

Assessment of Violin Timbre:
Examination of the Fourier Spectra and
Resonance Curves of Medium- and Low-
Quality Instruments

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Abstract

Musical instruments are complex producers of sound; the perceived single tone of a violin is actually a summation of the fundamental frequency and its harmonics. The variables in the violin's setup and corpus structure determine the strength of these harmonics, which produce its distinctive timbre.

As a cellist, I have found that different instruments produce vastly differing tones. Though prior studies have isolated single variables that determine one aspect of an instrument's timbre, this study examines how the harmonic spectrum of different-quality instruments objectively defines what an observer might subjectively describe as 'simple', 'harsh', or 'rich' tones.

I used a digitizing oscilloscope to produce the Fourier spectrum of the bowed A-strings (440 Hz) of a 'medium-quality violin' (MQV) and a 'low-quality violin' (LQV). I compared an isolated, bowed A-string to the two violins to examine the overall influence in timbre of a resonance cavity. I averaged four trials to distinguish the relative strength and placement of the harmonic overtones of the two qualities of instruments.

The study produced several striking conclusions: the combination of a strong fundamental and upper-register resonances, a wide frequency-range of strong harmonics, and a 440 Hz-centered Main Wood Resonance on the MQV are characteristic of its complex, harsh timbre. Conversely, the LQV has weak fundamental and centralized, strong middle-region characteristic of its flat, nasal timbre. Both instruments produced similar 'hump-back' curves, though the peak occurred at different frequencies. While I did not control the pressure, angle, and position of bow mechanically, I approximated 'normal' playing conditions. Hence, the conclusions drawn from this study characterize broad trends, rather than quantitative results.

Future tests could examine the variables in greater depth: a greater range of corpus qualities should be studied under varying performers to find if these conclusions are applicable to all violin qualities and are reproducible.

Acknowledgments

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Table of Contents

Cover Page	
Abstract.....	1
Acknowledgements.....	2
Table of Contents.....	3
Introduction.....	4-5
Hypothesis.....	6
Method.....	7-8
Experiment.....	9-10
Part 1: Round One Tests.....	11-12
Part 2: Round Two Tests.....	12-15
Part 3: Medium-Quality Instrument (MQV).....	15-17
Part 4: Low-Quality Instrument (LQV).....	18-21
Discussion.....	20-21
Conclusion.....	22-23
Bibliography.....	24
Enlarged Graphs.....	25-39
Appendices	
Appendix 1: Alternate Variables	
Appendix 2: Description of Violins	
Appendix 3: Pictures of Setup	
Appendix 4: Displays of Each Graph	

Introduction

The selection of an individual stringed instrument is pivotal in the musical career of a performer. A cellist myself, I have experienced the many variables that determine the character of an instrument¹. However, as a performer, I experience these variables compositely, and thus cannot readily describe each individual property of the instrument. This project is therefore designed to investigate this ‘composite timbre’ that determines the individuality of each instrument through the comparison of a violin’s Fourier spectra with its resonance curve, identifying the implication of the arrangement of partials within specific frequency regions. First, I must define several terms:

Timbre: “Characteristics of sound which allow the ear to distinguish sounds which have the same pitch and loudness...mainly determined by the harmonic content of a sound.” (Nave, 2005)

Fourier Analysis: A process that decomposes the partials of a resultant wave and plots the amplitude (volume, y axis) v. frequency (x axis) on a ‘Fourier spectrum’.

Resonance Curve: Graphical representation of an instrument’s level of resonance at each frequency (Y axis dB (volume), X axis Hz (frequency))

Luthier: One who constructs or repairs string instruments.

Fundamental: The frequency audible to the listener, the lowest frequency in a resultant wave.

Harmonic: A positive-integer multiple of a given frequency, or *fundamental*. Harmonic is used interchangeably with *partial* (a component with 1/n the period) or *overtone* (a multiple of the fundamental)².

Practically, this investigation may facilitate construction of modern violins, analysis of older violins³, and tonal adjustments of pre-existent instruments. This study will also address how the interaction between the Fourier spectrum and the resonance of a violin may produce timbres described subjectively as rich, clean, clear, and level.

The single frequency perceived by the listener is actually a summation of several frequencies – the fundamental note and certain harmonic overtones. The concurrent sinusoidal and cosinusoidal harmonic waves have periods 1/n times that of the fundamental. Their sum creates a *resultant wave*, with the same frequency as the fundamental, which is perceived as the pitch. The strength of harmonics (among other variables, discussed in appendix 1) produces the audible distinction between two instruments of the same or different families (strings, brass, woodwinds).

Because string instruments have ‘closed’ boundaries (see appendix 2 for greater discussion), the overtone spectrum contains all harmonics ($f_n = f_1 n$, where n=integral multiples (2,3,4...) of the fundamental f_1).

Any resultant wave can be decomposed into specific components with given amplitudes and phases (Berg, 1982). The oscilloscope visualizes the *Fourier decomposition*⁴ by showing the frequency and amplitude of each decomposed harmonic discretely.

¹ Because the dimensions of the ‘cello were modified from the violin to fit the human dimensions, the spectrum has several ‘flaws’ that are not present in a violin.

² Note that the 1st overtone is the 2nd harmonic

³ e.g. popular investigation for the ‘Cremona Secret’

⁴ Named after the French scientist and mathematician, Jean Baptiste Joseph Fourier (1768-1830)

When one bows or plucks the string, the vibrations (and partials) are transmitted by the bridge to the instrument's body, which resonates at the same frequencies as the generator (string). Sundberg remarks that, "*the resonator cannot give out any tones except those received from the generator, and it may not give out all of these.*" (1991). Thus, the acoustic quality of an instrument depends largely upon the degree of sympathy, or ease-of-resistance, between the generator and the resonator.

The body resonances may be found using tap tones, blow tones, and machine-driven oscillators. An oscillator produces a *resonance curve* by exciting the violin over a range of frequencies, graphing the amplitude of the oscillating violin-plates. Few resonance curves have been produced, however, due to the inaccessibility of hardware. Indeed, generating resonance curves of the violins was beyond the scope of this study; I instead employed the graphs generated by Carleen Hutchins and Arthur Benade (discussed later).

Two 'main' resonances are visible in the lower region of a resonance curve: the Main Wood Resonance (MWR) and the Main Air Resonance (MAR). The MWR is the lowest resonant frequency (*natural resonance*) of the violin's plates. The MAR occurs at the lowest frequency at which the air particles resonate within a cavity.

Rossing notes that the intensity of a single partial will noticeably "increase if [it] occurs at or near a prominent resonance of the violin body" (1982). While numerous variables - including density, geometric shape, width, and wood quality and type - may alter the resonances of the individual plates, the entire resonance cavity of the violin may also vary due to outside variables - rigidity and interaction between plates, varnish - explorable only through complex acoustical properties out of the scope of this study (Berg, 1982).

This study extends the work of prior investigations, drawing upon variables represented by the resonance curve and the partials. It will examine the direct interaction between the Fourier spectrum and the instrument's resonances by exploring the strengths of harmonic overtones on the A-strings of two contrasting qualities of violins. The following questions guide the hypothesis:

- What are the objective differences between varying violin qualities, and how do they produce such subjective descriptors as 'clean', 'brassy', 'rich', 'bright'?
- How well can an observer understand the resonator's properties given the instrument's timbre?
- To what extent do specific trends in an instrument's resonance curve determine the harmonic structure?

Hypotheses

- 1) The partials produced by a bowed isolated A-string will decay like $1/n$ because the 'ideal' string produces a sawtooth resultant wave⁵ and because boundary conditions permit all harmonics.
- 2) The spectra will include a minimal number of emphasized harmonics due to the absence of a complex resonator.

When the bowed A-string (440Hz) is attached to a medium-quality resonance cavity, the Fourier spectrum displays the following characteristics:

- 1) The Fourier spectrum of a medium-quality violin will be less consistent than that of the low-quality violin (deviating from the $1/n$ pattern), due to the body's widely-dispersed resonance peaks. Consequentially, the partials around the MWR will be enhanced.
- 2) The partials within the middle register (1000-2000Hz) will be relatively weak compared to the individual resonance peaks in the lower register⁶.
- 3) Given the inconsistently strong lower and upper registers, the timbre of the A-string of a middle-quality violin sounds deep or complex.

When the bowed A-string is attached to a low-quality resonance cavity, the Fourier spectrum displays the following characteristics:

- 1) The partials within the A-E frequency domain (440-659Hz) displays the same trend ($1/n$) as the 'isolated A-string'.
- 2) The partials in the middle register (1000-2000Hz) are magnified by the resonances of the body (as displayed by the resonance curve below).
- 3) The relatively weak upper register yields a weak, dark, yet flat overall timbre on the low-quality violin's A-string.

⁵ An ideal sawtooth resultant wave decays like $1/n$

⁶ caused by properties of the wood and air

METHOD

I designed the study to consider the variables that a performer encounters - mainly bow placement, pressure, and angle. Popular attempts to construct a mechanical-bowing device have had limited success⁷, as Lily Wang remarked that the timbre of her bowing-machine “sound[ed] less like music and more like noise” (Bauer, 1998). To investigate the timbre of the violins as heard in concert, I decided to bow the instruments myself, subjectively finding the equivalent tone qualities (replicating placement, pressure, and angle of the bow) produced by the violins. I thus held the violin vertically (as a ‘cello), as I am most experienced in bowing consistently in this position.

Given the wide range of wood resonances on a violin, I initially set the fundamental at the violin’s lowest string – G3 (196Hz). However, upon examining the G-string spectra, I found that the ‘cleanliness’ of the A-string’s spectrum was easier to view, partially due to the Main Air Resonance (~440Hz), which thus enhances the fundamental. Also, the human ear is most sensitive to frequencies between 1 and 4 kHz (Wolfe, 2005), which contains more visible harmonics on the A-string than on the G-string⁸.

I then investigated with which instruments I could find the greatest discrepancy in tone quality – equating to presumably greater visible differences. I decided to test a low-quality instrument (under \$500) against a medium-quality instrument (\$4000-\$6000) –contrasting modern studies using unaffordable superior-quality instruments. The lower-quality violin – described by Bossy and Carpentier as “easy and cheap for other researchers to obtain relatively similar instruments for comparison” (Wolfe, 2006) – was constructed with low-quality, machine-cut wood, thus inhibiting the resonances. The medium-quality violin was described as a factory instrument made with “acoustically good patterns... top-quality materials and an excellent oil varnish” (McKean, 2005). With violins in hand, I proceeded to find matching resonance curves.

Benade argues that all violins produce common resonance curves, influenced by standard variables (dimensions, general width) of all violin bodies (1976). Within different violin quality-ranges, the resonances will exhibit similar traits. Hutchins and Benade (1964) provided curves of low, medium, and high-quality violins. I matched these ‘representative curves’ to my two violins.

Because there may be discrepancy in the and experimental violins’ resonance the curves could well feature similar characteristics in amplitude, though on varying frequencies. In order to examine the ‘alignment’ of frequencies, I found the MAR and MWR of both instruments to compare to the Hutchins curves.

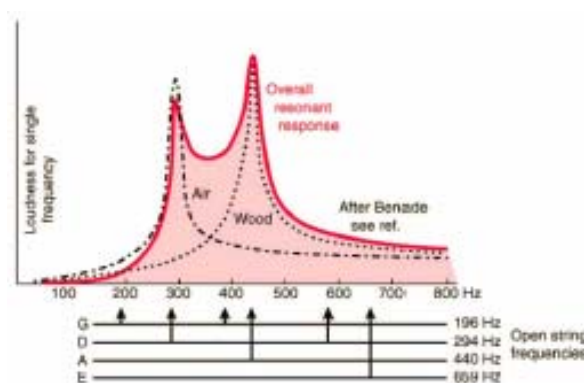


Figure 1: Benade ‘Generic’ Resonance Curve Hutchins curves, (accessed from hyperphysics.phy-astr.gsu.edu/hbase/music/viores.html)

⁷ For in depth study of mechanical bows, consult *Simulating Performance On a Bowed String* (Chafe, 1988) and *Playability Evaluation of a Virtual Bowed String Instrument* (Young, Serafin, 2003)

⁸ thus making fine variants in A-string timbre more perceptible

Finally, I designed the setup of the isolated A-string. To keep the string truly isolated (no resonator), my design had to ensure rigidly-fixed boundaries. I thus wound the A-string around two thin, wooden 'spools', which were clamped onto a thick metal pole. Since strings theoretically produce a consistent spectrum across all frequencies, it was unnecessary to tune the A-string to exactly 440 Hz. Thus, the string was tuned to approximately 180 Hz (appendix 3).

The Experiment

Materials:

- 2 violins of contrasting quality (appendix 2)
- One Super-Sensitive™ stainless string, plain wound, medium strength A-string⁹
- Sherman's Violin Rosin™ produced by Dodson's MFG. Company
- Tektronix™ TDS 420A 4-channel digitizing oscilloscope
- computer monitor
- Bogen™ Model C10C commercial microphone
- 3-1/2" floppy disk
- computer programs:
 - CNVRTWFM, Version 1.97¹⁰
 - Microsoft Excel®

Procedure:

- 1) Connect microphone to oscilloscope's BNC input. Plug in computer monitor to obtain a larger image than provided by oscilloscope screen.
- 2) Set oscilloscope to display the Fourier spectrum only. Set horizontal scale to 500 Hz per division, on a linear (rather than logarithmic scale). Set vertical scale to 8 mV per division.
- 3) Set oscilloscope FFT Waveform to 'Hamming' Window Function.
- 4) Arrange microphones, oscilloscope, monitor, and PC, so that the output sound of the violin is the only detected signal (though small, random deviations will be visible inherent to software error, amounting to ≤ 0.005 dB).
- 5) Hold violin ~4" from microphone, which is arranged perpendicularly to the G-side f hole of the violin (setup in appendix 3).¹¹
- 6) After selecting the "Run" button, bow A-string tuned to 440 Hz (without left-hand involvement). Once a clear sound is produced, freeze the oscilloscope with idle left hand. The image is then saved onto the floppy disk, and the file number is recorded on the log file.
- 7) Step 6 is repeated four times on medium- and on low-quality violins.
- 8) Isolated A-string is wound about two wooden spools and clamped to length equivalent to a violin (about 32.7 cm, ± 0.1 cm) (setup in appendix 3). Microphone held by assistant about 4 inches from the string. Performer bows string and freezes oscilloscope in similar fashion to step 5.
- 9) Perform 4 trials of bowed isolated A-string, save on floppy drive.
- 10) Assess the MWR of each instrument by lightly tapping the center of the back plate, simultaneously freezing the oscilloscope, while stabilizing the violin in front of the microphone as done in step 5.

⁹ The isolated string is the same model of string as those tested on violins

¹⁰ Download at: <http://www.linux.duke.edu/~mstenner/software/cnrvtfm/dist/>

¹¹ This ensures that both the wood and air resonances are accounted for in the same fashion as they would be perceived by an audience-member.

- 11) Find the MAR of each instrument by blowing into the G-side 'f' hole at approximately 45°. The microphone is held about 1 inch from the E-side 'f' hole.
- 12) The waveforms are saved as *.wfm files by the oscilloscope. Use CNVRTWFM to convert these files to *.dat files, which are compatible with Excel®.
- 13) Use Excel® to display data on linear graph and to take averages of data.

RESULTS

- For all graphs, x-axis (frequency) in Hertz, y-axis (amplitude, or volume) in arbitrary units (oscilloscope set at 8 mV scale)
- The quantitative unit (dB) is imprecise, given experimental error – thus, amplitude will be looked at comparatively only. The y-axis is fit to each individual graph due to automatic data transfer to Microsoft Excel[®].

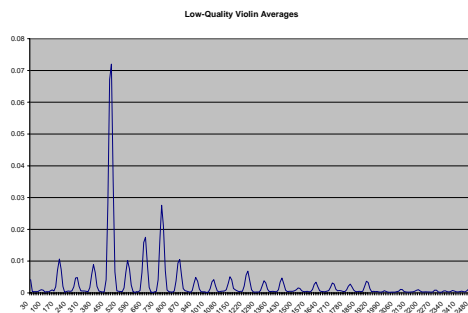
PART 1: ROUND ONE TESTS

There were several concerns once I analyzed the first round of results. First, there was a conspicuous lack of consistency in the amplitudes of harmonics in several trials of one test. Though I attributed this to experimental error –pertaining to the weight, pressure, and angle at which the string is bowed- I was also concerned about the presence of several peaks on non-harmonic frequencies – mainly at 290 and 1850 Hz on the isolated string and at 245 and 490 Hz on the two violins. I discussed this phenomenon with Dr. Richard Berg who verified my concern; the resonator enhances the harmonics of the string, but cannot produce harmonics of its own.

