TECHNOLOGY IN MUSIC ACOUSTICS AND PERFORMANCE SCIENCE

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Music Acoustics, if defined as a comprehensive „Science of Music", consequently must include 'Playing Music" and therefore covers a wide range of various phenomena to be analyzed and investigated. In particular, the fact that the player and the instrument fonn a control loop and interfere with each other requires on the one hand, physical and mathematical methods, and on the other, human physiology, psychology and brain science in order to understand the mechanisms of interaction (see Fig. 1). Consequently the target audience for the results differs: it varies from instrument makers, professional musicians, musicologists and neuroscientists to music teachers and music therapists, etc.

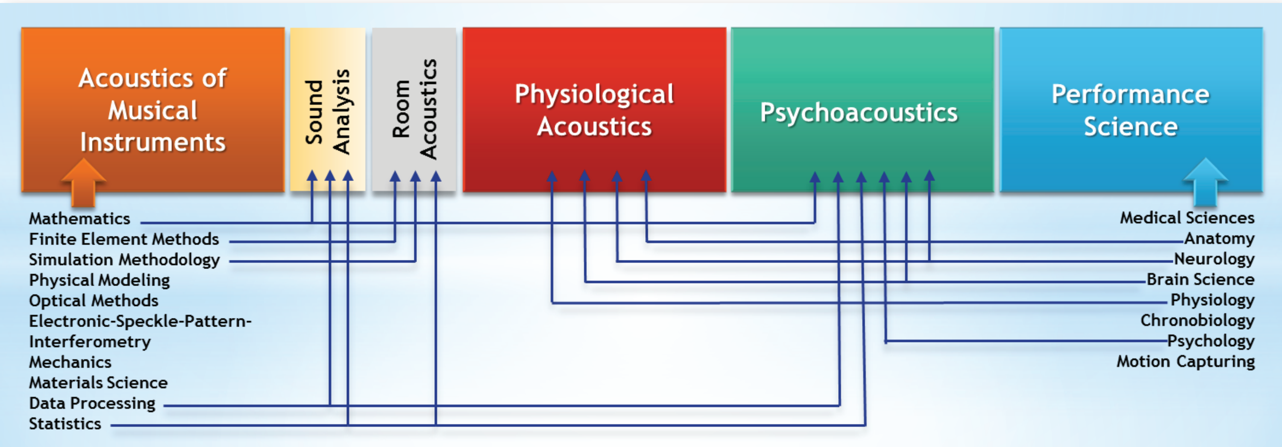


Fig. 1: Sub-disciplines of Music Acoustics with involved fields of science and their methods.

Although some basic findings were already made in ancient Greece (Pythagoras et al.), and the discoveries of the scientists of mediaeval times like Galileo Galilei, Marin Mersenne and Ernst Chladni, up to the famous scientists of the 19th century like Hermann von Helmholtz and Alfonso Giacomo Corti, enormously improved our understanding of the function of musical instruments and the perception of music, there still was a significant lack of knowledge - maybe caused by the traditional distinct separation of science and the arts in the 19th and early 20th century.

Additionally, the differences between the technical language and terminology used by acousticians and musicians traditionally prohibited a fruitful communication between scientists and artists. Consequently, the scientists did not understand the musicians, who created their own language to describe highly complex and partly tricky phenomena by one simple term and vice versa. A typical answer of an acoustician of the 20th century on the description of a phenomenon by a musician concerning, for example, the behavior of the musical instrument in a special situation, was: ‚What you tell me is due to physical reasons not possible!'

On the other hand acousticians mostly used over-simplified models of musical instruments because they could not handle the enormous amount of data or, as they lacked the experience of professional musicians, were not even able to realize all the parameters involved. Thus, many facts thought until now to be uncontroversial in the music acousticians' community, had to be revised over the last ten years.

The turnaround took place in the 80s and 90s of the last century and was caused by two trends:

First of all, more and more people had a university degree in music and in physics, engineering or humanities. This enabled them to understand both worlds: science and the arts. Their practical experience as professional musicians helped them to take all relevant parameters into consideration and to avoid an oversimplification of the object of research. In Europe, by and by, new centres developed where scientists exclusively worked in the field of Music Acoustics.

