# Science of Music / Musical Instruments

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Nov. 9, 2004

"**Music of the Spheres**" *Michail Spiridonov*, 1997-8

# QUESTION:
## Does EC/JH/JB/JP/PT/RJ/…
## {*Your Favorite Musician*}
## Need To Know *Physics* In
## Order To Play Great Music
## ???

**ANSWER:**

*"Physics !?! We don't need no steenking physics !!!"*

# However…

**Learning about & *investigating* the science underlying the music <u>can</u>:**

**1.    Help to improve & enhance the music…**

**2.    Help to improve & enhance the musical instruments…**

**3.    Help to improve & enhance our understanding of why music is <u>so</u> important to our species…**

# What is Sound?

Sound describes two different physical phenomena:

• Sound = A disturbance in a physical medium (gas/liquid/solid) which propagates in that medium. What is this exactly? How does this happen?

• Sound = An auditory sensation in one's ear(s)/in one's brain - what is this exactly??? How does this happen?

• Humans & other animal species have developed the ability to hear sounds - because sound(s) exist in the natural environment.

• All of our senses are a direct consequence of the existence of stimuli in the environment - eyes/light, ears/sound, tongue/taste, nose/smells, touch/sensations, balance/gravity, migratorial navigation/earth's magnetic field.

• Why do we have *two* ears? Two ears are the *minimum* requirement for spatial *location* of a sound source.

• Ability to locate a sound is very beneficial - e.g. for locating food & also for avoiding becoming food….

# Acoustics

• Scientific study of sound

• Broad interdisciplinary field - involving physics, engineering, psychology, speech, music, biology, physiology, neuroscience, architecture, etc….

•Different branches of acoustics:

>   • Physical Acoustics
>
>   • Musical Acoustics
>
>   • Psycho-Acoustics
>
>   • Physiological Acoustics
>
>   • Architectural Acoustics
>
>   • Etc...

# What *is* Music?

• **An aesthetically pleasing sequence of tones?**

• ***Why* is music pleasurable to humans?**

• **Music has always been part of human culture, as far back as we can tell**

• **Music important to human evolution?**

• ***Memory* of music much better (stronger/longer) than "normal" memory! Why? How?**

• **Music shown to *stimulate* human brain activity**

• **Music *facilitates* brain development in young children and in *learning***

• **Music/song is also important to other living creatures - birds, whales, frogs, etc.**

• **Many kinds of animals utilize sound to communicate with each other**

• **What is it about music that does all of the above ???**

## Human Development of Musical Instruments

• **Emulate/mimic human voice (some instruments much more so than others)!**

• **Sounds from musical instruments can evoke powerful emotional responses - happiness, joy, sadness, sorrow, shivers down your spine, raise the hair on back of neck, etc.**

# Musical Instruments

• Each musical instrument has its own characteristic sounds - quite complex!

• Any note played on an instrument has fundamental + harmonics of fundamental.

• Higher harmonics - brighter sound

• Less harmonics - mellower sound

• Harmonic content of note can/does change with time:

    • Takes time for harmonics to develop - "attack" (leading edge of sound)

    • Harmonics don't decay away at same rate (trailing edge of sound)

    • Higher harmonics tend to decay more quickly

• Sound output of musical instrument is not uniform with frequency

    • Details of construction, choice of materials, finish, etc. determine *resonant structure* (formants) associated with instrument - mechanical vibrations!

• See harmonic content of guitar, violin, recorder, singing saw, drum, cymbals, etc.

• See laser interferogram pix of vibrations of guitar, violin, handbells, cymbals, etc.

# Sound Waves
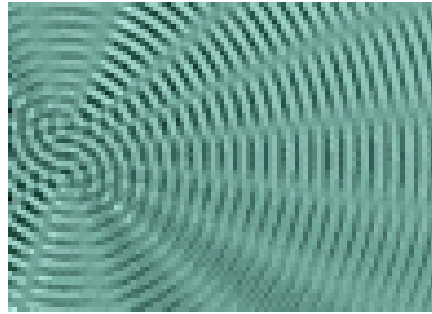
Sound propagates in a physical medium (gas/liquid/solid) as a wave, or as a sound pulse ( = a collection/superposition of traveling waves)

• An acoustical disturbance propagates as a collective excitation (i.e. vibration) of a group of atoms and/or molecules making up the physical medium.

• Acoustical disturbance, e.g. sound wave carries *energy*, *E* and *momentum*, *P*

• For a homogeneous (i.e. uniform) medium, disturbance propagates with a constant speed, *v*

• Longitudinal waves - atoms in medium are displaced longitudinally from their equilibrium positions by acoustic disturbance - i.e. along/parallel to direction of propagation of wave.

• Transverse waves - atoms in medium are displaced transversely from their equilibrium positions by acoustic disturbance - i.e. perpendicular to direction of propagation of wave.

• Speed of sound in air:  $v_{air} = \sqrt{(B_{air}/\rho_{air})}$ ~ 344 m/s (~ 1000 ft/sec) at sea level, 20 degrees Celsius.

• Speed of sound in metal, e.g. aluminum:  $v_{Al} = \sqrt{(Y_{Al}/\rho_{Al})}$  ~ 1080 m/s.

• Speed of transverse waves on a stretched string:  $v_{string} = \sqrt{(T_{string}/\mu_{string})}$ where mass per unit length of string, $\mu_{string} = M_{string}/L_{string}$

# Modal Vibrations of a "Singing" Rod:

A metal rod (e.g. aluminum rod) a few feet in length can be made to vibrate along its length – make it "sing" at a characteristic, resonance frequency by holding it precisely at its mid-point with thumb and index finger of one hand, and then pulling the rod along its length, toward one of its ends with the thumb and index finger of the other hand, which have been dusted with crushed violin rosin, so as to obtain a good grip on the rod as it is pulled.
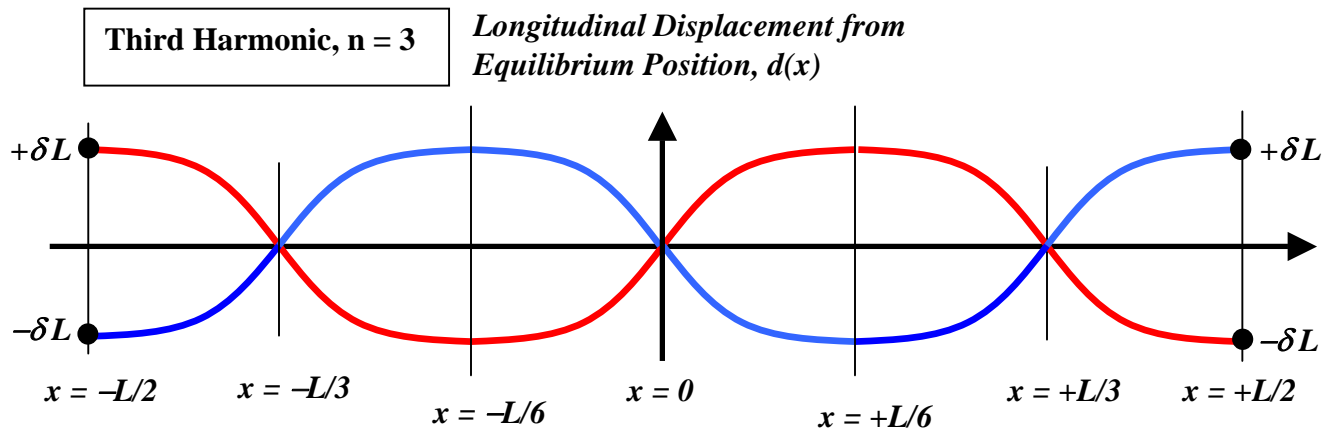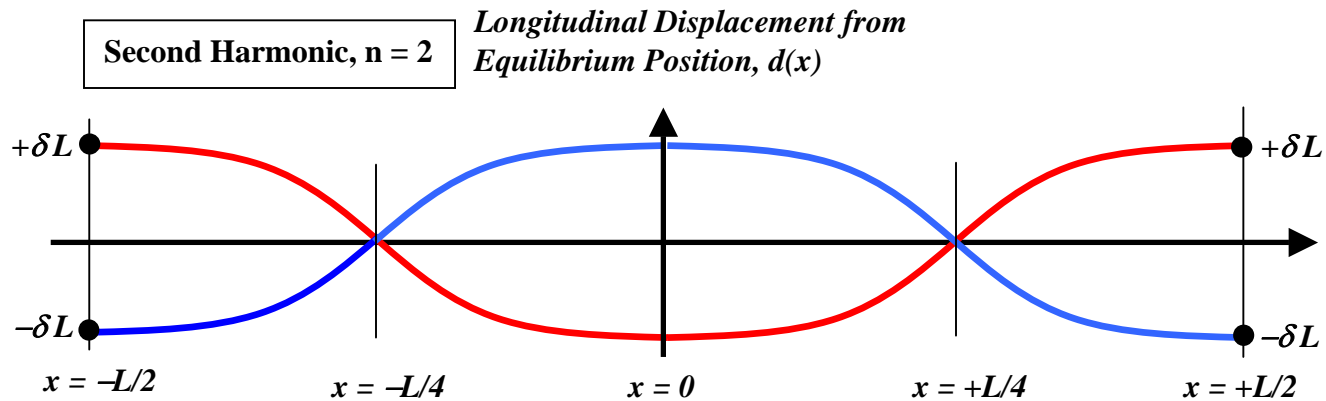


Hold rod here with thumb and index finger of one hand

Pull on rod here along its length with violin rosin powdered thumb and index finger of other hand, stretching the rod



Fundamental, n = 1

*Longitudinal Displacement from Equilibrium Position, d(x)*

$x = -L/2$          $x = 0$          $x = +L/2$
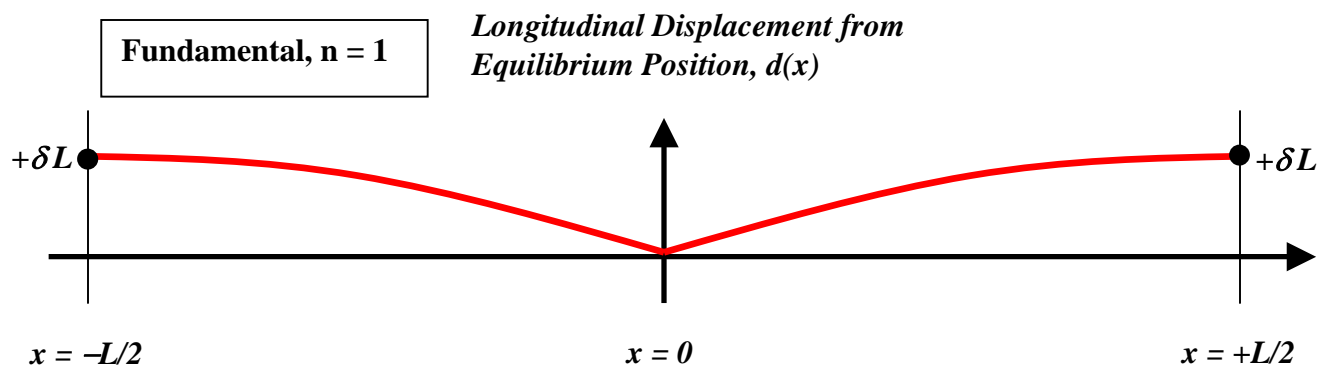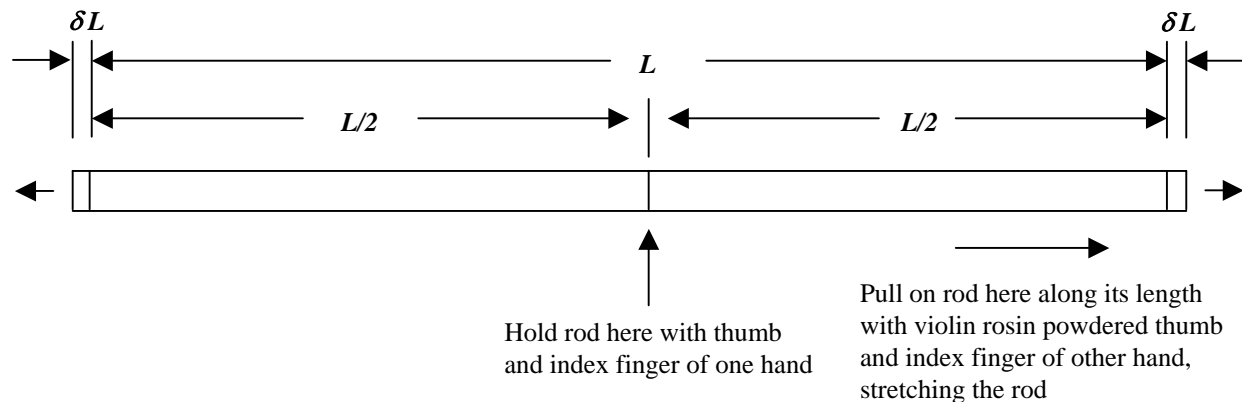
# Decay of Fundamental Mode of Singing Rod:



Amplitude vs. Time
Fundamental of Vibrating Rod @ f1 = 1670 Hz
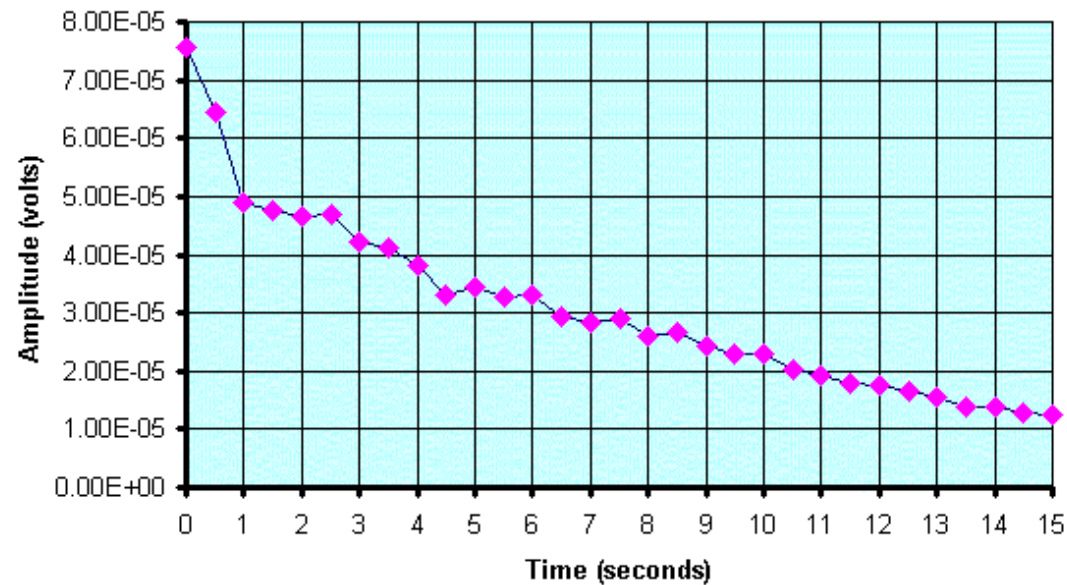
Of course, there also exist higher modes of vibration of the singing rod:



**Second Harmonic, n = 2** | *Longitudinal Displacement from Equilibrium Position, d(x)*

$+\delta L$   $+\delta L$

$-\delta L$   $-\delta L$

$x = -L/2$    $x = -L/4$    $x = 0$    $x = +L/4$    $x = +L/2$

**Third Harmonic, n = 3** | *Longitudinal Displacement from Equilibrium Position, d(x)*

$+\delta L$   $+\delta L$

$-\delta L$   $-\delta L$

$x = -L/2$   $x = -L/3$    $x = 0$    $x = +L/3$   $x = +L/2$

$x = -L/6$    $x = +L/6$

• See singing rod demo...

• If the singing rod is rotated - can hear Doppler effect & beats:

$\mathbf{v_t} = \Omega\, \mathbf{r} = \frac{1}{2}\,\Omega L$

$L/2$

$L/2$

$\phi$

$\mathbf{v_t} = \Omega\, \mathbf{r} = \frac{1}{2}\,\Omega L$

**Observer/Listener**
**Position**
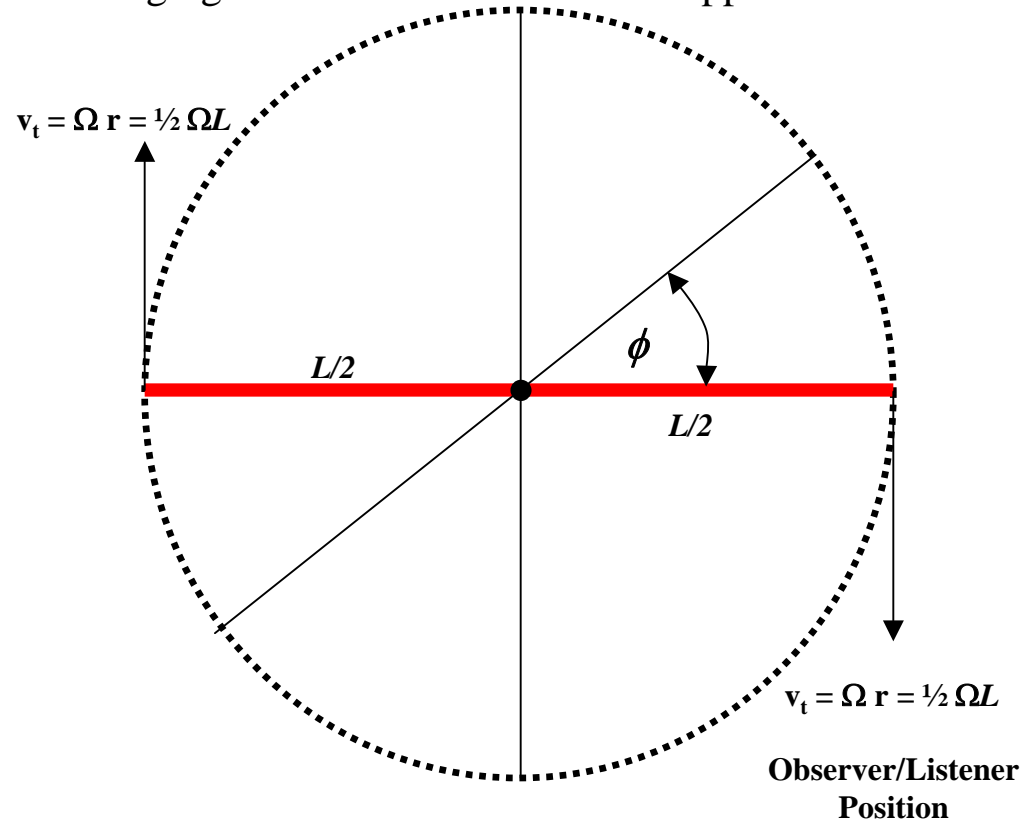
• Frequency of vibrations raised (lowered) if source moving toward (away from) listener, respectively

• Hear Doppler effect & beats of rotating "singing" rod...

Total Sound Amplitude vs. Time
Rotating Vibrating Rod
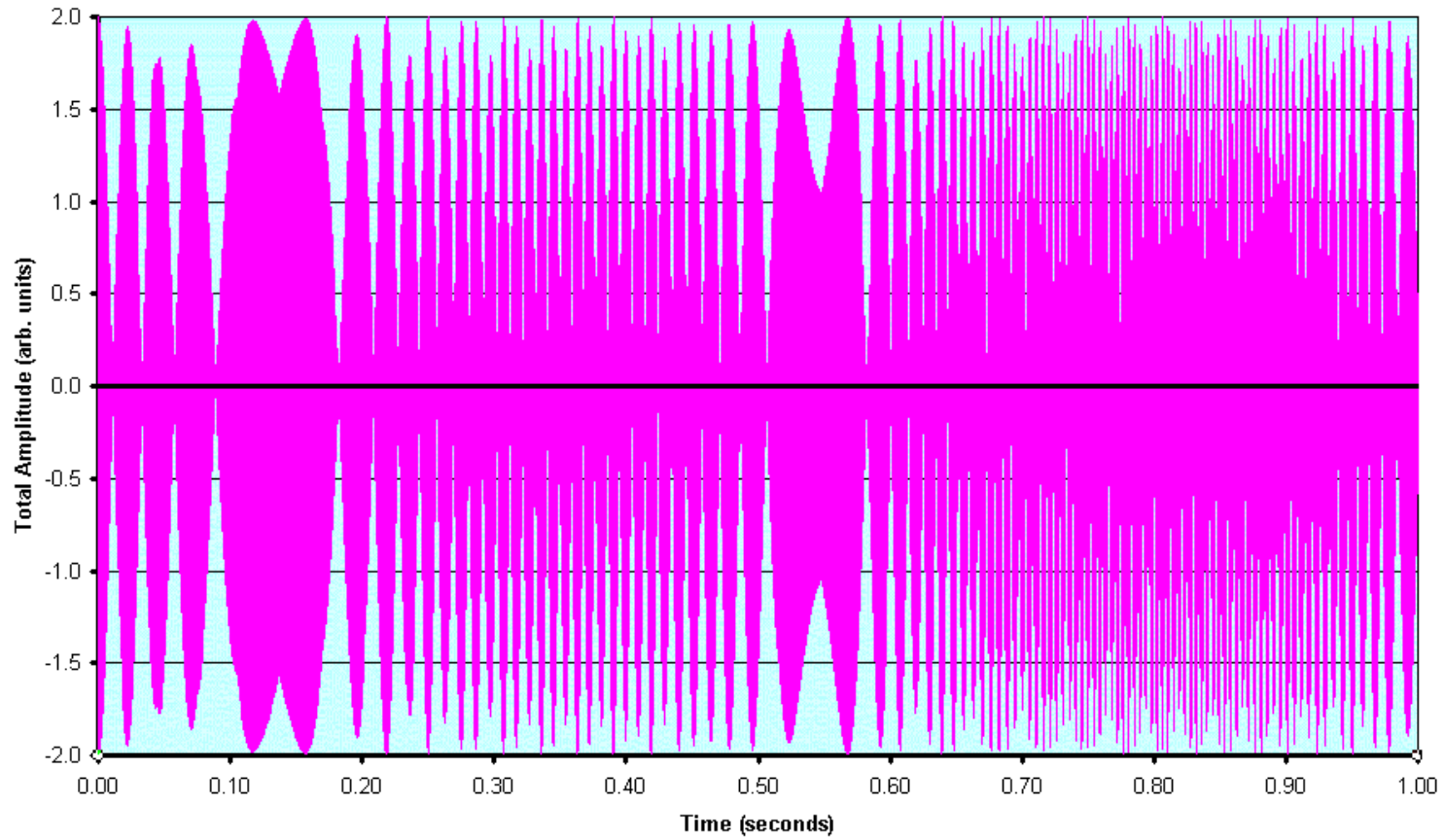
• Would Mandi Patrick (UIUC Feature Twirler) be willing to lead the UI Singing Rod Marching Band at a half-time show ???

# Harmonic Content of Complex Waveforms

From mathematical work (1804-1807) of Jean Baptiste Joseph Fourier (1768-1830),  the spatial/temporal shape of any *periodic* waveform can be shown to be due to linear combination of fundamental & higher harmonics!

Sound Tonal Quality - *Timbre* - harmonic content of sound wave

<u>Sine/Cosine Wave</u>: Mellow Sounding – fundamental, no higher harmonics
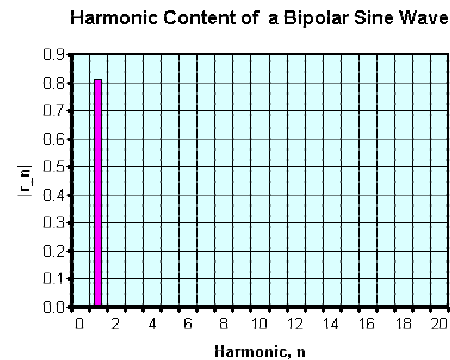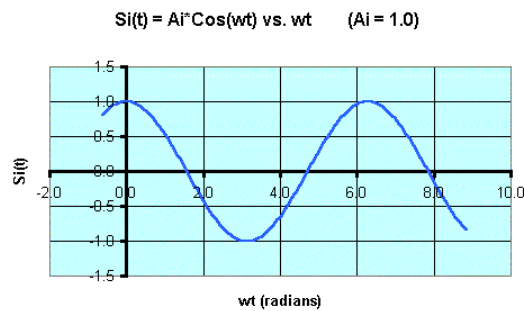


<u>Triangle Wave</u>: A Bit Brighter Sounding – has higher harmonics!

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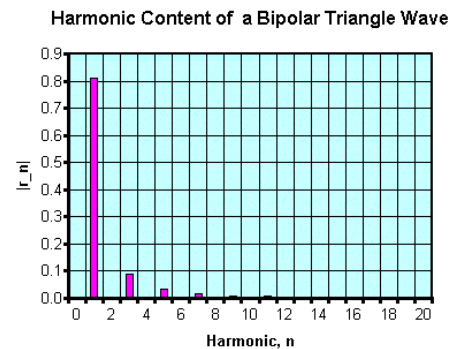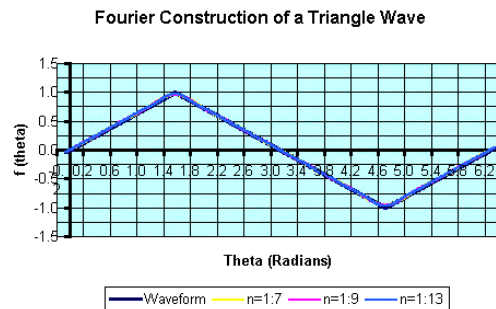
# Asymmetrical Sawtooth Wave: Even Brighter Sounding – even more harmonics!



Fourier Construction of a Sawtooth Wave

Harmonic Content of a Sawtooth Wave
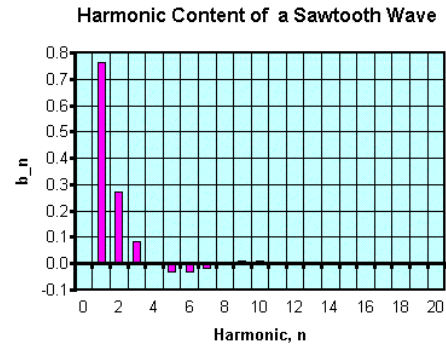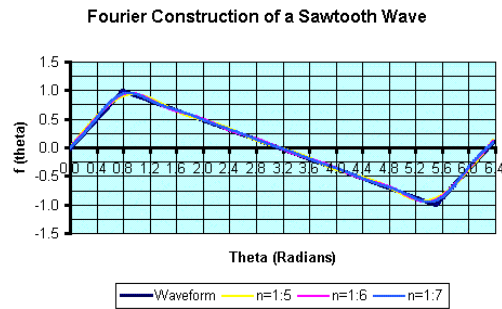
# Square Wave: Brighter Sounding – has the most harmonics!



Fourier Construction of a Square Wave

Harmonic Content of a Bipolar Square Wave (50% Duty Cycle)

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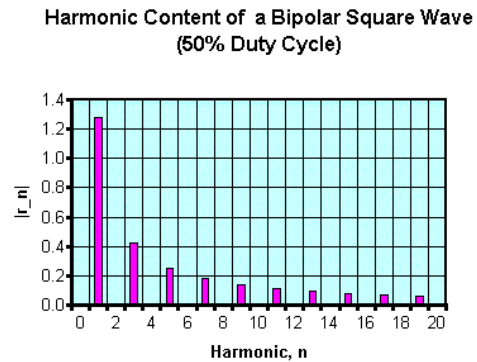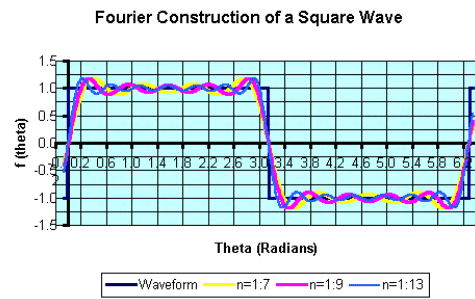
# **Standing Waves on a Stretched String**

Standing wave = superposition of left- and right-going traveling waves

• Left & right-going traveling waves reflect off of end supports

• Polarity flip of traveling wave occurs at fixed end supports. No polarity flip for free ends.

• Different modes of string vibrations - resonances occur!

• For string of length L with fixed ends, the lowest mode of vibration has frequency $f_1 = v/2L$ $(v = f_1\lambda_1)$ (f in cycles per second, or Hertz (Hz))

• Frequency of vibration, $f = 1/\tau$, where $\tau$ = period = time to complete 1 cycle

• Wavelength, $\lambda_1$ of lowest mode of vibration has $\lambda_1 = 2L$ (in meters)

• Amplitude of wave (maximum displacement from equilibrium) is A - see figure below - snapshot of standing wave at one instant of time, t:

Amplitude A

$L = \lambda_1/2$
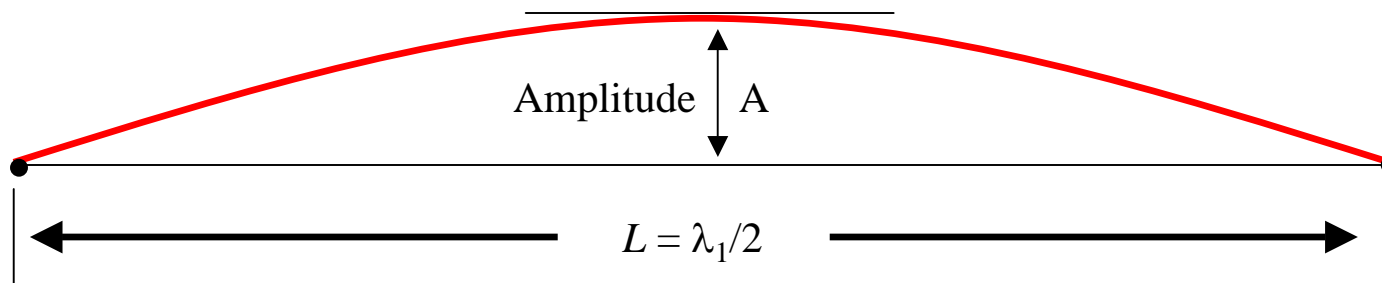
String can also vibrate with higher modes:

• Second mode of vibration of standing wave has $f_2 = 2v/2L = v/L$ with $\lambda_2 = 2L/2 = L$

Node

$L = \lambda_2$
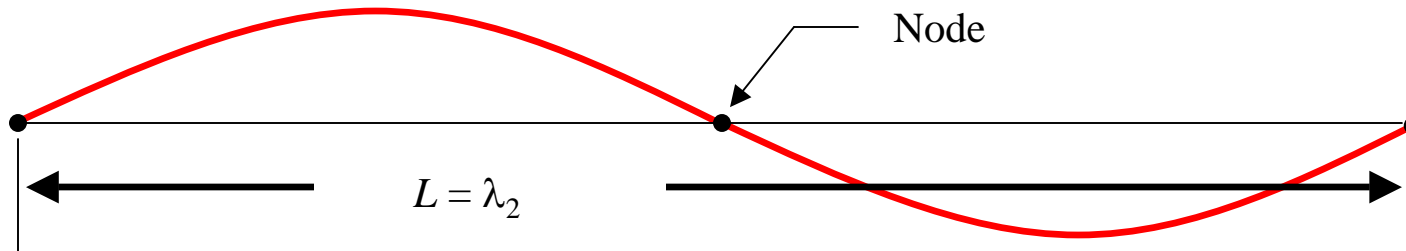
• Third mode of vibration of standing wave has $f_3 = 3v/2L$ with $\lambda_3 = 2L/3$

Nodes

$L = 3\lambda_3/2$
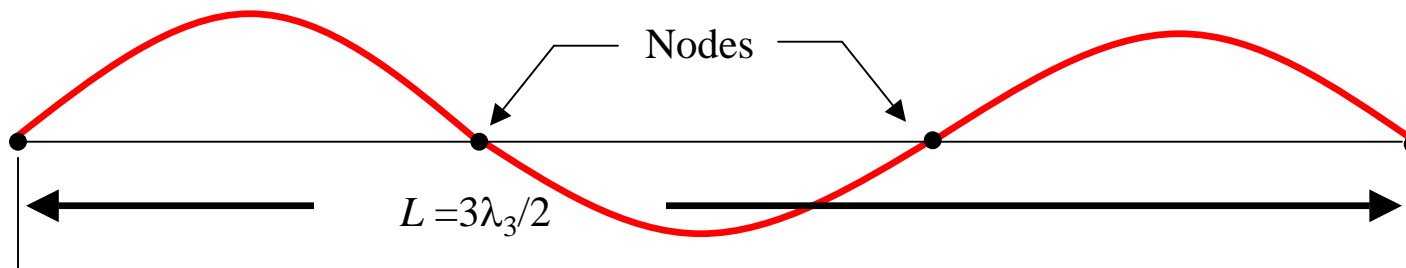
• The $n^{\text{th}}$ mode of vibration of standing wave on a string, where $n = $ integer $= 1,2,3,4,5,....$ has frequency $f_n = n(v/2L) = n f_1$, since $v = f_n \lambda_n$ and thus the $n^{\text{th}}$ mode of vibration has a wavelength of $\lambda_n = (2L)/n = \lambda_1/n$

When we e.g. pick (i.e. pluck) the string of a guitar, initial waveform is a triangle wave:

Pick

Nut @ Headstock

Bridge

$L$
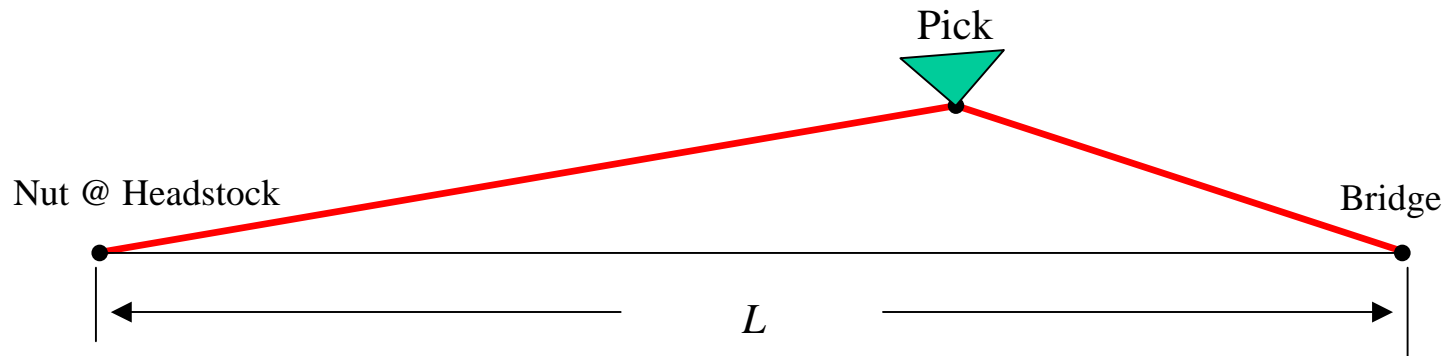
The geometrical shape of the string (a triangle) at the instant the pick releases the string can be shown mathematically (using Fourier Analysis) to be due to a linear superposition of standing waves consisting of the fundamental plus higher harmonics of the fundamental! Depending on where pick along string, harmonic content changes. Pick near the middle, mellower (lower harmonics); pick near the bridge - brighter - higher harmonics emphasized!

