Comparative Analysis of Acoustic/Electro-Mechanical Keyboard Instruments vs. Their Digitally Synthesized Counterparts

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1. Introduction

Having played piano for most of my life, and substantially longer than any other instruments I have since learned to play, keyboard instruments in all forms have always been an interest of mine. Over the course of many years and in a variety of settings, I came to the conclusion that I much preferred an actual acoustic piano to the digital versions often used in school ensembles by the virtue of their portability and volume, to the extent that I found it more difficult to play and as though I could not perform as well on digital pianos. While this difference in playability is partially due to the difference in action between actual key mechanisms and the weighted or unweighted plastic keys of digital counterparts, I had long been curious as to how well the sonic aspect of digitally produced sounds compared to the actual keyboard instruments they were attempting to emulate, and as a result chose this comparison between analog and digital keyboard instruments as a topic for this final project.

2. Equipment

While partially governed by the instruments that were available, focus was also placed on those commonly used in the music industry. As a result, the electro-mechanical/acoustic instruments used in analysis were as follows:

- Fender Rhodes Mark I electric piano (personally provided): Tone generation a result of striking thin cylindrical metal tines paired with a resonating tone arm and amplified by a single coil pickup at each note.

-Wurltizer 200a electric piano (vibrato off) (provided by Prof. Steve Errede): Tone generation a result of striking flat metal plates with a carefully shaped pyramid of solder at the end determining pitch, amplified by electro-static pickups at each note.

-Hammond M2 tonewheel organ (provided by the PHYS 406 lab): Tone generation a result of rotating toothed gears, each generating a pure frequency, each of which are amplified individually and combined manually to create different harmonic balances.

-A modern upright Yamaha piano (provided by the College of Music): Tone generation a result of striking a metal string under tension, amplified acoustically by a resonating sound board.

These instruments were then compared to a Roland Fantom S 61 key workstation (provided by the Athletic Bands). The Roland was selected as the digital counterpart to the vintage analog keys partially by virtue of being readily available, but after conducting a bit of research proved to be a good candidate for other reasons. Being a workstation keyboard (commonly used in production as opposed to live performance), a wide variety of instrument samples were available including numerous variants on the keyboards I was intending to compare. This was paramount to comparing the synthesizer and actual instrument, as it allowed options to find the closest sound on the synthesizer to the timbre produced by the actual instruments, which are not necessary uniform across all models, years, or individual instruments. Digital stage pianos, while generally carrying a reputation of greater fidelity in sound reproduction than workstations, fail to provide this range of sounds and for the purpose of waveform analysis would not give as clear a picture of how the digital synthesis compares to the analog instruments.

In terms of establishing a benchmark of quality of the synthesizer, some research indicated that the Fantom was of sufficiently high quality to expect high quality audio samples. Based on personal experience, instrument quality is typically well defined by price bracket, and as the Fantom retailed for approximately $2100 USD upon its release, it can be fairly confidently placed in the "high quality" bracket (based on the selection at a retailer such as Guitar Center, $2100 is in the top 80% by price), a categorization corroborated by generally positive reviews on online forums. Granted, online forums are by no means an entirely trustworthy source, but for an instrument several years old and without quantifiable means of establishing quality, price point and user reviews are sufficient and pretty much all that is available to get a rough idea.

Two devices were used to obtain the.WAV files necessary for the waveform analysis of each of the instruments: the acoustic piano was recorded using a MXL940 microphone connected to a computer using a Focusrite Scarlett 2i4 audio interface (96 kHz sampling rate with 24 bit conversion), and all others were recording using the phone jack inputs of the same interface, and in both cases the recordings were saved using Audacity software. The difference in recording methods for the piano and its synthesized version may account for some difference in the analysis of the waveform (frequency bias on the microphone skewing relative harmonic strengths, etc.) but for the sake of this study, it was assumed that any difference was negligible.

3. Method

For each instrument, a wide range of pitches were recorded to allow characterization of the different harmonic structures at low and high frequencies. Selected somewhat arbitrarily based on the range of the smallest keyboard, the Wurlitzer, D was selected as the note to be tested in the low and mid ranges with Bb tested in higher ranges (the lowest note on the Wurlitzer is a D and one of the highest is a Bb). These same notes were used for the recordings of the piano and Fender Rhodes, but were modified slightly when recording the Hammond organ. On the other keyboards, it could easily be established which octave (D4, D5, etc.) to which the recorded note corresponded. However, on the Hammond, each pitch is a produced by adding single harmonics together, and depending on which harmonics are selected, the octave of the resultant pitch can seem to change. As a result, every D available on the lower manual as well as the high Bb were tested with the drawbars set such that they sounded as similar as possible to the patch used on the Fantom.

The recorded notes were played once and allowed to decay before recording was stopped, ensuring a full time range of the possible harmonics available in the resultant recording. After saving the recordings as .WAV files on Audacity, these files were then transferred to one of the computers in the PHYS 406 lab to be processed using the Waveform Analysis application coded in MATLAB. After being processed by the program, the resultant graphs and images detailing the amplitude and frequency of the signal over time, as well as relative phase, amplitude, and frequency over time of particular harmonics selected were saved for further analysis.

Due to the limitations of the software, data from some of the higher frequency pitches was difficult to obtain and thus ultimately omitted, but data from all notes was not necessary to complete the analysis. The wide scope of pitches was largely to see if there was a difference between the lower and higher octaves, and the pitches that were able to be analyzed were sufficient to do so. For redundancy purposes, only select pitches (those exhibiting noticeable and relevant features) are included in the analysis portion

4. Analysis

Fender Rhodes vs. Fantom S Tine Rhodes

One of the more useful readouts from the MATLAB program in assessing the synthesized imitation of the analog instrument proved to be the spectrogram, plotting along three axes the amplitude, frequency and time development of the waveform, allowing for a three dimensional view of the sound. **Figure 1** shows the spectrogram generated from D1 on the Fender Rhodes and Fantom S.

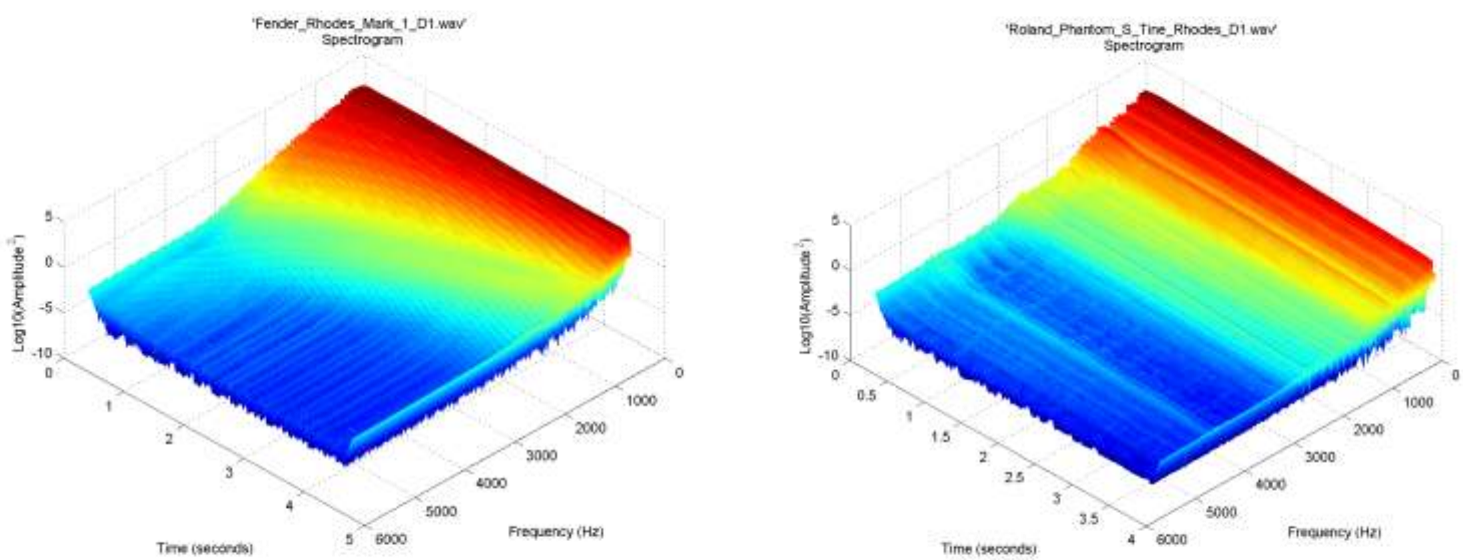


Figure 1: Spectrogram of D1 on a Fender Rhodes (left) and Roland Fantom S (right)

From the spectrographs, it is fairly obvious that there are several key differences in the behavior of the waveforms. While the synthesized version does appear to have a comparable number of harmonics spanning the same range of frequencies, the overall pattern of waveform as frequency increases in the synthesized version exhibits a decrease in amplitude much more abruptly than the smooth curvature of the pattern for the amplitude drop off in the electro-mechanical Rhodes, which can be observed in more detail in **Figure 2**.