The first groups were established around Johan Sundberg at the KTH in Stockholm, Jurgen Meyer at the TU Braunschweig (this group unfortunately was closed down 2003), two in Prague (VUZORT and one at the Music University) and a group strongly related to instrument making companies in Hradec Kralove (Czech Republic) as well as in Klingenthal (former DDR); groups in France included IRCAM in Paris, CNRS in Marseille, and one at the University of Lyon; a group was established around Murray Campbell at the University of Edinburgh (Scotland); and the Institute of Music Acoustics ‚Wiener Klangstil‘ at the University of Music and Performing Arts Vienna was founded in 1980. In Portugal, Spain, Italy, the UK and Norway, various scientists working in Music Acoustics could be found, but not embedded in a separate Institute. This development in Europe is unique, because elsewhere (e.g. USA, Asia and Australia) Music Acoustics Research was (and still is) represented by so-called ‚Lone Wolves‘ like Arthur Benade, Carol M. Hutchins and Tom Rossing from the USA, or Joe Wolfe and Neville Fletcher from Australia.

Secondly, the rapid increase of computing power in the years following the tum of the millennium finally allowed researchers to work with complex models and led for the first time to results effectively matching the reality.

Acoustics of Musical Instruments

Musical instruments are objects which act according to physical rules, but each of the quality parameters defined by the musicians contains several physical parameters with a different weighting. Additionally the control loop between the player and the instrument generates nonlinear effects.

The auditory quality of an instrument is defined by only one parameter: the sound color, specifically timbre which, of course, is in fact a mixture of the properties of the instrument, the artistic intention of the player and his ability to modify the sound offered by the instrument. For the player, however, the quality of an instrument is defined by several parameters like ‚Response‘, ‚Playability‘ (easy speaking or stiff), ‚Intonation‘, ‚Modulation Capability‘, ‚Dynamic Range‘, the offered basic sound color, etc.

Brass Wind Instruments

At first glance, it seems to be simple: we have a more or less cylindrical and/or conical tube with a closed end at the mouthpiece and an open end at the bell. The principles of function have been well known since the early 20th century: The human lips open and close like a valve (e.g. 440 times per second for an a1) and push overpressure pulses into the mouthpiece. These pulses form a sound wave with many harmonics and travel down inside the tube of the instrument toward the bell.

At the bell 90-94% of the energy is reflected, travels back to the mouthpiece and forms a ‚standing wave' with the original sound wave. The rest is radiated into the room and represents the sound of the instrument. This works only if the time span of the opening and closing of the lips exactly matches (or is an integer part of) the time required by the sound wave for its round trip from the mouthpiece to the bell and back. Therefore the basic properties and the parameter ‚Intonation' and to some extent the parameter ‚Response' can be quantified by an input impedance measurement inside the mouthpiece in the plane of the lips where the standing wave always forms a pressure antinode (Widholm 1995). With such an input impedance measurement (first done in the 1950s), one receives within a few seconds nearly all acoustical properties of the instrument and information on approximately 90% of its musical quality. Figure 2 shows the input impedance curves of a good quality (upper curve) and an extremely bad quality (lower curve) French Hom.

