed to produce destructive interference. Without a phase alignment technique, the phase between the noise and anti-noise signals may produce constructive interference which will increase the overall level of noise. In traditional ANC systems, phase alignment techniques are implemented using delayless signal transferring methods which allows a system to immediately emit the anti-noise signal and eliminate any changes in phase. While this may be practical for unfiltered anti-noise signals, filtered anti-noise signals must also implement a delayless filtering algorithm in order to minimize the computation time and change in phase between the two signals.

During early exploration of the waveforms, the waveform of the drone propeller noise closely resembled the triangle waveform, however, due to a high level of noisy data, it was difficult to determine any compounded waveform structures hidden within the noise. A triangle wave with the same dominant frequency was used as the anti-noise signal against the drone propeller noise. This method was able to achieve up to 4% reduction in overall level of noise. While the failure of this method was partially due to the lack of a phase alignment method, this method also made the true nature of the propeller noise waveform apparent. The waveform of the drone propeller noise resembled a triangle wave; however, it was also slightly skewed and slightly resembling a sawtooth wave. It was determined that this phenomenon was a result of rotational Doppler shifting caused by the high rotational speed of the propeller blades. As the propeller approaches a high rotational speed, the pressure ahead of the propeller blade experiences a sharp pressure gradient, while the pressure behind the propeller blade experiences a gradual pressure gradient. Theses differing pressure gradients correlate to a skewed waveform, which may increase the strengths of the harmonic frequencies as the waveform approaches a form similar to that of a sawtooth waveform. Through this experiment, it was determined that the waveform approximation algorithm must take into account the rotational speed of the propeller to better adapt to rotational Doppler shifting.

4 ANC THROUGH PITCH-SHIFT PHASE ALIGNMENT

Traditionally, ANC systems rely on delayless filtering algorithms [5][7] in order to minimize the amount of latency and minimize the drift in phase between the noise and anti-noise signals. However, for computationally expensive filtering algorithms, the latency introduced in these algorithms make it difficult to align the phases between signals. Because the drone propeller noise signal is highly repetitive and linear while the drone is stationary, the principle of beat frequencies can be implemented to align the phases between these linear signals.

4.1 Beat Frequencies

Beats are the result of the interference between signal noise signals with the same amplitudes but differing frequencies. When noise signals of differing frequencies are superimposed, the interference produces periodic points of constructive and destructive interference. A beat is the period between two consecutive points of destructive interference. The number of beats that occurs within a single second is known as the beat frequency. Each beat correlates to the period in which the phase between the two noise signals transitions from 180° to 360°, then from 0° to 180°. This means that the beginning and end of the beat correlates to a phase of 180° or maximum destructive interference.

4.2 Pitch-shifting Methods of Noise Signals

In order to take advantage of the principle of beats, the anti-noise signal must first shift its pitch so that its pitch is different from the drone noise signal. There are different methods of altering the pitch of a noise signal. For highly complex signals with many harmonic or compound signals, the Fast-Fourier transform (FFT) is generally implemented. In this method, the frequency domain of a signal is shifted up or down, and the reconstructed signal increases or decreases in pitch, respectively. While FFT method is generally effective, it is also computationally expensive and must use a sufficiently large input signal, and it can also introduce unwanted artifacts.

Another method of pitch-shifting a noise signal is by altering the sampling rate of the signal. This method is much more effective at altering the pitch of a noise signal by increasing or decreasing the number of samples being emitted within a second to increase or decrease the pitch of the output signal, respectively. The sampling rate of the signal samples affect the frequency of the samples as therefore the pitch of the output signal. The samples themselves are not altered in any way, so the characteristics of the noises, besides the frequency, is unaffected, and it does not introduce any artifacts within the noise signal. Because this method relies on altering the rate in which the samples of the signal are emitted, it is much less computationally expensive than the FFT method, however, this method must be supported by the hardware components of the ANC system. If the hardware does not support dynamic sampling rates, then more measures must be implemented in order to shifting the pitch of the noise signal back to its original pitch once the phase between the two signals are aligned.

Although altering the sample rate to alter the pitch of the signal is ideal, it is highly hardware dependent. However, the sampling rate method can also my mimicked using the resampling method. The resampling method alters the pitch of a noise signal by redistributing the samples over a shorter or larger number of samples, in order to increase and decrease the pitch of the noise signal, respectively. The signal is also interpolated in order to approximate the missing sample that are a result of the redistribution process. The result of the interpolation process can slightly reduce the details in the waveform of the noise signal; however, these effects are negligible. This process is less computationally expensive than the FFT method, and it can be implemented independently of hardware specifications. For these reasons, the resampling method is implemented in the PA-ANC system.