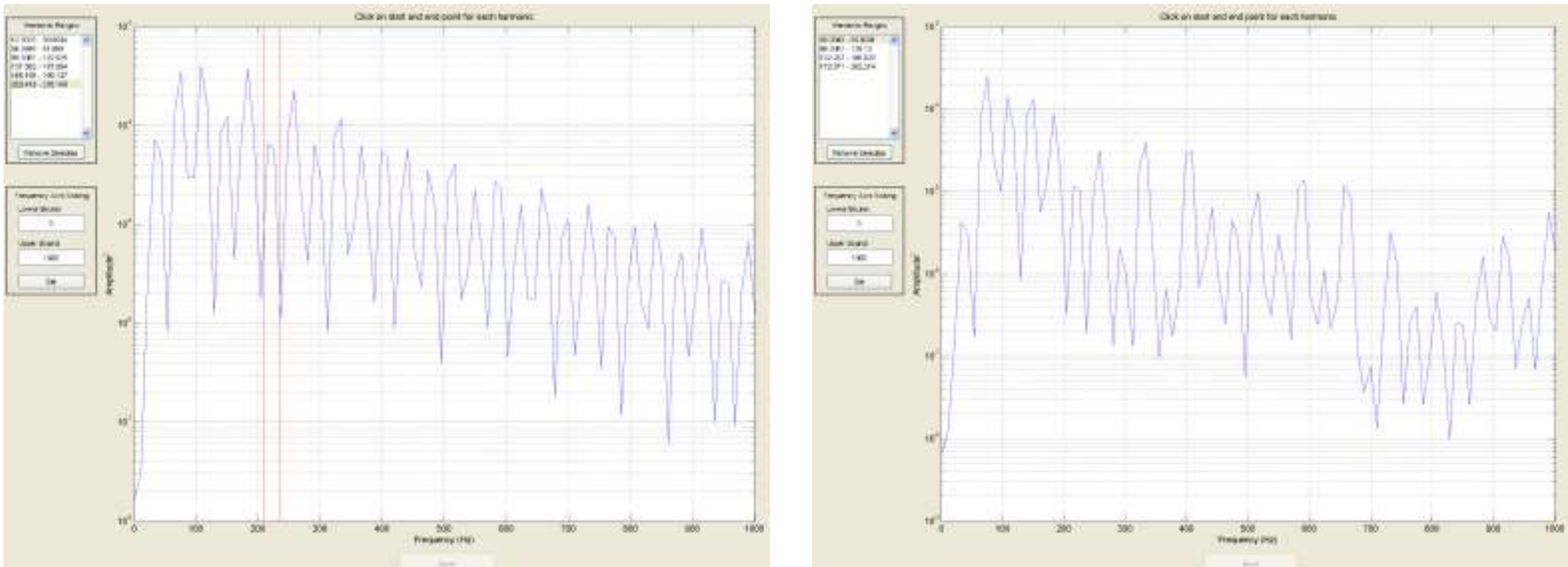


Figure 2: Detailed view of the amplitude of the frequencies over the harmonic spectrum (Rhodes left, Fantom right)

As can be seen, there is a sudden drop in the amplitude of the Fantom spectrum around 250Hz, and again around 500Hz and 700Hz with the harmonics in between each of those frequencies being more or less at the same amplitude. However, the harmonics of the Fender Rhodes fall off in amplitude much more smoothly, without the step wise appearance of the Fantom waveform.

Also easily seen in the spectrograph is the difference in the time decay of the various frequencies, with two distinct regions of note. First, in the Fantom spectrograph, across the entire frequency range the amplitude decreases rapidly for the first 0.5 seconds, then after a point of discontinuity begins to decay at a much less severe rate. Additionally , the spectrograph of the Rhodes indicates the higher harmonics decaying much faster than those of lower frequency, which makes sense mathematically as it relates to higher orders of a Fourier series being damped more rapidly when subjected to some sort of damping force (in this case the tine of the Rhodes being secured on one end) as well as physically, as it would require more energy to vibrate the metal tine at the higher frequencies, and as the energy of the system dissipates thermally and due to the aforementioned boundary condition those higher frequencies would cease to have enough energy driving their existence earlier than lower frequencies. However, in the Fantom spectrograph, the higher orders, relative to their initial amplitudes, do not decay nearly as much as in the Fender, and the continued presence of higher harmonics is a potential source of alterations to the timbral quality of the instrument and a deviation from the sound of the original.

Figure 3 shows the spectrograph results obtained from the same two instruments, but at the pitch of D4 as opposed to D1.

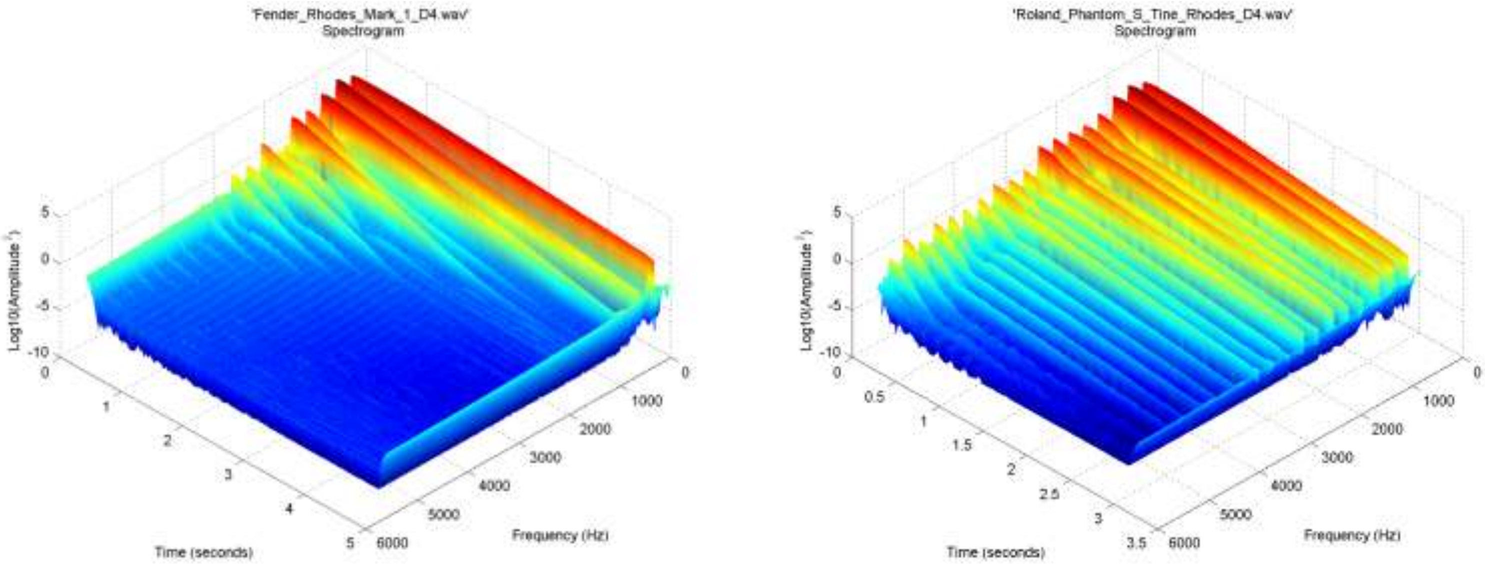


Figure 3: Spectrographs of D4 as played on a Fender Rhodes (left) and Roland Fantom S (right)

Again, many of the same features discussed above for the case of D1 are again visible at the higher pitch, and in greater detail as a result of there being fewer harmonics. Features of note are, again, the higher decay rate in many of the harmonics in the first 0.5 seconds of the Fantom recording followed, by a slower decay that lacks an upper harmonic bias as time progresses. **Figure 4** shows a plot of the amplitudes of the various frequencies versus time, and it is worth noting that for the three frequencies analyzed, the decay rate is approximately the same in the Fantom whereas in the Rhodes the high harmonics very clearly decay at a much faster rate, in accordance with what would be expected mathematically and physically.