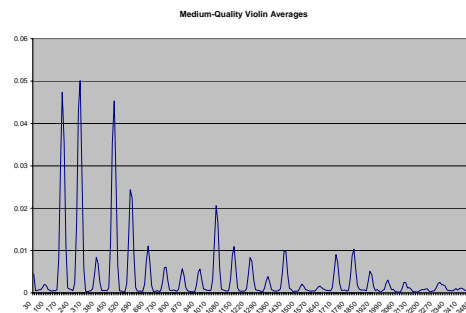
I performed a second round of tests using the same methodology, equipment, and setup, yet a different fundamental (discussed below). The data collected was more consistent and understandable. The averages of the data from round one of testing are displayed below:

Graphs 1.1-1.3

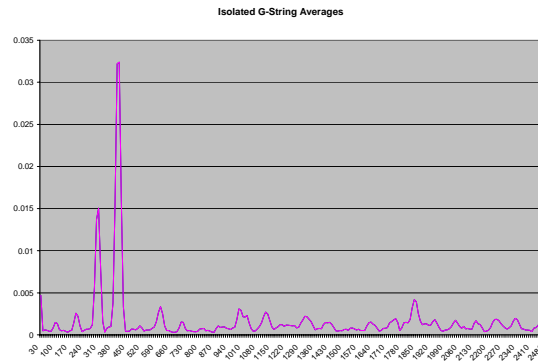
Low-Quality Violin Average



Medium-Quality Violin Average



Isolated G-String Average



ROUND TWO TESTS

PART 2: ISOLATED A-STRING

To determine the effect of the independent variable (quality of the resonating body) on the Fourier spectrum, I first determined the spectrum of the isolated string for comparison. We can assume that the Fourier spectrum of the isolated string would appear identically on each instrument, with minor variations due to imperfections in the individual string.

First, we must determine the frequencies at which harmonics overtones exist on any given A-string using the equation, $f_n = n f_1$ (n =any positive integer):

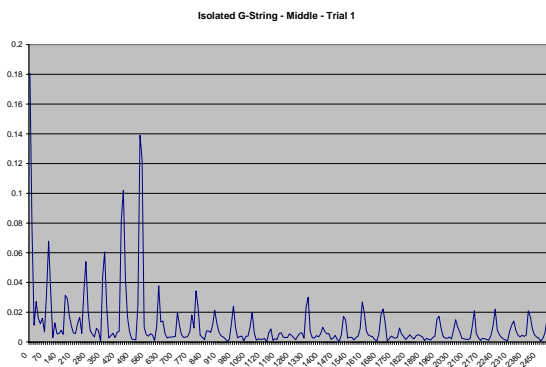
$f_1=440\text{Hz}$
$f_2=2(440)=880\text{Hz}$
$f_3=1320\text{Hz}$
$f_4=1760\text{Hz}$
$f_5=2200\text{Hz}$
$f_6=2640\text{Hz}$
$f_7=3080\text{Hz}$
$f_8=3520\text{Hz}$
$f_9=3960\text{Hz}$
$f_{10}=4400\text{Hz}$
$f_{11}=4840\text{Hz}$

f_1 =fundamental, f_2 =second harmonic, etc.

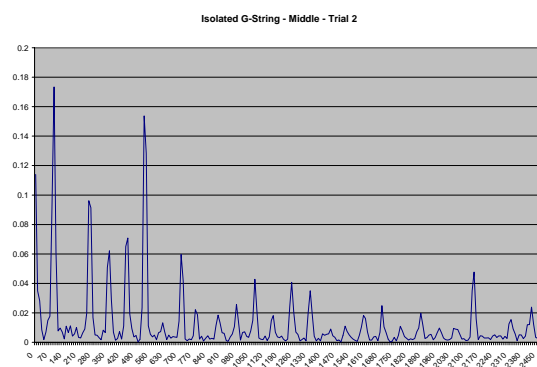
Below are the spectra of the four trials of the isolated A-string:

Graphs 2.1-2.4

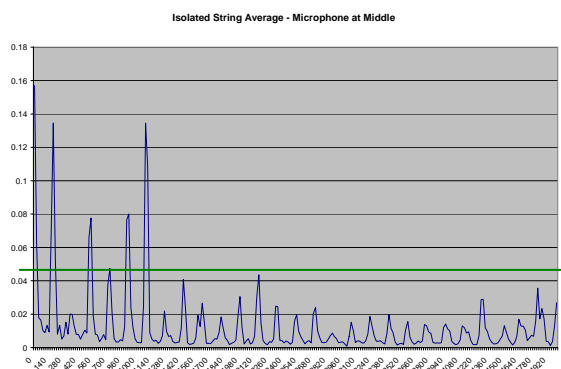
Middle: Trial 1



Middle: Trial 2

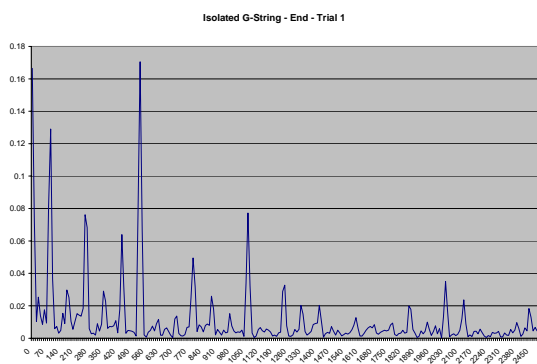


Middle: Average

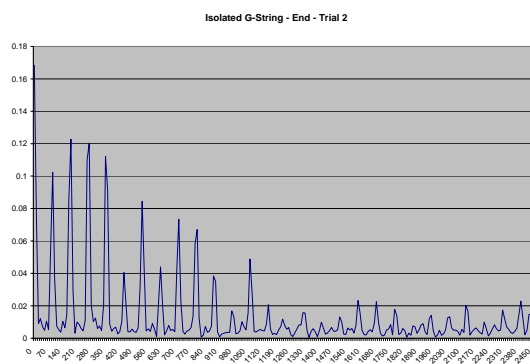


Graphs 2.5-2.7

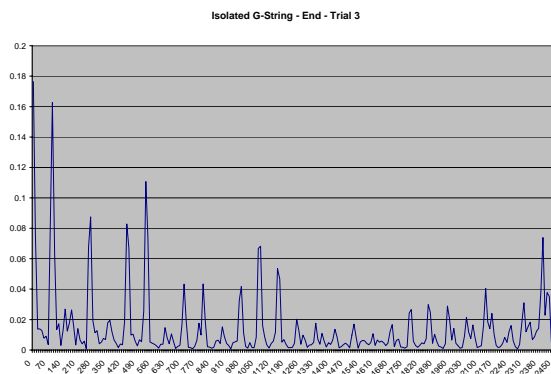
End: Trial 1



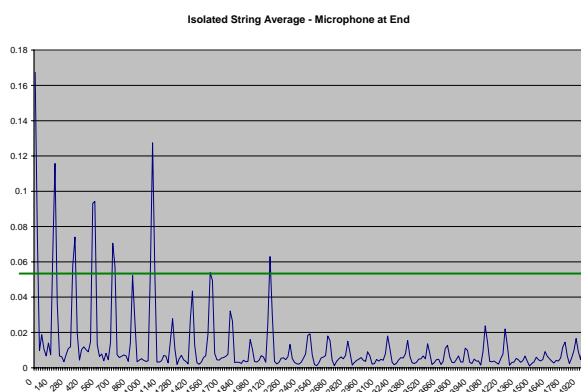
End: Trial 2



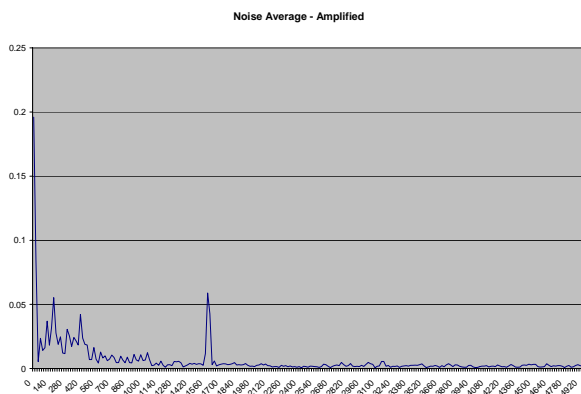
End: Trial 3



End: Average



Graph 2.8



Graphs 2.1-2.3 were acquired with the microphone held near the middle of the string. However, this method emphasized specific overtones over others, since the microphone was sitting at the *node*¹² of the second harmonic. I then recorded the isolated A-string with the microphone held near the opposite end of where I bowed (graphs 2.5-2.6). Graph 2.8 displays the audible and electronic noise inherent to the hardware. We can thus discard any peaks lower than about .05 dB (+/- 0.005dB), as demarked by the green lines on graphs 2.4 and 2.7 (at about

¹² *Node*: Point of zero amplitude (no resonance)

.05dB). According to Dr. Berg, the amplification system is completely *linear*: it magnifies all frequencies equally.

Theoretically, the difference in position of the microphone (relative to the middle of the string) should be visible in the relative strength of the even and odd harmonics. If the microphone were positioned closer to the middle, the even harmonics should be enhanced: any even harmonic has an *antinode*¹³ at the middle of the string. As the even integer-multiple increases, the difference is less apparent, since the antinodes begin to be set closer to the middle (when dividing a segment by two the distance between divisions grows smaller). Conversely, the odd harmonics should be stronger when the microphone is held further away from the center of the string. Indeed, these aforementioned phenomena are visible on graphs 2.4 and 2.7. The second ($\approx 420\text{Hz}$) and the fourth ($\approx 840\text{Hz}$) harmonics were stronger when the microphone was held towards the end of the string, while the fundamental ($\approx 210\text{Hz}$) and the third ($\approx 630\text{Hz}$) harmonics were stronger when the microphone was held towards the middle of the string. This finding would suggest that the audience member's angle in respect to the string would influence the perceived harmonic structure. However, if the subject were standing further away from the string (as in a concert hall), the sound would be diffused, and thus minimal angle adjustments would be imperceptible.

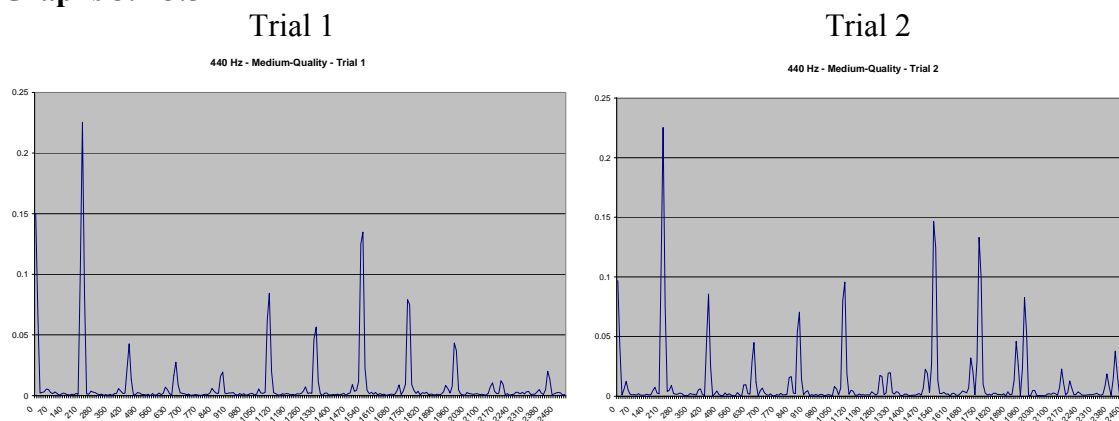
The graphs show that the isolated string timbre is composed mostly by the first six harmonics, with insignificant peaks on higher overtones. Of these first six harmonics, the fundamental, third, and sixth harmonics are strongest.

THE VIOLINS

PART 3: MEDIUM-QUALITY INSTRUMENT (MQV)

I then determined the Fourier spectrum of the MQV, which could then be compared to the isolated A-string. The enhanced partials in the following graphs can be attributed to the strength of the resonances of the violin's resonant cavity.

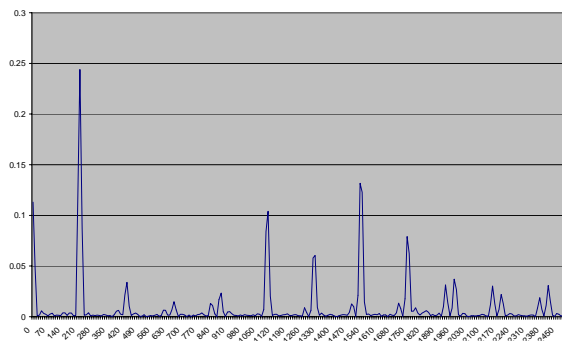
Graphs 3.1-3.5



¹³ *Antinode*: Point of greatest amplitude

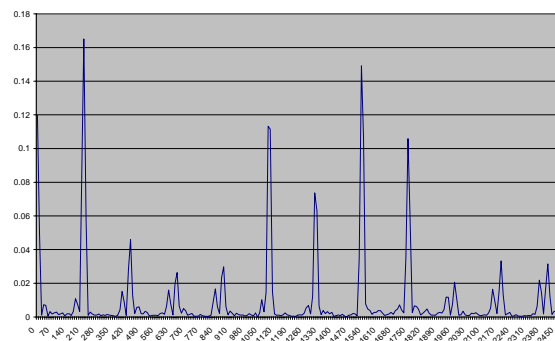
Trial 3

440 Hz - Medium-Quality - Trial 3



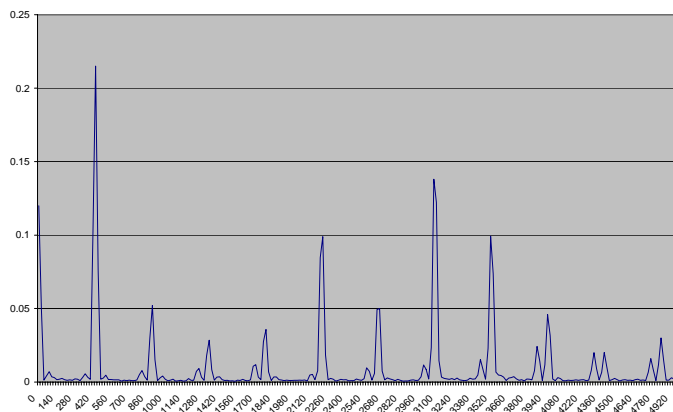
Trial 4

440 Hz - Medium-Quality - Trial 4

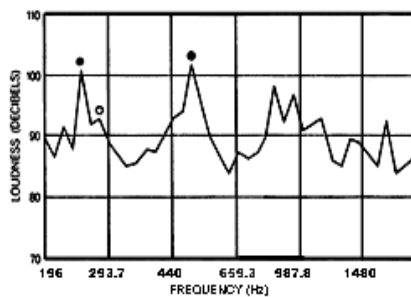


Middle-Quality Averages

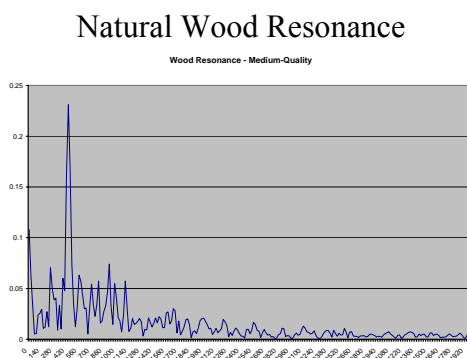
440 Hz - Averages - Medium-Quality



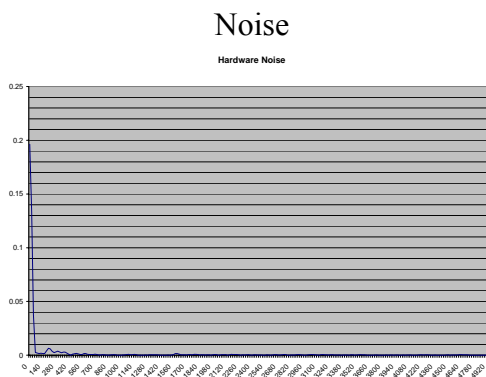
Graph 3.6



Graph 3.7



Graph 3.8



The strong fundamental is, unlike in the spectrum of the isolated string, notably the strongest frequency. We concur that there must be a strong wood resonance around 440 Hz, as indeed found in graph 3.7. The MWR is denoted by the second black dot in graph 3.6.

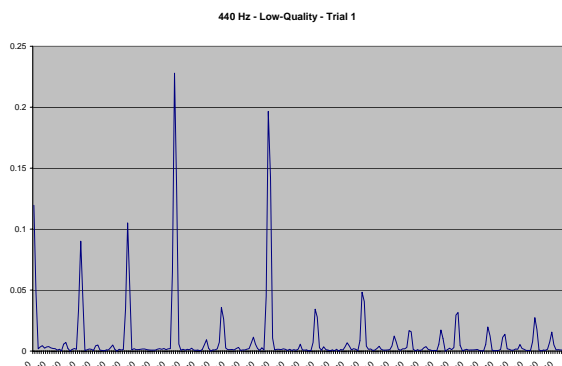
The ‘humpback’ form of the spectra is also noteworthy. The middle region (about 1000-2000Hz) is relatively weak compared to the enhanced upper region (2500-3500Hz). Though the resonance curve’s (3.7) domain only reaches 2000 Hz, the visible middle region does not embody this trend. Though this discrepancy might come from uncertainty about our violin’s resonance curve, it could also be due to the strength of the partials produced by the string. Indeed, consulting graphs 2.4 and 2.7, the second, third, and fourth harmonic overtones –which lay in the middle region of graph 3.5- are dwarfed by the strong fundamental and sixth harmonic. Likewise, while the fundamental is emphasized by this violin’s resonance cavity, the sixth harmonic (2640Hz) is diminished – perhaps due to weak resonances around this frequency.