4.3 Phase Alignment through Pitch-shifting and Beat Frequencies

In order to align the phase between the drone noise and anti-noise signals, the principle of beat frequencies can be used, however, the two signals must be of differing frequencies or pitch. To alter the pitch of the anti-noise signal, the resampling method is used to decrease the pitch of the anti-noise signal. When the pitch-shifted anti-noise signal is superimposed on the drone noise signal, the resulting noise signal will experience beat. The periodicity of the beats, the amount of time between two consecutive points of maximum destructive interference, can be measured. When the point of maximum destructive interference is observed, the phase of the two signals are aligned at 180°. At this point, the original anti-noise signal is emitted from the loudspeaker from the corresponding point in the pitch-shifted anti-noise signal. From this point on, the phase between the drone noise and anti-noise signals are aligned, and the reduction effect is sustained.

4.4 Approach

Spectral subtraction filtering is usually applied to the recorded audio signals rather than to the source of the noise itself. In the proposed system, spectral subtraction filtering is applied through an ANC implementation. In this implementation, the effects of noise reduction is observable in the real world. By averaging the waveform produced by the drone’s propellers, the spectral frequencies of the drone noise can be approximated. Using this average waveform as an anti-noise signal, certain frequencies are targeted and cancelled, thus leaving environmental noises, such as speech, unaffected.

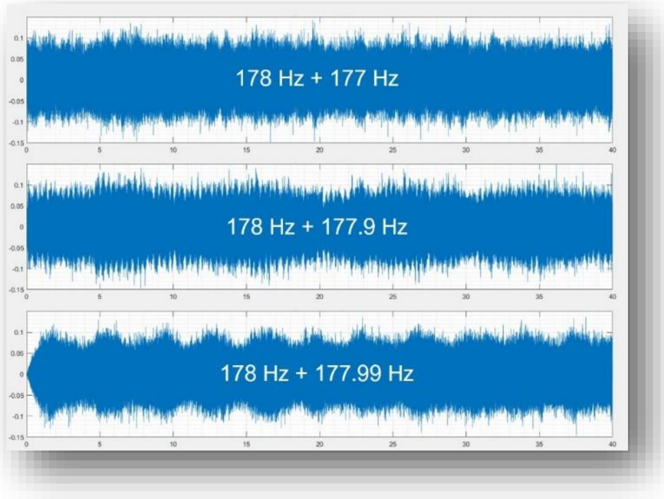

Figure 4.1 Interference pattern of propeller noise and anti-noise signals

ANC relies on the phase of the anti-noise signal in order to maximize the reduction of overall noise. This experiment will utilize pitch-shifting in order to align the phase of the anti-noise signal. When two signals with different frequencies are combined, a pattern of constructive and destructive interference (beats) is produced. For linear frequency signals, the interference is highly predictable, because the beat pattern repeats in regular intervals. When the overall noise is at its minimum, this is the point of maximum destructive interference and the point where the anti-noise signal is in the correct phase compared to the original noise signal. The periodicity of the destructive interference is proportional to the difference between the two frequencies. In Figure 4.1, a recording of the programmatically added to three anti-noise signals. The anti-noise signals in this case are produced by pitch-shifting the propeller noise (dominant frequency is 178 Hz) to 177 Hz, 177.9 Hz and 177.99 Hz respectively and inverting the signal.

When there is a beat frequency of 1 Hz between the noise and anti-noise signals, the period of the interference is very small and hard to observe. When the beat frequency is 0.1 Hz, the pattern becomes much more observable, but the period is still small enough to predict the next point of maximum destructive interference. When the beat frequency is 0.01 Hz, the period of interference is large enough to accurately predict the next point of maximum destructive interference.

Once the point of maximum destructive interference is reached, the anti-noise signal is shifted back to its original frequency, and, in theory, the destructive interference is sustained, and the overall noise is reduced.

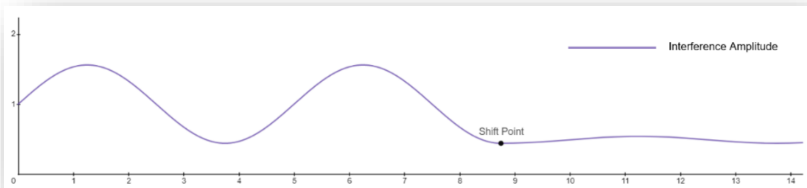

Figure 4.2 Predicted behavior of interference pattern of this system

4.5 Algorithms

4.5.1 Waveform Averaging

The waveform averaging algorithm relies on the dominant frequency of the input noise signal. Using the FFT, the frequency domain of the noise signal is determined. The dominant frequency F_{dom} is obtained by determining the frequency with the largest amplitude. The wavelength of the noise signal is determined by dividing the sampling frequency of the noise signal by the dominant frequency. The wavelength of the noise signal is usually of non-integer length. In order to minimize the difference between the wavelength of the noise signal and the calculated wavelength, the length of the calculated wavelength is multiplied by a factor n such that product of the length of the calculated wavelength and n are ±0.05 of an integer number. The product of n and the calculated wavelength is then used as a window for the averaged waveform. The samples of the noise signal are divided into partitions of the size of the window.