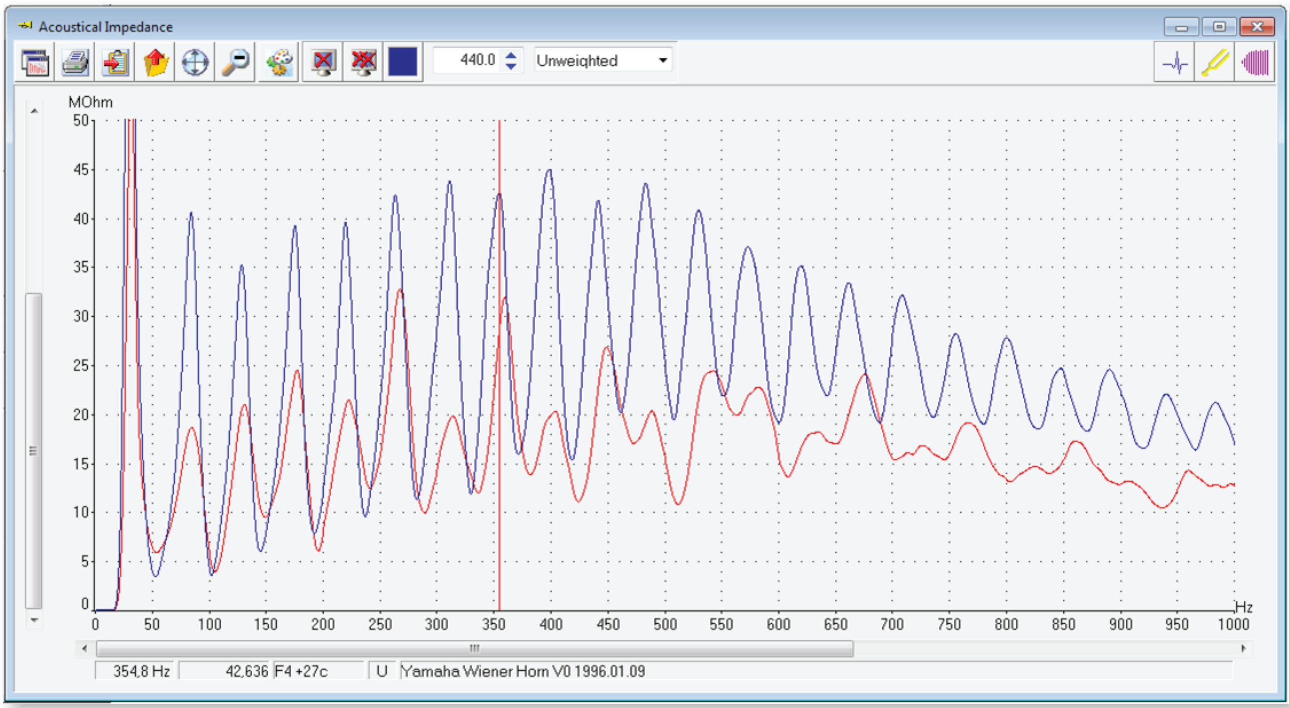


Fig. 2: Input impedance of a good quality (upper curve) and an inferior (lower curve) French Horn, measured with BIAS.

At frequencies where the curve forms a peak, a note can be played. As the measurement system - in contrary to the excitation signal of the player which contains a lot of harmonics - works with a sinusoidal excitation signal (chirp), the calculation of the intonation offered by the instrument is valid only for sinusoidal signals. To get practice-oriented results, the calculation must be done by a convolution integral, a so-called ‚weighted sum function'. Figure 3 shows an intonation plot for a mid-quality trumpet.

By a transformation of the data from the frequency into the time domain (Inverse FFT and Hilbert transformation), an ‚acoustic radar' can be simulated and helps us to look inside the instrument and to detect defects (see Figure 4).

If the sizes of the instrument (shape of the bore) are known, simulations can save the instrument maker the use of the ‚trial and error' method for improvements (see Figure 5 and Figure 6).

Transmission line models like that of Mapes Riordan (Mapes Riordan 1993), or spherical and multimodal models (Kausel et al. 1999) have proved their worth.

Fig. 3: Intonation analysis of a trumpet in Bb based on the measured input impedance. The chart shows the deviation of each playable note from the equally tempered scale in cent. Colors indicate the used fingering (valve combination).