Harmonic Content of a Bipolar Triangle Wave

Harmonic Content of a Sawtooth Wave
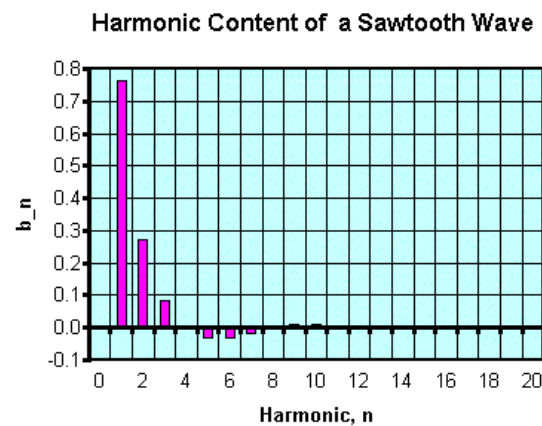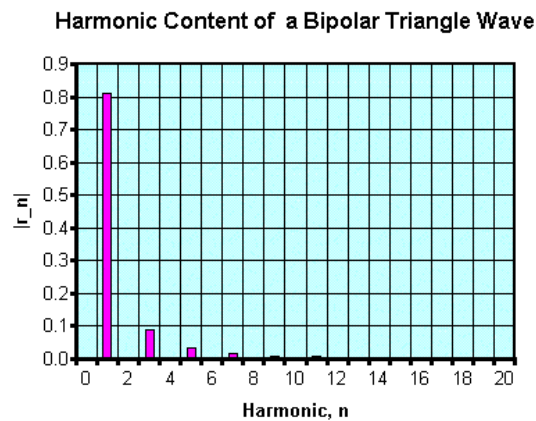
# Vibrational Modes of a Violin
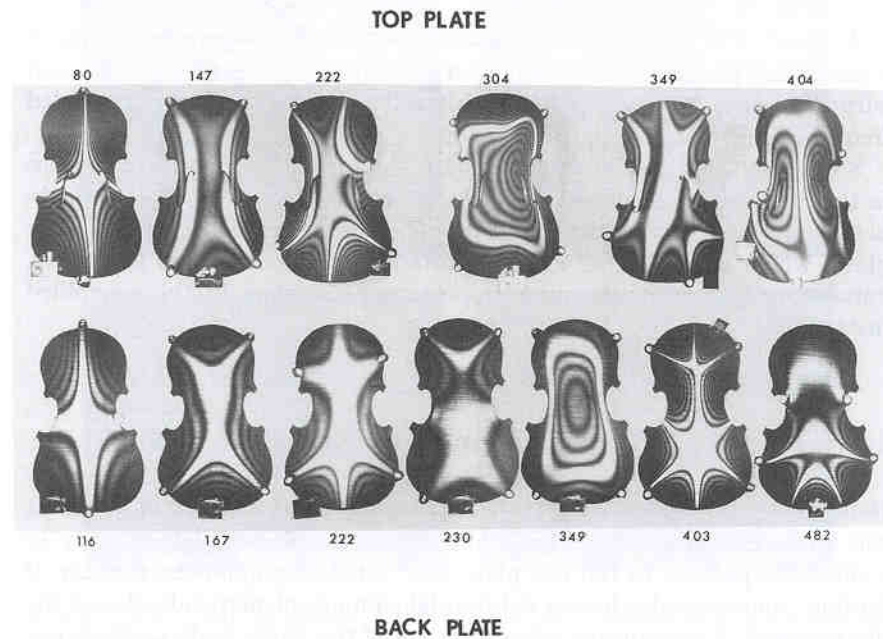


FIGURE 10.14. Time-average holographic interferograms of a free violin top plate and back plate (Hutchins et al., 1971).

# Harmonic Content of a Violin:

## Freshman Students, UIUC Physics 199 POM Course, Fall Semester, 2003
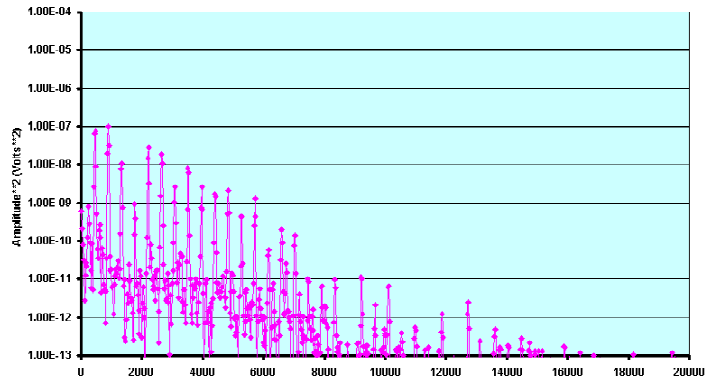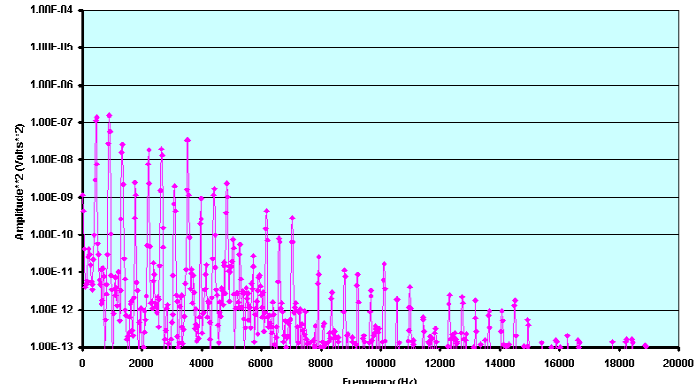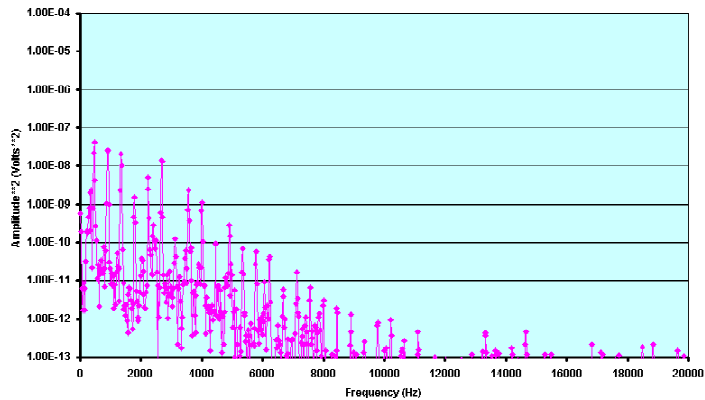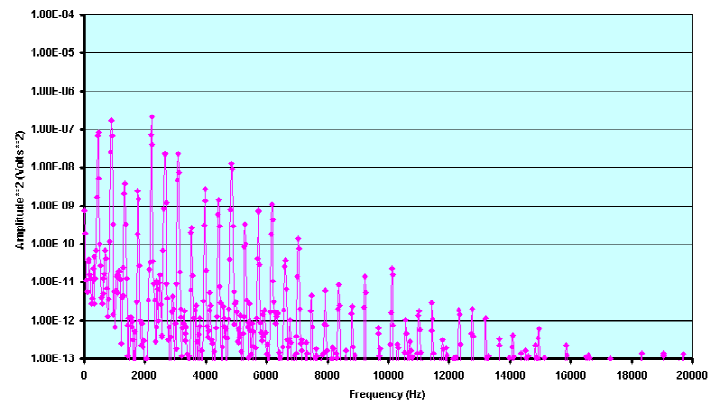
# Harmonic Content of a Viola – Open A2

**Laura Book (Uni High, Spring Semester, 2003)**



Viola Open A2    Volts**2 vs. Frequency
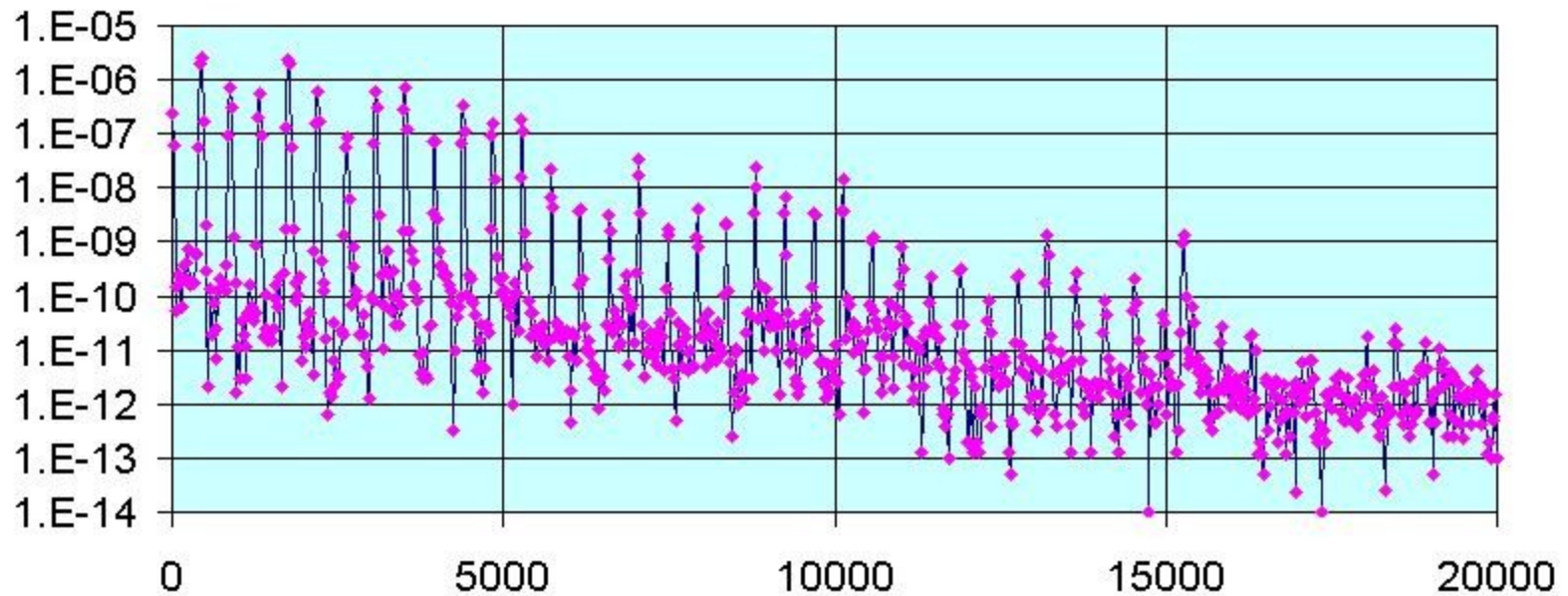
# Harmonic Content of a Cello:

## Freshman Students, UIUC Physics 199 POM Course, Fall Semester, 2003
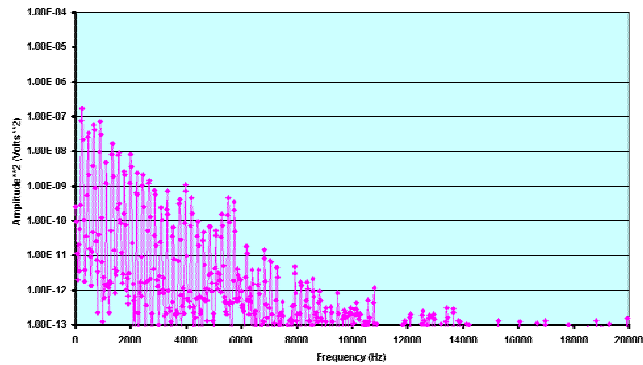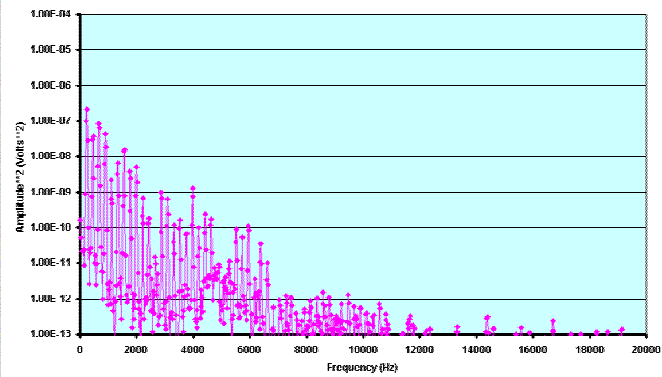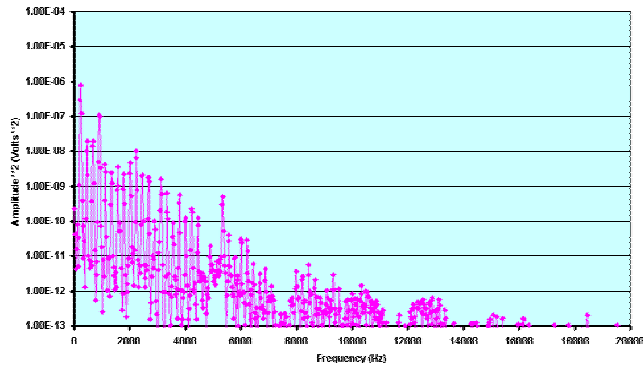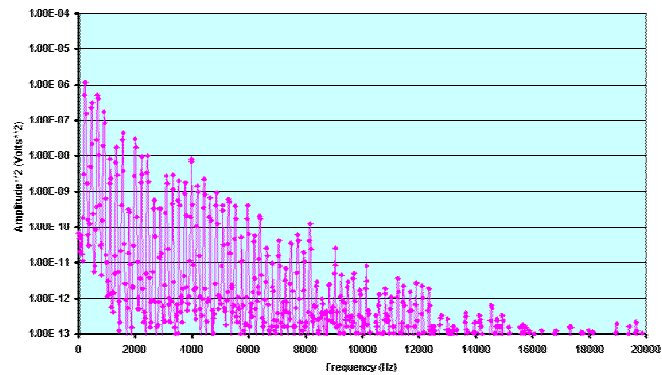
# Vibrational Modes of an Acoustic Guitar



268 Hz ($Q=52$)    553 Hz ($Q=66$)    628 Hz ($Q=83$)    672 Hz ($Q=61$)    731 Hz ($Q=72$)

873 Hz ($Q=75$)    980 Hz ($Q=48$)    1010 Hz ($Q=80$)    1174 Hz ($Q=58$)    1194 Hz ($Q=39$)
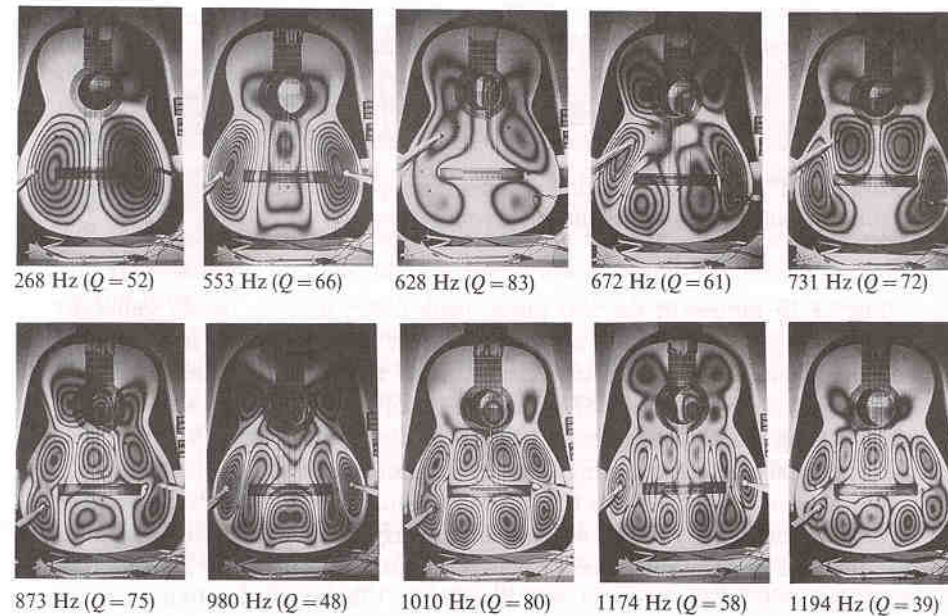
FIGURE 9.16. Time-averaged holographic interferograms of top-plate modes of a guitar (Guitar BR11). The resonant frequencies and $Q$ values of each mode are shown below the interferograms (Richardson and Roberts, 1985).

# Resonances of an Acoustic Guitar
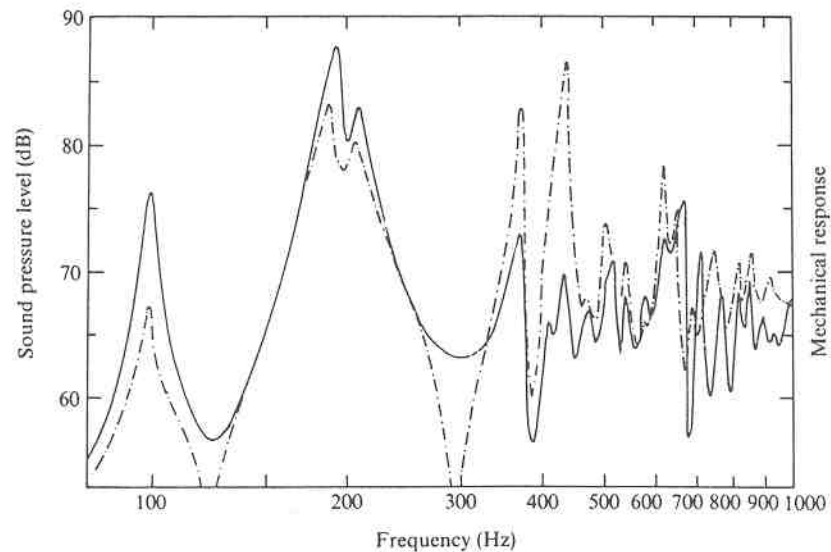


FIGURE 9.20. Mechanical frequency response and sound spectrum 1 m in front of a Martin D-28 folk guitar driven by a sinusoidal force of 0.15 N applied to the treble side of the bridge. Solid curve, sound spectrum; dashed curves, acceleration level at the driving point.

# Harmonic Content of 1969 Gibson ES-175 Electric Guitar

## Jacob Hertzog (Uni High, Spring Semester, 2003)



1969 ES-175 A 10th Fret    Volts**2 vs. Frequency
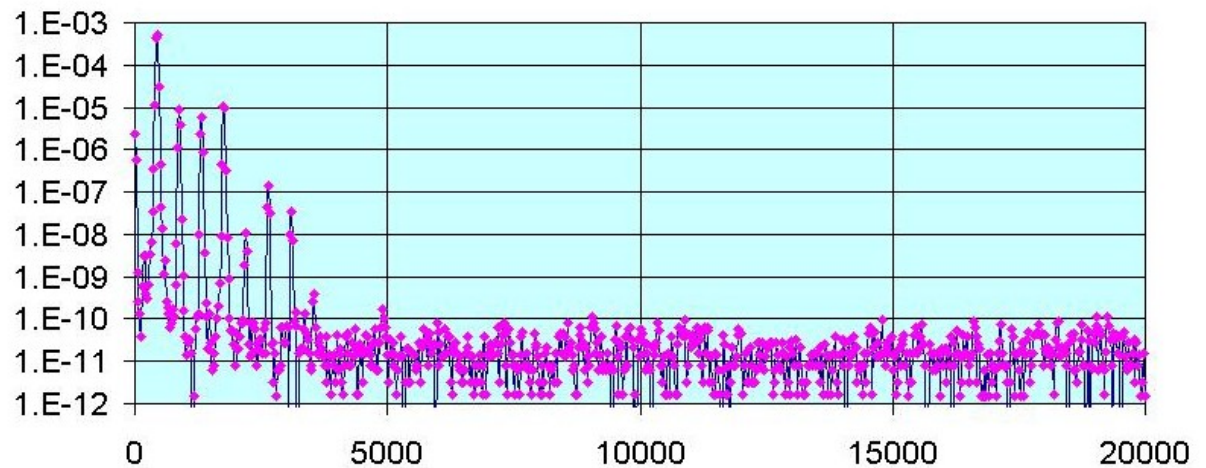
# Musical Properties of a 1954 Fender Stratocaster, S/N 0654 (August, 1954):

# **Measuring Mechanical Vibrational Modes of 1954 Fender Stratocaster:**

# Mechanical Vibrational Modes of 1954 Fender Stratocaster:

**1954 Strat S/N 0654**

E4 = 329.63 Hz (High E)

B3 = 246.94 Hz

G3 = 196.00 Hz

D3 = 146.83 Hz

A2 = 110.00 Hz

E2 = 82.407 Hz (Low E)



Legend: Body at Neck Heel — Body at Bridge — Headstock
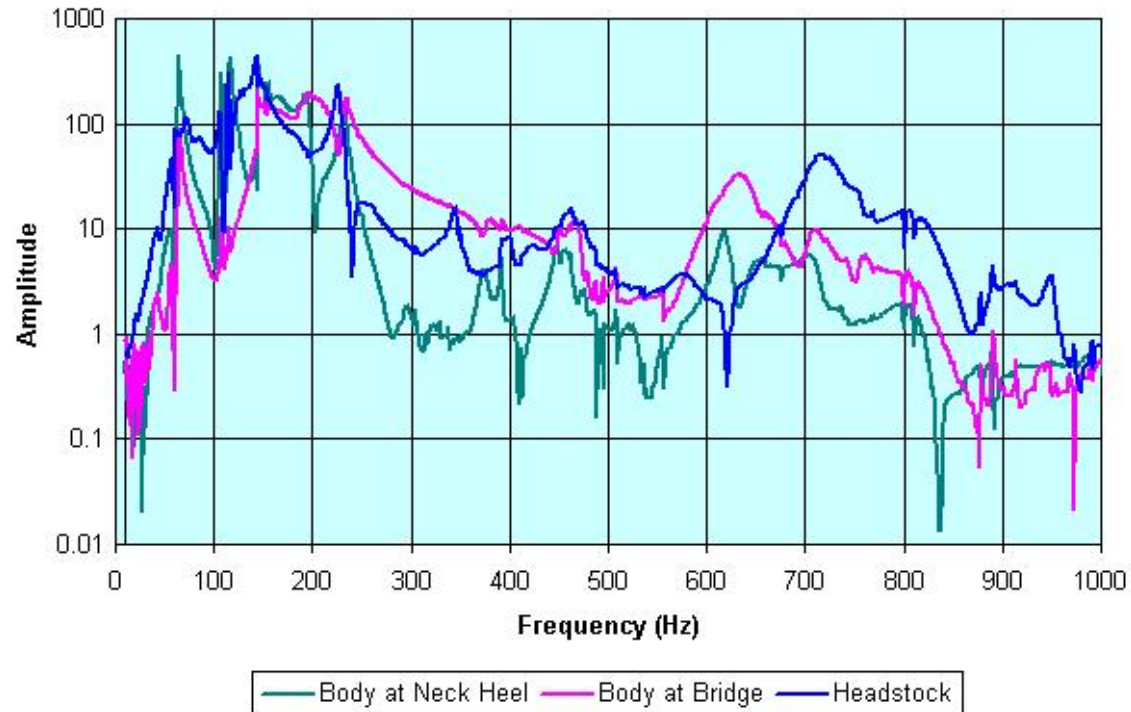
# UIUC Physics 398EMI Test Stand for Measurement of Electric Guitar Pickup Properties:

# Comparison of Vintage (1954's) vs. Modern Fender Stratocaster Pickups:



Fender Stratocaster Pickup Impedance, |Z| vs. Frequency
UIUC Physics 398 EMI   05/07/04
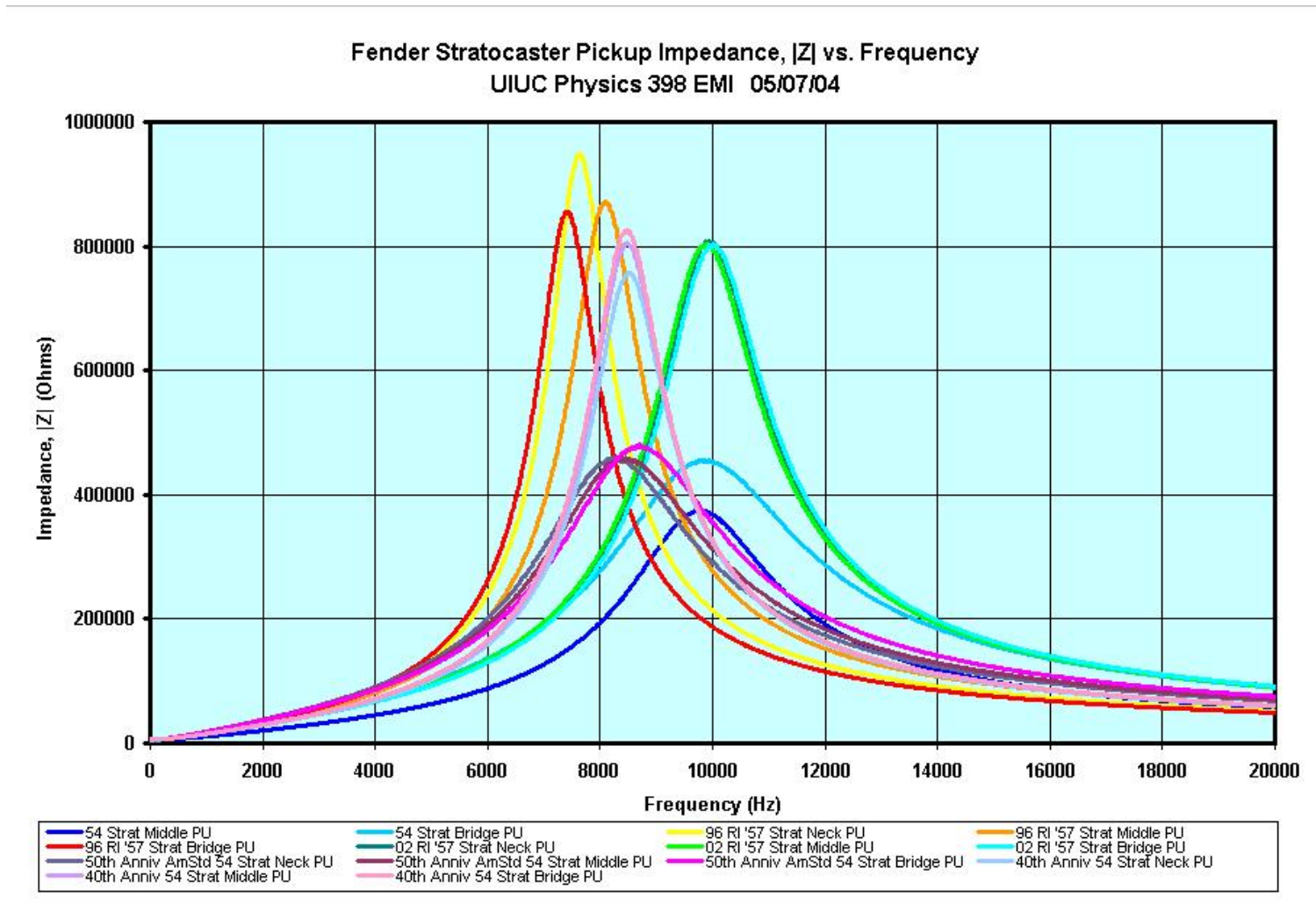
# Comparison of Vintage (1950's) vs. Modern Gibson P-90 Pickups:



Gibson P90 Pickup Impedance, |Z| vs. Frequency
UIUC Physics 398 EMI   11/10/03
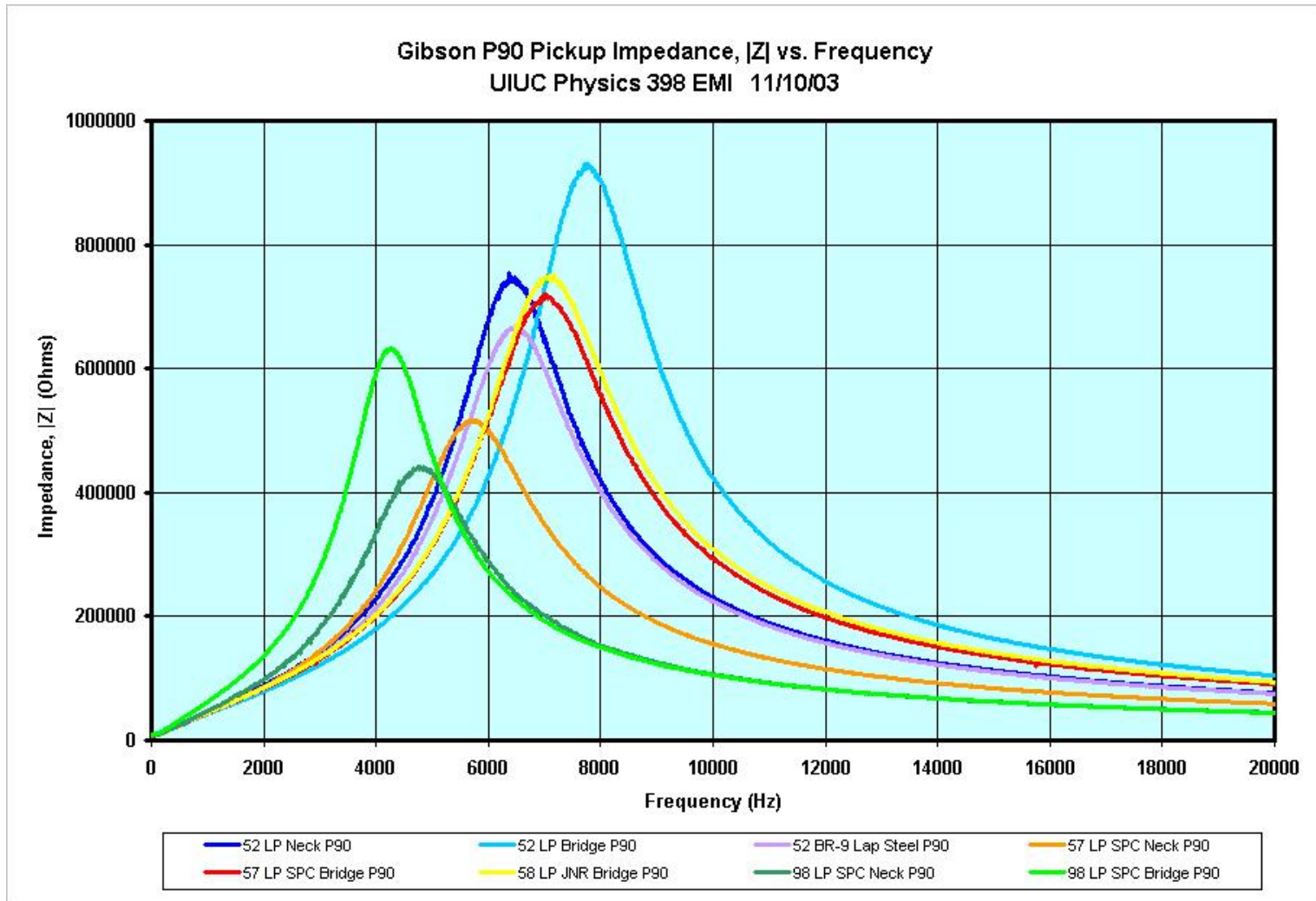
# X-Ray Comparison of 1952 Gibson Les Paul Neck P90 Pickup vs.

