Analysis of Bamboo as an Acoustical Medium

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Physics 406 Final Report

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Abstract

This semester I constructed and took measurements on a set of bamboo pan flute pipes. Construction and fine-tuning was done on 11 pipes that spanned notes in the D4 to D5 range in the equal temperament scale. After learning to play and doing some recordings of each individual note, I did harmonic wave analysis using Matlab. This yielded interesting results about the relative amplitudes and phases of each harmonic. Then, I did a verification of the fundamental frequency of an open close pipe by taking precise measurements of each individual pipe. The percent error of the calculated frequency and the measured frequency of the Matlab software was always in the .5% to 2% range. These were great results, and I will continue to learn to actually play the instrument.

Background

Bamboo is a fast growing plant that is actually the largest plant in the grass family. The plant has many uses given its good tensile strength and compressive strength. It has been made in anything from plates, paper, to even buildings. It has a fairly unique property in that it is mostly hollow as it grows. This allows fro its use as a musical instrument, mainly flutes. The flute, at its core, is one of the simplest woodwind instruments because it does not use a reed. Flutes are some of the earliest known musical instruments because of its simplicity of being a stimulated column of air. Bamboo flutes are found all over the world particularly in Asia and South America. So the bamboo plants naturally hollow nature makes them a perfect pair for the flute design.

In the context of pan pipes, the instrument at the focus of this project, the bamboo plant is exceptionally good. Although the plant naturally is hollow a membrane grows within the plant about every third of a meter or so. This distance depends upon the age of the plant and the particular species. The location of the membrane is also visible on the outside as what looks like a node or a knuckle in the plant. The pan flute is an open close pipe which is a very simplified Helmholtz resonator. The membrane of the plant provides a natural closed end for each individual pipe in the pan flute instrument.

Construction

The obvious first task was to create the instrument. So I started with 5-foot bamboo poles. I took some time to saw each one so that there were multiple smaller pipes that with one open end and one node about 3 cm from the end. The nodes of the bamboo poles are naturally occurring in the plant. So, I then organized them by diameter and length. For the actual instrument the pipes with larger diameters are easier to stimulate so it is better for the larger pipes with lower frequencies to have the larger diameters so that they entire instrument could have a similar ease of play. So then, I spent the majority of construction time sanding and filing the pipes in order to get them properly tuned. I used a standard cell phone tuner app. I spent that long of time given how precise it had to be. The lengths that I had to take off were on the order of a .5 cm to 1.5 cm. I did not want to risk taking off too much with sawing and sawing also did not produce a very even cut.

I did have some trouble with the D4 pipe, which was the longest pipe that is on the instrument. Since it was the lowest pitch that required the longest section of wood, but none of the lengths of bamboo in between the nodes were long enough alone. So I had to cut a length that had two nodes that was long enough to produce the note. Then I spent a lot of time devising a way to puncture the node in the middle. I ended up using blunt force and a circular file. Once there was a hole in the node I sanded away the remainder of it until the radius was about consistent with the rest of the cylinder.

So once a majority of the pipes were properly tuned I bound them together using twine. Using a basic cross knotting once near the end parallel to the blowholes. The second line was at an angle like the bend near the bottom of the instrument. Overall I am very pleased with how the instrument turned out. The pipes are nearly level and they are fairly easy to stimulate.

Verification of the fundamental harmonics correction

Another part of the analysis of the instrument was the relations of the dimensions of the pipes to the fundamental frequency. Theoretically, for a perfect open close acoustical pipe the fundamental frequency is proportional to the length and the speed of sound.

$$f=V_s/(4L) \tag{1}$$

This happens because theoretically there is a pressure node at the close and a pressure anode at the open end. This encompasses at very least one quarter of a wavelength. So the equation above is just an adapted version of Lambda*f=v.

However, given some real analysis of physical pipes there was a correction added to the formula based on another dimension.

$$f=V_S/4(L+.4D) \tag{2}$$

This is the new formula where D is the diameter of the open end of the pipe. I calculated the corresponding dimensions of the pan pipes of my instrument and used them to get theoretical fundamental frequencies. Using the frequencies received from the Matlab program as an experimental comparison, I calculated percent error with the calculated values. The percent errors ranged from about .5% to 2.5%. I am very satisfied with these results as they are noticeable closer to the experimental values than the formula without the correction. Those errors were closer to 5% or higher. The small amount of error could come from three aspects. I used the simple 343 m/s approximation of the speed of sound. The temperature of the time that I measured could have been different to a few significant figures. Looking at the small frequency versus time graphs from the Matlab wave analysis program we can see that the measured frequency alternates in about a 3 Hz range. When choosing an experimental value I visually chose a value that was based more on the mode and the peak amplitude value of the data because of outliers. The third error could simply come from my ability to play the instrument. When I would play at home or during labs I would tell that the frequency on simple tuner apps would change based on the way I would play. This came from things such as the speed at which I blew air across the opening. Given these sources of error I am very satisfied with the percent error, which had an average value of .8%.

The following chart and two figures are data from the above calculation. The chart has all the values of the pipes and the following calculations. The length and diameter columns are the appropriate measurements. The "Frequency (from calculation)" comes from the above equation two with the proper dimensions, while "without correction" comes from the completely theoretical equation one. The "Theoretical" column comes from the equal temperament scale. I included this to show a comparison of the notes to the desired pitch, which just shows how closely I tuned the pipes. The “measured” comes from the specific analysis of the sound from the Matlab wave analysis program. The percent error that is included is between the calculated fundamental frequency with the correction and the measured. The chart in figure one compares the values of the calculated, theoretical and measured columns.

Note	Length (m)	Diameter (m)	Frequency (from calculation) Hz	Without correction Hz
D5	0.143	0.01251	579.376	599.650
C5	0.157	0.01454	526.668	546.178
B4	0.167	0.0138	497.044	513.473
Bb4	0.174	0.0151	476.283	492.816
A4	0.19	0.0153	437.232	451.316
G4	0.207	0.0158	401.978	414.251
F4	0.238	0.0169	350.343	360.294
E4	0.256	0.0174	326.095	334.961
Eb4	0.268	0.0178	311.682	319.963
D4	0.296	0.0154	283.790	289.696

Note	Theoretical Hz	Measured Hz	Percent error (Calculated and Measured)
D5	587	580	0.11%
C5	523	524.1	0.49%
B4	493	490.1	1.42%
Bb4	466	473	0.69%
A4	440	436.2	0.24%
G4	392	393.8	2.08%
F4	349	351	0.19%
E4	329	325.8	0.09%
Eb4	311	312	0.10%
D4	293	291	2.48%

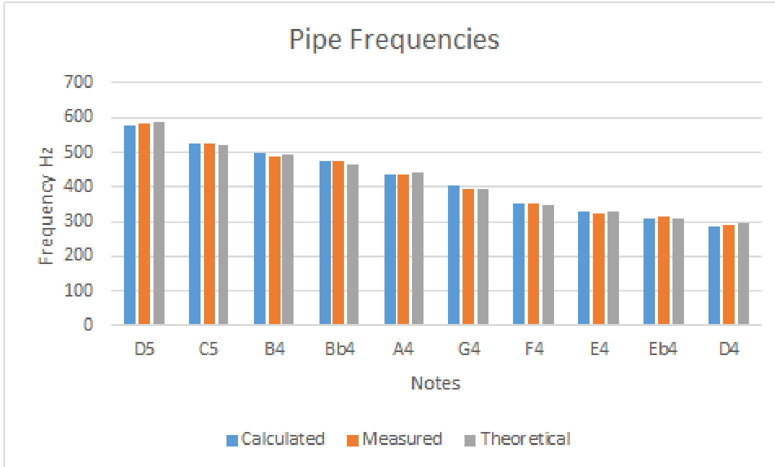


Figure 1: Comparison of Frequencies

General Harmonic Analysis

As stated before, there were 11 pipes in the instrument I constructed whose fundamental frequencies ranged from 291 Hz to 580 Hz. By running a recording of each instrument through a Matlab wave analysis program, I was able to visualize some properties of the sound that the instrument produces. The program produces many graphs that plot amplitude, phase, frequency, and time relative to each other.

There were a lot of interesting phenomena with the pipe notes. The harmonics are most present on the odd numbers. This is most readily visible in either the amplitude vs. frequency or the amplitude vs. harmonics graphs. Theoretically the odd harmonics should only be present but the even ones are there. They had high enough amplitude to be analyzed by the Matlab program without crashing.

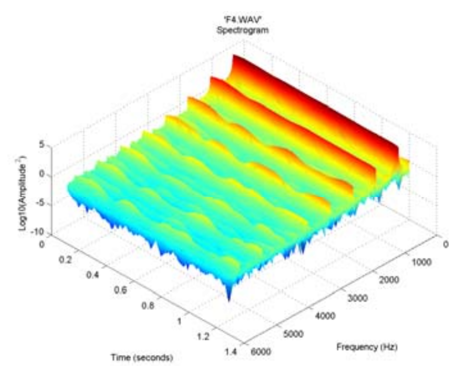


Figure 3: Waterfall Plot of F4

In some of the waterfall plots, the three-dimensional graphs comparing frequency amplitude and time, showed a few more interesting circumstances. For example figure 3, the waterfall plot of F4, had oscillations in amplitude of the higher frequencies. This could happen because when I was recording the note, I did not play the instrument at a consistent volume. However, it is interesting that the first three harmonics seem mostly unaffected by the oscillations.

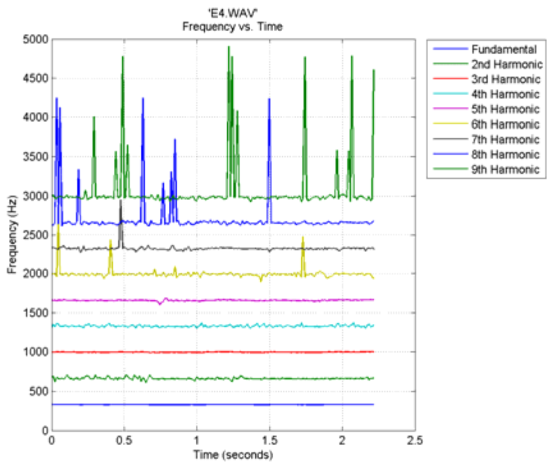


Figure 4: Frequencies of the E4 Harmonics

When doing analysis of the harmonics of the pipes, the program was able to accept nine harmonics of the note E4. Figure 4 shows the plot of the frequency of each individual harmonic versus time. For the first five they are very stable, which is good considering the desire for consistent harmonics for an instrument. I found while doing the sanding and fine-tuning that the frequency did have some small dependences on outside factors. I could change the pitch by altering air speed but that would only alter it by a few Hertz. It also depends on the properties of the air, mostly temperature, which I would see most often when I changed locations.

Another interesting property of the instruments was that the shapes of the frequency versus amplitude plots were consistent with subsequent stimulations. For a choice few notes, I recorded twice in order to compare some things with amplitude and stimulation method. Not only did are the harmonics in the same location but the shapes are also relatively the same. The third and fifth harmonics both have the same notches on the right side of their peaks. The even harmonics have similar slopes on either side of them. This is very interesting because this means that the overall harmonics of the stimulated sound is more dependent on the properties of the pipe and not outside factors.

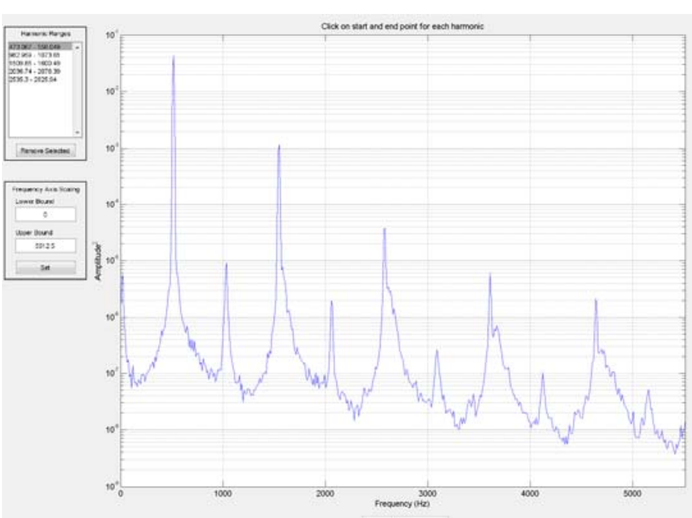


Figure 5: First C5

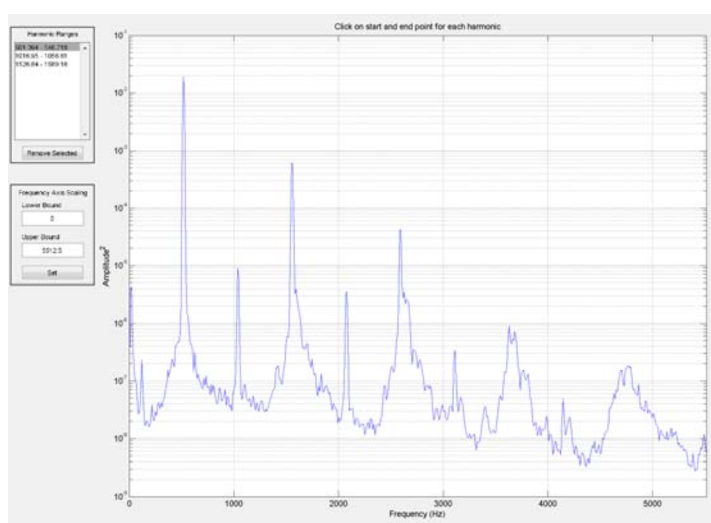


Figure 6: Second C5

Presence of Even harmonics

So theoretically for an acoustic open close pipe, the harmonics should only stimulate the odd harmonics. However for the analysis of the amplitudes versus frequency graphs there are clear spikes at the even harmonics. The spikes are all much smaller than the odd harmonics around them and usually by the eighth harmonic it is indistinguishable from the rest of the noise. The biggest reason I could think of for this is the fact that the nodes are not perfectly stable. They would be able to oscillate pressure and particle velocity levels. So if there is some oscillation allowed then there is the possibility. Similar reasons to the non-stiff nodes are the curved nature of the nodes and the uneven radius of the wood.

Professor Errede introduced another possibility to me. The system inside the bamboo pipes is not perfectly linear so there is the possibility of distortion. So, with the increase in amplitude of the sound field in the system would cause an increase in distortion. This would then lead to an increase in amplitude of the even harmonics. This is why I tried to play some notes again. I have included in the nearby figures 7 and 8, two times I had played the E4 note. On the second play through, the amplitudes of every note are visibly higher. This corroborates the idea that distortion and the non linear nature of the system could cause even harmonics.

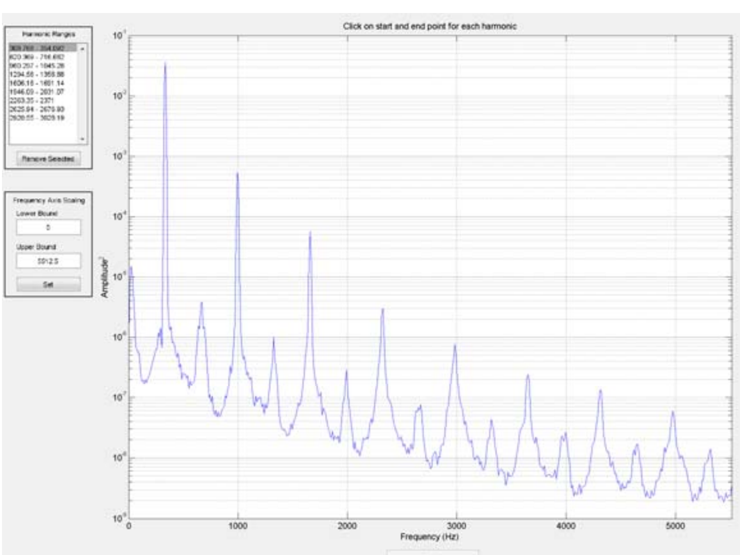


Figure 7: First E4

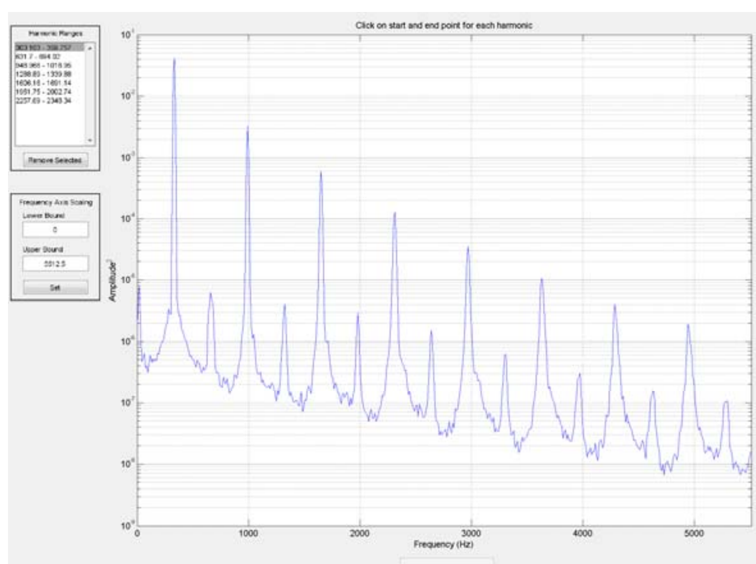


Figure 8: Second E4

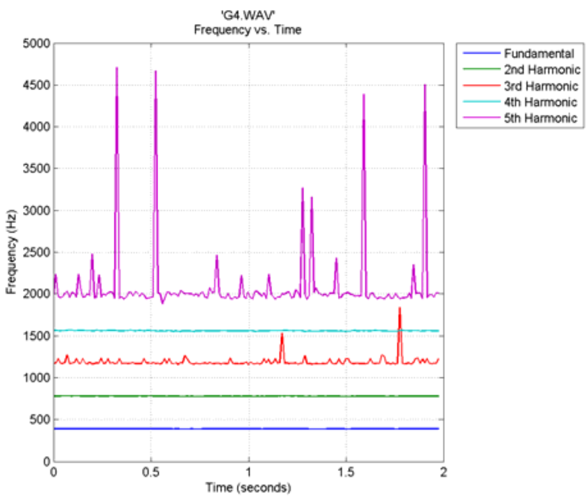
Conclusions

Overall, the construction and analysis of this pan flute instrument was a good experience. The construction process was surprisingly difficult because of how precise it had to be. It was very satisfying to see the hard work translate into a very nice sound and verifiable scientific principles. The very small percent error that came from the verification of the fundamental frequency analysis was very surprising. The test with the Matlab software provided a very good visual representation of the sound that came from the instrument that I made.

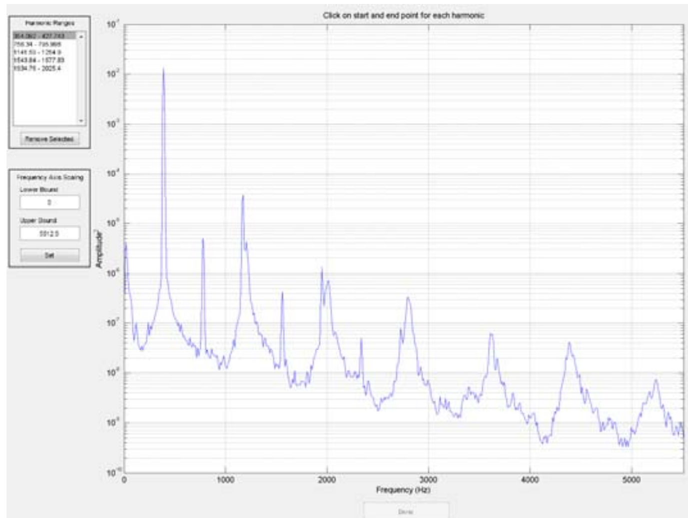
For future experiments, I would be interested to compare bamboo to other materials. I have seen pan flutes made of simple PVC pipe and comparing the harmonics of the two would provide useful insights about materials used to make instruments. I also would have liked to make a standard horizontal flute or a recorder like instrument, but time and material constraints prevented that. I am happy with the results hat came from this project and the instrument I now have.

