

Analysis of an Aeolian Harp

Music Minor Capstone Project



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Abstract

The Aeolian harp is a mysterious and ancient instrument, known throughout the centuries for its ability to produce eerie and mysterious tones when wind blows over its strings. This experiment and paired musical composition are both ways of exploring the properties of a wind harp. The instrument was placed inside a wind tunnel and recorded with different tunings while varying the wind speed. Analysis of these recordings provides confirmation that an Aeolian harp follows the general pattern predicted by fluid dynamics, but a few aspects differ from predictions made by the equations. These recordings were also used to create a composition from the sounds of the harp and those of nature. The composition is made of three parts, each representing an elemental force - earth, ocean, and wind, yet blending together to make a cohesive whole. The composition was inspired by the history and unique, eerie sounds of the Aeolian harp, and is publicly accessible on YouTube.

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Introduction

When wind moves over a string, such as a telephone wire or harp string, it can create a sound. When several of these strings are attached to an acoustic (or electrical) amplifier, the resulting harp can make music with no visible player. This gives the instrument a magical feel, because it creates sound without an obvious source. Named the Aeolian harp or wind harp, these instruments have been a great source of inspiration throughout history. The most elusive part of their functioning is the wind - it is very difficult to find naturally occurring and consistent laminar airflow. That is why this experiment will place the harp in a wind tunnel, where the exact speed of the wind is controlled and consistent laminar airflow is produced. This will allow testing of cause and effect to determine exactly which wind speed and tuning produce specific sounds from the harp, providing insight into how the harp functions and the music it has the potential to produce under the right conditions.

Background

History

The Aeolian harp or wind harp has been around for centuries. Named after Aeolius, the Greek god of the wind, these harps were in existence as early as 6 B.C. in Greece [1]. Like many concepts from Ancient Greece, they were revived during the Renaissance. The first modern aeolian harp was made around 1650 by Athanasius Kircher [2]. By the Romantic Era, these harps had become a commonplace feature of society. Poets considered these instruments to be playing nature's own music, drawing from the sounds to create poetry. There were a number of poems and even musical compositions inspired or derived from the sounds of the Aeolian harp. Two musical examples are Chopin's *Aeolian Harp Etude*, and Sergei Lyapunov's *Harpes éoliennes*. There is even a special stop on some German pipe organs that imitates the sound of the wind harp [2]. However, Aeolian harps are far less common today, occasionally appearing as sculptures or lawn ornaments [1].

Physics

The sound produced by the harp is caused by the von Karman vortex street effect, creating swirling vertices as seen in Figure 1. This effect is why an Aeolian harp generates only overtones – the fundamental tone (which you would get if you plucked the string) remains silent[3]. This is because the vertices are caused by wind deflecting off the string, not the movement of the string itself. Each

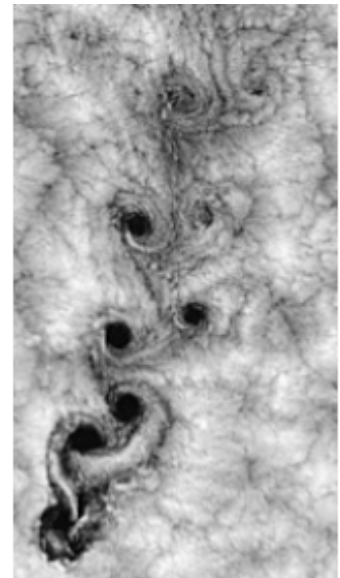


Figure 1: Karman Vortex Effect in Clouds

swirl in the figure represents a harmonic - as the circles grow smaller the frequency of the harmonics rise. The set of harmonics produced are dependent upon the length, tension, and diameter of the strings, as well as wind speed and fluid density[4]. When the strings produce a constant tone, it is a phenomenon in fluid mechanics called vortex-induced vibration (VIV). It is a complex relationship that is not fully understood [5]. However, there are several relevant equations from physics that apply to this effect and musical instruments in general.