Graph 3.8 displays the noise level with the mechanical amplification halved. Given the minimal amount of noise apparent, we omit noise as a major source of systematic error.

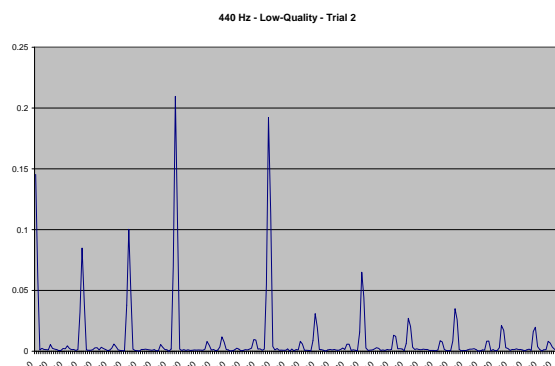
PART 4: LOW-QUALITY INSTRUMENT (LQV)

Graphs 4.1-4.5

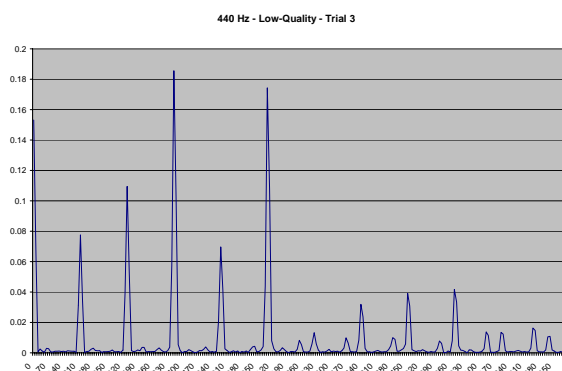
Trial 1



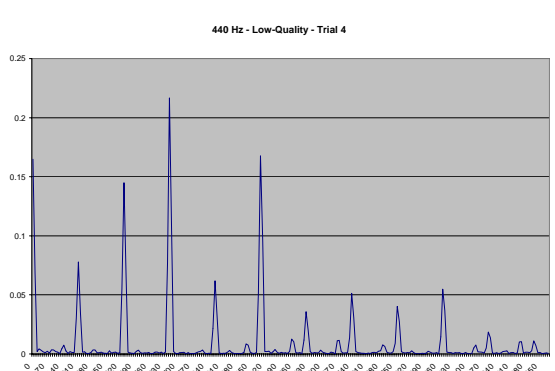
Trial 2



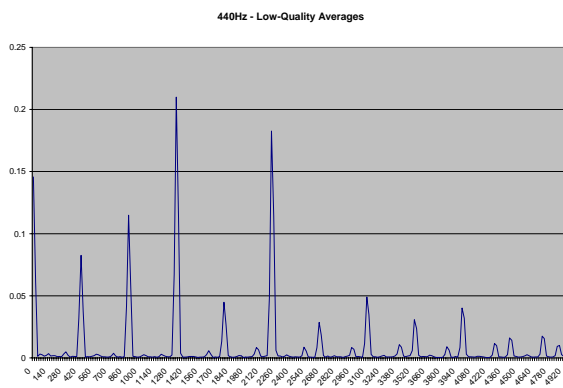
Trial 3



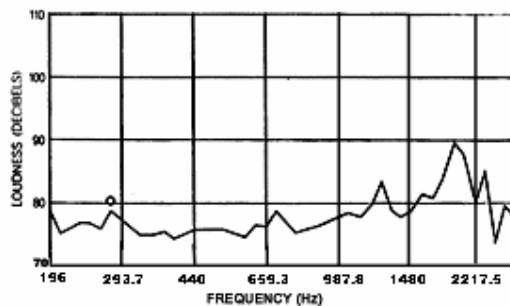
Trial 4



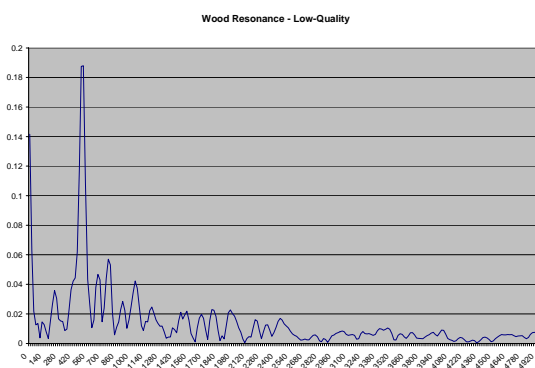
Low-Quality Average



Graph 4.6

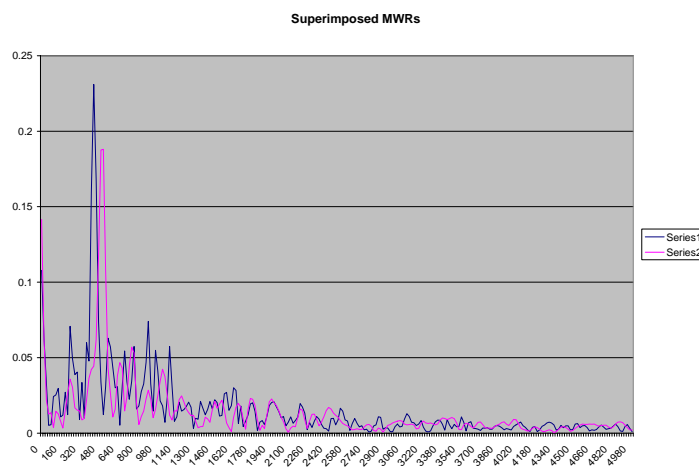


Graph 4.7



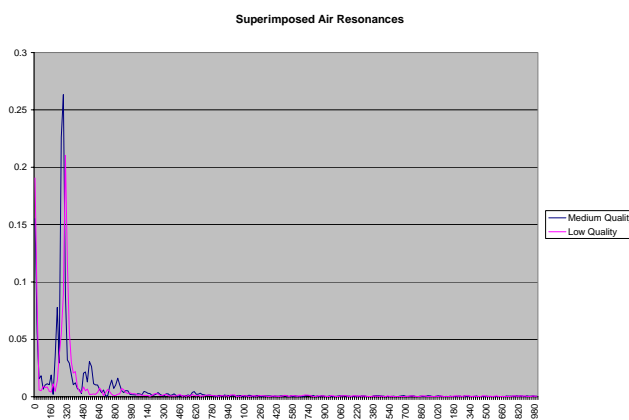
Graph 4.8

Series 1: MQV
Series 2: LQV



Graph 4.9

Series 1: MQV
Series 2: LQV



The LQV possesses a middle-region-centric curve. Unlike the MQV, where the strongest peak (fundamental) lies on the wood's main resonance, the poor quality of wood on the LQV lends little resonance in this area. According to graph 4.6, this violin does not even have a MWR. I thus performed the same test as with graph 3.7, and received mystifying results: The tap tone did exist around 480 Hz. Thus, we could conclude that though a MWR does exist—contrary to the resonance curve; it is sufficiently far away from 440 Hz that it does not enhance the fundamental. According to Benade, higher-quality violins tend to have MWRs near 440 Hz, while the resonance may be significantly higher on lower-quality instruments; this is visible in graph 4.8. From this observation, however, we must conclude that while the trends of the Hutchins resonance curve (4.6) may resemble the resonances of our violin, there are significant differences between the two. In more precise future tests, it is pivotal to obtain the resonance curve of the tested instruments. For our study, however, we can conclude that the weak fundamental is the sole product of poor wood quality.

While the spectra of the low-quality violin differ greatly from those of the MQV, the same 'humpback' trend appears in both. The peak on the LQV's curve occurs on the third harmonic (1320Hz), in contrast to the MQV's emphasized eighth harmonic (3520Hz). The third and fifth harmonics (2200Hz) are clearly emphasized by the resonator; conversely, the upper harmonics are inhibited. Given the domain limitations of the resonance curve (4.6), we simply assume that the violin's resonances plateau at a low level of resonance after the peak around 2000 Hz.

DISCUSSION

Graph 4.9 is presented to compare the differences between the resonances of the tested violins with the resonance curves provided by Hutchins and Benade; however, the MAR would have minimal implication on our study given that the fundamental (440Hz) lays above this resonance peak. We note that the MAR on the MQV occurs at 280 Hz (± 10 Hz), similar to graph 3.6. The MAR on the LQV is found at 300 Hz (± 10 Hz), varying from graph 4.6 by at least 20 Hz. Thus, while the lower resonances of 3.6 closely resemble those of our MQV, the resonances of graph 4.6 may differ significantly (as already found with the graph's MWR). However, the MARs do verify our previous conclusions; while the LQV is characterized by a narrow response

(displayed on 4.9 as a narrow, single peak), the MQV is conversely broad (on 4.9, wider range of frequencies excited).

The ‘double peaks’ in the spectra of the two violins are produced from faults inherent to the oscilloscope. According to Dr. Berg, the *windowing process*¹⁴ causes these peaks to occur. They can be omitted in our discussion of the strength of partials, because they do not directly obscure the data.

The peaks at 0 Hz on all graphs are a property of the *Fast Fourier Transform*¹⁵; they are irrelevant to audible properties. The peaks have been included to show that the x-axis is properly aligned.

¹⁴ For more information on FFT Windows, consult p. 3-39 of “Fast Fourier Transforms” found at: www.austincc.edu/cloud/manuals/Tektronix/70970103.PDF

¹⁵ For more information, consult Eric Weisstein’s “Fast Fourier Transform”, available at: <http://mathworld.wolfram.com/FastFourierTransform.html>

CONCLUSION

We can now identify the strengths and weaknesses of the hypothesis, and answer our question: How does the quality of resonator affect a violin's timbre?

The proposed $1/n$ pattern of the isolated A-string can be confuted due to oversimplification. While the string's spectrum displays no apparent trend, the standing wave is comprised of only several larger harmonics in the lower register. The first six harmonics are all present, though the fundamental, third, and sixth are particularly strong. Because the peaks are dense in the lower region and nonexistent in the middle and upper regions, we can describe the isolated string's timbre as 'simple', or 'flat'. Berg remarks that while "a simple sinusoidal wave sounds pure or plain"¹⁶...as large-amplitude harmonics are added, the tone becomes richer." Thus, we can expect that once the resonating cavity has been added, a greater range of harmonics will be amplified, and the timbre will therefore sound more 'complex'. As we have found, this level of complexity sets different violins apart from others.

As predicted, the overall trend of the MQV's Fourier spectrum did deviate more from the isolated string's spectrum than the LQV's. While the fundamental of the MQV's was enhanced by the Main Wood Resonance, the upper register (seventh and eighth harmonics) was also enhanced by the resonances of the body. Conversely, the fewer number of wood resonances of the LQV's body caused its spectrum to mirror the isolated string's relatively strong medium register. Consequentially, the LQV's tone is more similar to the isolated string's (clean, flat), while the MQV's tone is richer (a greater range of strong harmonics) and more vibrant (caused by stronger harmonics in the upper register).

While the MQV produced stronger upper and lower registers, the middle register was relatively weak. The LQV was the exact inverse. Since this was the hypothesized result, one can understand the general spectrum to a lesser degree by merely examining the violin's resonance curve (from which the hypothesis was founded on).

Schleske has performed numerous tests similar to this study. He concludes that the ear's sensitivity in the 1000-1800 Hz region establishes the 'nasal (or middle) region' as the most influential region in violin timbre. If the resonance is too strong, the tone is "nasal, tight, vulgar, and thus immediately 'transparent'". If the 'corpus (or lower) region' (450-550Hz) is too weak, he describes the tone as 'flat' or 'weak'. If the 'brilliance (or upper) region' (2000-3500Hz) is too strong, then the tone is 'harsh', while if too weak, it is 'dull' (Schleske, 2003).

Given both my and Schleske's findings, we conclude that a medium-quality resonator produces a complex, harsh timbre – the product of an emphasized upper region and a strong response across a wide range of frequencies. Similarly, a low-quality resonator produces a flat, weak, and nasal timbre – the product of an emphasized middle region, weak fundamental, and thus a narrow range of response.

Several questions invite further research:

- Why is it more difficult to produce a consistent harmonic structure without a resonator (isolated string)?
- What variables affect each resonance frequency-region of the body?
- To what extent does bow position alter the spectrum?¹⁷
- How does the perceiver's reference angle to the instrument change the timbre?

¹⁶ Similar to the spectrum produced as one whistles

¹⁷ (We have found tentative answers to this question in the differences between spectra in Round One)

In addition to the various sources of experimental error previously identified, the oscilloscope also contributes minimally to the distortion of results. According to Dr. Berg, an 8-bit oscilloscope contributes $\sim 1\%$ error¹⁸ while the commercial microphone additionally contributes $< 1\%$ error.

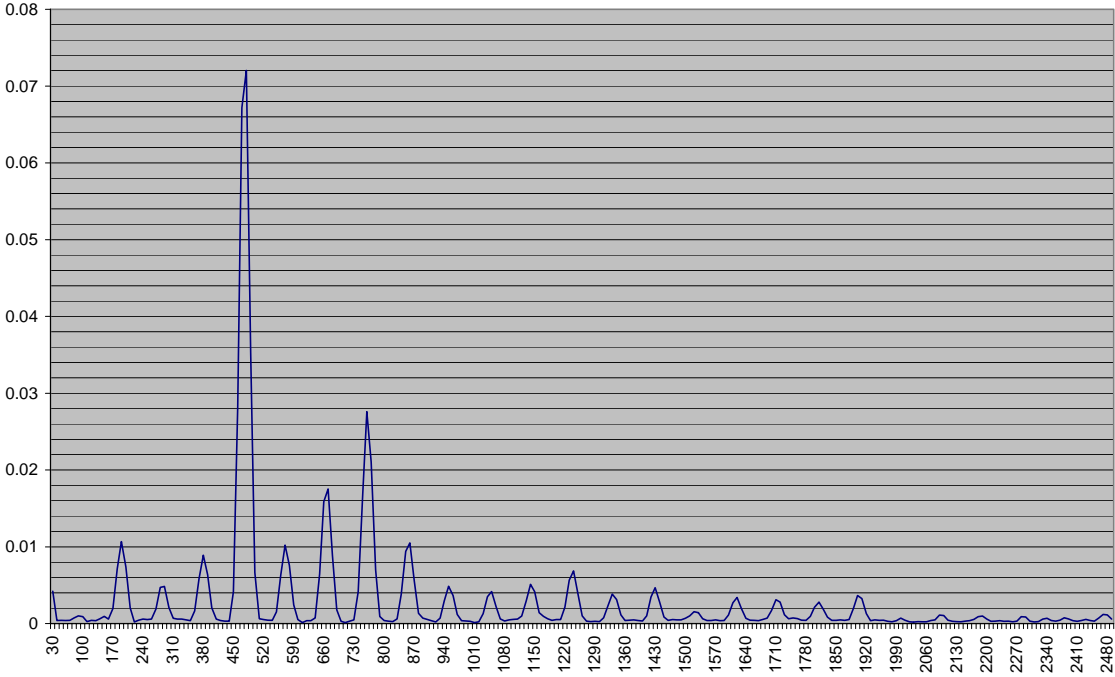
These conclusions assume that instruments of comparable quality have similar geometric shape, wood width, and bridges. The findings of this study are still applicable –even considering this error- to both the consumer, who seeks a violin embodying specific qualities, and the luthier, who continues to manipulate the overwhelming number of variables in order to investigate subjectively what this study has determined objectively: how the resonator changes the harmonic structure, and, ultimately, how the audience perceives the spectrum.