## 1998 Gibson Les Paul Neck P90 Pickup

### SME & Richard Keen, UIUC Veterinary Medicine, Large Animal Clinic
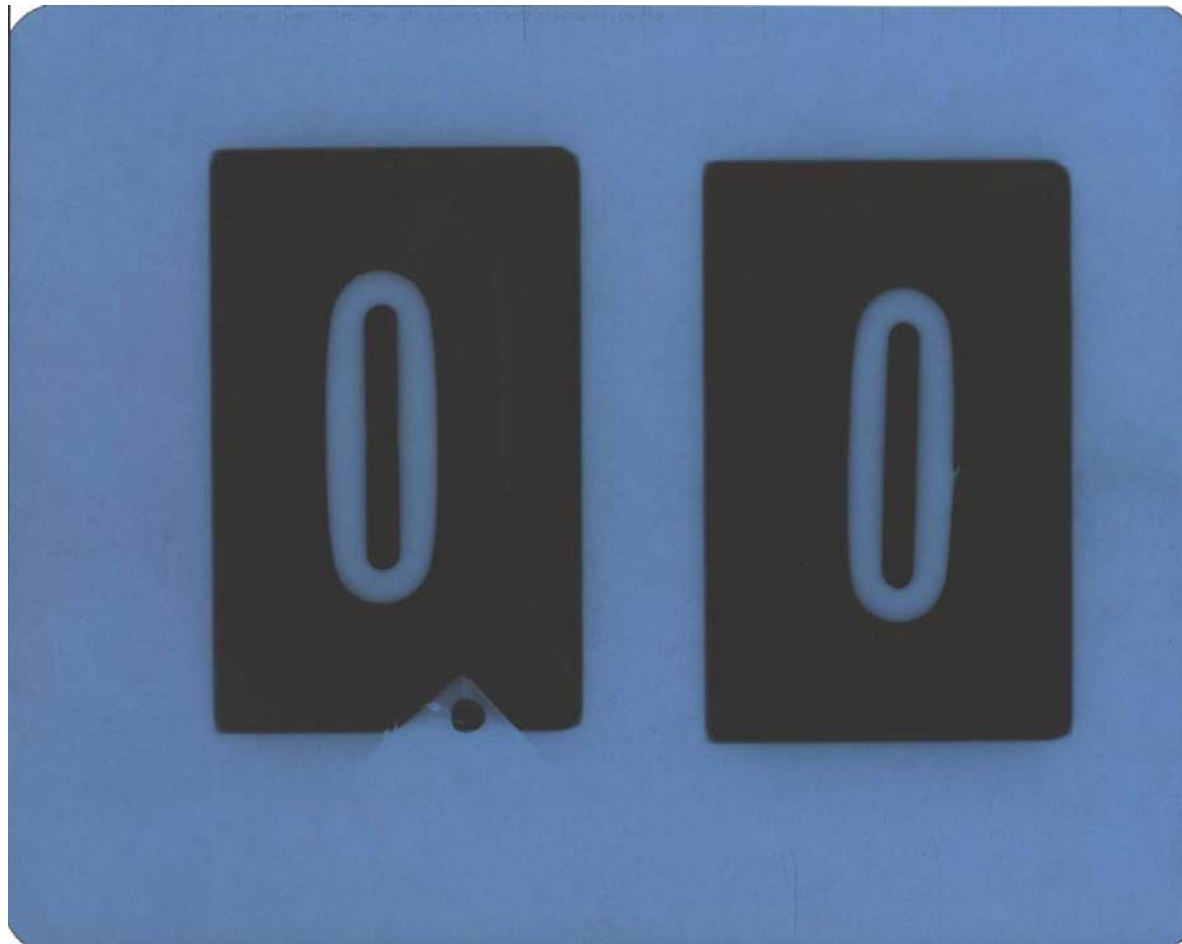
# Study/Comparison of Harmonic Properties of Acoustic and Electric Guitar Strings

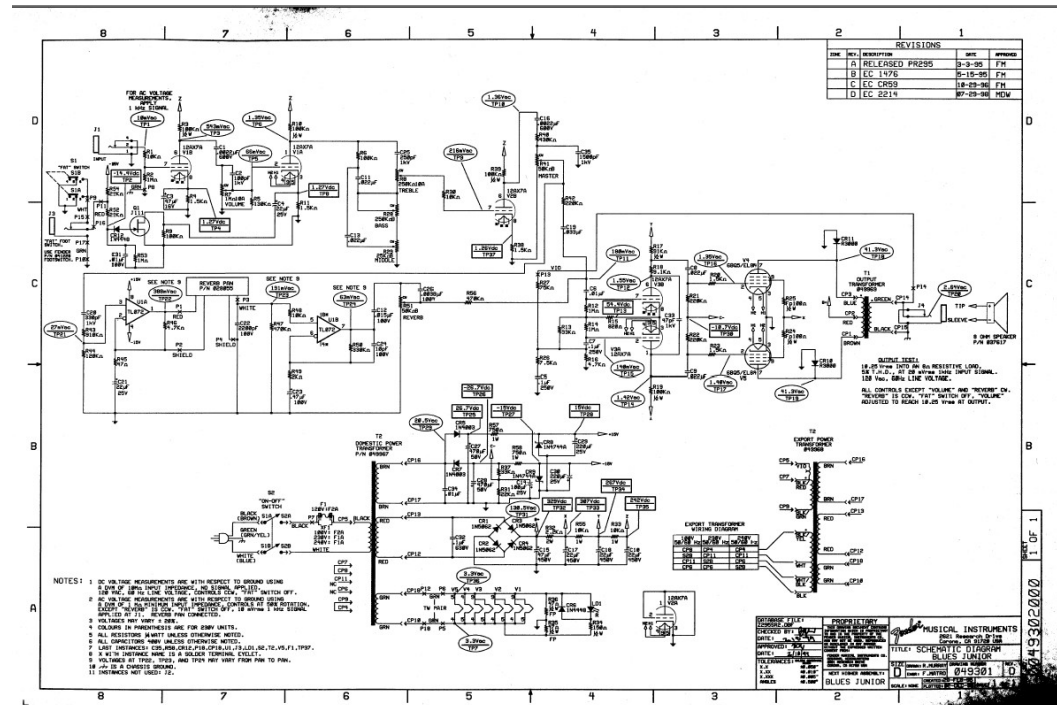## Ryan Lee (UIUC Physics P398EMI, Fall 2002)



Low E-string, 0.052 gauge, plucked near bridge pickup:
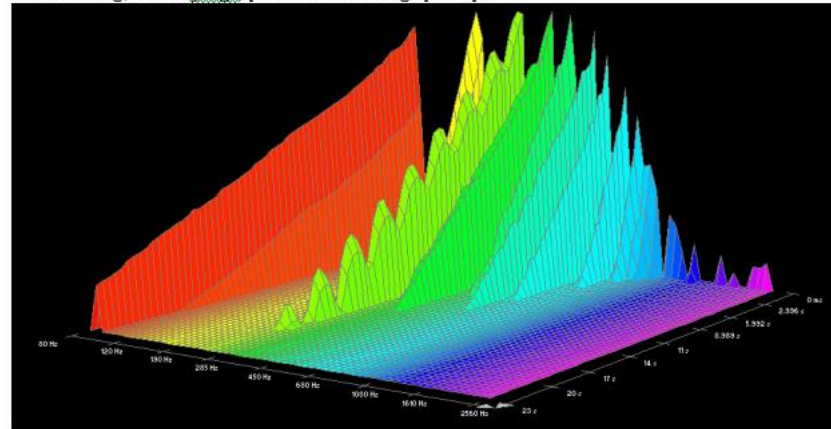


Low E-string, 0.052 gauge, plucked near neck pickup:
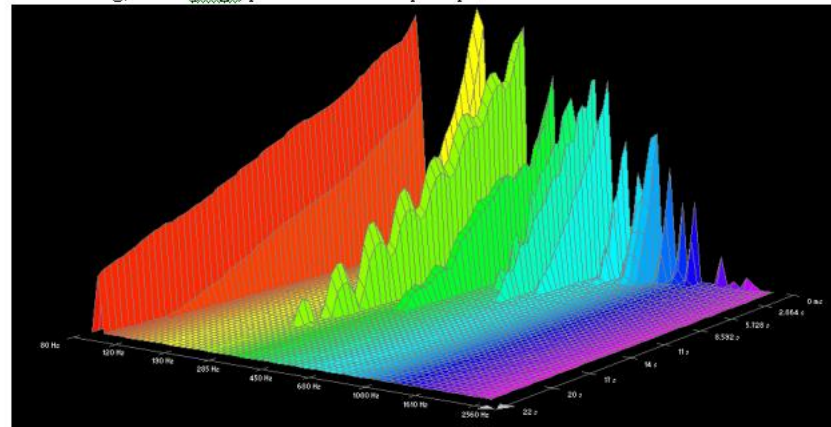
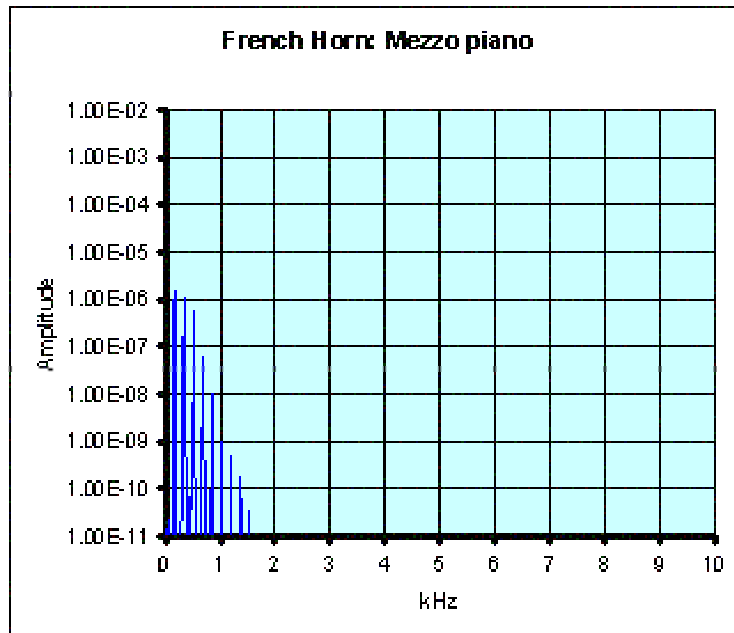**Venerable Vintage Amps – Many things can be done to improve/red-line their tonal properties…**



FENDER "DELUXE" SCHEMATIC
MODEL 5E3
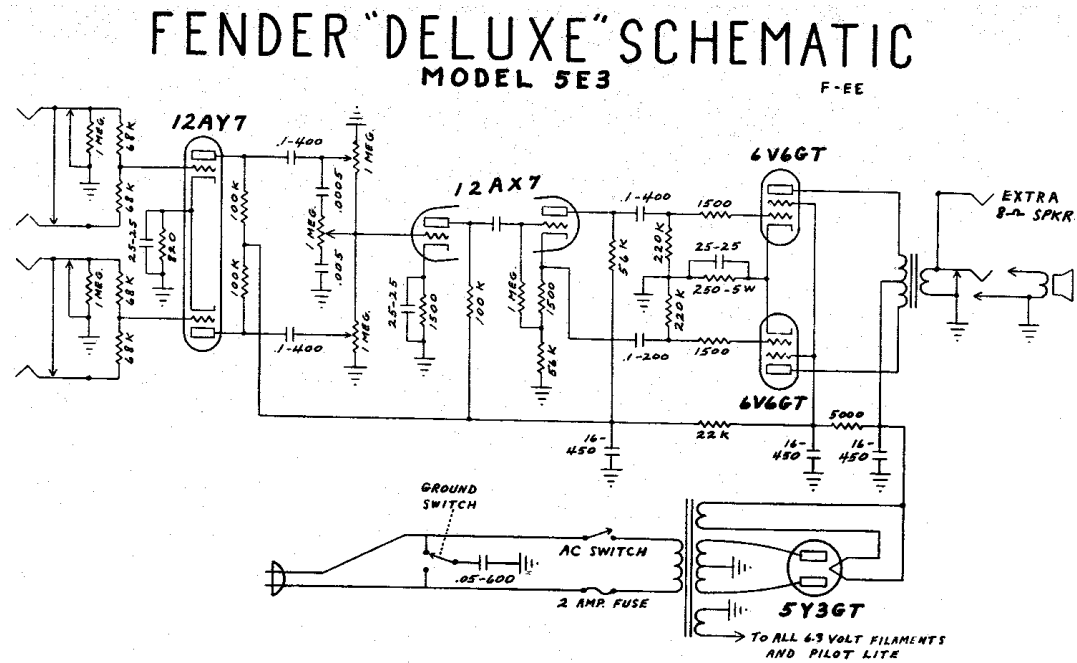
# Modern Amps, too…

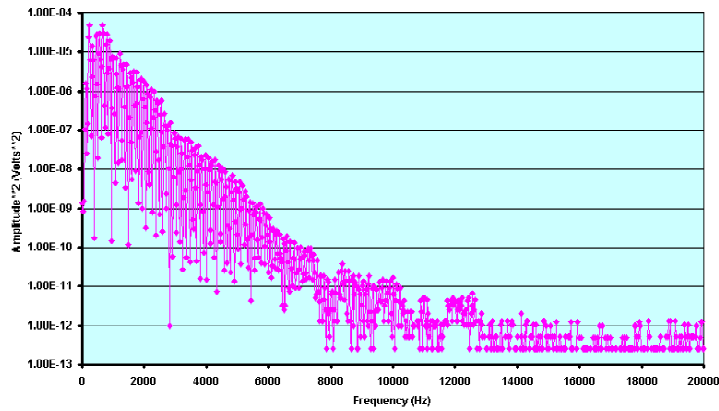# Harmonic Content of a Conn 8-D French Horn: Middle-C (C4)

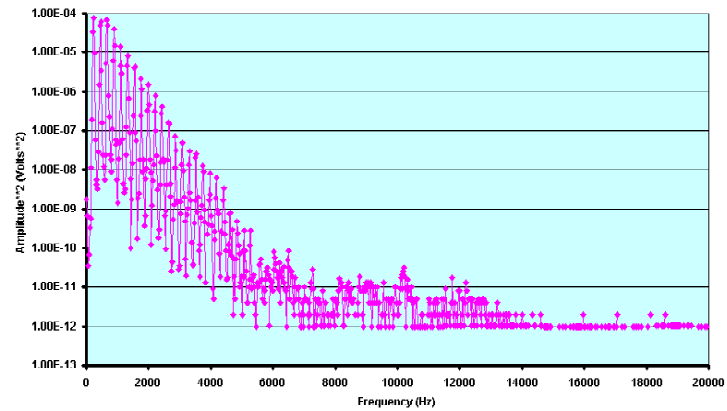**Chris Orban UIUC Physics Undergrad, Physics 398EMI Course, Fall Semester, 2002**
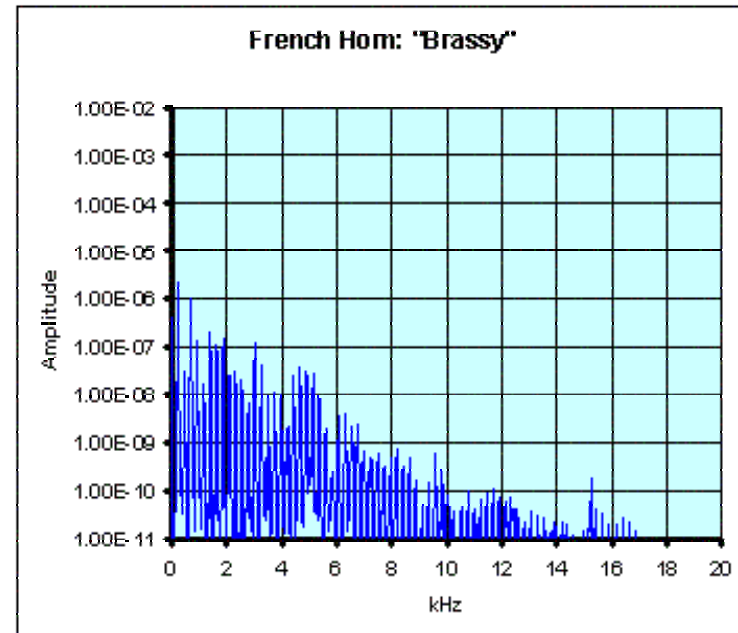
# Harmonic Content of a Trombone:

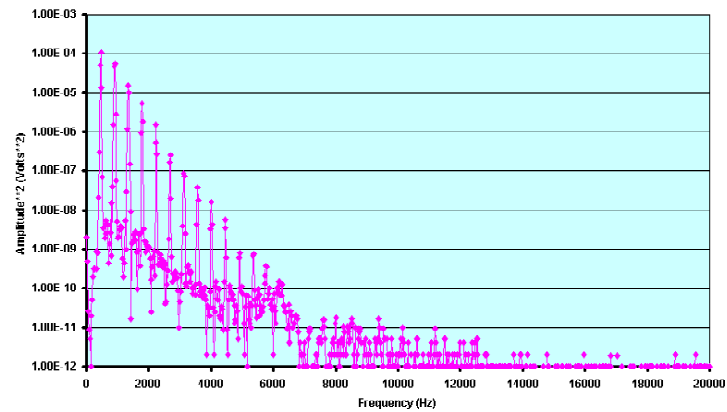## Freshman Students in UIUC Physics 199 POM Class, Fall Semester



Trombone A2
A**2 vs Frequency



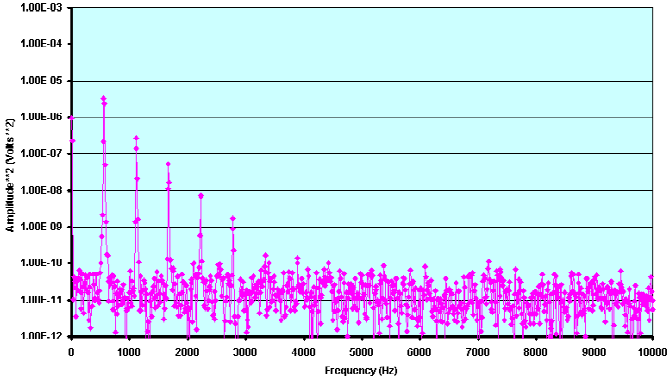Trombone A3
A**2 vs Frequency



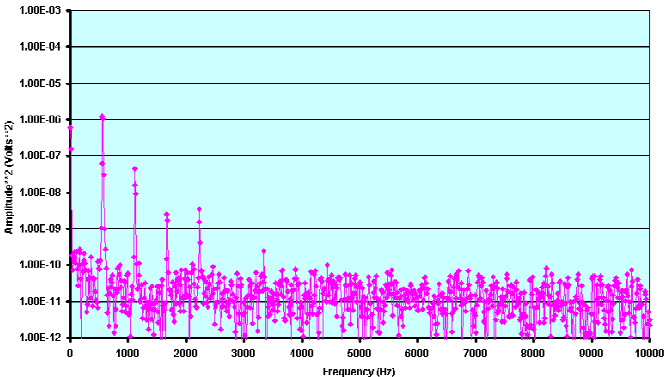Trombone A4
A**2 vs Frequency

# Comparison of Harmonic Content of Metal, Glass and Wooden Flutes:

## Freshman Students in UIUC Physics 199 POM Class, Fall Semester, 2003
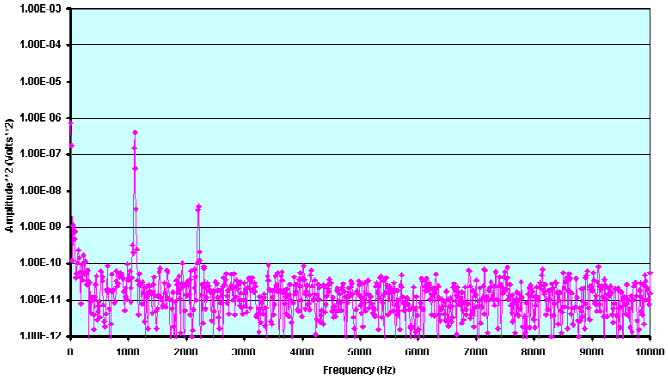


Metal Flute Open C5#
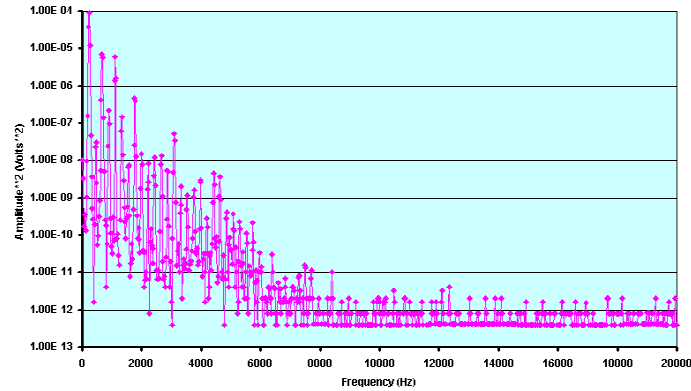A**2 vs Frequency



Glass Flute C5#
A**2 vs Frequency



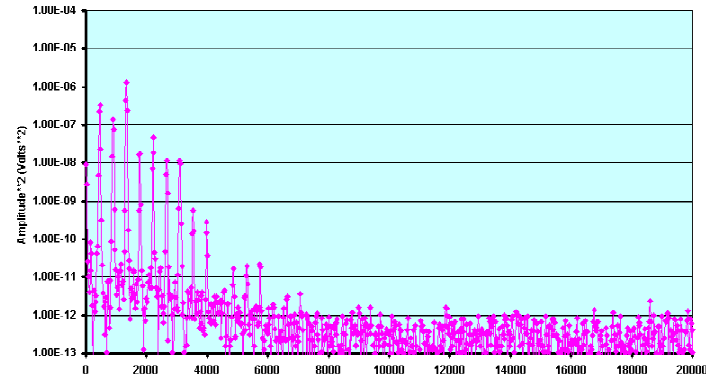Wood Flute Open C6#
A**2 vs Frequency

# Harmonic Content of a Clarinet:

## Freshman Students in UIUC Physics 199 POM Class, Fall Semester
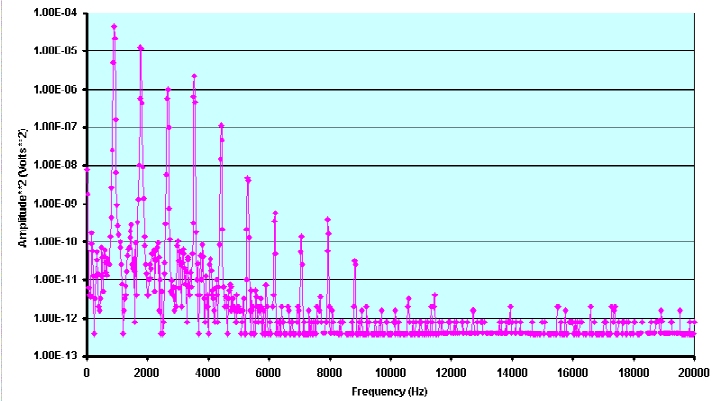


**Clarinet A3**
A**2 vs Frequency



**Clarinet A4**
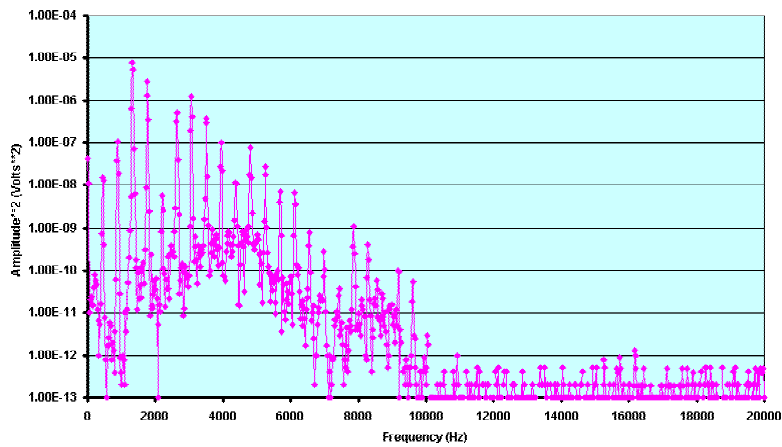A**2 vs Frequency



**Clarinet A5**
A**2 vs Frequency
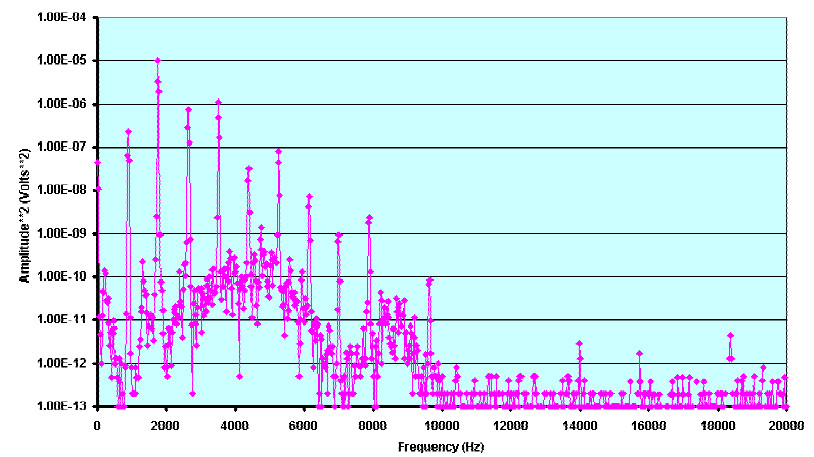
# Harmonic Content of an Oboe:

## Freshman Students in UIUC Physics 199 POM Class, Fall Semester, 2003



Oboe Concert A (A4)
A**2 vs Frequency

Oboe A5
A**2 vs Frequency

# Harmonic Content of a Tenor Sax:

## Freshman Students in UIUC Physics 199 POM Class, Fall Semester, 2003
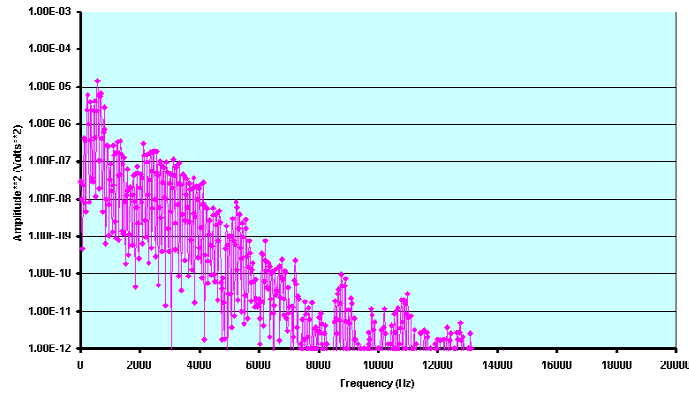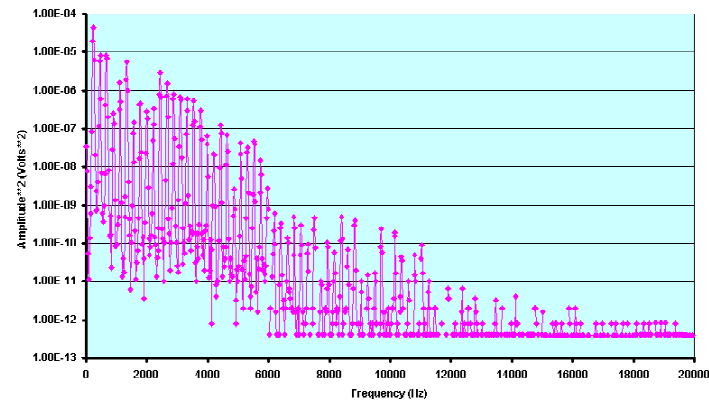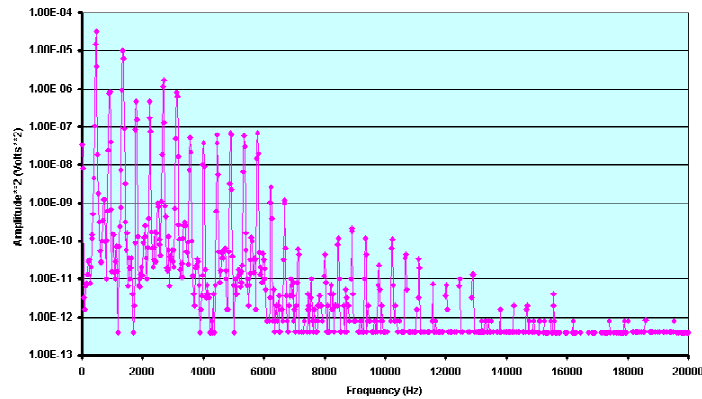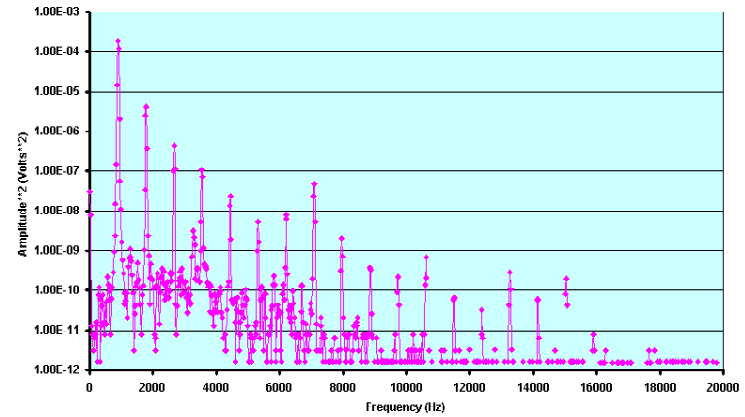
# Harmonic Content of an Alto Sax:

## Freshman Students in UIUC Physics 199 POM Class, Fall Semester, 2003
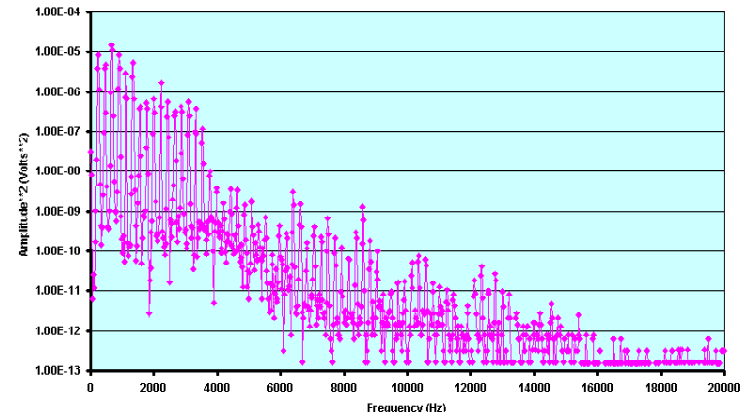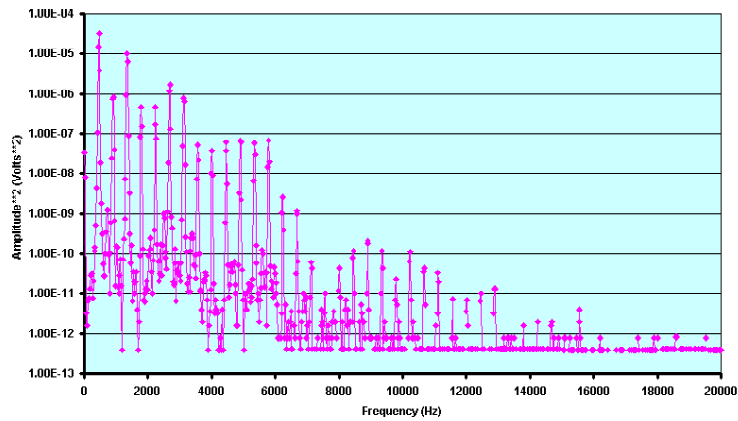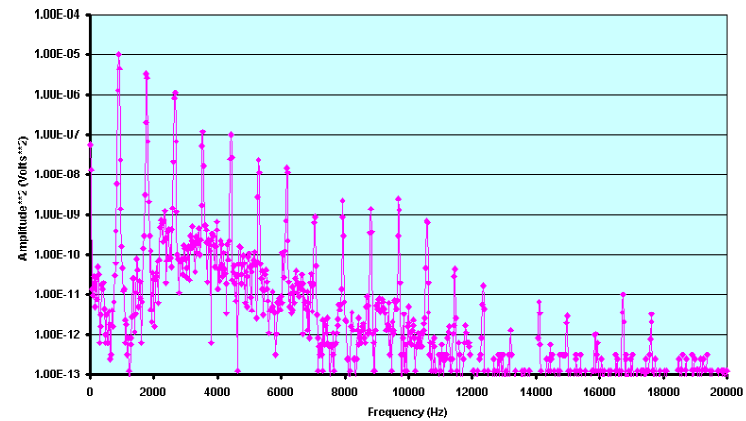
# Harmonic Content of the Bassoon:

## Prof. Paul Debevec, SME, UIUC Physics Dept. Fall Semester, 2003



Bassoon B2b
A**2 vs Frequency
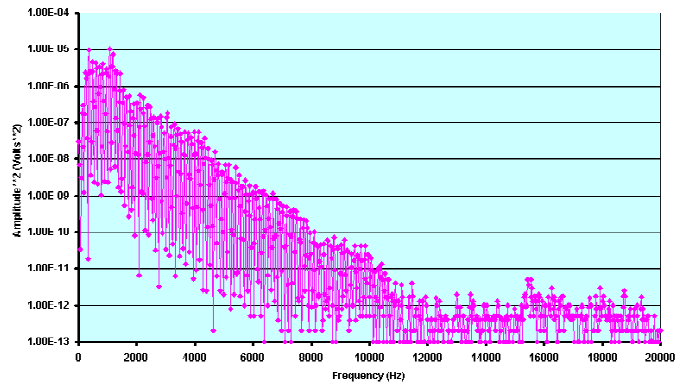


Bassoon B3b
A**2 vs Frequency
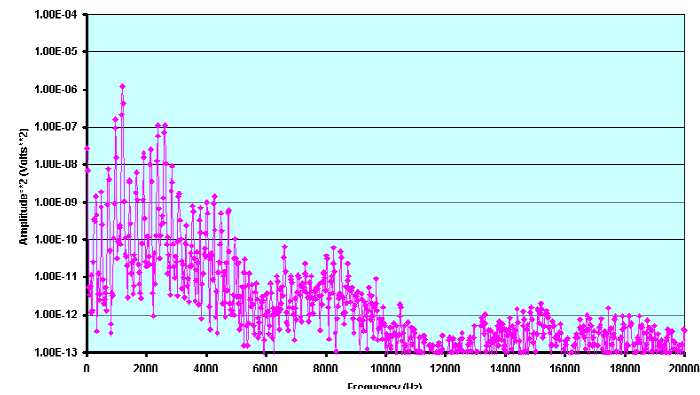


Bassoon Concert Bb (B4b)
A**2 vs Frequency
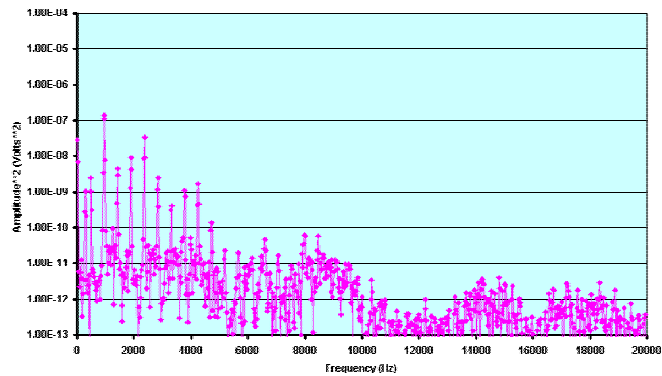


Bassoon B5b
A**2 vs Frequency
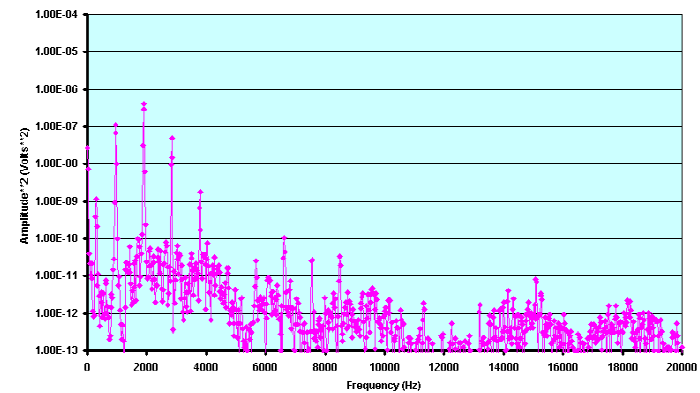
# Time-Dependence of the Harmonic Content of Marimba and Xylophone:

**Roxanne Moore, Freshman in UIUC Physics 199 POM Course, Spring Semester, 2003**
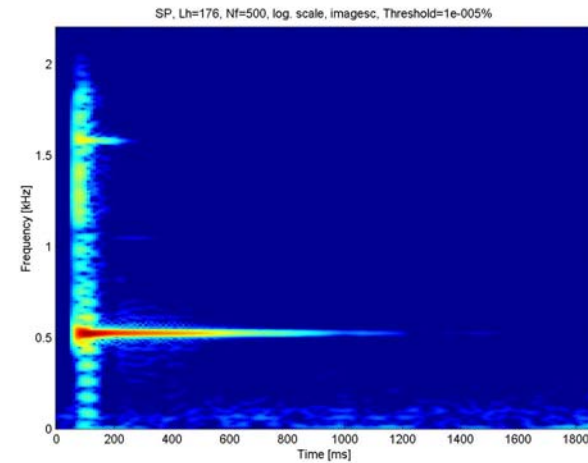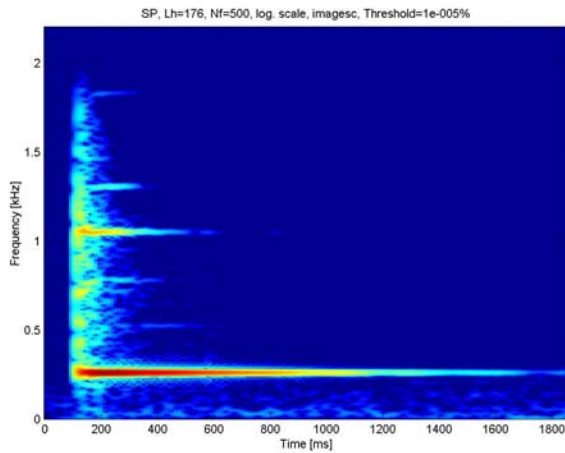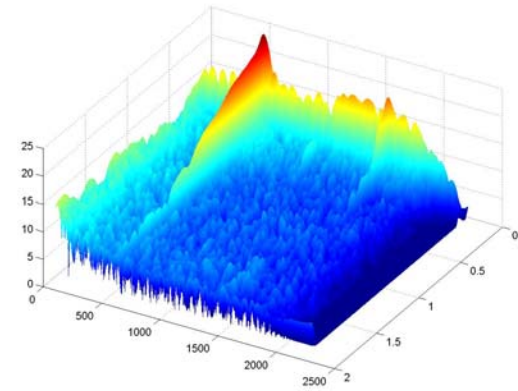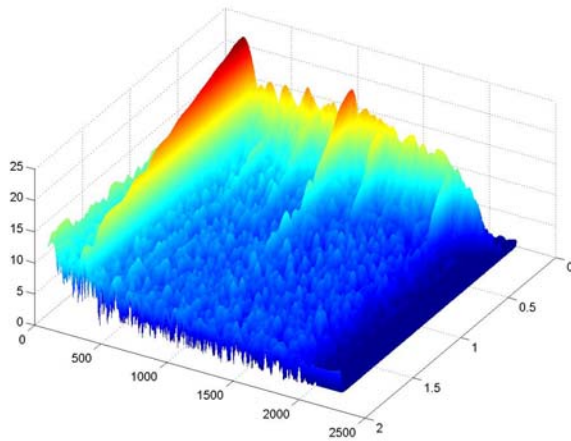
# Vibrational Modes of Membranes and Plates

# (Drums and Cymbals)
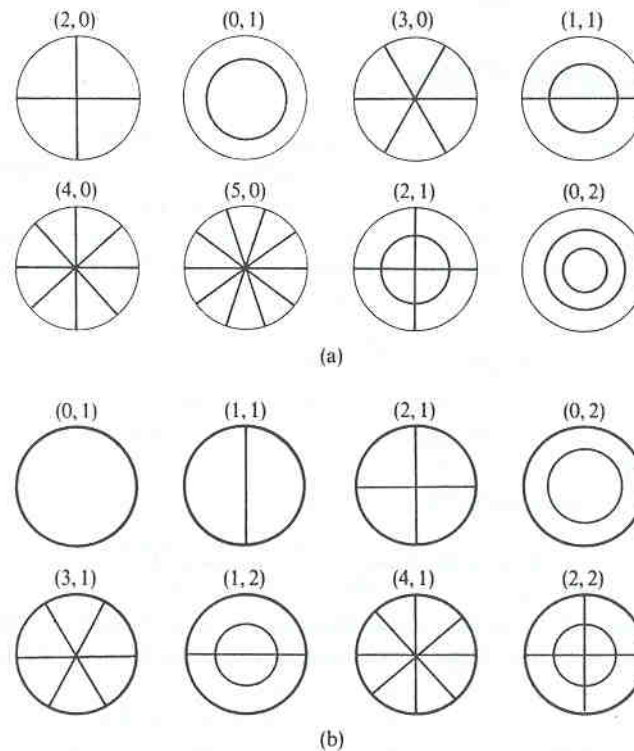


FIGURE 3.8. Vibrational modes of circular plates: (a) free edge and (b) clamped or simply supported edge. The mode number $(n, m)$ gives the number of nodal diameters and circles, respectively.

# Study/Comparison of Acoustic Properties of Tom Drums

Eric Macaulay (*Illinois Wesleyan University*), Nicole Drummer, SME (*UIUC*) Dennis Stauffer (Phattie Drums)

**Eric Macaulay**
(*Illinois Wesleyan University*)

**NSF REU Summer Student @ UIUC Physics, 2003**

**Investigated/Compared Bearing Edge Design – Energy Transfer from Drum Head => Shell of Three "identical" 10" Diameter Tom Drums**

**Differences in Bearing Edge Design of Tom Drums (Cutaway View):**

**Recording Sound(s) from Drum Head vs. Drum Shell:**
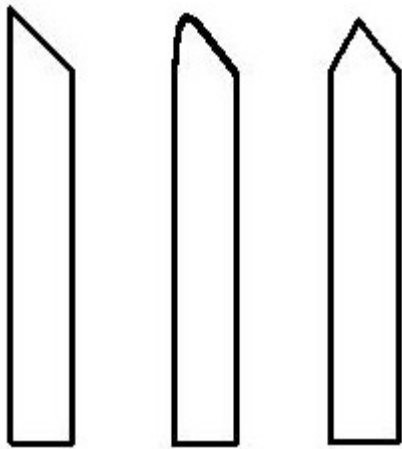


**Single 45º**

**Rounded 45º (Classic)**

**and Double 45º (Modern)**

# Analysis of Recorded Signal(s) From 10" Tom Drum(s):

## {Shell Only Data (Shown Here)}
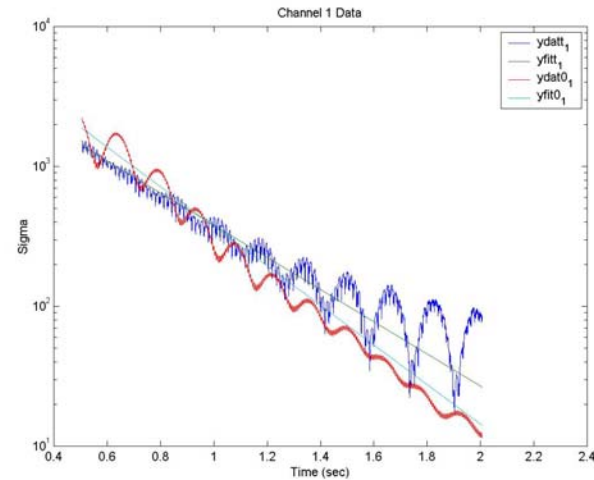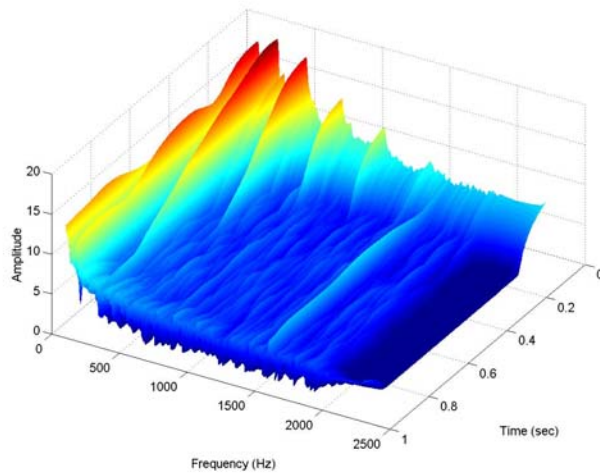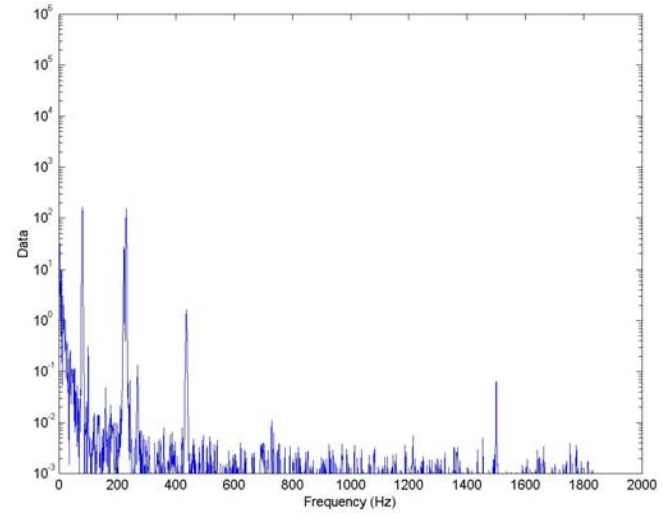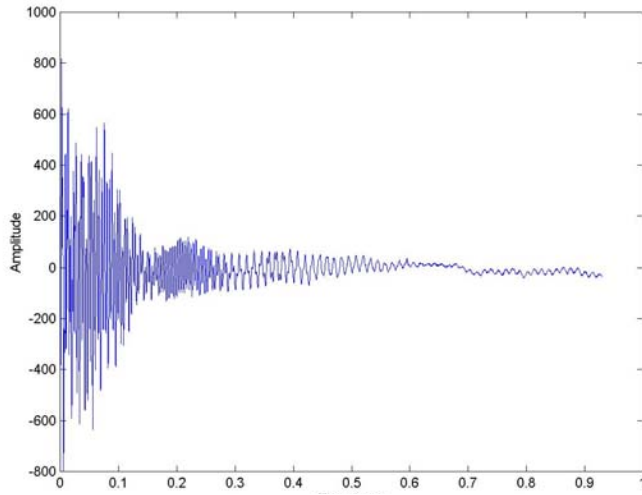
# Progression of Major Harmonics for Three 10" Tom Drums



Harmonics 1-5: Shell Only vs. Shell+Lugs vs. Everything (All @ T=75)
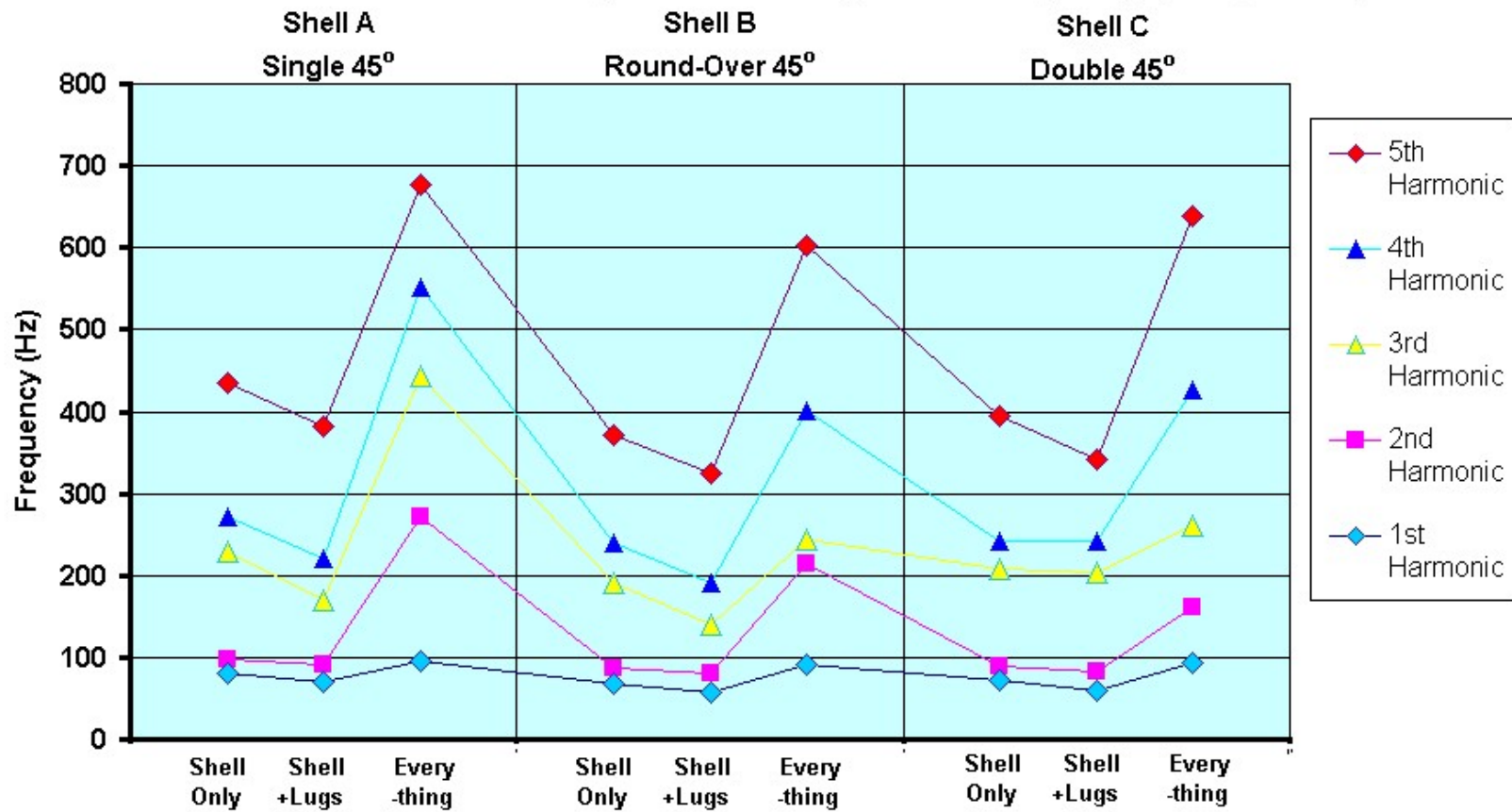
**Ratio of Initial Amplitude(s) of Drum Shell/Drum Head vs. Drum Head Tension.**

**Drum A = Single 45$^o$, Drum B = Round-Over 45$^o$, Drum C = Double-45$^o$.**

**At Resonance, the Double-45$^o$ 10" Tom Drum transferred more energy from drum head => drum shell. Qualitatively, it sounded best of the three.**



(Shell Y(0))/(Head Y(0)) vs Drum Dial Tension
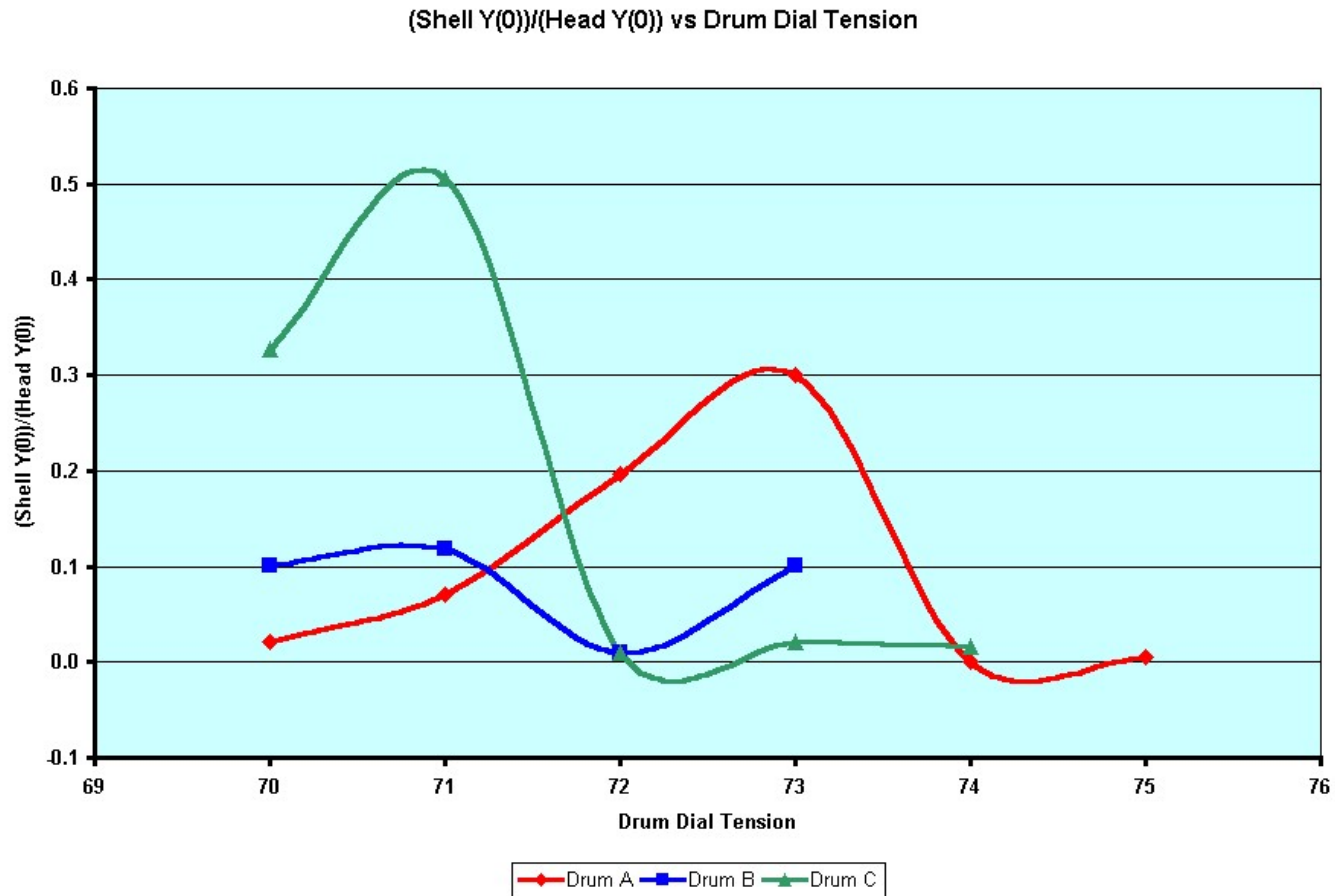
# Harmonic Content vs. Time of a Snare Drum

## Eric Macaulay (Illinois Wesleyan University), Lee Holloway, Mats Selen, SME (UIUC), Summer 2003
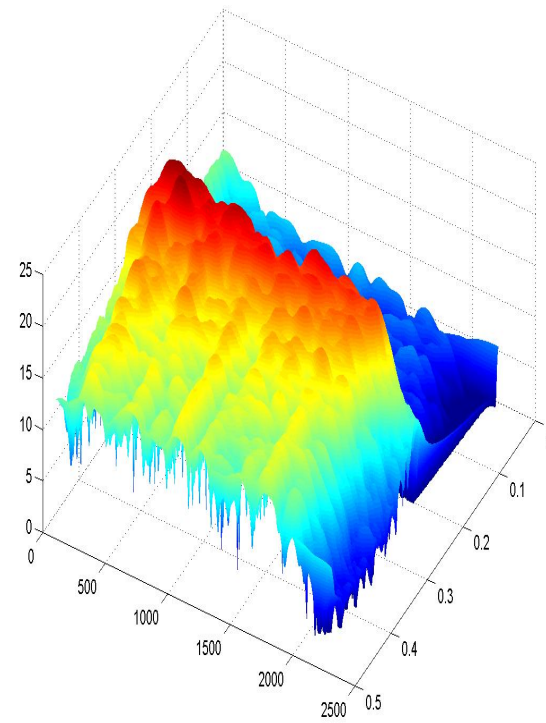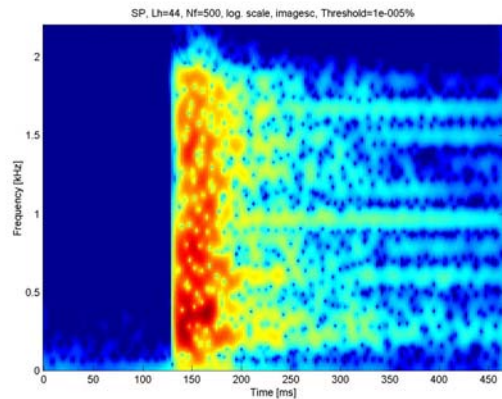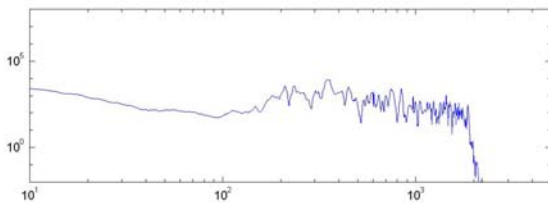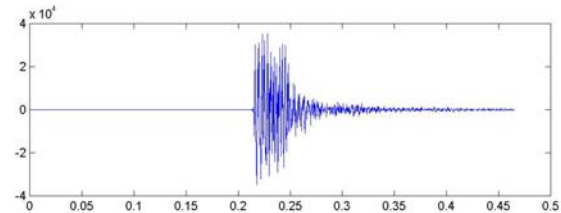
# Harmonic Content vs. Time of Tibetan Bowl

## Eric Macaulay (Illinois Wesleyan University), Lee Holloway, Mats Selen, SME (UIUC)
## Summer, 2003
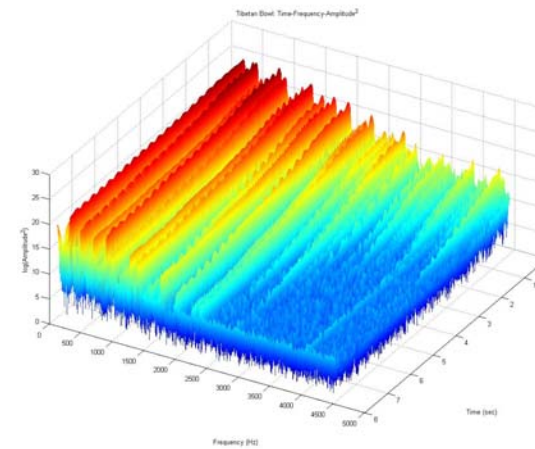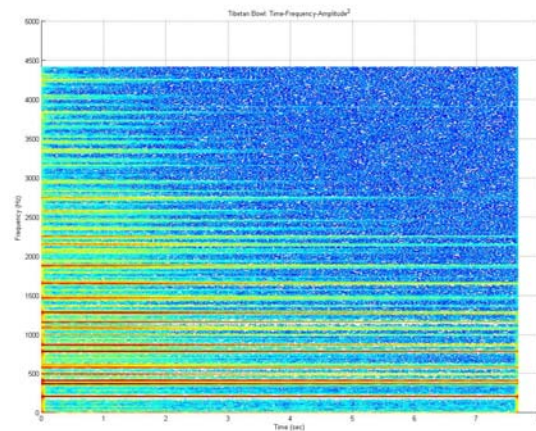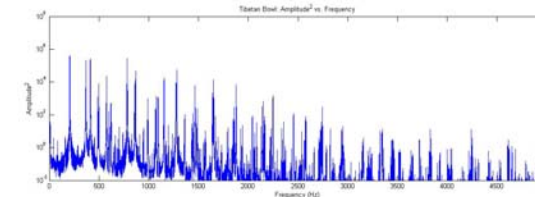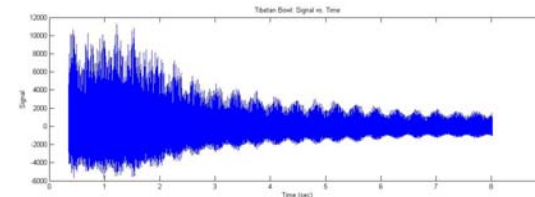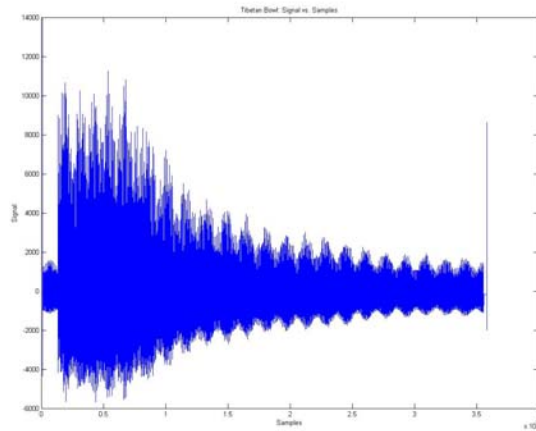
# Tibetan Bowl Studies – Continued:
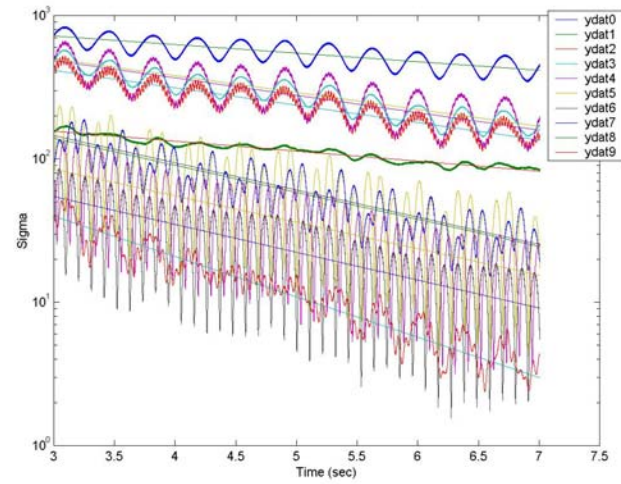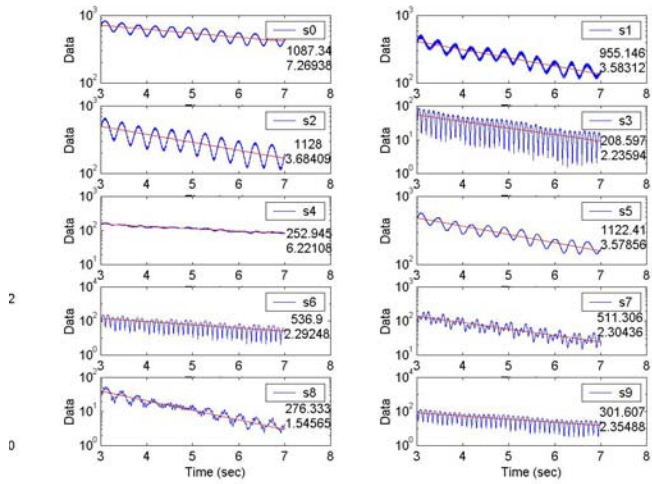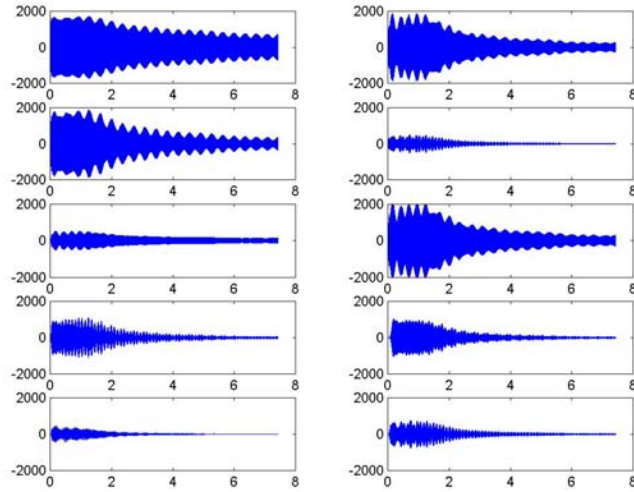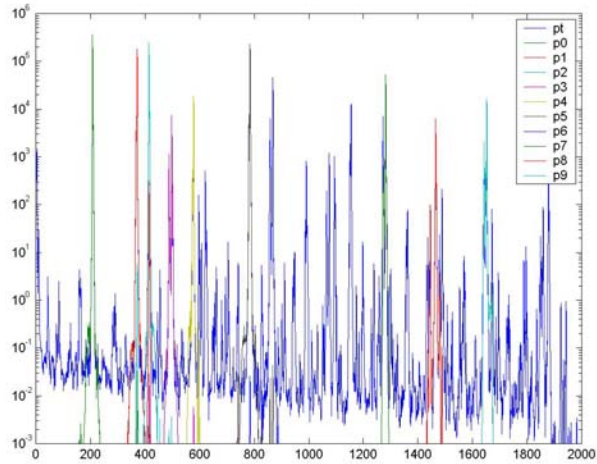
# Tibetan Bowl Studies II:  Joseph Yasi (Rensselaer Polytechnic), SME (UIUC)