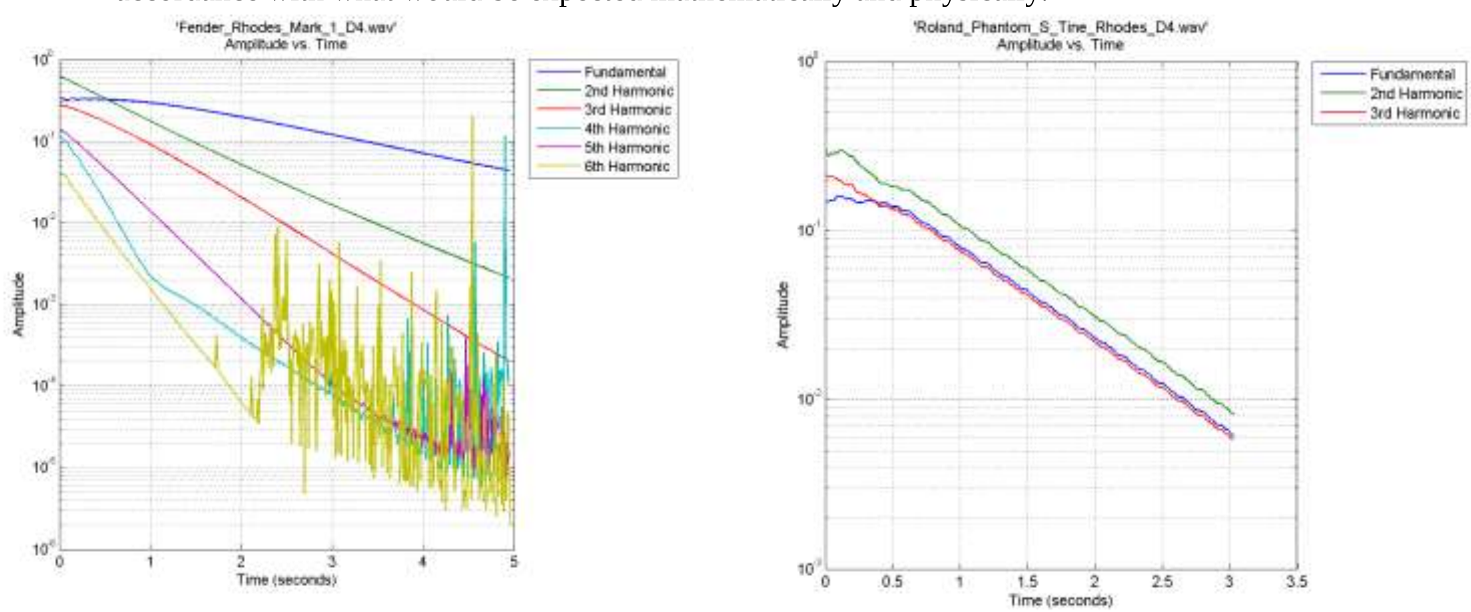


Figure 4: Amplitude vs. Time of various frequencies of a D4 played on a Fender Rhodes (left) and Fantom S (right), although also exhibiting anomalous behavior for the higher orders on the Rhodes graph likely due to limitations on the computing software when dealing with high frequencies

Another feature echoed in the D4 that was also seen in the D1 is the apparent step wise decay of the harmonic amplitudes in the Fantom compared to the Rhodes, as seen by the harmonic plots in **Figure 5.**

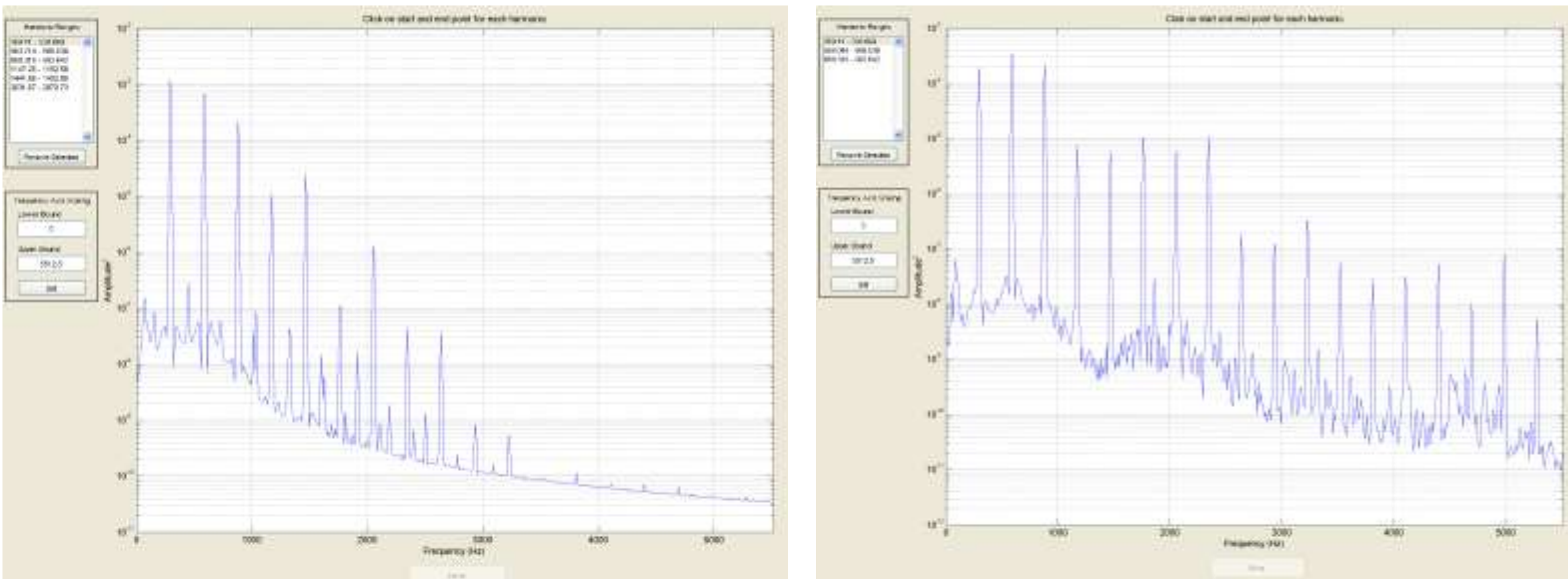


Figure 5: Plots of the frequencies and amplitudes of the various harmonics of a D4 played on a Fender Rhodes (left) and Roland Fantom S (right)

At approximately 1000, 2300, and two a lesser extent, 4000 Hz, the same clustering of amplitudes across varying frequencies occurs in the Fantom, and since it echoes the same behavior as that of the D1 frequency spectrum, it appears as though this grouping is the product of whatever Fourier modeling is being used to generate the particular tone on the synthesizer. Also of note is the presence of numerous higher order harmonics that fail to exist at all on the Rhodes, where the physically vibrating tines pose limitations on which harmonics can be excited, whereas a synthesized waveform has no such limitations. This same trend is exhibited as the pitch continues to rise, as exhibited in **Figure 6** and the spectrograph for Bb5 on both instruments, with the Fantom having several higher harmonics that are not present on the Rhodes at all, which would further suggest a quantifiable difference in tone quality between the instruments as a result of the added frequencies.