Each element of a partition is added to the corresponding element of all other partitions. Each element of the sum of partitions is then divided by the number of partitions, resulting in the average waveform. The signs of the average waveform is then inverted to produce the anti-noise signal. The result of the waveform averaging algorithm is illustrated in Figure 4.3.

Input: Single channel drone propeller noise signal NP
Output: Single channel average waveform signal $avgWave$

Step 1: Use FFT to analyze frequency spectrum
Step 2: Let F_{dom} = frequency with max amplitude
Step 3: Let $Wavelength = \frac{Sampling\ Frequency\ of\ Signal}{F_{dom}}$
Step 4: Let $Window = round(n * Wavelength)$ where n is an integer such that $(n * Wavelength)\%1 \geq 0.95$ or $(n * Wavelength)\%1 \leq 0.05$
Step 5: START ITERATION LOOP
$avgWave += NP[i * Window : (i + 1) * Window]$
$i += Window$
END ITERATION LOOP
Step 6: $avgWave = -1 * \frac{avgWave}{i}$

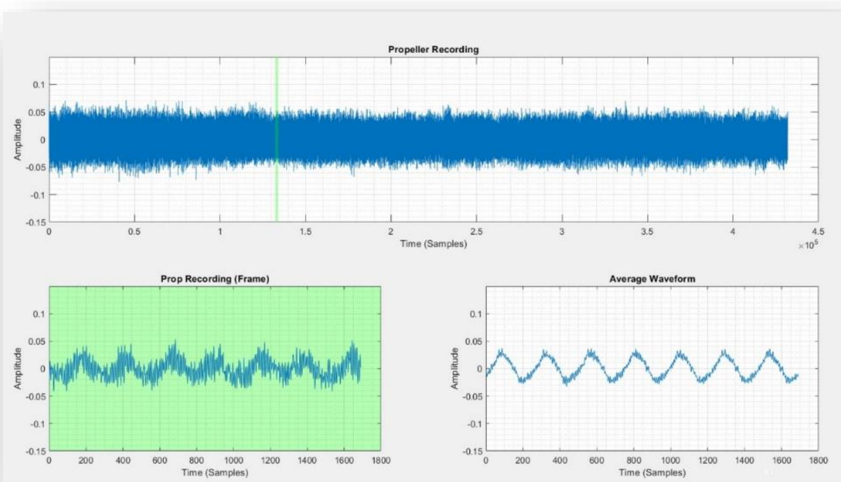

Figure 4.3 Average waveform (right) compared to a portion of the propeller noise (left)

4.5.2 Periodicity of Interference

The periodicity algorithm is an adaption of the sliding window algorithm. The algorithm will first read the next reading frame produced by the recording device and find the average amplitude of that frame and store into an array. It will then find the index of the minimum value of the previous h elements and append it into a list of indices W which serves as the sliding window. h is an integer that corresponds to the sensitivity of the algorithm. As h increases, the sensitivity of the algorithm decreases and accuracy increases. With each iteration of this loop, the first element of W is truncated and the index of the next minimum value is appended. If all elements in W have the same value, then append that value to a list on indices M. M will contain the indices of points of maximum destructive interference. The periodicity of interference is equal to the average of the differences between each element and its adjacent element in M.

Input: Interference signal between propeller noise and anti-noise signals NI
Output: Periodicity of maximum destructive interference P

Step 1: Let f be an array of samples in a single reading frame from a recording device
Step 2: Let n be the number of reading frames in a recording
Step 3: Let A be an array of size n
Step 4: Let M be a list of indices
Step 5: Let Win be an array of size h initialized as zeroes
Step 6: START ITERATION LOOP
    $A[i] = mean(|f_i|)$
    $Win = \left[Win[2:h]\, , indexOf\left(min(A[i-(h-1) : i])\right)\right]$
    if all elements in Win are the same AND $W[1]$ is not in M
        $Append(M, W[1])$
  END ITERATION LOOP
Step 7: Let $P = 0$
Step 8: START ITERATION LOOP
    $P += M[j+1] - M[j]$
  END ITERATION LOOP
Step 9: $P = \frac{P}{size(M)-1}$

5 EVALUATION

Traditional ANC systems are effective at reducing the noise produced by drone propellers although the anti-noise signal is unfiltered. Modern ANC techniques implement filtering algorithms to produce a more effective anti-noise signal and further reduce the noise produced by drone propellers. The effectiveness of the PA-ANC system is compared to a baseline effectiveness of the traditional ANC techniques.

