Acoustical Physics Research in the UIUC Physics of Music/Musical Instruments Course(s)
and
Professional Careers in Acoustics

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UIUC Physics

I. Acoustical Physics Research in the UIUC Physics of Music/Musical Instruments Course(s)

- **Created/developed & have been teaching lecture-lab-demo UIUC POM course(s) for > decade (since 2000). Initially focused solely on stringed & electronic musical instruments; scope has now broadened/broadening out in many directions…**

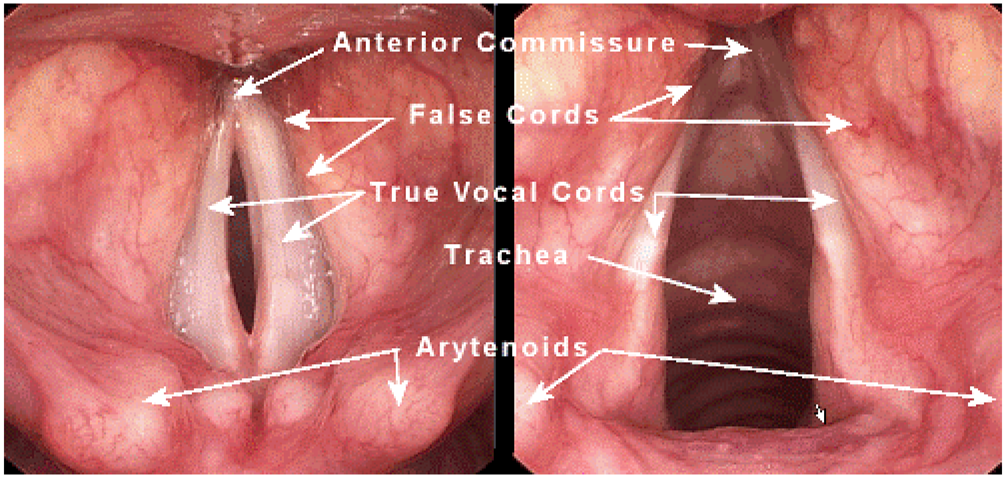
- **Upper-level Physics 406 course emphasizes the fully-complex nature of (arbitrary) sound fields. We primarily work in the frequency-domain, but also connect to time-domain (via Fourier Transforms), and vice-versa.**

- **The theoretical/mathematical formalism and experimental techniques developed for acoustics course can used directly e.g. in E&M, optics, QM (with appropriate/ suitable modifications).**

- **Very useful techniques for other physics courses, other fields of research!**

- **We give (just) a *few* examples of UIUC POM acoustics results on following slides:**

The Human Voice – The first / earliest musical instrument… unique to each human!



When singing (& talking), the human vocal cords vibrate as a 1-D system (e.g. like a guitar string) – production of *integer* related harmonics of fundamental:

$$f_n = nf_1 \quad n = 1, 2, 3, \ldots.$$

n.b. If we instead had e.g. a *2-D circular membrane* for producing musical sounds, would *not* have such a relation:

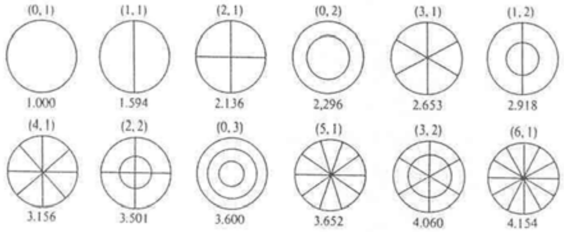
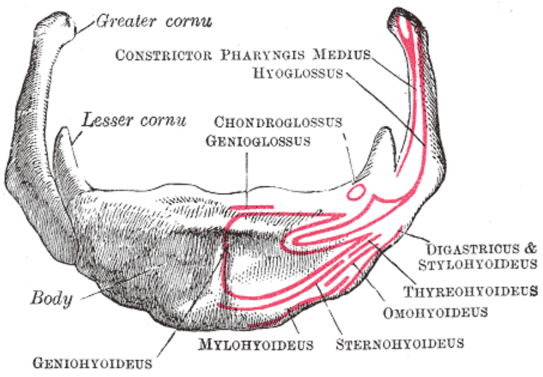


FIGURE 3.6. First 14 modes of an ideal membrane. The mode designation (m, n) is given above each figure and the relative frequency below. To convert these to actual frequencies, multiply by $(2.405/2\pi a)\sqrt{T/\sigma}$, where a is the membrane radius.

$$\nabla^2 \psi = \tfrac{1}{c^2} \partial^2 \psi \big/ \partial t^2$$

$$f_{\ell mn}^{3D} \propto \sqrt{\alpha \ell^2 + \beta m^2 + \gamma n^2}$$

This mathematical physics fact has *important / profound* consequences for the development of music and musical instruments by humans….

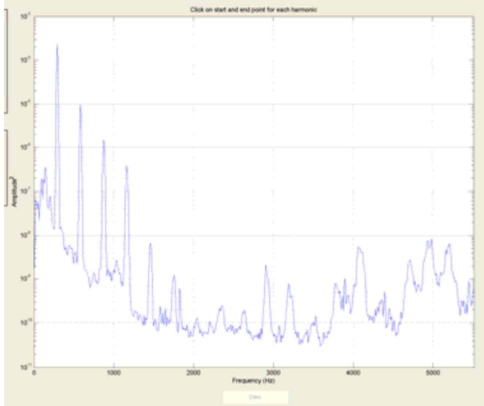


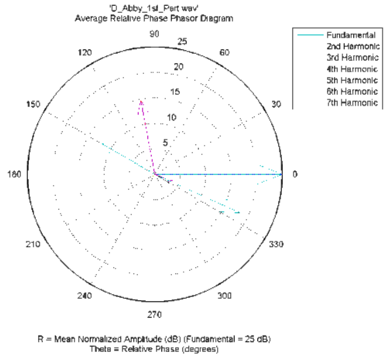
The hyoid bone (present in many mammals) is unique to Homo sapiens – enables production of a *wide* range of sounds that other animals *cannot* produce – allowing wider range of the tongue, pharyngeal and laryngeal movements – necessary for human speech (*and* song)…

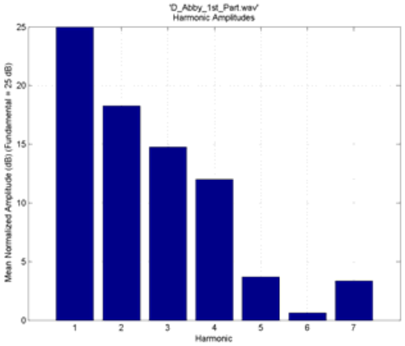
⇒ **It is NO accident that the musical instruments that we humans have developed mimic the human voice, human rhythms….**

Harmonic Content of the Human Voice – First Human Musical Instrument:
Comparison of 3 UIUC Physics 193POM/UIUC Women's Choir students singing D4 "Ooooh" (293.66 Hz):