¹⁸ An 8-bit oscilloscope allocates one bit (of which there are seven) to sign (positive or negative). Thus, $2^7=128$

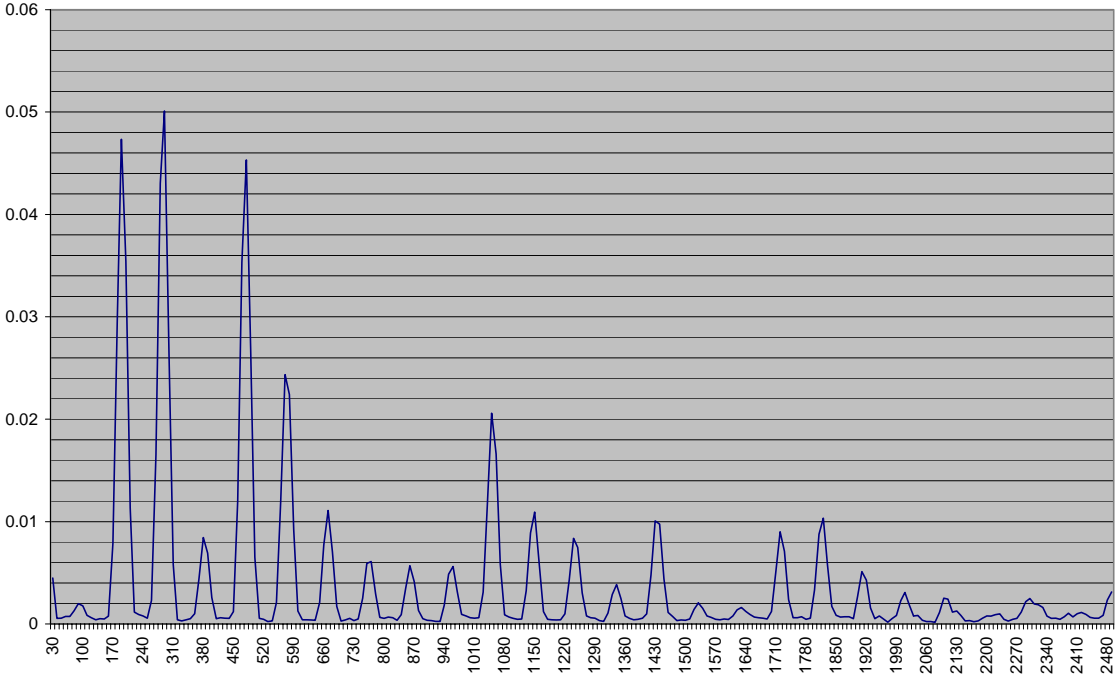
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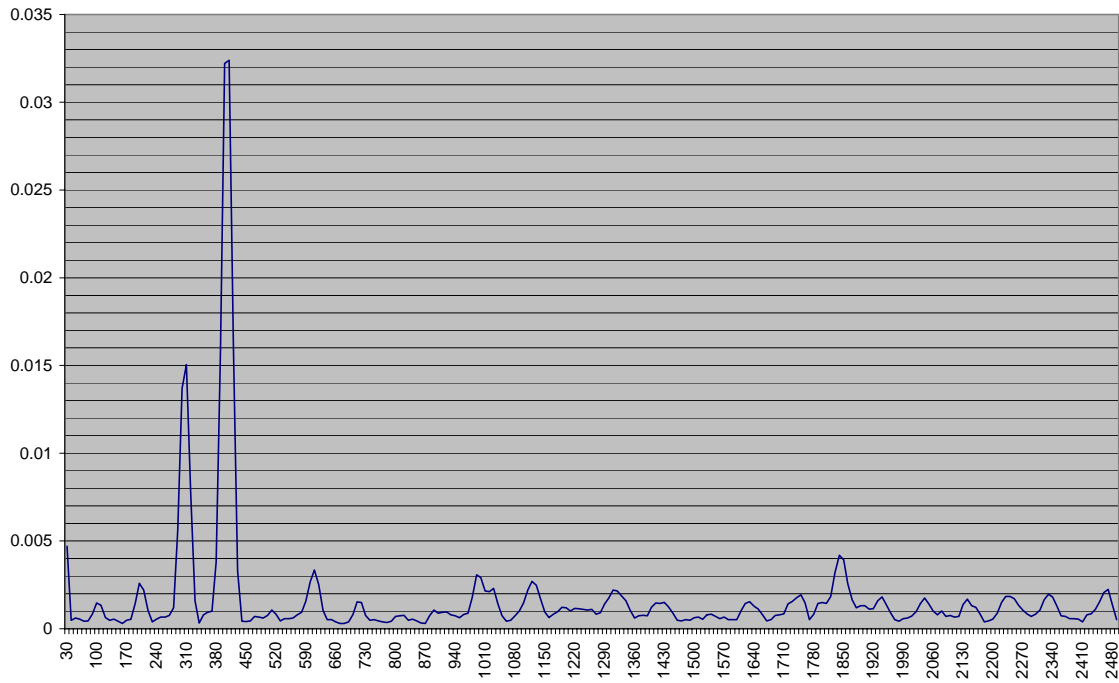
Low-Quality Violin Averages



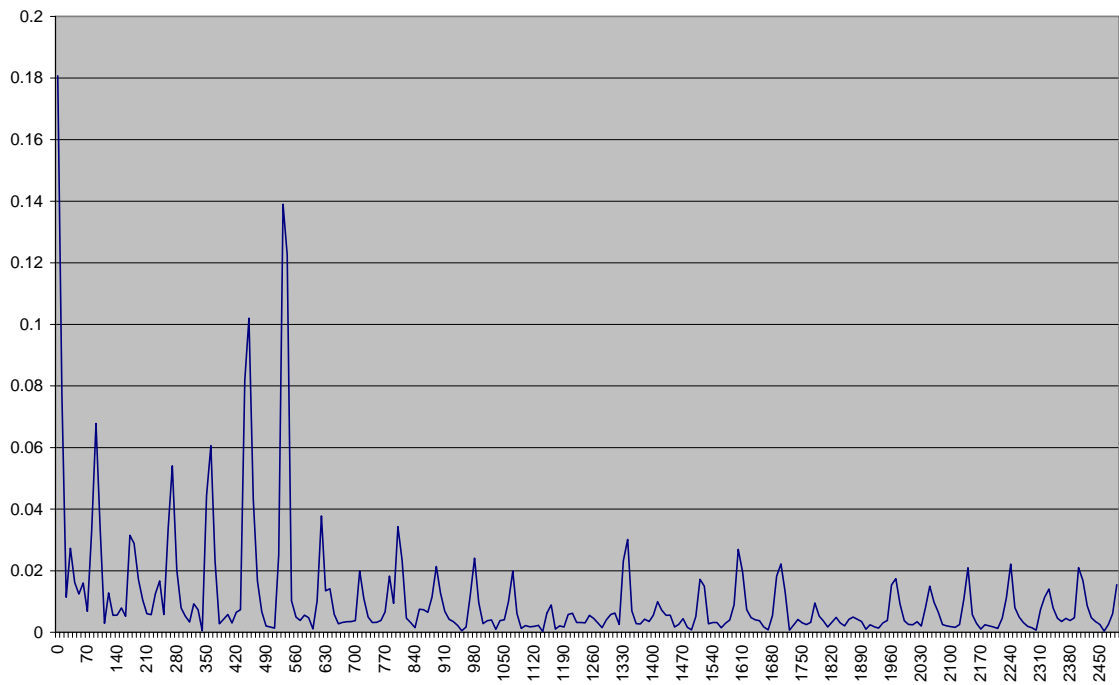
Medium-Quality Violin Averages



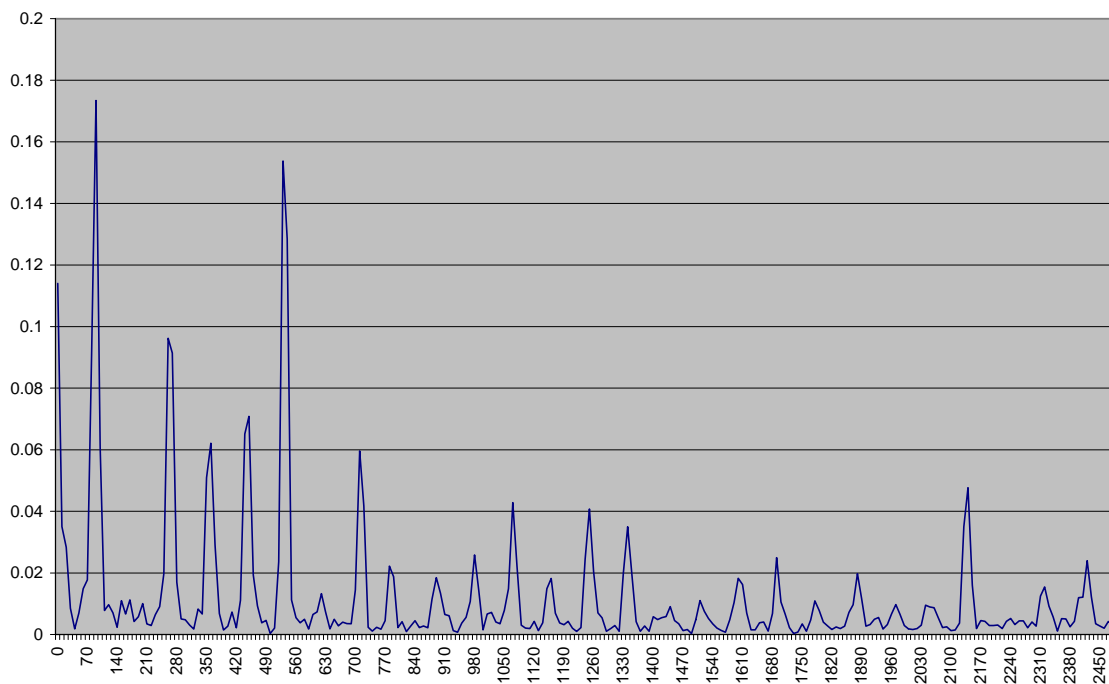
Isolated G-String Averages



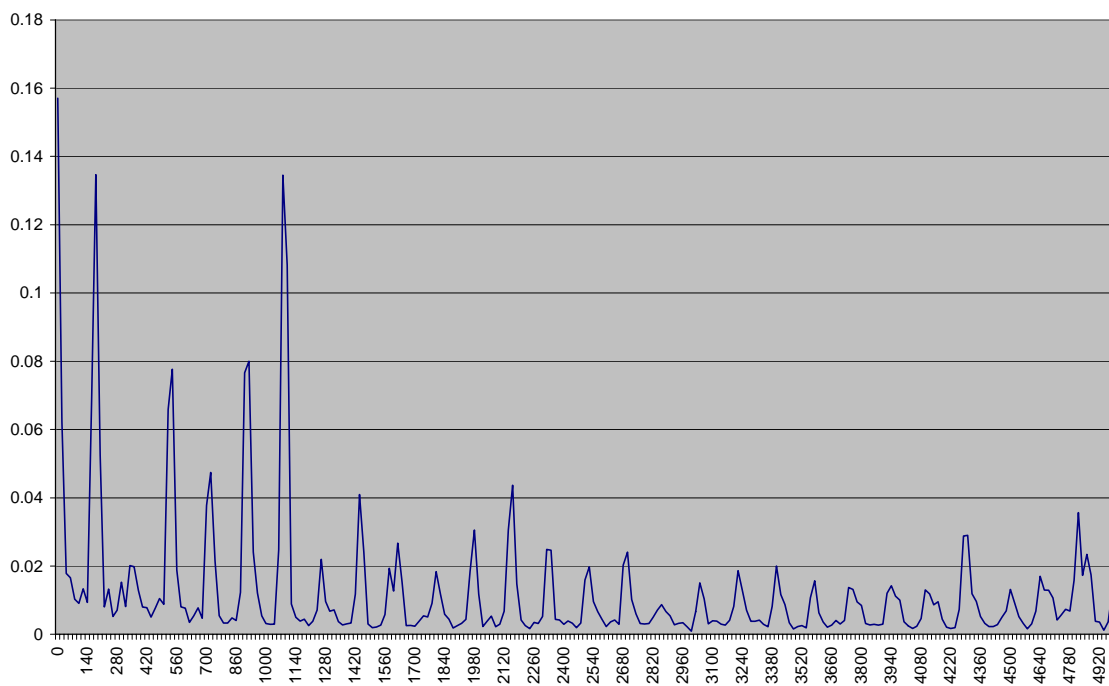
Isolated G-String - Middle - Trial 1



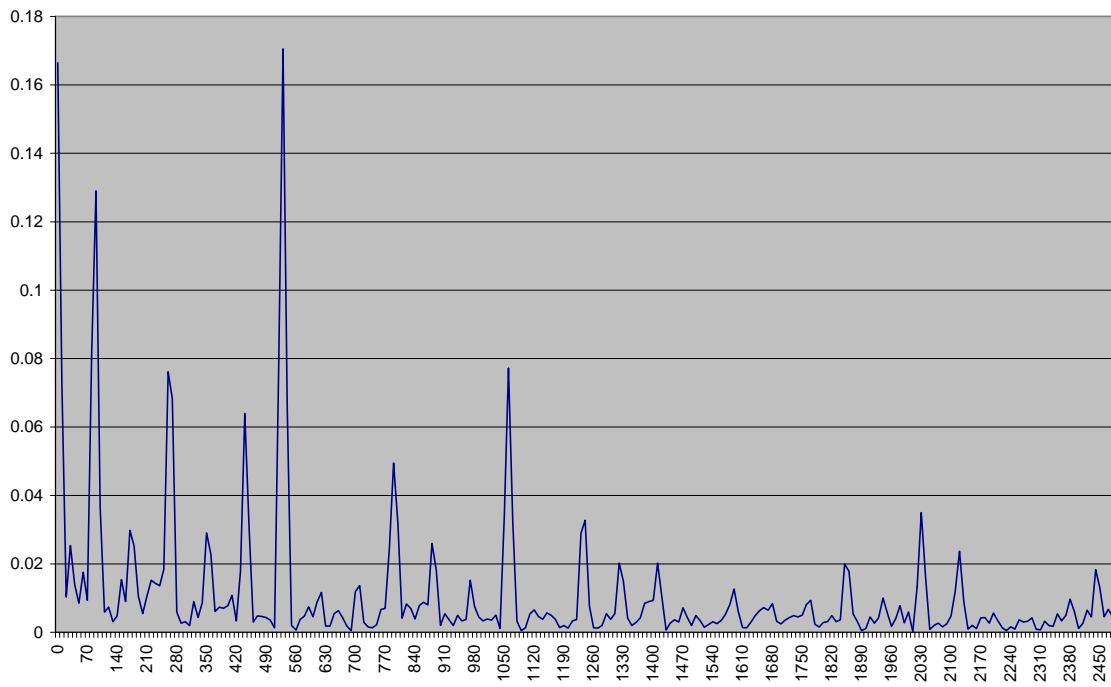
Isolated G-String - Middle - Trial 2



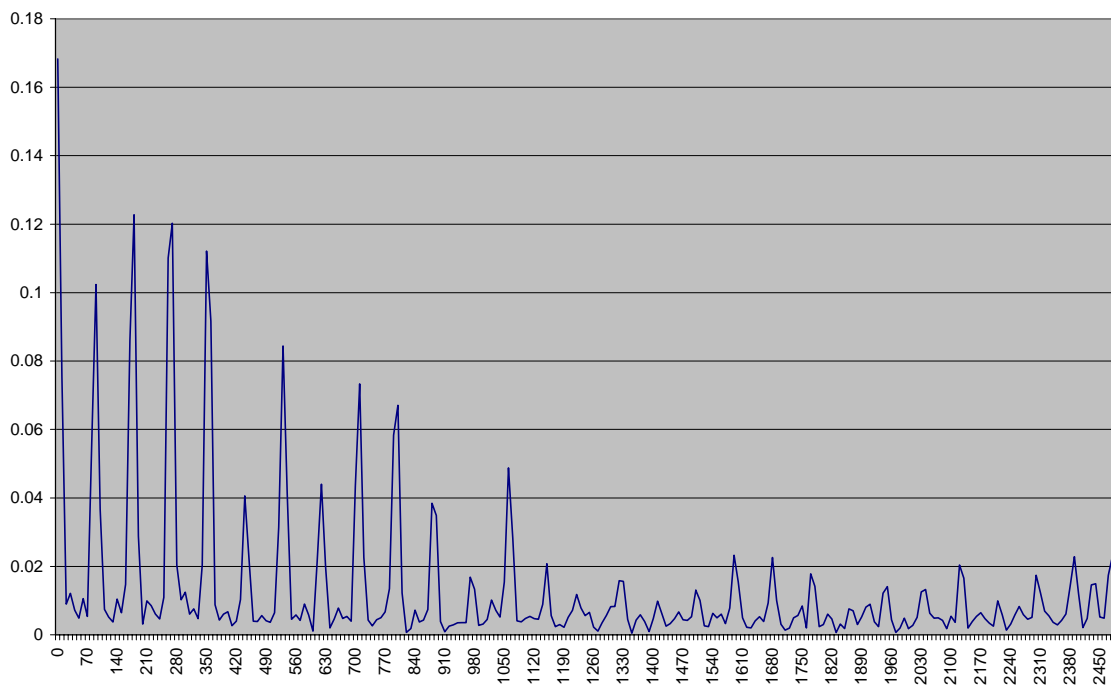
Isolated String Average - Microphone at Middle