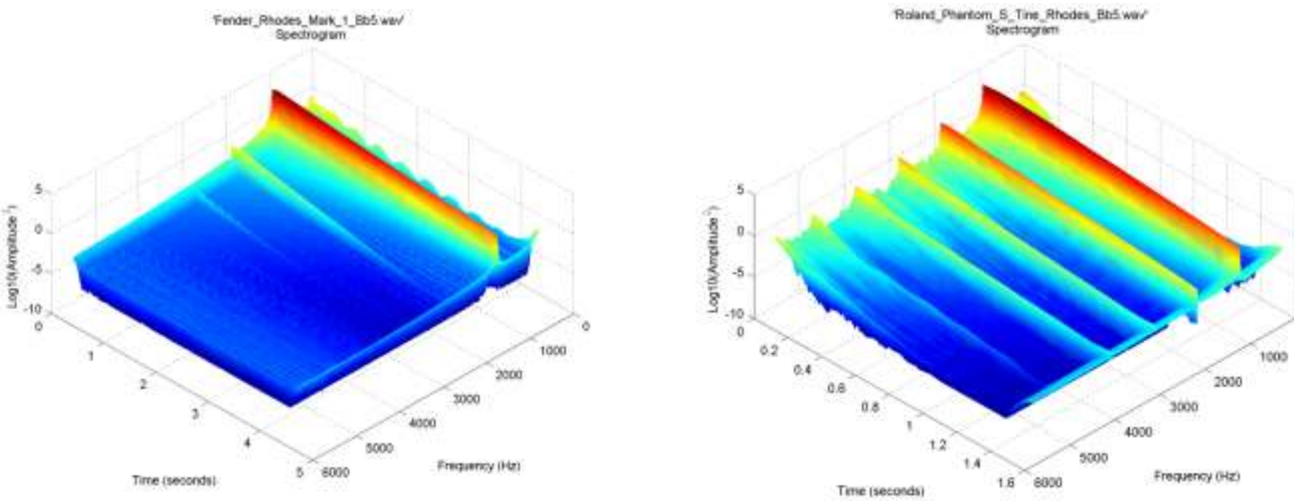


Figure 6: Spectrograph of Bb5 played on a Fender Rhodes (left) and Fantom S (right)

Wurlitzer 200a vs. Roland Fantom S Wurly

Again using the spectrograph to gain an initial understanding of the waveform generated by a Wurlitzer 200a, it was evident from the onset that it was substantially different from that of a Fender Rhodes. While the amplitudes of the Rhodes frequencies decayed monotonically, those of the Wurlitzer oscillated overtime and varied as a function of frequency and time, as seen in **Figure 7.**

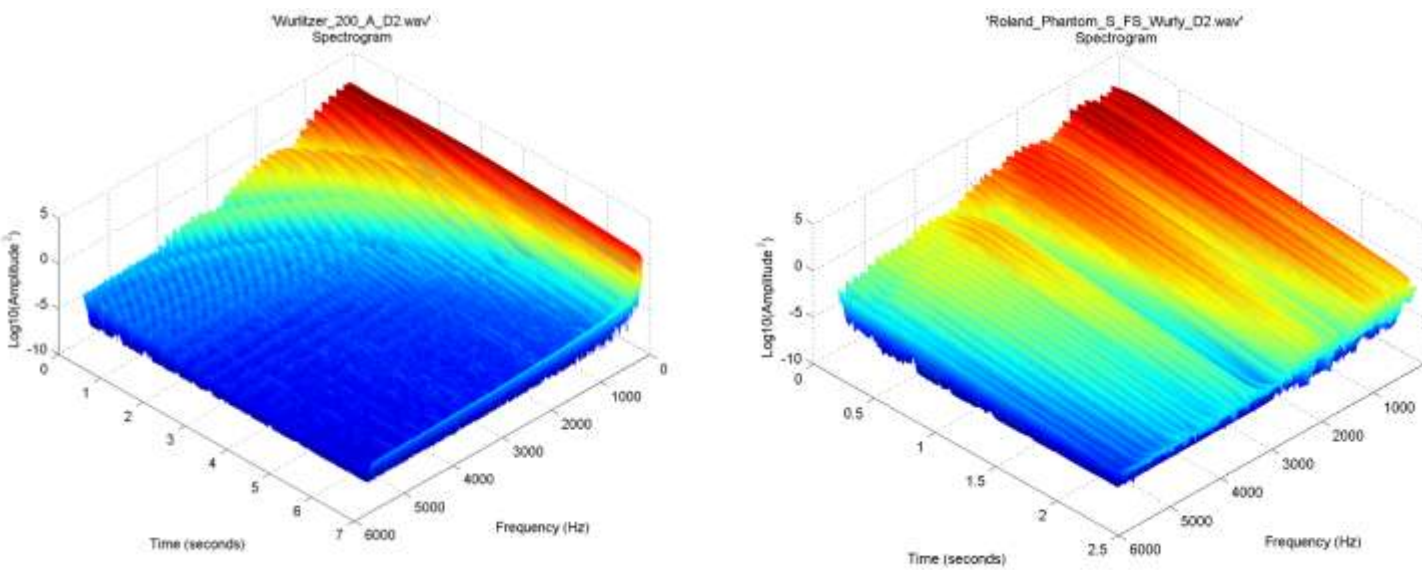
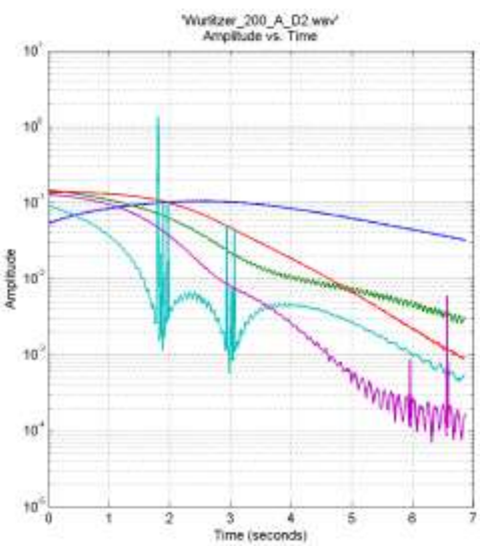


Figure 7: Spectrograph of a D2 on a Wurltizer 200a (left) and Fantom S (right)

While the Fantom waveform does exhibit a slight oscillation in the amplitudes at certain frequencies, the overall pattern fails to match that of the Wurlitzer in which the frequencies at which the amplitude changes varies with time. Instead, the frequencies exhibiting amplitude oscillation in the Fantom remain essentially constant over the entire time range. Granted, the length of each recording is such that the Fantom shows a much smaller range, but it is still clear that as time evolves the areas of lower amplitude remain fairly consistently at the same frequency, unlike that of the Wurlitzer. Across the frequency domain, the amplitudes of the harmonics display similar behavior to that of the Rhodes, both in the real and synthesized versions. Analogous to the Rhodes, the higher harmonics on actual Wurlitzer decay far more rapidly than the lower frequencies, whereas in the Fantom, again by virtue of being synthesized and not restricted by the physical limitations of a vibrating member, is able to sustain for a longer period of time before being damped. Again, for this particular sample the time difference requires a more detailed look at the data to compare the signal decay, but a glance at the amplitude vs. time graphs seen in **Figure 8** illustrate that the synthesized version exhibits consistent decay rates across the various harmonics while those of the Wurlitzer generally decay faster as the frequency of the harmonic increases.



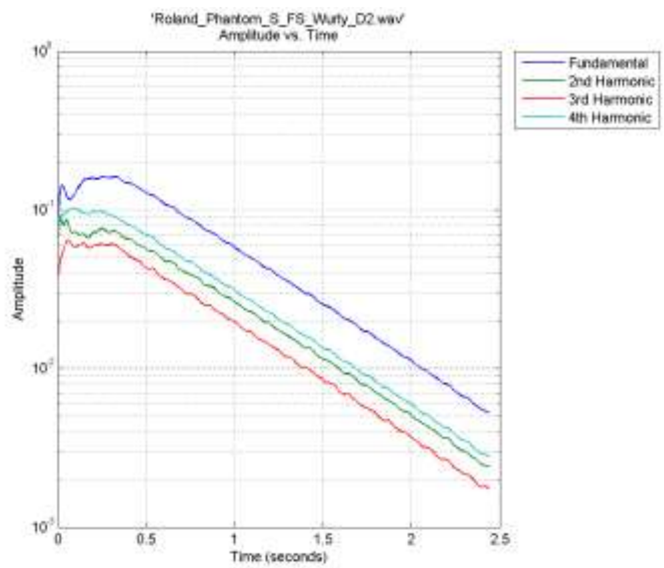


Figure 8: Amplitude vs. time of various harmonic frequencies of a D2 played on a Wurlitzer 200a (left) and Roland Fantom S (right)

When looking at the D5, again a more detailed view is available as a result of a lower number of total harmonics, and the spectrograph of the Wurlitzer and the Fantom are seen in **Figure 9**.