The frequency of the vortices shed by the string when air flows over it can be predicted by the Strouhal frequency, calculated from the Strouhal number (St). This number is a variable that describes the relationship between the Strouhal frequency f_s , air speed u , and diameter d shown in Eq. 1[4]. The Strouhal number for a cylinder is around 0.2 [6].

$$St = \frac{f_s d}{u} \quad (1)$$

The natural harmonic frequencies of a string f_η can be derived from tension T , length l and linear mass μ , where η is the harmonic number.

$$f_\eta = \frac{\eta}{2l} \sqrt{\frac{T}{\mu}} \quad (2)$$

When the natural harmonics of the string and the strouhal frequency converge, *Vortex Induced Vibration* occurs [4]. There is a range from 0.8 to 1.27 of this convergence point where lock-in occurs, and the sound and pitch produced are expected to be relatively consistent[4]. This phenomenon is what creates the unique sound of the harp.

Harmonic Series

The notes produced by the harp are also predicted by the harmonic series. Mathematically, the tones of a harmonic series are predicted by integer multiples of the frequency. For example, a series starting at 220 Hz would have a harmonic at 440Hz, 660Hz, 880Hz, 1100Hz and so on. This would correspond to the musical pitches A, A, E, A, C# etc... The pitch intervals of a harmonic series are an octave, fifth, fourth, major third, then a minor third [7]. The intervals continue to get smaller as frequencies increase. An example harmonic series is shown in figure 2.

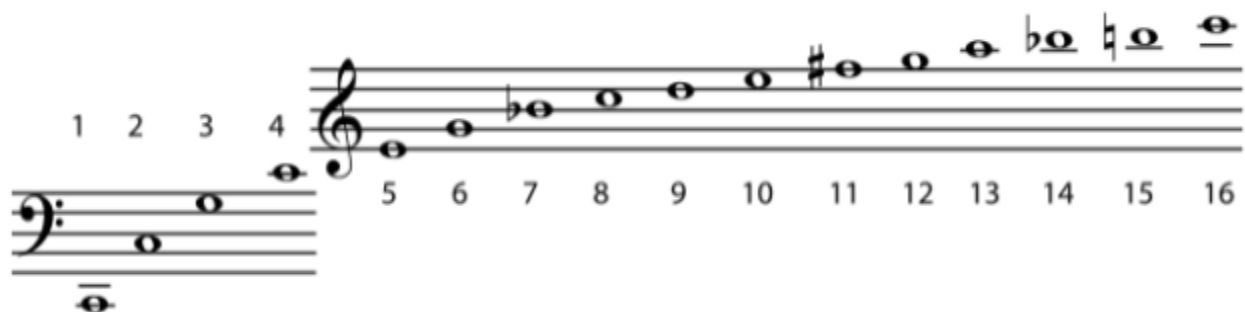


Figure 2: Harmonic Series with C as fundamental [7]

The first note of the series is referred to as the fundamental or first harmonic, the second note as the second harmonic, the third note as the third harmonic and so forth. It is worth noting that as the notes get higher in the series, they tend to be out of tune from the pitches shown above. This is because the standardized pitches typically used in music differ from the exact frequencies predicted by the harmonic series. The standardized tones in music are called equal temperament, and they allow instruments to play in different keys without dramatically retuning, and also provide a clear definition of each note based on frequency. Figure 3 provides the variation in cents (100ths of a semitone) as the harmonic series compares to equal temperament. The amount of variation is consistent between the same notes in different octaves [8].

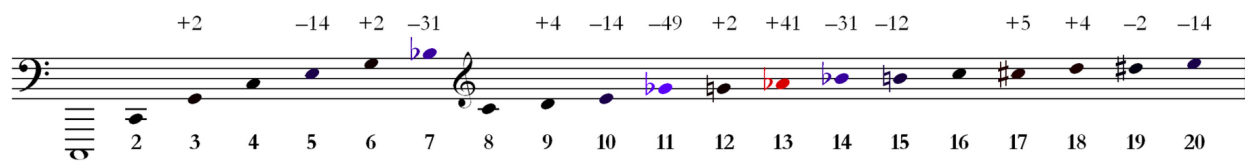


Figure 3: Variation from Equal Temperament[8]

One important place this series can be found is in brass instruments. When played with open keys or valves, the instrument will produce the tones of the harmonic series from only changes in embouchure. Indeed, the first brass instruments were limited to these tones because keys and valves had not yet been invented. Most traditional bugle calls or brass fanfares use only the notes of the harmonic series, as seen in this common wake-up call in figure 4.