APPENDIX

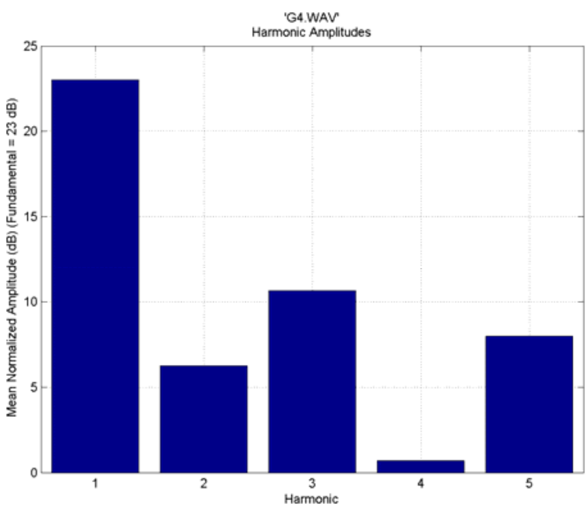
G4



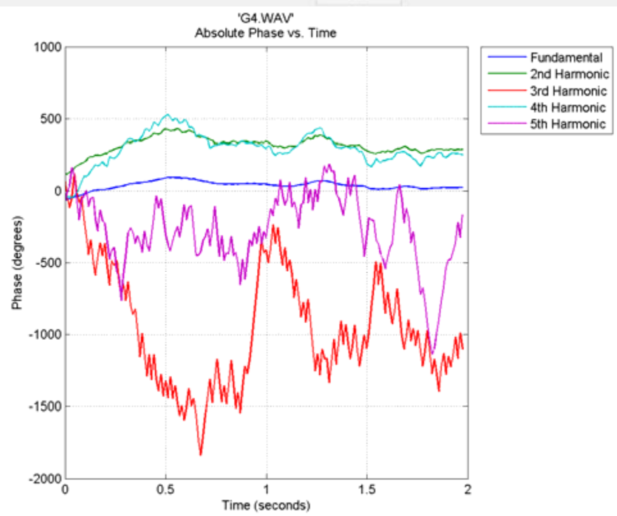
'G4.WAV'
Frequency vs. Time
Frequency (Hz)
Time (seconds)
Fundamental
2nd Harmonic
3rd Harmonic
4th Harmonic
5th Harmonic



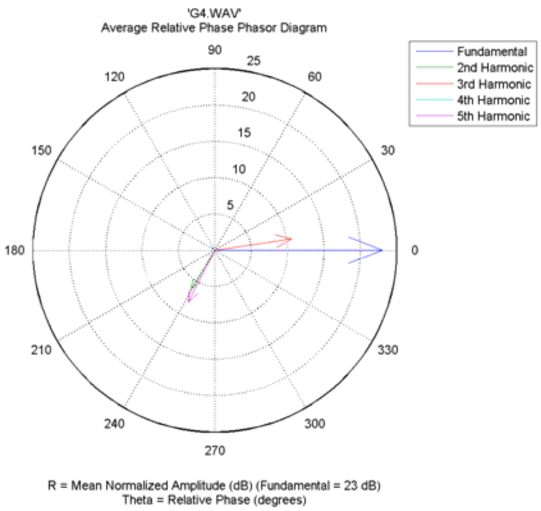
Click on start and end point for each harmonic
Frequency (Hz)
Amplitude

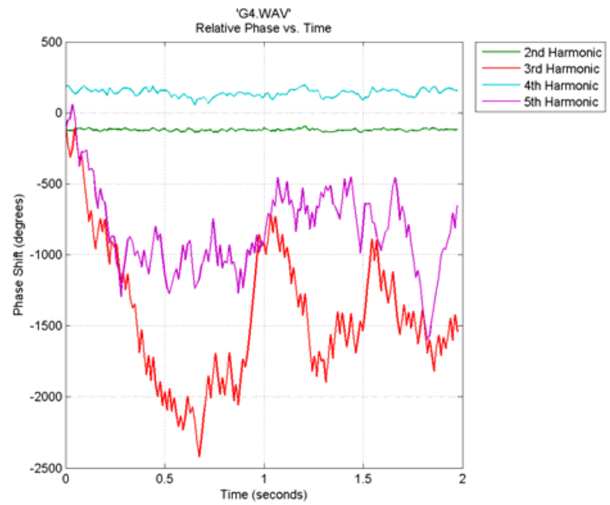


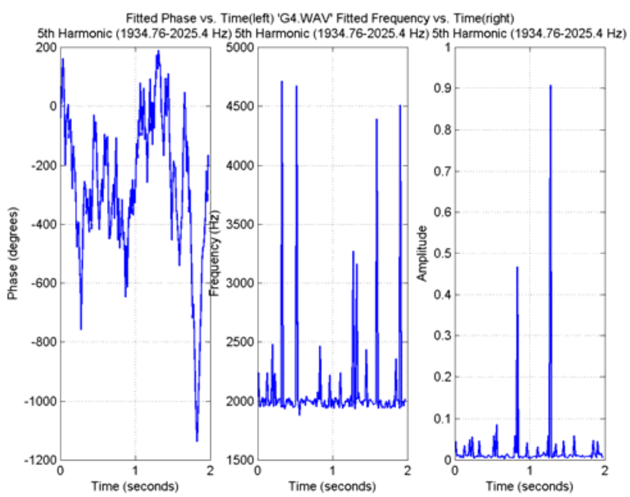
'G4.WAV'
Harmonic Amplitudes
Mean Normalized Amplitude (dB) (Fundamental = 23 dB)
Harmonic

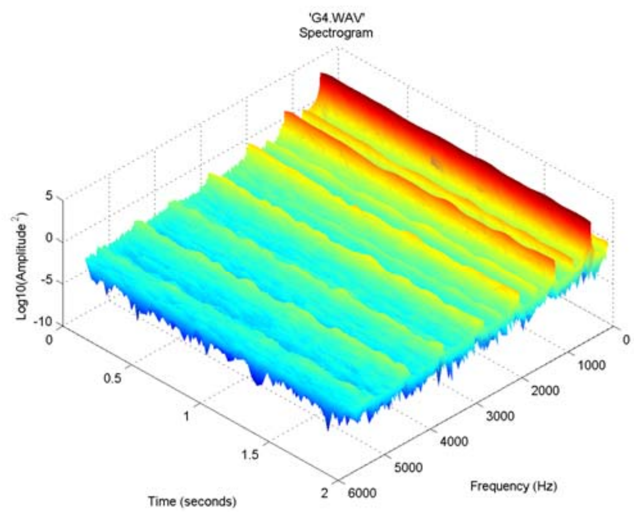


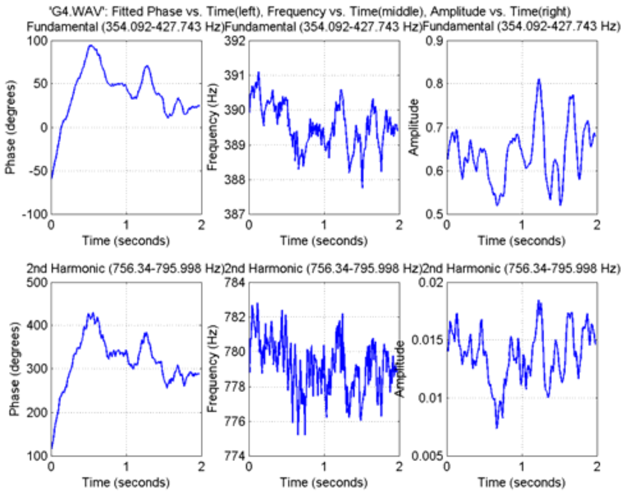
'G4.WAV'
Absolute Phase vs. Time
Phase (degrees)
Time (seconds)
Fundamental
2nd Harmonic
3rd Harmonic
4th Harmonic
5th Harmonic

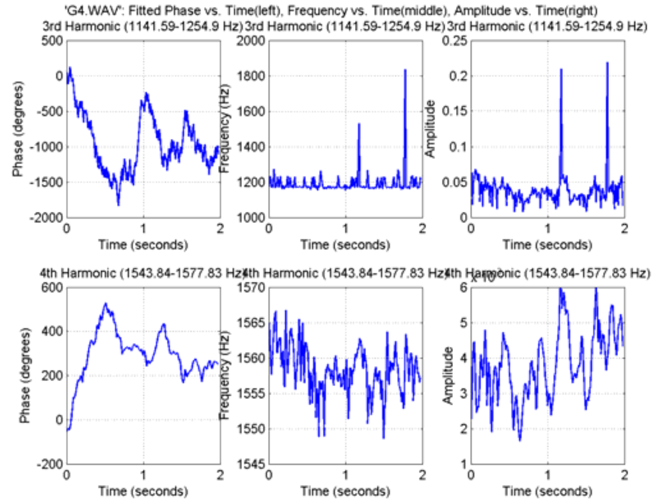

'G4.WAV'
Average Relative Phase Phasor Diagram
Fundamental
2nd Harmonic
3rd Harmonic
4th Harmonic
5th Harmonic
R = Mean Normalized Amplitude (dB) (Fundamental = 23 dB)
Theta = Relative Phase (degrees)

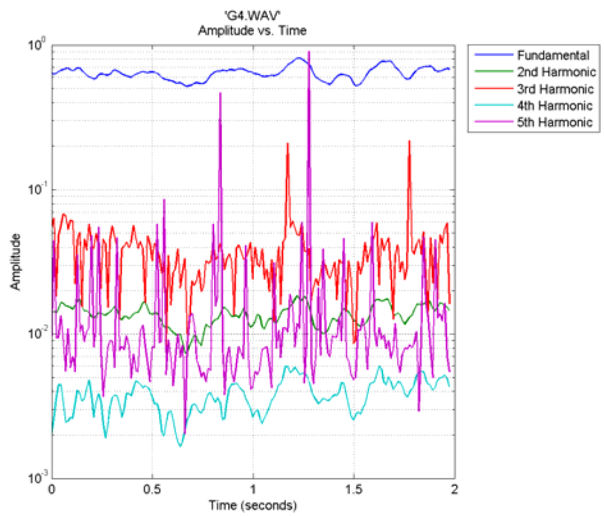

'G4.WAV'
Relative Phase vs. Time
2nd Harmonic
3rd Harmonic
4th Harmonic
5th Harmonic
Phase Shift (degrees)
Time (seconds)


Fitted Phase vs. Time(left) 'G4.WAV' Fitted Frequency vs. Time(right)
5th Harmonic (1934.76-2025.4 Hz) 5th Harmonic (1934.76-2025.4 Hz) 5th Harmonic (1934.76-2025.4 Hz)
Phase (degrees)
Frequency (Hz)
Amplitude
Time (seconds)

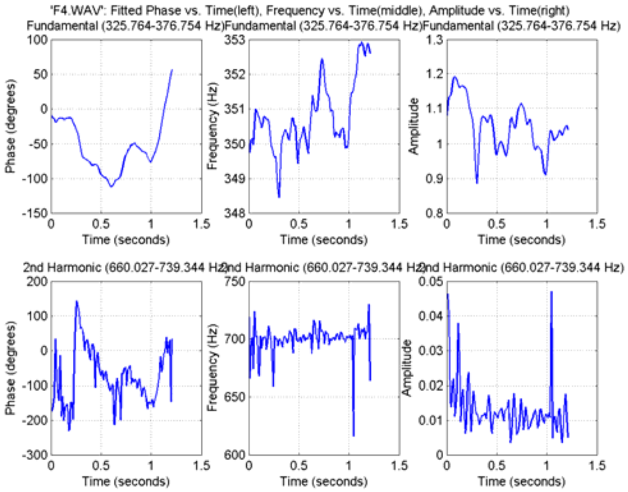

'G4.WAV'
Spectrogram
Log10(Amplitude 2)
Time (seconds)
Frequency (Hz)

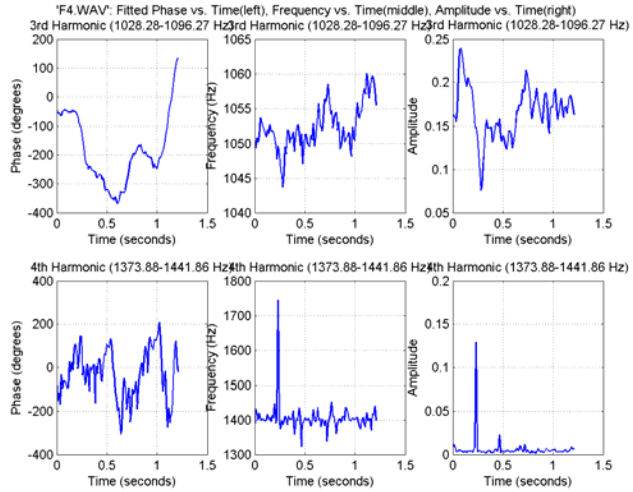

'G4.WAV': Fitted Phase vs. Time(left), Frequency vs. Time(middle), Amplitude vs. Time(right)
Fundamental (354.092-427.743 Hz)
2nd Harmonic (756.34-795.998 Hz)
Phase (degrees)
Frequency (Hz)
Amplitude
Time (seconds)

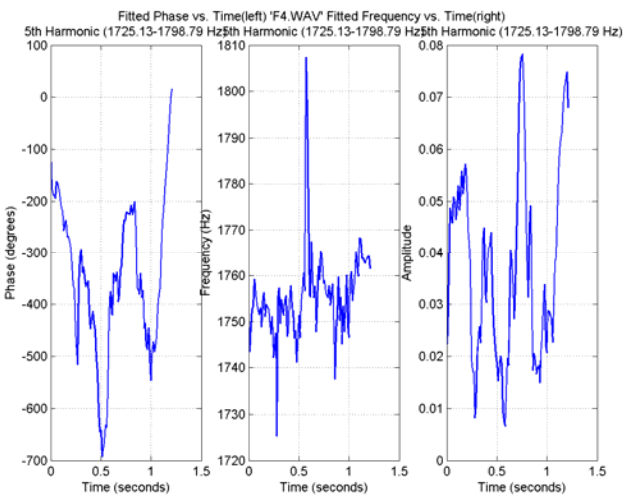

'G4.WAV': Fitted Phase vs. Time(left), Frequency vs. Time(middle), Amplitude vs. Time(right)
3rd Harmonic (1141.59-1254.9 Hz)
4th Harmonic (1543.84-1577.83 Hz)
Phase (degrees)
Frequency (Hz)
Amplitude
Time (seconds)

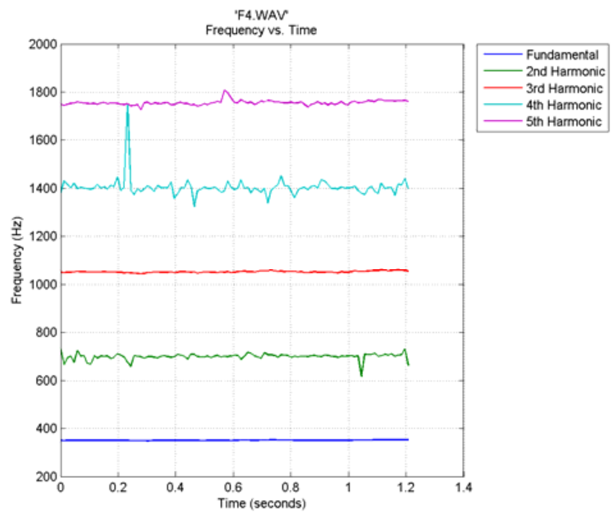

'G4.WAV'
Amplitude vs. Time
Fundamental
2nd Harmonic
3rd Harmonic
4th Harmonic
5th Harmonic
Amplitude
Time (seconds)

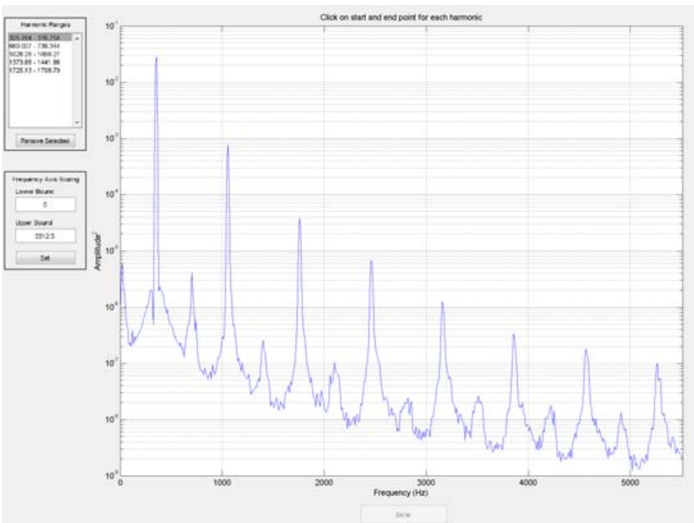
F4

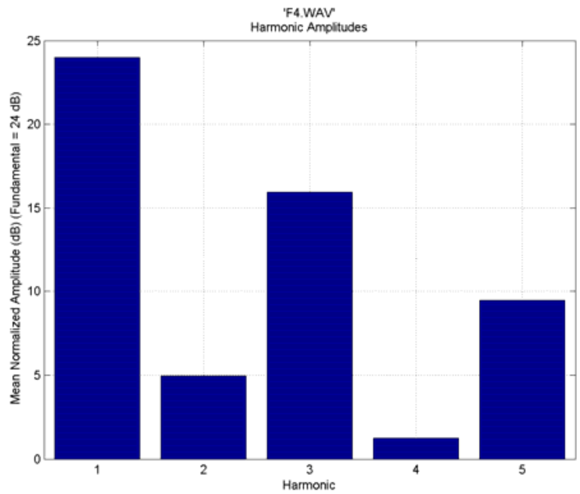

'F4.WAV': Fitted Phase vs. Time(left), Frequency vs. Time(middle), Amplitude vs. Time(right)
Fundamental (325.764-376.754 Hz)
2nd Harmonic (660.027-739.344 Hz)
Phase (degrees)
Frequency (Hz)
Amplitude
Time (seconds)

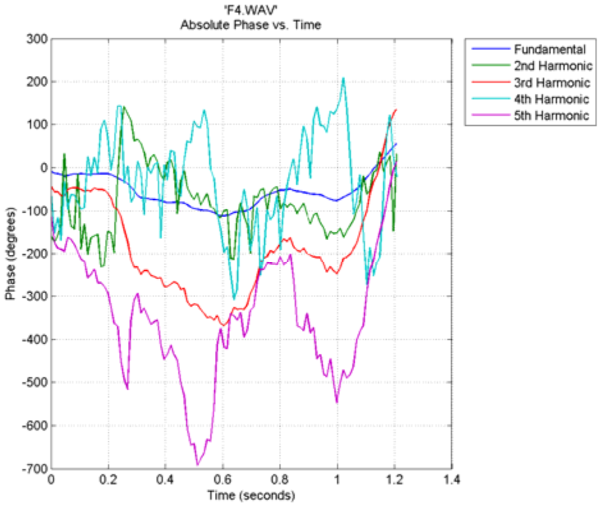

'F4.WAV': Fitted Phase vs. Time(left), Frequency vs. Time(middle), Amplitude vs. Time(right)
3rd Harmonic (1028.28-1096.27 Hz)
4th Harmonic (1373.88-1441.86 Hz)
Phase (degrees)
Frequency (Hz)
Amplitude
Time (seconds)