## Summary, 2004
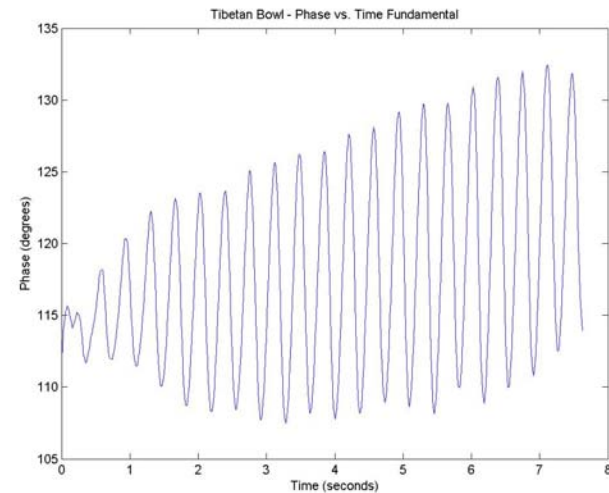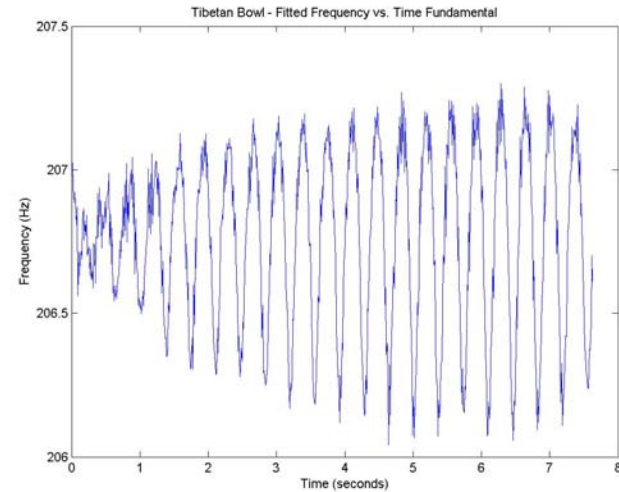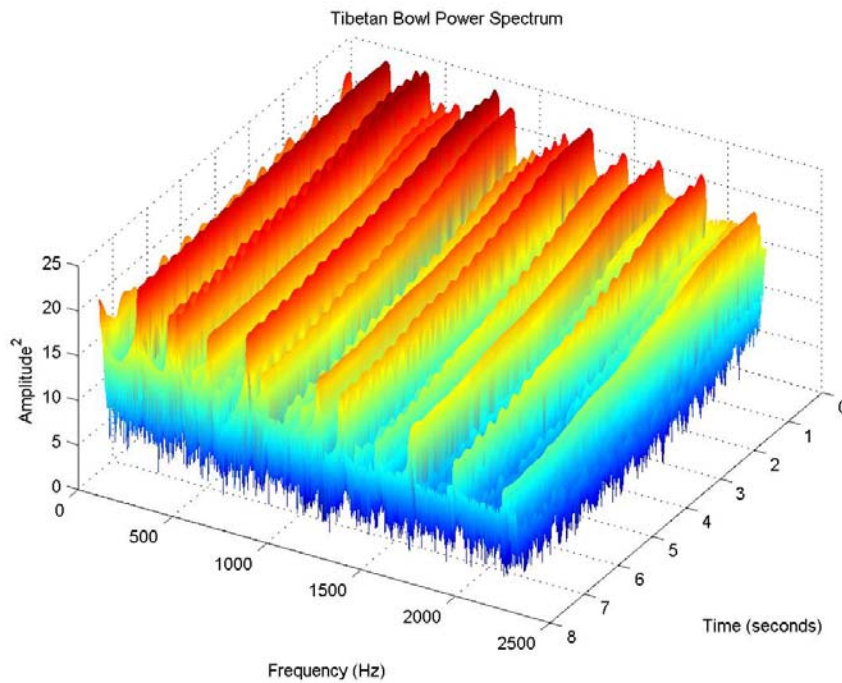


**Frequency & phases of harmonics (even the fundamental) of Tibetan Bowl are not constants !!!**

Tibetan Bowl
Amplitude^2 vs Frequency
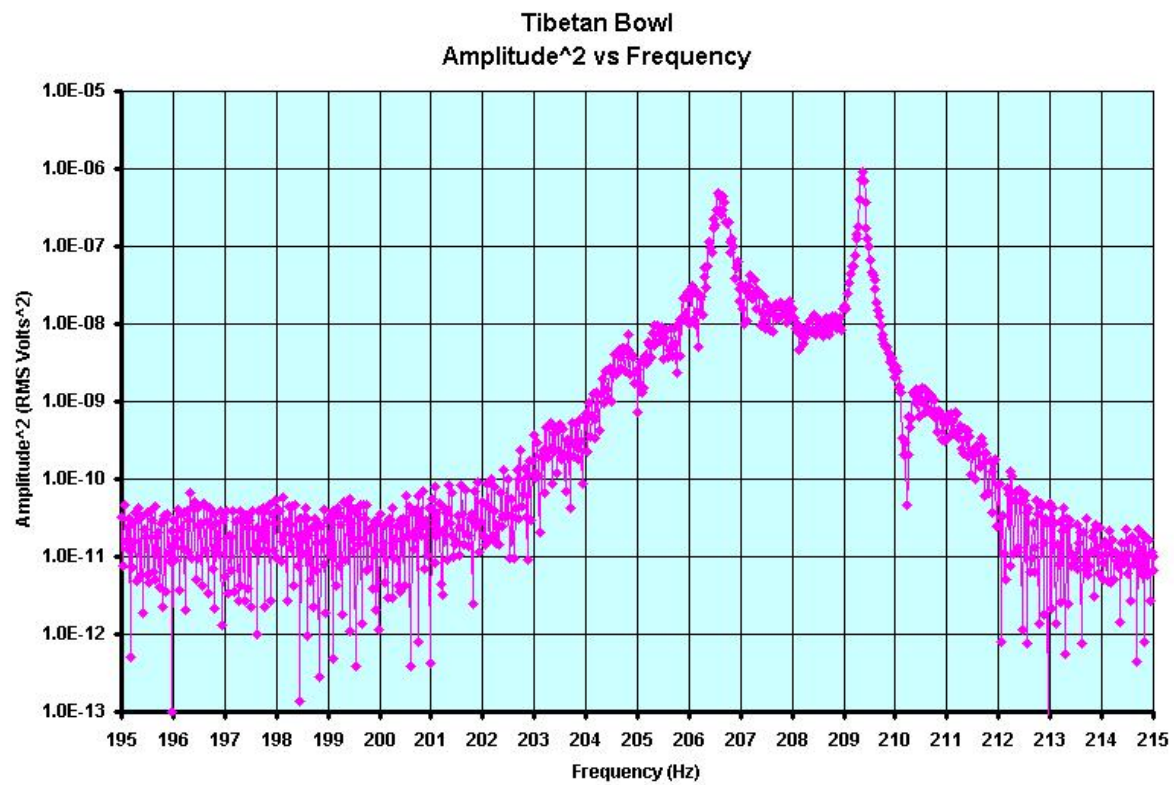
## Beats Phenomenon

Linearly superpose (i.e. add) two signals $A_1(t)$ and $A_2(t)$ with similar frequencies, $\omega_2 \sim \omega_1$.

$$A_1(t) = A_{10}Cos\big(\omega_1(t)t\big) \qquad\qquad A_2(t) = A_{20}Cos\big(\omega_2(t)t + \Delta\varphi_{21}(t)\big)$$

$$A_{tot}(t) = A_1(t) + A_2(t) = A_{10}Cos\big(\omega_1(t)t\big) + A_{20}Cos\big(\omega_2(t)t + \Delta\varphi_{21}(t)\big)$$

Phasor Relation:
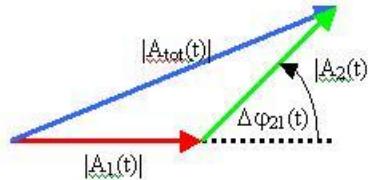


Intensity:

$$I_{tot}(t) = \big|A_{tot}(t)\big|^2 = \big|A_1(t) + A_2(t)\big|^2$$

$$I_{tot}(t) = A_{10}^2 Cos^2\big(\omega_1(t)t\big) + A_{20}^2 Cos^2\big(\omega_2(t)t + \Delta\varphi_{21}(t)\big) + 2A_{10}A_{20}Cos\big(\omega_1(t)t\big)Cos\big(\omega_2(t)t + \Delta\varphi_{21}(t)\big)$$

Define:

$$\vartheta_1(t) \equiv \omega_1(t)t \qquad\qquad \vartheta_2(t) \equiv \big(\omega_2(t)t + \Delta\varphi_{21}(t)\big)$$

Identity:

$$Cos\,\vartheta_1 Cos\,\vartheta_2 \equiv \tfrac{1}{2}\big[Cos(\vartheta_2 + \vartheta_1) + Cos(\vartheta_2 - \vartheta_1)\big]$$

Thus:

$$I_{tot}(t) = A_{10}^2 Cos^2\big(\omega_1(t)t\big) + A_{20}^2 Cos^2\big(\omega_2(t)t + \Delta\varphi_{21}(t)\big)$$
$$+ A_{10}A_{20}\big[Cos\big((\omega_2(t) + \omega_1(t))t + \Delta\varphi_{21}(t)\big) + Cos\big((\omega_2 - \omega_1)t - \Delta\varphi_{21}(t)\big)\big]$$

Define:

$$\Omega_{21}(t) \equiv \big(\omega_2(t) + \omega_1(t)\big) \qquad\qquad \Delta\omega_{21}(t) \equiv \big|\omega_2(t) - \omega_1(t)\big|$$

Then:

$$\boxed{I_{tot}(t) = A_{10}^2 Cos^2\big(\omega_1(t)t\big) + A_{20}^2 Cos^2\big(\omega_2(t)t + \Delta\varphi_{21}(t)\big) + A_{10}A_{20}\big[Cos\big(\Omega_{21}(t)t + \Delta\varphi_{21}(t)\big) + Cos\big(\Delta\omega_{21}(t)t - \Delta\varphi_{21}(t)\big)\big]}$$

Identity:

$$Cos^2\vartheta = Cos\,\vartheta\,Cos\,\vartheta \equiv \tfrac{1}{2}\big[Cos\,0 + Cos\,2\vartheta\big] = \tfrac{1}{2}\big[1 + Cos\,2\vartheta\big]$$

Then:

$$\boxed{\begin{aligned} I_{tot}(t) &= \tfrac{1}{2}A_{10}^2\big[1 + Cos^2\,2\big(\omega_1(t)t\big)\big] + \tfrac{1}{2}A_{20}^2\big[1 + Cos^2\,2\big(\omega_2(t)t + \Delta\varphi_{21}(t)\big)\big] \\ &+ A_{10}A_{20}\big[Cos\big(\Omega_{21}(t)t + \Delta\varphi_{21}(t)\big) + Cos\big(\Delta\omega_{21}(t)t - \Delta\varphi_{21}(t)\big)\big] \end{aligned}}$$

# Chicago-Style Harp: Paul Linden (Sean Costello) A-Harp A440
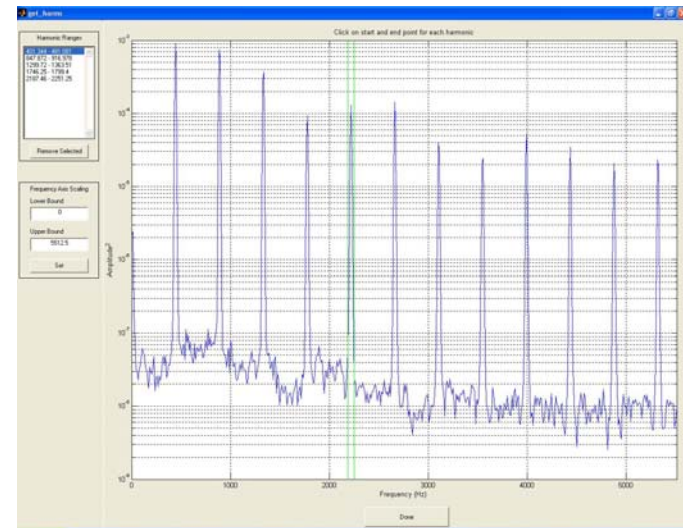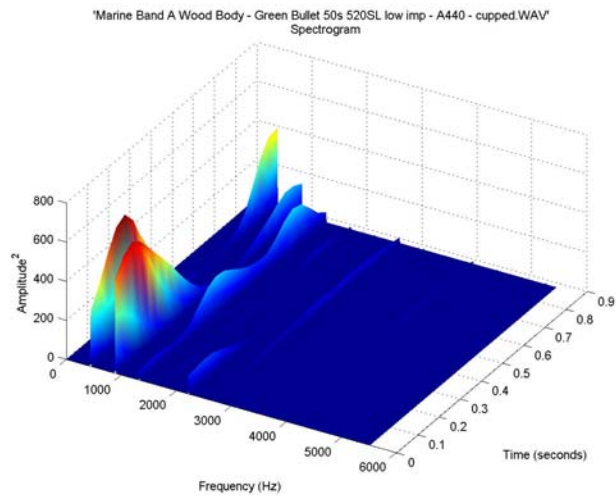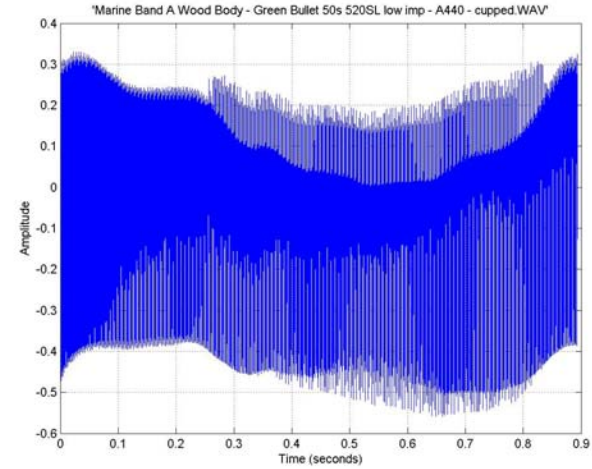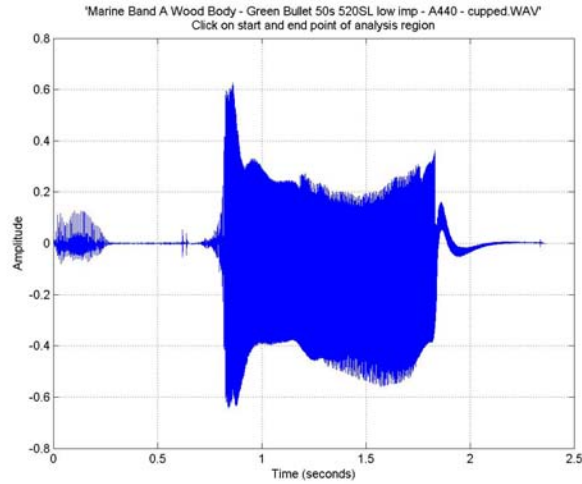
# Harp: 1st Five Harmonics – Amplitude, Frequency & Phase vs. Time:
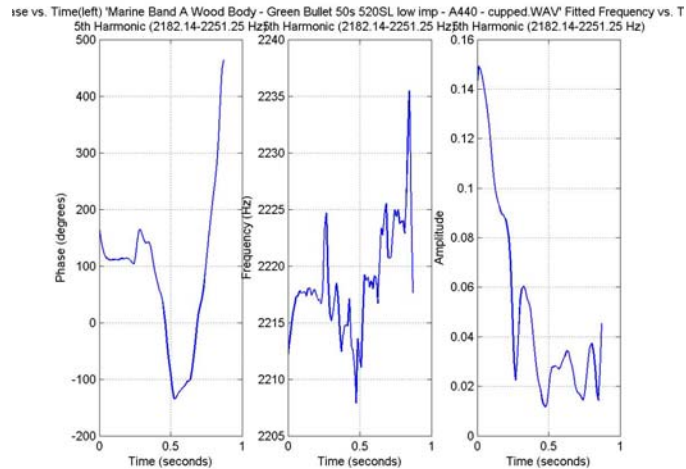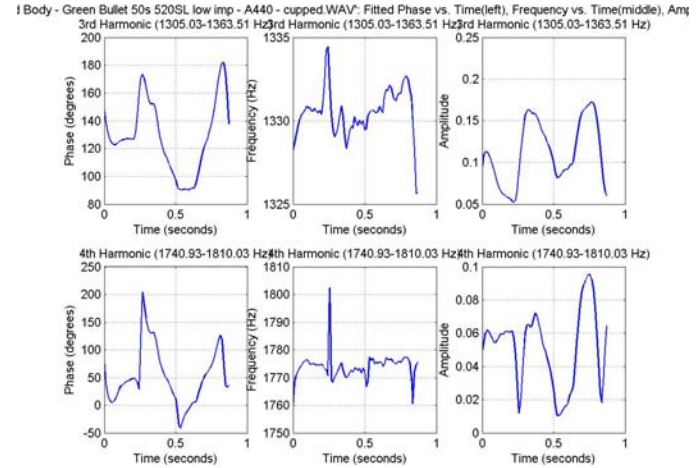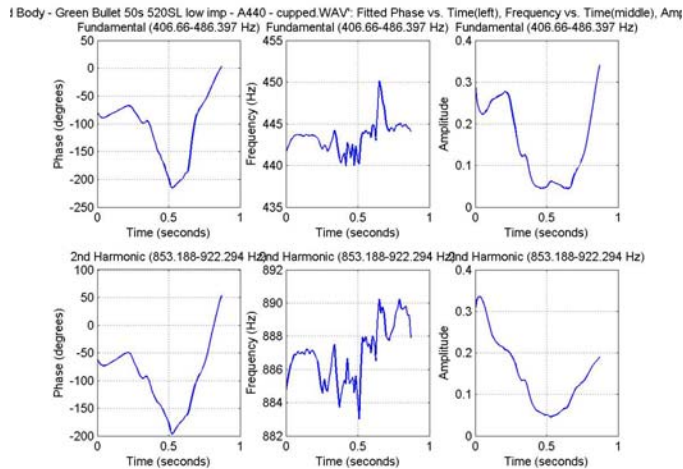
# Harp – Aggregate Plots of Amplitude, Frequency & Phase vs. Time:
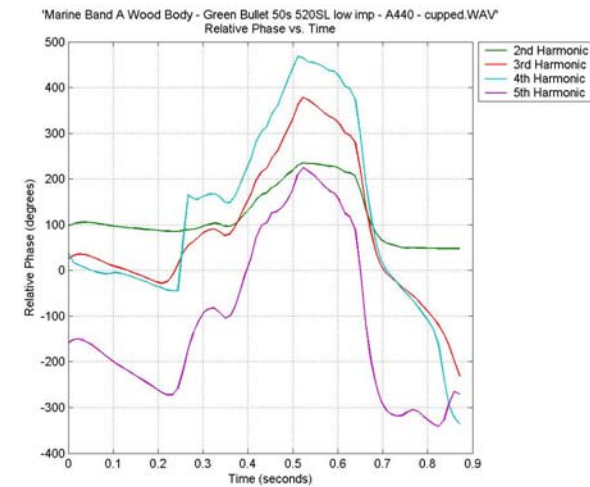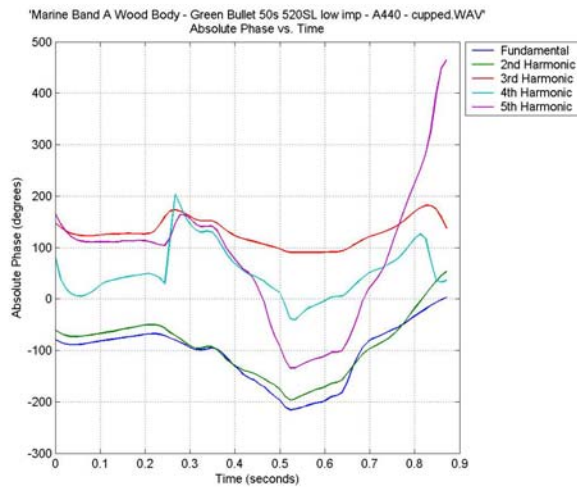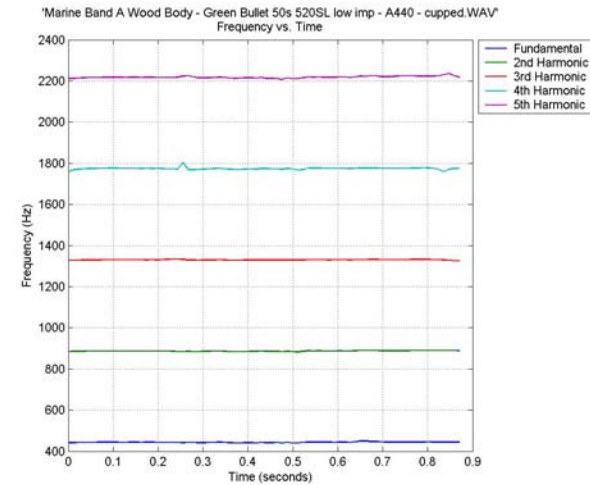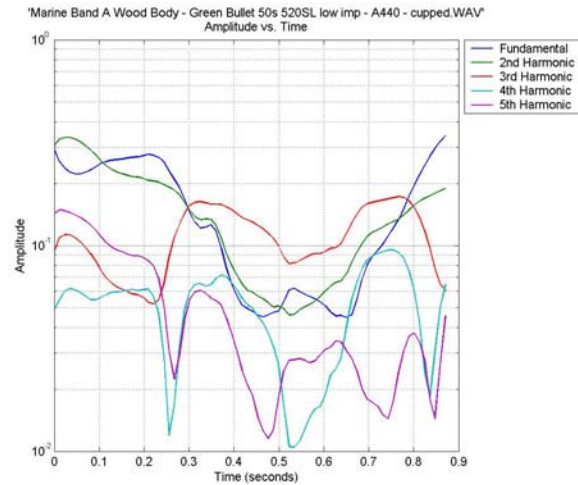
# Harp: Time-Averaged Intensity and Phasor Diagram for Harmonics



'Marine Band A Wood Body - Green Bullet 50s 520SL low imp - A440 - cupped.WAV'
Harmonic Amplitudes



'Marine Band A Wood Body - Green Bullet 50s 520SL low imp - A440 - cupped.WAV'
Average Relative Phase Phasor Diagram

R = Mean Normalized Amplitude (dB) (Fundamental = 6 dB)
Theta = Relative Phase (degrees)
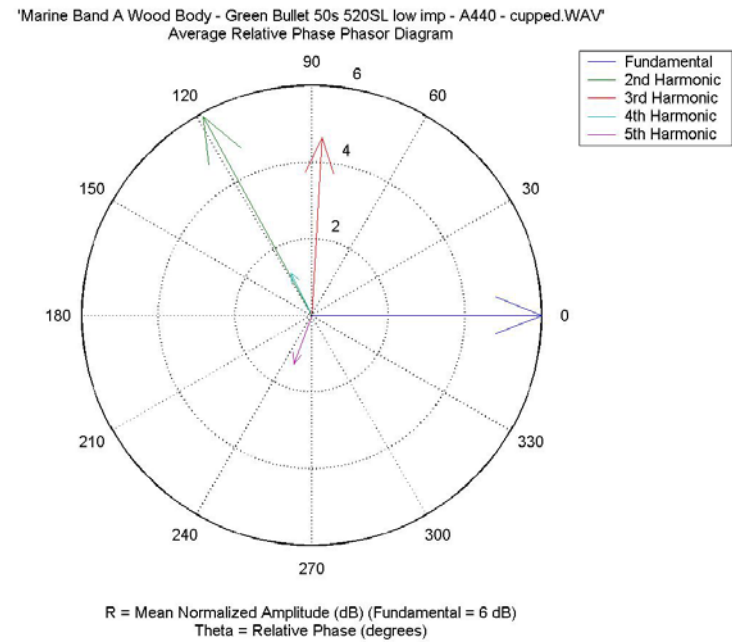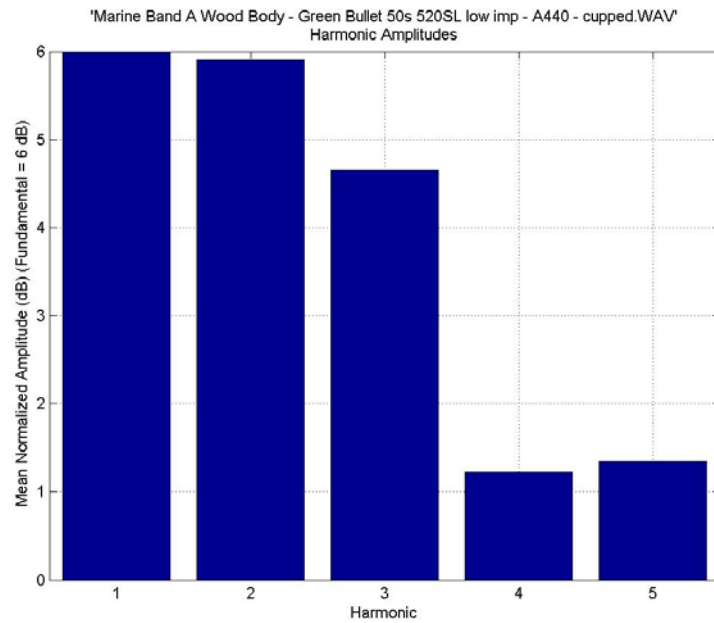
# Vibrational Modes of Cymbals:



Modes of an 18 inch Medium Crash Cymbal
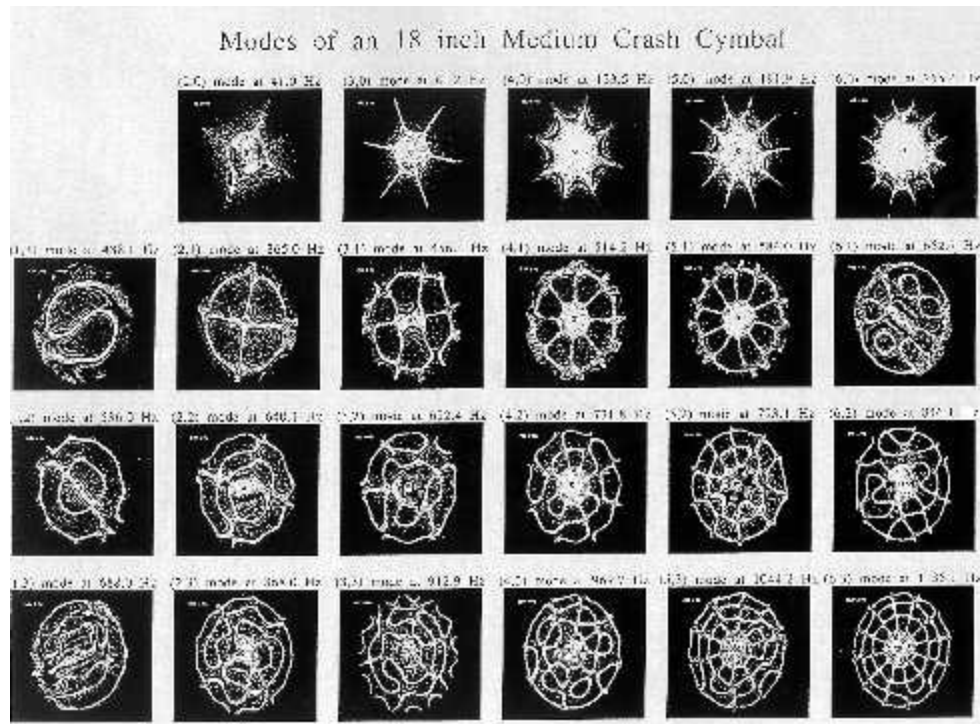
# **Vibrational Modes of Handbells:**
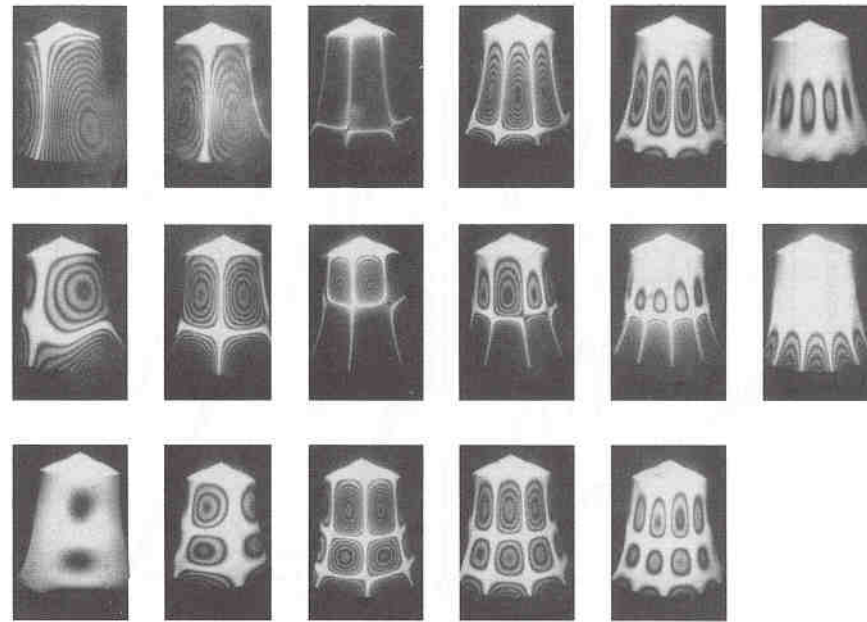


FIGURE 21.16. Time-average hologram interferograms of vibrational modes in a $C_5$ handbell (Rossing et al., 1984).

