Musical A

Part A

Part A Musical Acoustics and Signal Processing

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In the Hornbostel/Sachs classification of musical instruments first published in 1914, the instrument families were ordered according to their physical driving mechanism, such as bowed, plucked, or struck instruments. This scheme reflects the nature of systematic musicology, which aims to search for universals in music that govern all musical genres around the world.

Still, musical acoustics itself is much older. Joseph Sauveur (1653–1716), who coined the term acoustics in the sense we use it today, was already sorting vibrating systems in terms of strings, membranes or plates at this time, well in accordance with musical instruments. This also reflects the close correspondence between music, physics, geometry and arithmetic, which was present in ancient times with the Pythagoreans or in the music theory of Archytas of Tarrent (428–347). Music was part of the Quadrivium in Renaissance times, for example in the music theory of Johannes Kepler in his *Harmonices Mundi* from 1619. Music was also often close to mathematics and geometry in the work of mathematicians like Mersenne, Zarlino, Euler or Gauss, philosophers like Rene Descartes or physicians like Hermann von Helmholtz, who in his *On the sensations of tone as a physiological basis for the theory of music* from 1863, was able to derive the Western tonal system from acoustical, physiological and psychological findings.

However, investigations of musical instruments in detail were only prominently carried out first by Felix Savart (1791–1841) on the violin. Savart, known to physicists due to the Biot–Savart law of magnetostatics, also invented an octobass: a huge double bass so high that it needed two floors and two players, one bowing on the first floor and one pressing down the strings on the second. Later, Helmholtz was the first to visualize the sawtooth motion of a violin string by stroboscopy. He and Lord Rayleigh were also among the first to investigate the organ theoretically as well as experimentally.

After World War II research on musical instruments intensified, as is reflected in the work of the *Cutgut Acoustical Society* in England, *the Physikalisch-Technische Bundesanstalt* in Braunschweig or the *Institut de Recherche et Coordination Acoustique/Musique* (*IRCAM*) in Paris and by many individuals mainly in the US, Canada, Europe, Australia and Japan. Other parts of the world where musicological research is performed were concentrating not so much on musical acoustics but more on music ethnology, such as in China or India, although an Indian researcher, Chandrasekhara Venkata Raman (1888-1970) was the first to develop a theory on the bowed string.

Today musical acoustics, which has been growing tremendously over the last decades, is a very active and lively scene with increasing numbers of researchers. The instrument industry, which has always been working in this field in very close contact with researchers, is profiting from the results in musical acoustics, which is also reflected in patents and applications improving instrument quality and design. Indeed many myths about musical instruments are around among instrument builders, and musical acoustics may help here too. Related industries like the software-developing market, which has been building synthesizers and virtual musical instruments in recent years, have increasingly profited from models of musical instruments developed in musical acoustics to realize more realistic-sounding plugins or synthesizers, mainly in the domain of physical modeling.

After about two hundred years of research in musical acoustics, many open questions are still present in the field. The present models, although often sounding very realistic, are still quite restricted to certain instrument types or articulations. A basic understanding of the role of turbulence in wind instruments is an ongoing debate since many researchers, starting from Helmholtz and Rayleigh, found the organ to be a linear system that does not correspond to our understanding of turbulence. The role of forced oscillations in musical instruments and the difference between the eigenmodes of guitar and violin bodies and the forced oscillation patterns found empirically when driving the instrument with strings are also an ongoing debate. Furthermore the radiation of a musical instrument, its dependency on the driving point, or its transient nature are not fully understood yet. The role of material, its stiffness and, maybe even more importantly, its damping, is not yet understood at all. This list could be continued. So not only are details of musical instruments still under debate, but often the basic process of tone production is still discussed.

The reason for these ongoing debates may be seen in the extreme sensitivity of the human ear. We judge the quality of an instrument not by just producing sound at all; we are interested and fascinated by the details of the sound, the range of articulatory possibilities of an instrument, its character and *musicality*. Therefore musical acoustics is a discipline with many open questions and hopefully many fascinating new results in the future.

The present section gives a systematic overview on basics in the field as well as addressing open questions and providing insight into ongoing debates. The choice of topics is also related to the position of musical acoustics in the field of systematic musicology: opening links to signal processing and applications via mathematical modeling of instruments, music ethnology through discussion of wood properties, basic driving mechanisms or non-Western instruments, or music psychology by discussing timbre- or articulation-related aspects of the instruments. In the end, musical instruments are the source of a musical performance and provide the possibilities a musician might use to express themself. Very often tools become music and improvements to the instruments only triggered new musical styles, sounds and extended techniques.