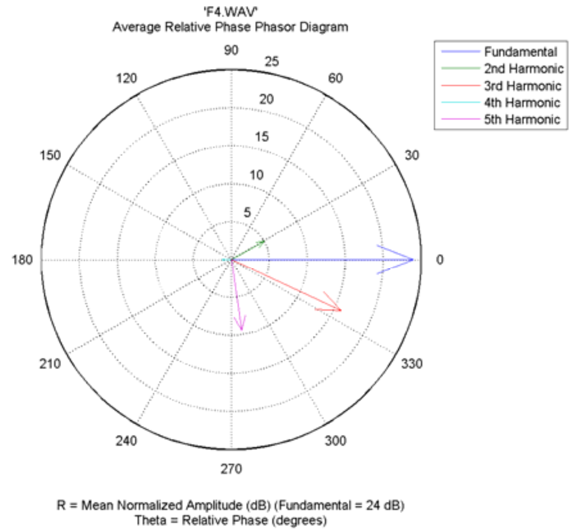

Fitted Phase vs. Time(left) 'F4.WAV' Fitted Frequency vs. Time(right)
5th Harmonic (1725.13-1798.79 Hz)
Phase (degrees)
Frequency (Hz)
Amplitude
Time (seconds)

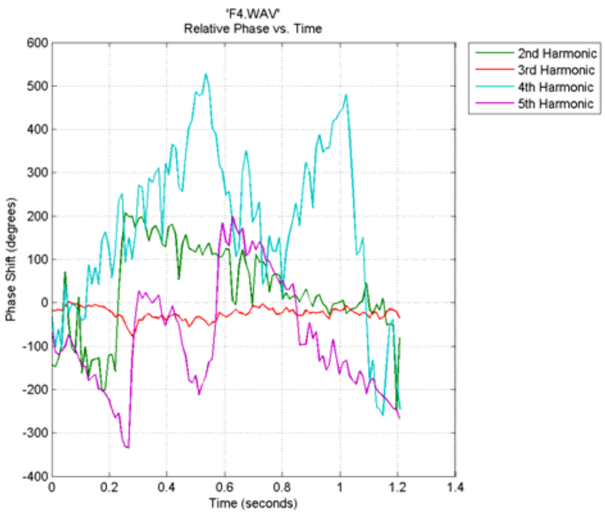

'F4.WAV'
Frequency vs. Time
Fundamental
2nd Harmonic
3rd Harmonic
4th Harmonic
5th Harmonic
Frequency (Hz)
Time (seconds)

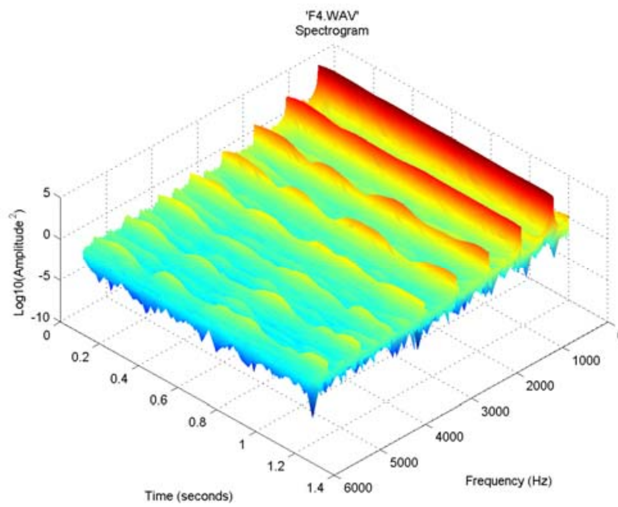

Click on start and end point for each harmonic
Harmonic Ranges
Remove Selected
Frequency Axis Scaling
Lower Bound
Upper Bound
Set
Frequency (Hz)
Done

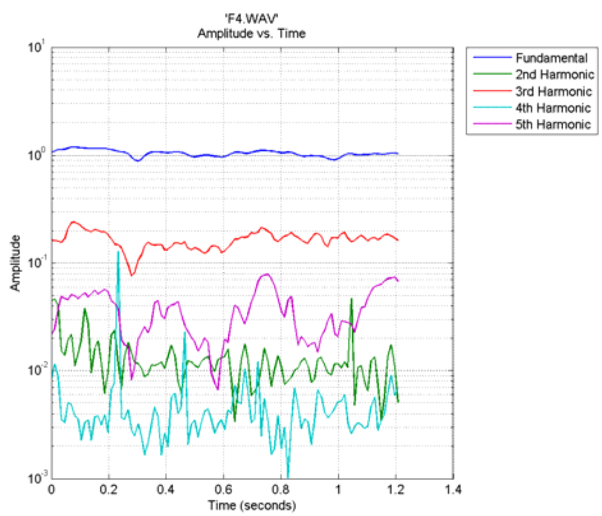

'F4.WAV'
Harmonic Amplitudes
Mean Normalized Amplitude (dB) (Fundamental = 24 dB)
Harmonic


'F4.WAV'
Absolute Phase vs. Time
Phase (degrees)
Time (seconds)
Fundamental
2nd Harmonic
3rd Harmonic
4th Harmonic
5th Harmonic
300
200
100
0
-100
-200
-300
-400
-500
-600
-700
0
0.2
0.4
0.6
0.8
1
1.2
1.4

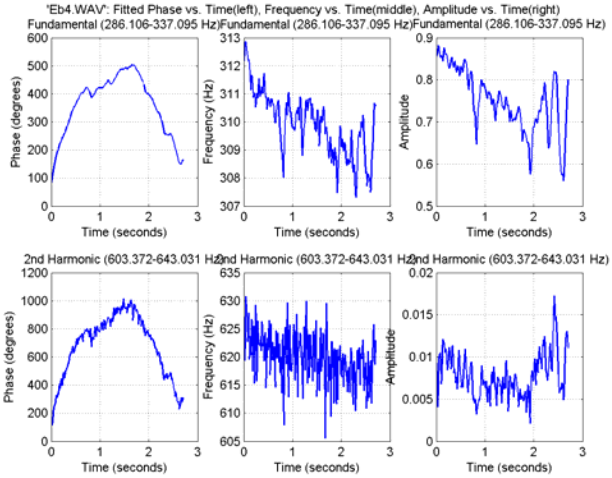

'F4.WAV'
Average Relative Phase Phasor Diagram
Fundamental
2nd Harmonic
3rd Harmonic
4th Harmonic
5th Harmonic
90
120
60
150
30
180
0
210
330
240
300
270
5
10
15
20
25
R = Mean Normalized Amplitude (dB) (Fundamental = 24 dB)
Theta = Relative Phase (degrees)

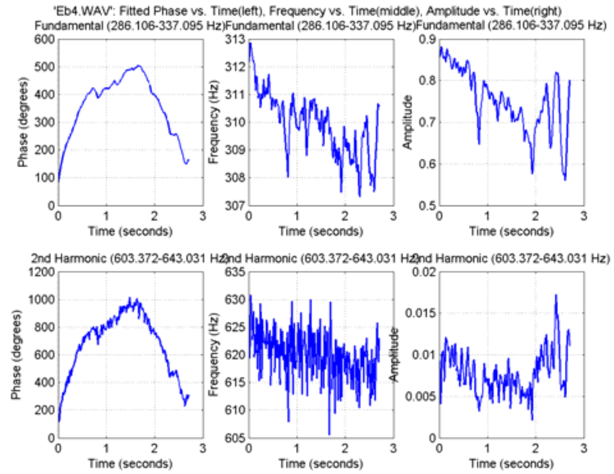

'F4.WAV'
Relative Phase vs. Time
Phase Shift (degrees)
Time (seconds)
2nd Harmonic
3rd Harmonic
4th Harmonic
5th Harmonic
600
500
400
300
200
100
0
-100
-200
-300
-400
0
0.2
0.4
0.6
0.8
1
1.2
1.4

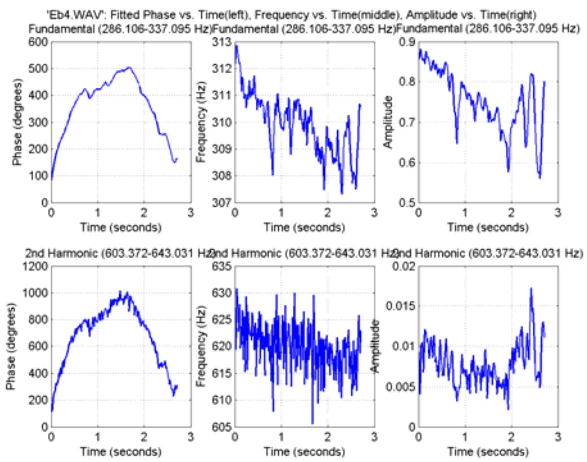

'F4.WAV'
Spectrogram
Log10(Amplitude^2)
5
0
-5
-10
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Time (seconds)
0
1000
2000
3000
4000
5000
6000
Frequency (Hz)

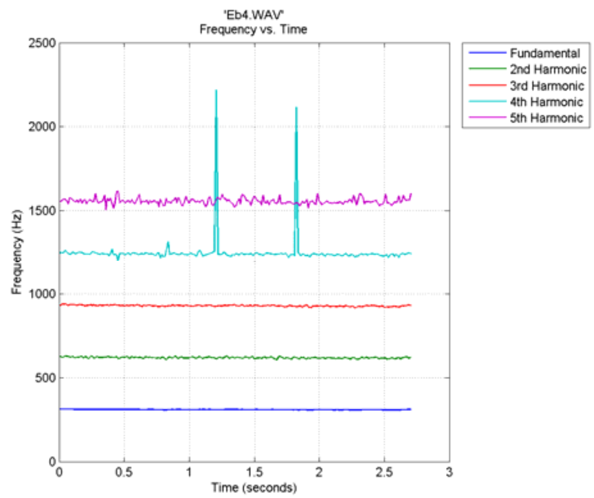

'F4.WAV'
Amplitude vs. Time
Amplitude
Time (seconds)
Fundamental
2nd Harmonic
3rd Harmonic
4th Harmonic
5th Harmonic
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
0
0.2
0.4
0.6
0.8
1
1.2
1.4

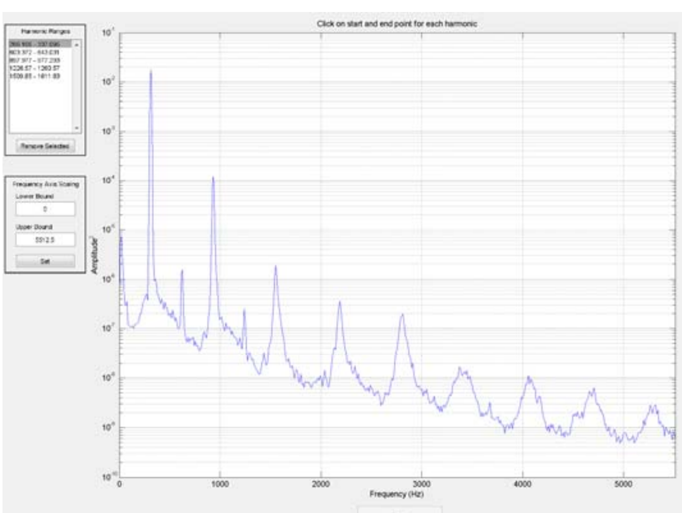
Eb4

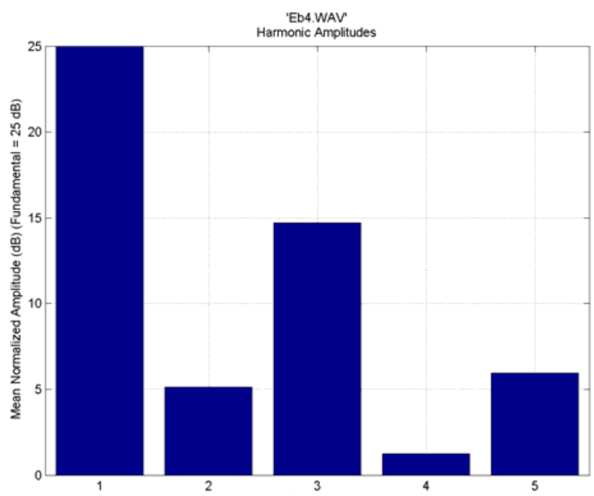

'Eb4.WAV': Fitted Phase vs. Time(left), Frequency vs. Time(middle), Amplitude vs. Time(right)
Fundamental (286.106-337.095 Hz)
2nd Harmonic (603.372-643.031 Hz)
Phase (degrees)
Frequency (Hz)
Amplitude
Time (seconds)

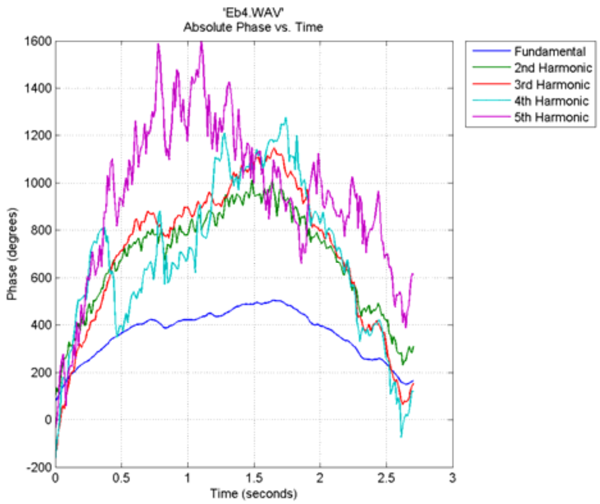

'Eb4.WAV': Fitted Phase vs. Time(left), Frequency vs. Time(middle), Amplitude vs. Time(right)
Fundamental (286.106-337.095 Hz)
2nd Harmonic (603.372-643.031 Hz)
Phase (degrees)
Frequency (Hz)
Amplitude
Time (seconds)

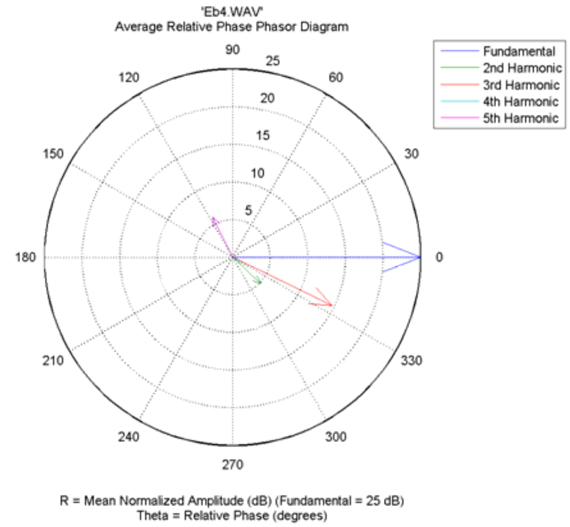

'Eb4.WAV': Fitted Phase vs. Time(left), Frequency vs. Time(middle), Amplitude vs. Time(right)
Fundamental (286.106-337.095 Hz)
2nd Harmonic (603.372-643.031 Hz)
Phase (degrees)
Frequency (Hz)
Amplitude
Time (seconds)

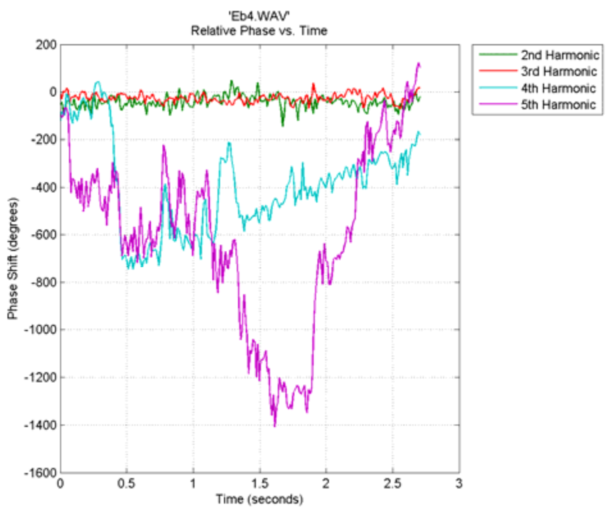

'Eb4.WAV'
Frequency vs. Time
Fundamental
2nd Harmonic
3rd Harmonic
4th Harmonic
5th Harmonic
Frequency (Hz)
Time (seconds)

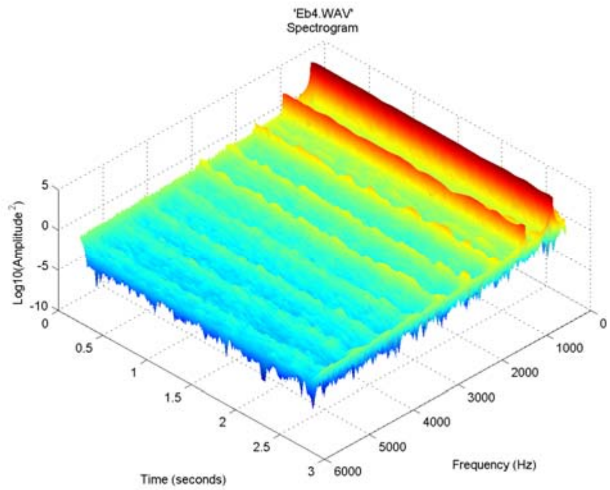

Click on start and end point for each harmonic
Frequency (Hz)

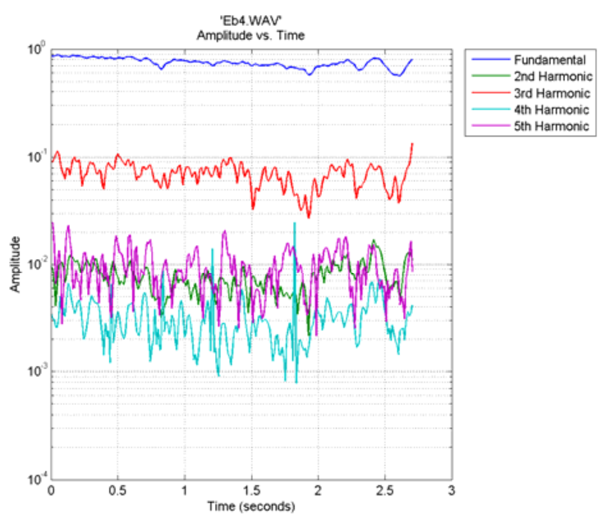

'Eb4.WAV'
Harmonic Amplitudes
Mean Normalized Amplitude (dB) (Fundamental = 25 dB)
Harmonic


'Eb4.WAV'
Absolute Phase vs. Time
Phase (degrees)
Time (seconds)
Fundamental
2nd Harmonic
3rd Harmonic
4th Harmonic
5th Harmonic

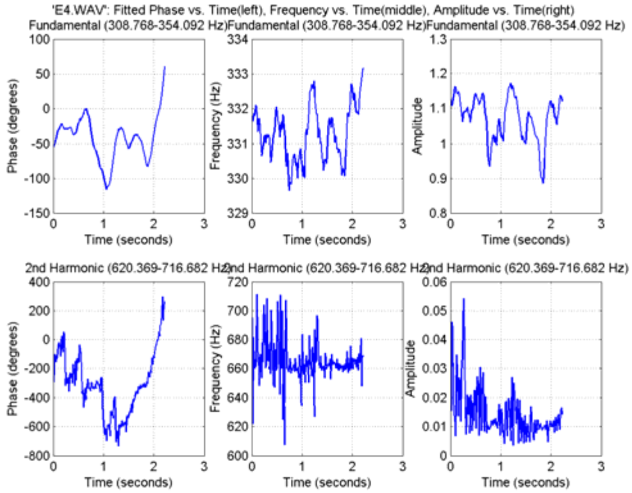

'Eb4.WAV'
Average Relative Phase Phasor Diagram
Fundamental
2nd Harmonic
3rd Harmonic
4th Harmonic
5th Harmonic
R = Mean Normalized Amplitude (dB) (Fundamental = 25 dB)
Theta = Relative Phase (degrees)

