Teaching Physics of Music

Thomas D. Rossing

Many physics departments teach courses in physics of music or musical acoustics as general education courses that students use to fulfill a science requirement. Such courses have become quite popular at many colleges and universities. Although career-oriented students often question the value of liberal arts or general education courses, many students have some interest in music, and courses in the physics of music are a route to acquiring science literacy. I have enjoyed teaching courses in musical acoustics for over 50 years, and in recent years I have devoted much of my research effort to musical acoustics and have written several books on the subject.

Acoustics is the science of sound. When I was a physics graduate student more than half a century ago, we were advised to take a course in vibration and sound (from *Vibration and Sound* by Morse) before taking quantum mechanics (from *Quantum Mechanics* by Schiff). [Does anyone else remember these classic textbooks?] Now one has to "shop the catalog" at most universities to find an acoustics course, and it is more likely to be offered in electrical or mechanical engineering or in speech and hearing than in physics. I jokingly tell my physics students that acoustics is just like quantum mechanics without the h-bar.

Musical acoustics deals with the production of musical sound, the transmission of sound to the listener, and its perception by the listener. Transmission of musical sound to the listener includes the study of concert hall and room acoustics, but it also includes the recording and reproduction of sound, which relies on applications of physics. The perception of sound is an important part of the interdisciplinary subject of *psychoacoustics, which* includes psychology, music, and the hearing sciences, as well as physics.

Few music performance majors have a strong interest in physics, and they are often not aware of the importance of understanding the scientific basis of music. Hence, a conscious effort has to be made to try to convince them that: a) they can learn to understand the science of sound; b) understanding musical acoustics will help them to be better musicians. Most experienced concert artists know how to interact with different types of concert halls, friendly or unfriendly, but they have learned this by trial and error over the years. I tell my students that studying musical acoustics gives them a head start. I claim that Stradivari knew much about the physics of violins but it took him and his colleagues 300 years to learn it. This learning curve can certainly be shortened by a course in the physics of music!

Fortunately there are several good textbooks available for teaching physics of music. Publishers tell me that our text *The Science of Sound*, now in its 3rd edition, is the best seller among them. This text, which includes considerably more material than can be covered in a one-semester course, is modular, so that instructors can select the modules that best suit their objectives and the interests of their students.

It is highly recommended that both laboratory and classroom demonstration experiments be a part of a physics of music course. I am a strong believer in the old adage that "*I hear, I forget; I see, I remember; I do, I understand.*" The 3rd edition of *The Science of Sound* describes "Experiments for Home and Classroom Demonstration" at the end of each chapter, as well as a list of recommended laboratory experiments. I give students extra credit for preparing classroom demonstration experiments of their own design.

For several years, Andrew Morrison and I taught a course Acoustics, Music, and Hearing on the Internet using the Blackboard platform. Our intent was to make it available to students, especially at community colleges, where no qualified teacher was available. However on our own campus, students submitted their homework and took exams using the Internet. Students submitted answers to review questions in advance of classroom discussion and then submitted their homework on the Internet. Examinations were given in a proctored setting in a computer laboratory.

Course content

- At Northern Illinois University a one-semester course in Acoustics, Music and Hearing included the following modules from *The Science of Sound*:
    1. Vibrations, Waves, and Sound
    2. Perception and Measurement of Sound
    3. Musical Instruments
    4. The Human Voice.

- The module on perception and measurement included four chapters on Hearing; Sound Pressure, Power and Loudness; Pitch and Timbre; and Combination Tones and Harmony. The relationship of the subjective attributes of sound to the physical quantities is a central problem of psychoacoustics, and it has received a great deal of attention in recent years. Some of these relationships are illustrated in the table below in which + represents a weak dependency, ++ a moderate dependency, and +++ a strong dependency.

