Visualizing Music:

Connecting Electronic and Acoustic Performance with the Spectrogram and Oscilloscope

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ABSTRACT

Ryan McQuay Meredith: Visualizing Music –
Connecting Electronic and Acoustic Performance with the Spectrogram and Oscilloscope

Historically, there are many trends in the techniques we use to analyze music, most of which are centered around pitch or rhythm. There is a distinct lack of normative techniques for analyzing timbre and texture; however, there are multiple tools we can use to get a more detailed interpretation of timbre and texture beyond just a score. The visual we are most familiar with is the single-line waveform we see in digital audio workstations, but technological instruments are now much more capable of other visuals. A spectrogram gives an added level of clarity to the visual, allowing us to see the full spectrum of overtones present in an entire recording. Another piece of equipment, the oscilloscope, also produces visuals but in a much different format. Instead of creating a graph-like visual, the oscilloscope creates what is essentially a film. By using all three of these different visualization techniques and dissecting music composed for these tools, we can glean new compositional perspectives that would be previously invisible, once again demonstrating the limitations notation inadvertently adds to our musical experience.

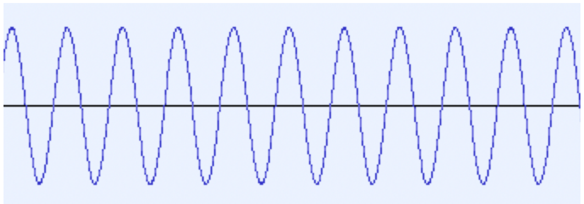
As a student in music composition, I have been exposed to countless different styles and idioms of music through a traditional composition seminar class format. In many classes, my professors would pick a recording of a piece of music to play for the class, usually something from the past ten years with strikingly “modern” attributes, and then ask us to discuss what we heard. While I enjoyed being exposed to new and intriguing music, I would always get frustrated when the class’s vocabulary failed to describe what we were hearing past “electronic” or “like a horror-movie.” I specifically remember one seminar where we listened to a recent composition by Lesley Mok from 2021 performed by the JACK Quartet, titled *Pooling light.* Mok’s music features many gestural extremes and extended techniques for each player in the string quartet. The harmonic content is rich, evocative, and immensely deliberate in orchestration, but we failed as a class to articulate why the contrasts we heard in timbre we there. Intrigued, I explored how we might be able to isolate the musical parameter of timbre in analysis.

Mok’s music, to no discredit, does resemble the style of many ultra-modern circles and horror films. Both genres are highly concerned with timbre and texture. Unlike ideas of rhythm, dynamics, or pitch, ideas concerning timbre are difficult to verbalize, and we often gravitate towards connections to other music and poetic language to describe what we hear. A small percentage of people in the world have what is called synesthesia, where they have strong associations between colors and the sounds they hear. Most of us don’t have this unique sensory capability, but we all experience music as energy over time, completely invisible. What if we could *see* how that energy moves through space? A concrete visual could provide a more useful analytical tool than any one person’s description of music in prose.

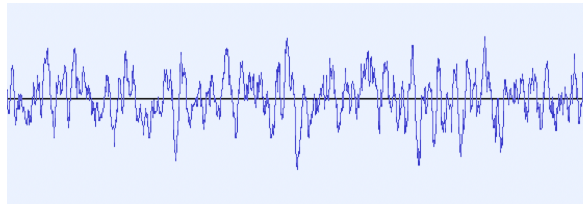
When we visualize what a sound might look like, we might think of waveform diagrams we learned as children in math and science classes. Those one-dimensional depictions of waves, the same as we would see in a digital audio workstation, display the sound on only one axis over