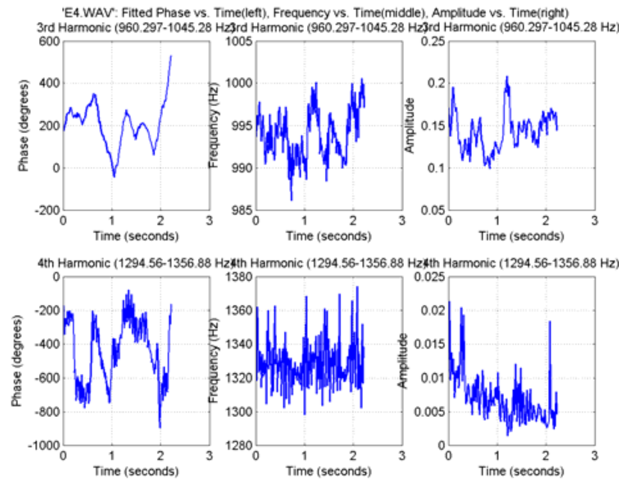

'Eb4.WAV'
Relative Phase vs. Time
Phase Shift (degrees)
Time (seconds)
2nd Harmonic
3rd Harmonic
4th Harmonic
5th Harmonic

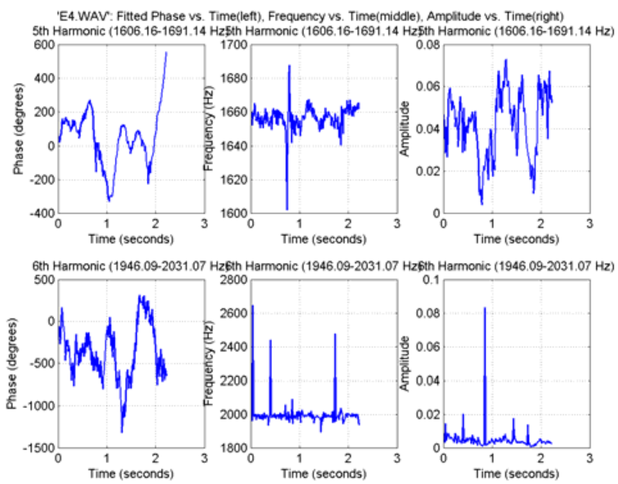

'Eb4.WAV'
Spectrogram
Log10(Amplitude^2)
Time (seconds)
Frequency (Hz)

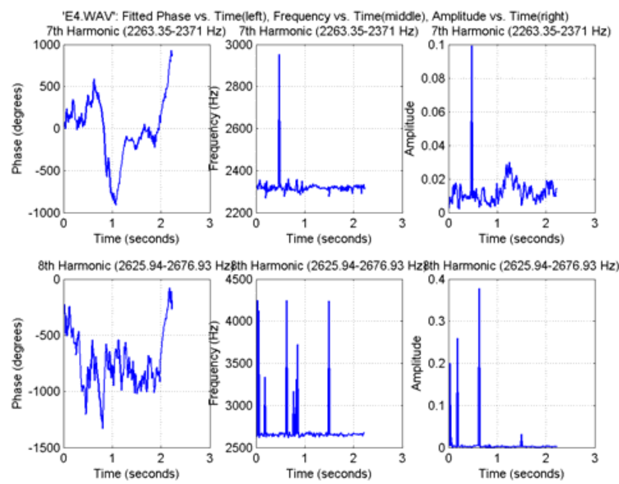

'Eb4.WAV'
Amplitude vs. Time
Amplitude
Time (seconds)
Fundamental
2nd Harmonic
3rd Harmonic
4th Harmonic
5th Harmonic

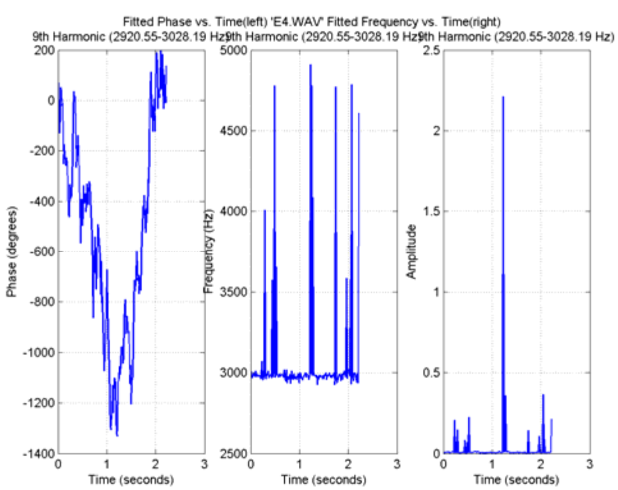
E4

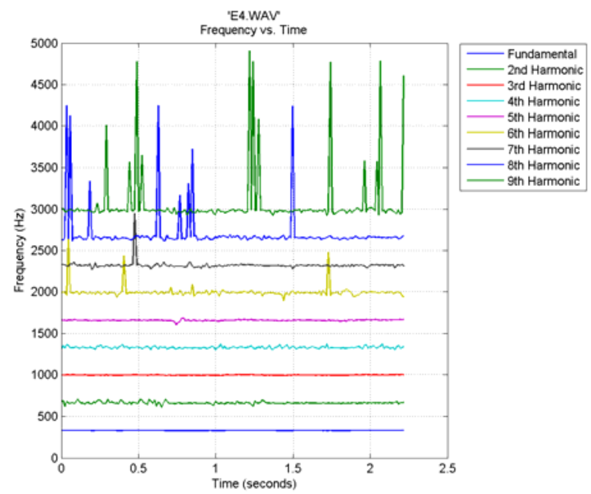

'E4.WAV': Fitted Phase vs. Time(left), Frequency vs. Time(middle), Amplitude vs. Time(right)
Fundamental (308.768-354.092 Hz)
2nd Harmonic (620.369-716.682 Hz)
Phase (degrees)
Frequency (Hz)
Amplitude
Time (seconds)

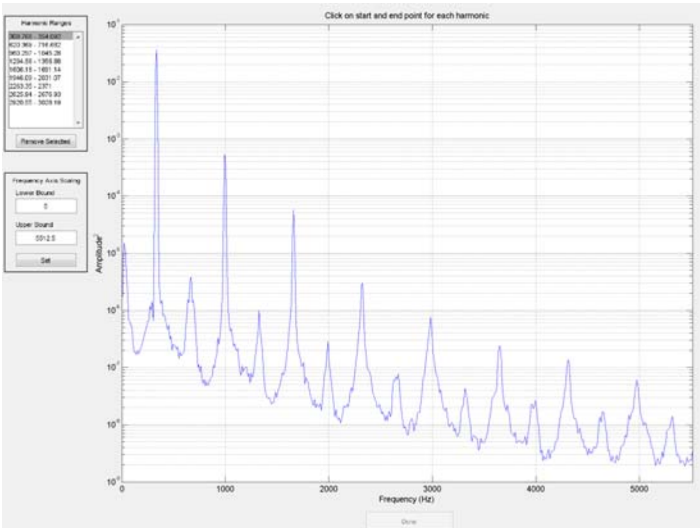

'E4.WAV': Fitted Phase vs. Time(left), Frequency vs. Time(middle), Amplitude vs. Time(right)
3rd Harmonic (960.297-1045.28 Hz)
4th Harmonic (1294.56-1356.88 Hz)
Phase (degrees)
Frequency (Hz)
Amplitude
Time (seconds)

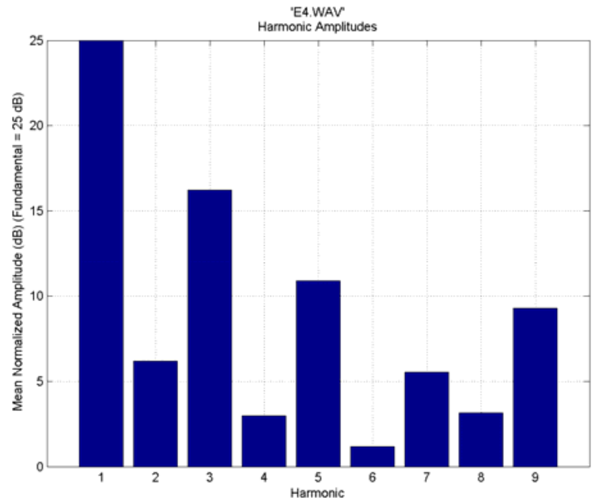

'E4.WAV': Fitted Phase vs. Time(left), Frequency vs. Time(middle), Amplitude vs. Time(right)
5th Harmonic (1606.16-1691.14 Hz)
6th Harmonic (1946.09-2031.07 Hz)
Phase (degrees)
Frequency (Hz)
Amplitude
Time (seconds)

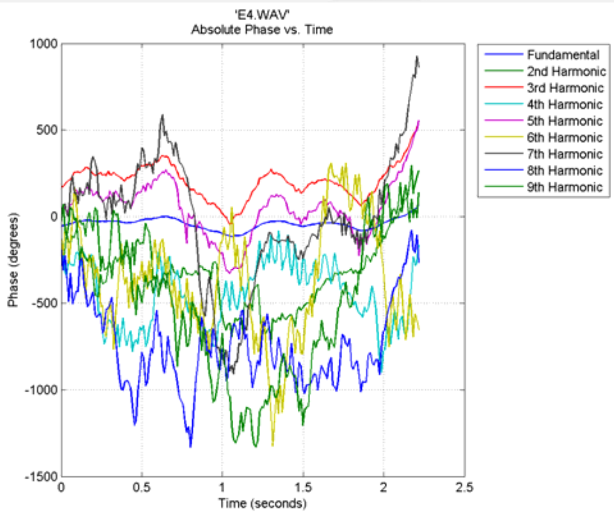

'E4.WAV': Fitted Phase vs. Time(left), Frequency vs. Time(middle), Amplitude vs. Time(right)
7th Harmonic (2263.35-2371 Hz)
8th Harmonic (2625.94-2676.93 Hz)
Phase (degrees)
Frequency (Hz)
Amplitude
Time (seconds)

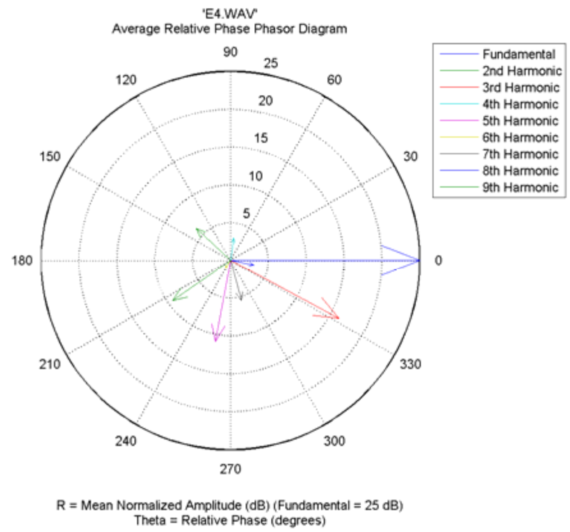

Fitted Phase vs. Time(left) 'E4.WAV' Fitted Frequency vs. Time(right)
9th Harmonic (2920.55-3028.19 Hz)
Phase (degrees)
Frequency (Hz)
Amplitude
Time (seconds)

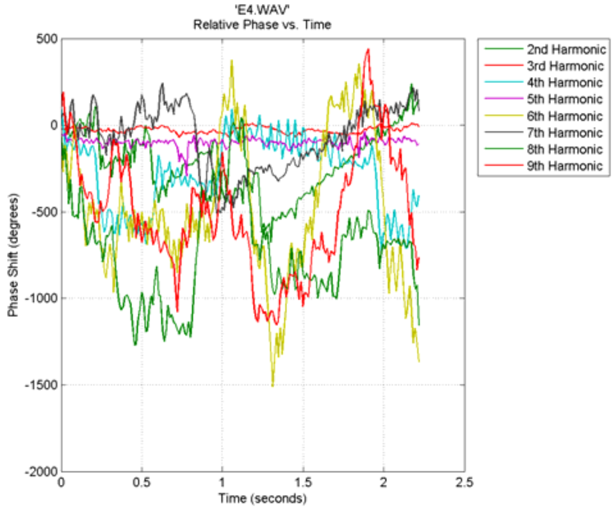

'E4.WAV'
Frequency vs. Time
Frequency (Hz)
Time (seconds)
Fundamental
2nd Harmonic
3rd Harmonic
4th Harmonic
5th Harmonic
6th Harmonic
7th Harmonic
8th Harmonic
9th Harmonic

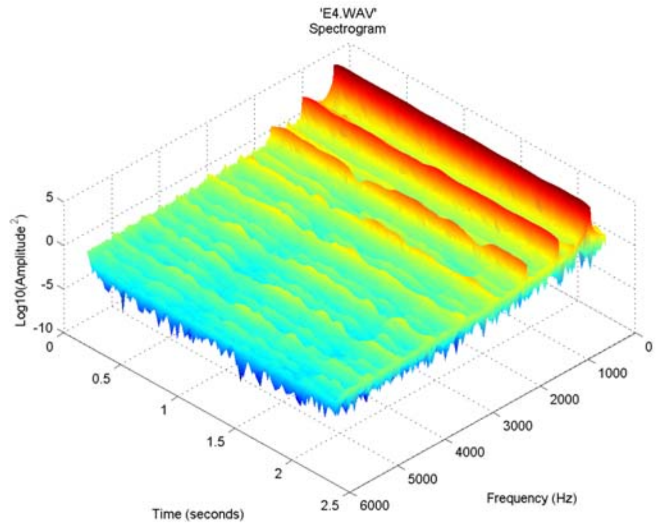

Click on start and end point for each harmonic
Frequency (Hz)
0
1000
2000
3000
4000
5000

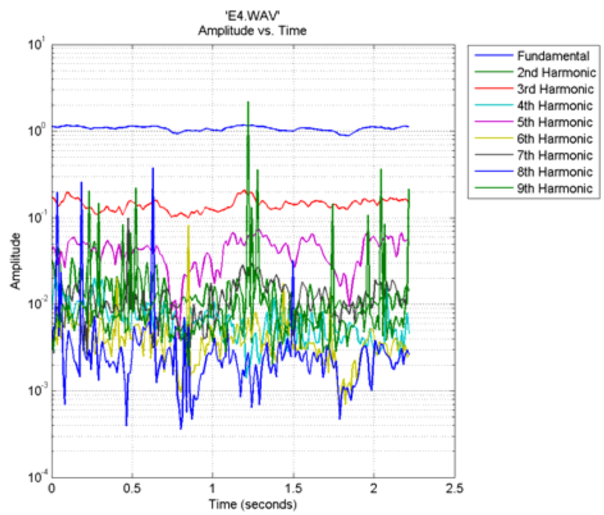

'E4.WAV'
Harmonic Amplitudes
Mean Normalized Amplitude (dB) (Fundamental = 25 dB)
Harmonic


'E4.WAV'
Absolute Phase vs. Time
Phase (degrees)
Time (seconds)
Fundamental
2nd Harmonic
3rd Harmonic
4th Harmonic
5th Harmonic
6th Harmonic
7th Harmonic
8th Harmonic
9th Harmonic

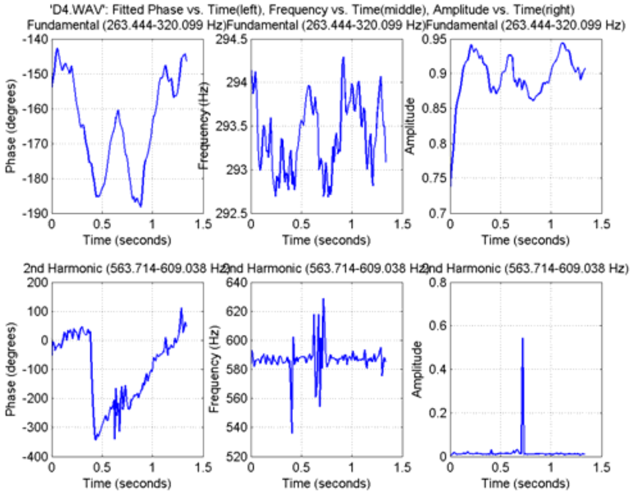

'E4.WAV'
Average Relative Phase Phasor Diagram
Fundamental
2nd Harmonic
3rd Harmonic
4th Harmonic
5th Harmonic
6th Harmonic
7th Harmonic
8th Harmonic
9th Harmonic
R = Mean Normalized Amplitude (dB) (Fundamental = 25 dB)
Theta = Relative Phase (degrees)

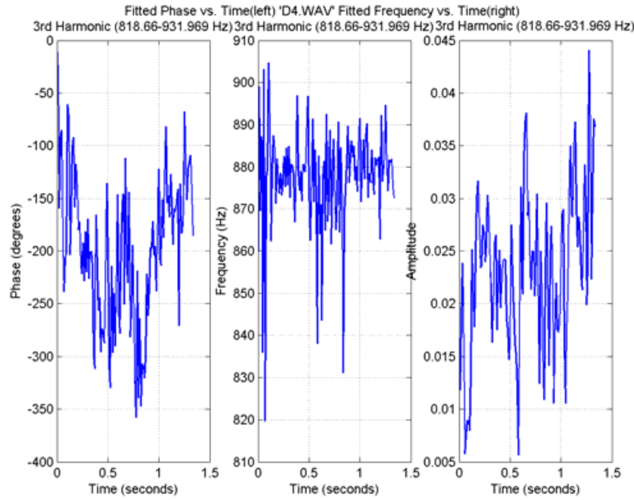

'E4.WAV'
Relative Phase vs. Time
Phase Shift (degrees)
Time (seconds)
2nd Harmonic
3rd Harmonic
4th Harmonic
5th Harmonic
6th Harmonic
7th Harmonic
8th Harmonic
9th Harmonic

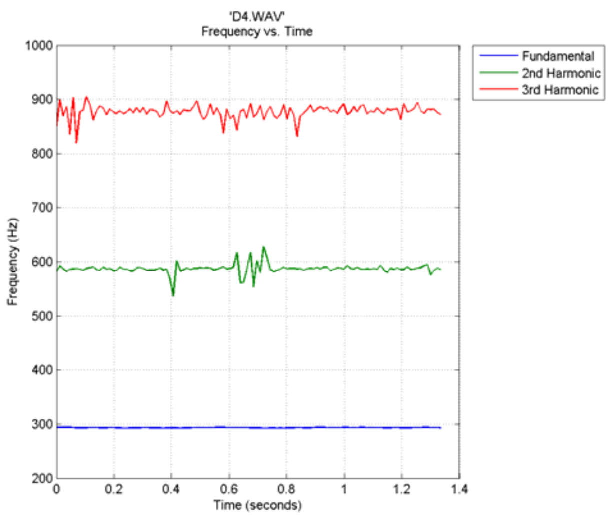

'E4.WAV'
Spectrogram
Log10(Amplitude²)
Time (seconds)
Frequency (Hz)