PHYSICAL PARAMETER	SUBJECTIVE QUALITY			
	LOUDNESS	PITCH	TIMBRE	DURATION
PRESSURE	+++	+	+	+
FREQUENCY	+	+++	++	+
SPECTRUM	+	+	+++	+
DURATION	+	+	+	+++
ENVELOPE	+	+	++	+

- The module on musical instruments included five chapters on String Instruments (violin and guitar), Brass Instruments; Woodwind Instruments; Percussion Instruments; and Keyboard Instruments (piano, harpsichord, and organ). Students were encouraged to bring their own instruments to class to demonstrate them, and we often displayed sound waveforms and spectra as they played them in different ways.

- Missing from the course were subjects such as musical scales, acoustics of concert halls, electronic and computer music, and audio and electroacoustics. This was because we taught another one-semester course using the same text that included these subjects. Some students became interested enough in the subject during the first semester to continue on in the second semester.

At Stanford University, I teach a one-quarter course in Musical Acoustics that covers the basic modules listed above. This past quarter, however, we substituted a module on room acoustics for the musical instrument module. This was because we taught 3 one-credit mini-courses on musical instruments as an experiment. We have found that often music students (unless they are preparing to teach music) are less interested in the acoustics of musical instruments other than their own.

The mini-course on percussion instruments included: 1. Mallet percussion instrument; 2. Drums; 3. Plates and gongs; 4. Bells; 5. Caribbean steelpans and the HANG (a hand-played steel instrument). Guest lecturers included David Wessel (University of California) and Garry Kvistad (Woodstock Percussion in New York). The mini-course wound up with a concert of Steve Reich percussion music played by 3 professional percussionists plus Stanford faculty and students.

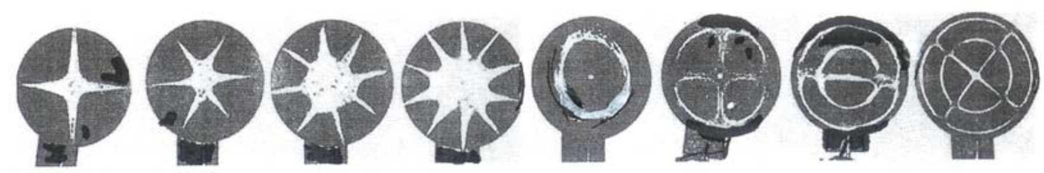
Mini-course on Percussion (Guest lecturers: *Garry Kvistad*, founder of Woodstock Percussion and percussionist with Steve Reich and Nexus, and *David Wessel*, Director of the Center for New Music and Audio Technologies, UC Berkeley)	
Mini-course on Violins (Guest lecturer: *Joseph Curtin* noted violin maker and MacArthur fellow)	

The mini-course on violins, taught by noted violin maker, Joseph Curtin, and myself, included concerts by violinists Mari Kimura and Livia Sohn as well as participation by the St. Lawrence String Quartet. Kimura's concert included a piece by Jean Claude Risset featuring tones of anonymously low frequencies produced by bowing with a large bow force.