Figure 4: A traditional bugle wake-up call [7]

Harp Construction

A few years ago, I built an Aeolian harp as a personal project. It is made of several types of wood, nylon monofilament, and zither pegs. The nylon monofilament is cylindrical, an important property to create the physics effects introduced above. The design of the harp is roughly based on Arthur Robb's sketch [9]. It is technically a zither because the strings run across the sounding board, instead of perpendicular to it. However, all stringed instruments designed to be played by the wind are commonly referred to as Aeolian harps. The instrument works best when placed in a laminar airflow, which can be generated at home by placing the harp in one window and opening another at the other end of the house. It can also be placed in front of a fan, or in a wind tunnel as it was for this experiment.

All of this research raised the question of how to scientifically analyze the sounds of the harp, and if the harp would follow the principles laid out in the equations. If the wind were controlled, would the harp produce a consistent and predictable sound? What would the qualities of that sound be as related to the harmonic series?

Methodology

The harp was placed in a closed-loop wind tunnel and a recording device attached on the side of the harp away from the wind (see figure 4). This was the best microphone placement to get clear recordings of the harp without an excessive amount of wind noise. This wind tunnel is most commonly used by aerospace students and faculty to test new aircraft designs. The wind speed can be set from 5-100 m/s and is controlled by up/down arrow buttons with a display showing the fan frequency, which is directly related to the wind speed.



Figure 4: Images of Experimental Setup

Some of the early experimentation included adding the harp cover and turning the harp to 45deg and 90deg from the direction of the wind. These changes actually reduced the sound from the harp, so all further testing was done with just the harp with the strings perpendicular to the wind vector. Wind direction is shown by the blue arrow in figure 4.

For the actual experimentation, the harp was tuned to different patterns and pitches. Each trial consisted of testing the harp at a range of wind speeds, usually 5.3 to 10.5 m/s. The wind speed was changed in increments, in order to record sounds across a variety of wind speeds. Tunings that were tested include:

- All strings tuned to A
- All strings tuned to B
- One string tuned up a half step (B, C)
- Half the strings tuned up a half step (B, C)
- Half the strings tuned up a fifth (B, F#)
- Half the strings tuned up an octave (A, A)
- Pentatonic tuning (C#, D#, F#, G#, A#)

Using the equations from the background, a spreadsheet was created to calculate the ideal wind speed for the harp with a variety of tunings. This was also tested. It is worth noting that the harp frequently went out of tune, especially when the pitch of a string was changed dramatically.

Recordings were taken with a TasCam DR-05 stand-alone microphone, and audio was processed with Audacity and Sonic Visualizer software.

Results

As predicted, the harp produced notes of the harmonic series based on the tuning of the string. Below is a table of the data gathered from the recordings, showing the pitches and volume as it relates to wind speed. The data was collected using Sonic Visualizer, a software program which can plot the frequency and volume of