5.1 Experimental Setup

Figure 5.1 The setup of preliminary experiments include a microphone, blue speaker (unaltered) and a red speaker where the polarity of the input signal is hardwired. In the PA-ANC experiments, the red speaker is replaced by the drone propeller, which is mounted to a stand, and the Raspberry Pi controlling it is also mounted to the stand.

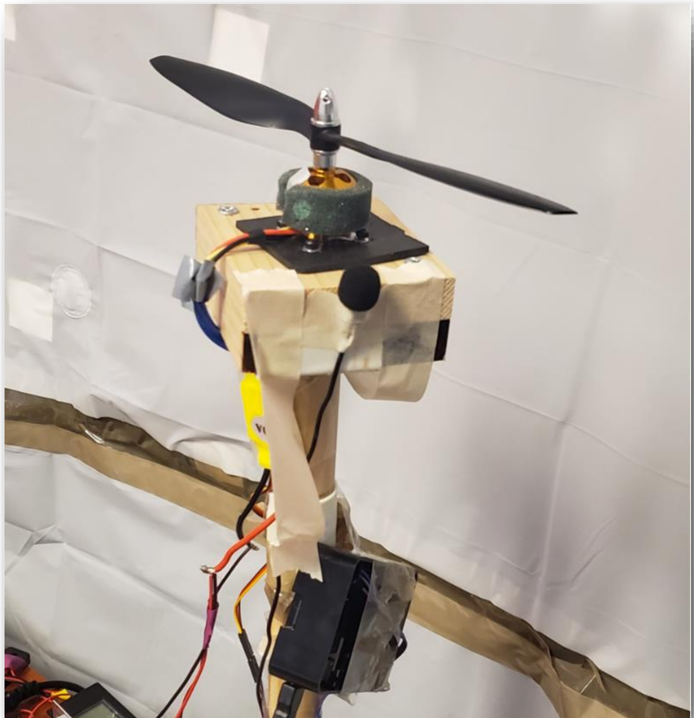

Figure 5.2 Drone propeller and Raspberry Pi [16] mounted to the stand

The proposed system was tested using a single propeller in order to test its effectiveness. The propeller is attached to a three-phase brushless motor, which is mounted to a stand. A Raspberry Pi, controlled over a Wi-Fi connection, is used to control the rotational speed of the motor [16]. A Bluetooth speaker attached to a tripod is used as the loudspeaker that emits the anti-noise signal. A microphone, attached to a stand, is used as the primary microphone as well as the error microphone. The propeller, loudspeaker, and microphone are arranged such that these components are located 45 inches apart. This setup is located in a sound booth lined with sound insulating foam, which prevented reverberations from flat surfaces. The PA-ANC system was developed using MATLAB in order to take advantage of its audio and signal processing toolkits [15]. Figure 5.1 depicts the sound booth in which the experiments were conducted. The propeller in Figure 5.2 replaces the red speaker during experimentation. In future implementations, the system will experiment with a multi-propeller drone capable of flight.

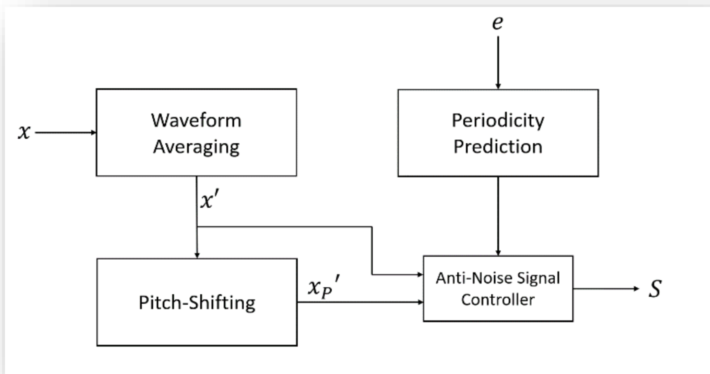

Figure 5.3 System design of the PA-ANC system

In Figure 5.3, the system design is illustrated. The proposed PA-ANC system is designed as a feed-forward configuration. x represents the input noise (propeller noise). The input is analyzed by the waveform averaging algorithm, and the averaged waveform x' is transferred to the anti-noise signal controller and the pitch-shifting algorithm. After the anti-noise signal is pitch-shifted, it is then transferred to the anti-noise controller. The error signal e is analyzed by the periodicity prediction algorithm which controls the anti-noise signal controller. The anti-noise signal controller determine if the output signal S is the averaged waveform x' or the pitch-shifted averaged waveform $x_P{}'$.