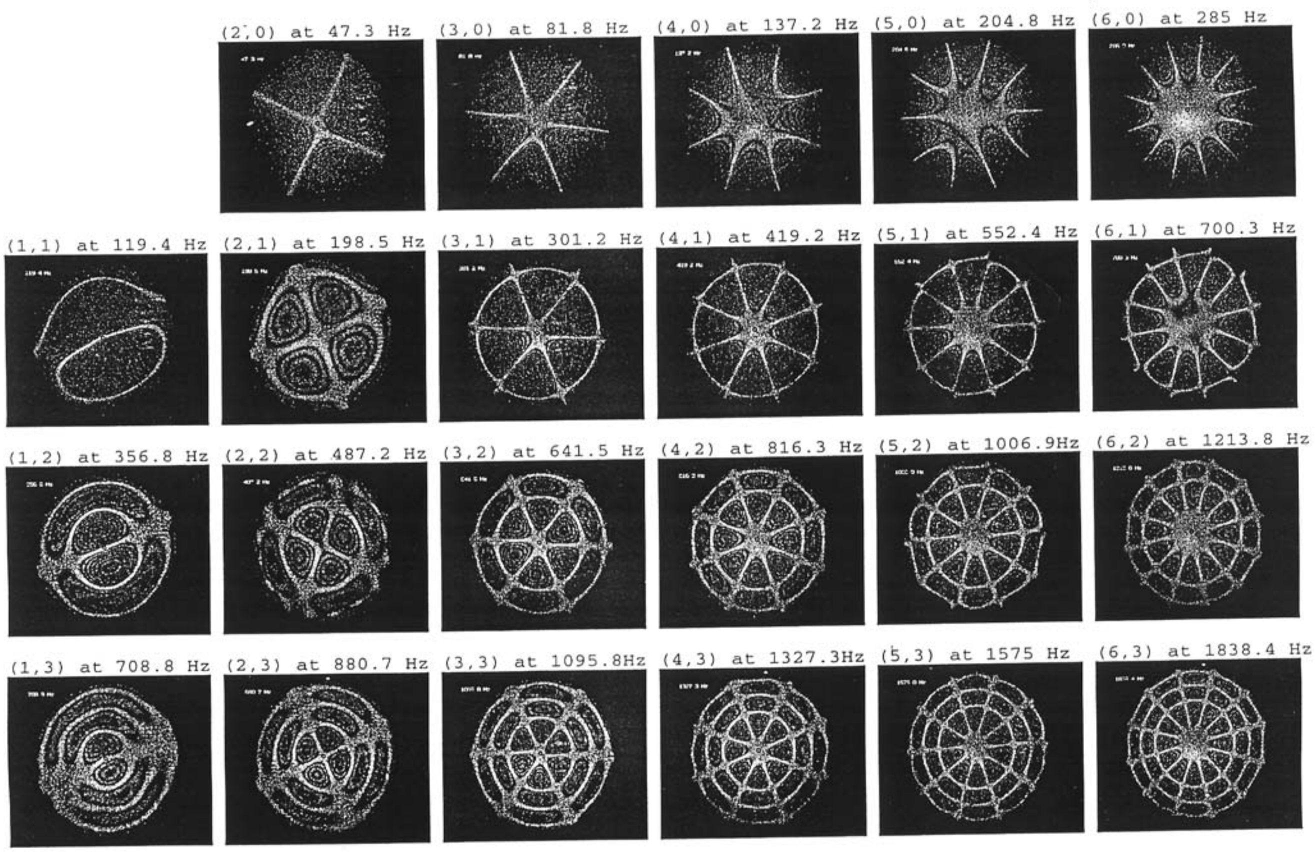
Studying modes of oscillation in musical instruments

Most musical instruments depend upon vibrations of strings, membranes, plates, or air columns to produce sound. Thus many of the laboratory and demonstration experiments in a musical acoustics course might well be aimed at understanding simple and complex vibrations in such systems. Strings and air columns are one-dimensional systems, and the modes of vibration in an ideal string or air column (neglecting the stiffness of a string or the end correction of an air column) will have frequencies that are harmonics of a fundamental. Not so for vibrating membranes and plates. Determining mode frequencies and mode shapes in vibrating membranes, plates, drums, cymbals, gongs, etc. can be challenging as well as instructive for students in an introductory acoustics course.