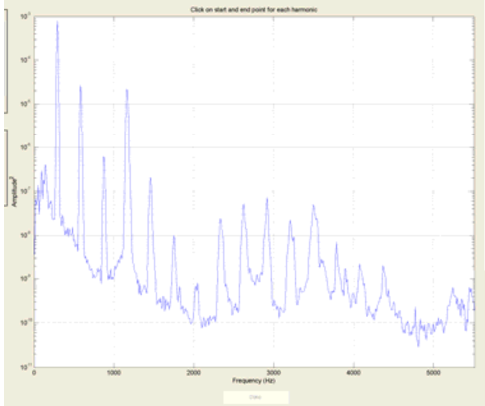
Abby

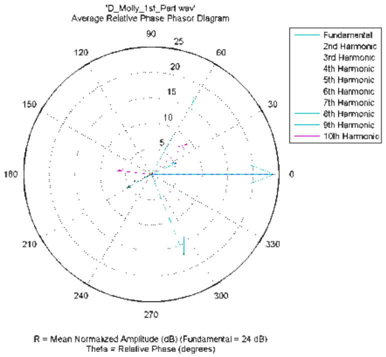


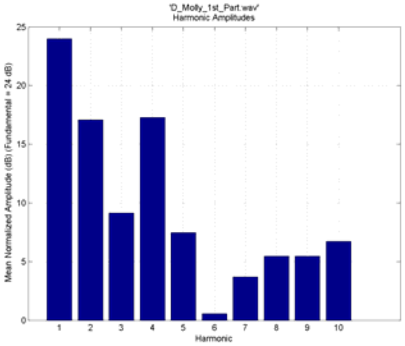




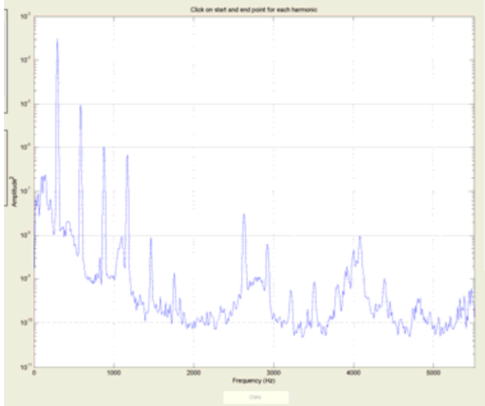
Molly

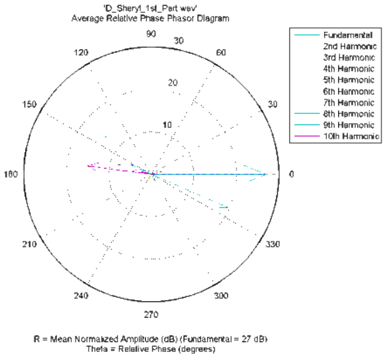


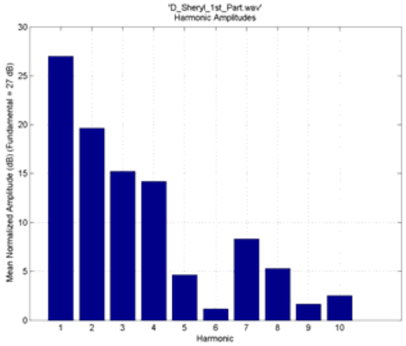




Cheryl

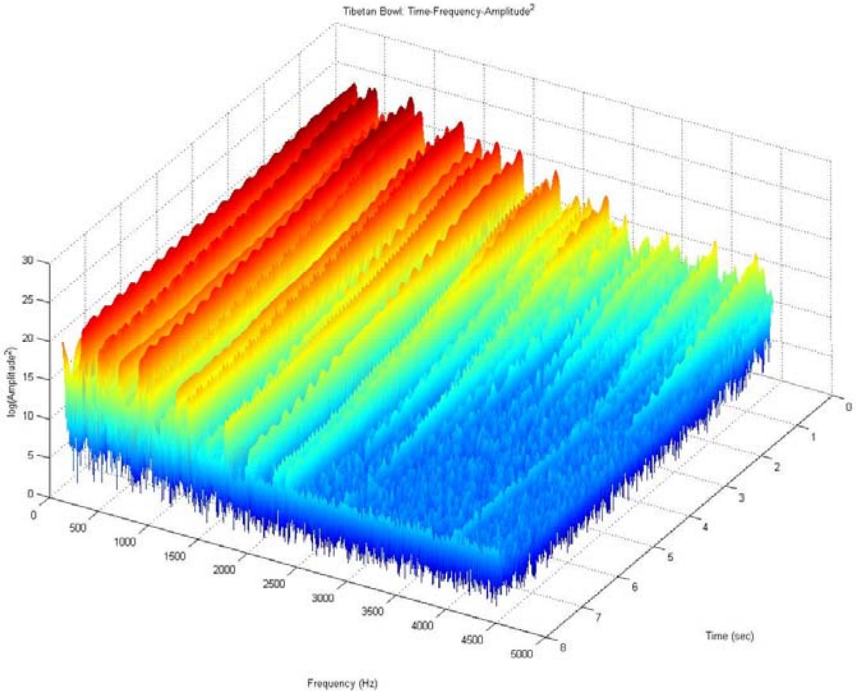


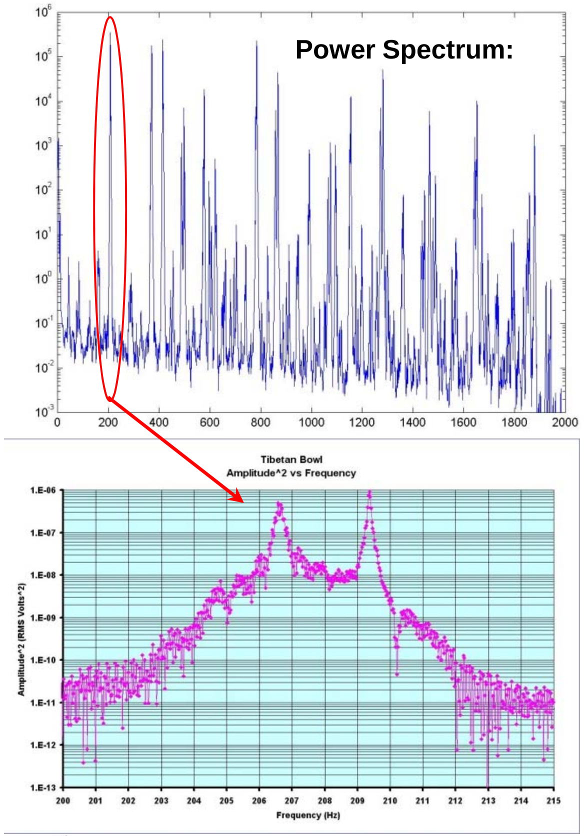


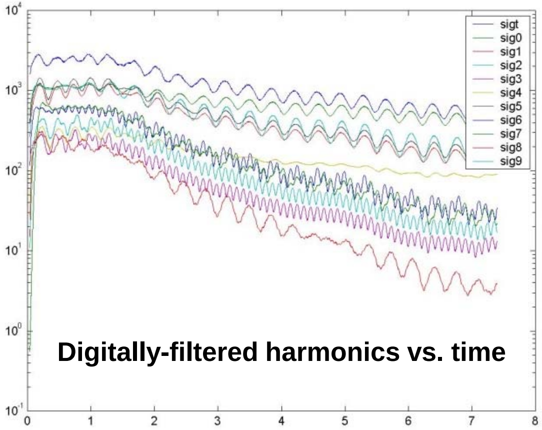


Some Experimental Results from UIUC Physics of Music/Musical Instruments Course(s):

Analyze the harmonic content (amplitude, frequency *and* phase info *vs*. time) of quasi-steady complex sounds produced by musical instruments, human voice, etc. using 24-bit digital audio recorder + reference omni-directional condensor mic ⇒ .wav file
e.g. Tibetan Bowl:



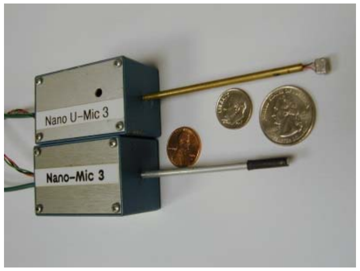


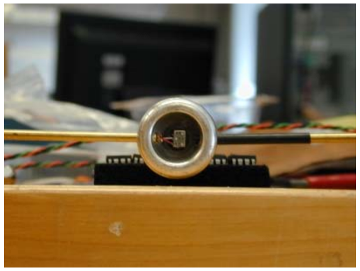


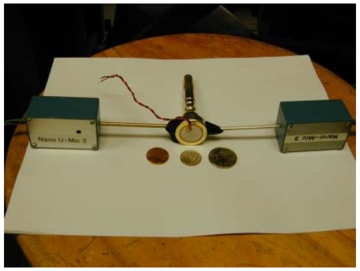
Frequency-Domain Measurements of Complex Harmonic/Periodic Sound Fields

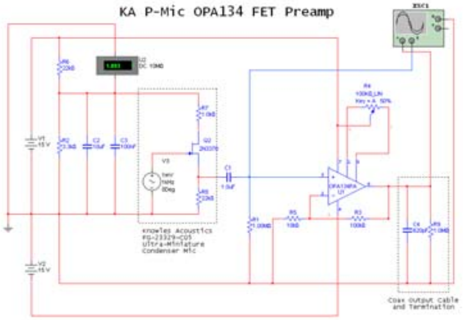
Complex sound field at point in space *uniquely* determined if simultaneously measure pressure *p* and particle velocity *u* (= <velocity> of air molecules, spatially averaged over an infinitesimal volume element d^3V).

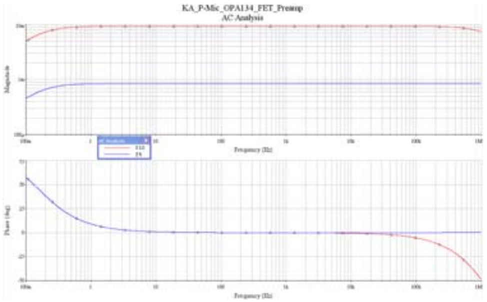
World's smallest *p* & Δ*p* condensor mics !!!

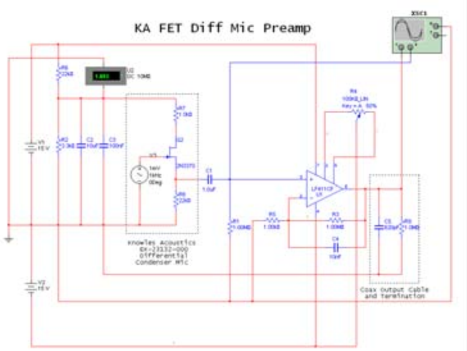


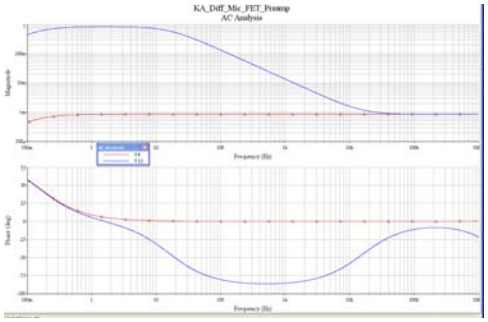












1-D Euler Eqn for *inviscid* fluid flow:

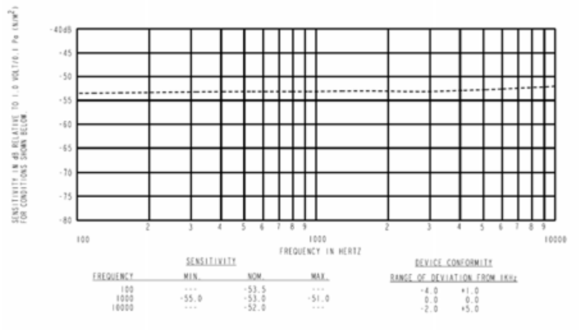
$$\frac{\partial \tilde{u}_z(z,t)}{\partial t} = -\frac{1}{\rho_o}\frac{\partial \tilde{p}(z,t)}{\partial z} \qquad \rho_o = 1.204\,kg/m^3 \text{ for air } @\ NTP$$

Integrate:

$$\tilde{u}_z(z,t) = -\frac{1}{\rho_o}\int_{-\infty}^{t}\frac{\partial \tilde{p}(z,t')}{\partial z}dt' \simeq -\frac{1}{\rho_o \Delta z}\underbrace{\int_{-\infty}^{t}\Delta\tilde{p}(z,t')\,dt'}_{\substack{op-amp\\ integrator}}$$

Sensitivity & Absolute Calibration of *p*/*u*-Mics

Omni-directional Condensor P-mic



SENSITIVITY

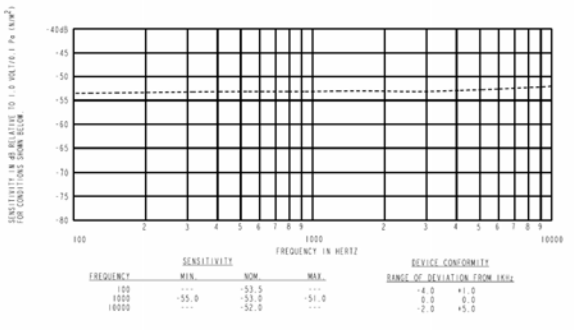
FREQUENCY	MIN.	NOM.	MAX.
100	---	-53.5	---
1000	-55.0	-53.0	-51.0
10000	---	-52.0	---