The PA-ANC system begins by recording the drone noise for 13 seconds. The first 3 seconds are then removed in order to remove artifacts that may appear when the recording device starts recording. The waveform averaging algorithm is performed on the 10 seconds of audio data in order to produce a general shape of the wave. The waveform averaging algorithm takes into account non-integer wavelengths (measured in samples). It will use a window size that is multiple of the wavelength of the dominant frequency such that the window size is of approximately integer size (tolerance of ± 0.05). If the window is of non-integer size, it will drift during the averaging algorithm and will result in a flat signal.

After producing the average waveform, the pitch is shifted slightly, and it is played against the propeller through a speaker. The interference is recorded concurrently, and the changing amplitudes are analyzed using the periodicity algorithm. This algorithm was slightly modified to operate in real time. Once it reaches the next predicted point of maximum destructive interference, the pitch of the average wave signal is shifted back to its original pitch.

5.2 Evaluation Methodology

In order to measure the effectiveness of the system relative to ambient levels, the average amplitude of the ambient noise was subtracted from the average amplitude of the noise signal. The resulting number correlates to the average amplitude of the noise added to the environment. This measure ensured that the results of these experiments measured the effectiveness of the system regardless of the level of ambient noise. When measuring the amplitudes of the interference pattern, average of the absolute values of each recording frame were computed. A single recording from of the recording device contained 1024 samples which facilitated the computation needed to measure the noise level by partitioning the signal data into manageable sections. The individual samples of the signal cannot be used to determine noise level as it measures a small portion of the signal needed to produce noise. By computing these average frame values, the level of noise of the signal at a given moment can be accurately measure.

The overall level of noise of the signals are compared using its overall average amplitude. The average amplitude is calculated by determining the average of the absolute value of all sample values in the signal. All of the recordings are made using the same microphone and sensitivity settings; therefore, the measurements can be reliably compared.

5.3 Results

5.3.1 Key Findings

Experimental results demonstrated that the pitch-shifting method successfully produced patterns of constructive and destructive interference when played again the drone propeller. At points of maximum destructive interference, this method was able to reliably achieve 20-40% reduction in noise from the overall noise produced by the drone propeller.

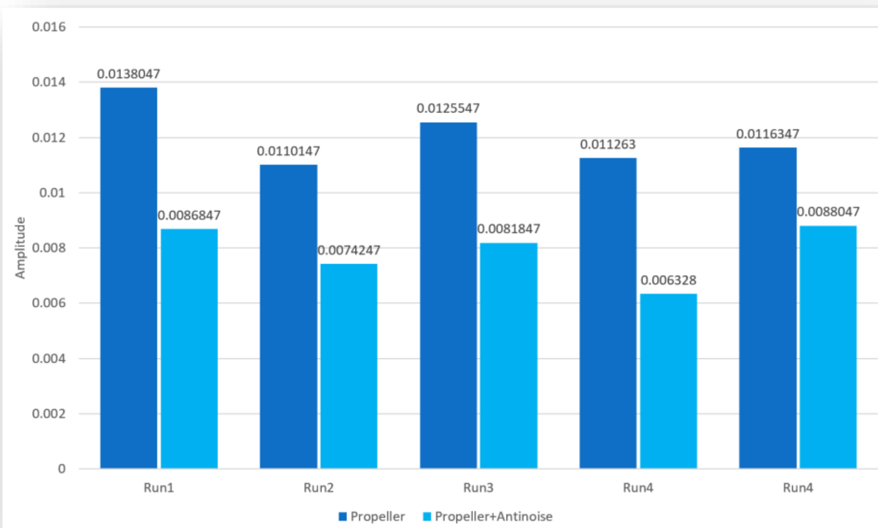

Figure 5.4 The averaging amplitude of the propeller noise signal compared to the lowest amplitude measured from the PA-ANC system

Figure 5.4 illustrates the results of the PA-ANC system during five runs of the experiment. The PA-ANC system achieved its highest level of noise reduction of 43.82% during Run4 and its lowest level of noise reduction of 24.32% during Run5 at its lowest point of maximum destructive interference when compared to ambient levels of noise. The pitch-shifting alignment strategy was able to reliably align the anti-noise signal against the propeller noise signal to reliably favor destructive interference.

The waveform averaging algorithm was able to produce an anti-noise signal that had high similarity to the recorded drone noise. It was also able to successfully smooth out the ambient noise and recreate the waveform produced solely by the propeller. During the tests of the PA-ANC system, the averaged waveform proved to be effective as it was able to significantly reduce the level of noise produced by the propeller.