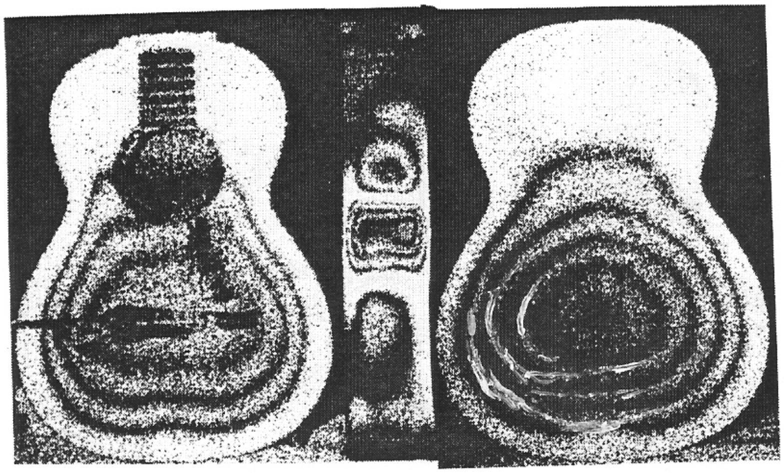
- One time-honored method for determining mode shapes and frequencies in vibrating membranes and plates is to sprinkle salt (or similar granular material) on the plate, set it into motion at various resonance frequencies, and observe how the salt collects along nodal lines. The nodal patterns thus obtained are generally referred to as Chladni patterns in honor of E. F. F. Chladni who popularized them in the 18th century. Chladni patterns of a flat circular plate are shown below.



- Although Chladni patterns locate the nodal lines, they do not give detailed information about the amplitudes in the vibrating regions between nodes. Scanning the nearfield sound with a small microphone gives a pretty fair estimate of relative amplitudes, but a more accurate indication of amplitude can be obtained by means of holographic interferometry. Holographic interferograms of modes of vibration in cymbal are shown below. Note the regular arrangement of nodal lines and nodal circles.



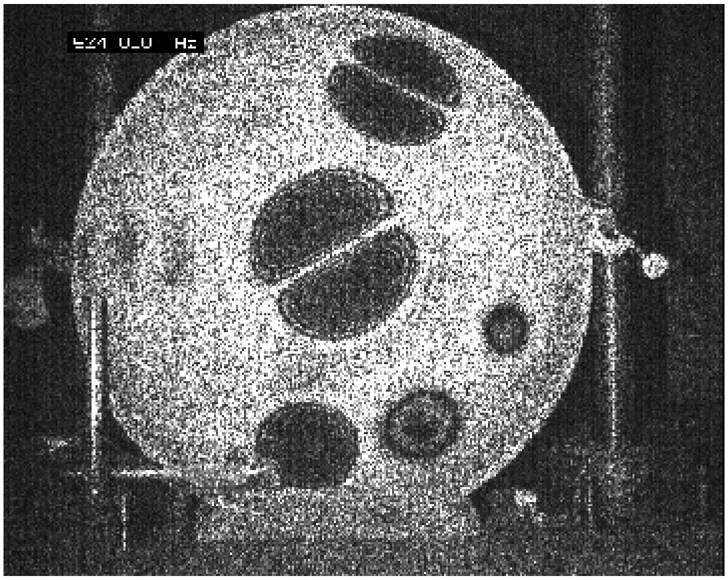
By means of mirrors it is possible to record holographic interferograms of different views of an instrument at the same time. The interferogram below shows the top plate, the rib, and the back plate of a classical guitar as it vibrates in its fundamental mode.