DEVICE CONFORMITY

RANGE OF DEVIATION FROM 1KHz

-4.0	+1.0
0.0	0.0
-2.0	+5.0

Differential P-mic



SENSITIVITY

FREQUENCY	MIN.	NOM.	MAX.
100	---	-53.5	---
1000	-55.0	-53.0	-51.0
10000	---	-52.0	---

DEVICE CONFORMITY

RANGE OF DEVIATION FROM 1KHz

-4.0	+1.0
0.0	0.0
-2.0	+5.0

Calibrate Mics e.g. in *SPL* = 94.0 *dB* sound field:

$$SPL = 94.0\,dB = 20\log_{10}\left(p/p_{ref}\right) = 20\log_{10}\left(u_z/u_{ref}\right)$$

$$\Rightarrow\ p = 1.0\ RMS\ Pascals,\quad u_z = 2.42\ RMS\ mm/sec$$

Typical Mic Sensitivities:

$$S_{p-mic} \sim 280\ \ RMS\ mV/RMS\ Pa$$

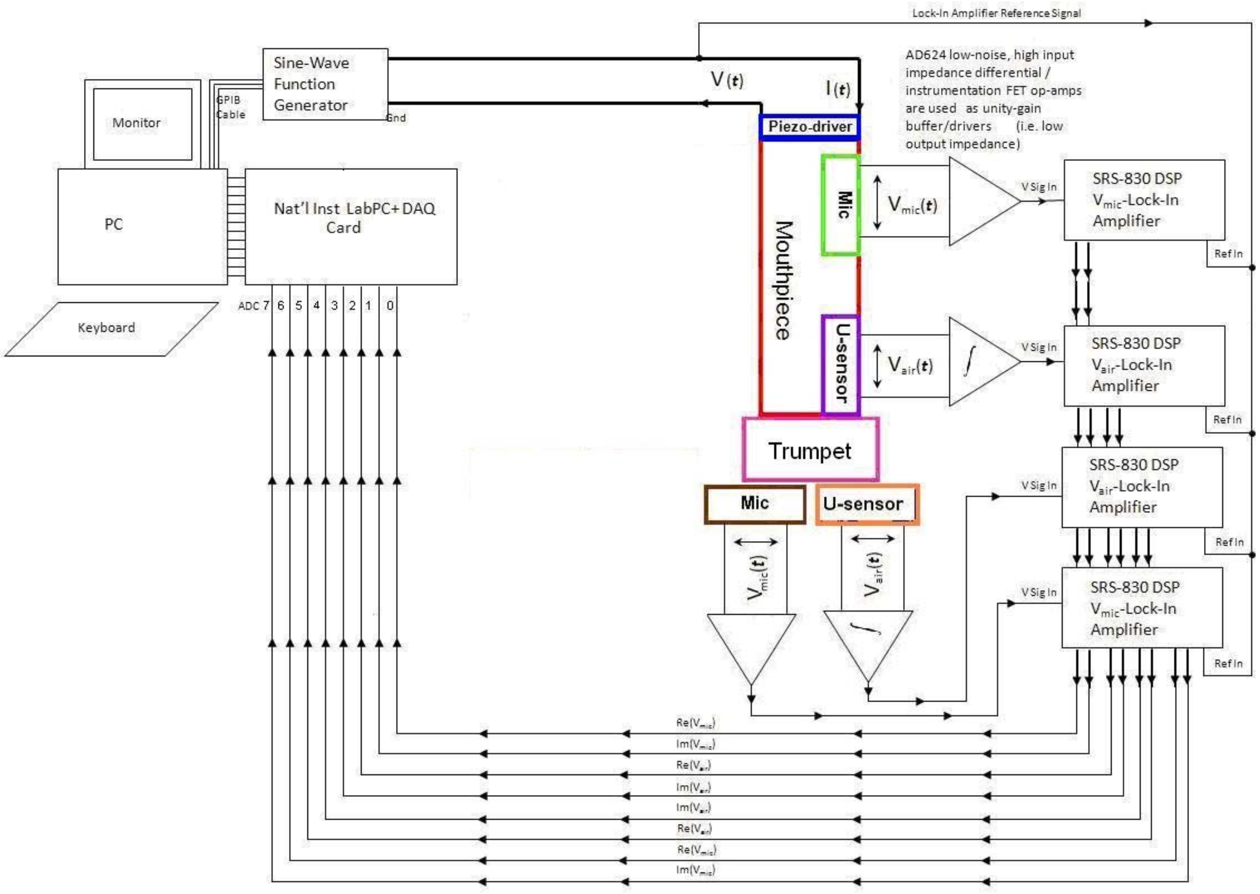
$$S_{u-mic} \sim\ \ 90\ \ RMS\ mV/RMS\ Pa^*,\quad 1.0\ RMS\ Pa^* = 2.42\ RMS\ mm/sec$$

$$p_{ref}\left(f = 1\,KHz\right) = 2\times10^{-5}\ RMS\ Pascals$$

$$u_{ref}\left(f = 1\,KHz\right) = 4.8\times10^{-8}\ RMS\ m/s$$

Extech SPL Calibrator

Block Diagram of PC-Based DAQ System



Lock-in Amplifiers (LIA's) measure the in-phase (="Real") and 90º out-of phase {*aka* "quadrature"} (="Imaginary") amplitude components (w.r.t. reference sine-wave function generator signal, e.g.

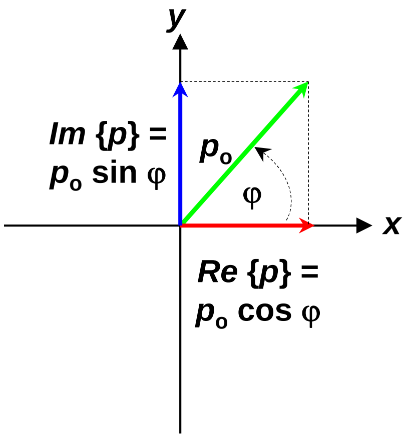
$$p(t) = p_o \cos(\omega t + \varphi)$$

$$= p_o \cos \omega t \cos \varphi$$

$$- p_o \sin \omega t \ \sin \varphi$$

$$Re\{p\} = p_o \cos \varphi$$

$$Im\{p\} = p_o \sin \varphi$$



Time Domain (*instantaneous* pressure/particle velocity):

Use e.g. Digital Oscilloscope/Digital Recorder to Measure:

$$\left.\begin{aligned} p(\vec{r},t) &= p_o(\omega)\cos\left[\omega t+\varphi_p(\omega)\right] \\ u_z(\vec{r},t) &= u_{o_z}(\omega)\cos\left[\omega t+\varphi_{u_z}(\omega)\right] \end{aligned}\right\} \begin{aligned} &\textit{n.b.}\text{ phase-referenced w.r.t.} \\ &\text{sine-wave fcn generator} \end{aligned}$$

Complexify:

$$\tilde{p}(\vec{r},t) = p_o(\omega)e^{i(\omega t+\varphi_p(\omega))} = FT\{\tilde{p}(\vec{r},\omega)\}$$

$$\tilde{u}_z(\vec{r},t) = u_{o_z}(\omega)e^{i(\omega t+\varphi_{u_z}(\omega))} = FT\{\tilde{u}_z(\vec{r},t)\}$$

Compute:

$$\xi_z(\vec{r},t) = \int \tilde{u}_z(\vec{r},t)\,dt = \frac{1}{i\omega}\tilde{u}_z(\vec{r},t)$$

$$a_z(\vec{r},t) = \frac{\partial \tilde{u}_z(\vec{r},t)}{\partial t} = i\omega\tilde{u}_z(\vec{r},t)$$

$$\tilde{Z}_z(\vec{r},t) = \tilde{p}(\vec{r},t)/\tilde{u}_z(\vec{r},t) = I.I.R.(\vec{r},t)$$

$$\begin{aligned} \tilde{I}_z(\vec{r},t) &= \tfrac{1}{2}\tilde{p}(\vec{r},t)\cdot\tilde{u}_z(\vec{r},t) \\ &= \tfrac{1}{2}p_o(\omega)\cdot u_{o_z}(\omega)e^{i\left[\varphi_p(\omega)-\varphi_{u_z}(\omega)\right]}\left[1+e^{-2i\left[\omega t+\varphi_p(\omega)\right]}\right] \\ &= \tfrac{1}{2}I_{o_z}(\omega)e^{i\varphi_{I_z}(\omega)}\left[1+e^{-2i\left[\omega t+\varphi_p(\omega)\right]}\right] \end{aligned}$$

$$w(\vec{r},t) = \frac{1}{4\rho_o c^2}\left|\tilde{p}(\vec{r},t)\right|^2 + \frac{1}{4}\rho_o\left|\tilde{u}_z(\vec{r},t)\right|^2$$

Frequency Domain:

Use e.g. LIA (and/or Spectral Analysis Techniques) to Measure:

$$\tilde{p}(\vec{r},\omega) = p_o(\omega)e^{i(\omega t+\varphi_p(\omega))} = FT\{\tilde{p}(\vec{r},t)\} \quad \{Pascals\}$$

$$\tilde{u}_z(\vec{r},\omega) = u_{o_z}(\omega)e^{i(\omega t+\varphi_{u_z}(\omega))} = FT\{\tilde{u}_z(\vec{r},t)\} \quad \{mm/sec\}$$

Compute:

$$\xi_z(\vec{r},\omega) = \int \tilde{u}_z(\vec{r},\omega)\,dt = \frac{1}{i\omega}\tilde{u}_z(\vec{r},\omega) \quad \{mm\}$$

$$a_z(\vec{r},\omega) = \frac{\partial \tilde{u}_z(\vec{r},\omega)}{\partial t} = i\omega\tilde{u}_z(\vec{r},\omega) \quad \{mm/sec^2\}$$

$$\begin{aligned} \tilde{Z}_z(\vec{r},\omega) &= \tilde{p}(\vec{r},\omega)/\tilde{u}_z(\vec{r},\omega) \quad \{Acoustic\ Ohms\,(Pa\text{-}sec/m)\} \\ &= \tfrac{1}{2}p_o(\omega)\cdot u_{o_z}(\omega)e^{i\left[\varphi_p(\omega)-\varphi_{u_z}(\omega)\right]} = Z_{o_z}e^{i\varphi_{Z_z}(\omega)} \end{aligned}$$

$$\begin{aligned} \tilde{I}_z(\vec{r},\omega) &= \tfrac{1}{2}\tilde{p}(\vec{r},\omega)\cdot\tilde{u}_z^*(\vec{r},\omega) \quad \{Watts/m^2\} \\ &= \tfrac{1}{2}p_o(\omega)\cdot u_{o_z}(\omega)e^{i\left[\varphi_p(\omega)-\varphi_{u_z}(\omega)\right]} = I_o e^{i\varphi_{I_z}(\omega)} \end{aligned}$$

$$w(\vec{r},\omega) = \frac{1}{4\rho_o c^2}\left|\tilde{p}(\vec{r},\omega)\right|^2 + \frac{1}{4}\rho_o\left|\tilde{u}_z(\vec{r},\omega)\right|^2 \{Joules/m^3\}$$

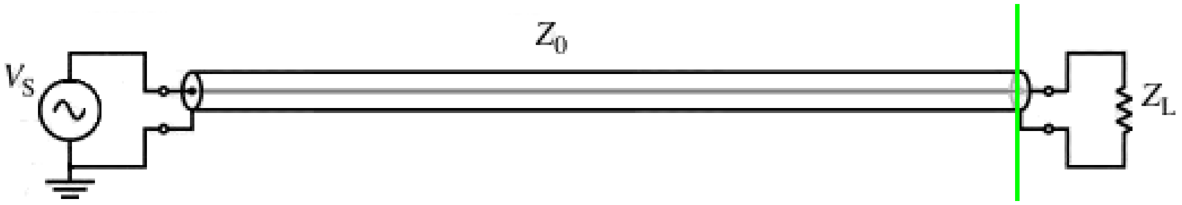
Real part of complex ***I***, ***Z*** associated with *propagating* sound