The periodicity algorithm was able to accurately predict the periods of maximum destructive interference in linear noise signals (signals with static dominant frequencies), however, due to slight changes in the rotational speed of propeller, interference patterns changed drastically and unpredictably. In practice, the prediction algorithm performed poorly to predict a future point of destructive interference.

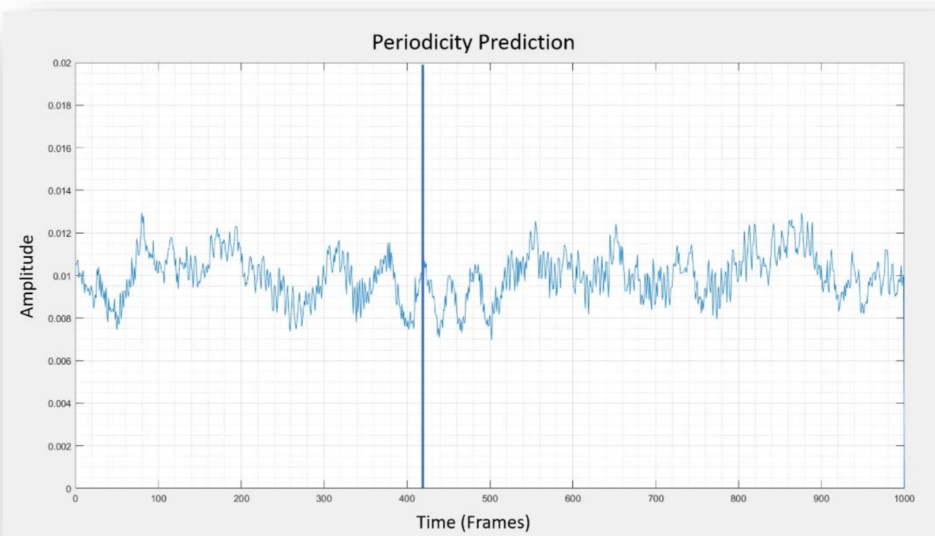

Figure 5.5 Recorded interference pattern before and after switch

As an alternative, the system will find a minimum amplitude and shift the pitch when the current amplitude is less than the minimum measured value with a tolerance of 5%. This alternative algorithm performed well in practice. In Figure 5.5, the alternative algorithm was able to pitch shift at a point of maximum destructive interference. It is apparent that the propeller is changing frequencies, as the distance between any two consecutive points of interference differ greatly, this alternative algorithm provides a reliable, computationally inexpensive method to determine at what point to shift the pitch of the anti-noise signal.

5.3.2 Observations of the PA-ANC System

Observations made during experimentation highlighted mechanics that may have had an effect on the performance on ANC systems. During the many tests of the waveform averaging algorithm, it was found that the waveform of the drone propeller noise signal varied in shape, despite the noise being audibly similar.

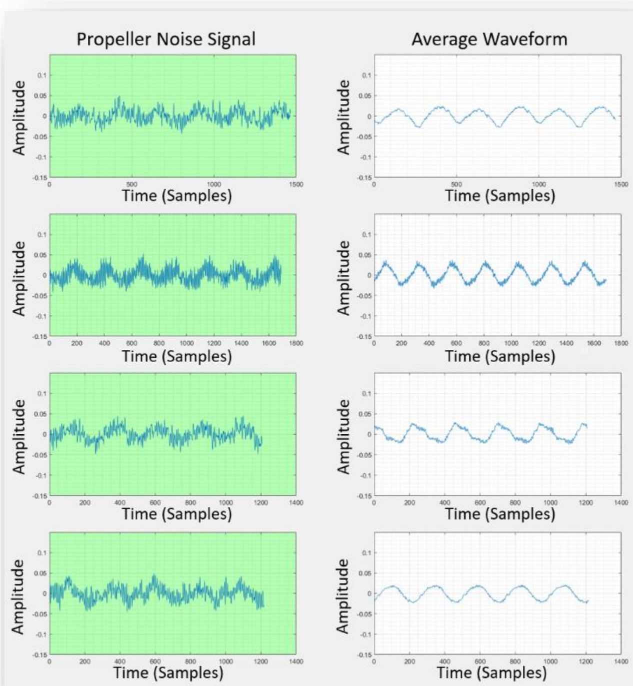

Figure 5.6 Waveform of the recorded signal from propeller (left column) compared to its averaged waveform (right column)

In Figure 5.6, four waveforms are illustrated. These noise signals are produced from the same propeller and were recorded from the same distance and location relative to the propeller. A suspected cause of this is the modulated signal used to operate the propeller's motor. Small disturbances in the orientation of the propeller can cause the motor to increase or decrease in rotational speed. In these experiments, the propeller was attached to a three-phase brushless motor. The modulation of the signal used to control the motor, as well as small variations is torque as the propeller rotated may have cause the waveform to change its shape over time.