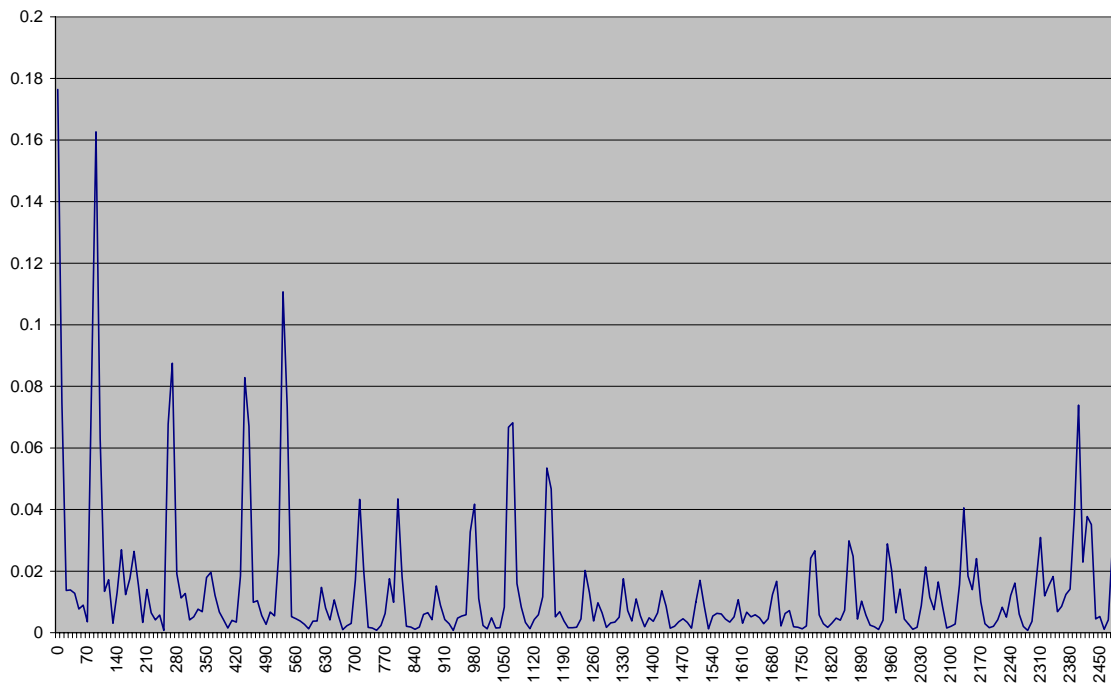
Isolated G-String - End - Trial 1



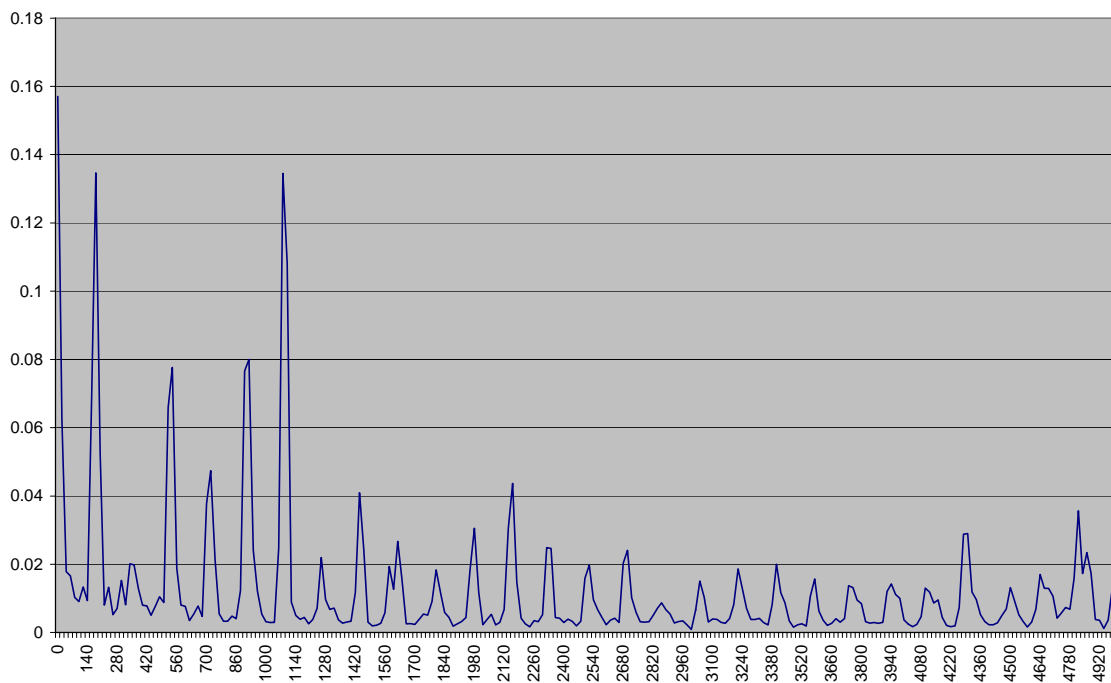
Isolated G-String - End - Trial 2



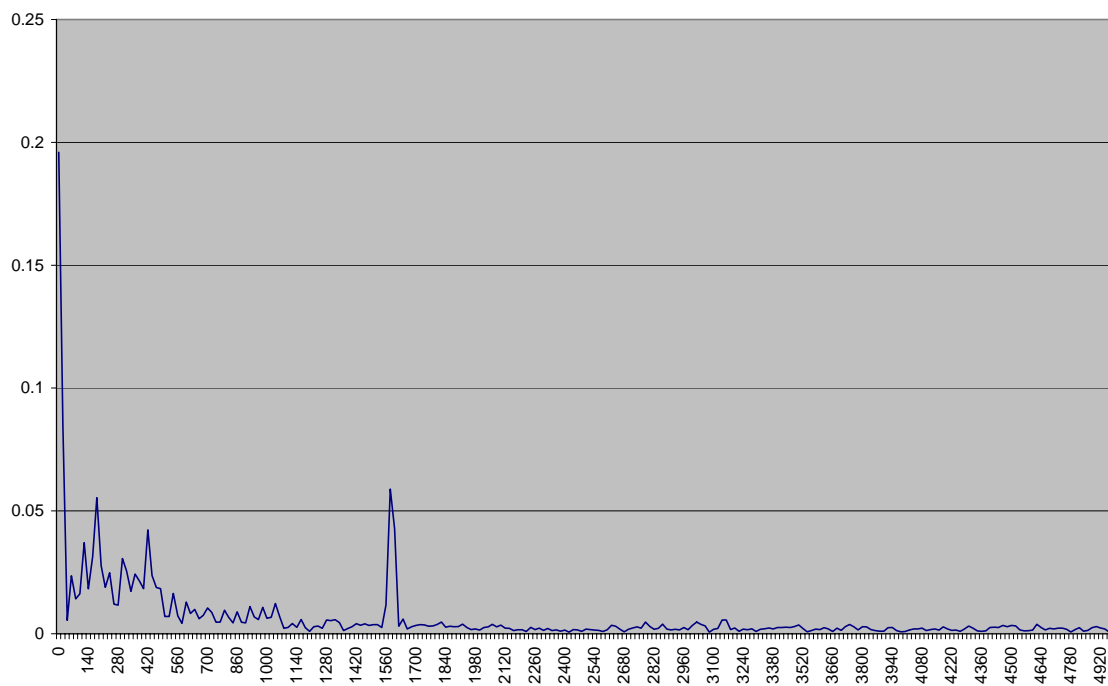
Isolated G-String - End - Trial 3



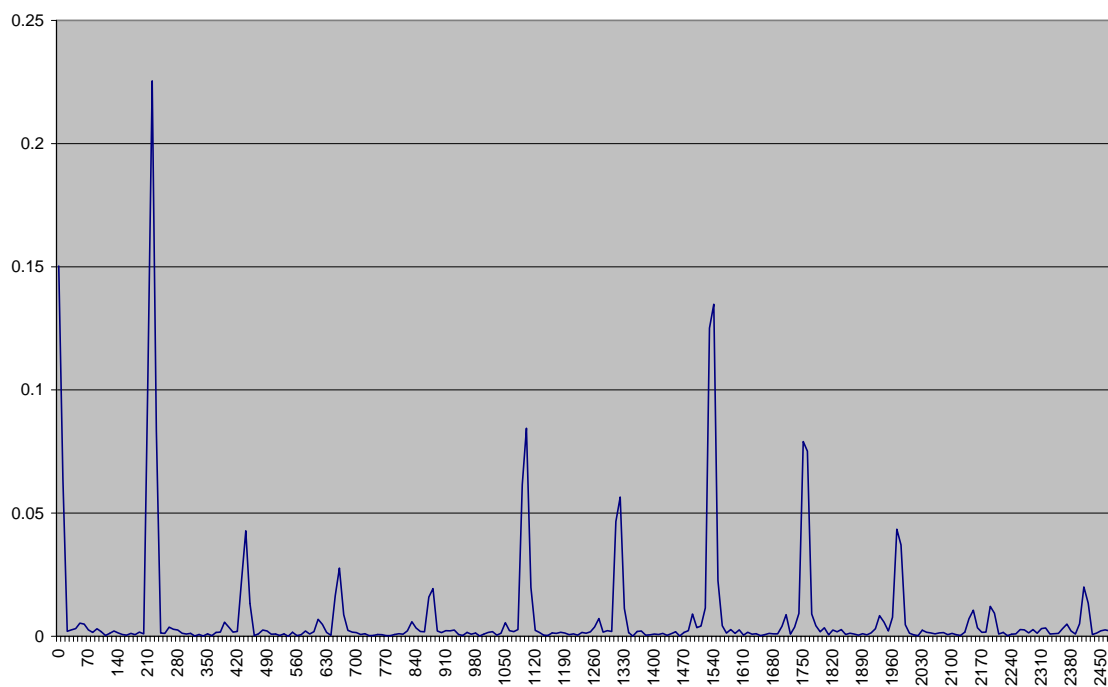
Isolated String Average - Microphone at Middle