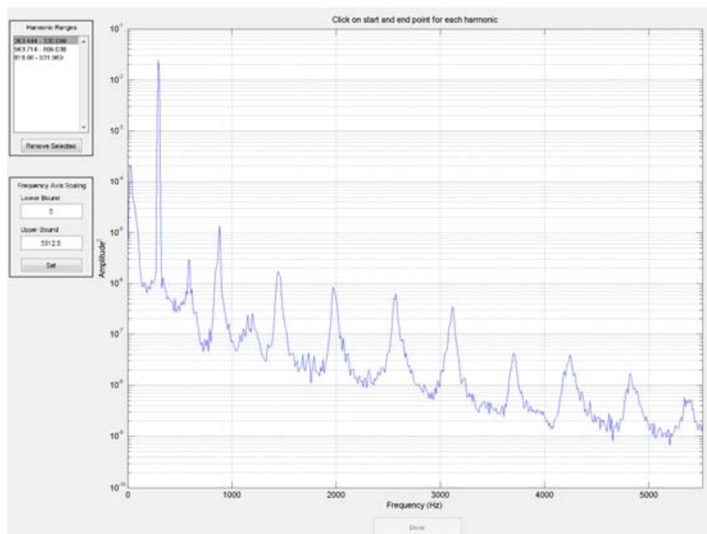

'E4.WAV'
Amplitude vs. Time
Amplitude
Time (seconds)
Fundamental
2nd Harmonic
3rd Harmonic
4th Harmonic
5th Harmonic
6th Harmonic
7th Harmonic
8th Harmonic
9th Harmonic

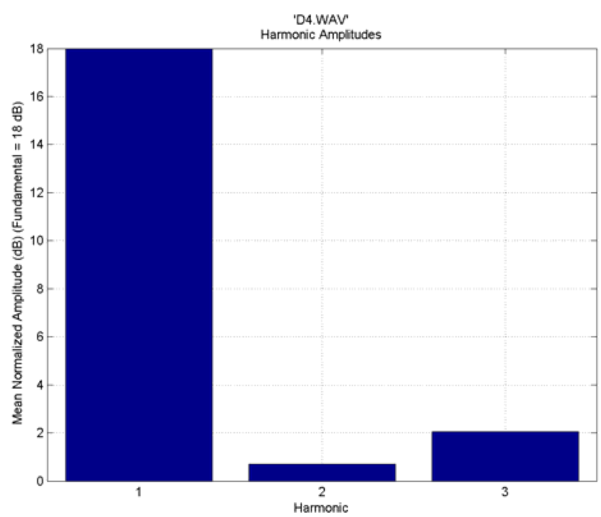
D4

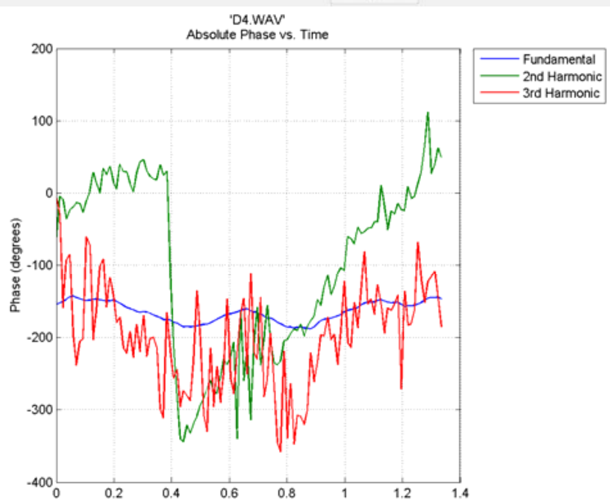

'D4.WAV': Fitted Phase vs. Time(left), Frequency vs. Time(middle), Amplitude vs. Time(right)
Fundamental (263.444-320.099 Hz)
2nd Harmonic (563.714-609.038 Hz)
Phase (degrees)
Frequency (Hz)
Amplitude
Time (seconds)

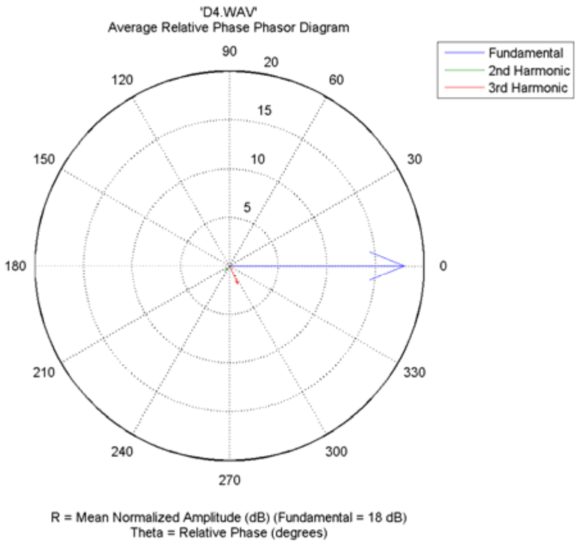

Fitted Phase vs. Time(left) 'D4.WAV' Fitted Frequency vs. Time(right)
3rd Harmonic (818.66-931.969 Hz)
Phase (degrees)
Frequency (Hz)
Amplitude
Time (seconds)

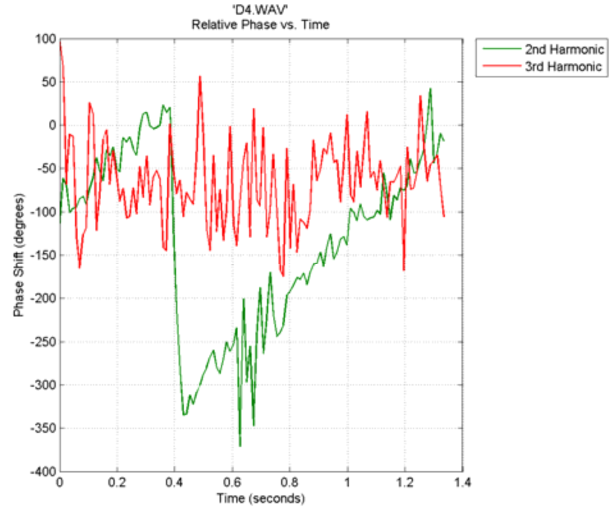

'D4.WAV'
Frequency vs. Time
Fundamental
2nd Harmonic
3rd Harmonic
Frequency (Hz)
Time (seconds)

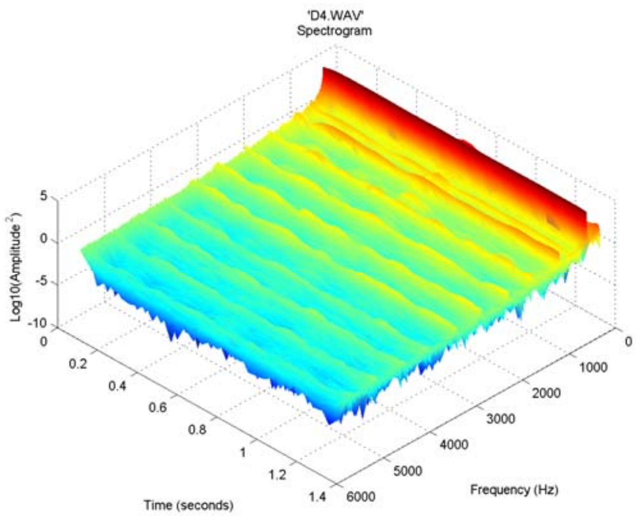

Click on start and end point for each harmonic
Amplitude
Frequency (Hz)

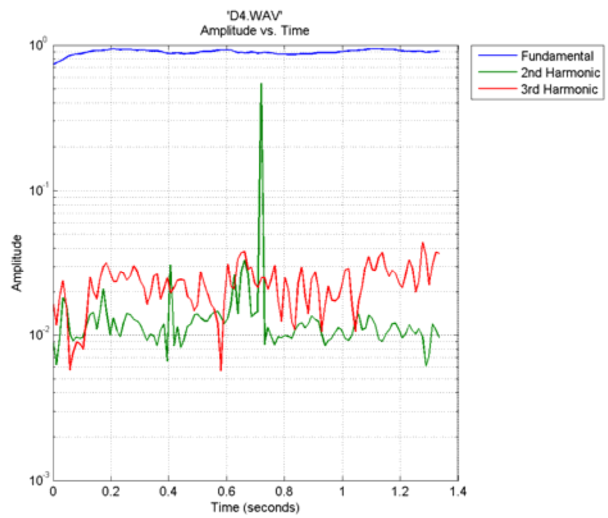

'D4.WAV'
Harmonic Amplitudes
Mean Normalized Amplitude (dB) (Fundamental = 18 dB)
Harmonic


'D4.WAV'
Absolute Phase vs. Time
Fundamental
2nd Harmonic
3rd Harmonic
Phase (degrees)
Time (seconds)

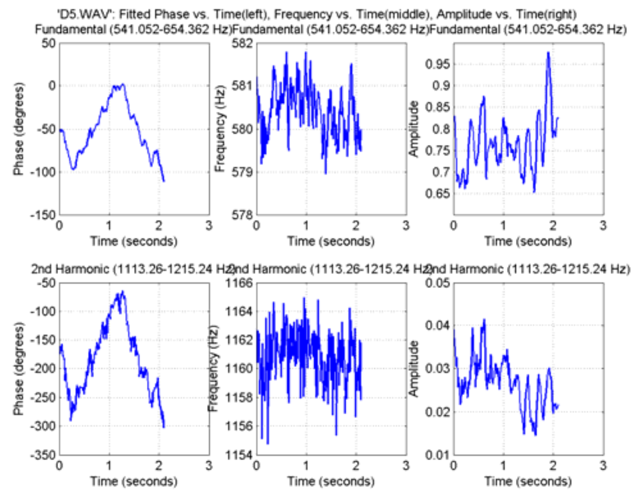

'D4.WAV'
Average Relative Phase Phasor Diagram
Fundamental
2nd Harmonic
3rd Harmonic
R = Mean Normalized Amplitude (dB) (Fundamental = 18 dB)
Theta = Relative Phase (degrees)


'D4.WAV'
Relative Phase vs. Time
2nd Harmonic
3rd Harmonic
Phase Shift (degrees)
Time (seconds)

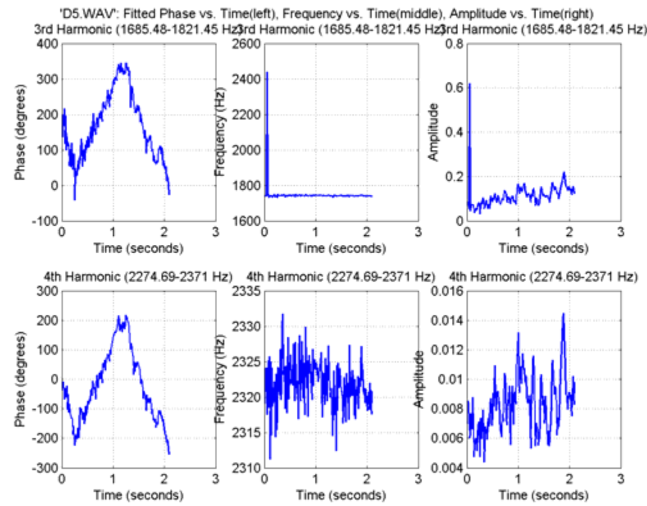

'D4.WAV'
Spectrogram
Log10(Amplitude^2)
Time (seconds)
Frequency (Hz)


'D4.WAV'
Amplitude vs. Time
Fundamental
2nd Harmonic
3rd Harmonic
Amplitude
Time (seconds)

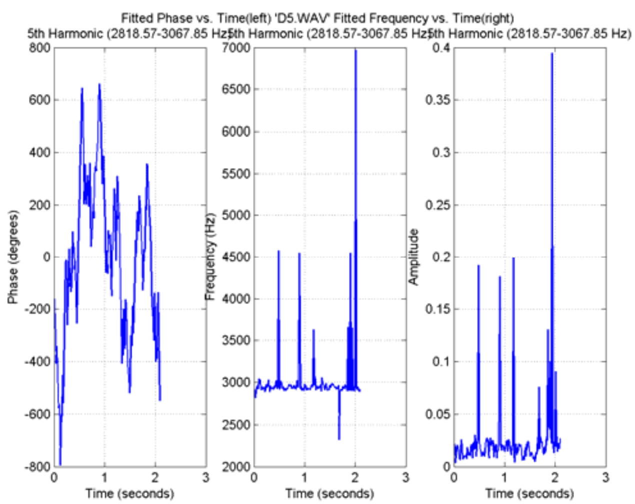
D5



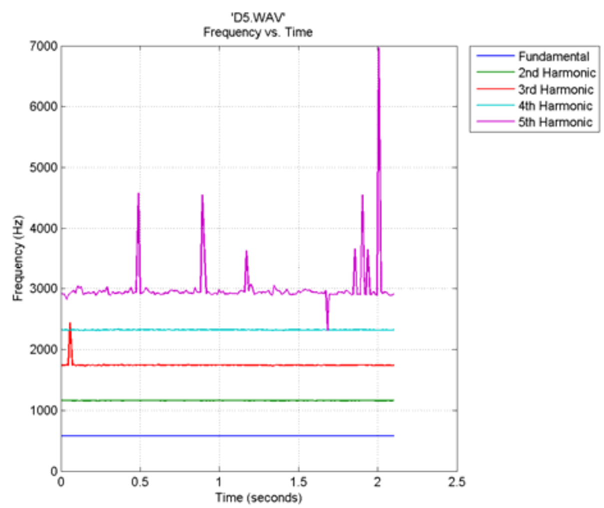
'D5.WAV': Fitted Phase vs. Time(left), Frequency vs. Time(middle), Amplitude vs. Time(right)
Fundamental (541.052-654.362 Hz)
Fundamental (541.052-654.362 Hz)
Fundamental (541.052-654.362 Hz)
2nd Harmonic (1113.26-1215.24 Hz)
2nd Harmonic (1113.26-1215.24 Hz)
2nd Harmonic (1113.26-1215.24 Hz)
Phase (degrees)
Frequency (Hz)
Amplitude
Time (seconds)



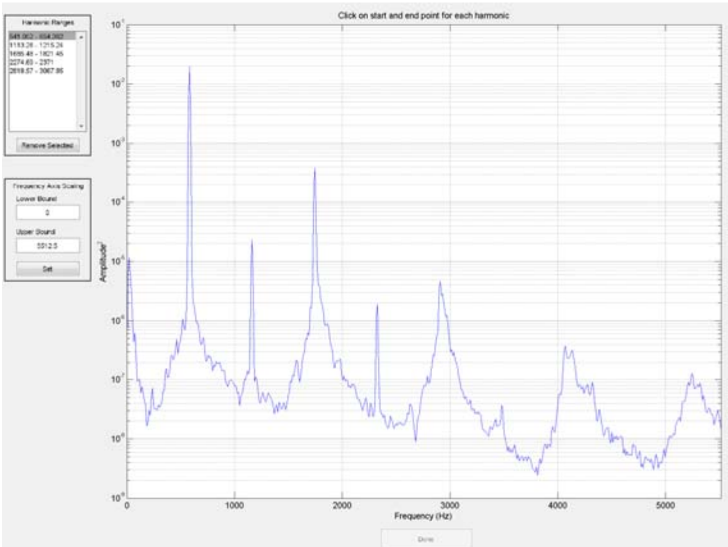
'D5.WAV': Fitted Phase vs. Time(left), Frequency vs. Time(middle), Amplitude vs. Time(right)
3rd Harmonic (1685.48-1821.45 Hz)
3rd Harmonic (1685.48-1821.45 Hz)
3rd Harmonic (1685.48-1821.45 Hz)
4th Harmonic (2274.69-2371 Hz)
4th Harmonic (2274.69-2371 Hz)
4th Harmonic (2274.69-2371 Hz)
Phase (degrees)
Frequency (Hz)
Amplitude
Time (seconds)

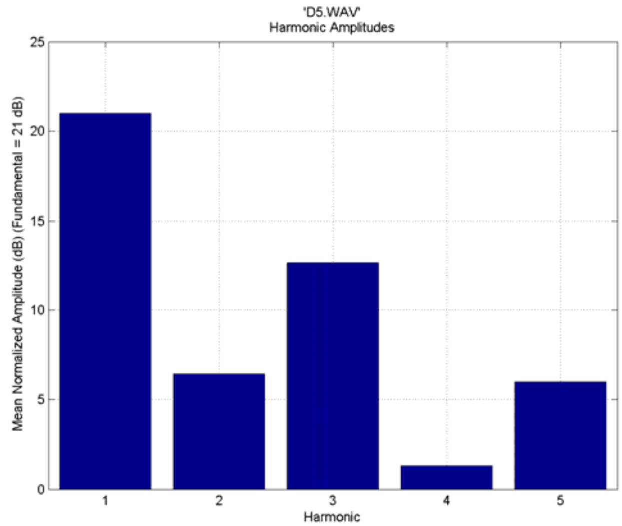


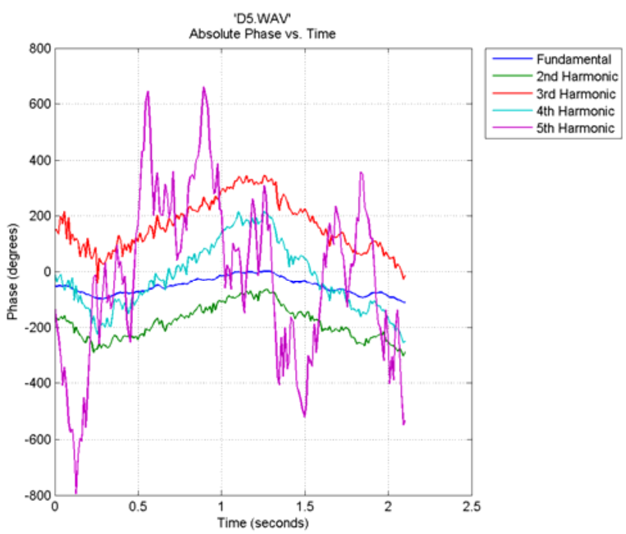
Fitted Phase vs. Time(left) 'D5.WAV' Fitted Frequency vs. Time(right)
5th Harmonic (2818.57-3067.85 Hz)
5th Harmonic (2818.57-3067.85 Hz)
5th Harmonic (2818.57-3067.85 Hz)
Phase (degrees)
Frequency (Hz)
Amplitude
Time (seconds)

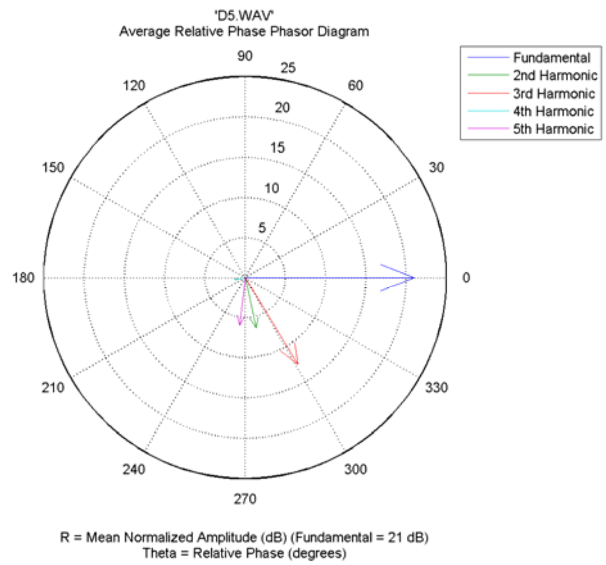


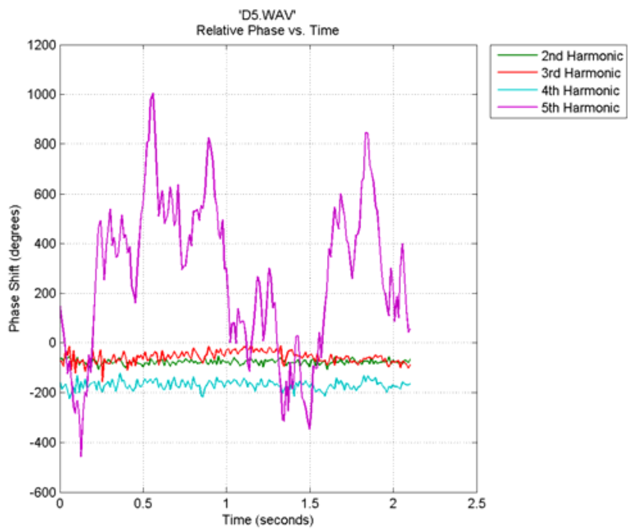
'D5.WAV'
Frequency vs. Time
Fundamental
2nd Harmonic
3rd Harmonic
4th Harmonic
5th Harmonic
Frequency (Hz)
Time (seconds)