# How Do Our Ears Work?
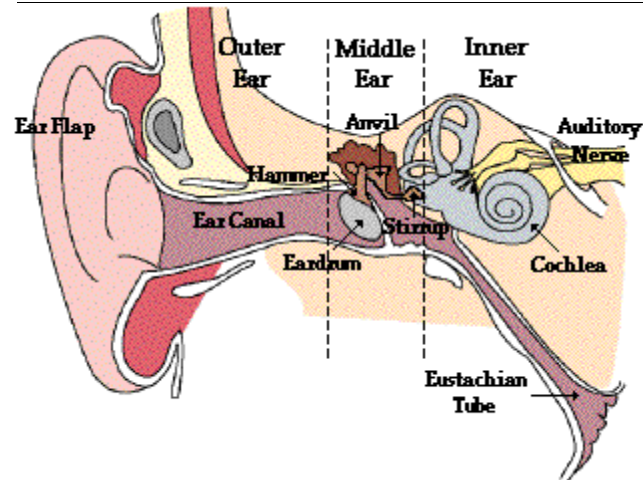


- Sound waves are focussed into the ear canal via the ear flap (aka pinna), and impinge on the ear drum. Folds in pinna for enhancing determination of *location* of sound source!

- Ossicles in middle ear - hammer/anvil/stirrup - transfer vibrations to oval window - membrane on cochlea, in the inner ear.

- Cochlea is filled with perilymph fluid, which transfers sound vibrations into Cochlea.

- Cochlea contains basilar membrane which holds ~ 30,000 hair cells in Organ of Corti.

- Sensitive hairs respond to the sound vibrations – preserve both amplitude and phase information – send signals to brain via auditory nerve.

- Brain processes audio signals from *both* ears - you *hear* the "sound"

- Human hearing response is ~ logarithmic in sound intensity/loudness.
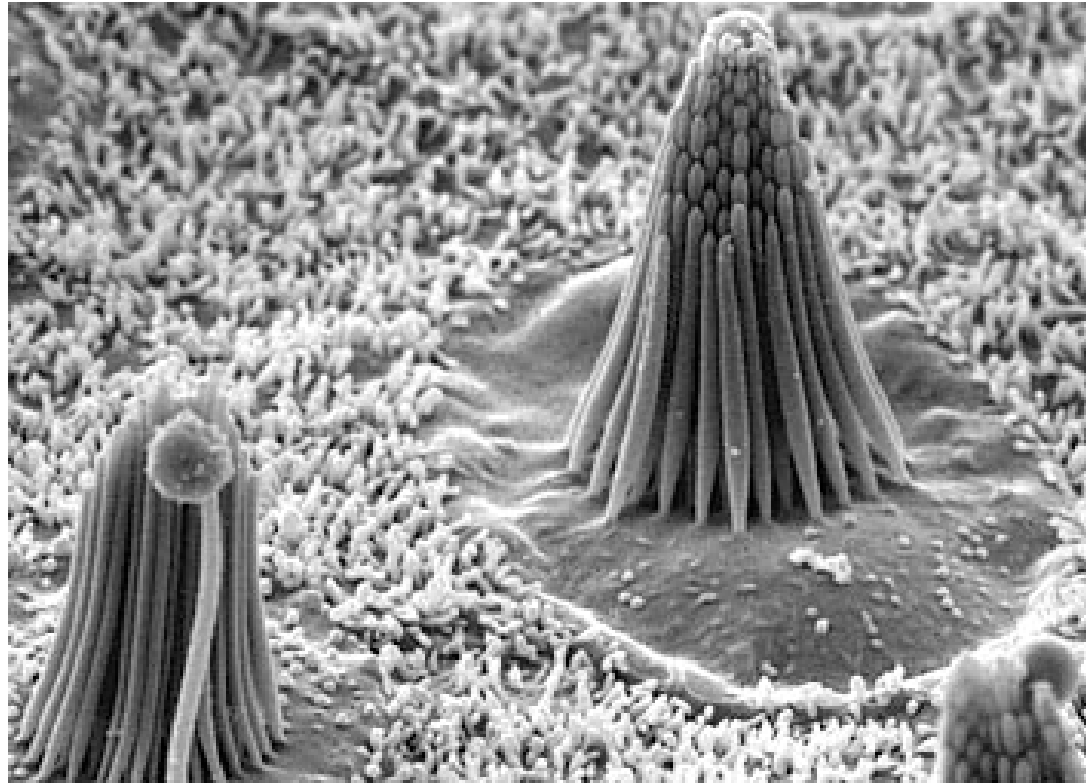
**Scanning Electron Micrograph of Clusters of (Bullfrog) Hair Cells**

# Our Hearing – Pitch-Wise is not Perfectly Linear, Either:

## Deviation of Tuning from Tempered Scale Prediction



FIG. 3. Stretched tuning on the piano; average of sixteen pianos.
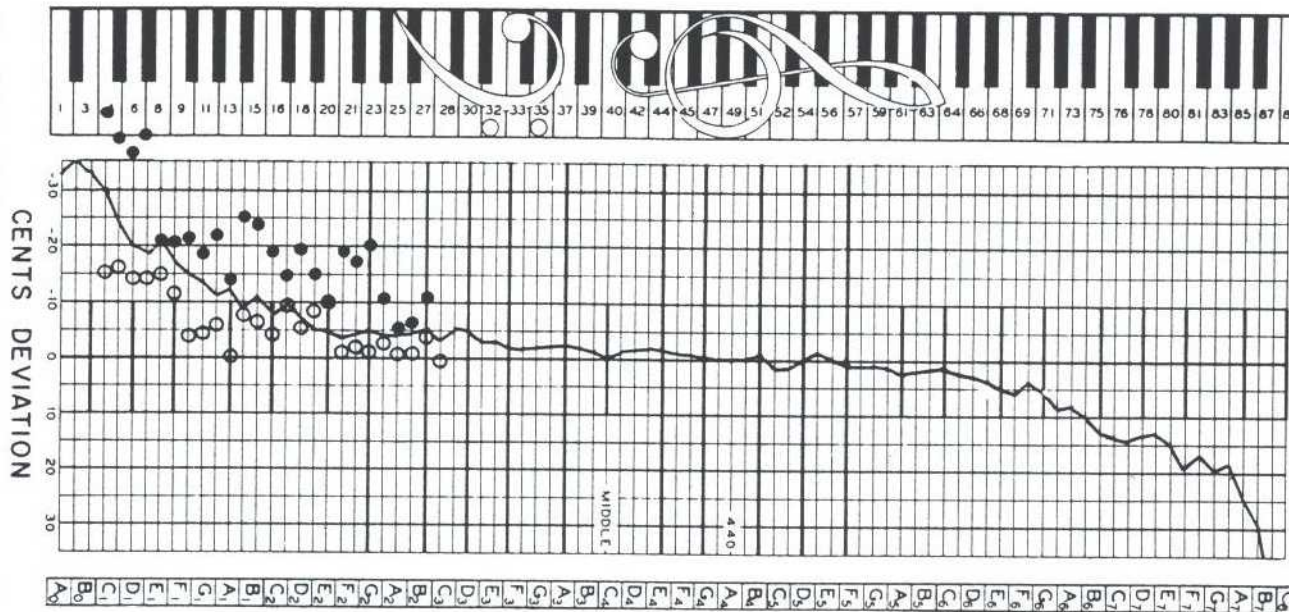
A perfectly tuned piano (tempered scale)
would sound *flat* in the upper register
and sound *sharp* in the lower register

# Consonance & Dissonance

Ancient Greeks - Aristotle and his followers - discovered using a *Monochord* that certain combinations of sounds with *rational number* (*n/m*) frequency ratios were pleasing to the human ear, for example (in *Just Diatonic Scale*):

• **Unison** - 2 simple-tone sounds of *same* frequency, i.e. $f_2 = (1/1) f_1 = f_1$ (= e.g. 300 Hz)

• **Minor Third** - 2 simple-tone sounds with $f_2 = (6/5) f_1 = 1.20 f_1$ (= e.g. 360 Hz)

• **Major Third** - 2 simple-tone sounds with $f_2 = (5/4) f_1 = 1.25 f_1$ (= e.g. 375 Hz)

• **Fourth** - 2 simple-tone sounds with $f_2 = (4/3) f_1 = 1.333 f_1$ (= e.g. 400 Hz)

• **Fifth** - 2 simple-tone sounds with $f_2 = (3/2) f_1 = 1.50 f_1$ (= e.g. 450 Hz)

• **Octave** - one sound is 2nd harmonic of the first - i.e. $f_2 = (2/1) f_1 = 2 f_1$ (= e.g. 600 Hz)

• Also investigated/studied by Galileo Galilei, mathematicians Leibnitz, Euler, physicist Helmholtz, and many others - debate/study is still going on today...

• These 2 simple-tone sound combinations are indeed very special!

• The resulting, overall waveform(s) are *time-independent* – they create <u>standing</u> waves on basilar membrane in cochlea of our inner ears!!!

• The human brain's signal processing for these special 2 simple-tone sound consonant combinations is especially easy!!!

**Example:**

**Consonance of Unison**

Two simple-tone signals with:

$f_2 = (1/1) f_1 = 1 f_1$

(e.g. $f_1 = 300$ Hz

and $f_2 = 300$ Hz)



A2(t)=A20*Sin(w2*t) vs. A1(t)=A10*Sin(w1*t)
A20 = A10 = 1.0, f2/f1 = 1/1 = 1.000000

A'2(t)=A20*Cos(w2*t) vs. A1(t)=A10*Sin(w1*t)
A20 = A10 = 1.0, f2/f1 = 1/1 = 1.000000

Atot(t) = A1(w1*t) + A2(w2*t) vs. (w1*t)
A20 = A10 = 1.0, f2/f1 = 1/1 = 1.000000
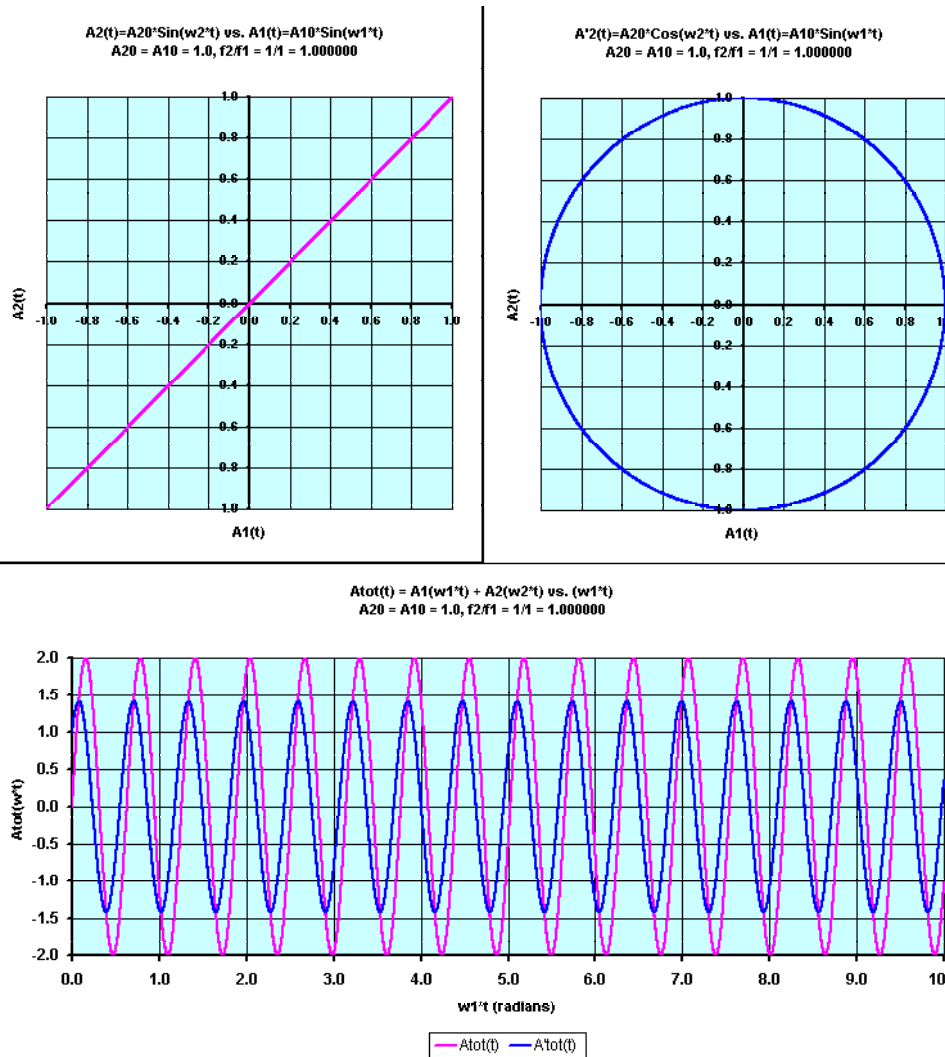
**Example:**

**Consonance of Second**

Two simple-tone signals with:

$f_2 = (9/8) f_1 = 1.125 f_1$

(e.g. $f_1 = 300$ Hz

and $f_2 = 337.5$ Hz)
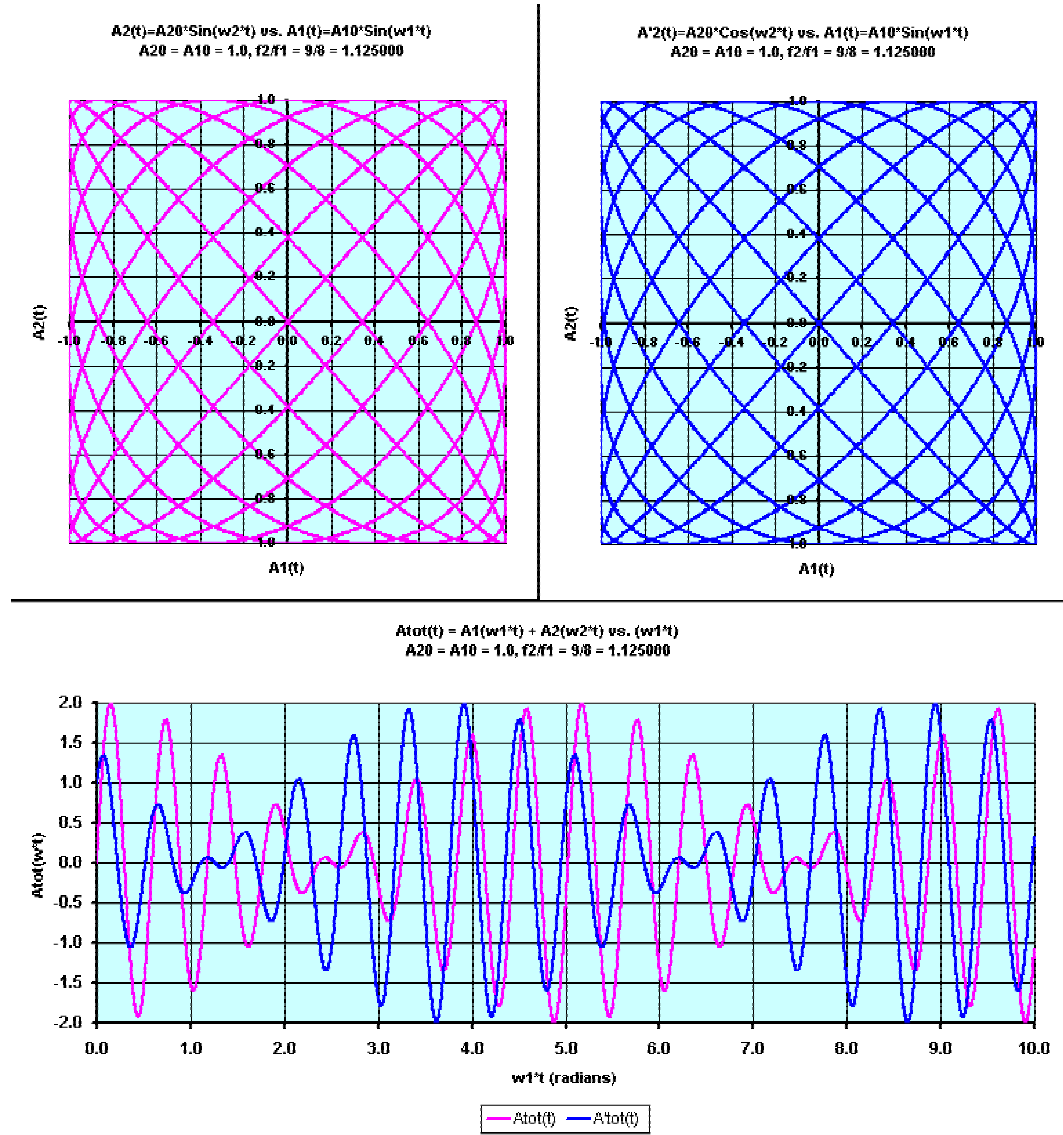
**Example:**

**Consonance of Minor 3rd**

Two simple-tone signals with:

$f_2 = (6/5) f_1 = 1.20 f_1$

(e.g. $f_1 = 300$ Hz

and $f_2 = 360$ Hz)
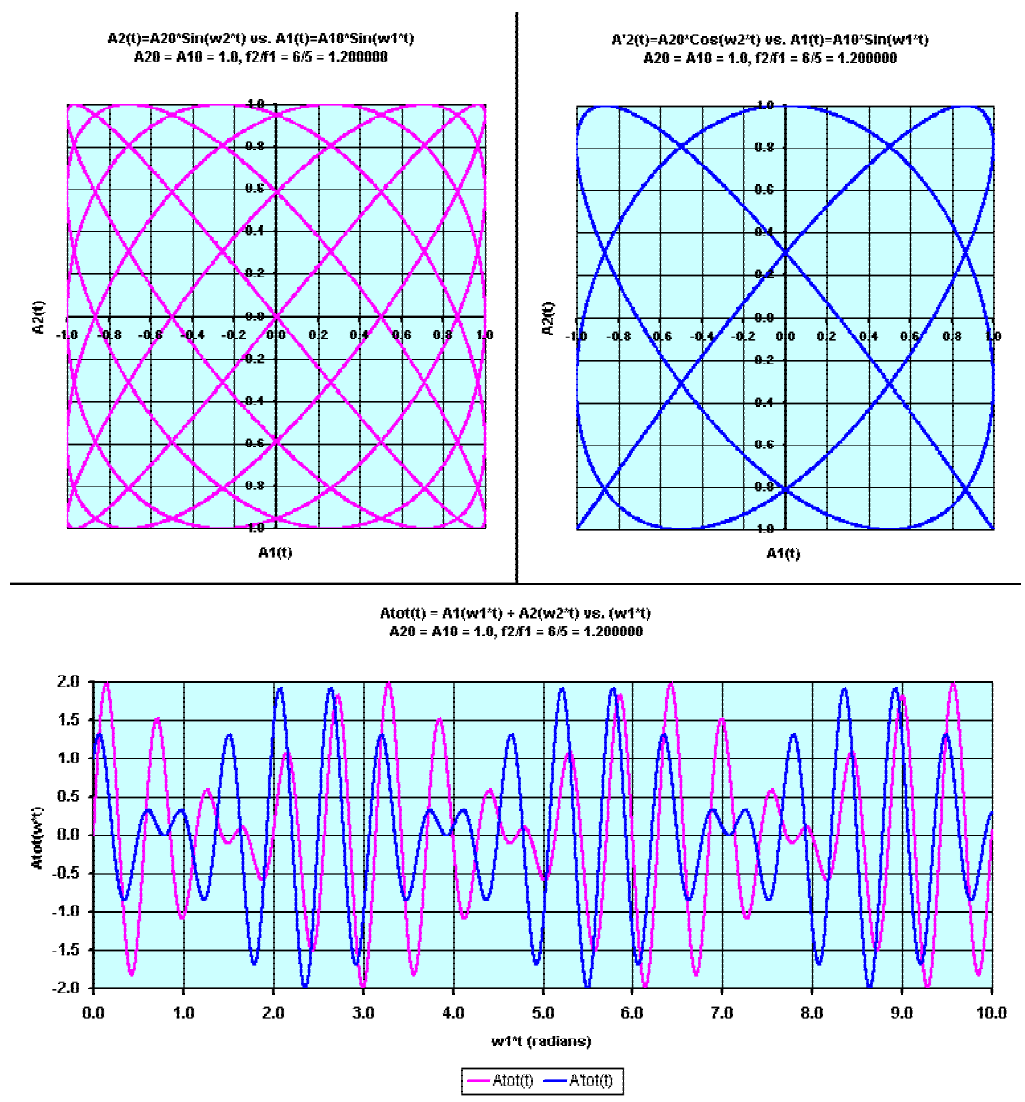
**Example:**

**Consonance of Major 3rd**

Two simple-tone signals with:

$$f_2 = (5/4) f_1 = 1.25 f_1$$

(e.g. $f_1 = 300$ Hz

and $f_2 = 375$ Hz)



A2(t)=A20*Sin(w2*t) vs. A1(t)=A10*Sin(w1*t)
A20 = A10 = 1.0, f2/f1 = 5/4 = 1.250000

A'2(t)=A20*Cos(w2*t) vs. A1(t)=A10*Sin(w1*t)
A20 = A10 = 1.0, f2/f1 = 5/4 = 1.250000

Atot(t) = A1(w1*t) + A2(w2*t) vs. (w1*t)
A20 = A10 = 1.0, f2/f1 = 5/4 = 1.250000
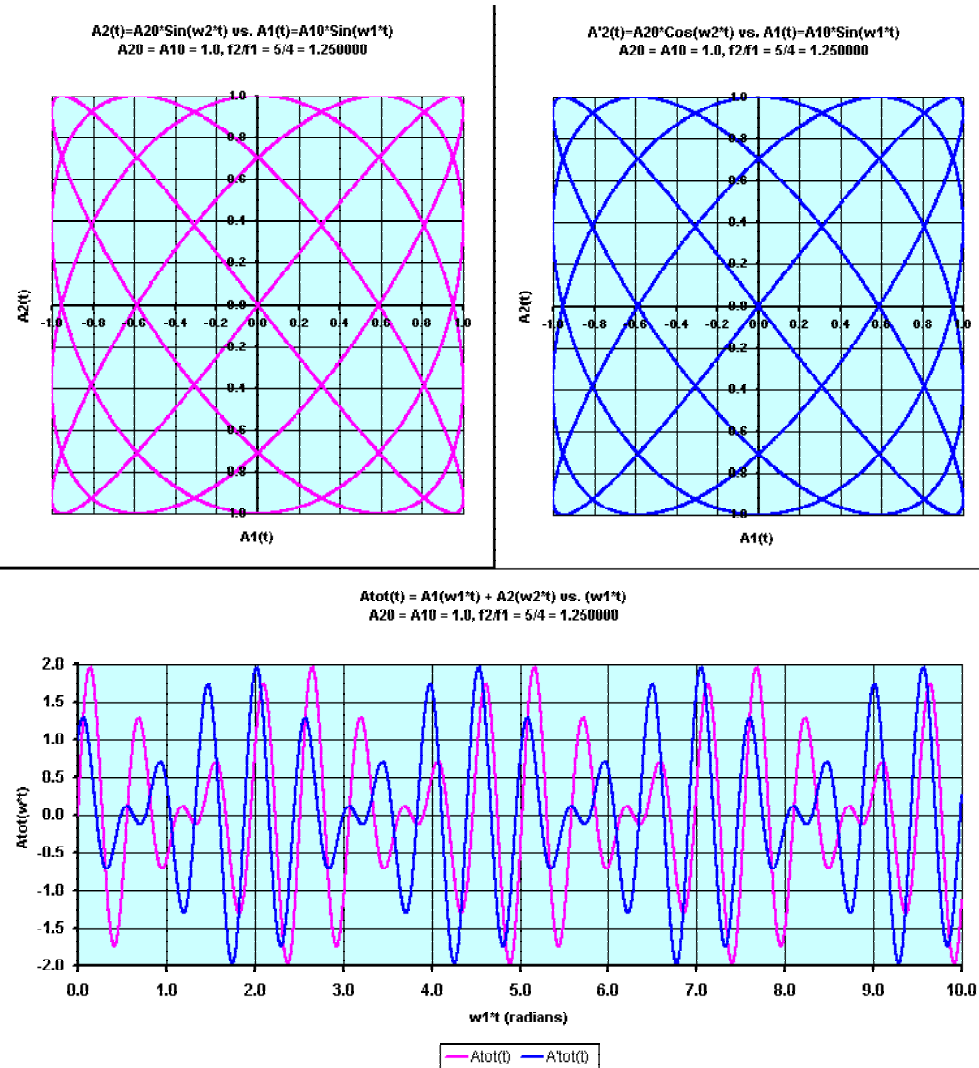
**Example:**

**Consonance of Fourth**

Two simple-tone signals with:

$f_2 = (4/3) f_1 = 1.333 f_1$

(e.g. $f_1 = 300$ Hz

and $f_2 = 400$ Hz)
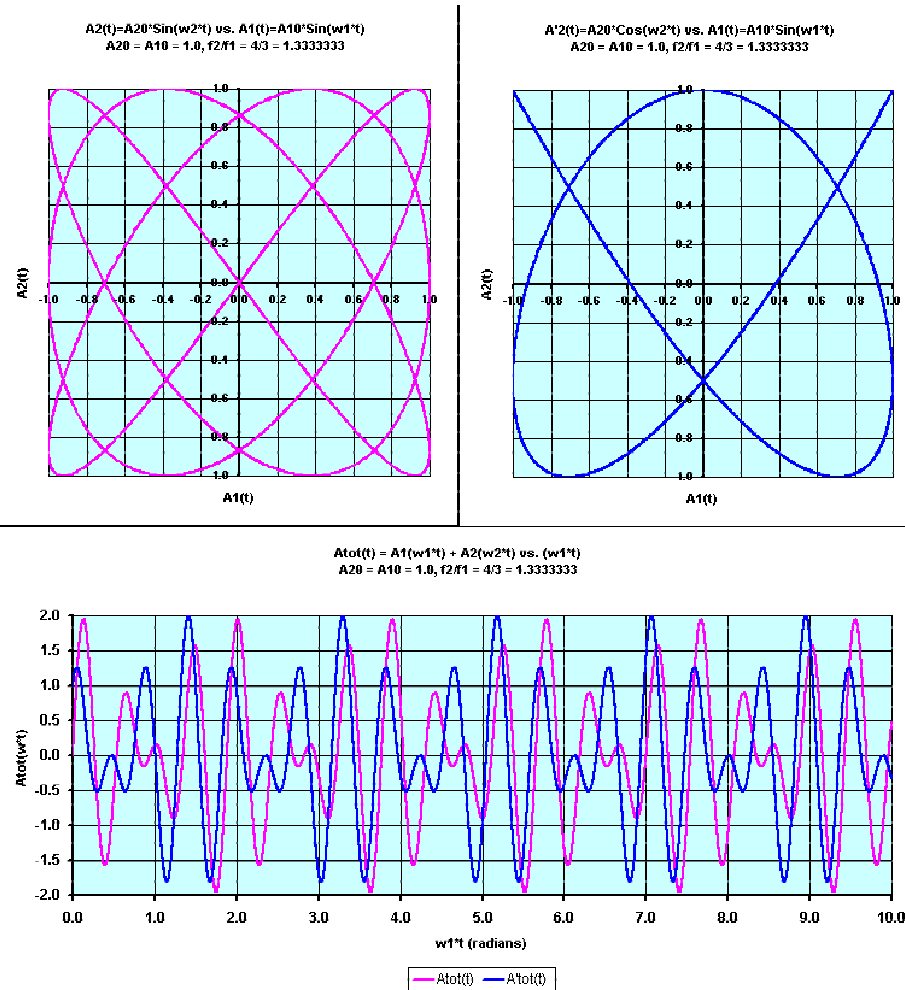
**Example:**

**Consonance of Fifth**

Two simple-tone signals with:

$f_2 = (3/2) f_1 = 1.5 f_1$

(e.g. $f_1 = 300$ Hz

and $f_2 = 450$ Hz)



A2(t)=A20*Sin(w2*t) vs. A1(t)=A10*Sin(w1*t)
A20 = A10 = 1.0, f2/f1 = 3/2 = 1.5000000

A'2(t)=A20*Cos(w2*t) vs. A1(t)=A10*Sin(w1*t)
A20 = A10 = 1.0, f2/f1 = 3/2 = 1.5000000

Atot(t) = A1(w1*t) + A2(w2*t) vs. (w1*t)
A20 = A10 = 1.0, f2/f1 = 3/2 = 1.5000000
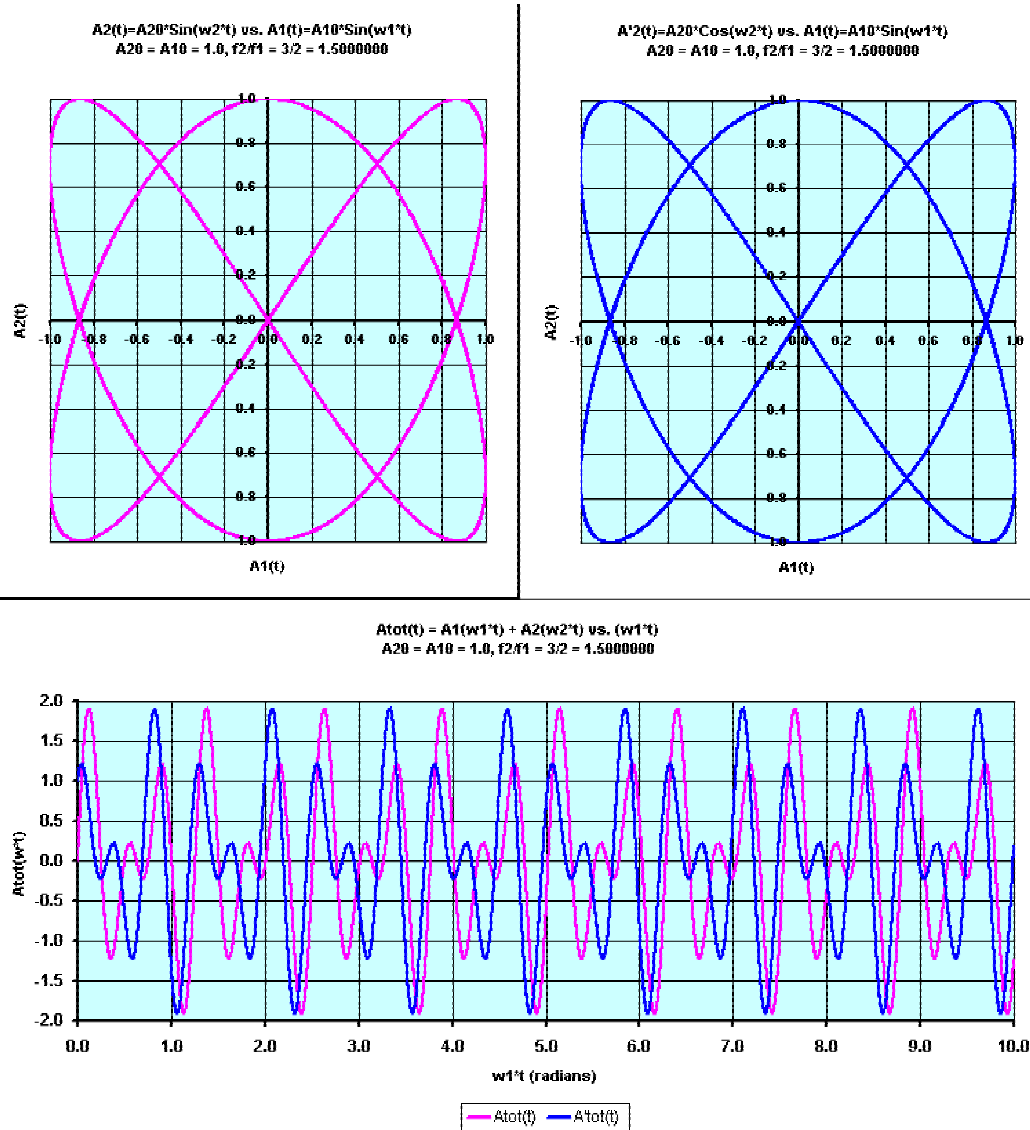
**Example:**