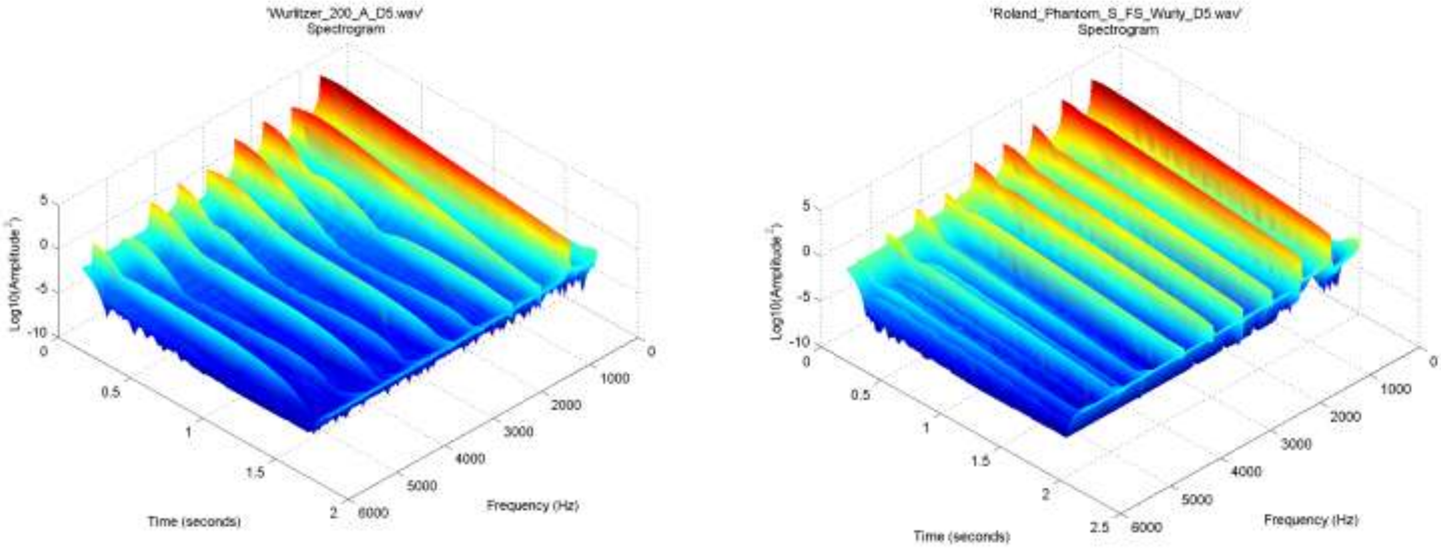


Figure 9: Spectrograph of a D5 played on a Wurlitzer 200a (left) and Roland Fantom S (right)

A point of distinction compared to many of the other plots obtained thus far is that the number of harmonics present in both the real and synthesized waveforms is fairly comparable. The relative amplitudes are not necessarily consistent between the instruments, but the number of harmonics is substantially closer than in the case of the Rhodes.

In terms of time evolution of the D5, shown in the amplitude vs. time plots shown in **Figure 10**, it appears to be a general trend across all of the synthesized wave forms for the higher harmonics decay at the same rate as lower ones.

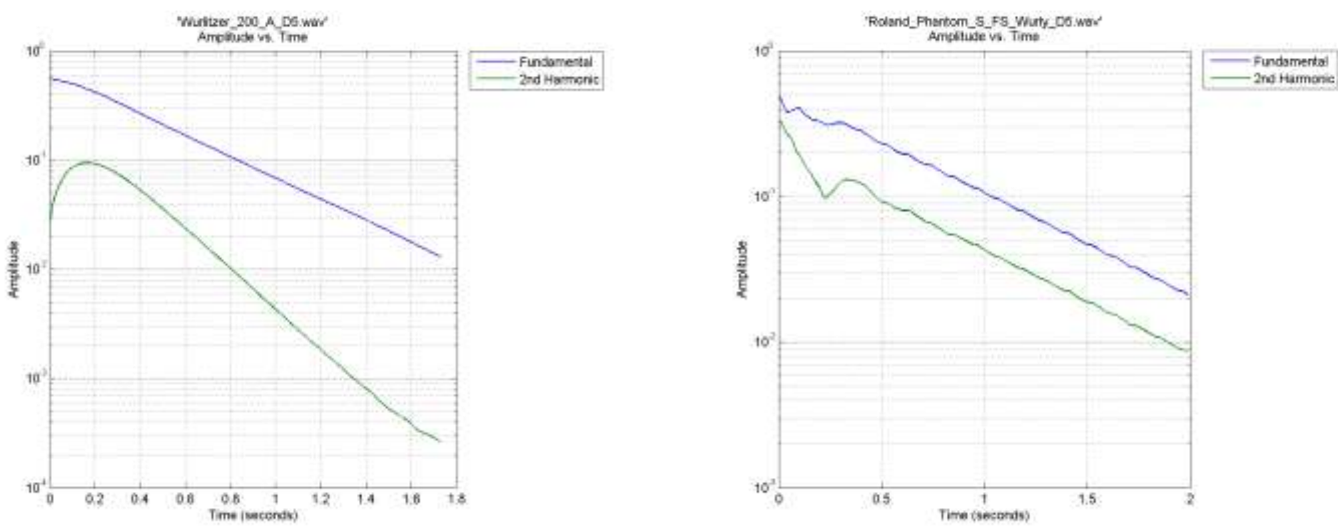


Figure 10: Amplitude vs. time plots of a D5 on a Wurlitzer 200a (left) and a Roland Fantom S (right)

It is of note, however, that in both the spectrograph and amplitude vs. time plots the Wurlitzer exhibits a non-monotonic decay such that the amplitude decreases in “humps” (decreasing, then increasing, the decreasing again, and so forth). While not perfectly imitated by the Fantom, at around 0.25 seconds a similar “hump” can be seen in the amplitude of the 2nd harmonic.

A comparison of the spectrographs of Bb5 played on both instruments (**Figure 11)** exhibits many of the same aspects of D5, with a much closer alignment of harmonic range and relative amplitudes than on the Rhodes or the Wurlitzer D2, suggesting that as the pitch frequency increases, at least in the case of the Wurlitzer, the synthesis gets progressively closer to the sound of the actual instrument.

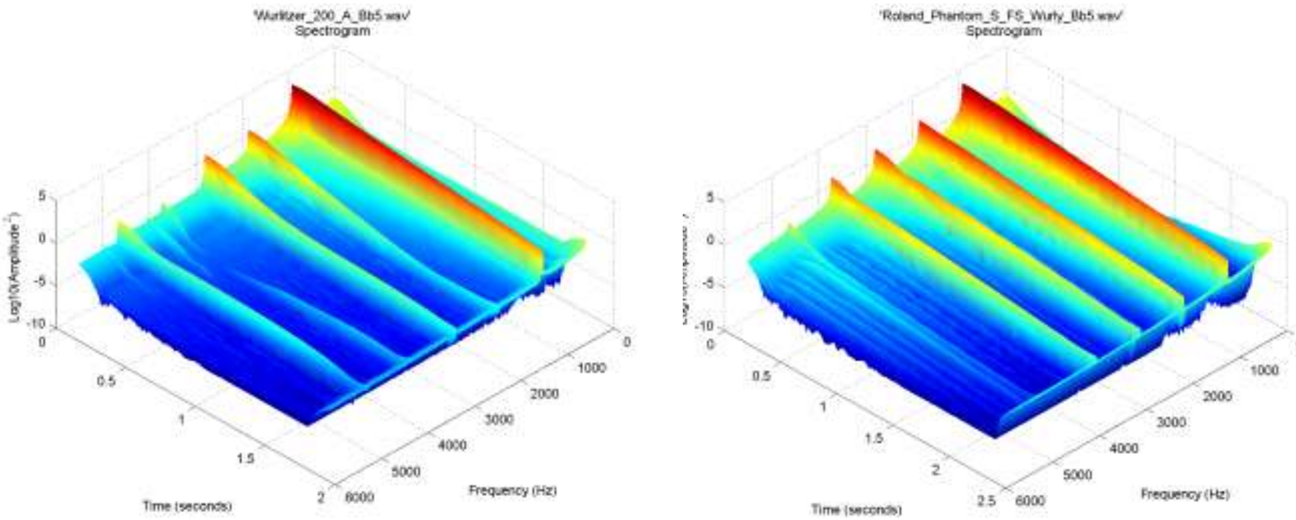


Figure 11: Spectrograph of a Bb5 on a Wurlitzer 200a (left) and Roland Fantom S (right)

Hammond M2 vs. Roland Fantom Soap Opera

Comparison of the organ sound files proved to be slightly more difficult than the other instruments. Primarily, this was because none of the patches available on the synthesizer sounded exactly like the sounds capable of being produced by the Hammond. However, eventually a close comparison was obtained, but to a lesser degree than the similarities between the simulation and actual Rhodes or Wurlitzer. Additionally, the organ patches on the synthesizer all featured large amounts of vibrato (part of the characteristic organ sound), leading to some difficulties in being analyzed by the computer software. The vibrato was disabled on the Hammond and the analysis was run without difficulty, but due to technical limitations, only one of the pitches tested on the synthesizer (D4) was successfully run through the computer program, but is still presented here and compared to a comparable pitch from the Hammond. The spectrograph is shown in **Figure 12**, with three different pitches from the Hammond and the one produced by the Fantom.