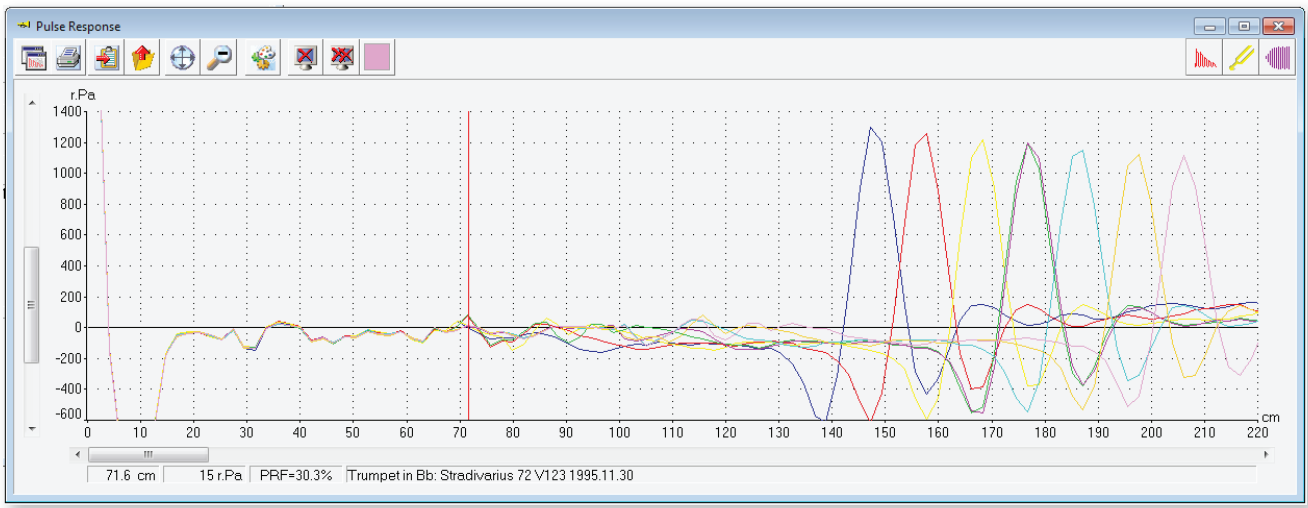


Fig. 4: Pulse response of the trumpet of Fig. 4-3. The peaks (right) indicate the end of the bell (blue: open instrument, red: first valve pressed, and so on). The redcursor marks a constriction caused by the first valve at 76.1 cm.

$$a_{11} = \frac{x_1}{x_0}\left[\cosh(\Gamma L) - \left(\frac{1}{\Gamma L}\right)\sinh(\Gamma L)\right]$$

$$a_{12} = \frac{x_0}{x_1} Z_c \sinh(\Gamma L)$$

$$a_{21} = \left[\left(\frac{x_1}{x_0} - \left(\frac{1}{\Gamma x_0}\right)^2\right)\sinh(\Gamma L) + \left(\frac{\Gamma L}{(\Gamma x_0)^2}\right)\cosh(\Gamma L)\right]$$

$$a_{22} = \frac{x_0}{x_1}\left[\cosh(\Gamma L) - \left(\frac{1}{\Gamma x_0}\right)\sinh(\Gamma L)\right]$$

Fig. 5: Input impedance of a matrix element.

$$Z_L = \frac{\rho c}{\pi R_a^{\,2}}\left(\frac{(k R_a)^2}{4} + i0.6133(k R_a)\right)$$

Fig. 6: End resistance at the bell.

Intensive research in this area led in 1999 to the world‘s first ‚Optimiser‘ software package for brass instruments (Kausel 2001) which allows the input of targets in terms of instrument makers (see Figure 7 and Figure 8). After the measurement of an existing instrument, the player specifies his wishes in terms of musicians and the optimizer software tells the instrument maker which parts he has to modify to get the desired improvements. Last but not least, the Optimizer can be used to ‚clone‘ instruments or to create new instruments from scratch.