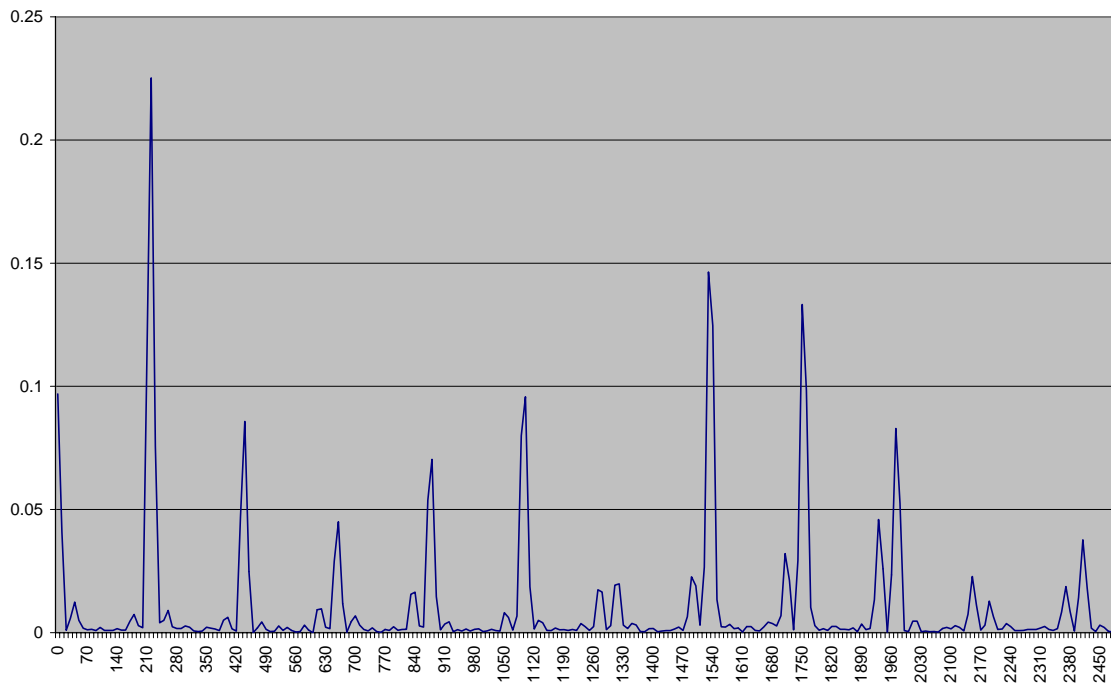
Noise Average - Amplified



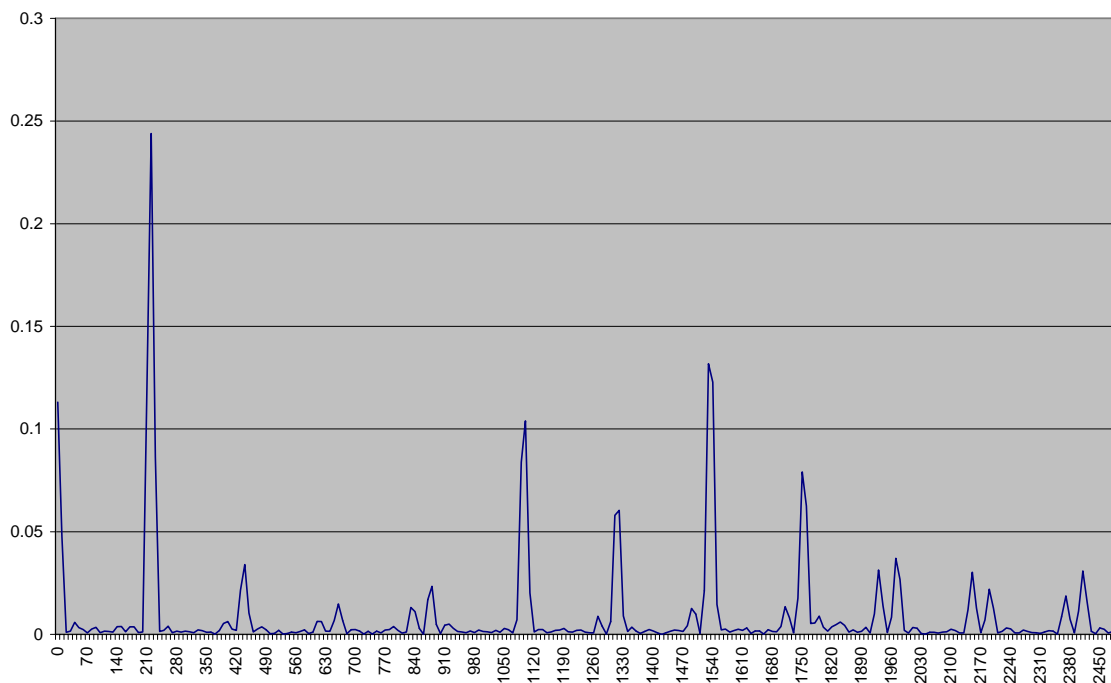
440 Hz - Medium-Quality - Trial 1



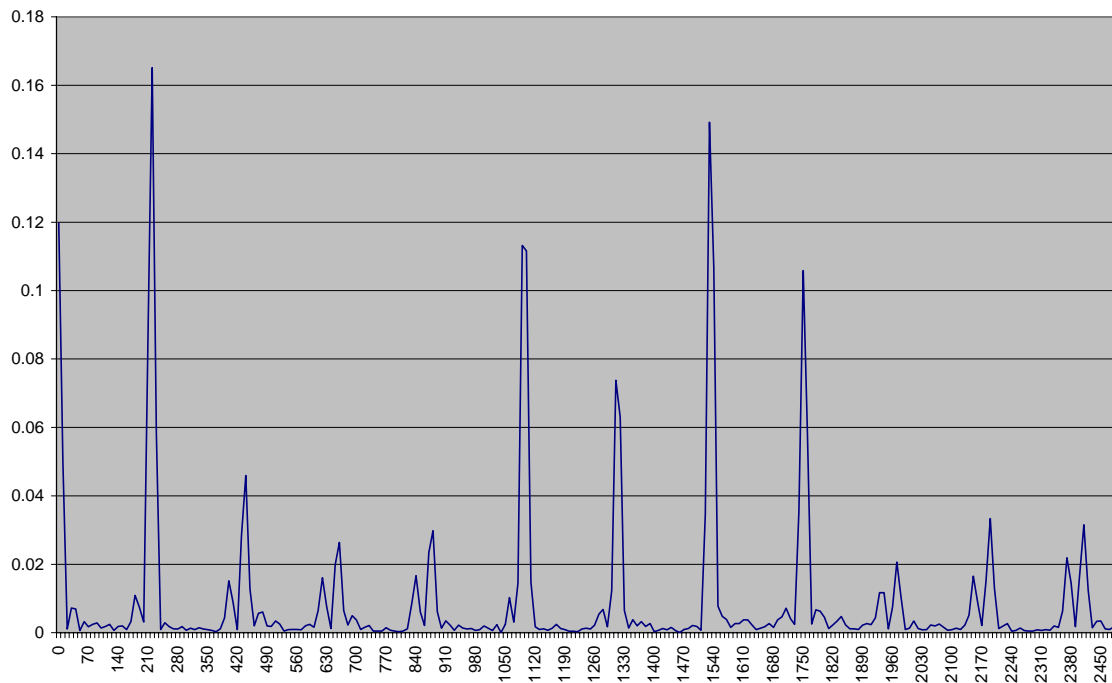
440 Hz - Medium-Quality - Trial 2



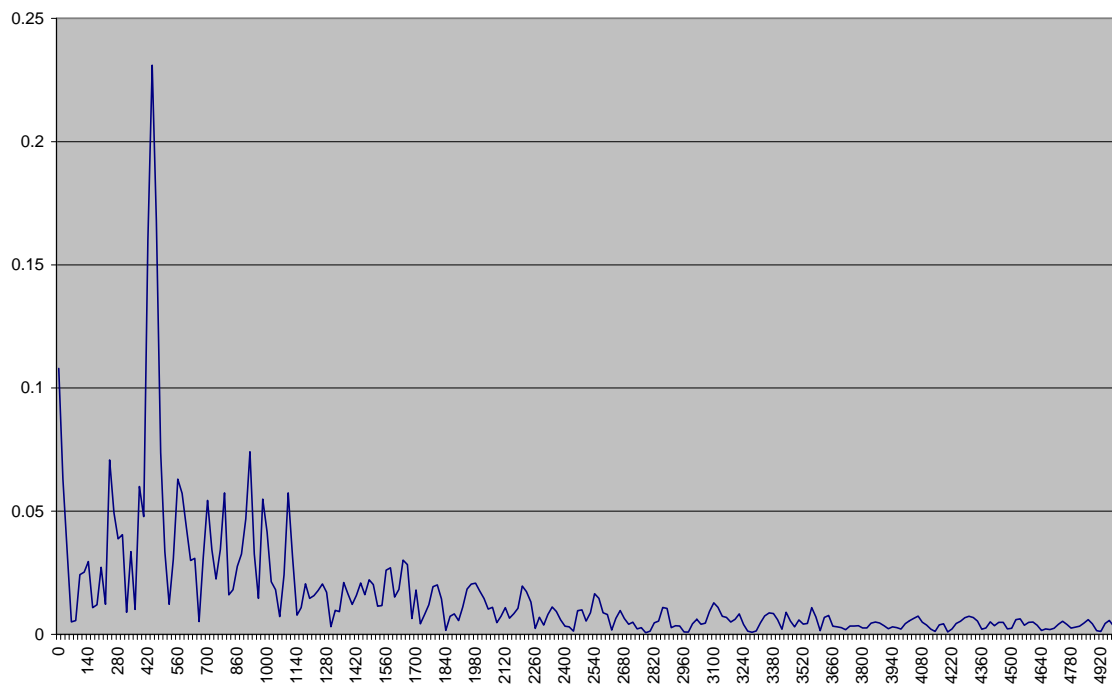
440 Hz - Medium-Quality - Trial 3



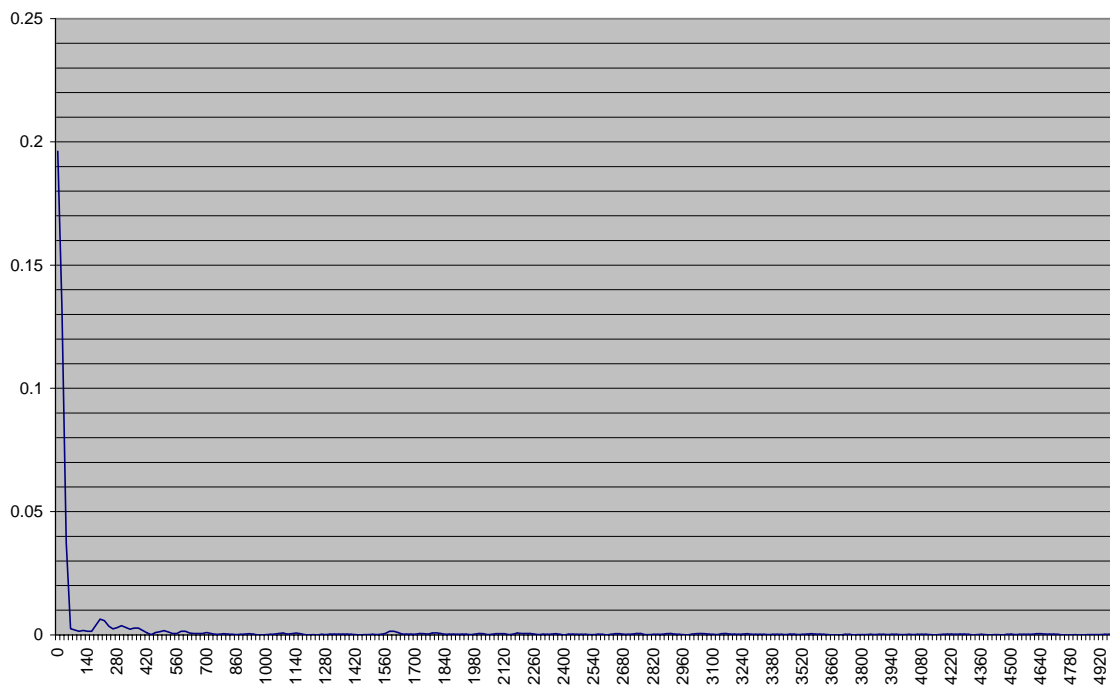
440 Hz - Medium-Quality - Trial 4



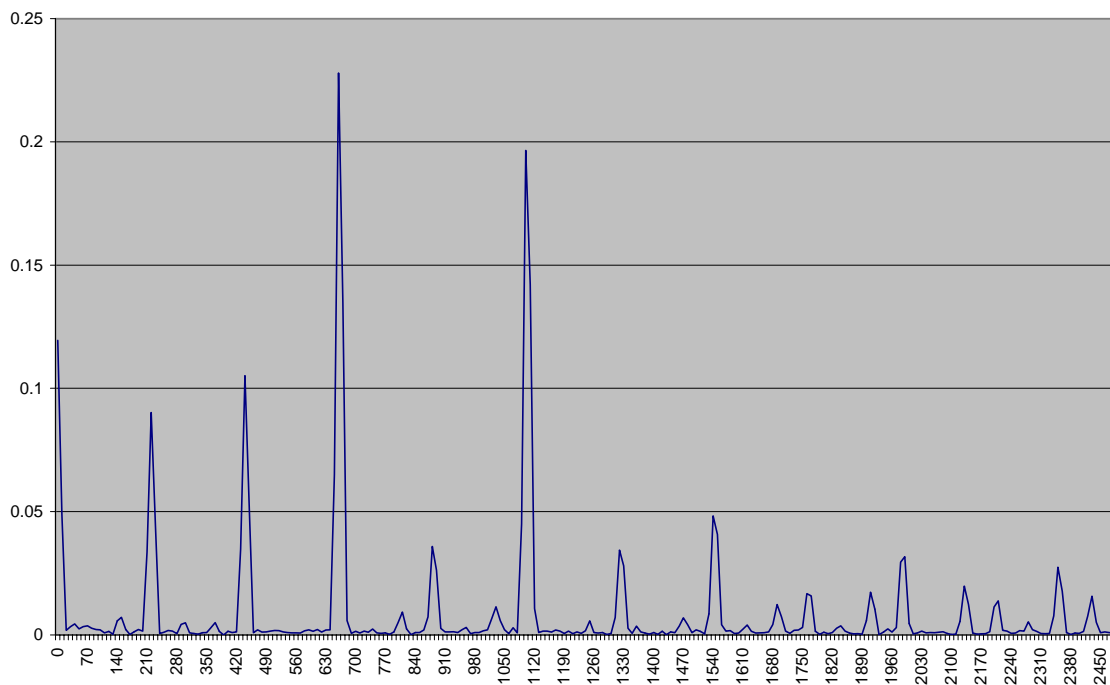
Wood Resonance - Medium-Quality



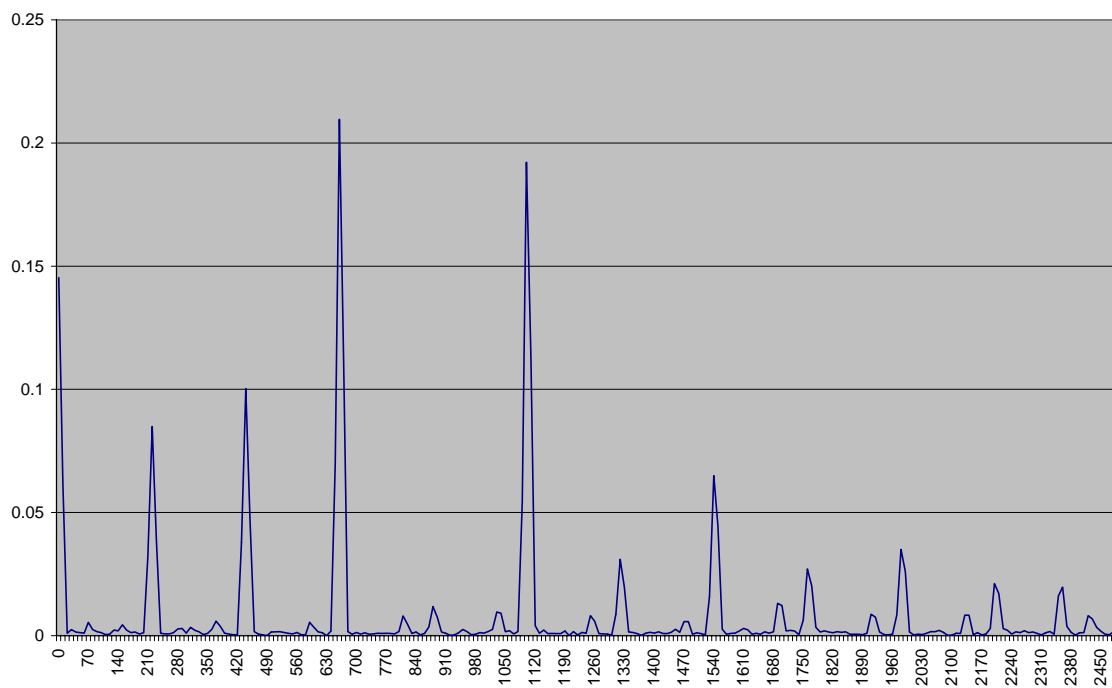
Hardware Noise



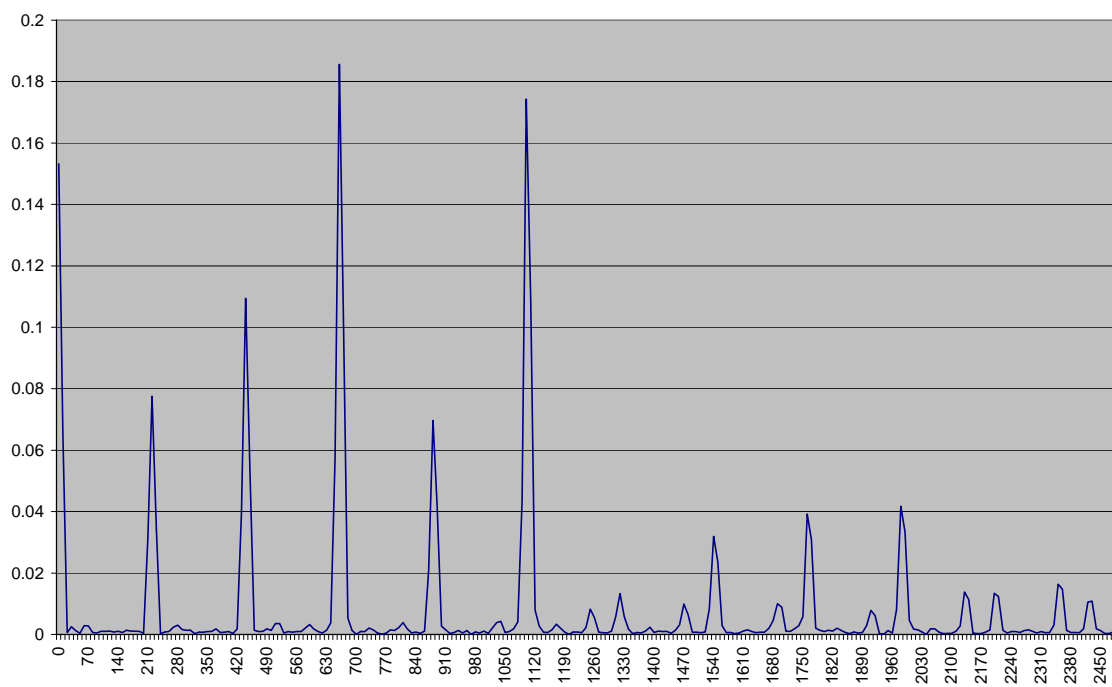
440 Hz - Low-Quality - Trial 1



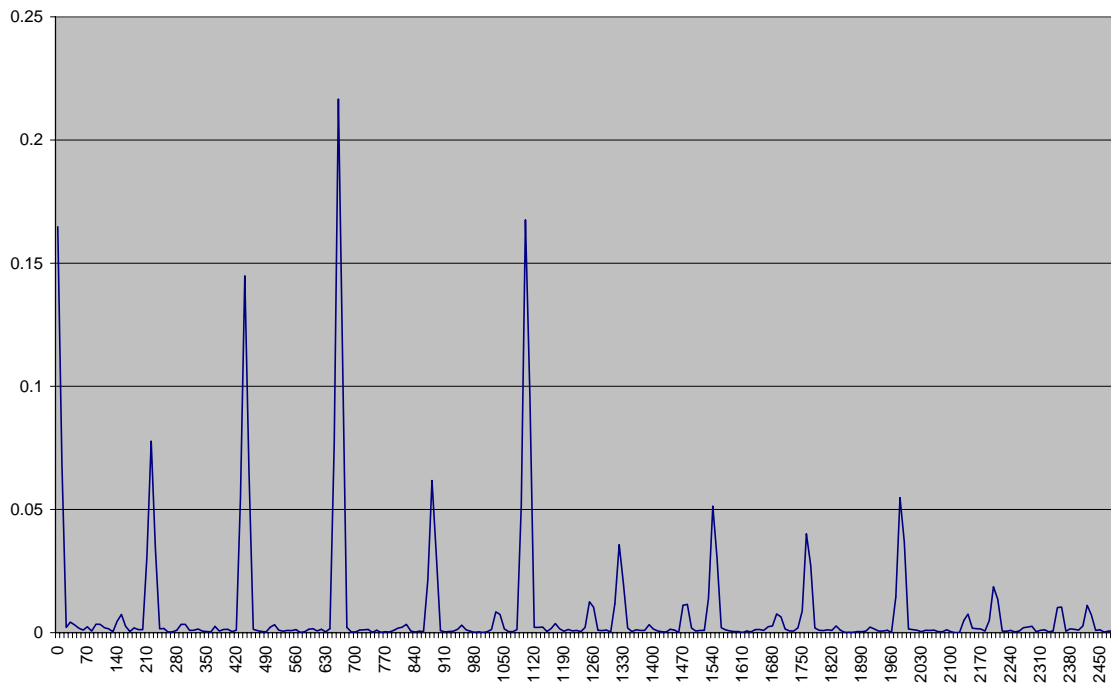
440 Hz - Low-Quality - Trial 2



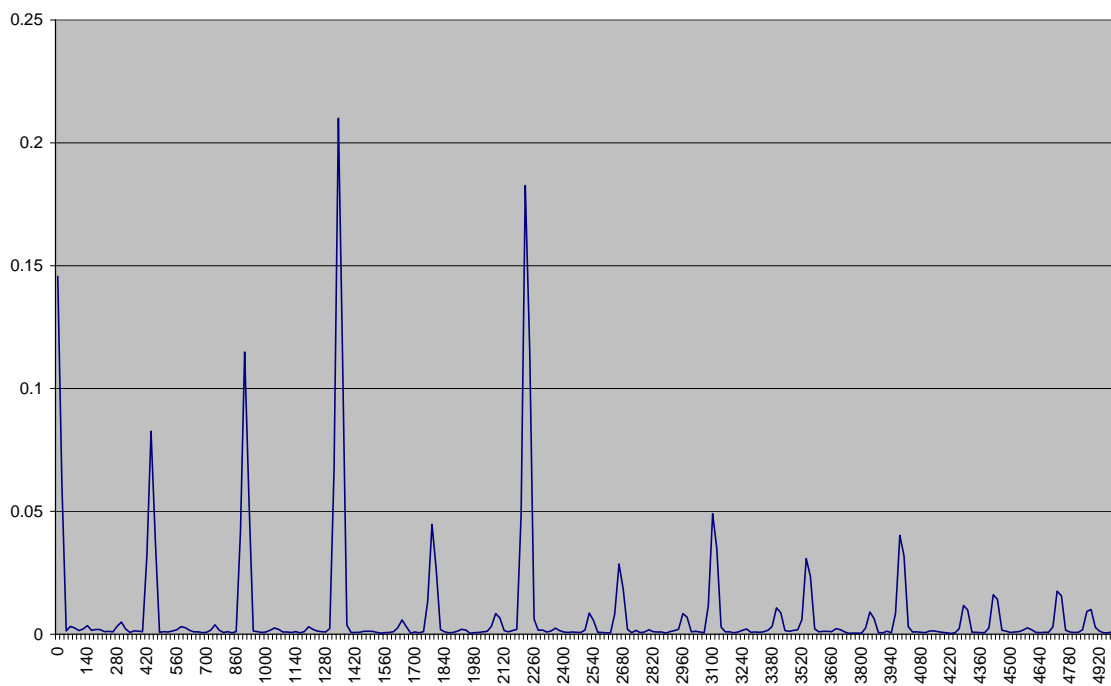
440 Hz - Low-Quality - Trial 3



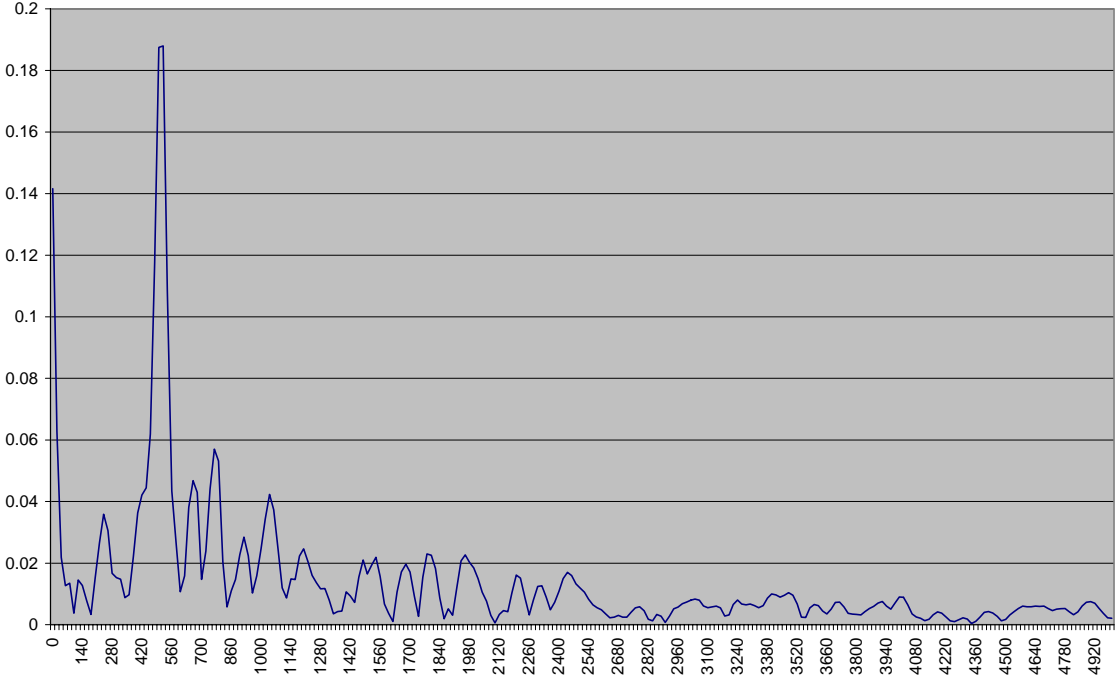
440 Hz - Low-Quality - Trial 4



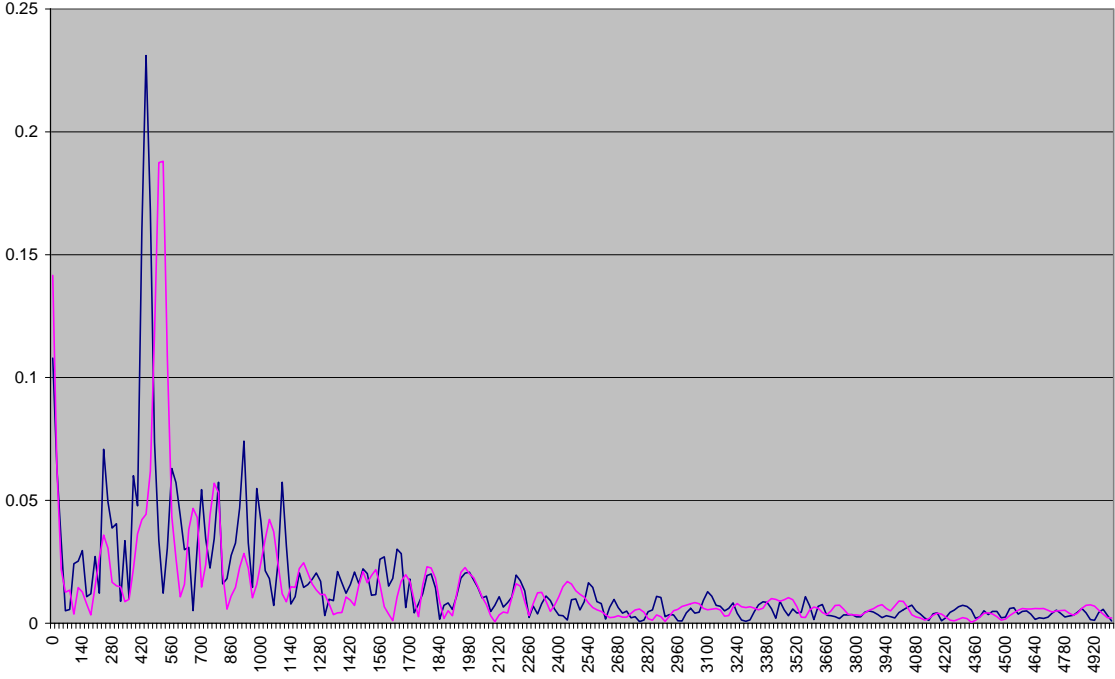
440Hz - Low-Quality Averages



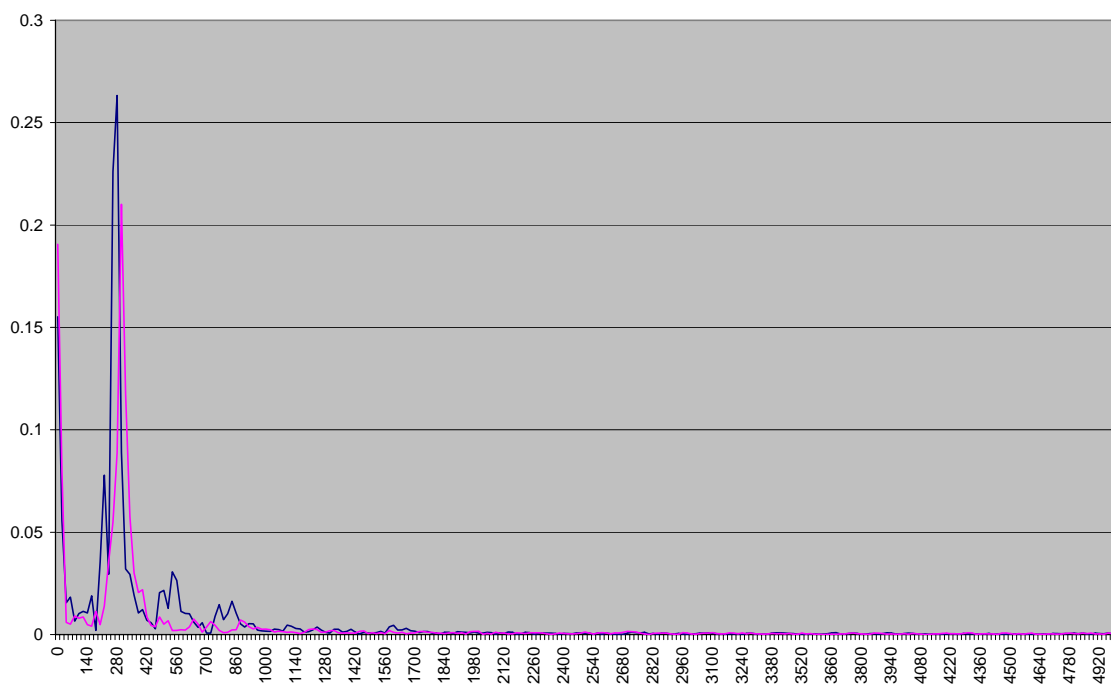
Wood Resonance - Low-Quality



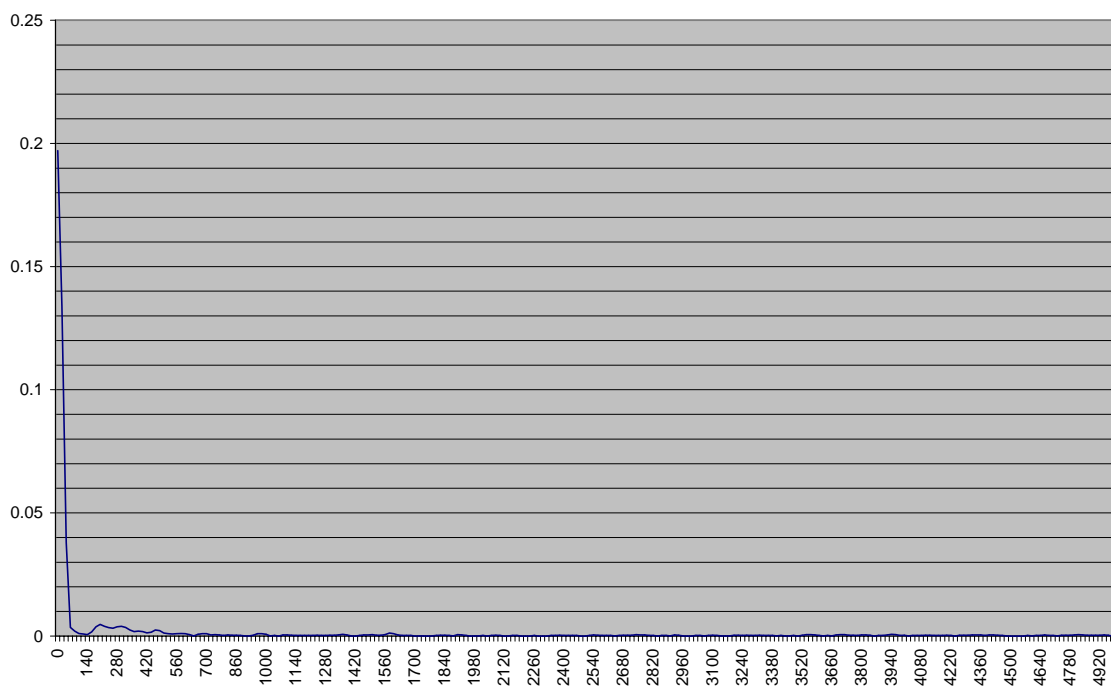