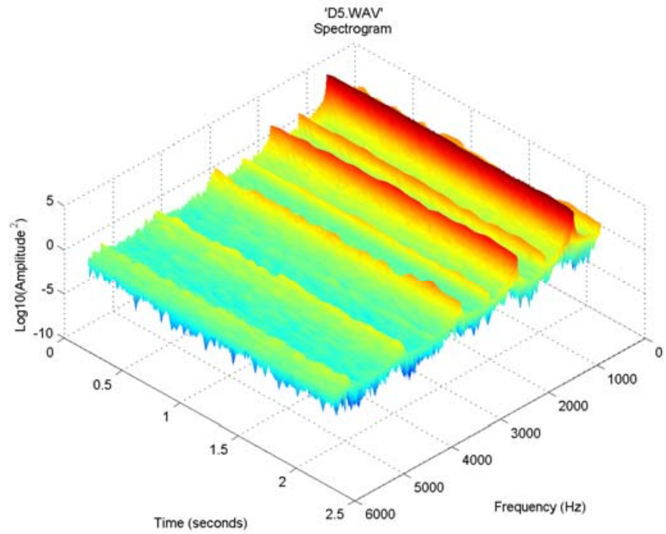

Click on start and end point for each harmonic
Frequency (Hz)
0
1000
2000
3000
4000
5000

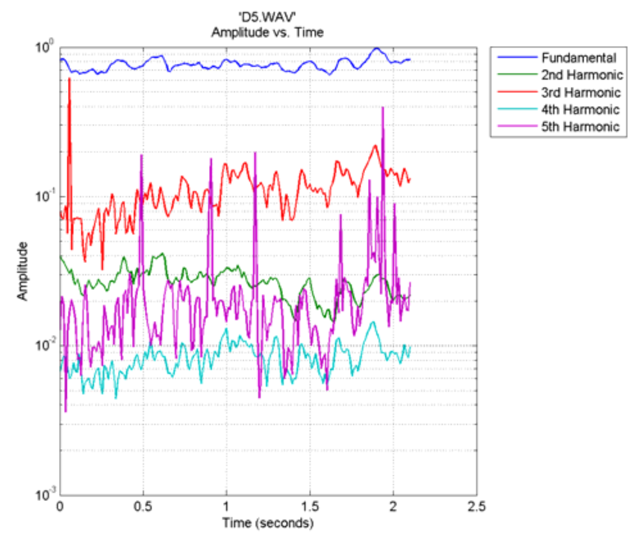

'D5.WAV'
Harmonic Amplitudes
Mean Normalized Amplitude (dB) (Fundamental = 21 dB)
Harmonic
0
5
10
15
20
25
1
2
3
4
5


'D5.WAV'
Absolute Phase vs. Time
Phase (degrees)
Time (seconds)
Fundamental
2nd Harmonic
3rd Harmonic
4th Harmonic
5th Harmonic
800
600
400
200
0
-200
-400
-600
-800
0
0.5
1
1.5
2
2.5

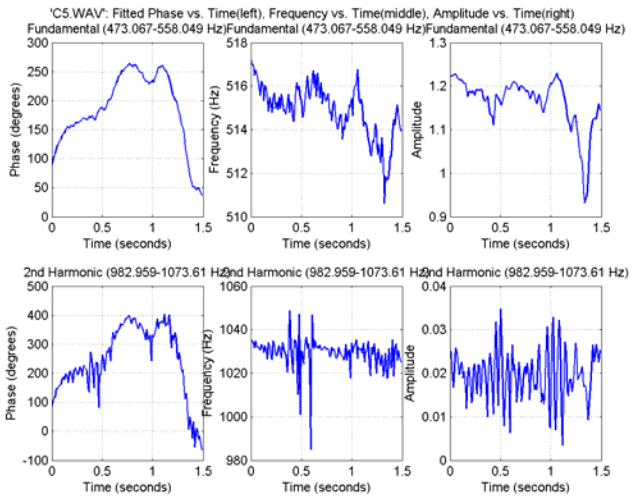

'D5.WAV'
Average Relative Phase Phasor Diagram
Fundamental
2nd Harmonic
3rd Harmonic
4th Harmonic
5th Harmonic
90
60
30
0
330
300
270
240
210
180
150
120
5
10
15
20
25
R = Mean Normalized Amplitude (dB) (Fundamental = 21 dB)
Theta = Relative Phase (degrees)

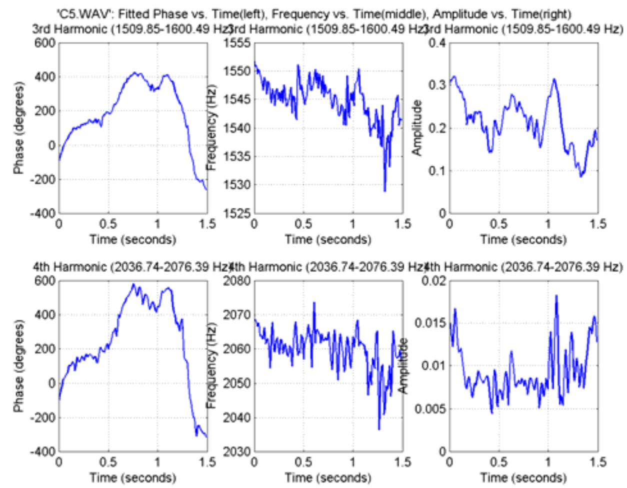

'D5.WAV'
Relative Phase vs. Time
Phase Shift (degrees)
Time (seconds)
2nd Harmonic
3rd Harmonic
4th Harmonic
5th Harmonic

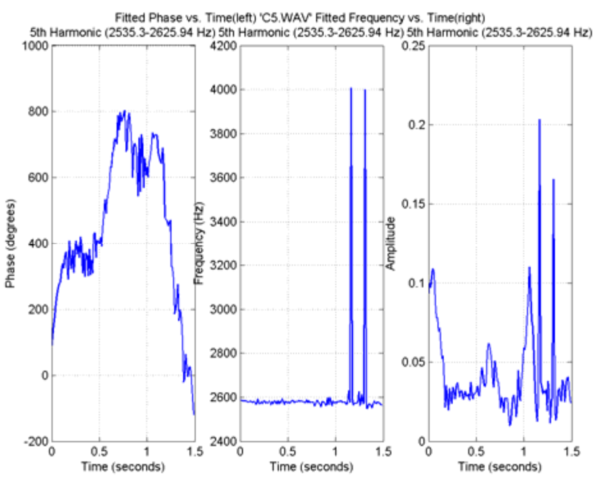

'D5.WAV'
Spectrogram
Log10(Amplitude^2)
Time (seconds)
Frequency (Hz)

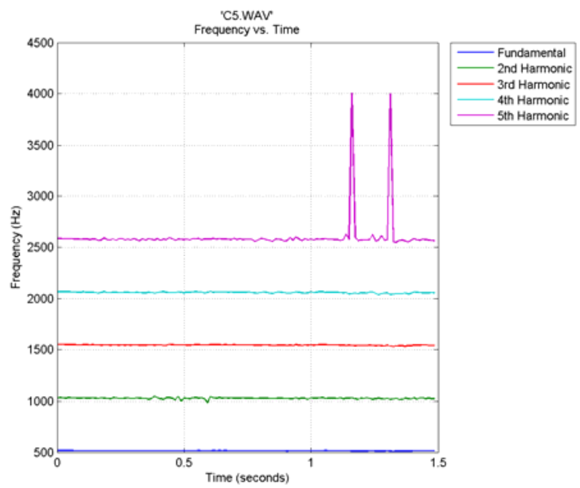

'D5.WAV'
Amplitude vs. Time
Amplitude
Time (seconds)
Fundamental
2nd Harmonic
3rd Harmonic
4th Harmonic
5th Harmonic

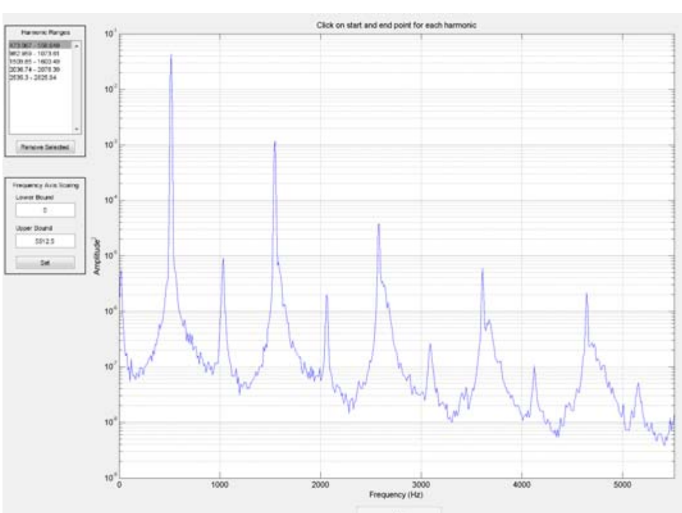
C5

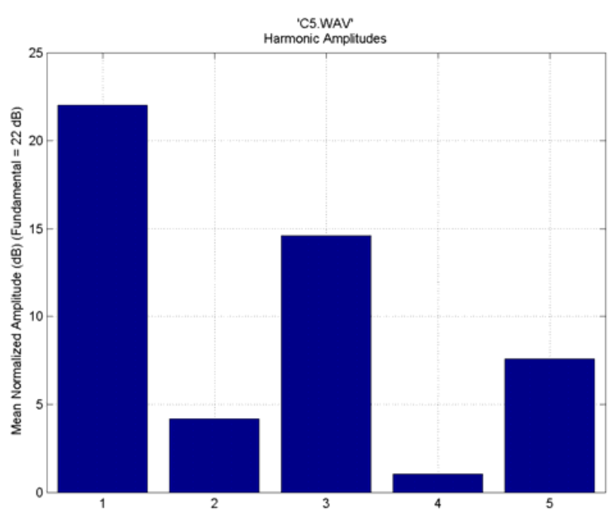

'C5.WAV': Fitted Phase vs. Time(left), Frequency vs. Time(middle), Amplitude vs. Time(right)
Fundamental (473.067-558.049 Hz)
2nd Harmonic (982.959-1073.61 Hz)
Phase (degrees)
Frequency (Hz)
Amplitude
Time (seconds)

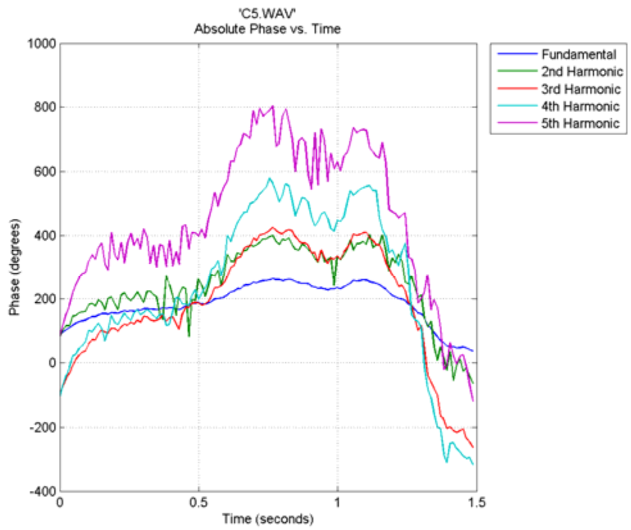

'C5.WAV': Fitted Phase vs. Time(left), Frequency vs. Time(middle), Amplitude vs. Time(right)
3rd Harmonic (1509.85-1600.49 Hz)
4th Harmonic (2036.74-2076.39 Hz)
Phase (degrees)
Frequency (Hz)
Amplitude
Time (seconds)


Fitted Phase vs. Time(left) 'C5.WAV' Fitted Frequency vs. Time(right)
5th Harmonic (2535.3-2625.94 Hz)
Phase (degrees)
Frequency (Hz)
Amplitude
Time (seconds)

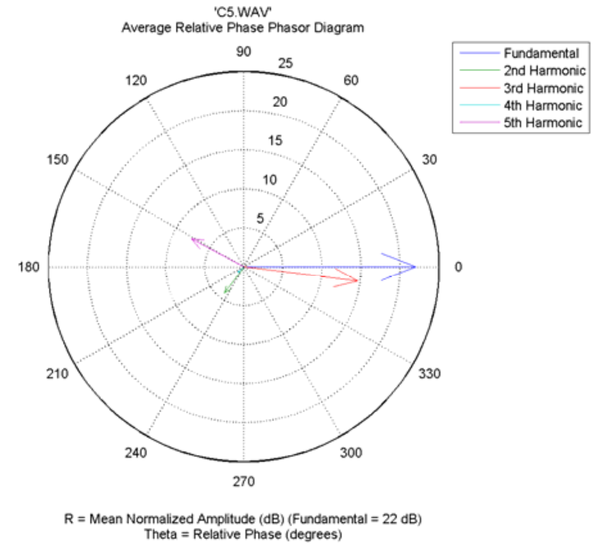

'C5.WAV'
Frequency vs. Time
Fundamental
2nd Harmonic
3rd Harmonic
4th Harmonic
5th Harmonic
Frequency (Hz)
Time (seconds)


Click on start and end point for each harmonic
Frequency (Hz)

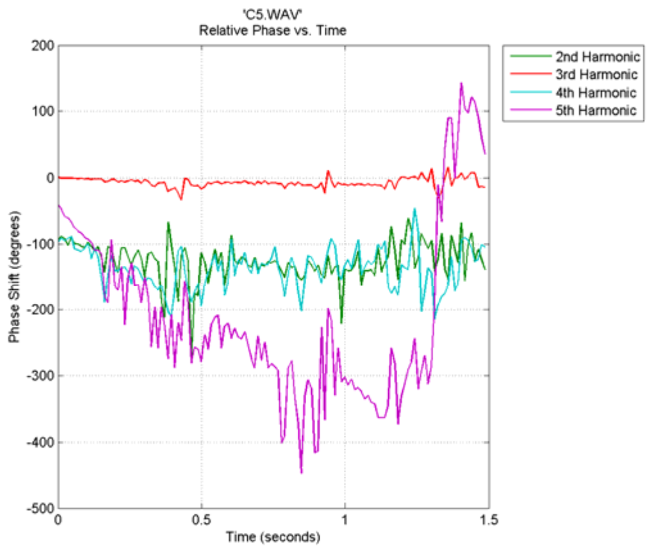

'C5.WAV'
Harmonic Amplitudes
Mean Normalized Amplitude (dB) (Fundamental = 22 dB)
Harmonic



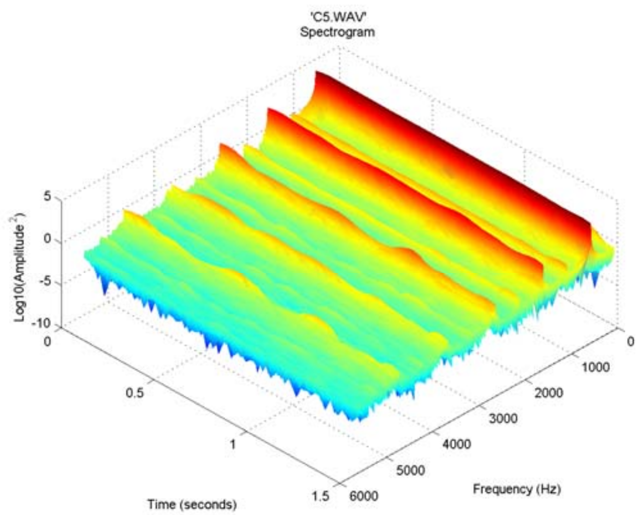
'C5.WAV'
Absolute Phase vs. Time
Phase (degrees)
Time (seconds)
Fundamental
2nd Harmonic
3rd Harmonic
4th Harmonic
5th Harmonic



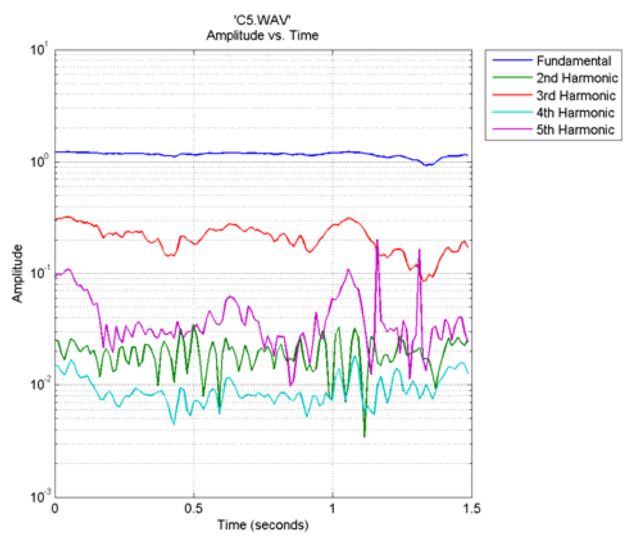
'C5.WAV'
Average Relative Phase Phasor Diagram
Fundamental
2nd Harmonic
3rd Harmonic
4th Harmonic
5th Harmonic
R = Mean Normalized Amplitude (dB) (Fundamental = 22 dB)
Theta = Relative Phase (degrees)



'C5.WAV'
Relative Phase vs. Time
Phase Shift (degrees)
Time (seconds)
2nd Harmonic
3rd Harmonic
4th Harmonic
5th Harmonic

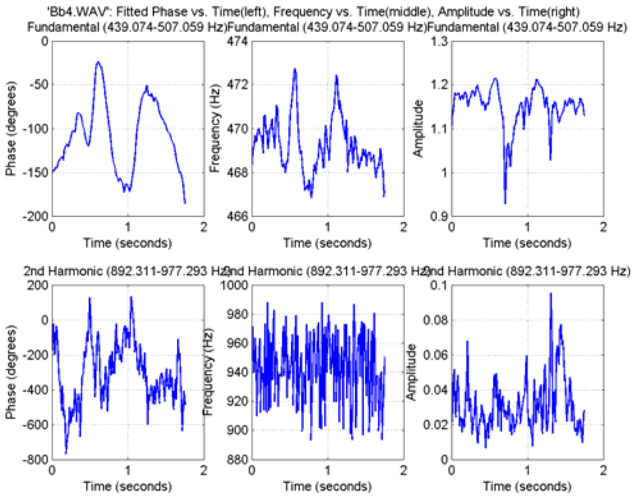


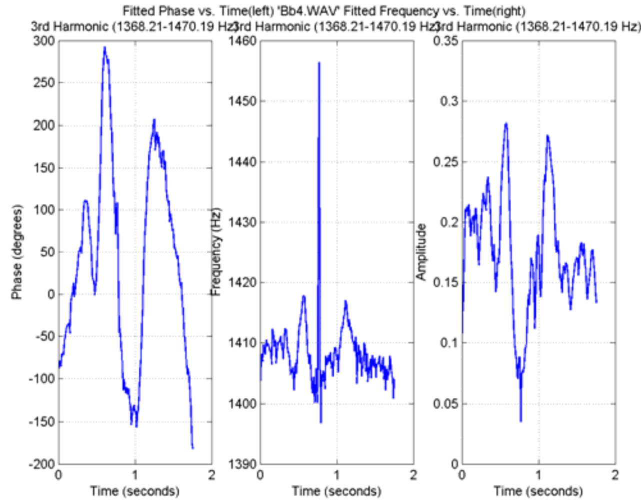
'C5.WAV'
Spectrogram
Log10(Amplitude²)
Time (seconds)
Frequency (Hz)