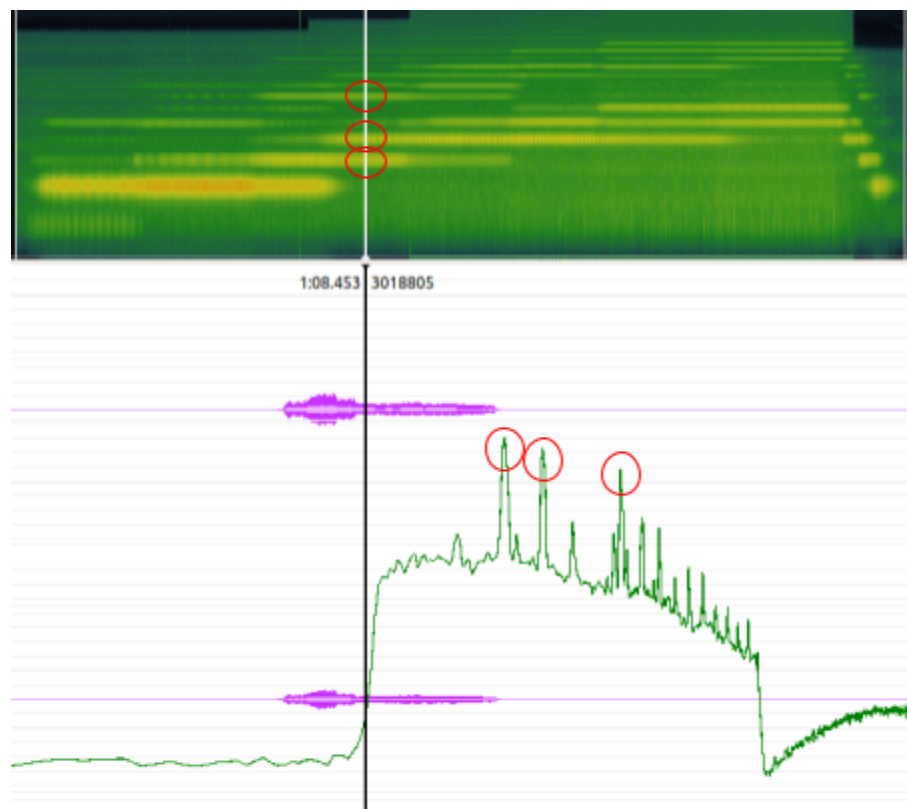


Figure 6: Data Collection

sound at a certain point in time. In the example in figure 6, the spectrogram shows the overall audio clip, while the exact breakdown of that point in the audio is shown on the graph below. The three circled peaks would be the tones recorded into the table below.

Tuning	Prominent Tones Produced (Hz), Approximate Note, Volume (-dB)				
Tunnel Frequency (Hz)	6	7	8	9	10
Wind Speed (m/s)	5.28	6.16	7.04	7.92	8.8
All strings A	(721, F, 20)	(721, F, 18) (947, Bb, 28) (1421, F, 32)	(721, F, 23) (974, Bb, 23)	(947, Bb, 24) (1195, D, 23) (1895, Bb 28)	(947, Bb, 30) (1195, D, 25) (1453, F, 28)
All strings B	(754, F#, 23)	(754, F#, 19) (1034, B, 26)	(754, F#, 18) (1034, B, 24) (2024, B, 32)	(754, F#, 25) (1034, B, 24) (2541, D# 32)	(1034, B, 24) (1281, D#, 29)
Half Step	(775, G, 24)	(775, G, 21) (1034, C, 26)	(775, G, 20) (1034, C, 23)	(775, G, 28) (1034, C, 25)	(1034, C, 22) (1281, E, 29) (1561, G, 31)
Fifth	(732, F#, 24)	(732, F#, 20) (991, B, 26)	(732, F#, 20) (991, B, 26) (1109, C# 21)	(732, F#, 29) (991, B, 26) (1109, C#,19) (1238, D#, 27)	(991, B, 25) (1109, C#, 19) (1238, D#, 23)
Octave	(657, E, 22)	(657, E, 22) (872, A, 24)	(872, A, 24) (1098, C# 28)	(872, A, 22) (1098, C# 24)	(1098, C# 21) (1314, E, 27)
Pentatonic	(571, D, 30) (624, D# 32) (711, F, 23) (764, F#, 28)	(646, E, 27) (689, F, 20) (764, G, 28) (861, A, 28)	(689, F, 23) (861, A, 24) (1066, C, 26) (1163, D, 27)	(861, A, 26) (926, A# 23) (1066, C, 27) (1163, D, 25) (1206, D# 29)	(926, A# 25) (1087, C# 29) (1152, D, 32) (1227, D# 26) (1443, F# 27)

Frequency Results Table: Part 1

For purposes of readability, the table was split into two parts. The first part has the lower wind speeds, the second part the higher. The volume is labeled in negative decibels (-dB) so the lower the second number in each pair, the higher the volume of the frequency. In the cases where all the strings were tuned to the same note, there are clear frequencies that line up with notes from the harmonic series. For example, when all strings were tuned to A, the frequencies were 721, 947 and 1421 Hz. These correspond to the 3rd ($238*3$), 4th ($238*4$), and 6th ($238*6$) harmonics of

238 Hz - it seems the tuning of the A was a little off. Interestingly, the harp always started on the 3rd harmonic - the 2nd harmonic was never more than a very quiet undertone, and the fundamental never sounded in any of the testing.