Imaginary part of complex ***I***, ***Z*** associated with *non-propagating* sound energy (e.g. in “near-field” *r* << λ of sound source, or e.g. in SWT (where **Re{*I*, *Z*}** ~ 0))

Acoustic Impedance Analogous to Electrical Impedance

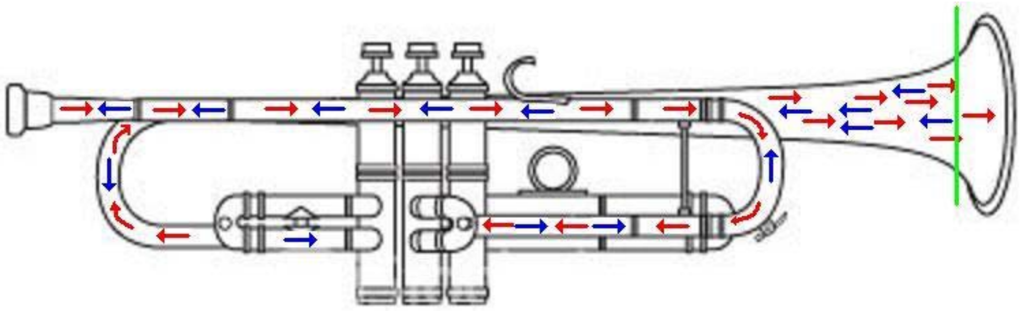
Electrical Impedance

$$\tilde{Z}_e = \frac{\tilde{V}}{\tilde{I}}$$



Specific Acoustic Impedance

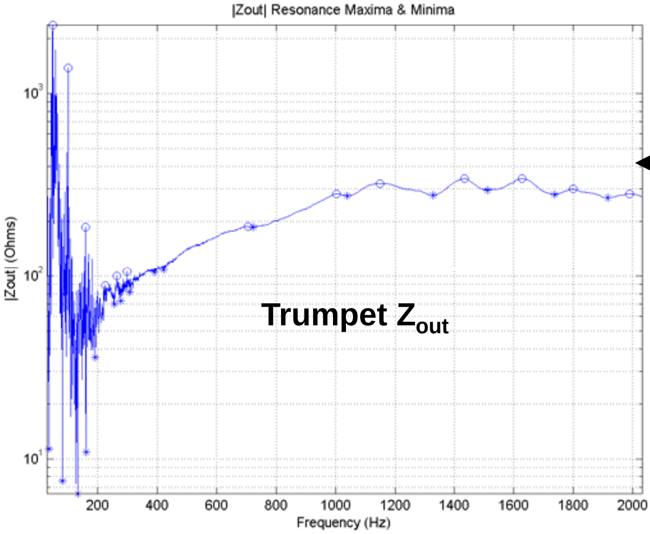
$$\tilde{Z}_a = \frac{\tilde{P}}{\tilde{U}}$$



Frequency-dependent impedance mismatch @ bell end means wave reflection, constructive interference of standing waves @ mouthpiece reinforces buzzing of player's lips!

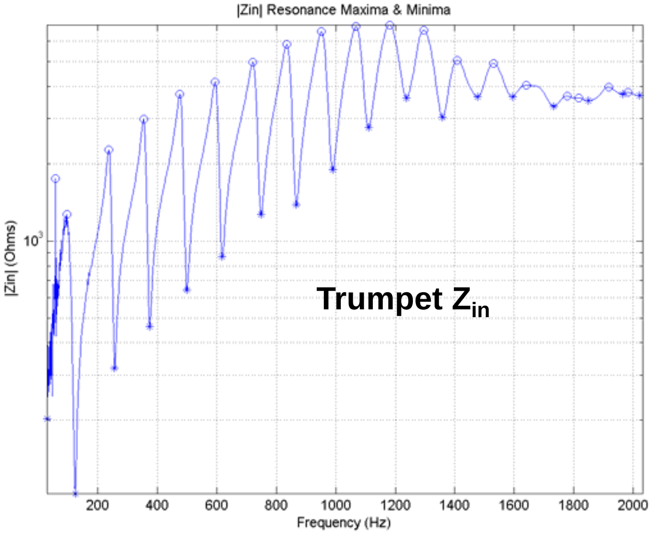
$|Z_{in}|$ maxima (@ pressure *maxima*, particle velocity *minima*) occur for constructive interference) – corresponds to standing waves,
i.e. define the *playable* notes on the instrument!

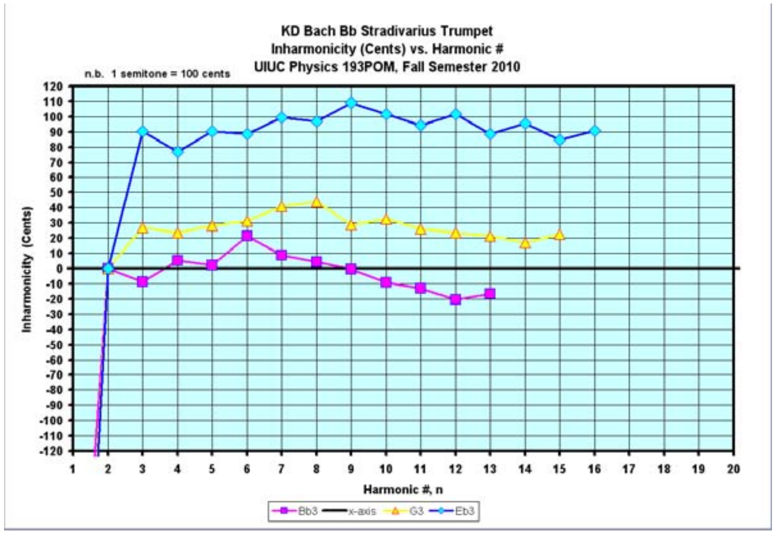
Measure input & output impedances Z(f) = p(f)/u(f) of brass/wind instruments
⇒ Maxima of $Z_{in}(f)$ defines which notes are playable on the instrument:



Free-Field
$Z_o = \rho_o c$

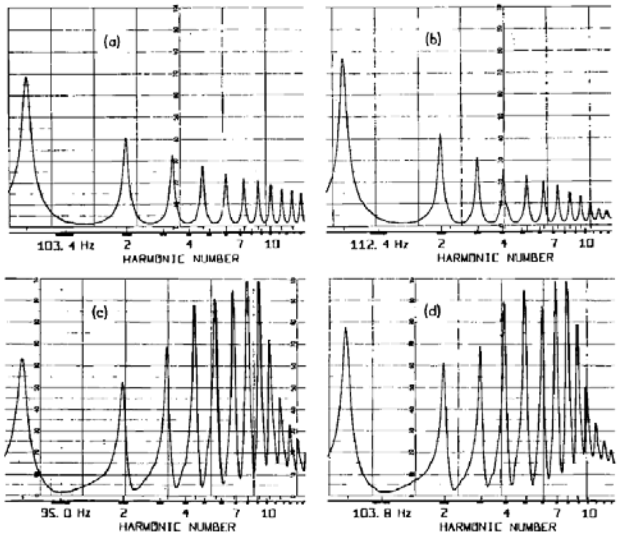
~ 415 Ac. Ohms





Acoustical Properties of Individual Components of Trumpet
J. Backus, JASA 60, 460-80, 1976

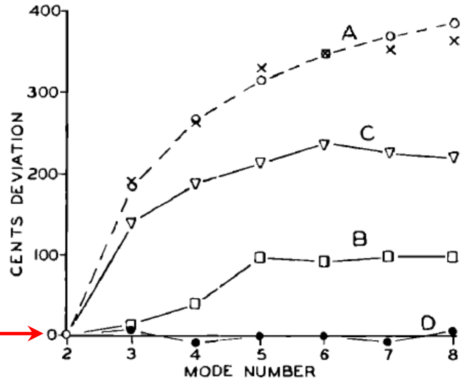
(a) Z (Tubing) **(b) Z (Tubing + Bell)**



(c) Z (Mouthpiece + Leader Pipe + Tubing) **(d) Z (MP+LP +Tubing + Bell)**

FIG. 2. Input impedance curves for (a) a length of cylindrical tubing; (b) tubing plus trumpet bell; (c) tubing plus mouthpiece and leader pipe; and (d) tubing plus bell plus mouthpiece and leader pipe. Full scale is 1000 Ω.

Trumpet Inharmonicity:



(A) Tubing

(C) Mouthpiece + Leader Pipe + Tubing

(B) Tubing + Bell

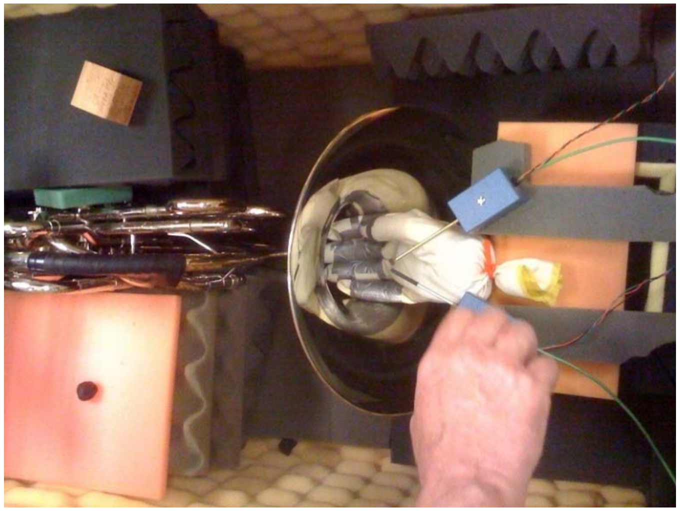
(D) MP+LP +Tubing + Bell

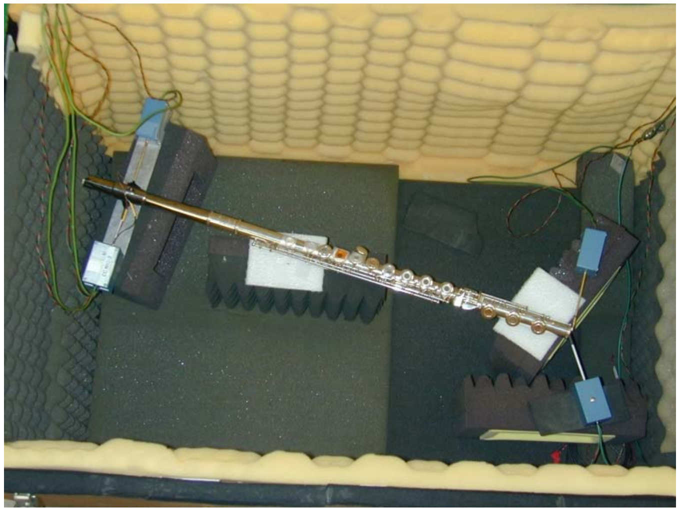
“A miracle occurs!” →

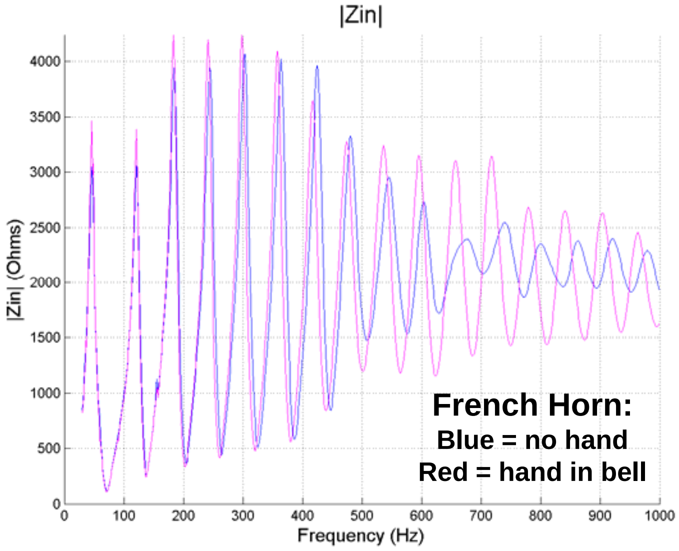
FIG. 3. Plots of the discrepancies in cents between the nth resonance and the nth harmonic, with the second resonance coinciding with the second harmonic. (a) Cylindrical tubing; (b) tubing plus bell; (c) tubing plus leader pipe and mouthpiece; and (d) tubing plus bell plus leader pipe and mouthpiece.

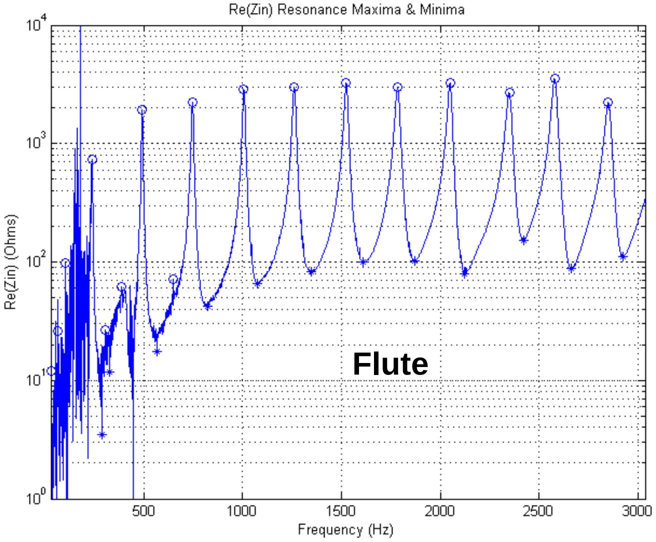
n.b. The design of the trumpet – centuries old instrument {1500 BCE; valves added ~ 1793) {as well as many other musical instruments} didn’t have the benefit of the modern scientific knowledge of acoustics that we have today – musical solution(s) arrived at iteratively, by persistent effort(s) !!!

Have Measured Acoustic Properties of {Many} Other Brass/Wind Instruments, e.g.

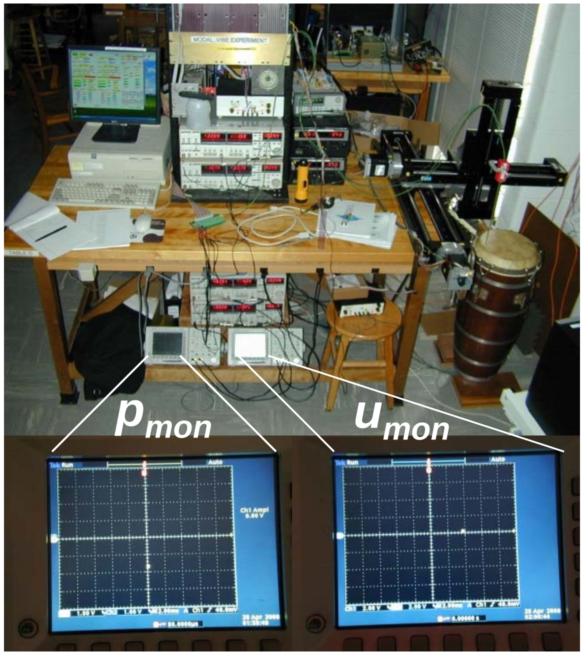




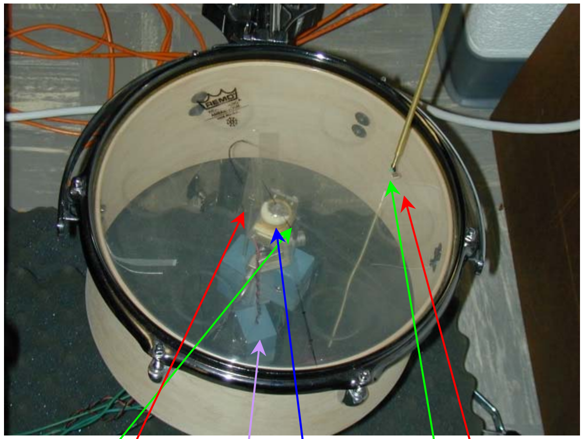




UIUC P406POM Modal Vibes DAQ Experiment: *Phase-Sensitive* Near-Field Acoustic Holography!



***p*-complex plane** ***u*-complex plane**

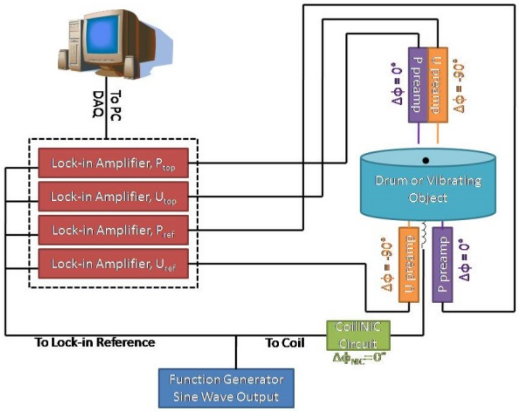


***p, u* monitor mics**

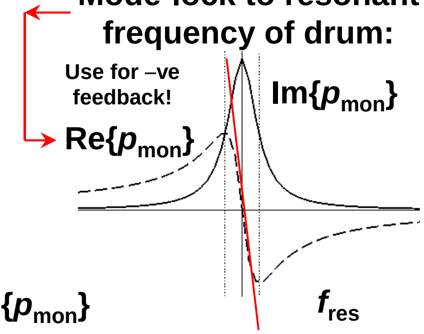
CC NIC + coil driver + rare-earth magnet pair

***p, u* scan mics**

Block Diagram of Modal_Vibes DAQ System:



Mode-lock to resonant frequency of drum:



Use for –ve feedback!

Im{p_{mon}}

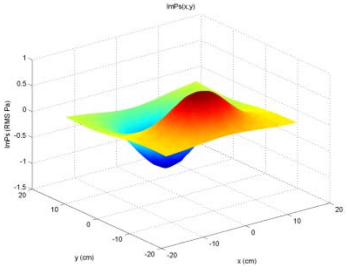
Re{p_{mon}}

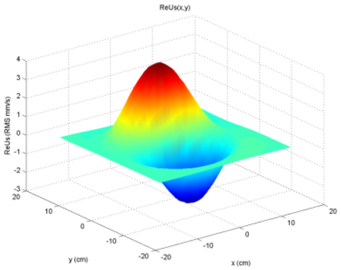
Doumbek:

J_{11} Vibrational Mode of Doumbek:

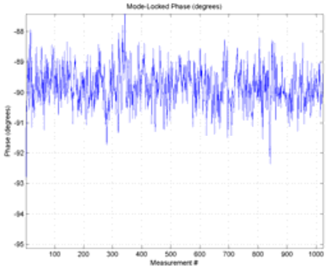
(32x32 = 1024 scan points, 1 cm step size)