FIGURE 1: Two Single-Line Visualizations made in Audacity, Ryan McQuay Meredith

1.1) A = 440Hz sin wave



1.2) *Great Things* for Orchestra



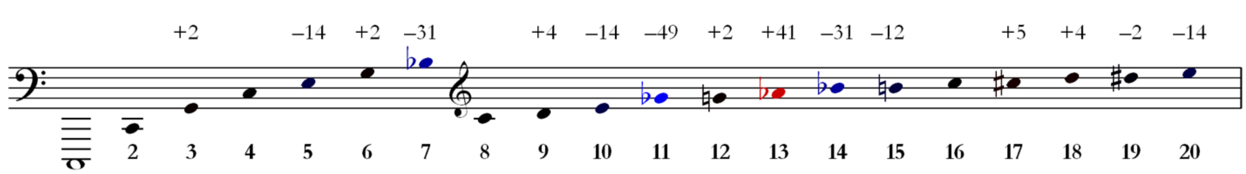
time. In figure 1.1, I have created a basic visual of a 440Hz wave, or the pitch A3. The single-line visual is comprised of hundreds of thousands of consecutive samples. Each sample has a Y value that maps onto the X axis, time. The shape of the line and the placement of each sample is determined by the mathematical average of every pitch present at that exact moment. So naturally, the more information in the recording, the more information that is compressed and averaged into a single mono signal. In figure 1, we can see two separate single-line visuals made in audacity using these methods. The visual in figure 1.1 is a sin wave, and the visual in figure 1.2 is a fully orchestrated section of my composition, *Great Things*, for orchestra. The differences between the two lines are clearly apparent; the line in figure 1.1 will produce a cleaner, clearer, visual. Although, these kinds of depictions of sound are critically flawed because they only operate in one dimension, whereas humans experience sound in three dimensions over time. The single-line gives us useful information, but I wanted to explore more informative visuals.

A unique piece of software called a Spectrogram is able to expand the one-dimensional single-line into a score-like graph showing all the overtones present and their prominence. By seeing the total amount of information happening within the sound at any given point in time, new connections that would previously be invisible can be made. The musical score and the spectrogram are connected in format. Both read from left to write and organizing pitches from highest to lowest, top to bottom (generally speaking for musical scores). Figure 3 (page 4) shows various Spectrograms of different kinds of sounds. Unfortunately, both musical scores and spectrograms lack a tangible connection to the actual experience of listening to the sound.

Generally speaking, there are clear trends in academia for the ways we analyze music, and they don't always focus on the actually listening experience with the music. Earlier in my undergraduate education when I studied music from the "common practice period," our classes would mainly focus on pitch in the musical score. Many music students spend multiple semesters learning how to analyze scores using lead-sheets and roman numerals, with some exploration of set theory towards the end of their programs. An exceptional professor will go beyond, including detailed analyses of rhythm and meter, large and small-scale metric forms, compositional processes, contemporary music, and diverse composers who uses those structures. However, even with the exceptions, students and teachers alike must constantly be reminded to *listen* to the music they are studying. There seems to be a distinct lack of techniques for analyzing timbre, which could provide a concrete analytical connection to the physical listening experience.

To analyze timbre, we first must understand what creates identifiable timbres. Essentially, the overtone series, or harmonic series, and the balance of the naturally occurring partials above the fundamental pitch, creates an identifiable sound that our brains can naturally distinguish. Let us take a second to un-pack all of that information. In figure 2, you can see a notated score example of harmonic series of the fundamental pitch C1. The partials are labeled

FIGURE 2: Intonation of the Harmonic Series, uploaded by MusicMaker5376 to *Wikipedia*

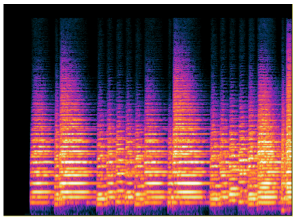


below the staff from 2 to 20, the lower partials usually being easiest to hear naturally. In music, we have used many tuning systems over the centuries. The common thread between many of these systems is an appeal to the natural intonation of the harmonic series. The partials of the series are tuned to just intonation, meaning the pitches are the result of whole number interval ratios in relation to the fundamental pitch. Pianos and electronic instruments, for example, are usually tuned in equal temperament which divides the octave into 12 equally spaced semitones. The result is some pitches in the chromatic scale are out of tune when compared to the harmonic series. The numbers above the partials in figure 2 denotes the intonation adjustment that needs to be made in cents from equal temperament to achieve just intonation. There are 100 cents per semitone, and certain partials require more of an adjustment than others. Partials with a "+" need to be raised and partials with a "–" need to be lowered. The blue and red pitches require the greatest adjustments. Generally speaking, the partials gradually get more and more difficult to hear the higher they go. Ultimately those pitches are heard, but our brains identify them as part of the fundamental. The prominence of each overtone is unique to what or who is making the sound and where it is being made.