5.3.3 Benchmarks and Comparison

In order to compare the effectiveness of the PA-ANC system, various benchmarks were implemented. The effectiveness of the PA-ANC system was compared to traditional ANC techniques as well as a control test of the PA-ANC system using generated tones.

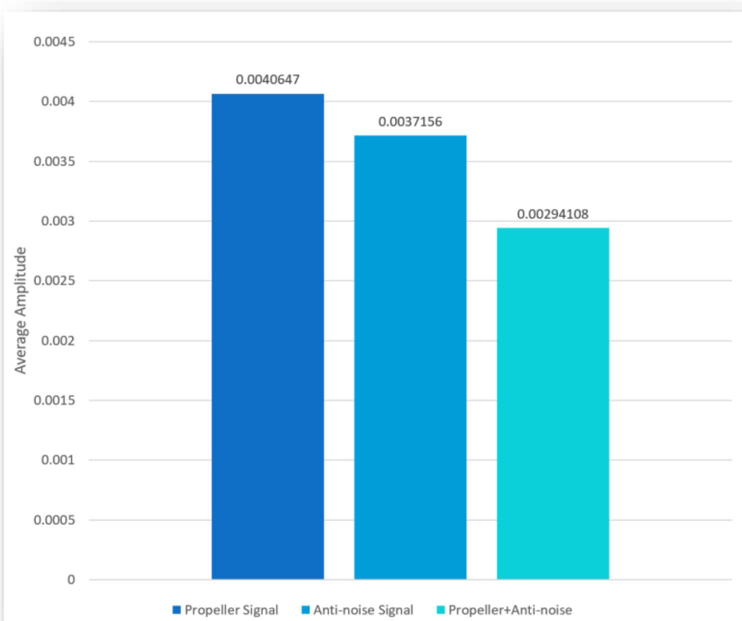

Figure 5.7 Noise reduction between propeller and unfiltered anti-noise signals

Traditional ANC systems use the unfiltered drone noise signal as the anti-noise signal. As a baseline measurement of the effectiveness of ANC systems on drone propellers, the traditional ANC technique was implemented and tested against the drone propeller. In the first experiment, the anti-noise signal was a one-minute recording of the drone propeller noise. The recording was inverted and emitted from a loudspeaker located 45 inches from the propeller. The interference was then recorded, and the average amplitude of the interference was determined. Using this method, a 27.64% reduction in noise was observed as seen in Figure 5.7.

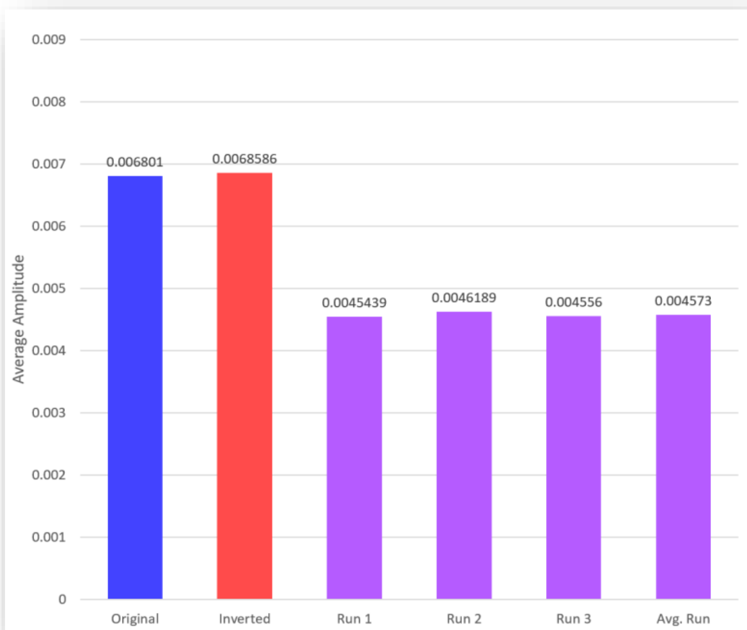

Figure 5.8 Noise reduction of traditional ANC using speakers

The traditional ANC system was then implemented using two speakers. One speaker, used instead of the propeller itself, emitted the recorded drone propeller audio signal in order to replicate the noise produced by the drone propeller. The other speaker was altered such that the polarity of the input signal is reverse. This speaker will emit an inverted noise signal relative to the input signal, therefore, this speaker is used as the anti-noise speaker. Figure 5.8 displays the results of 3 runs of this experiment. This ANC method was able to achieve a 33.47% reduction in noise level. This experiment was used in order to measure the effect of noise reduction on the same signal and measure the expected level of noise reduction on linear signals.