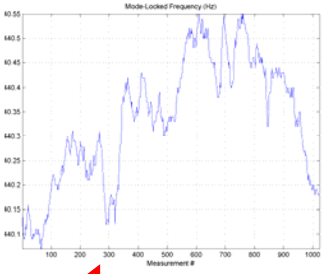
Im{p(x,y)} **Re{u(x,y)}**





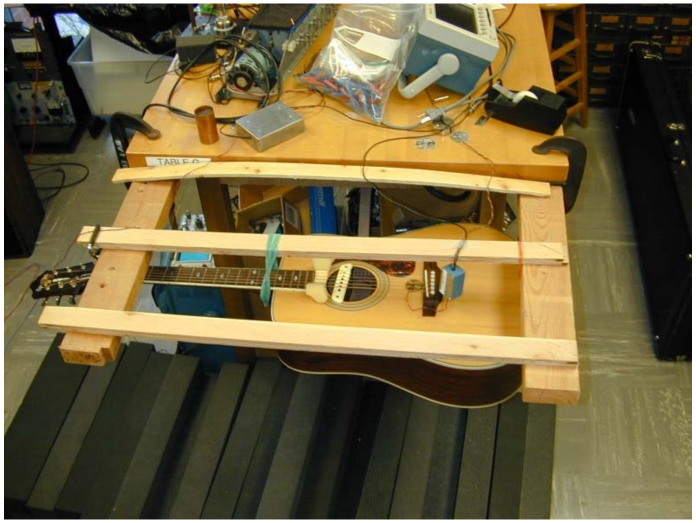
Phase{p_{mon}} f_{res}

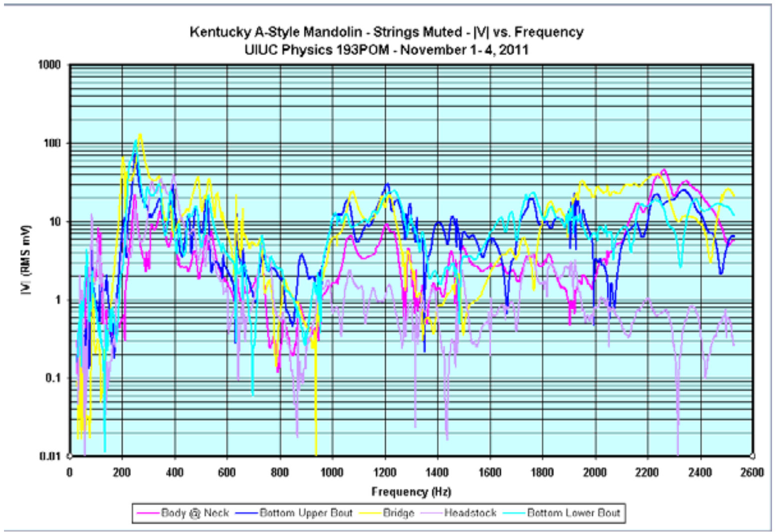


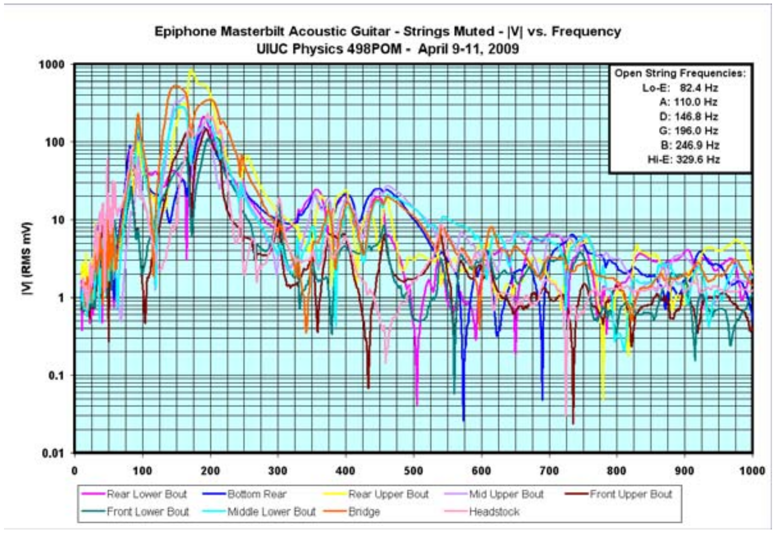


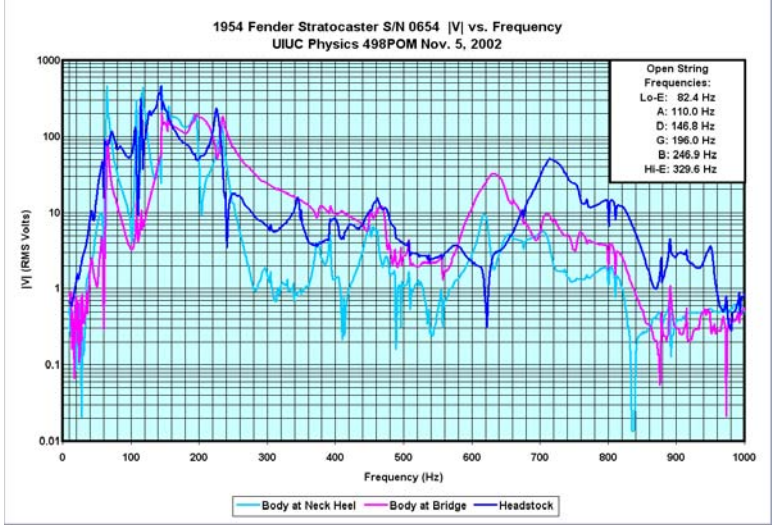
Drums *very* sensitive to ambient temperature changes!

Mechanical Modal Vibrations of Stringed Instruments:



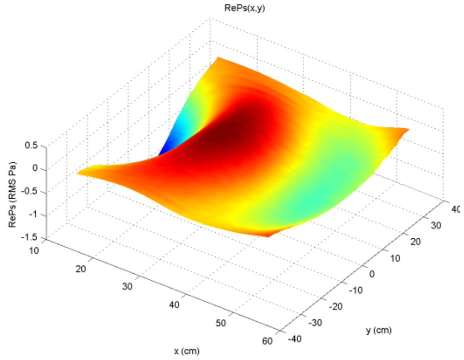




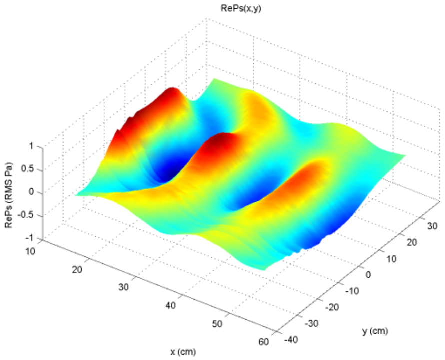


Complex Sound Field of Loudspeakers/Arrays of Loudspeakers:

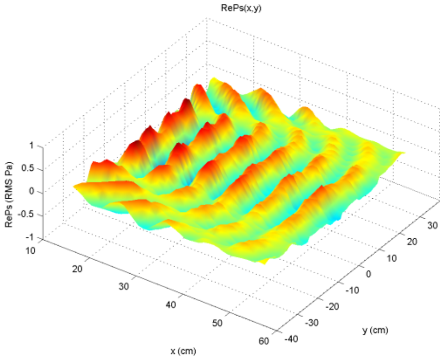
f = 1 KHz



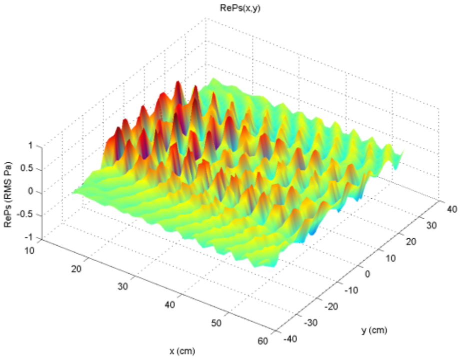
f = 2 KHz



f = 5 KHz

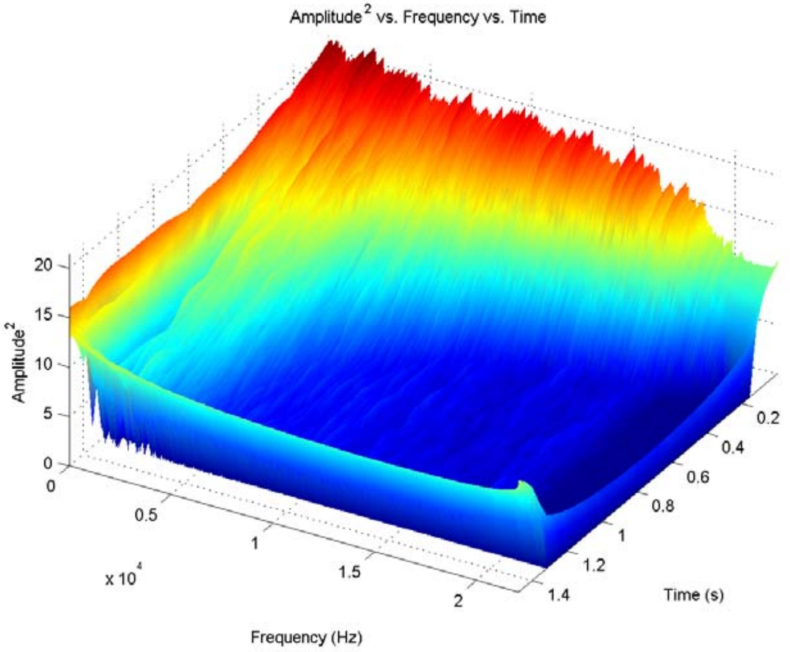


f = 10 KHz

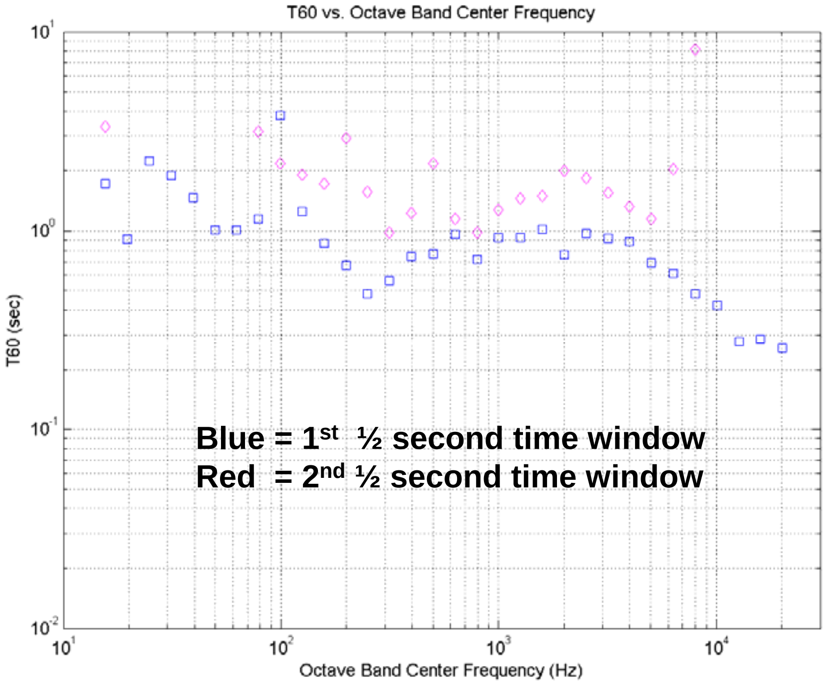


Auditorium/Room Acoustics:

Inject white noise (flat frequency spectrum) into a room, allow it to equilibrate, then adiabatically rapidly shut off sound source and measure exponential decay rate of sound vs. frequency (32 1/3-octave bands):



Recording Studio, UIUC School of Music



Blue = 1st ½ second time window
Red = 2nd ½ second time window

$$\boxed{T_{60} \equiv -\tfrac{1}{2}\ln\left(10^{-6}\right)\cdot\tau_p \simeq 6.91\tau_p}$$

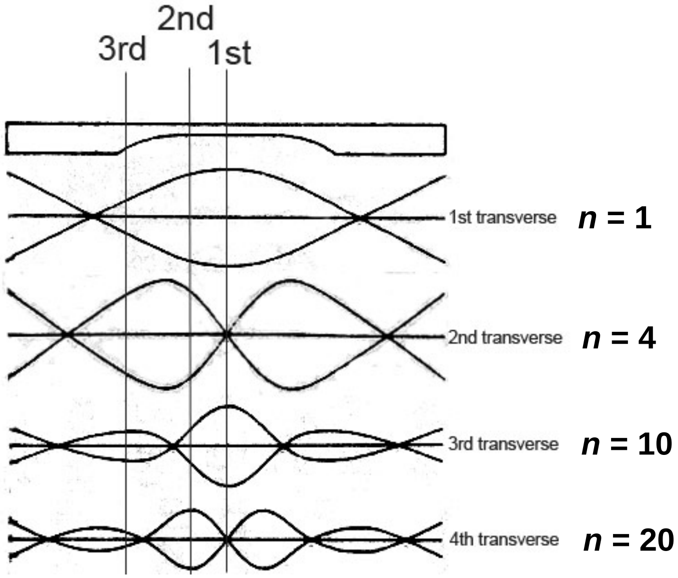
Time for sound to fall to 1 millionth of initial intensity

$(\Delta SIL = -60\text{ dB} = 10\log_{10}(I_{final}/I_{init})$)

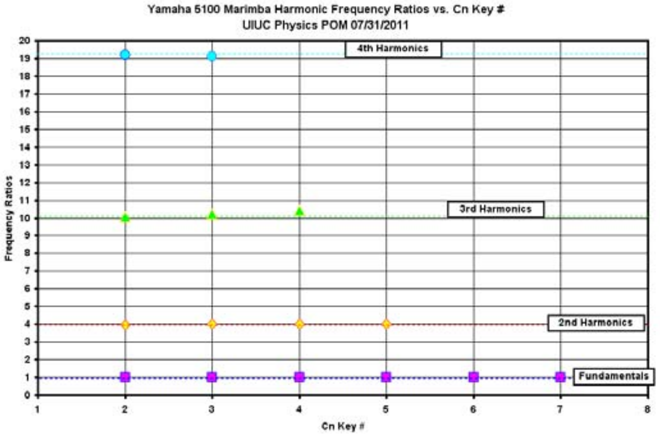
n.b. *Many* other room acoustics quantities can be/are measured!