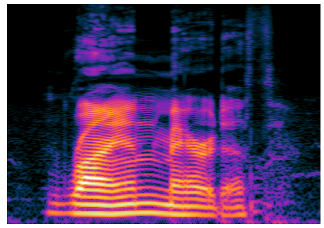
In order to see all of this overtone information, we want to use a spectrogram. Audacity, a free digital audio workstation available for download on the internet, has a spectrogram feature which allows us to visualize all the overtones present in a mono recording. In figure 3, we can see a variety of spectrograms I created using this software. Figure 3.1 is the beginning of one of my compositions for trombone choir, figure 3.2 is a recording of me speaking my own name, and figure 3.3 is a digitally created 440Hz sin wave. In figure 3.1, we can see the overall timbral complexity of the trombone. The overtones generally decay as we reach the top border of the spectrogram. However, towards the bottom of the graph, we can see groupings of three pitches stacked on top of each other resembling western triads. This is especially interesting because

FIGURE 3: Various Spectrograms created within Audacity, Ryan McQuay Meredith

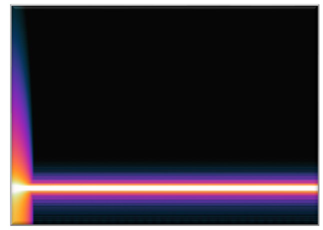
3.1) Trombone Choir Composition



3.2) “Ryan Meredith”



3.3) A = 440 Hz sin wave



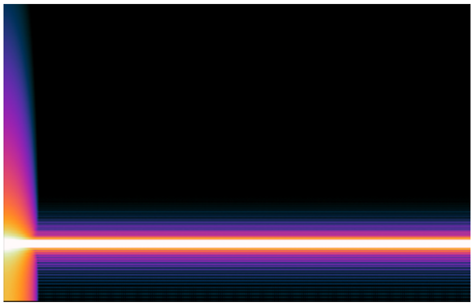
there are no triads present within the score. The melody is voiced from the very beginning in parallel perfect fourths. The resulting voicing of the overtones when played on the trombone is multiple triads spanning upward.

In figure 3.2, we can see that the human voice is far more complex than wind instruments. Although, this does make sense given human babies can distinguish between voices as early as the first few months of life. Possibly one of the most interesting uses of the spectrogram is with the voice. At the very bottom of the graph, we can see the natural resting register of that specific voice, in this case my own voice. We can see the natural inflections in the text, as well as all the intricate manipulations of overtones above the fundamental that our teeth, tongues, vocal chambers, and the venue are entirely responsible for. We can also see in that same spectrogram the timbral difference between each syllable. Notice the bright balance of overtones in the beginning of the spectrogram with the syllable “Ry,” in contrast with the muddy balance of overtones towards the end, with the percussive “dith” sound.

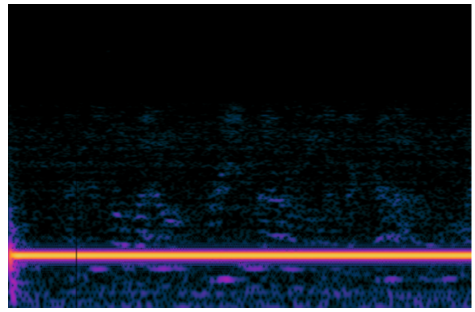
The last spectrogram of the three, figure 3.3, starkly contrasts the content of the first two. This sound is known as a sin wave which is digitally created with one pure fundamental tone and no overtones present. This “pure tone” is visualized on the spectrogram as a laser-like straight line. However, in real-life, overtones will always occur above a fundamental frequency. If we play a sin wave over a speaker and capture a spectrogram of the performance, we will see which

FIGURE 3.3-4: Two Spectrograms of the Same Sin Wave, Ryan McQuay Meredith

3.3) A = 440Hz sin wave played in a Digital Audio Workstation



3.4) A = 440Hz sin wave played and recorded in Ryan's apartment.