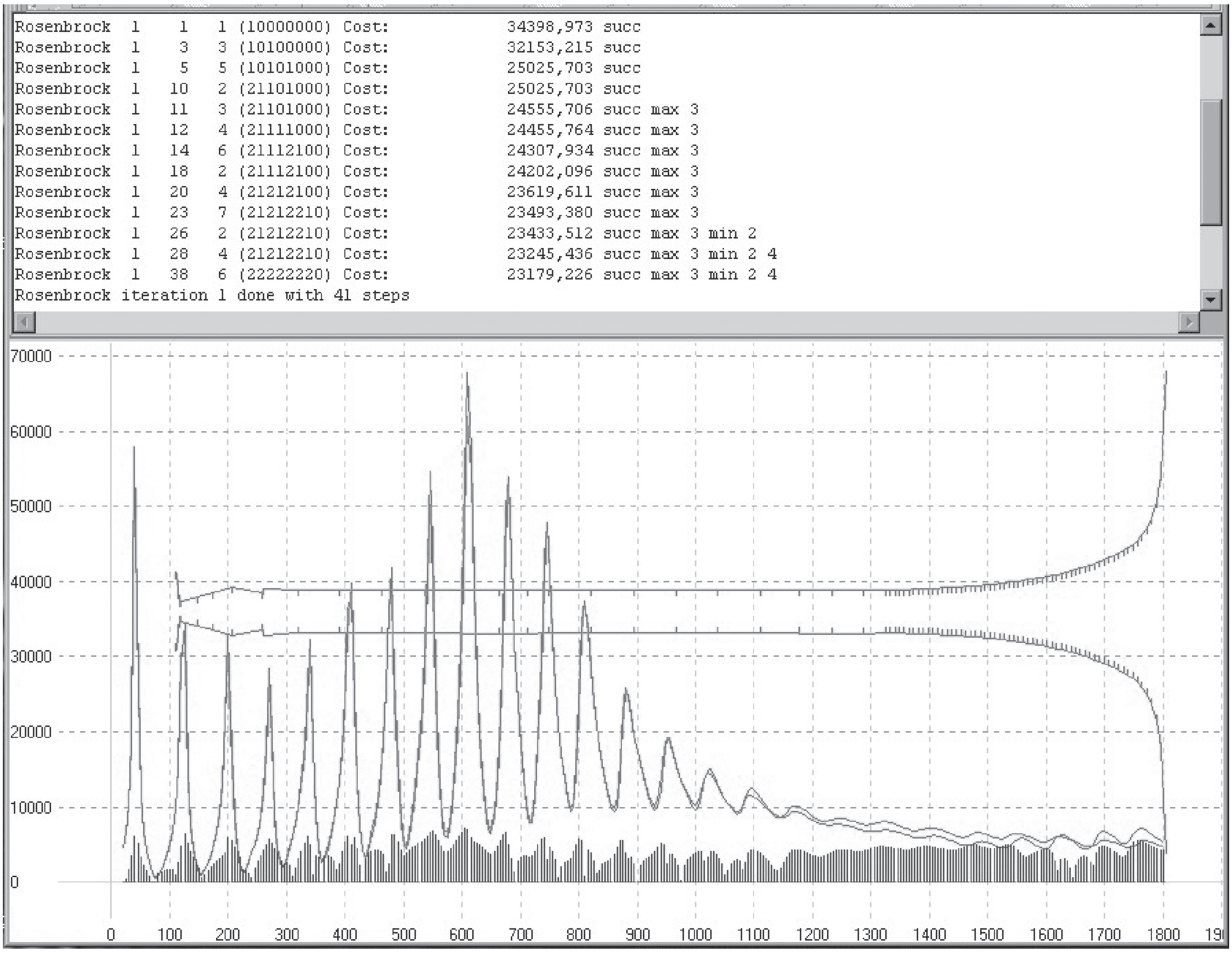
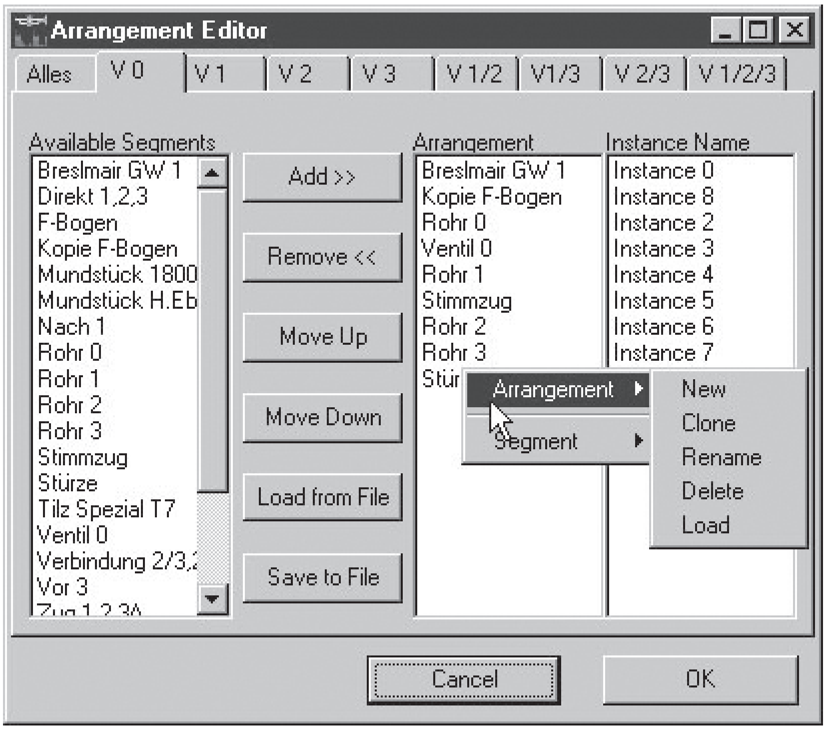