Superimposed MWRs



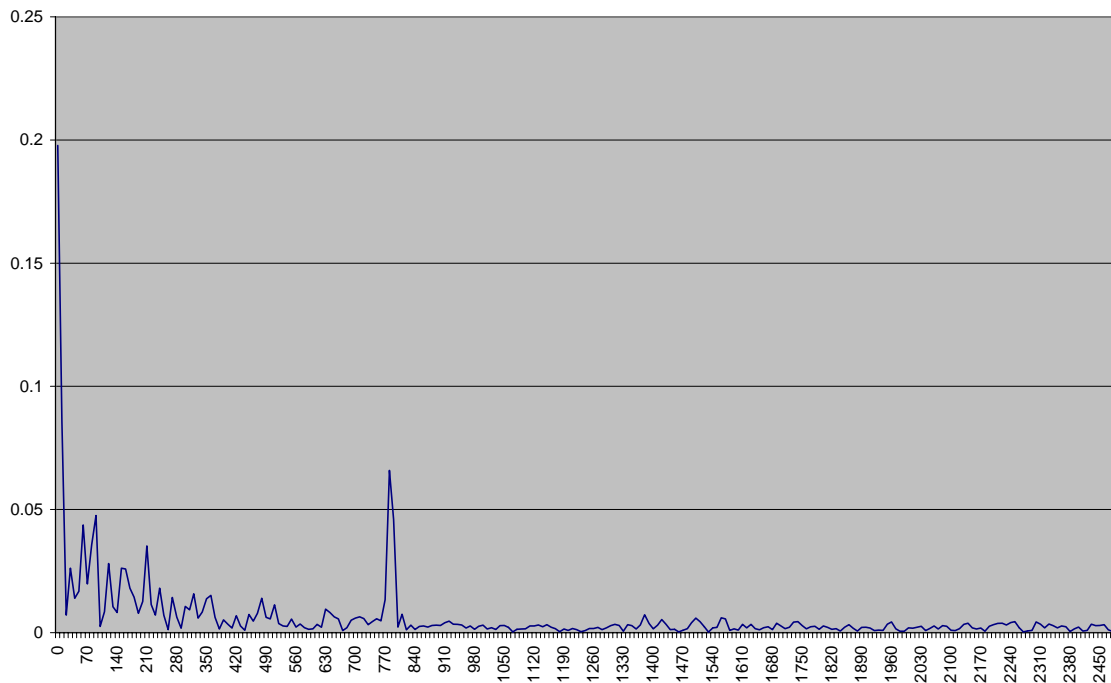
Superimposed Air Resonances



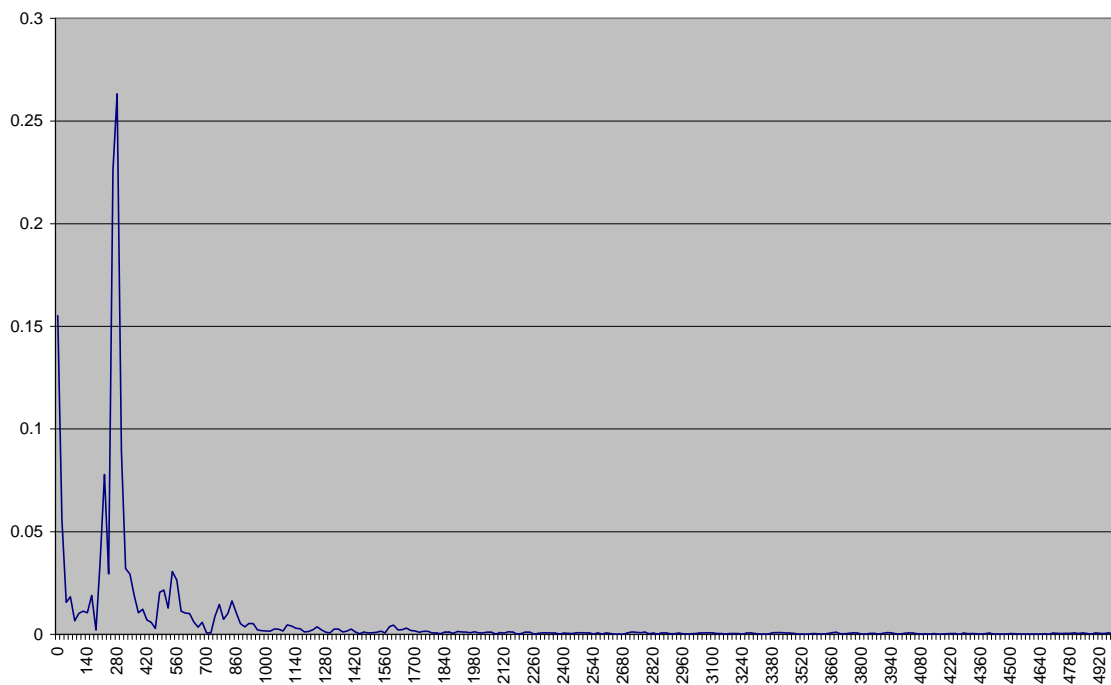
Noise - Trial 2



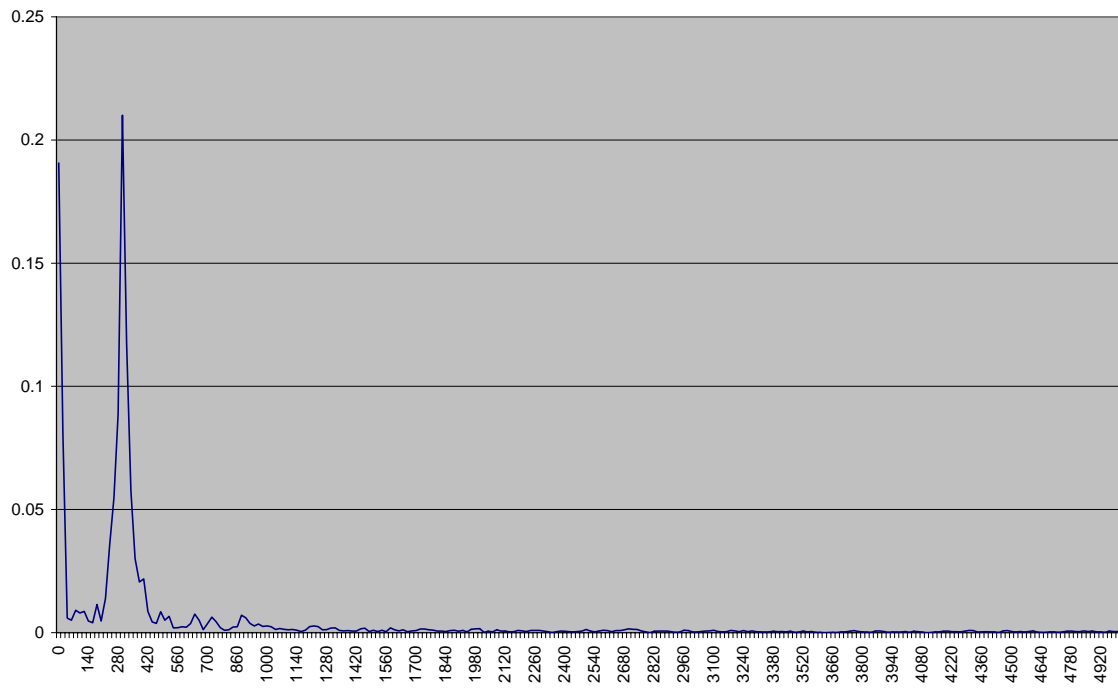
Noise - Amplification - Trial 2



Air Resonance - Medium-Quality



Air Resonance - Low-Quality



APPENDIX 1

While, according to David Einstein¹⁹, the timbre of an instrument “depend[s] in part on the spectrum of the harmonics produced within a single note” (without changing finger position or tension and mass of string), there are many other factors that may affect the tone quality of a given pitch, including attack-and-decay transients, inharmonicities, directional radiation pattern, vibrato, and the chorus effect²⁰ (Berg, 1982). Thus, while the intimate interaction between the generator and the resonator may determine only one aspect of the instrument’s timbre, however, it is classified one of the strongest and most identifiable factors (Sundberg, 1991).