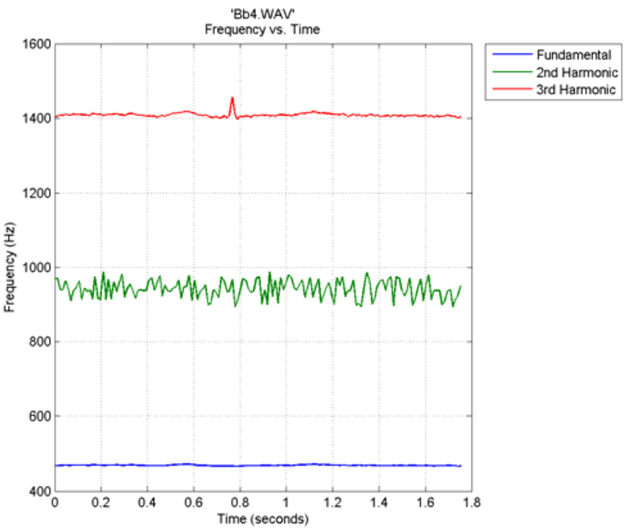


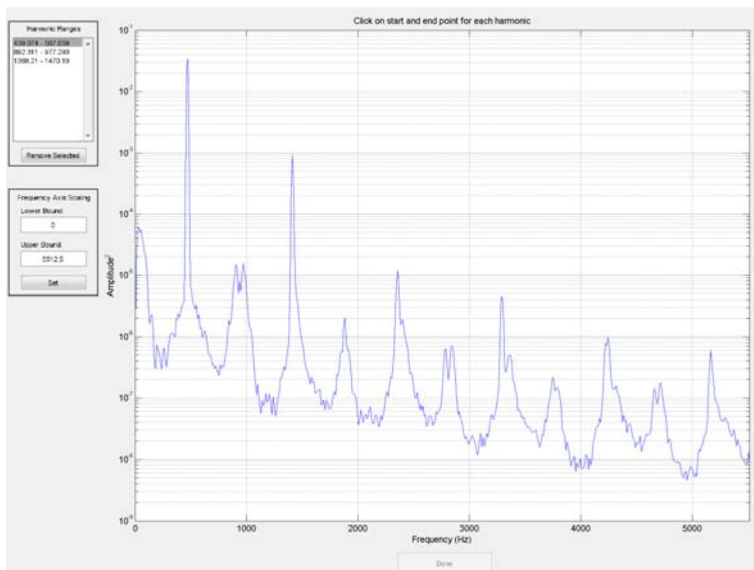
'C5.WAV'
Amplitude vs. Time
Amplitude
Time (seconds)
Fundamental
2nd Harmonic
3rd Harmonic
4th Harmonic
5th Harmonic

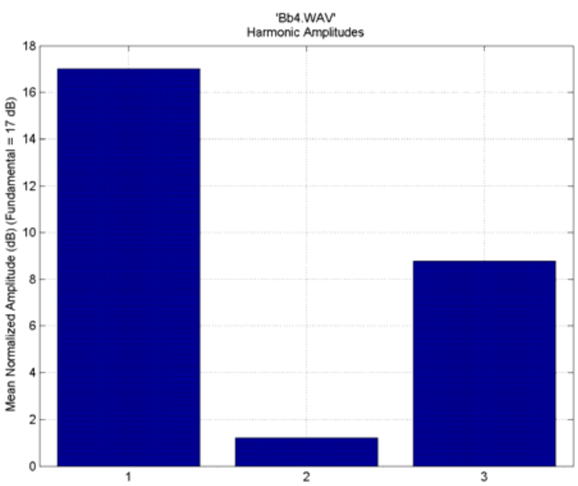
Bb4

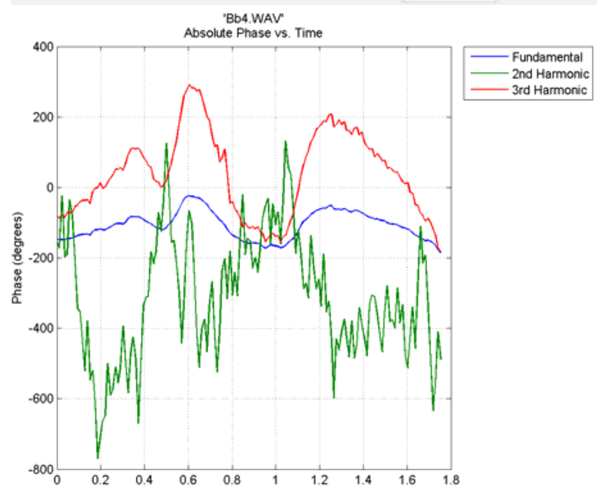

'Bb4.WAV': Fitted Phase vs. Time(left), Frequency vs. Time(middle), Amplitude vs. Time(right)
Fundamental (439.074-507.059 Hz)
2nd Harmonic (892.311-977.293 Hz)
Phase (degrees)
Frequency (Hz)
Amplitude
Time (seconds)

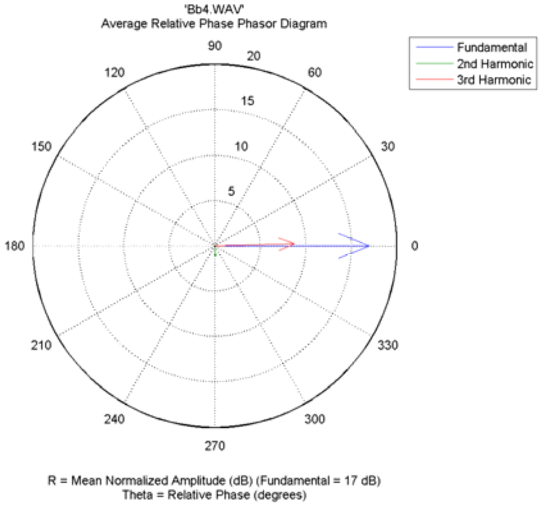

Fitted Phase vs. Time(left) 'Bb4.WAV' Fitted Frequency vs. Time(right)
3rd Harmonic (1368.21-1470.19 Hz)
Phase (degrees)
Frequency (Hz)
Amplitude
Time (seconds)

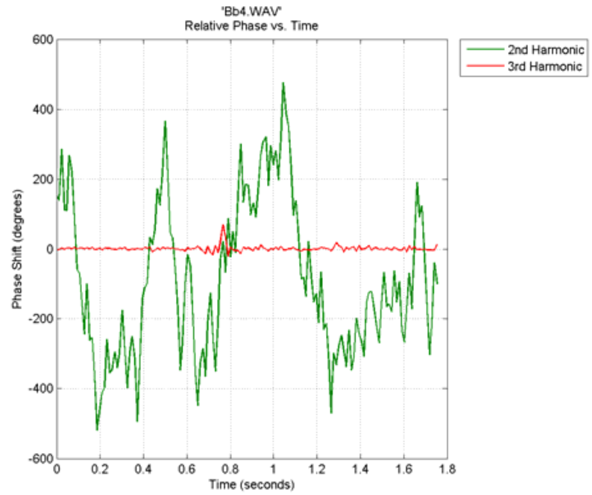

'Bb4.WAV'
Frequency vs. Time
Fundamental
2nd Harmonic
3rd Harmonic
Frequency (Hz)
Time (seconds)

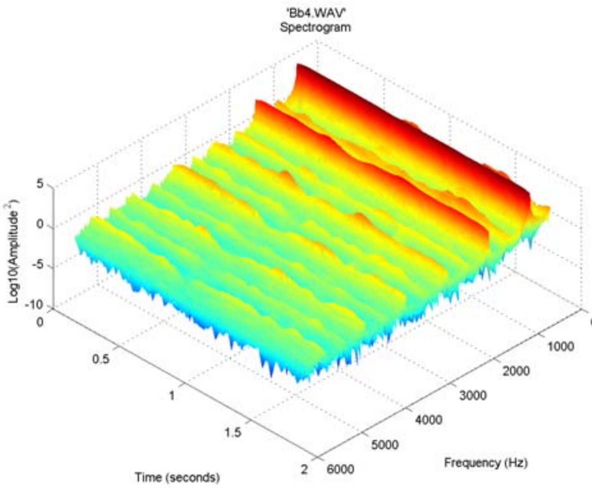

Click on start and end point for each harmonic
Frequency (Hz)

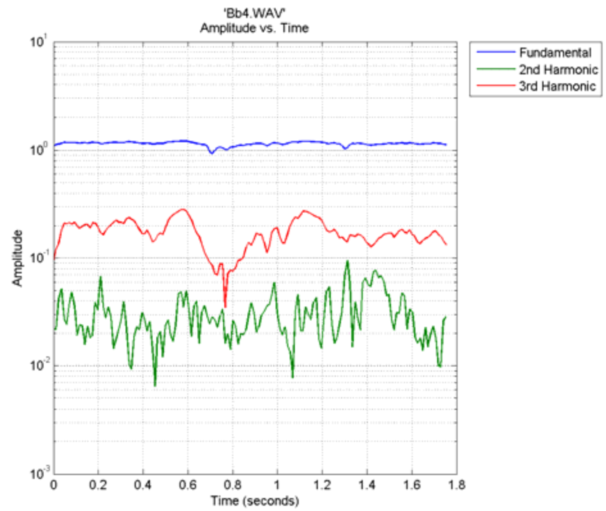

'Bb4.WAV'
Harmonic Amplitudes
Mean Normalized Amplitude (dB) (Fundamental = 17 dB)
Harmonic


'Bb4.WAV'
Absolute Phase vs. Time
Fundamental
2nd Harmonic
3rd Harmonic
Phase (degrees)
Time (seconds)

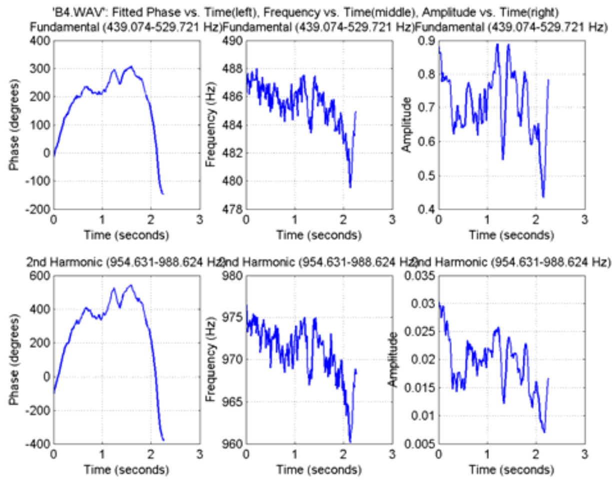

'Bb4.WAV'
Average Relative Phase Phasor Diagram
Fundamental
2nd Harmonic
3rd Harmonic
R = Mean Normalized Amplitude (dB) (Fundamental = 17 dB)
Theta = Relative Phase (degrees)

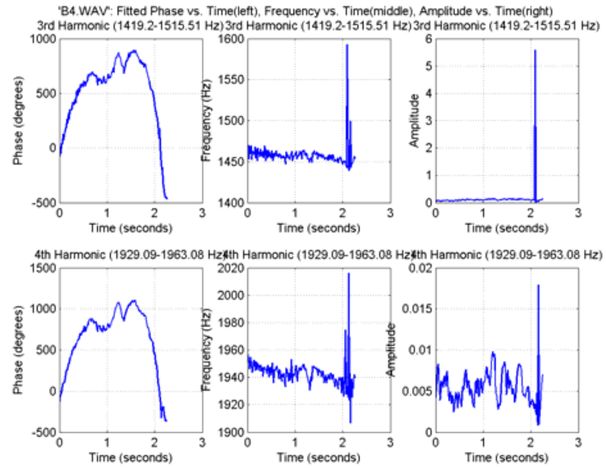

'Bb4.WAV'
Relative Phase vs. Time
2nd Harmonic
3rd Harmonic
Phase Shift (degrees)
Time (seconds)

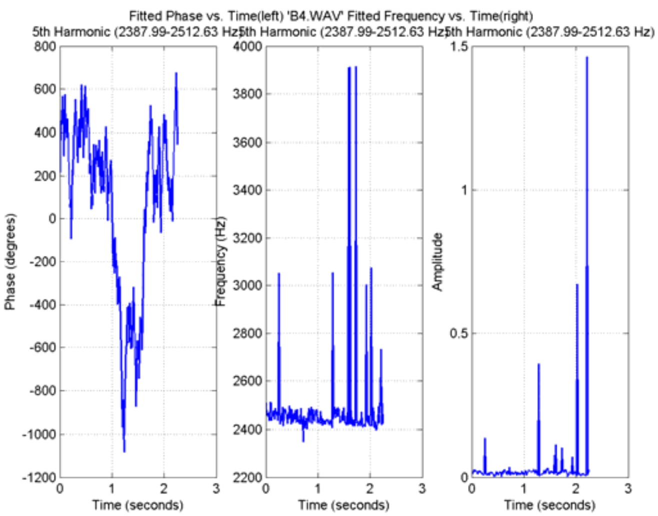

'Bb4.WAV'
Spectrogram
Log10(Amplitude ^{2})
Time (seconds)
Frequency (Hz)

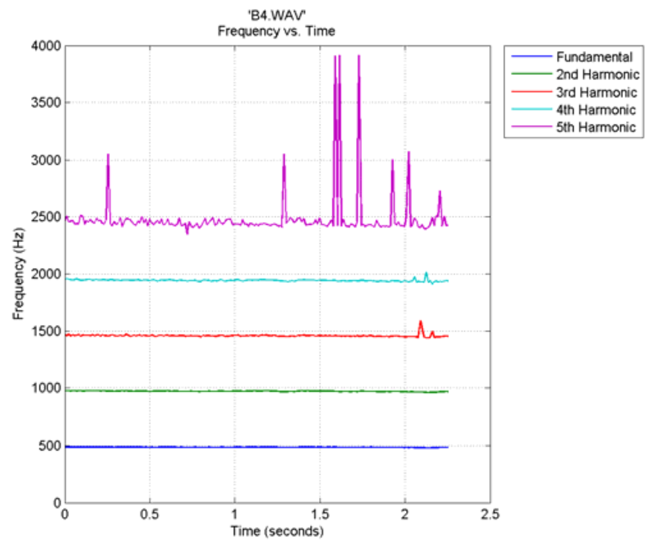

'Bb4.WAV'
Amplitude vs. Time
Fundamental
2nd Harmonic
3rd Harmonic
Amplitude
Time (seconds)

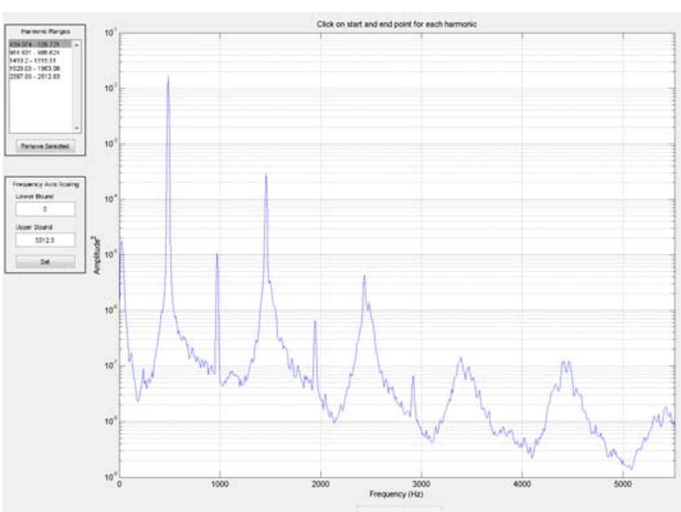
B4

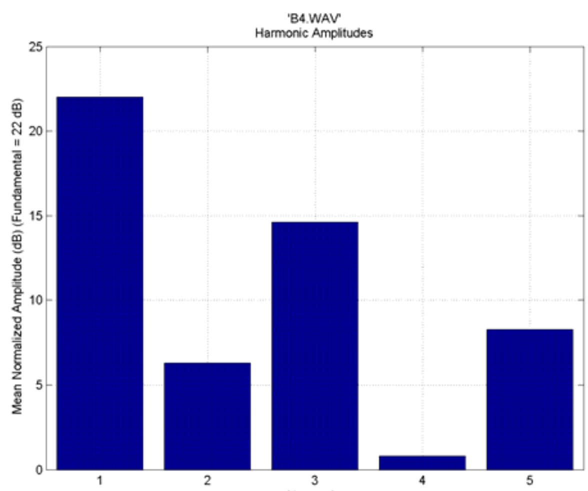

'B4.WAV': Fitted Phase vs. Time(left), Frequency vs. Time(middle), Amplitude vs. Time(right)
Fundamental (439.074-529.721 Hz)
2nd Harmonic (954.631-988.624 Hz)
Phase (degrees)
Frequency (Hz)
Amplitude
Time (seconds)

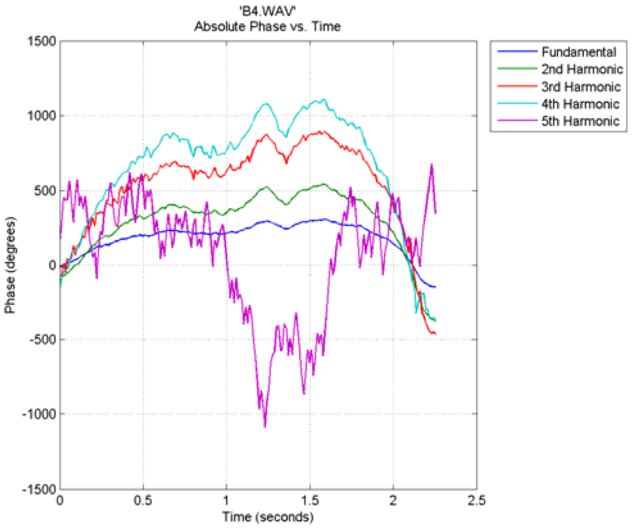

'B4.WAV': Fitted Phase vs. Time(left), Frequency vs. Time(middle), Amplitude vs. Time(right)
3rd Harmonic (1419.2-1515.51 Hz)
4th Harmonic (1929.09-1963.08 Hz)
Phase (degrees)
Frequency (Hz)
Amplitude
Time (seconds)

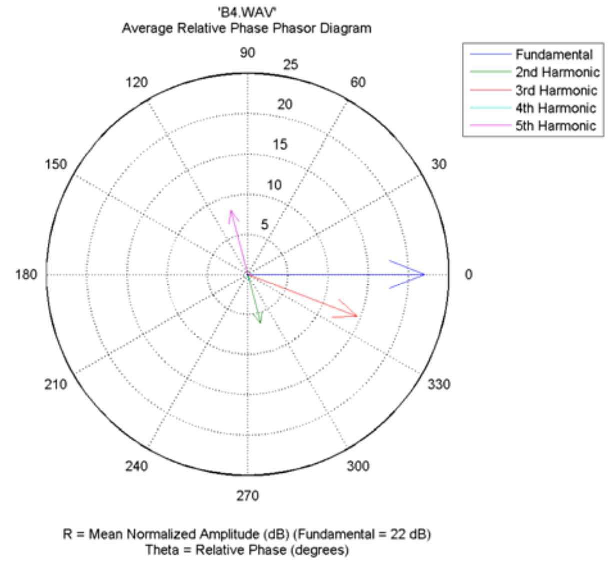

Fitted Phase vs. Time(left) 'B4.WAV' Fitted Frequency vs. Time(right)
5th Harmonic (2387.99-2512.63 Hz)
Phase (degrees)
Frequency (Hz)
Amplitude
Time (seconds)