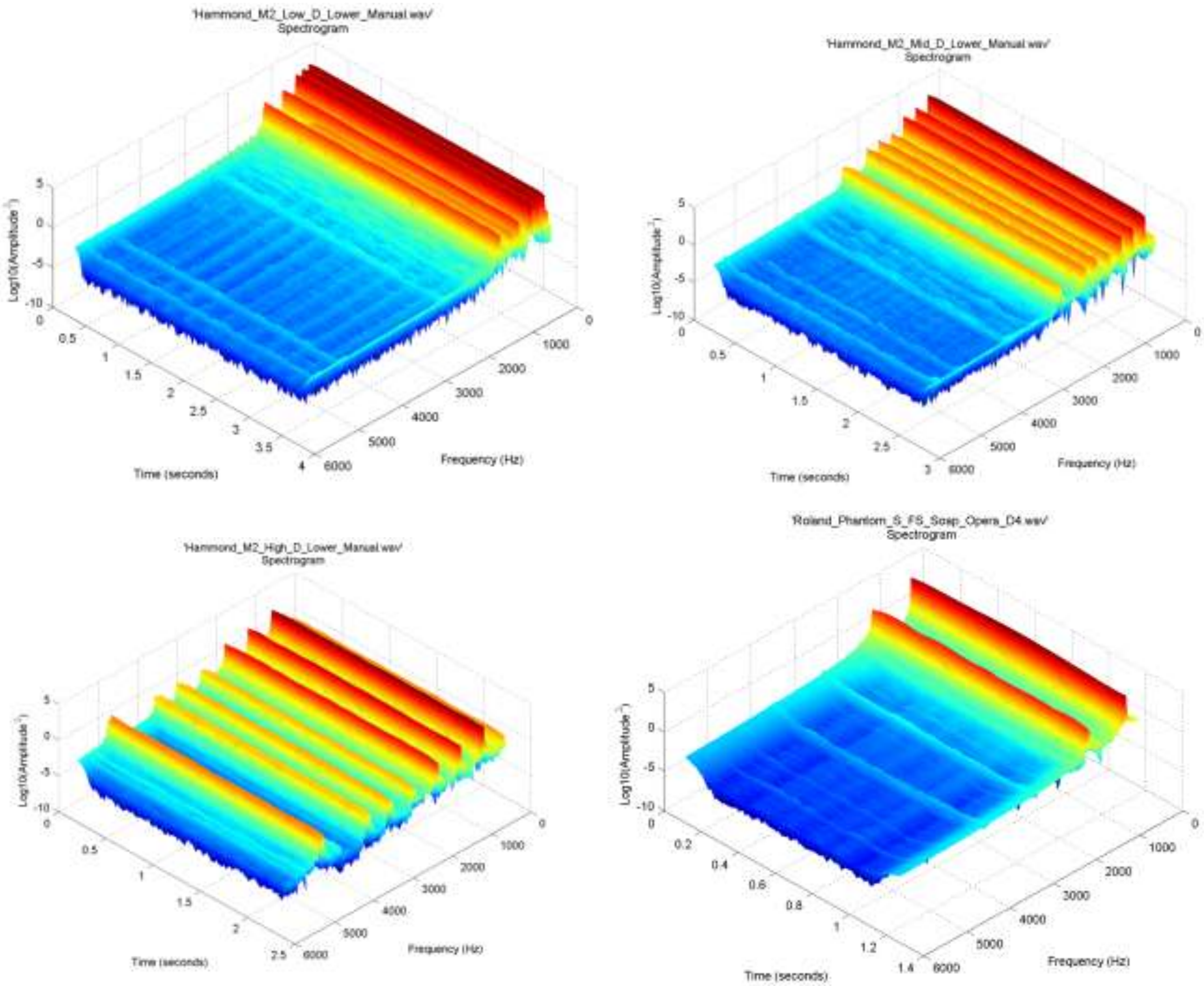


Figure 12: Spectrograph of low D on the Hammond Lower Manual (top left), middle D (top right), high D (bottom left), and D4 played on a Fantom S.

The pattern seen in the spectrograph differs greatly from the other instruments used in the study. Most obvious is the lack of decay in amplitude, but this is to be expected given the mechanism by which organs make sound is powered and rotational, not subject to any damping forces. Regarding a comparison between the synthesized waveform compared to the actual organ, there are far less harmonics, whereas the synthesized Rhodes and Wurlitzer featured many more. This is possibly a result of the mismatched patch-organ relationship, although the Hammond could easily be made to have only two harmonics by changing the drawbar settings, simply because Hammond organs produce pitches by adding a number of pure frequency harmonics together to create a pitch, and this could be limited to only two. However, it is still surprising that the synthesizer would feature an organ patch with only two harmonics given the complexity of the other patches used in this study.

Unrelated to any comparison, but still of interest, is the spread of the frequencies of the Hammond. Since the drawbars used to add harmonics do so in terms of intervals (the fundamental, a fifth above the fundamental, an octave of principle, an octave and a third, and so forth), the progressive spreading of the frequency range of the higher pitches increases as a result of the frequency multiples of the fundamental being march larger than the lower multiples of the lower fundamentals. It makes perfect sense in terms of acoustics, but is nonetheless interesting when graphed out to see the progression of the frequency spread as the pitch jumps up an octave. But ultimately, in this comparison anyway, it appears that the synthesized organ is in fact very different from the original instrument.

Yamaha Piano vs. Roland Fantom S So Real

The final comparison of instruments is perhaps the most relevant, as of all the instruments listed a piano is most prohibitively large and disagreeable to movement, and arguably the most important to be able to synthesize in a small portable package as a result. The spectrograph of D1 is shown in **Figure 13.**

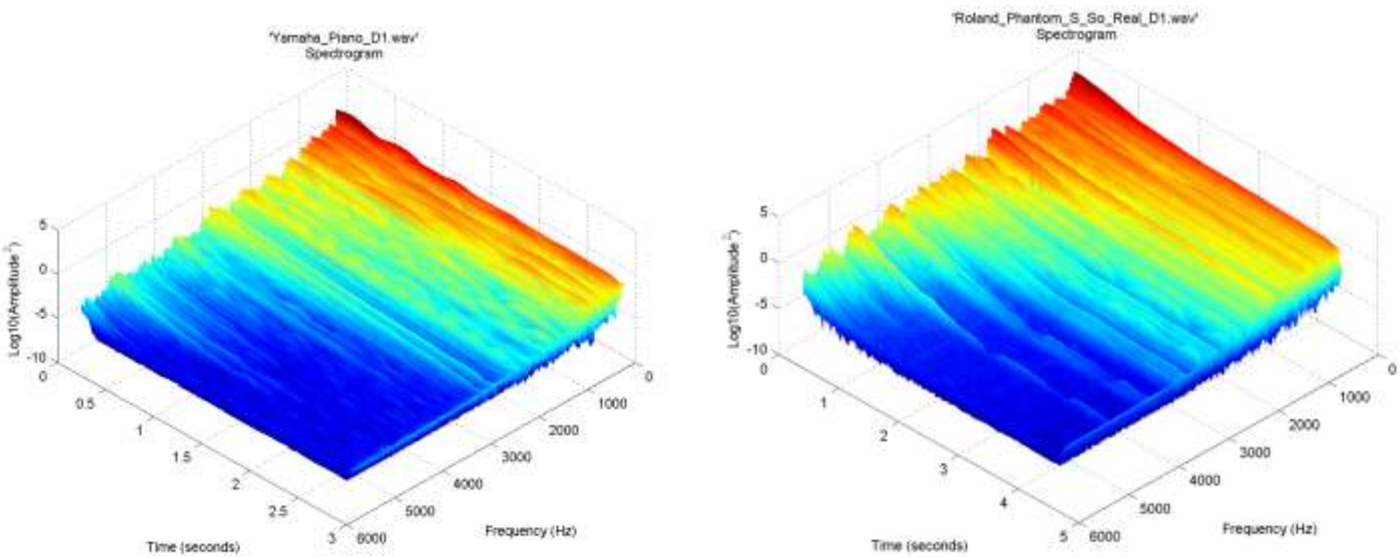


Figure 13: Spectrograph of a Yamaha piano (left) and Roland Fantom S (right)