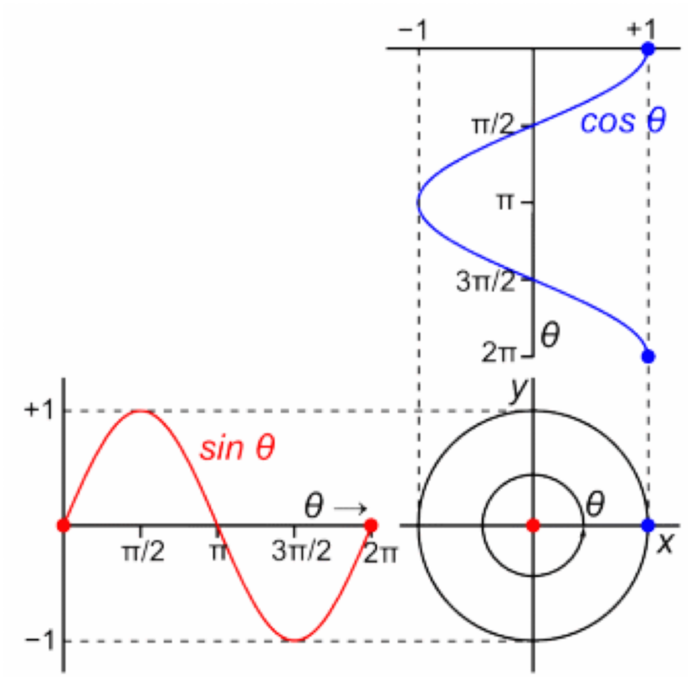


overtones are most prominent in that specific venue, with that specific sound, speaker, and microphone. In figure 3, we can see the difference between two spectrograms of the same sin wave, one played in digital space, and one played and recorded in my apartment. With both of these spectrograms placed side by side, we can see the one in figure 3.4 has much more information and is slightly dimmer, or dynamically softer, than figure 3.3. The most pertinent detail is that the spectrogram in figure 3.3 can be digitally reproduced endlessly because of the highly controlled digital audio workspace environment. The spectrogram in figure 3.4 is based on a digitally performed pitch, but the resulting visual is essentially a spectrographic finger-print impression of the venue which can be altered by any number of phenomena. The spectrogram has countless uses as a tool for education, performance, and composition. Generating a visual which functions like a score but is void of any traditional notation is more accessible and delivers more specific information on what is actually happening within the sound. The only flaw with the spectrogram is that while it provides a new perspective, it feels far removed from the actual sonic experience of listening to the sound as it is happening. When we listen to music, the moment is gone in an instant, but with the spectrogram we can constantly see where we have been and where we are going.

In 1849, a piece of electrical equipment called the oscilloscope was invented by German physicist, Ferdinand Braun. The first oscilloscope was used to monitor high voltage electrical equipment, and it wasn't until the 1970s that the general public had access to Tektronics brand oscilloscopes that could be used in a musical application (Britannica 2022). This technology was groundbreaking for the scientific visualization of sound because unlike the other visuals, the oscilloscope can visualize a stereo audio signal. The oscilloscope displays one instance of the stereo sound at a time in a radial format, as opposed to a horizontal, single-line, graph-like depiction of a sound. Instead of creating a visual which is read from left to right, the oscilloscope creates what is essentially a film directly generated by the sound being listening to. On the oscilloscope, what we know as a sin wave, pure tone with no colorful overtones, would look like a perfect circle. Oscilloscope visuals do not perfectly reflect how sound interacts with three-dimensional space, but they are more accurate than the previous examples . The purity of a perfect circle does match the aural experience of hearing a "pure" sin wave in affect. If we were to add more overtones and coloration to that pitch, the perfect circle would distort proportionally to the sound. Verbalizing differences between complex timbres is purely subjective, but the oscilloscope is able to produce objective, more useable, data visualizing those differences. Using this technology, is it possible to compose acoustic music designed in the same way to produce resulting visuals? In doing so, we might be able to develop more concrete analyses of timbre.

The oscilloscope introduces a complete paradigm shift in the visualization of sound. Spectrograms and single-line waveforms can only display a mono signal. The oscilloscope uses a stereo signal with independent left and right channels to produce a visual generated by the sound, more similar to how we actually experience sound. The oscilloscope displays one instance of the signals at a time in a radial format, meaning there is a central point in the image where X and Y