Fig. 7: Screenshot of the ‚Optimizer‘ during work. Upper part: Cost factors of the various parameters; lower part: plot of the shape, target impedance and weights for each frequency of the target impedance.



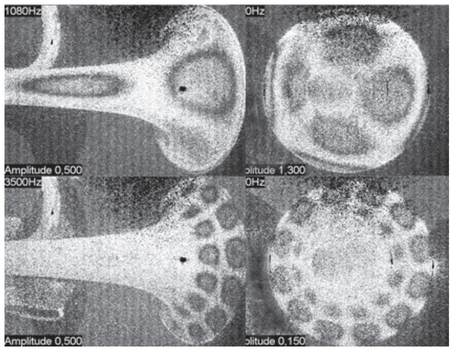


Fig. 9: Vibration of a baroque trumpet bell at 1080 and 3500 Hz (ESPI).

Fig. 8: Screenshot of the ‚Optimizer'. The arrangement editor allows the combination of various parts to get a complete instrument.

A never-ending controversial topic between acousticians and musicians is the fact that brass players have fixed ideas about the influence of the wall material (alloy) on the timbre and response of an instrument whereas acousticians tend to summarize their point of view by a sentence attributed to Richard Smith, a former trumpet virtuoso and now a well-lmown instrument maker in York, UK: ‚It's all in the bore'. The fact is that the pitch of a played note is defined by the length and shape of the tube. The response (how easy it is to produce the desired note) is mainly defined by the shape of the tube, the mouthpiece and the damping caused by the wall thickness. The timbre depends on the properties of the lips, the damping caused by the wall thickness and the texture of the inner surface. To clear up this subject, it is necessary to take a closer look at brass instruments.

Recent research supposes that it has to do not only with one vibrating system· (standing wave, air column inside the tube), but with three independent vibrating systems: the air column, the wall of the tube and the instrument as a whole (see Figure 9, 9a and Figure 10). The vibration of the wall at the pressure antinodes is a parasitic vibration and can cause damping effects on the air column under particular circumstances (Kausel et al. 20 I 0).