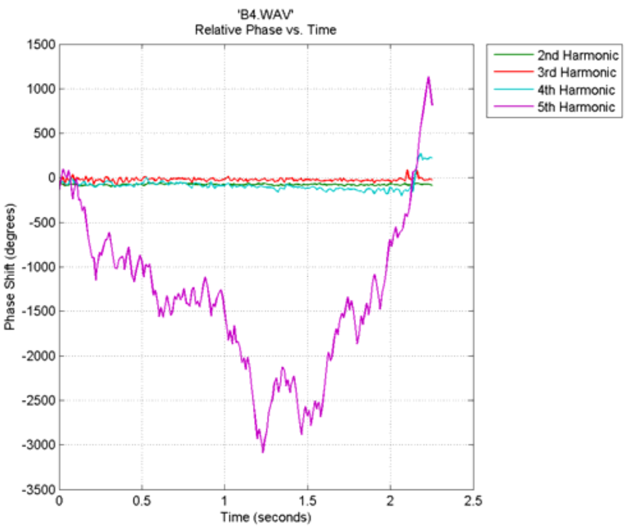

'B4.WAV'
Frequency vs. Time
Fundamental
2nd Harmonic
3rd Harmonic
4th Harmonic
5th Harmonic
Frequency (Hz)
Time (seconds)

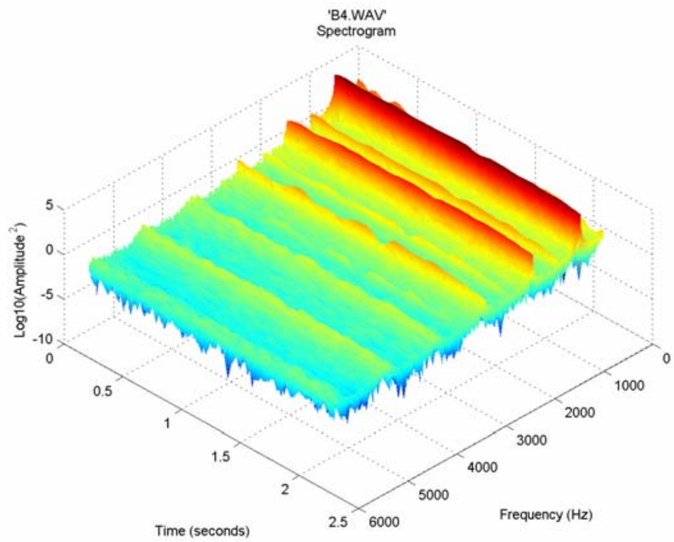

Click on start and end point for each harmonic
Frequency (Hz)

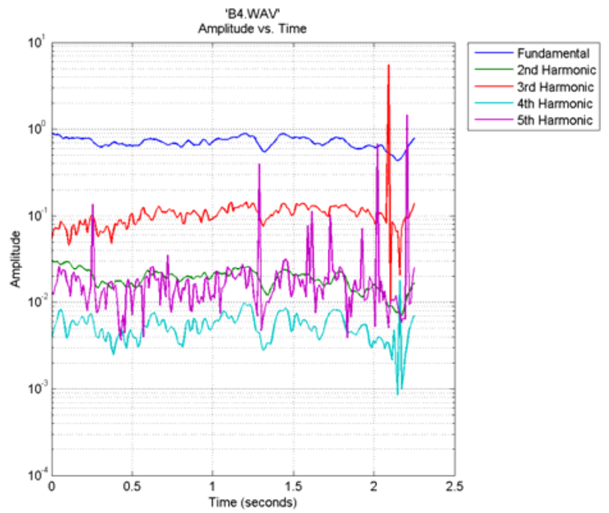

'B4.WAV'
Harmonic Amplitudes
Mean Normalized Amplitude (dB) (Fundamental = 22 dB)
Harmonic


'B4.WAV'
Absolute Phase vs. Time
Fundamental
2nd Harmonic
3rd Harmonic
4th Harmonic
5th Harmonic
Phase (degrees)
Time (seconds)

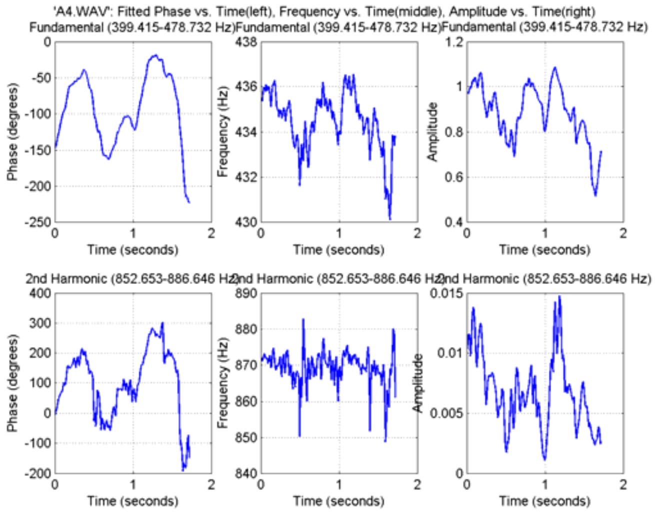

'B4.WAV'
Average Relative Phase Phasor Diagram
Fundamental
2nd Harmonic
3rd Harmonic
4th Harmonic
5th Harmonic
R = Mean Normalized Amplitude (dB) (Fundamental = 22 dB)
Theta = Relative Phase (degrees)

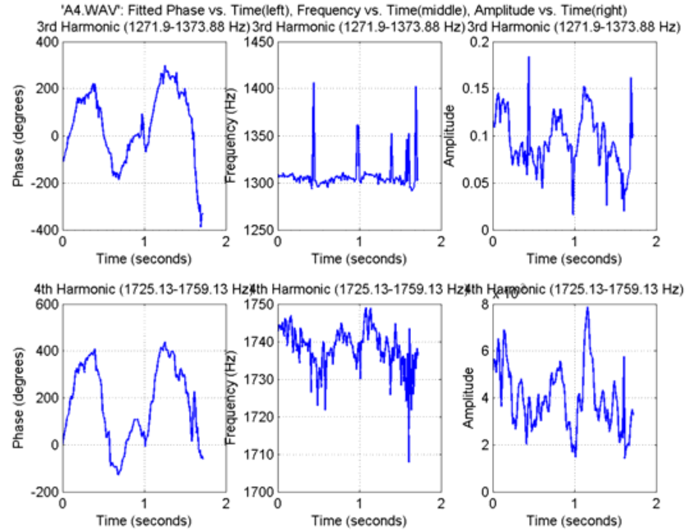

'B4.WAV'
Relative Phase vs. Time
2nd Harmonic
3rd Harmonic
4th Harmonic
5th Harmonic
Phase Shift (degrees)
Time (seconds)

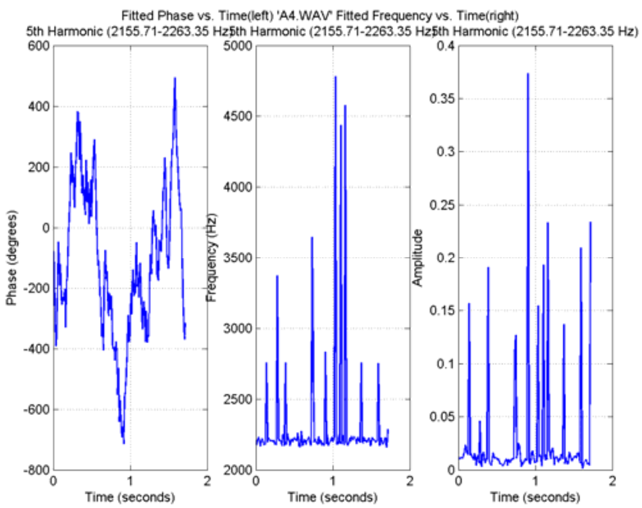

'B4.WAV'
Spectrogram
Log10(Amplitude^2)
Time (seconds)
Frequency (Hz)

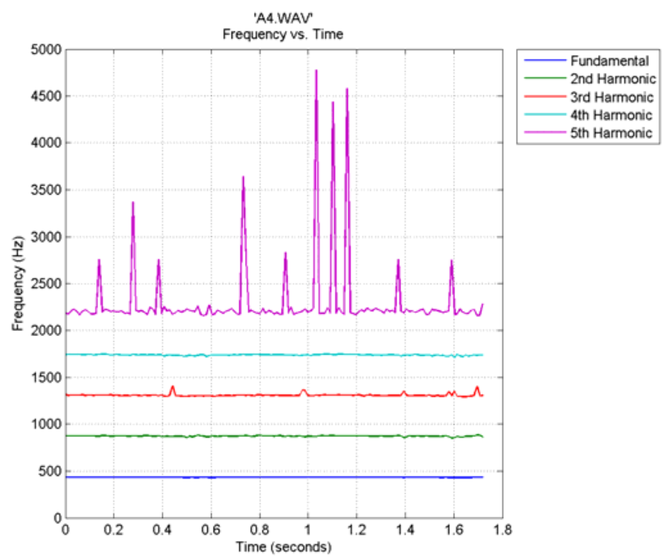

'B4.WAV'
Amplitude vs. Time
Fundamental
2nd Harmonic
3rd Harmonic
4th Harmonic
5th Harmonic
Amplitude
Time (seconds)

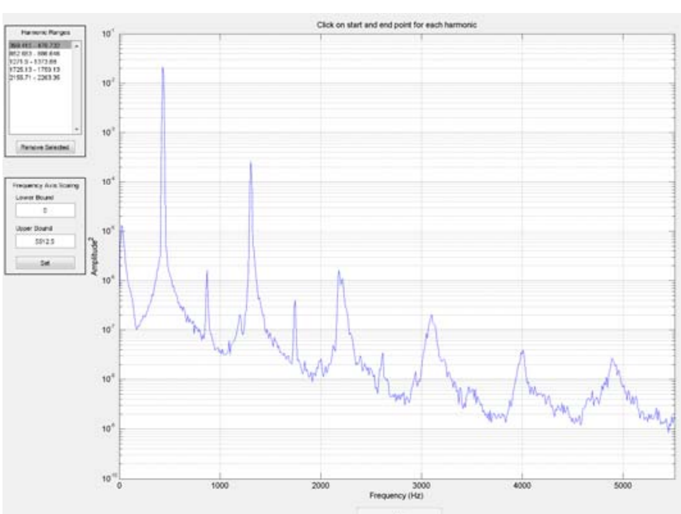
A4

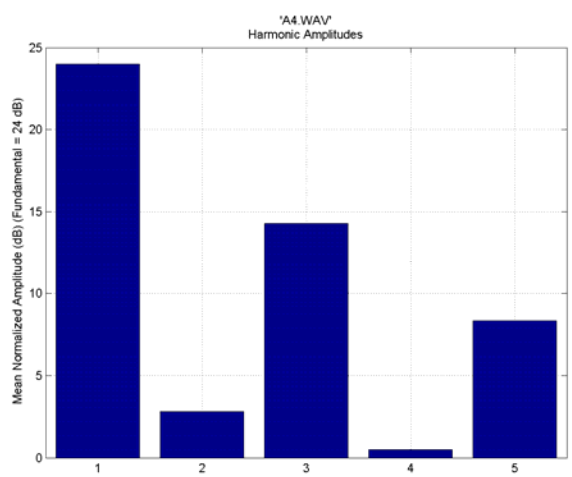

'A4.WAV': Fitted Phase vs. Time(left), Frequency vs. Time(middle), Amplitude vs. Time(right)
Fundamental (399.415-478.732 Hz)
2nd Harmonic (852.653-886.646 Hz)
Phase (degrees)
Frequency (Hz)
Amplitude
Time (seconds)

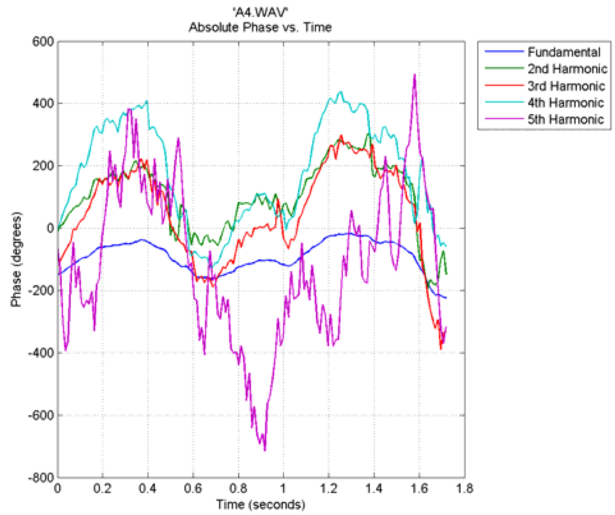

'A4.WAV': Fitted Phase vs. Time(left), Frequency vs. Time(middle), Amplitude vs. Time(right)
3rd Harmonic (1271.9-1373.88 Hz)
4th Harmonic (1725.13-1759.13 Hz)
Phase (degrees)
Frequency (Hz)
Amplitude
Time (seconds)

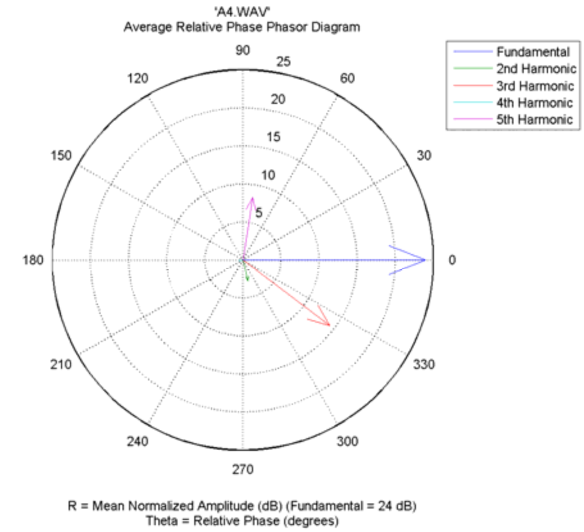

Fitted Phase vs. Time(left) 'A4.WAV' Fitted Frequency vs. Time(right)
5th Harmonic (2155.71-2263.35 Hz)
Phase (degrees)
Frequency (Hz)
Amplitude
Time (seconds)

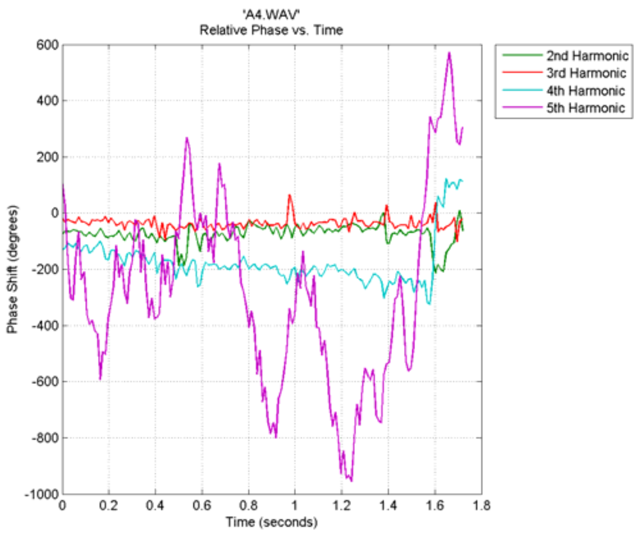

'A4.WAV'
Frequency vs. Time
Frequency (Hz)
Time (seconds)
Fundamental
2nd Harmonic
3rd Harmonic
4th Harmonic
5th Harmonic

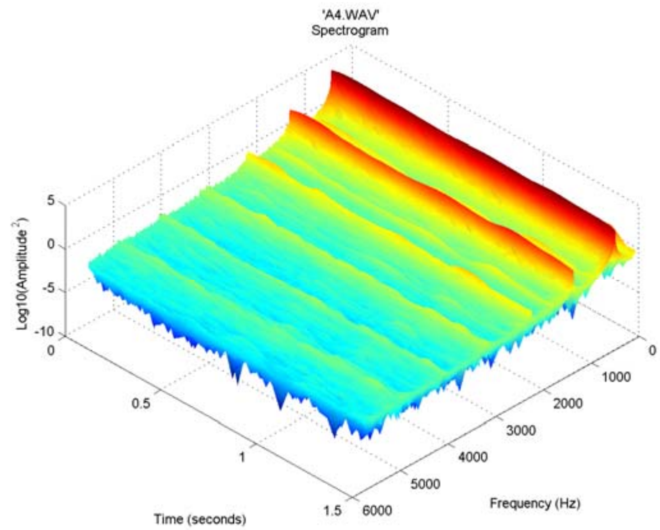

Click on start and end point for each harmonic
Harmonic Ranges
Remove Selected
Frequency Axis Scaling
Lower Bound
Upper Bound
Set
Frequency (Hz)
Done

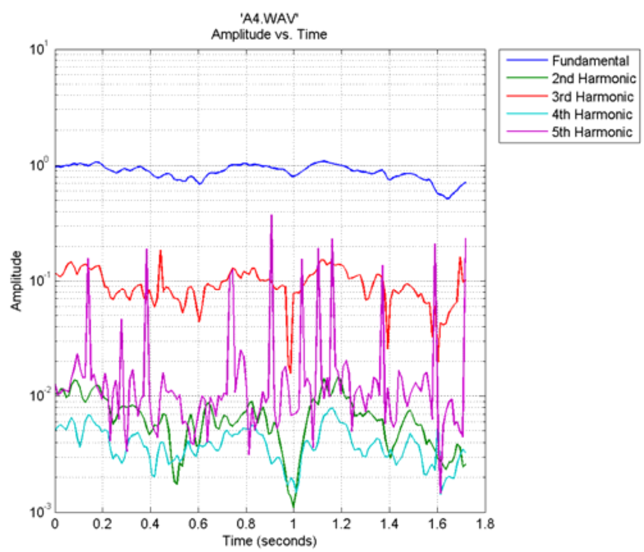

'A4.WAV'
Harmonic Amplitudes
Mean Normalized Amplitude (dB) (Fundamental = 24 dB)
Harmonic


'A4.WAV'
Absolute Phase vs. Time
Fundamental
2nd Harmonic
3rd Harmonic
4th Harmonic
5th Harmonic
Phase (degrees)
Time (seconds)


'A4.WAV'
Average Relative Phase Phasor Diagram
Fundamental
2nd Harmonic
3rd Harmonic
4th Harmonic
5th Harmonic
R = Mean Normalized Amplitude (dB) (Fundamental = 24 dB)
Theta = Relative Phase (degrees)


'A4.WAV'
Relative Phase vs. Time
2nd Harmonic
3rd Harmonic
4th Harmonic
5th Harmonic
Phase Shift (degrees)
Time (seconds)


'A4.WAV'
Spectrogram
Log10(Amplitude^2)
Time (seconds)
Frequency (Hz)


'A4.WAV'
Amplitude vs. Time
Fundamental
2nd Harmonic
3rd Harmonic
4th Harmonic
5th Harmonic
Amplitude
Time (seconds)