Once more, it can be seen that the higher harmonics in the Fantom are much less present in the actual piano, continuing the trend exhibited by the Rhodes and the Wurlitzer. It is also fairly evident that, once again, the sustain of the notes in the Fantom is greater for many of the harmonics than it is in the actual piano, particularly in higher orders. A more detailed view of the amplitude relationship versus time is presented in **Figure 14.**

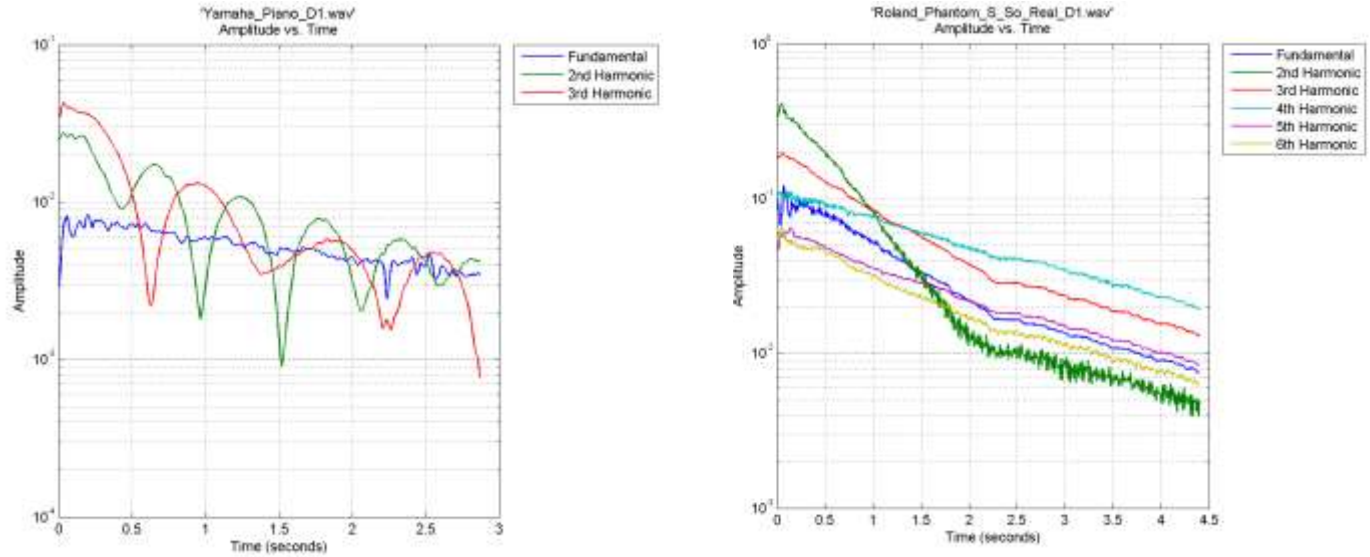


Figure 14: Amplitude vs. time of a D1 on a Yamaha piano (left) and Roland Fantom S (right)

This detailed view also illustrates the uniform rate of decay in the Roland, particularly after a two second interval where the decay is more rapid and of a different hierarchy, as well as an oscillation in the amplitudes of the Yamaha piano not present in the Roland. It is possible this is due to excitation of other strings (known as sympathetic resonance) or simply an acoustic effect of the sound producing mechanism transferring energy, but regardless of the cause it would certainly add a much different sound to the note being played when compared to the Roland.

To see if this behavior continues at higher frequency pitches, **Figure 15** shows a spectrograph of a mid range D4 on the Yamaha and the Roland.

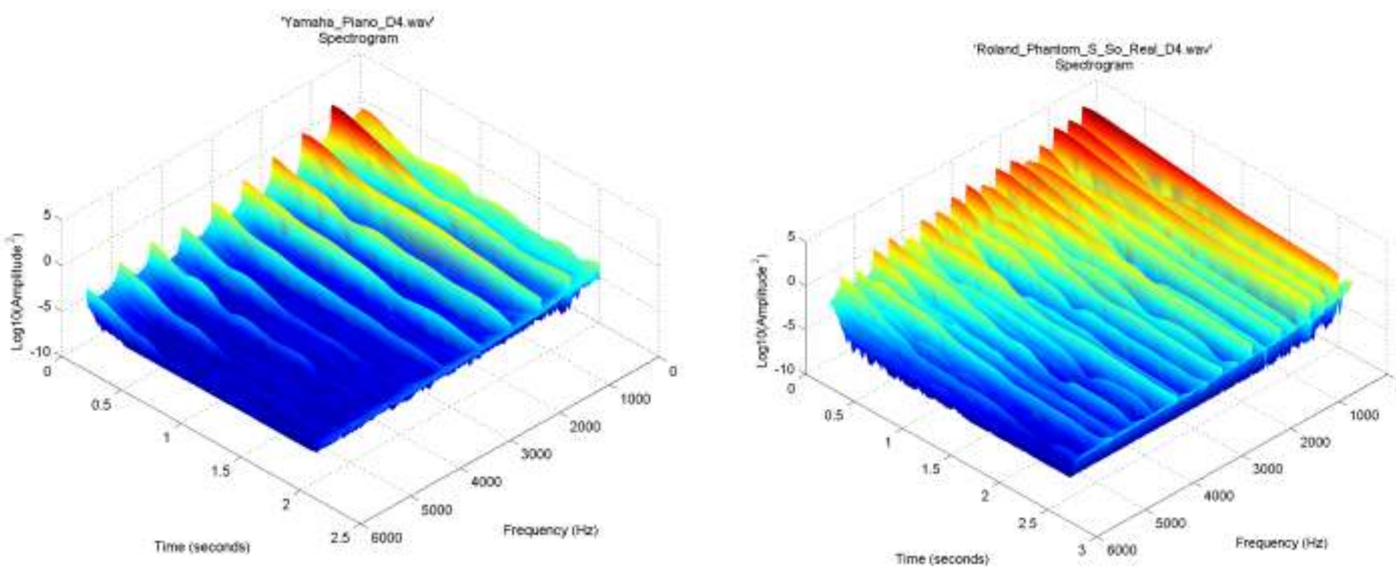


Figure 15: Spectrograph of a D4 on a Yamaha piano (left) and Roland Fantom S (right)

The most noticeable difference between the two spectrographs is the difference in the number of harmonics. Not only are the higher harmonics more present in the Roland, but as with the Tines Rhodes patch, there are simply more harmonics total, again likely due to the actual instruments being restricted in terms of vibrational energies and damping. However, it is worth noting that oscillation of the amplitudes as time progresses is still seen in the Yamaha, and is also more evident in the Roland at this higher pitch, as seen in the amplitude plots in **Figure 16**.

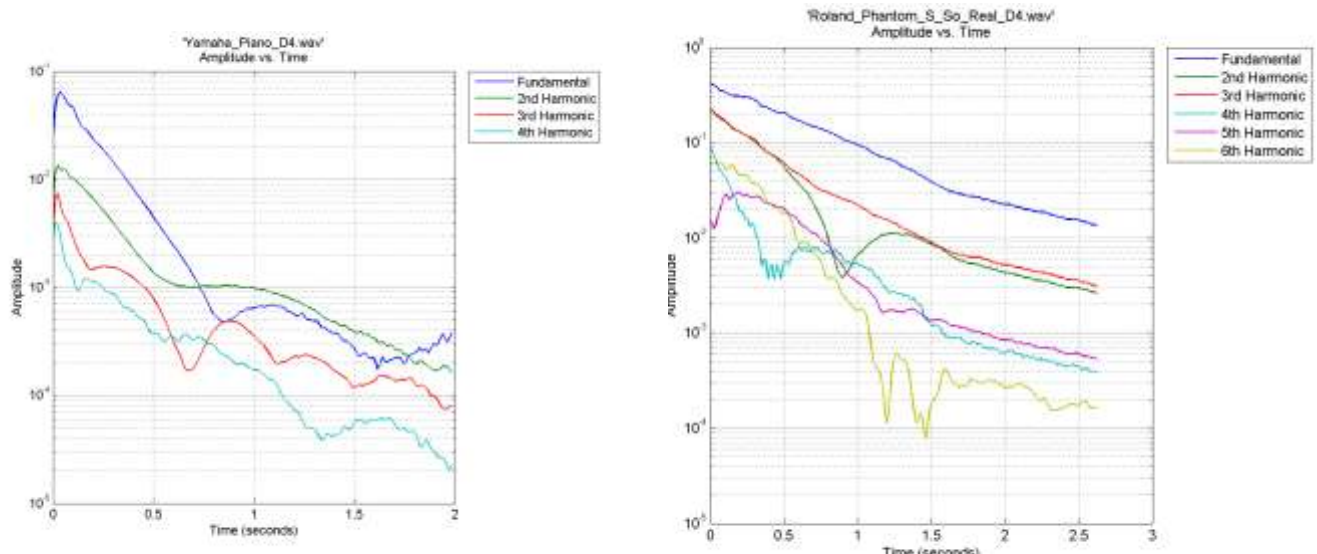


Figure 16: Amplitude vs. time of a D4 played on a Yamaha piano (left) and Roland Fantom S (right)