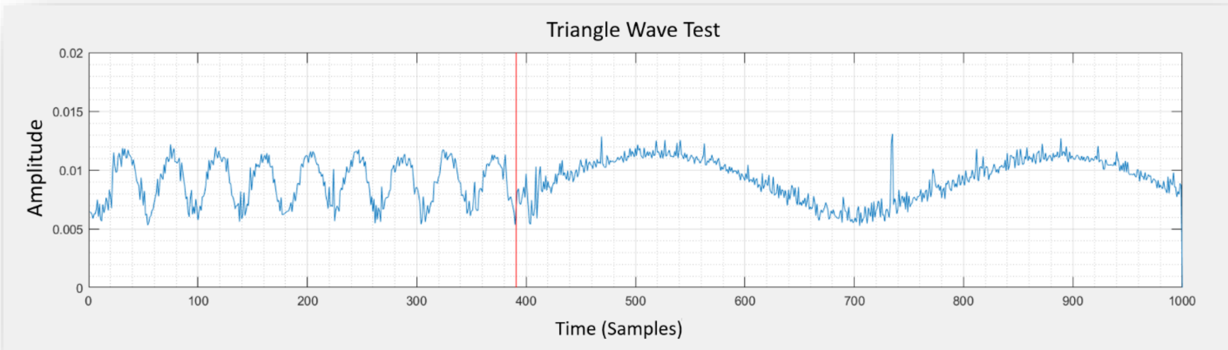

Figure 5.9 PA-ANC tested against 186 Hz Triangle wave

As a benchmark of the PA-ANC system's performance against drone propeller noise, this system was tested using a 186 Hz triangle wave signal. The PA-ANC relies on the dominant frequency of a noise signal. If the noise signal is linear in nature, the system should perform exceptionally well to reduce the noise. In Figure 5.9 the periodicity of interference increases significantly after the anti-noise signal is shifted back to its original pitch. As the periodicity increases, the difference between of pitch between the anti-noise and propeller noise signals decrease. The original pitch of the anti-noise signal must differ very slightly to the pitch of the noise due to the observed interference pattern after the shift to the original pitch. This may be due integer window size computed in the waveform averaging algorithm. The pitch of a noise signal can have a non-integer wavelength. When playing the anti-noise signal, a drift in phase occurs. This effect can be observed over relatively long periods of time.

6 CONCLUSIONS

Drone noise further exacerbates the issue of noise pollution. While noise pollution can have negative effects such as overpowering and ruining audio recordings, it may also contribute to the negative mental and physical illnesses linked to noise pollution such as fatigue, hearing loss, and hypertension. The proposed PA-ANC system aimed to solve this problem by implementing methods of spectral analysis and active noise cancellation to reduce the overall noise produced by a drone propeller. By isolating the dominant frequencies of the propeller noise and phase-shifting a generated anti-noise, this method of noise control was able to achieve and 43.82% reduction in noise.

While this reduction in noise could not be sustained, these experimented revealed the characteristics of drone propeller noise signals and highlighted key features that may improve the effectiveness of future ANC systems. Harmonic frequencies contribute largely to the observed loudness of a noise signal. The waveform of the noise signal determines the number and strength of the harmonic frequencies and, therefore, the observed loudness of the noise. Periodic signals, such as the drone propeller noise signal, can be approximated by averaging the wavelength of the noise signal, and by using the generated waveform as the anti-noise signal, the spectral frequencies of the drone propeller noise can be targeted and reduced. The waveform averaging algorithm was able to accurately reproduce the true nature of the noise produced by the drone propeller by smoothing the noisy data form the input signal and preserving the waveform of the propeller noise signal. Pitch-shifting the anti-noise signal presented an effective method of aligning the phase of the signals by relying on the produce beat frequency in order to predict the points of maximum destructive interference and maximum the noise reduction effect.

Future improvements to this system will incorporate factors such as hardware specifications as well as parallel computing in order to reduce latency of certain computations and allow the system to better adapt to changes in noise over time. The use of software or hardware that supports dynamic sampling rates may also reduce the latency of the system by eliminating the need to resample the anti-noise signal and, instead, instantly change the sample output rate. A dynamic sampling rate may also facilitate in continuous updating after aligning the phase in order to sustain the noise reduction effect. Periodic updating of the averaged waveform as well as continuous error signal checking may also improve the effectiveness and robustness of the PA-ANC system.

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