Tuning	Prominent Tones Produced (Hz), Volume (-dB)				
Tunnel Frequency (Hz)	11	12	13	14	15
Wind Speed (m/s)	9.68	10.56	11.44	12.32	13.2
All strings A	(1195, D, 27) (1453, F, 24)	(1195, D, 23) (1453, F, 25) (1690, Ab 27)	(1421, F, 24) (1690, Ab 25)	No Data	No Data
All strings B	(1034, B, 33) (1529, F# 28) (2799, F, 28)	(1529, F#, 25) (2799, F, 29)	No Data	No Data	No Data
Half Step	(1034, C, 23) (1281, E, 28) (1561, G, 31)	(1281, E, 28) (1561, G, 24)	No Data	No Data	No Data
Fifth	(1109, C# 19) (1328, E, 24) (1475, F#, 25)	(1109, C# 27) (1328, E, 21) (1475, F# 24)	(1328, E, 22) (1475, F# 25) (1744, A, 27) (1841, A# 27)	(1475, F#, 25) (1744, A, 27) (1841, A# 25) (2003, B, 29)	(1841, A# 23) (2003, B, 30) (2207, C# 22)
Octave	(1098, C# 22) (1314, E, 27) (1744, A, 35)	(1314, E, 25) (1744, A, 23) (2627, E, 31)	(1314, E, 30) (1744, A, 23) (3488, A, 33)	(1744, A, 23) (2175, C# 24) (3898, B, 27)	(1744, A, 23) (2175, C# 19)
Pentatonic	(1152, D, 28) (1227, D# 29) (1443, F# 26) (1529, G, 28)	(1238, D# 29) (1464, F# 28) (1529, G, 29) (1690, G# 31)	(1238, D# 31) (1400, F, 29) (1464, F#, 29) (1529, G, 29) (1690, G# 33)	(1464, F# 31) (1550, G, 26) (1744, A, 27) (1841, A# 25) (1906, B, 28)	No Data

Frequency Results Table: Part 2

Another trend was how each individual frequency would increase then die away as the wind speed increased. This can be seen in the spectrogram in figure 6 and is also supported by the data gathered into the table. Each harmonic would typically only appear for a range of 2-3 m/s, typically loudest at the midpoint. This finding correlates with the prediction of a lock-in frequency predicted by physics models in [4]. What was really interesting is the way that these

frequencies overlapped - there could be multiple frequencies produced at the same wind speed, creating a chord from strings tuned to the same pitch. Because the fundamental does not sound, the harmonics cannot be considered overtones, although there were sometimes overtones present at much lower volumes.

The overlapping lock-in frequencies are illustrated in a graphical format in figure 7. Each horizontal bar represents one frequency, the darker the bar the more prevalent that frequency was. There are fairly clear delineations (marked with white arrows) where the wind speed was increased. As predicted by the equations in the background section, higher wind speeds generate higher frequencies from the harp. The lowest dark red line is the 3rd harmonic, with the 2nd harmonic the lighter orange beneath it.

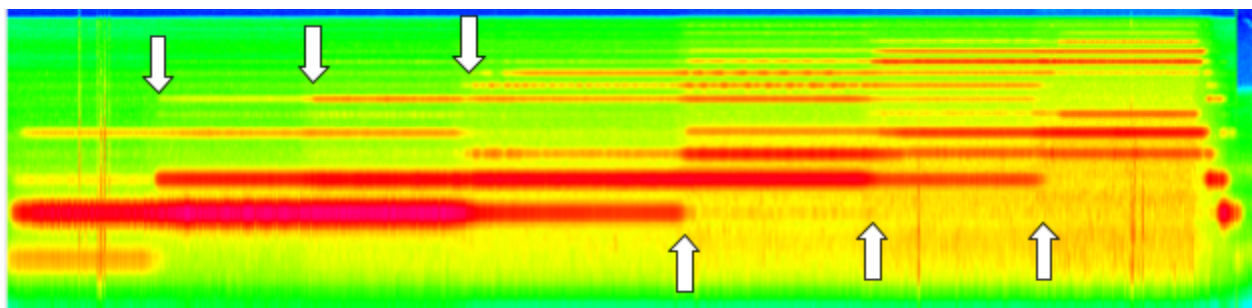


Figure 7: Spectrogram - harp tuned to B

A more surprising result was the visual analysis of the test condition where half the strings of the harp were tuned up a half step. The beating sound caused by this dissonant tuning can be clearly heard in the recording, however visual analysis showed a relatively steady frequency peak, with the beating sounds graphically appearing in the volume rather than the pitch.