**Consonance of Sixth**

Two simple-tone signals with:

$f_2 = (5/3) f_1 = 1.666 f_1$

(e.g. $f_1 = 300$ Hz

and $f_2 = 500$ Hz)
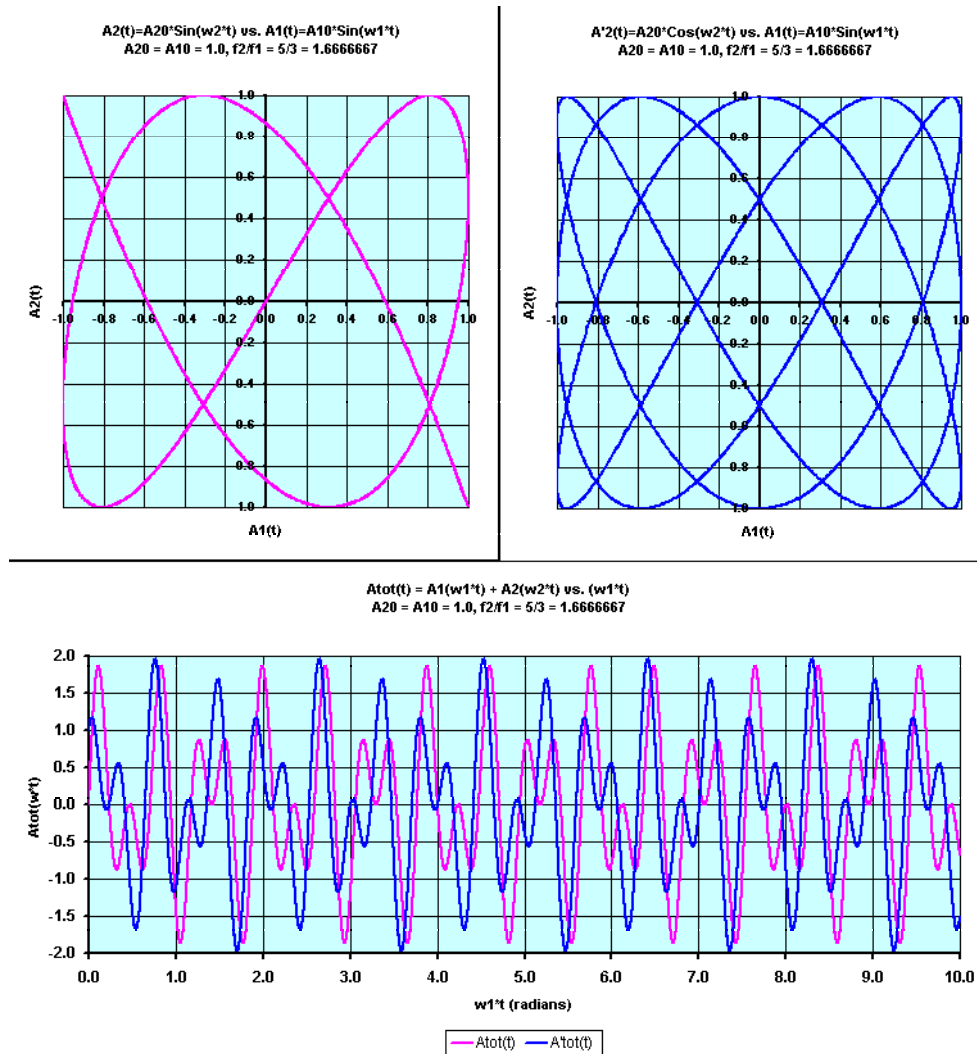
**Example:**

**Consonance of Seventh**

Two simple-tone signals with:

$f_2 = (15/8) f_1 = 1.875 f_1$

(e.g. $f_1 = 300$ Hz

and $f_2 = 562.5$ Hz)



A2(t)=A20*Sin(w2*t) vs. A1(t)=A10*Sin(w1*t)
A20 = A10 = 1.0, f2/f1 = 15/8 = 1.8750000

A'2(t)=A20*Cos(w2*t) vs. A1(t)=A10*Sin(w1*t)
A20 = A10 = 1.0, f2/f1 = 15/8 = 1.8750000

Atot(t) = A1(w1*t) + A2(w2*t) vs. (w1*t)
A20 = A10 = 1.0, f2/f1 = 15/8 = 1.8750000
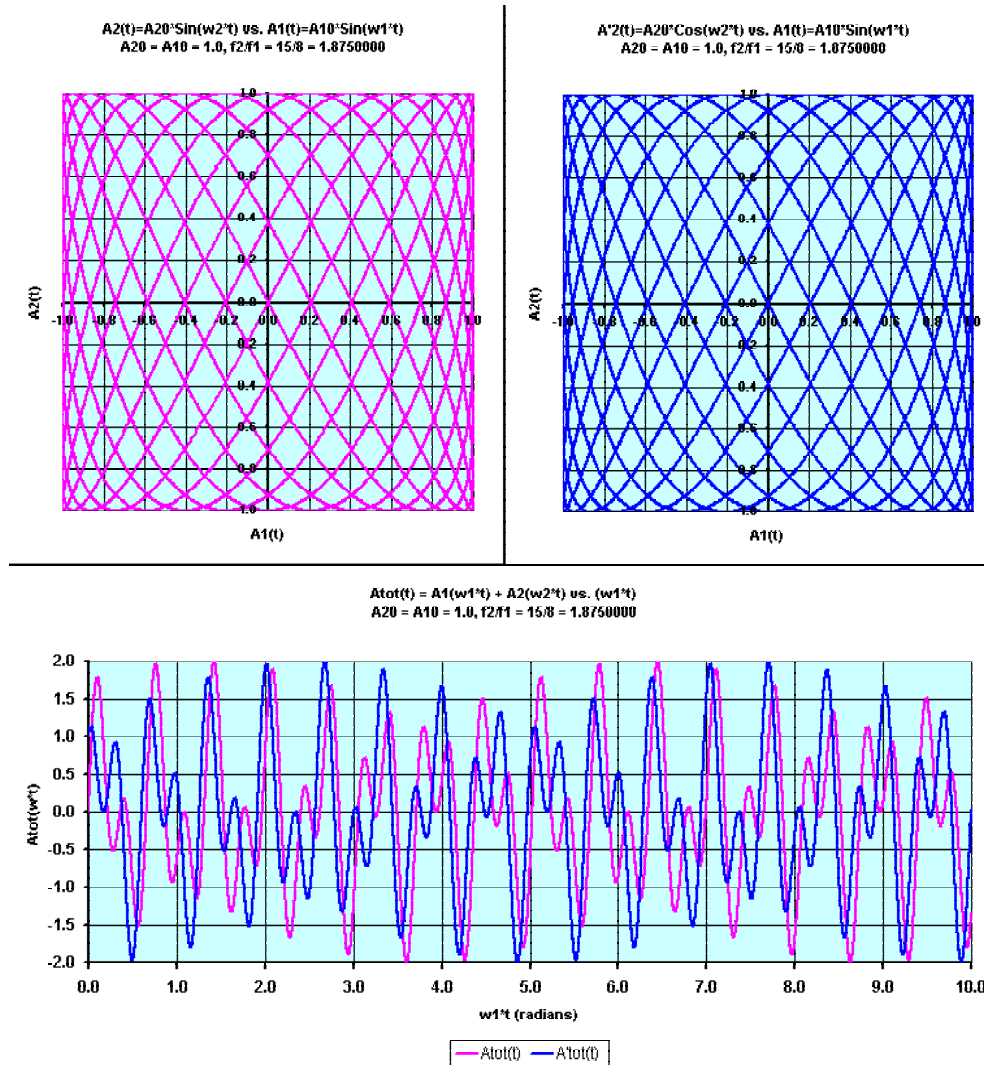
## Example:

## Consonance of Octave

Two simple-tone signals with:

$$f_2 = (2/1)f_1 = 2f_1$$

(e.g. $f_1 = 300$ Hz

and $f_2 = 600$ Hz)



A2(t)=A20*Sin(w2*t) vs. A1(t)=A10*Sin(w1*t)
A20 = A10 = 1.0, f2/f1 = 2/1 = 2.0000000



A'2(t)=A20*Cos(w2*t) vs. A1(t)=A10*Sin(w1*t)
A20 = A10 = 1.0, f2/f1 = 2/1 = 2.0000000



Atot(t) = A1(w1*t) + A2(w2*t) vs. (w1*t)
A20 = A10 = 1.0, f2/f1 = 2/1 = 2.0000000
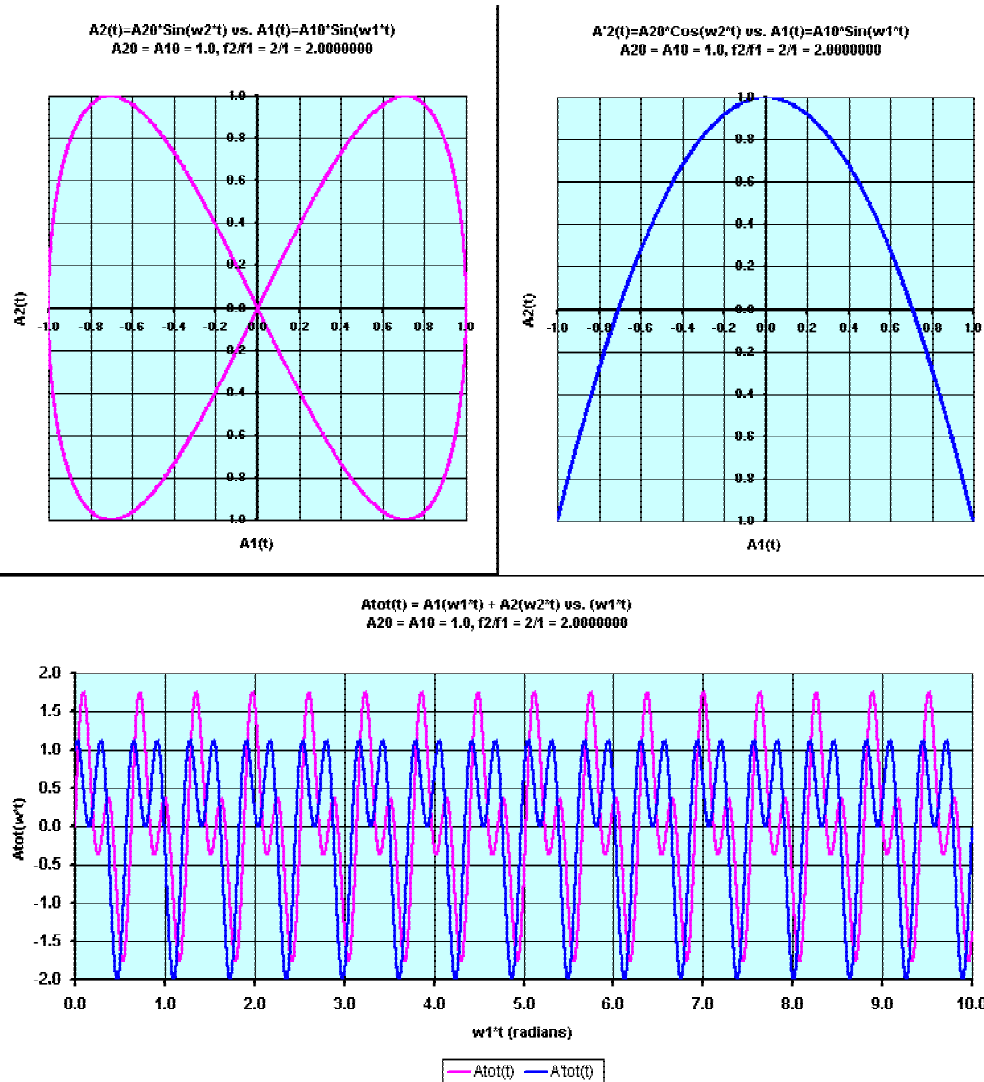
## Example:

## Consonance of 1st & 3rd Harmonics

Two simple-tone signals with:

$f_2 = (3/1)f_1 = 3f_1$

(e.g. $f_1 = 300$ Hz

and $f_2 = 900$ Hz)



A2(t)=A20*Sin(w2*t) vs. A1(t)=A10*Sin(w1*t)
A20 = A10 = 1.0, f2/f1 = 3/1 = 3.0000000

A'2(t)=A20*Cos(w2*t) vs. A1(t)=A10*Sin(w1*t)
A20 = A10 = 1.0, f2/f1 = 3/1 = 3.0000000

Atot(t) = A1(w1*t) + A2(w2*t) vs. (w1*t)
A20 = A10 = 1.0, f2/f1 = 3/1 = 3.0000000

**Example:**

**Consonance of 1st & 4th Harmonics**

Two simple-tone signals with:

$f_2 = (4/1) f_1 = 4 f_1$

(e.g. $f_1 = 300$ Hz

and $f_2 = 1200$ Hz)



A2(t)=A20*Sin(w2*t) vs. A1(t)=A10*Sin(w1*t)
A20 = A10 = 1.0, f2/f1 = 4/1 = 4.0000000

A'2(t)=A20*Cos(w2*t) vs. A1(t)=A10*Sin(w1*t)
A20 = A10 = 1.0, f2/f1 = 4/1 = 4.0000000

Atot(t) = A1(w1*t) + A2(w2*t) vs. (w1*t)
A20 = A10 = 1.0, f2/f1 = 4/1 = 4.0000000

**Example:**

**Consonance of 1st & 5th Harmonics**

Two simple-tone signals with:

$$f_2 = (5/1) f_1 = 5 f_1$$

(e.g. $f_1 = 300$ Hz

and $f_2 = 1500$ Hz)



A2(t)=A20*Sin(w2*t) vs. A1(t)=A10*Sin(w1*t)
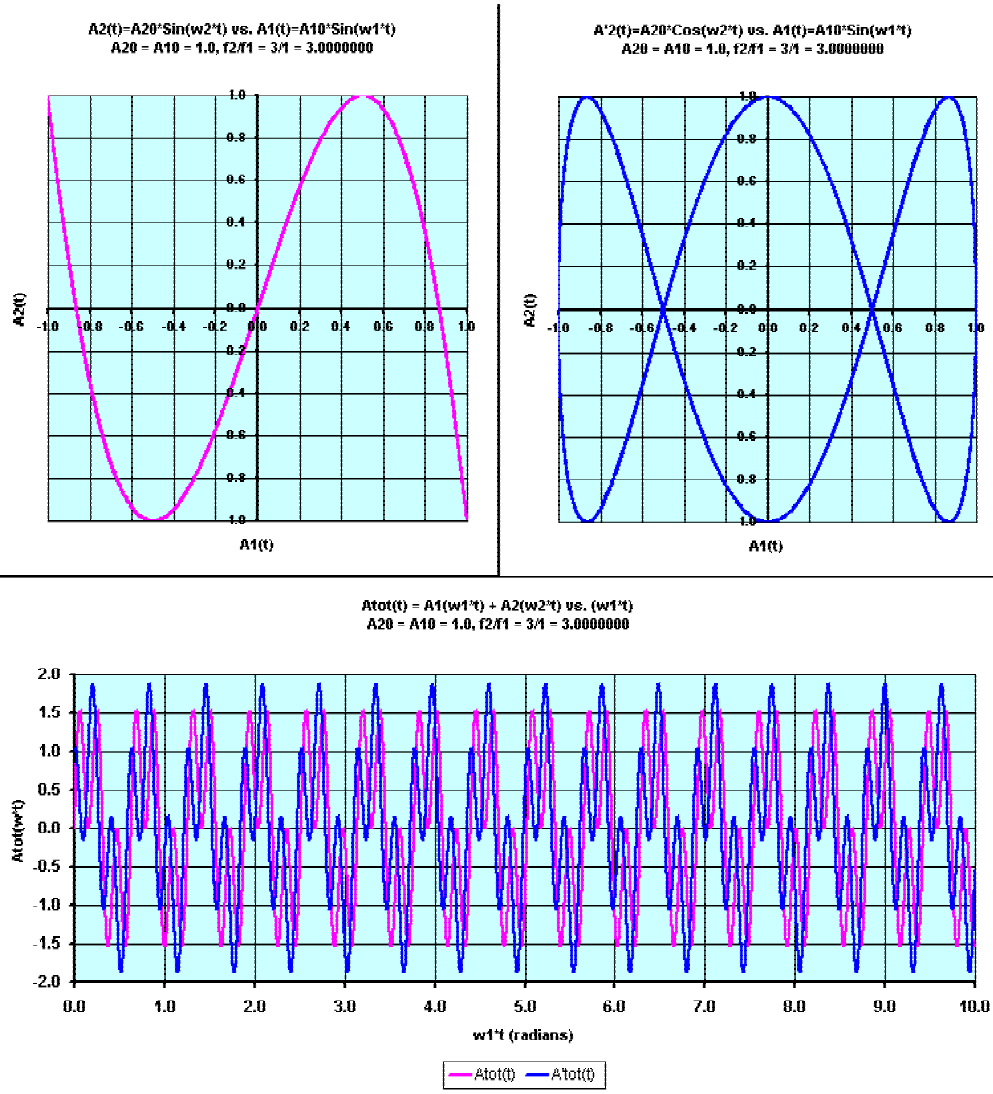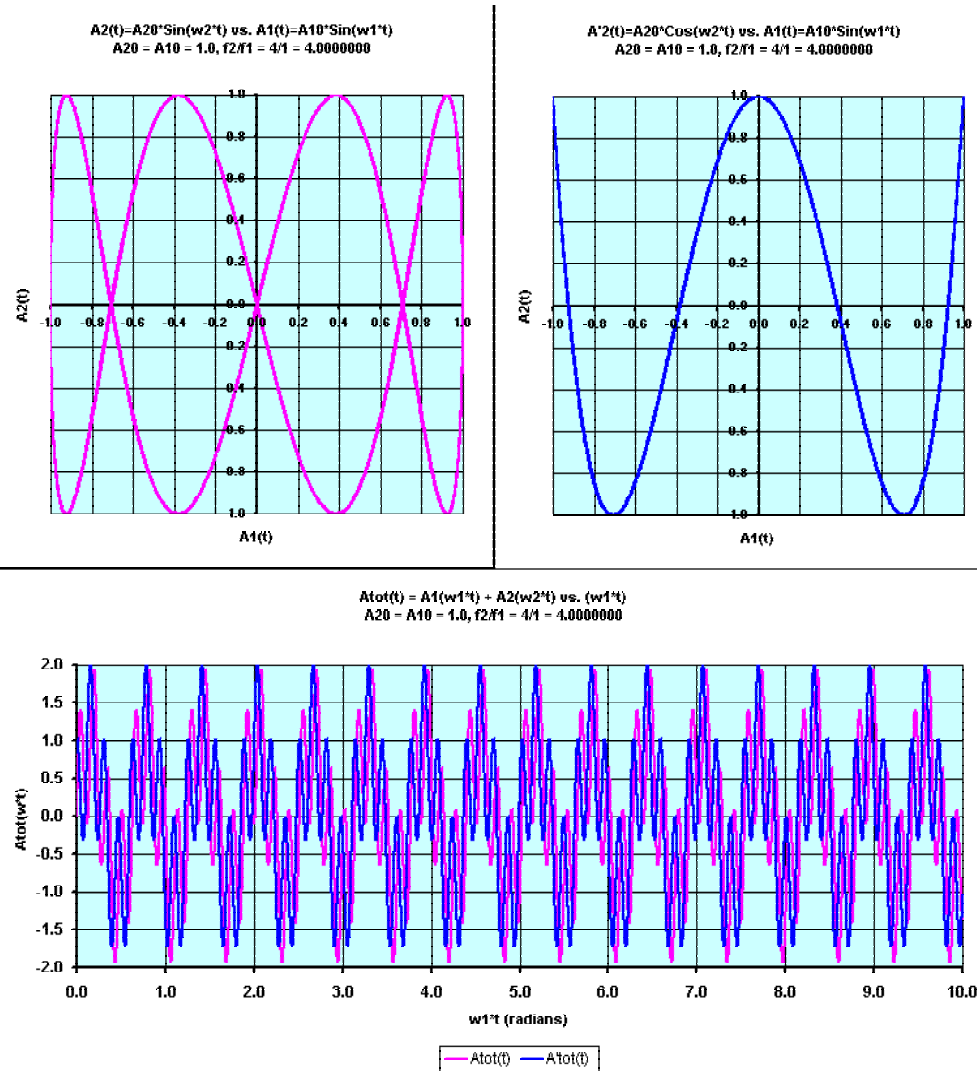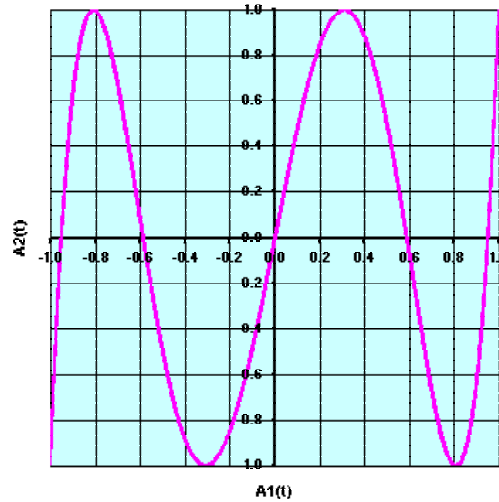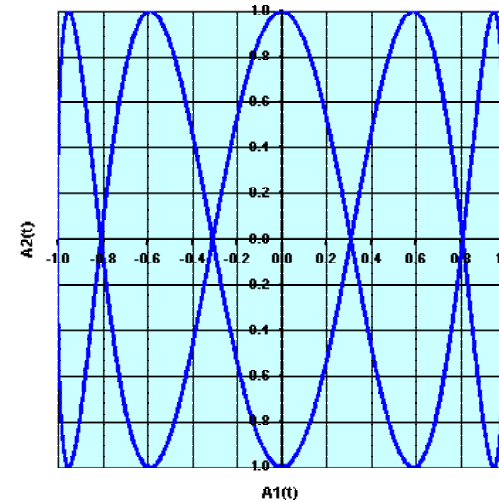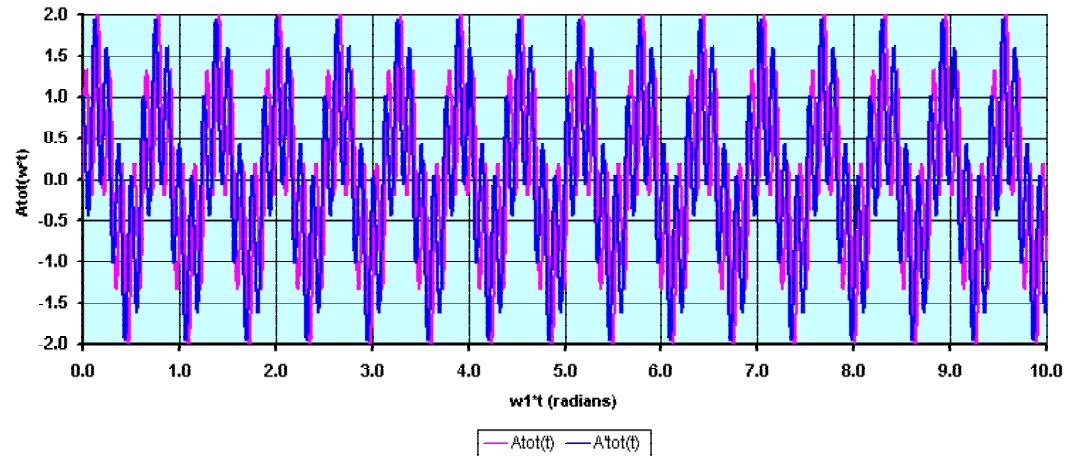A20 = A10 = 1.0, f2/f1 = 5/1 = 5.0000000

A'2(t)=A20*Cos(w2*t) vs. A1(t)=A10*Sin(w1*t)
A20 = A10 = 1.0, f2/f1 = 5/1 = 5.0000000

Atot(t) = A1(w1*t) + A2(w2*t) vs. (w1*t)
A20 = A10 = 1.0, f2/f1 = 5/1 = 5.0000000

# Consonance of Harmonics
## Just Diatonic Scale

**Fundamental Frequency, $f_o = 100$ Hz**

| | | | Unison | Second | ??? | ??? | Minor 3rd | Major 3rd | Fourth | Fifth | Sixth | Seventh | Octave |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Harmonic** | | | C-C | D-C | ???-C | ???-C | E♭-C | E-C | F-C | G-C | A-C | B-C | C-C |
| **#** | | | 1:1 | 9:8 | 8:7 | 7:6 | 6:5 | 5:4 | 4:3 | 3:2 | 5:3 | 15:8 | 2:1 |
| 1 | | | 100.0 | 112.5 | 114.3 | 116.7 | 120.0 | 125.0 | 133.3 | 150.0 | 166.7 | 187.5 | 200.0 |
| 2 | | | 200.0 | 225.0 | 228.6 | 233.3 | 240.0 | 250.0 | 266.7 | 300.0 | 333.3 | 375.0 | 400.0 |
| 3 | | | 300.0 | 337.5 | 342.9 | 350.0 | 360.0 | 375.0 | 400.0 | 450.0 | 500.0 | 562.5 | 600.0 |
| 4 | | | 400.0 | 450.0 | 457.1 | 466.7 | 480.0 | 500.0 | 533.3 | 600.0 | 666.7 | 750.0 | 800.0 |
| 5 | | | 500.0 | 562.5 | 571.4 | 583.3 | 600.0 | 625.0 | 666.7 | 750.0 | 833.3 | 937.5 | 1000.0 |
| 6 | | | 600.0 | 675.0 | 685.7 | 700.0 | 720.0 | 750.0 | 800.0 | 900.0 | 1000.0 | 1125.0 | 1200.0 |
| 7 | | | 700.0 | 787.5 | 800.0 | 816.7 | 840.0 | 875.0 | 933.3 | 1050.0 | 1166.7 | 1312.5 | 1400.0 |
| 8 | | | 800.0 | 900.0 | 914.3 | 933.3 | 960.0 | 1000.0 | 1066.7 | 1200.0 | 1333.3 | 1500.0 | 1600.0 |
| 9 | | | 900.0 | 1012.5 | 1028.6 | 1050.0 | 1080.0 | 1125.0 | 1200.0 | 1350.0 | 1500.0 | 1687.5 | 1800.0 |
| 10 | | | 1000.0 | 1125.0 | 1142.9 | 1166.7 | 1200.0 | 1250.0 | 1333.3 | 1500.0 | 1666.7 | 1875.0 | 2000.0 |
| 11 | | | 1100.0 | 1237.5 | 1257.1 | 1283.3 | 1320.0 | 1375.0 | 1466.7 | 1650.0 | 1833.3 | 2062.5 | 2200.0 |
| 12 | | | 1200.0 | 1350.0 | 1371.4 | 1400.0 | 1440.0 | 1500.0 | 1600.0 | 1800.0 | 2000.0 | 2250.0 | 2400.0 |
| 13 | | | 1300.0 | 1462.5 | 1485.7 | 1516.7 | 1560.0 | 1625.0 | 1733.3 | 1950.0 | 2166.7 | 2437.5 | 2600.0 |
| 14 | | | 1400.0 | 1575.0 | 1600.0 | 1633.3 | 1680.0 | 1750.0 | 1866.7 | 2100.0 | 2333.3 | 2625.0 | 2800.0 |
| 15 | | | 1500.0 | 1687.5 | 1714.3 | 1750.0 | 1800.0 | 1875.0 | 2000.0 | 2250.0 | 2500.0 | 2812.5 | 3000.0 |
| 16 | | | 1600.0 | 1800.0 | 1828.6 | 1866.7 | 1920.0 | 2000.0 | 2133.3 | 2400.0 | 2666.7 | 3000.0 | 3200.0 |
| 17 | | | 1700.0 | 1912.5 | 1942.9 | 1983.3 | 2040.0 | 2125.0 | 2266.7 | 2550.0 | 2833.3 | 3187.5 | 3400.0 |
| 18 | | | 1800.0 | 2025.0 | 2057.1 | 2100.0 | 2160.0 | 2250.0 | 2400.0 | 2700.0 | 3000.0 | 3375.0 | 3600.0 |
| 19 | | | 1900.0 | 2137.5 | 2171.4 | 2216.7 | 2280.0 | 2375.0 | 2533.3 | 2850.0 | 3166.7 | 3562.5 | 3800.0 |
| 20 | | | 2000.0 | 2250.0 | 2285.7 | 2333.3 | 2400.0 | 2500.0 | 2666.7 | 3000.0 | 3333.3 | 3750.0 | 4000.0 |
| 21 | | | 2100.0 | 2362.5 | 2400.0 | 2450.0 | 2520.0 | 2625.0 | 2800.0 | 3150.0 | 3500.0 | 3937.5 | 4200.0 |
| 22 | | | 2200.0 | 2475.0 | 2514.3 | 2566.7 | 2640.0 | 2750.0 | 2933.3 | 3300.0 | 3666.7 | 4125.0 | 4400.0 |
| 23 | | | 2300.0 | 2587.5 | 2628.6 | 2683.3 | 2760.0 | 2875.0 | 3066.7 | 3450.0 | 3833.3 | 4312.5 | 4600.0 |
| 24 | | | 2400.0 | 2700.0 | 2742.9 | 2800.0 | 2880.0 | 3000.0 | 3200.0 | 3600.0 | 4000.0 | 4500.0 | 4800.0 |
| 25 | | | 2500.0 | 2812.5 | 2857.1 | 2916.7 | 3000.0 | 3125.0 | 3333.3 | 3750.0 | 4166.7 | 4687.5 | 5000.0 |
| 26 | | | 2600.0 | 2925.0 | 2971.4 | 3033.3 | 3120.0 | 3250.0 | 3466.7 | 3900.0 | 4333.3 | 4875.0 | 5200.0 |
| 27 | | | 2700.0 | 3037.5 | 3085.7 | 3150.0 | 3240.0 | 3375.0 | 3600.0 | 4050.0 | 4500.0 | 5062.5 | 5400.0 |
| 28 | | | 2800.0 | 3150.0 | 3200.0 | 3266.7 | 3360.0 | 3500.0 | 3733.3 | 4200.0 | 4666.7 | 5250.0 | 5600.0 |
| 29 | | | 2900.0 | 3262.5 | 3314.3 | 3383.3 | 3480.0 | 3625.0 | 3866.7 | 4350.0 | 4833.3 | 5437.5 | 5800.0 |
| 30 | | | 3000.0 | 3375.0 | 3428.6 | 3500.0 | 3600.0 | 3750.0 | 4000.0 | 4500.0 | 5000.0 | 5625.0 | 6000.0 |
| 31 | | | 3100.0 | 3487.5 | 3542.9 | 3616.7 | 3720.0 | 3875.0 | 4133.3 | 4650.0 | 5166.7 | 5812.5 | 6200.0 |
| 32 | | | 3200.0 | 3600.0 | 3657.1 | 3733.3 | 3840.0 | 4000.0 | 4266.7 | 4800.0 | 5333.3 | 6000.0 | 6400.0 |