In Chap. 2 *Wilfried Kausel* gives a comprehensive and systematic mathematical introduction to musical acoustics starting with one-dimensional vibrating systems. After introducing a mass-spring system and deriving complex numbers he considers the wave equation on strings and in ducts including reflections, forced oscillations and impedance. He also discusses stiffness in one-dimensional media and longitudinal vibrations in bars, explaining many mathematical functions in detail as used in musical acoustics on an everyday basis.

Wilfried Kausel then enlarges the one-dimensional picture of Chap. 2 into a two- and three-dimensional one in Chap. 3. He derives and discusses the mathematics of membranes as used in drums or string instruments like the banjo and turns over to stiff two-dimensional geometries like rectangular and circular plates as basic components of stringed instruments. He then gives the basic equations for three-dimensional geometries as cavities or rooms and discusses modes and resonances.

Switching from abstract mathematical models to basic material, in Chap. 4 *Chris Waltham* and *Shigeru Yoshikawa* discuss wood used for musical instruments, mainly for stringed, wind and percussion instruments. After a summary of common tonewoods they discuss many aspects of the relation between wood and the sound of the instrument. They conclude that even if knowledge about wood does not guarantee a high quality sound from the instrument, it still helps to avoid many mistakes and errors in instrument building.

Measuring musical instrument vibrations is nontrivial and *Thomas Moore* in Chap. 5 discusses the techniques used in the field. He discusses the use of microphone arrays in terms of acoustic holography, where the vibrations of radiating musical instrument surfaces are measured using multiple microphones recording the radiated sound, which is then back-propagated to the instrument surface. Another powerful tool introduced is laser Doppler interferometry, where deflections of the instrument surface are measured as phase shifts in a split laser beam. Finally, accelerometer measurements are discussed using piezoelectric crystals attached to the instruments.

Turning then to stringed instruments, *Nicholas Giordano* in Chap. 6 gives a brief overview of pianos, guitars and violins. He introduces the basic differential equations of the instruments while discussing the driving mechanisms, the energy transfer and the modes of vibrations. The paper is rich with many complex and interesting phenomena associated with the instruments, which cannot always be discussed in detail but where the appropriate literature is referenced.

Turning to wind instruments, *Benoit Fabre*, *Avraham Hirschberg* and *Joël Gilbert* in Chap. 7 give an overview of the clarinet, the oboe, the harmonica, the trombone, and the modern transverse flute. The instruments are classified along a general model system consisting of a nonlinear generator and a linear resonator holding as a general principle for the very diverse systems of single and double reed and wind jet instruments. The paper presents models that can easily be implemented as physical models, which can end in sound-producing software tools.

In Chap. 8, *András Miklós* and *Judit Angster* present measurements and a model of the organ pipe. They emphasize the role of the attack transient, the very first beginning of the sound, which perceptually is the most salient part of musical tones in general. The instrument is discussed as a coupled system of a hydrodynamically oscillating air jet and a resonating pipe with wall losses. The measurements of the attack show a complex transient phase known to organ builders as *chiff*, which is known to be a quality criterion for organ pipes.

In Chap. 9, *Andrew Morrison* and *Thomas Rossing* give an introduction to percussion instruments with many examples, as well as theoretical and experimental findings. The drums of a rock or jazz drum set with snare, bass drum and tom-toms are discussed as well as instruments from other parts of the world like Caribbean steelpans, Indian tablas, Chinese stone chimes, Indonesian gongs or Japanese drums. Many laser interferometry measurements of the instruments' eigenmodes are shown and systematic investigations in terms of tuning systems and strike notes are discussed.

Discussing the role of nonlinearities in musical instruments in Chap. 10, *Rolf Bader* distinguishes between nonlinearities that lead to an enhancement of the brightness of musical instrument timbres and those nonlinearities that are crucial for musical tone production. He finds synchronization in harmonic overtone structures in wind instruments as a result of synchronization within these instruments driven by turbulent damping. Applying this finding to other instrument families, a general understanding of musical instruments as self-organized systems is possible.

The section closes in Chap. 11 with *Michael Vorländer* presenting room acoustics as the link between musical instruments and the audience in a concert hall. He discusses basic aspects of room acoustics while introducing ray-tracing algorithms for modeling concert spaces. Using the resulting impulse response as a filter function for a dry musical signal in a fast convolution algorithm, he shows that the acoustic space can be reproduced in silico, making it possible for architects to estimate the room acoustics during the process of designing a space.