When analyzing the data gathered from the trial where half the strings on the harp were tuned up a fifth, the pattern of the 2nd harmonic being prevalent in the sound holds true. The two fundamental tones of this trial were B3 (247Hz) and F#4 (370 Hz). The first two notes that enter are harmonics of B3 ($732=247*3$, $991=247*4$). But the next frequency to appear is not an integer of B3 (247 Hz). Instead, it is 2nd harmonic of the strings tuned to F#4 ($1109=370*3$). This

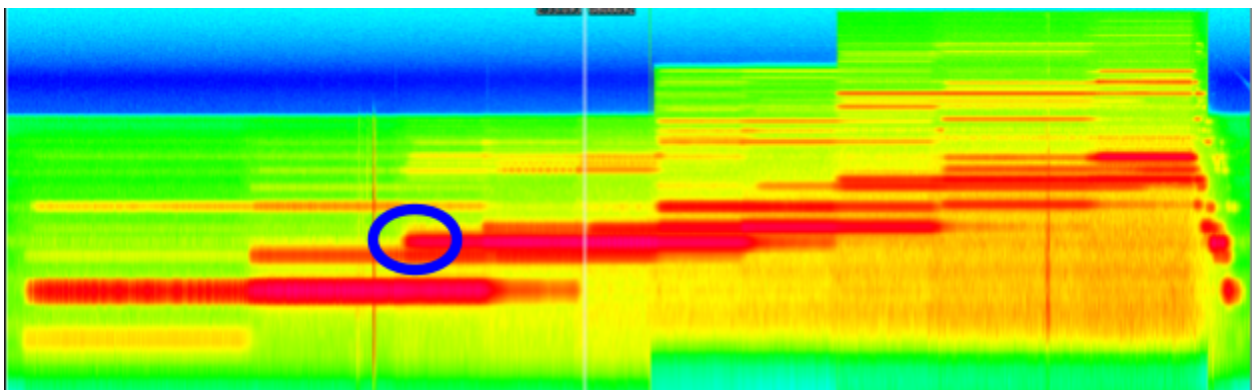


Figure 8: Spectrogram - harp tuned to B and F#

appearance is circled in blue in figure 8. The shift in ‘color’ in the chord produced by the harp is also clearly audible in the recording.

The trial where the harp was tuned to a pentatonic scale was more complex. In contrast to the clean peaks of earlier recordings (such as in figure 6), the frequencies in the pentatonic recording showed overlapping tones. Illustrated by two different time samples taken from the frequency spectrum, the crowded peaks on the graphs in figure 9 indicate that there was probably some cancellation going on. Still, the harp produced consistent patterns of frequencies at different wind speeds, creating an eerie, discordant sound.

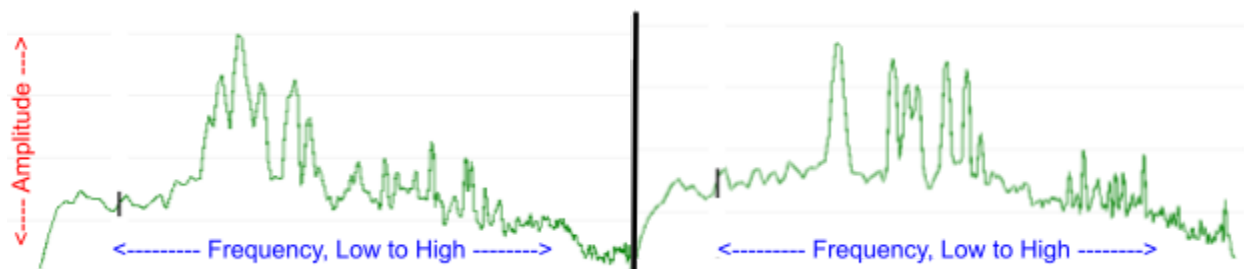


Figure 9: Time Samples from Pentatonic Tuning

One part of the analysis where the results differed from the physics predictions was in predicting the ideal wind speed. The tuning for the normal range of the harp was too low for the wind tunnel, so a string was tuned higher to bring the ideal wind speed to within the parameters of the tunnel. At 880 Hz, the equations predicted an ideal wind speed of 4.4 m/s. The string did not sound at the predicted ideal speed. A control test was done with a string at 220Hz - that string sounded, but at a higher wind speed than the ideal predicted for the frequency of the string.