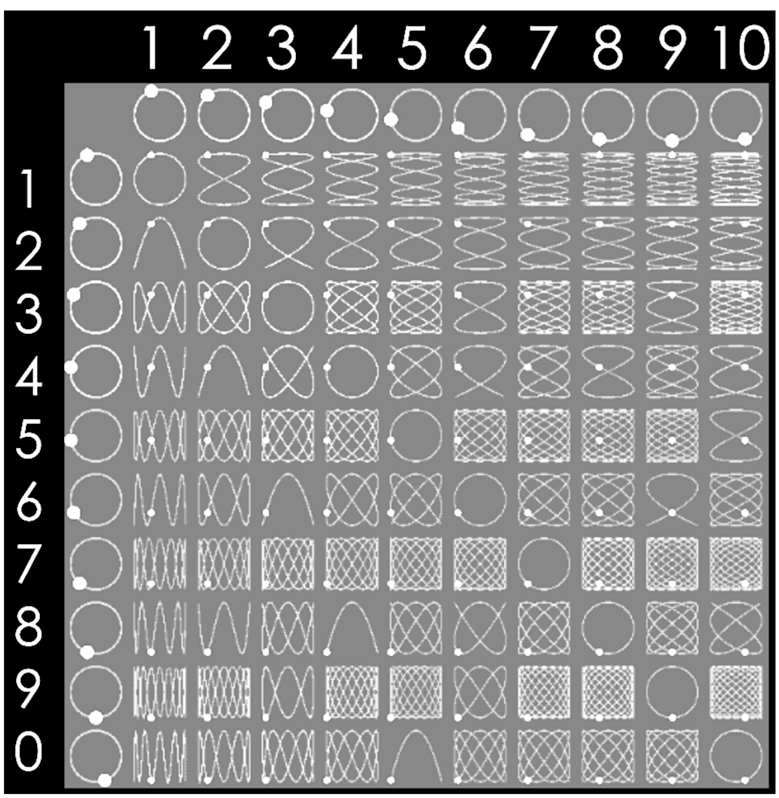
FIGURE 5: Mathematical Construction of a Circle on an XY-Oscilloscope, Cornell ECE



both equal zero. In figure 5, we can see how the oscilloscope generates all of its visuals. The left and right channels are mapped to their own individual axes, X and Y, in a perpendicular orientation. The more complex the left and right channels are, the more complex the resulting visual. While a spectrogram dissects the entire overtone content within a mono signal, the oscilloscope uses the compressed stereo signals to produce a visual.

Apart from circles and sin waves, what visuals are the oscilloscope capable of producing? The oscilloscope can visualize any sound, but as we would expect, sounds like the voice and full orchestra are going to produce visuals resembling chicken scratch when processed. However, there are unique and artistic visuals the oscilloscope can produce when fed the right information. Ever Since the ancient mathematician, Pythagoras (~570 - ~490 BCE), first discovered just intonation on the monochord, we have had the perfect intervals: the perfect unison, fourth, fifth, and octave (Britannica 2022). Every single interval has what is known as a harmonic ratio in just intonation, which is a reduced fraction of the higher frequency in the interval over the lower frequency. Our perfect intervals which Pythagoras discovered, have the simplest harmonic ratios. The ratios occur in the same order that the intervals occur in the harmonic series: unison (1), octave (1/2), fifth (2/3) , fourth (3/4) , major third (4/5), et cetera. When these intervals are put into the oscilloscope, one pitch in each channel, it produces what is known as a Lissajous curve. Every single interval imaginable has its own unique Lissajous curve which rotates 90 degrees when inverted. In figure 6, we can see a chart with one-hundred different Lissajous curves built on whole number ratios. Perfect unisons and octaves will always create a circle, perfect fourths create a pretzel shape, perfect fifths create beautiful weaves, and the patterns continually get more and more complex as the ratio rises. Most importantly of all, Lissajous curves are naturally occurring, but in order to produce these patters on the oscilloscope the stereo signal must be "pure" like a sin wave.

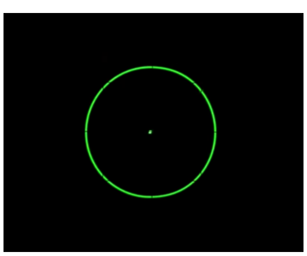
FIGURE 6: 100 Lissajous Curves, William Jordan, uploaded to *Medium.com*