Alternate Variables

S. Handel, an experimentalist in psychoacoustics and professor of Psychology at the University of Tennessee, verified the pertinence of these variables in his 1995 study, where he suggested that, “the cues for timbre depend on context: the duration, the context, and the frequencies of the notes, the set of comparison sounds, the task, and the experience of the subjects.” While Handel seems to suggest that a great deal of timbre quality is due to the perceiver, other studies seem to suggest that timbre is based on a composition of more objective variables. As part of his PhD dissertation, John M. Grey, a graduate from Stanford University, recorded and analyzed 16 tones from 12 orchestral instruments in order to understand the components of an instrument’s timbre (Grey, 1977). He performed a “time-spectrum analysis” in order to verify that listeners base their judgments on three dimensions: the “spectral energy distribution of the sound” (strength of resonances), “synchrony of onset and decay between the harmonics and the spectral flux” (pertaining to the Fourier Spectrum: composition of frequencies that make up the ‘composite sound’ of which is audible to the listener), and the temporal characteristics (attack and decay transients) (Grey). While the first of the three ‘dimensions’ encompasses only several of the many variables that affect the tone of an instrument –for example, the resonance placement, resonance response and formants- this set of variables is most frequently studied by modern acoustical physicists.

¹⁹ 2007 graduate from Yale University, author of unpublished study, “The Effect of Mutes on Fourier Spectra of the Trombone”

²⁰ For more information, consult p. 103-106 of “Richard Berg’s Physics of Sound”

Appendix 2

Each family of instrument produces a different form of resultant wave, determined by the ‘boundary conditions’ of the medium. Zobel explains that “*the way that the medium is held at its ends, either fixed or open, controls the wavelengths of the standing waves*” (2006).

Instruments with two similar boundaries (both ‘open’ or ‘closed’) produce an overtone series containing both even and odd harmonics, while instruments with opposite boundaries²¹ (one ‘open’, other ‘closed’) produce only odd harmonics. Thus, because string instruments have ‘closed’ boundaries²², the overtone spectrum contains all harmonics ($f_n = f_1 n$, where $n = \text{integral multiples } (2, 3, 4, \dots)$ of the fundamental (fig.1).

Mathematically, each component wave (P_n) (at harmonic n) is represented by a sinusoidal function relating angular velocity ($\omega = 2\pi f$) to the period (t): $P_n = (1/n)\sin(n\omega_0 t)$. Thus, the resultant wave²³ is represented as follows:

$$P_r = P_1 + P_2 + P_3 + \dots$$

$$P_r = \sin(\omega_0 t) + (1/2)\sin(2\omega_0 t) + (1/3)\sin(3\omega_0 t) + \dots$$

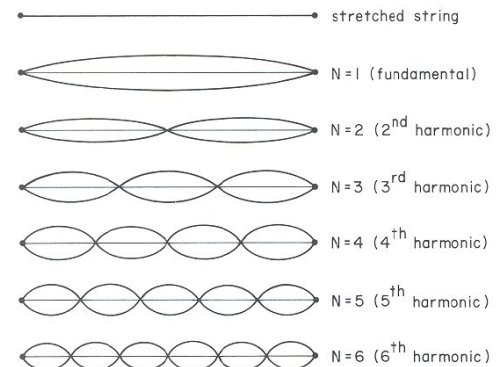


Figure 2: Harmonics on a string (Berg, 1982)

²¹ Most notably single-reed woodwinds

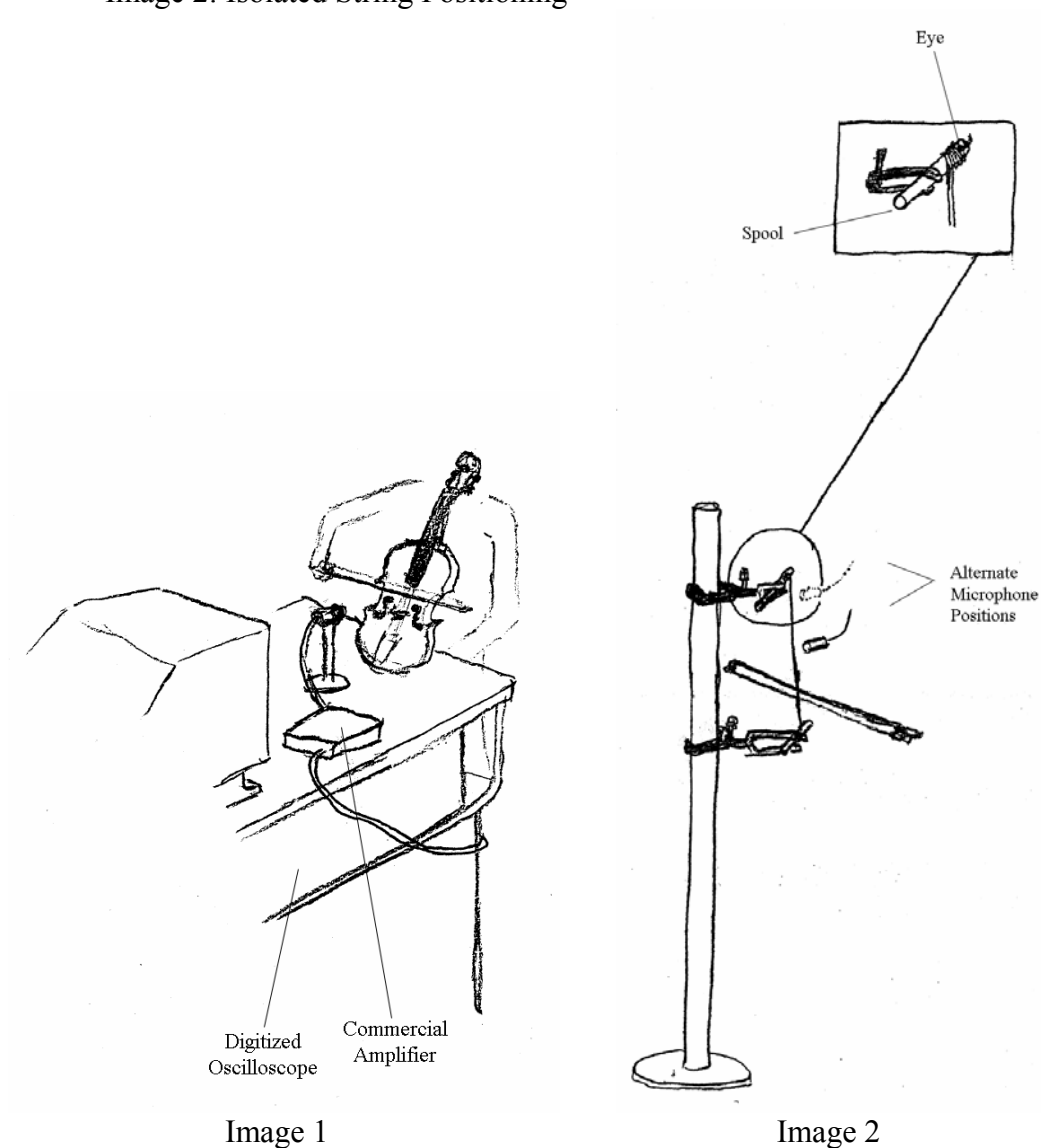
²² Both sides of the string remain fixed while the string vibrates

²³ The resultant wave of a string instrument is known as a *saw-tooth wave*

Appendix 3: Setup

Image 1: Violin Positioning

Image 2: Isolated String Positioning



Note: Because the spools are fixed in the setup of the isolated string (fig. 2), the string is very difficult to tune precisely. It is also quite difficult to get a high tension due to human limitations. Thus, in my testing, the string was tuned to approximately 180 Hz.

Appendix 4: Violins

Low Quality:

Lark. Produced in Shanghai, China

<http://www.lark-violin.com/>

Medium-Quality:

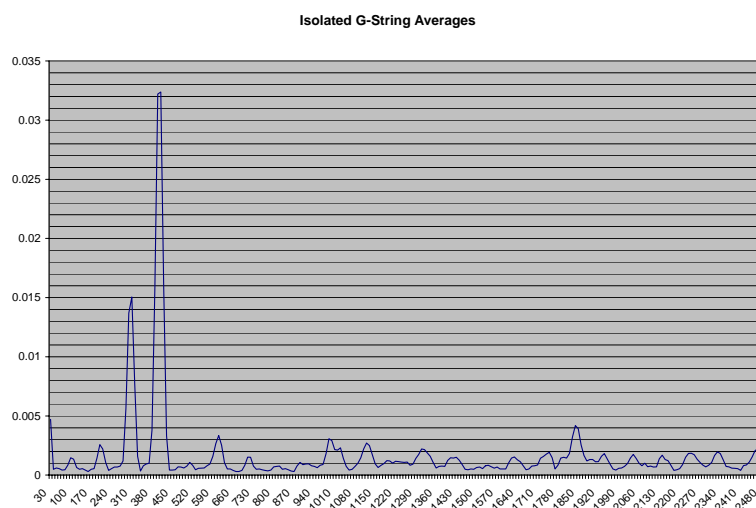
Ernst Heinrich Roth. Produced in Bubenreuth/Erlangen, Germany. 1959. Modeled after Antonio Stradivarius 1714

http://www.roth-violins.de/index_eng.htm

Appendix 5: Graphs from Round 1 Testing

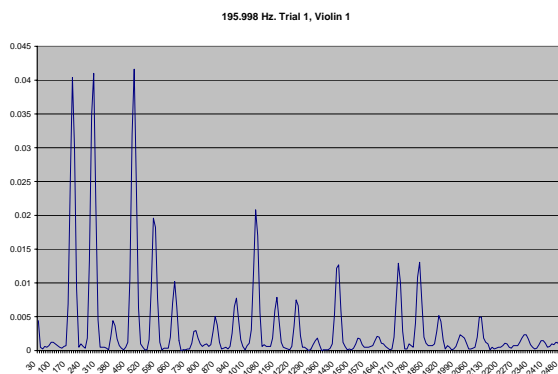
Isolated String

Isolated String Averages

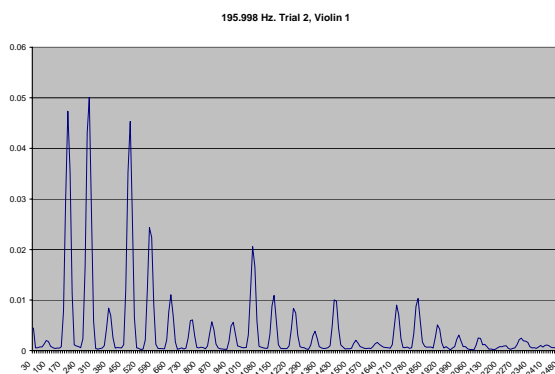


Medium Quality Violin

Trial 1 – Medium-Quality Violin

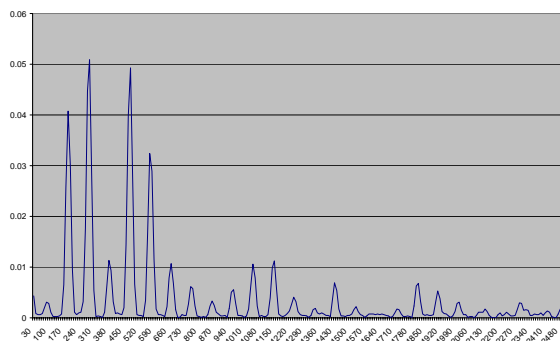


Trial 2



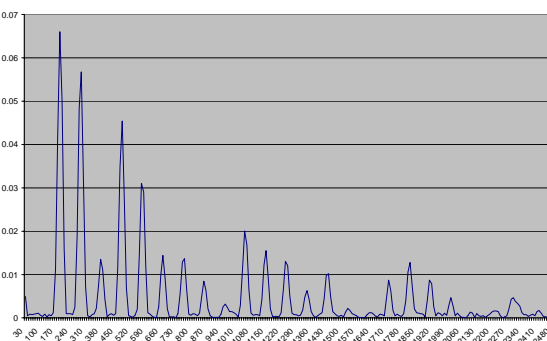
Trial 3

195.998 Hz. Trial 3, Violin 1



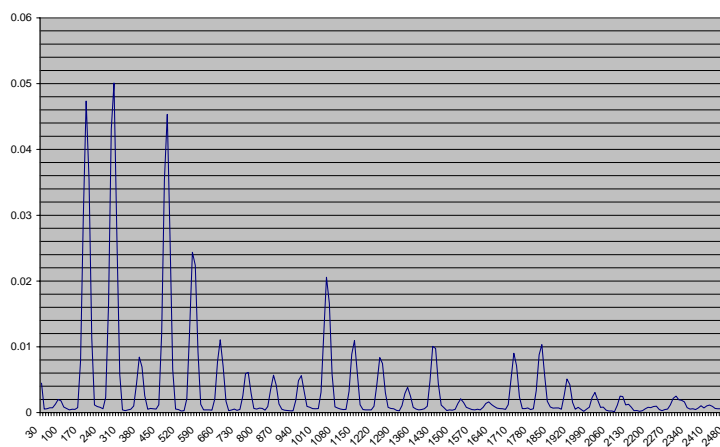
Trial 4

195.998 Hz. Trial 4, Violin 1



Medium Quality Violin Averages

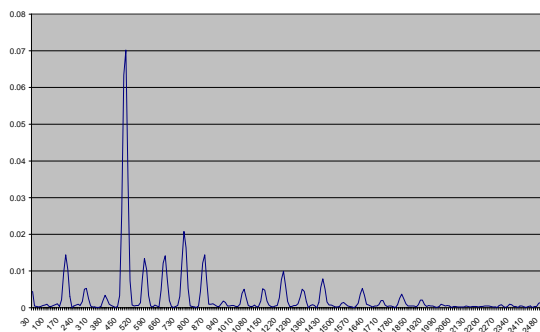
Medium-Quality Violin Averages



Low-Quality Violin

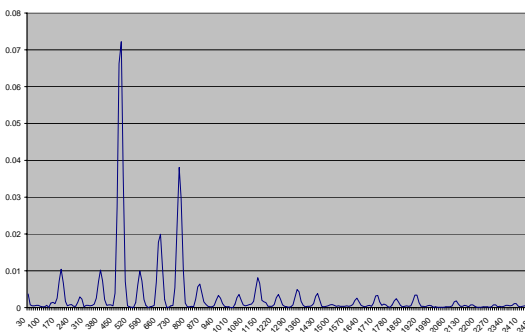
Trial 1 – Low-Quality Violin

195.998 Hz. Trial 1, Violin 2



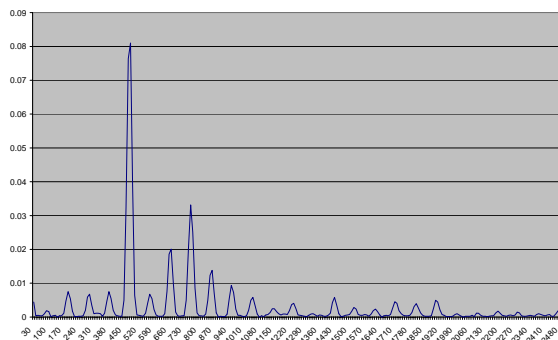
Trial 2

195.998 Hz. Trial 2, Violin 2



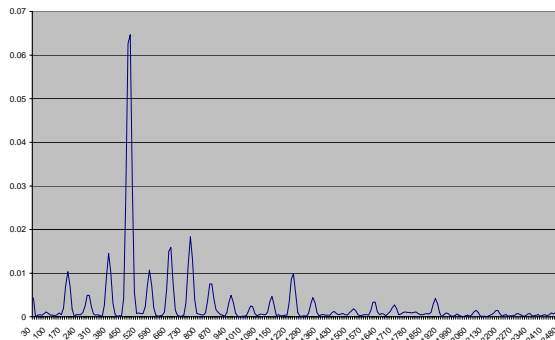
Trial 3

195.998 Hz. Trial 3, Violin 2



Trial 4

195.998 Hz. Trial 4, Violin 2



Low-Quality Violin Average

Low-Quality Violin Averages