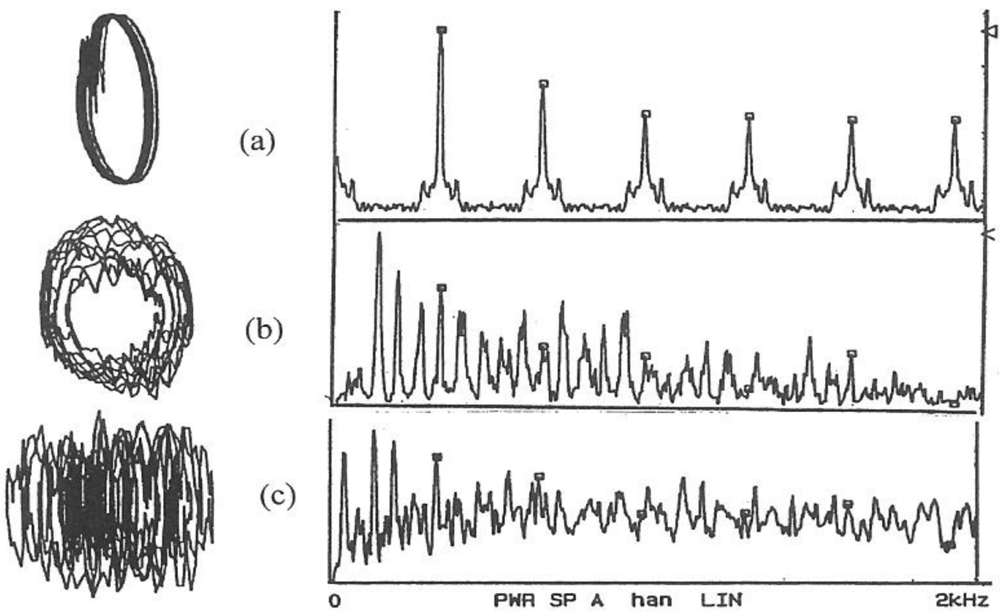
An interesting new instrument is the HANG, a hand-played steel instrument.
A cousin of the Caribbean steelpan, the HANG is enjoying great popularity around the world. The instruments have eight or nine notes arranged around a central deep note and tuned to one of several scales.

DING side

Individual notes of the HANG, like the Caribbean steelpan, are tuned by carefully hammering the steel surface of the steel surface. Tuned modes of vibration in each note generally have frequencies in the ratios of 1 : 2 : 3, so they sound the fundamental, the octave, and the twelfth. Holographic interferograms of a HANG driven sinusoidally near the bottom of the photo show excitation of the 3 harmonic modes in various notes on the instrument. The nonlinear coupling between the note areas is especially interesting.



Several instruments are particularly interesting because of their nonlinear behavior. Cymbals are characterized by a prominent “aftersound” which develops several milliseconds after they are struck. This aftersound is actually the result of chaotic vibration that develops along with doubling or tripling of the vibration period at large amplitude. Phase plots (displacement vs. velocity) and sound spectra of a cymbal at small and large amplitude are shown below.



Chinese opera gongs show a marked pitch glide due to nonlinear behavior after being struck a substantial blow. The pitch glide may be either upward or downward, depending upon the exact shape of the gong. These are often termed “softening” and “hardening” spring behavior, respectively

Music technology

Several universities have started programs in music technology. A few years ago the Acoustical Society of America sponsored a special session on teaching musical technology. Most of the established programs were in Europe, but since that time a number of programs have started in the United States as well. Some universities, such as London Metropolitan University, have programs in musical instrument design and construction. At most places, however, music technology implies electronic music technology, including computer analysis and synthesis of musical sounds. In the third edition of our textbook *The Science of Sound*, Part VII is devoted to Electronic Music Technology. There are chapters on Electronic Music Technology and its Origins, Analog Electronic Music, Digital Audio Signal Processing, and Computer Music and Virtual Acoustics. In this book we define music technology as “the sum total of what we know how to do in order to make music,” and electronic music technology as “that part of music technology based primarily on the field of electronics and, especially, digital electronics.”

Advances in music technology have led to what might be termed “artificial musical intelligence,” which describes the creation of new musical sounds as well as the re-creation of traditional musical sounds by artificial means. It increasingly includes the incorporation of new sounds into computer-based media, such as virtual reality, movies, games and web-based communication. As we use a computer keyboard and mouse less and less, our interactions with machines will become more like our interactions with each other.

The future?

I believe that it is fair to say that the future of musical acoustics is very favorable. Whereas most of us older generation of practitioners began our careers in other fields of physics or engineering, a new generation of teachers has been trained in musical acoustics and will advance the science to greater heights. Will acoustics courses once again be offered by leading physics departments?

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