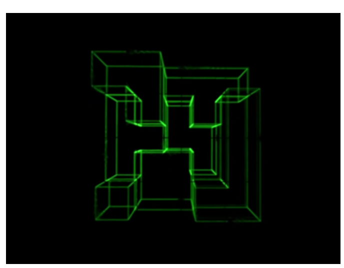
If the desired visual is the end goal of the composition, we can mathematically reverse-engineer the left and right audio signals to produce any visual we like. This genre of composition is called Oscilloscope Music, very recently pioneered by audio-visual electronic music composer and oscilloscope expert, Jerobeam Fenderson. In every piece of oscilloscope music, sound is being visualized on the screen exactly as you are hearing it. Fenderson's compositions are short but beyond captivating. He composed, *Oscilloscope Music*, a complete original album of audio-visual music specifically for the oscilloscope designed to be both aurally and visually interesting. By carefully controlling the shape of every aspect of the signal before it is interpreted by the oscilloscope, Fenderson and other oscilloscope composers are able to produce literal movies of floating spaceships, Tyrannosaurus rex, racecars, biking in the mountains, and of course, Lissajous curves, just to name a few possibilities. In figure 7, I have included snapshots of three separate moments from three different works in Fenderson's album, *Oscilloscope Music*. If you take the time to experience Jerobeam Fenderson's compositions, you will notice that despite the unimaginable complexity of the image, he is able to keep the pitch content interesting throughout. The electronic sounds are aggressive, but the listening discomfort is excusable because of the literal and direct connections to the visual.

FIGURE 7: Visuals from three pieces in *Oscilloscope Music*, Jerobeam Fenderson

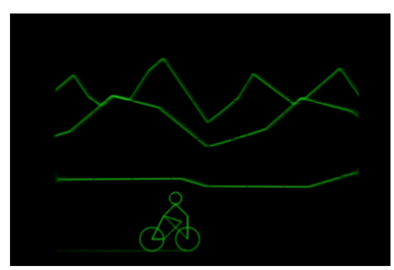
7.1) "Circle"



7.2) "Blocks"



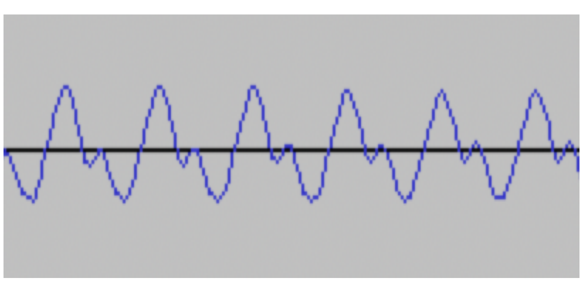
7.3) "Reconstruct"



Immediately, I wondered what practical applications oscilloscope music could have for other genres of music. Even through music composed for the oscilloscope is mechanically very complex, I wondered: it is possible that any of these visual effects can be replicated acoustically? Acoustic instruments present a number of issues because every instrument has its own unique timbre profile (as seen in fig. 3). Physically manipulating those timbre profiles to produce a desired tone takes years of experience to master, so naturally certain acoustic instruments will translate better than others onto the oscilloscope. If we find acoustic instruments that a have similar "pure" timbral quality to their sound, like flutes or strings, we could theoretically use them to draw lissajous curves on the oscilloscope. In figure 8, I have made two visualizations of the same isolated recording of my partner playing the flute, one single-line, and the other a full spectrogram. In figure 8.2, the overtones very gradually decay as they get higher, and no overtone is unevenly accented within the gradient. Because of this, the mathematical single-line average, as seen in figure 8.1, is cleaner and more closely resembles a sin wave. Using an online XY-Oscilloscope simulation program developed by Jerobeam Fenderson, I was able to process my own stereo audio signals to test some visuals. I recorded my partner playing a C5 on the flute and then the G5 a perfect fifth above that. I panned each pitch to its respective channel, fed the audio to the virtual oscilloscope, and the resulting visual can be seen in figure 9.

FIGURE 8: Two Visuals of the Same Single Pitch on the Flute, Ryan McQuay Meredith