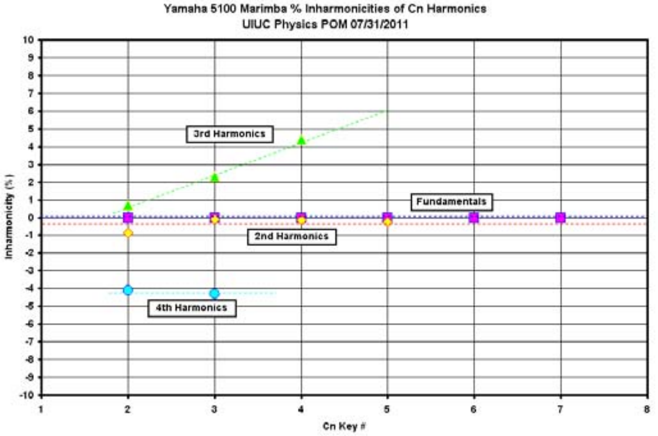
Marimba Studies:

Mallet strike location – varies harmonic content/tone:



Sculpting of underside of marimba bar tunes bar, and harmonic content: 1 (fund), 4th, 10th & 20th…



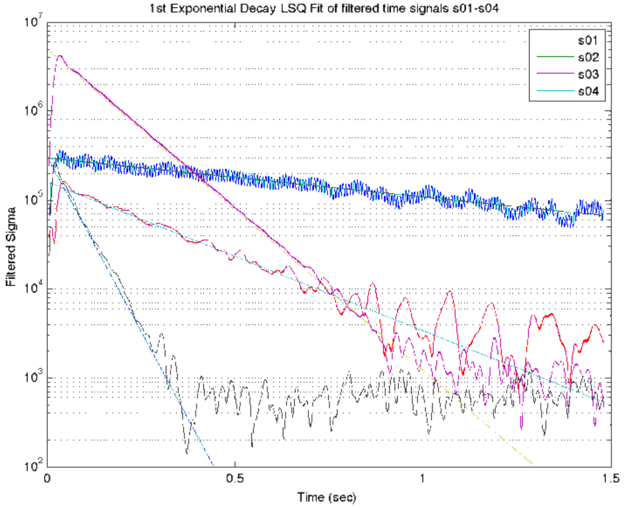


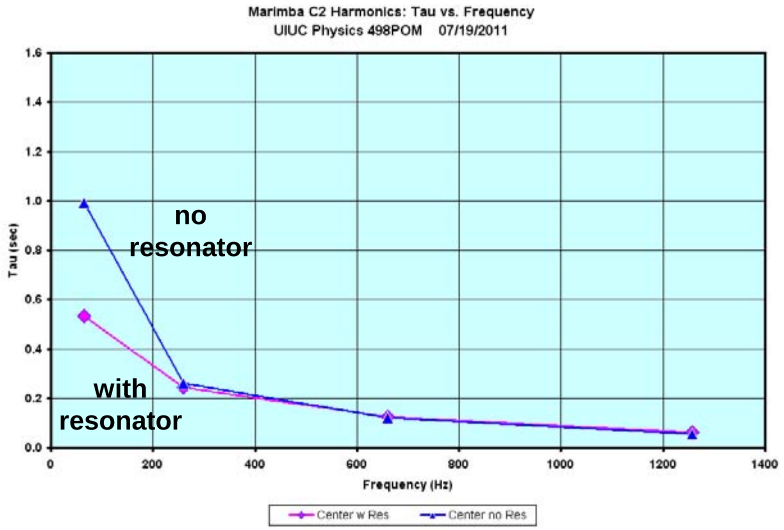
Resonators underneath marimba = open-closed organ pipe, matched to fundamental of each bar.

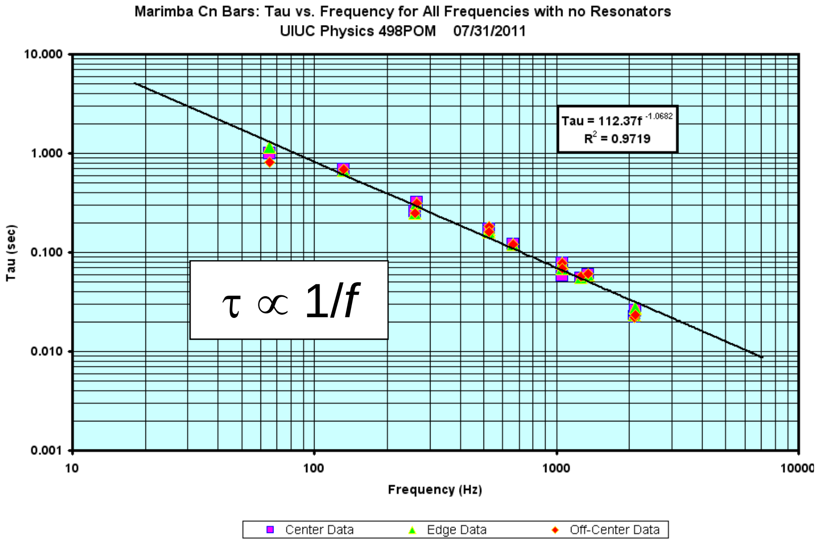
$f_n = nf_1$, n = 1,3,5,7…{odd harmonics}

$\Rightarrow$ Boosts fundamental

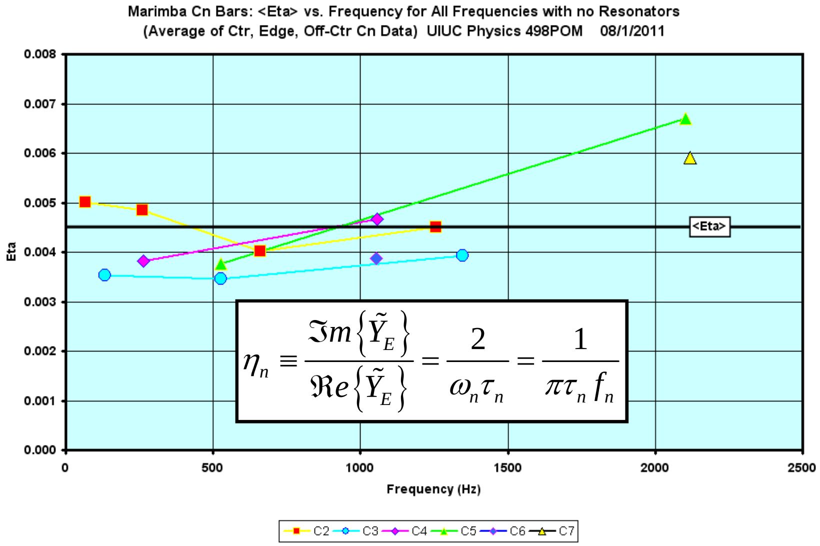
Marimba Studies – Measurement of the decay time(s) of harmonics of the C_n marimba bars (n = 2:7) and extraction of absorption coefficient η of rosewood


1st Exponential Decay LSQ Fit of filtered time signals s01-s04


Marimba C2 Harmonics: Tau vs. Frequency
UIUC Physics 498POM 07/19/2011


Marimba Cn Bars: Tau vs. Frequency for All Frequencies with no Resonators
UIUC Physics 498POM 07/31/2011

$$\tau \propto 1/f$$

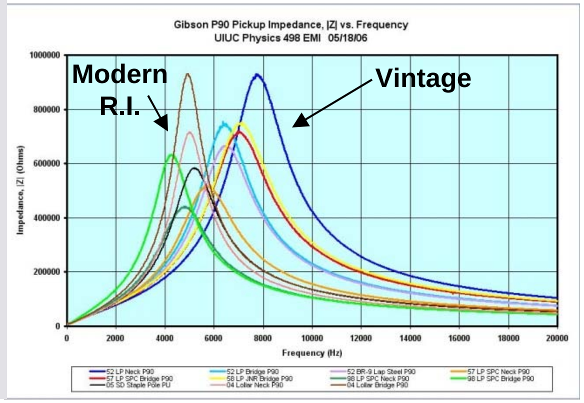

Marimba Cn Bars: <Eta> vs. Frequency for All Frequencies with no Resonators
(Average of Ctr, Edge, Off-Ctr Cn Data) UIUC Physics 498POM 08/1/2011

$$\eta_n \equiv \frac{\Im m\{\tilde{Y}_E\}}{\Re e\{\tilde{Y}_E\}} = \frac{2}{\omega_n \tau_n} = \frac{1}{\pi \tau_n f_n}$$

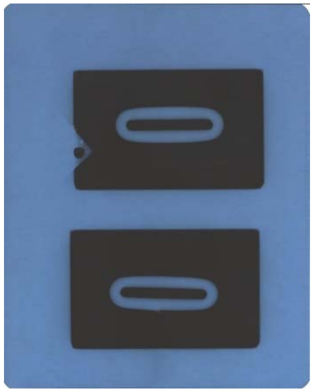
<u>A Test of My Own Long-Term Musical Memories</u>:

I played {electric} guitar in mid-60's – mid-70's; started playing again in ~ mid-90's:
"Faithful" modern-day re-issues of vintage guitars didn't sound like the <u>real</u> <u>deal</u> to *my* ears...
Due to false memories, or actual truth??? I explicitly checked : Measured $Z(f) = V(f)/I(f)$ vs. f

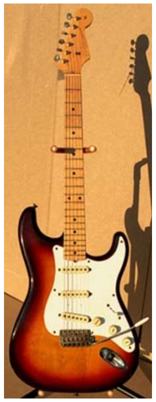
Gibson P-90's in Les Pauls, Les Paul Jr, …