**Dissonance of Harmonics**

**Just Diatonic Scale**

**Fundamental Frequency,**

$f_o = 100$ Hz

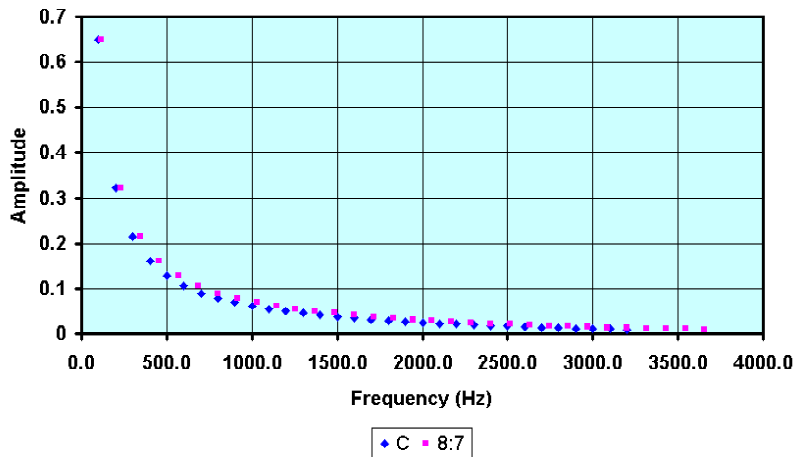| Harmonic | Unison C-C | Second D-C | ??? ???-C | ??? ???-C | Minor 3rd Eb-C | Major 3rd E-C | Fourth F-C | Fifth G-C | Sixth A-C | Seventh B-C | Octave C-C |
|---|---|---|---|---|---|---|---|---|---|---|---|
| # | 1:1 | 9:8 | 8:7 | 7:6 | 6:5 | 5:4 | 4:3 | 3:2 | 5:3 | 15:8 | 2:1 |
| 1 | 100.0 | 112.5 | 114.3 | 116.7 | 120.0 | 125.0 | 133.3 | 150.0 | 166.7 | 187.5 | 200.0 |
| 2 | 200.0 | 225.0 | 228.6 | 233.3 | 240.0 | 250.0 | 266.7 | 300.0 | 333.3 | 375.0 | 400.0 |
| 3 | 300.0 | 337.5 | 342.9 | 350.0 | 360.0 | 375.0 | 400.0 | 450.0 | 500.0 | 562.5 | 600.0 |
| 4 | 400.0 | 450.0 | 457.1 | 466.7 | 480.0 | 500.0 | 533.3 | 600.0 | 666.7 | 750.0 | 800.0 |
| 5 | 500.0 | 562.5 | 571.4 | 583.3 | 600.0 | 625.0 | 666.7 | 750.0 | 833.3 | 937.5 | 1000.0 |
| 6 | 600.0 | 675.0 | 685.7 | 700.0 | 720.0 | 750.0 | 800.0 | 900.0 | 1000.0 | 1125.0 | 1200.0 |
| 7 | 700.0 | 787.5 | 800.0 | 816.7 | 840.0 | 875.0 | 933.3 | 1050.0 | 1166.7 | 1312.5 | 1400.0 |
| 8 | 800.0 | 900.0 | 914.3 | 933.3 | 960.0 | 1000.0 | 1066.7 | 1200.0 | 1333.3 | 1500.0 | 1600.0 |
| 9 | 900.0 | 1012.5 | 1028.6 | 1050.0 | 1080.0 | 1125.0 | 1200.0 | 1350.0 | 1500.0 | 1687.5 | 1800.0 |
| 10 | 1000.0 | 1125.0 | 1142.9 | 1166.7 | 1200.0 | 1250.0 | 1333.3 | 1500.0 | 1666.7 | 1875.0 | 2000.0 |
| 11 | 1100.0 | 1237.5 | 1257.1 | 1283.3 | 1320.0 | 1375.0 | 1466.7 | 1650.0 | 1833.3 | 2062.5 | 2200.0 |
| 12 | 1200.0 | 1350.0 | 1371.4 | 1400.0 | 1440.0 | 1500.0 | 1600.0 | 1800.0 | 2000.0 | 2250.0 | 2400.0 |
| 13 | 1300.0 | 1462.5 | 1485.7 | 1516.7 | 1560.0 | 1625.0 | 1733.3 | 1950.0 | 2166.7 | 2437.5 | 2600.0 |
| 14 | 1400.0 | 1575.0 | 1600.0 | 1633.3 | 1680.0 | 1750.0 | 1866.7 | 2100.0 | 2333.3 | 2625.0 | 2800.0 |
| 15 | 1500.0 | 1687.5 | 1714.3 | 1750.0 | 1800.0 | 1875.0 | 2000.0 | 2250.0 | 2500.0 | 2812.5 | 3000.0 |
| 16 | 1600.0 | 1800.0 | 1828.6 | 1866.7 | 1920.0 | 2000.0 | 2133.3 | 2400.0 | 2666.7 | 3000.0 | 3200.0 |
| 17 | 1700.0 | 1912.5 | 1942.9 | 1983.3 | 2040.0 | 2125.0 | 2266.7 | 2550.0 | 2833.3 | 3187.5 | 3400.0 |
| 18 | 1800.0 | 2025.0 | 2057.1 | 2100.0 | 2160.0 | 2250.0 | 2400.0 | 2700.0 | 3000.0 | 3375.0 | 3600.0 |
| 19 | 1900.0 | 2137.5 | 2171.4 | 2216.7 | 2280.0 | 2375.0 | 2533.3 | 2850.0 | 3166.7 | 3562.5 | 3800.0 |
| 20 | 2000.0 | 2250.0 | 2285.7 | 2333.3 | 2400.0 | 2500.0 | 2666.7 | 3000.0 | 3333.3 | 3750.0 | 4000.0 |
| 21 | 2100.0 | 2362.5 | 2400.0 | 2450.0 | 2520.0 | 2625.0 | 2800.0 | 3150.0 | 3500.0 | 3937.5 | 4200.0 |
| 22 | 2200.0 | 2475.0 | 2514.3 | 2566.7 | 2640.0 | 2750.0 | 2933.3 | 3300.0 | 3666.7 | 4125.0 | 4400.0 |
| 23 | 2300.0 | 2587.5 | 2628.6 | 2683.3 | 2760.0 | 2875.0 | 3066.7 | 3450.0 | 3833.3 | 4312.5 | 4600.0 |
| 24 | 2400.0 | 2700.0 | 2742.9 | 2800.0 | 2880.0 | 3000.0 | 3200.0 | 3600.0 | 4000.0 | 4500.0 | 4800.0 |
| 25 | 2500.0 | 2812.5 | 2857.1 | 2916.7 | 3000.0 | 3125.0 | 3333.3 | 3750.0 | 4166.7 | 4687.5 | 5000.0 |
| 26 | 2600.0 | 2925.0 | 2971.4 | 3033.3 | 3120.0 | 3250.0 | 3466.7 | 3900.0 | 4333.3 | 4875.0 | 5200.0 |
| 27 | 2700.0 | 3037.5 | 3085.7 | 3150.0 | 3240.0 | 3375.0 | 3600.0 | 4050.0 | 4500.0 | 5062.5 | 5400.0 |
| 28 | 2800.0 | 3150.0 | 3200.0 | 3266.7 | 3360.0 | 3500.0 | 3733.3 | 4200.0 | 4666.7 | 5250.0 | 5600.0 |
| 29 | 2900.0 | 3262.5 | 3314.3 | 3383.3 | 3480.0 | 3625.0 | 3866.7 | 4350.0 | 4833.3 | 5437.5 | 5800.0 |
| 30 | 3000.0 | 3375.0 | 3428.6 | 3500.0 | 3600.0 | 3750.0 | 4000.0 | 4500.0 | 5000.0 | 5625.0 | 6000.0 |
| 31 | 3100.0 | 3487.5 | 3542.9 | 3616.7 | 3720.0 | 3875.0 | 4133.3 | 4650.0 | 5166.7 | 5812.5 | 6200.0 |
| 32 | 3200.0 | 3600.0 | 3657.1 | 3733.3 | 3840.0 | 4000.0 | 4266.7 | 4800.0 | 5333.3 | 6000.0 | 6400.0 |

**Harmonic Amplitudes for Unison: C & C (Frequency Ratio 1:1)**
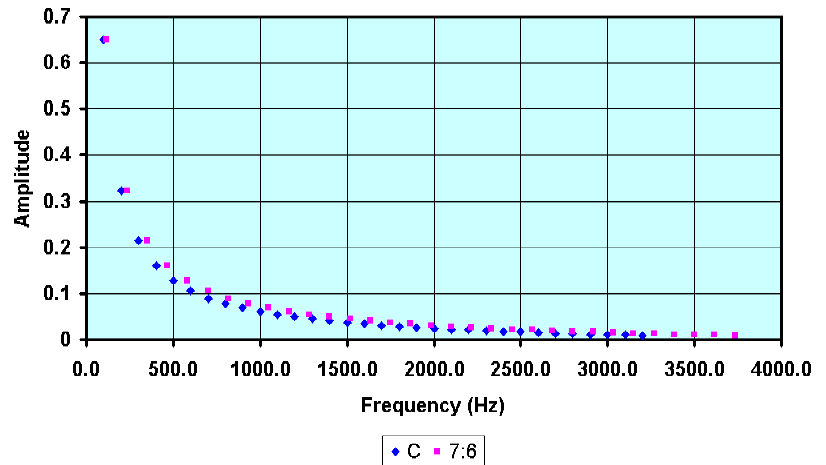**Sawtooth Waveforms, fo = 100 Hz, First 32 Harmonics**
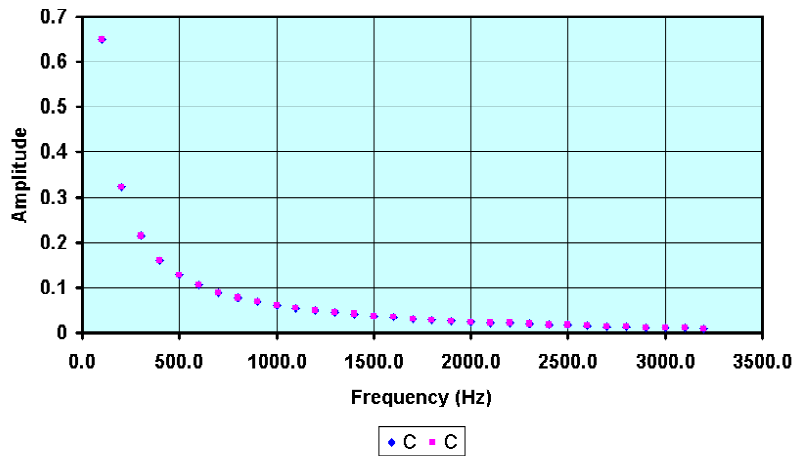


**Harmonic Amplitudes for Second: D & C (Frequency Ratio 9:8)**
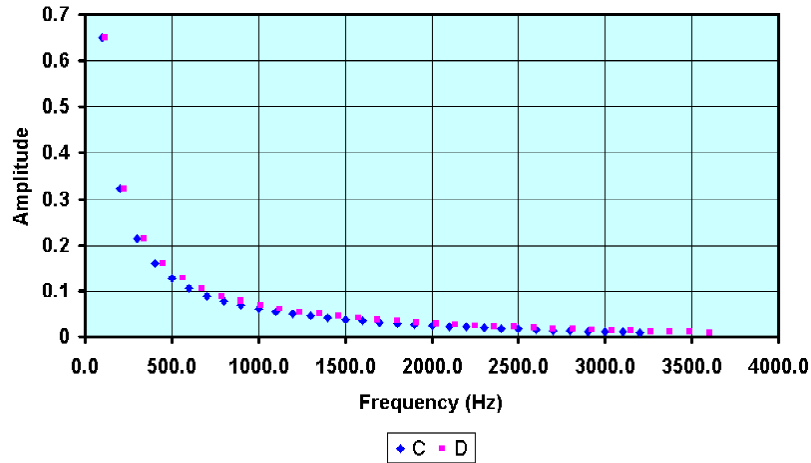**Sawtooth Waveforms, fo = 100 Hz, First 32 Harmonics**
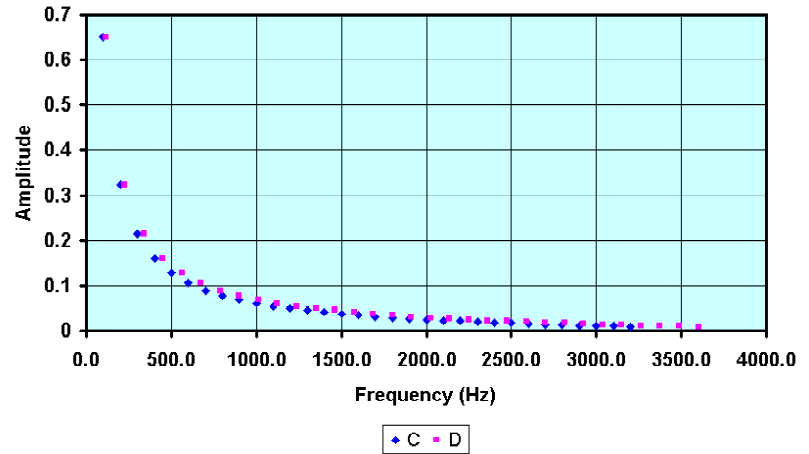


**Harmonic Amplitudes for ??? & C (Frequency Ratio 8:7)**
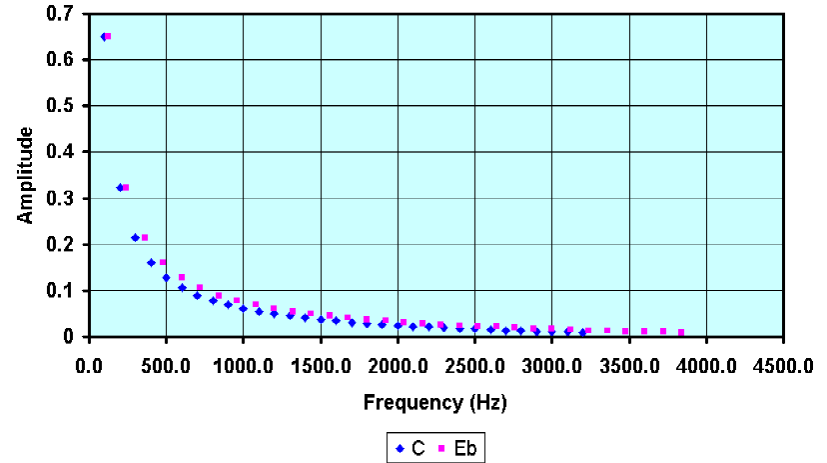**Sawtooth Waveforms, fo = 100 Hz, First 32 Harmonics**



**Harmonic Amplitudes for ??? & C (Frequency Ratio 7:6)**
**Sawtooth Waveforms, fo = 100 Hz, First 32 Harmonics**



Millikin University
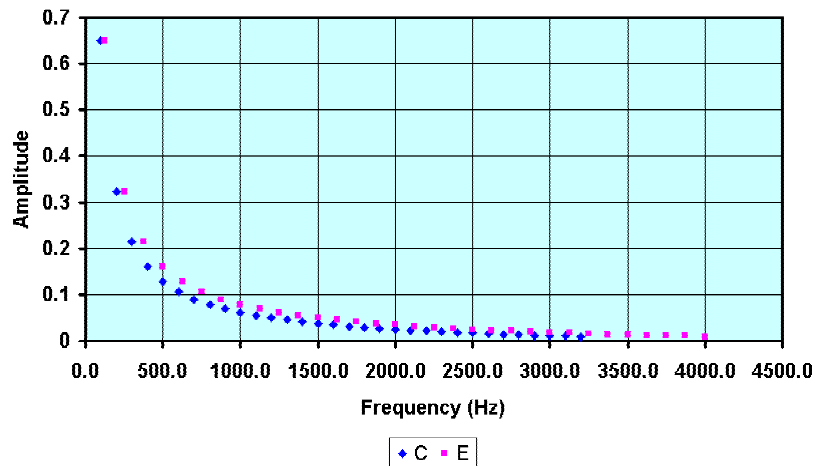November 9, 2004

Prof. Steve Errede, UIUC Physics

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**Harmonic Amplitudes for Second: D & C (Frequency Ratio 9:8)**
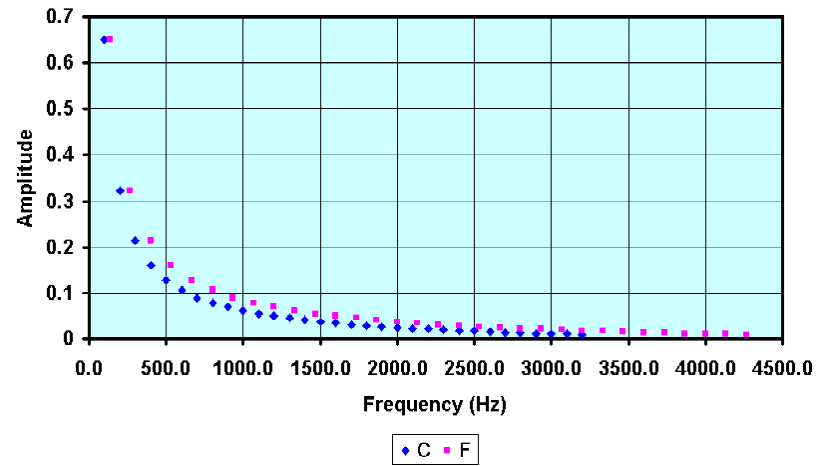Sawtooth Waveforms, fo = 100 Hz, First 32 Harmonics

**Harmonic Amplitudes for Minor 3rd: Eb & C (Frequency Ratio 6:5)**
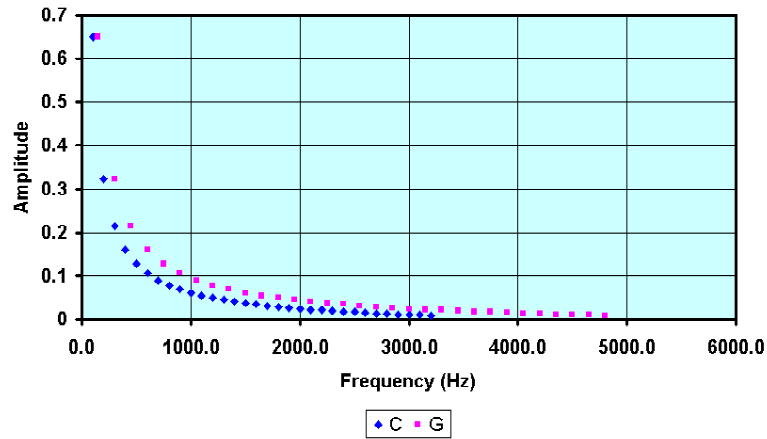Sawtooth Waveforms, fo = 100 Hz, First 32 Harmonics

**Harmonic Amplitudes for Major 3rd: E & C (Frequency Ratio 5:4)**
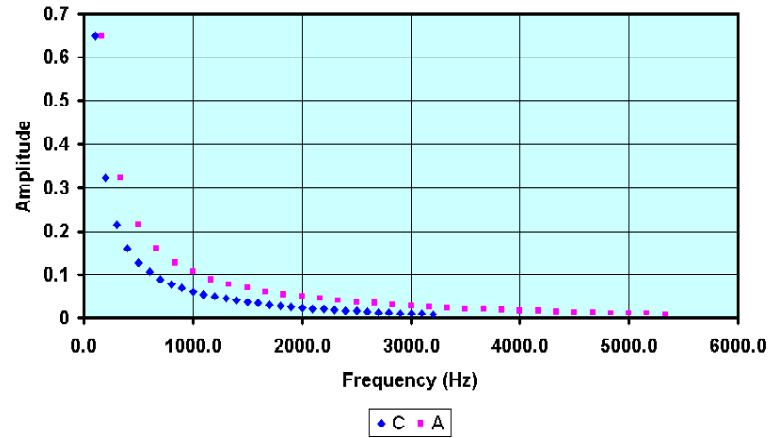Sawtooth Waveforms, fo = 100 Hz, First 32 Harmonics

**Harmonic Amplitudes for Fourth: F & C (Frequency Ratio 4:3)**
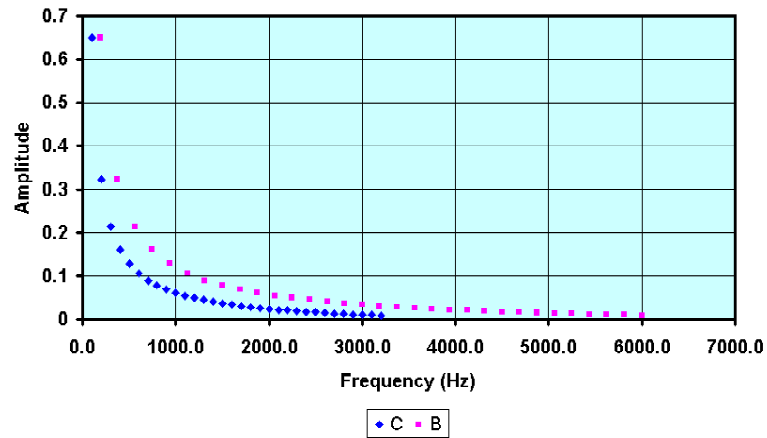Sawtooth Waveforms, fo = 100 Hz, First 32 Harmonics

Harmonic Amplitudes for Fifth: G & C (Frequency Ratio 3:2)
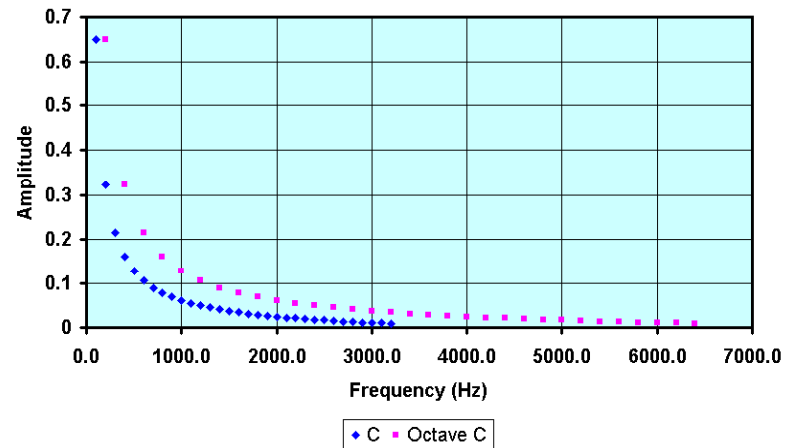Sawtooth Waveforms, fo = 100 Hz, First 32 Harmonics

Harmonic Amplitudes for Sixth: A & C (Frequency Ratio 5:3)
Sawtooth Waveforms, fo = 100 Hz, First 32 Harmonics

Harmonic Amplitudes for Seventh: B & C (Frequency Ratio 15:8)
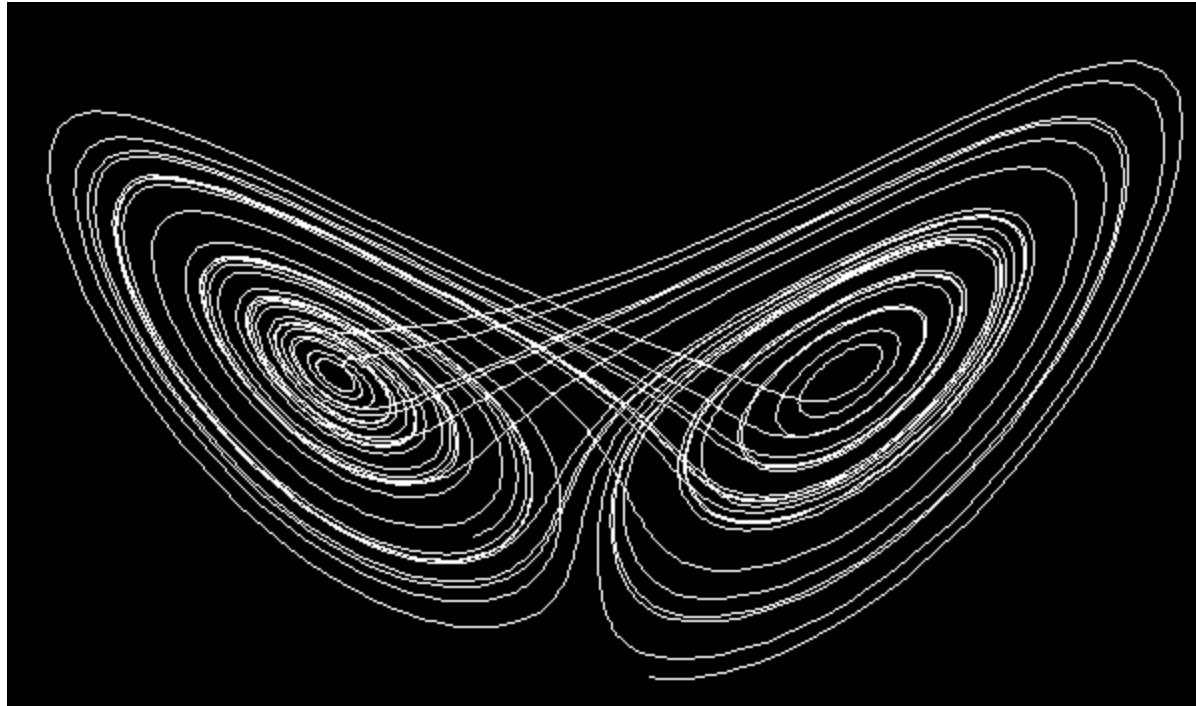Sawtooth Waveforms, fo = 100 Hz, First 32 Harmonics

Harmonic Amplitudes for Octave: C & C (Frequency Ratio 2:1)
Sawtooth Waveforms, fo = 100 Hz, First 32 Harmonics

# **Fractal Music**

## Lorentz's Butterfly - Strange Attractor



Iterative Equations:
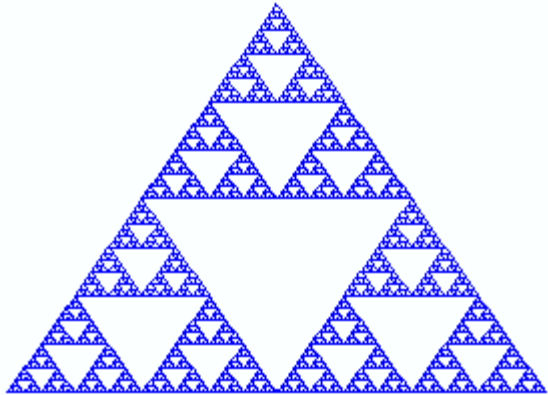dx/dt = 10(y - x)
dy/dt = x(28 - z) - y
dz/dt = xy - 8z/3.

Initial Conditions:
Change of t = 0.01 and
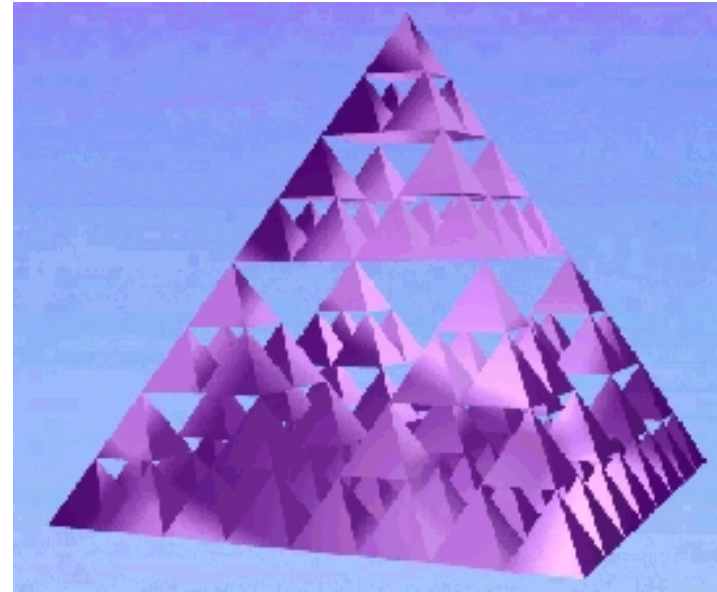the initial values
x0 = 2, y0 = 3 and z0 = 5

# Fractal Music



## The Sierpinski Triangle

is a fractal structure with fractal dimension 1.584.

The area of a Sierpinski Triangle is ZERO!



## 3-D Sierpinski Pyramid

Beethoven's Piano Sonata no. 15, op. 28, 3rd Movement (Scherzo) is a combination of binary and ternary units iterating on diminishing scales, similar to the Sierpinski Structure !!!

# Fractal Music in Nature – chaotic dripping of a leaky water faucet!

**Convert successive drop time differences and drop sizes to frequencies**

**Play back in real-time (online!) using FG – can *hear* the sound of chaotic dripping!**
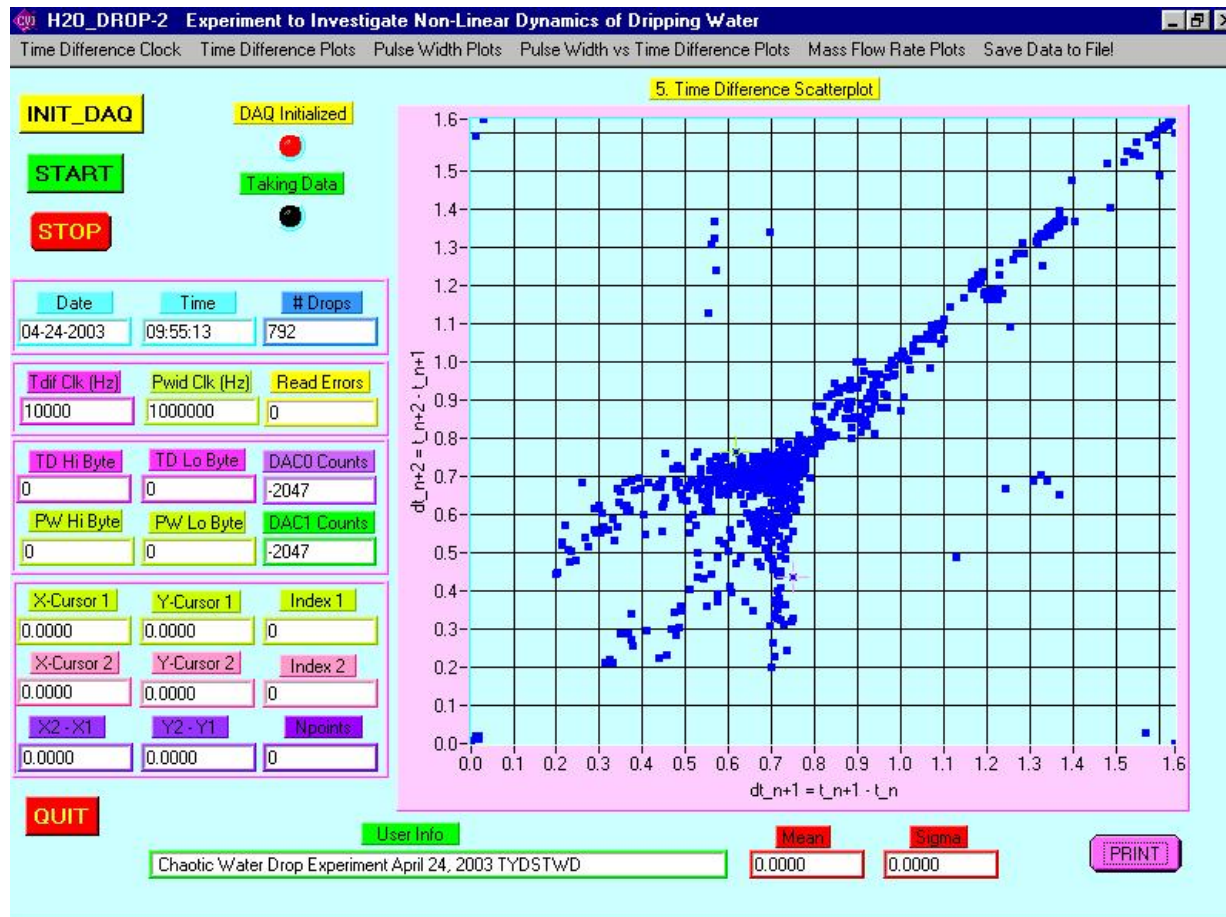
# Conclusions and Summary:

• Music is an intimate, very important part of human culture

• Music is deeply ingrained in our daily lives - it's everywhere!

• Music constantly evolves with our culture - affected by many things

• Future: Develop new kinds of music...

• Future: Improve existing & develop totally new kinds of musical instruments...

• There's an immense amount of physics in music - much still to be learned !!!

• Huge amount of fun – combine physics & math with music – can hear/see/touch/feel/think!!

## *MUSIC*

## Be a Part of It - Participate !!!

## Enjoy It !!!

## Support It !!!

For additional info on Physics of Music at UIUC - see e.g.

**UIUC Physics 199 Physics of Music Web Page:**

**http://wug.physics.uiuc.edu/courses/phys199pom/**

**UIUC Physics 398 Physics of Electronic Musical Instruments Web Page:**

**http://wug.physics.uiuc.edu/courses/phys398emi/**