8.1) Single line visual of a flute playing C5



8.2) Spectrogram of a flute playing C5

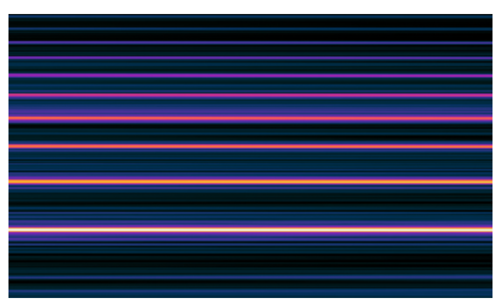
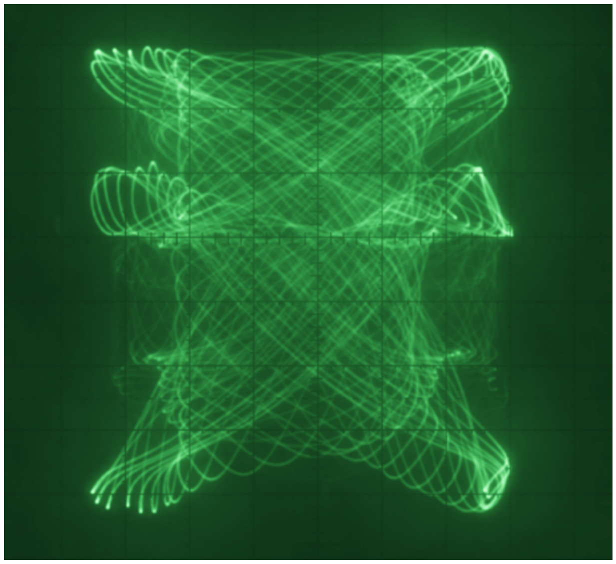


FIGURE 9: A Perfect Fifth Played by Two Flutes – Oscilloscope, Ryan McQuay Meredith



As you can see in the visual, composing Lissajous curves with acoustic instruments on the oscilloscope *is* possible. The techniques in order to do so are limited and hard to control, but not impossible to work with.

Using a combination of all three of these kinds of visuals, we can interpret even the most complex timbres. As we saw in figure 1, when the single-line visual gets “messy” or overly complicated, the visual only really shows us the total dynamic, pacing, and the general complexity of sound. The spectrographic visuals (see fig. 3) give us an incredible amount of information, including dynamics of every overtone, pacing, and more rhythmic clarity. Oscilloscope visuals (see. fig. 6,7, and 9) stand out as unique because we experience them in the same way that we experience the music. These visuals could even be used in conjunction with a live performance to produce a total multi-media experience directly unified by the actual music being created. By using these various and unique ways to visualize music during the compositional process, we can glean new perspectives and connections which would otherwise be impossible to see through just notation.

Annotated bibliography

"Blocks," *Oscilloscope Music,* composed by Jerobeam Fenderson, Youtube, 3 Oct. 2016. 3'33".

A single frame from Jerobeam Fenderson's composition, "Blocks," is used to show the visual capabilities of the instrument (see figure 7.2).

"Circle," *Oscilloscope Music,* composed by Jerobeam Fenderson, Youtube, 3 Oct. 2016. 3'18".

A single frame from Jerobeam Fenderson's composition, "Circle," is used to show the visual capabilities of the instrument (see figure 7.1).

Intonation of the Harmonic Series, annotated score uploaded by MusicMaker5376, "Harmonic Series (music)," *Wikipedia,* (7 Jan. 2007).

This figure is used to explain the harmonic series in figure 1.

Jerobeam Fenderson and Hansi3D, *XXY Oscilloscope*, online browser-based program, dood.al/oscilloscope, 2013.

This software is a virtual, online, stereo oscilloscope simulator which can visualize your own audio files. I used this program to create my own oscilloscope visuals in figure 9.

Mechanics of an Oscilloscope, annotated mathematical graphic, "Oscilloscope Music." *Cornell School of Electrical and Computer Engineering* (January 2022): page 5.

This research paper on oscilloscope music conducted by electrical and computer engineering students at Cornell explains the intricate inner workings of the oscilloscope and how to reverse-engineer and design visuals for the instrument.

"Reconstruct," *Oscilloscope Music,* composed by Jerobeam Fenderson, Youtube, 3 Oct. 2016. 5'19".

A single frame from Jerobeam Fenderson's composition, "Reconstruct," is used to show the visual capabilities of the instrument (see figure 7.3).

Samantha Cobado, Eric Kahn, and Ruby Min. "Oscilloscope Music." *Cornell School of Electrical and Computer Engineering* (January 2022): pp.1-22.

This figure is used to explain how a perfect circle can be drawn with sin waves on the oscilloscope (see fig. 4).

100 Lissajous Curves, animated .gif by William Jordan, "How To Make Gorgeous Lissajous Patterns in Unity! EASY," *Medium.com* (9 Apr. 2019)

This figure is used to illustrate all the unique Lissajous curves, or intervallic patterns, that can be drawn on the oscilloscope, varying from simple to highly complex (see fig. 6).