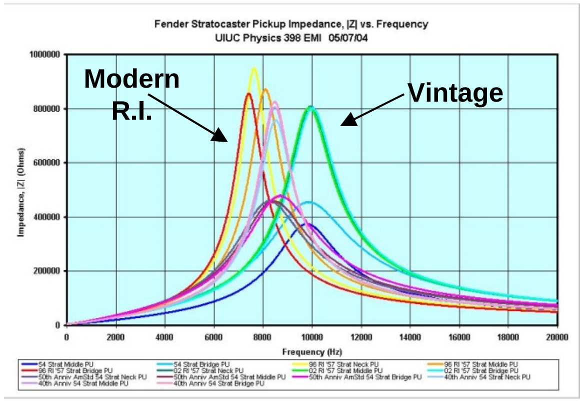


X-ray of P-90 PUs from '52 (top) vs. '98 R.I. (bottom) Gibson Les Paul Guitars:

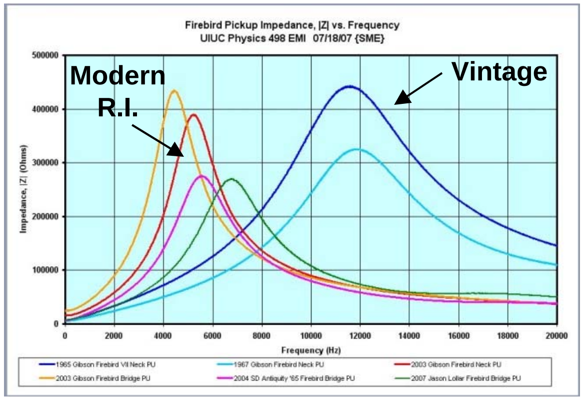


Fender Stratocaster Pickups





Gibson Firebird Pickups



Examples of Other Academic Acoustics Research Topics:

- Acoustic Black Holes – ADS/CFT Correspondence
- 3-D Acoustic Cloaking
- Acoustic Zeeman Effect
- Acoustic Casimir Effect
- Acoustic Aharonov-Bohm Effect
- Acoustic Diodes/Sonic Crystals
- Acoustical Lasers (UIUC Prof. R.L. Weaver)
- Seismic Noise “Interferometry” (UIUC Prof. R.L. Weaver) – also relevant to e.g. ocean noise, room noise!

- ***Much*** material (POM lecture notes, lab handouts, experimental results, acoustics-related software, student final reports, NSF Summer REU/UIUC Senior Thesis final reports, etc… posted/available on the 2 UIUC Physics of Music/Musical Instruments Website(s):
  - **Physics 193POM – Freshman "Discovery" Physics of Music/Musical Instruments** (less technical):

    http://courses.physics.illinois.edu/phys193/

  - **Physics 406 – Acoustical Physics of Music** (upper-level undergrad (juniors/seniors – more technical):

    http://courses.physics.illinois.edu/phys406/

- ***UIUC Undergrad Acoustics Research Opportunities***:
  - **Prof. Errede**: P193POM & P406 courses, Senior Thesis, Indep't. Study
  - **Prof. Weaver:** Senior Thesis, Indep't. Study
  - **ECE Profs:** ECE Acoustics Courses (Labs), Senior Thesis, Indep't. Study

- There also exists ***support*** – from the **UIUC Office of the Provost** – for Undergrad Research – see website:

  http://provost.illinois.edu/our/

- See also **UIUC CoE Illinois Scholars Undergraduate Research (ISUR) Program**:

  https://wiki.engr.illinois.edu/display/isur/Home

  Will need to Upload Application & Project Proposal (deadline is: Friday, March 19, 2014 at 11:59 pm):

  https://wiki.engr.illinois.edu/display/isur/Application+Forms

Other Acoustics-Related Courses, Activities @ UIUC:

Engineering Physics Custom Technical Option for Acoustical Physics (EPCTOAP)

ECE-210/211 Analog Signal Processing/Lab (prereq = ECE-110)		4 credit hours
ECE-310/311 Digital Signal Processing/Lab (prereq = ECE-210)		3 credit hours (optional)
ECE-473 Fundamentals of Engineering Acoustics (prereq = MATH 285/286)		3 credit hours
ECE-402 Electronic Music Synthesis	(prereqs MUS-103, ECE-290, ECE-310)	3 credit hours (optional)
ECE-403 Audio Engineering	(prereqs ECE-210 & ECE-310)	4 credit hours (optional)
ECE-417 Multimedia Signal Processing	(prereqs ECE-313 & ECE-310)	4 credit hours (optional)
ECE-545 Advanced Physical Acoustics	(prereq: ECE-473)	4 credit hours (optional)

Phys-402 Light	4 credit hours (optional)
Phys-404 Electronic Circuits	4 credit hours (optional)
Phys-406 Acoustical Physics of Music/Musical Instruments	4 credit hours
Phys-497/499 Senior Thesis – Acoustical Physics	4 credit hours

MUS-402 Musical Acoustics (prereqs MUS-101, MATH 112 or equivalent)	3 credit hours (optional)

See also other possible Music courses at http://ems.music.uiuc.edu/courses/, e.g.
MUS-407/409 Electro-Acoustic Music Techniques I/II
MUS-448 Intro to Computer Music
MUS-499 Advanced Computer Music

There may also be courses in UIUC Speech and Hearing Science:
See http://shs.illinois.edu/Undergraduates/CoreCourses.aspx

UIUC engineering undergrads very active in Audio Engineering Society (AES) – check out:
http://www.aes.org/sections/view.cfm?section=215, http://uiucaudio.tumblr.com/home
Contact(s): Prof. Lippold Haken l-haken@illinois.edu, UIUC AES: uiucaudio@gmail.com

PhD Graduate Study in Acoustics:

US:

Penn State:	http://www.acs.psu.edu/ , http://www.cav.psu.edu/
MSU:	http://www.pa.msu.edu/acoustics/
Georgia Tech:	http://www.acoustics.gatech.edu/
Virginia Tech:	http://www.val.me.vt.edu/
Stanford:	https://ccrma.stanford.edu/research
Boston U:	http://www.bu.edu/me/research/research-laboratories-and-groups/acoustics-and-vibrations/
Purdue:	http://www.purdue.edu/research/phase/
UT Austin:	http://www.me.utexas.edu/areas/acoustics/ http://www.texasacoustics.org/

See also websites of:

Acoust. Soc.America:	http://acousticalsociety.org/
see especially:	http://asa.aip.org/asagrad/gpdir.cm.html
SAE International:	http://www.sae.org/
see especially:	http://www.sae.org/careers/

World:

Edinburgh:	http://www.acoustics.ed.ac.uk/
New South Wales:	http://www.phys.unsw.edu.au/music/
Adelaide:	http://www.mecheng.adelaide.edu.au/avc/
Sydney:	http://sydney.edu.au/architecture/programs_of_study/postgraduate/audio_acoustics.shtml
Helsinki:	http://www.acoustics.hut.fi/
Denmark (2 yr MSc):	http://studyindenmark.dk/study-programmes/programmes-in-english/engineering-acoustics
Salford:	http://www.salford.ac.uk/computing-science-engineering/research/acoustics
Southampton:	http://www.southampton.ac.uk/engineering/undergraduate/courses/acoustical_engineering_list.page
Liverpool:	http://www.liv.ac.uk/architecture/research/acoustics-research-unit/
Cambridge:	http://acoustics.eng.cam.ac.uk/

II. Professional Careers in Acoustics

- ***Many*** **opportunities – all things acoustic – is an** ***extremely*** **broad field !!!**
- **Noise/Vibration Reduction: Living Environment(s), Appliances, Automobiles, Airplanes, Rockets, Boats/Submarines, Lawn Equipment, Wind Turbines/Wind Farms, Hearing Protection, etc.…**
- **Musical Instruments – all kinds/all types – develop new ones !!!**
- **Concert Halls, Recording Studios, Control Rooms, Home Audio, Cinema/Theater, Churches, …**
- **Live Sound Reinforcement, Sound Engineers – Live or Recording Studio…**
- **Voice/Sound Recognition/Identification**
- **Telecommunications Industry, Internet Audio, etc.**
- **Desktop/Laptop PC's, Cellphones, etc.**
- **Biomedical/Ultrasound Imaging Applications**
- **Doppler Laser Holography/Velocimetry - N & V, fluid flow, medical applications, …**

- **Typical <salary> ~ $65-85K. Starting salary (obviously) less, senior people e.g. @ Apple ~ $140K**

- ***Many*** **summer internship opportunities in acoustics – e.g. use Google!**

Partial/Non-Exhaustive/Incomplete List of Acoustics-Related Organizations:

Acentech Incorporated:	Architectural Consultants	http://www.acentech.com/
Acoustical Systems, Inc:	Enclosures, Noise Reduction	http://www.acousticalsystems.com/
ACO Pacific, Inc:	Measurement Microphones	http://www.acopacific.com/
Boeing:	Aircraft & Aerospace Products	http://www.boeing.com/boeing/
Bose Corporation:	Sound Reinforcement	http://www.bose.com/
D'Addario:	Strings, Drumheads, Reeds	http://www.daddario.com
E-A-R/Aearo Co.:	Hearing Protection	http://earsc.com/
Fender	Electric Guitars/Amplifiers	http://www.fender.com/careers/
Fleetguard, Inc:	Vehicle Exhaust Systems	http://www.cumminsfiltration.com/
JBL Professional:	Loudspeakers	http://www.jblpro.com/
Klipsch:	Loudspeakers	http://www.klipsch.com/
Knowles Electronics:	Microphones	http://www.knowles.com/
Meyer Sound, Inc:	Loudspeakers	http://www.meyersound.com/
NASA:	*Many* aspects of acoustics!	*many* websites !!!
Raytheon:	Sonar Systems	http://www.raytheon.com/
Shure, Inc:	Microphones	http://www.shure.com/
Wenger Corp:	Architectural Acoustics Products	http://www.wengercorp.com/
Wyle Acoustics:	Architectural Acoustics Products	http://www.wyleacoustics.com/

List of UIUC Undergrad Students in POM Class or NSF Summer REU Who Now Have/Are Pursuing Acoustics-Related Careers:

Noam Pikelny	Master Banjo Player	http://noampikelny.com/
Ben Juday/Ben Hay/Rob Marshall	Started Own Company (2003)!	www.analogoutfitters.com
Alan Carter	Johnson Controls	
Matt Winkler	Analytical & Recording Engineer	
Chuck Stelzner	RAND Corporation	
Robby Regalbuto	Shure Incorporated	
John Nichols	Knowles Electronics	
Rob Marshall	Shure Incorporated	
Eric J. Macaulay	Acoustics Grad Student @ MSU	
Gregoire Tronel	Acoustics Grad Student @ GA Tech	

**Analog Outfitters Booth
@ 2014 NAMM Show, LA**