While it becomes especially clear in this figure that, especially as note pitch gets higher, the sustain on the Roland is much longer relative to that of the Yamaha, there is a clear oscillation of the amplitude in the 2^{nd}, 4^{th}, 5^{th}, and 6^{th} harmonics, providing a much closer comparison to the decay of all four harmonics in the Yamaha, far better than in the D1.

Increasing the pitch to Bb5, the accuracy of the overall emulation appears to decrease, as evidenced by the numerous higher order harmonics not nearly as present in the acoustic piano, as seen in the spectrograph **(Figure 17)** and harmonic range plot (**Figure 18).**

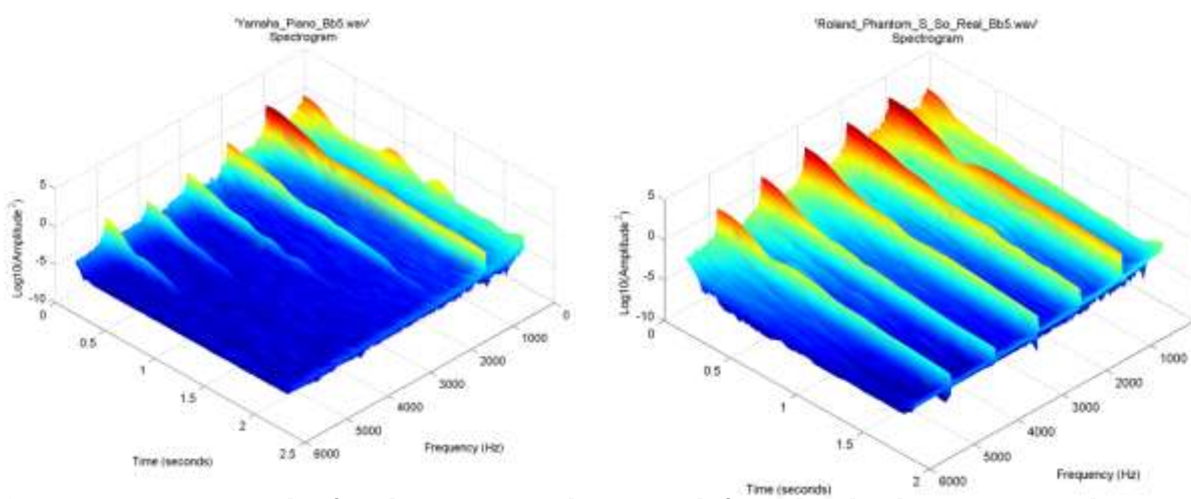
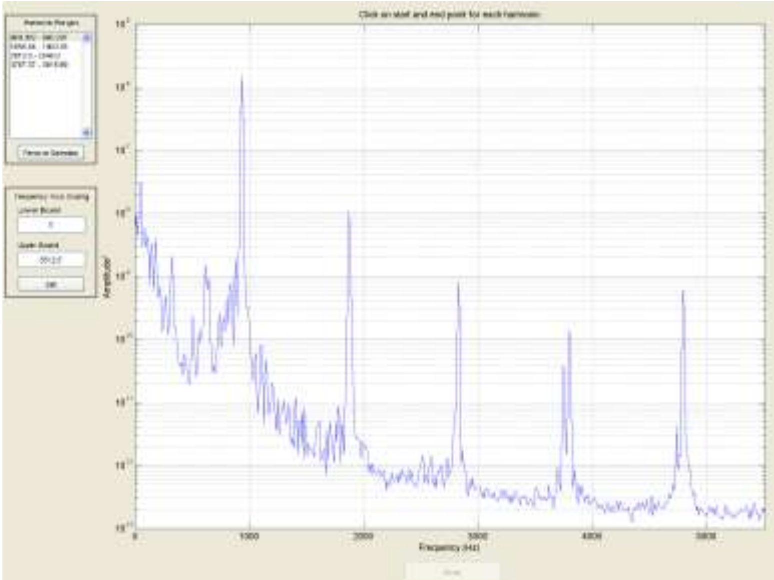


Figure 17: Spectrograph of a Bb5 on a Yamaha piano (left) and Roland Fantom S (right)



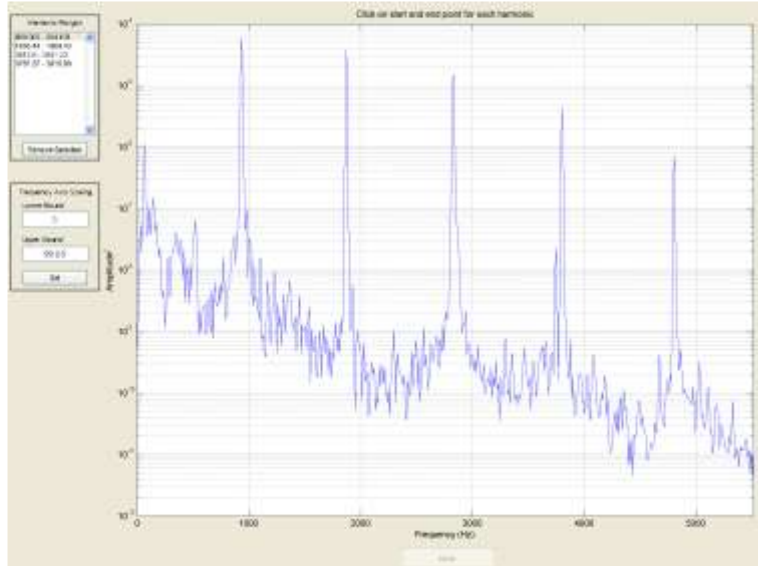


Figure 18: Harmonic ranges of a Bb5 on a Yamaha piano (left) and Roland Fantom S (right)

5. Conclusion

Throughout most of the instruments tested (the organ samples being the anomalous case), the synthesized sounds exhibited several trends distinguishing them from those generated by the actual instruments, and are as follows:

1. The synthesized waveforms on occasion exhibited a greater number of harmonics than those in the actual instruments
2. In addition to being present in greater number, higher order harmonics were also much stronger in amplitude in the synthesized waveforms than in the actual instruments
3. The time decay of the waveforms was much more uniform across the frequency spectrum in the synthesized version compared to the shorter decay times of the higher frequencies in the actual instruments

While none of these differences are blatantly obvious to the ear, the contributions of each could potentially explain a tangible difference in quality between the synthesizer and the actual keyboards that would support evidence that the synthesizer is “worse” than the actual instruments. The higher order harmonics present in the synthesizer, while of a smaller amplitude, may very well contribute to a brighter, harsher sound than found in the actual instruments that exhibit a lower biased, more mellow tone. This is exemplified by the lack of decay in these higher harmonics in the synthesized versions, emphasizing a brighter tinnier sound as it decays rather than a focus on the fundamental in the actual instruments. Being qualitative assessments, this cannot quite be asserted as a fact, but in the course of this study there was certainly enough evidence to support claims that even in an expensive workstation, the sound banks aren’t quite up to the standards of the actual instruments and those looking for the best quality sound may be wise to continue pursuing the real deal.

Acknowledgements:

Special thanks to Prof. Steve Errede and the UIUC Physics Department, Prof. Barry Houser and the Athletic Bands Department, Jake Annala, and John Meehan for supplying equipment.

References:

Forum regarding details about the Fantom S:

http://en.audiofanzine.com/workstation/roland/Fantom-S-61/user_reviews/