Composition

The project as a whole has two main parts: this paper, which presents the experimental methods, analysis and results, and a composition. Inspired by the natural sounds of the harp, the composition is an audiovisual experience incorporating themes of nature. Part One incorporates sounds of the earth, including some singing frogs, a bubbling brook and the ominous reverberations of a stampede in the distance. The voice of the harp rhythmically rises and falls, with each new peak growing louder and more discordant as the stampede grows closer. Part Two is inspired by the ocean, especially the push and pull of the sea and the competing forces of the waves. The sound of the waves crashing onto a rocky coast is echoed in the two conflicting voices of the harp, fighting to be heard. Part Three draws inspiration from the air, echoing some of the rhythm from the first section. The voice of the harp grows more harmonious, as different harmonics from the same recording are introduced, building a fuller chord. The shrill sound of the wind wrapping around poles provides a counterpoint to the harp, generating tension that is eventually resolved as the wind fades away, leaving only the echoing sound of the harp.

The video displays the frequency spectrum and the amplitude breakdown between the two stereo channels. This allows the user to see movement in the voice of the harp instead of just hearing it. It also provides more information of each chord and the harmonics created by the string. Each section of the composition receives title text, and brief explanations of how to interpret the graphics appear, in muted text. This is to provide a listener unfamiliar with frequency graphs a better idea of what is going on without distracting from the music. It is also quite mesmerizing to watch the different frequencies emerge from the background nature sounds.

Link to the audiovisual composition: <https://www.youtube.com/watch?v=f-E8wOofK0o>

Conclusion

This project was a great opportunity to explore the unique instrument that is the Aeolian harp. The instrument has a long history, but the existing theories in physics do not fully explain the sounds that the harp produces. However, there is a clear correlation between the tuning of the harp, the wind speed, and the frequencies produced that is predicted by the convergence of the Strouhal frequency and natural harmonics of the string. The harp was recorded with different tunings across a range of wind speeds. These recordings were analyzed and incorporated into an original composition.

There are a couple areas for further research on this topic. The first is answering the question of why the first harmonic does not sound on the harp. Is it just this particular instrument, or is it a widespread phenomena? Can it be replicated with a Karman Vortex Effect outside of Aeolian harps? The second area for further research is on properties of the harp. How do different string materials affect the harmonics? How might different methods of constructing the harp (using metal, different sizes and shapes etc...) affect the sound produced?

Finally, a big thank you to Professor Olinger of the WPI Aerospace Program for assisting with the wind tunnel and answering some of my physics questions. This has been a very fun project.

Works Cited

- [1] Daniel, "Wind Music: The History of the Aeolian Harp," Feb. 08, 2014.
https://www.mohicanwindharps.com/Wind-Music-The-History-of-the-Aeolian-Harp_b_19.html (accessed Mar. 19, 2021).
- [2] M. S. Abeln, "Rome of the West."
<http://www.romeofthewest.com/2012/09/aeolian-harps.html> (accessed Apr. 01, 2021).
- [3] "Aeolian harp," *Wikipedia*. Mar. 19, 2021. Accessed: Mar. 19, 2021. [Online]. Available:
https://en.wikipedia.org/w/index.php?title=Aeolian_harp&oldid=1012929698
- [4] R. Selfridge, D. J. Moffat, and J. D. Reiss, "REAL-TIME PHYSICAL MODEL OF AN AEOLIAN HARP," *Int. Congr. Sound Vib.*, vol. 24, Jul. 2017.
- [5] "Vortex-induced vibration," *Wikipedia*. Feb. 01, 2021. Accessed: Mar. 19, 2021. [Online]. Available:
https://en.wikipedia.org/w/index.php?title=Vortex-induced_vibration&oldid=1004276045
- [6] N. D. Katopodes, "Strouhal Number - an overview | ScienceDirect Topics."
<https://www.sciencedirect.com/topics/engineering/strouhal-number> (accessed Apr. 01, 2021).
- [7] C. Schmidt-Jones, "4.6 Harmonic Series II," *EarMaster*. <https://www.earmaster.com> (accessed Apr. 28, 2021).
- [8] "Harmonic series (music)," *Wikipedia*. Apr. 20, 2021. Accessed: Apr. 28, 2021. [Online]. Available:
[https://en.wikipedia.org/w/index.php?title=Harmonic_series_\(music\)&oldid=1018843225](https://en.wikipedia.org/w/index.php?title=Harmonic_series_(music)&oldid=1018843225)
- [9] A. Robb, "The Little Aeolian Harp Page." <http://www.art-robb.co.uk/aeol.html> (accessed May 11, 2021).