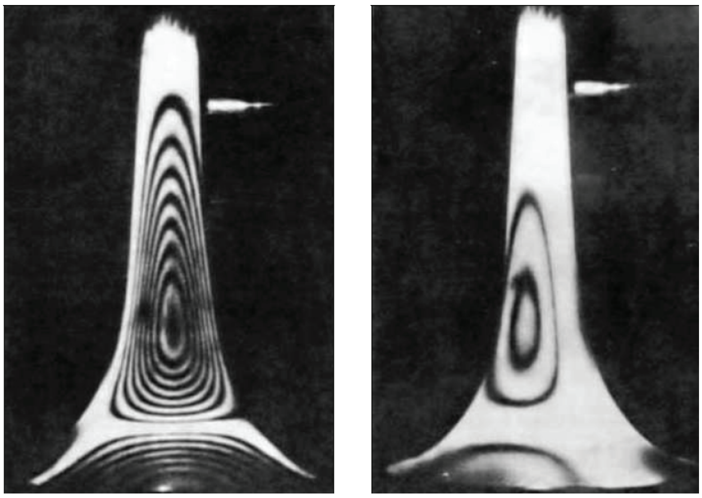


Fig. 9a: Dependence of the vibration amplitude of the bell section on the wall thickness.
Left: 0.3 mm
Right: 0.4 mm

Both are excited with a shaker using the same excitation signal.

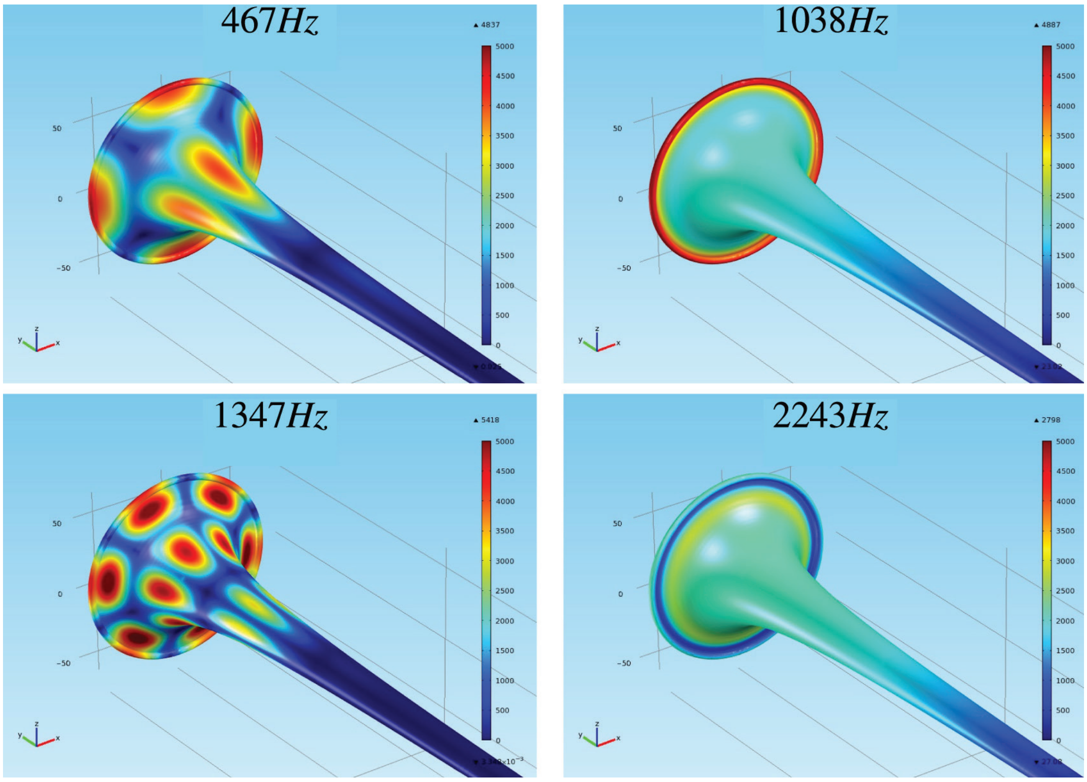


Fig. 10: Simulation of trumpet bell vibration. Left: radial modes; right: axial modes including longitudinal vibration.

As braces provide a fixed stiff connection between two parts of the tube, they can inhibit wall vibration if positioned at a pressure antinode. All these effects on the musical quality of brasses are the object of recent research work (Chatziioannou et al. 2012). The third vibrating system (see Figure 11) takes the instrument as a combination of various levers and also includes longitudinal/axial vibration caused and transferred to the instrument by the lips and teeth of the player.

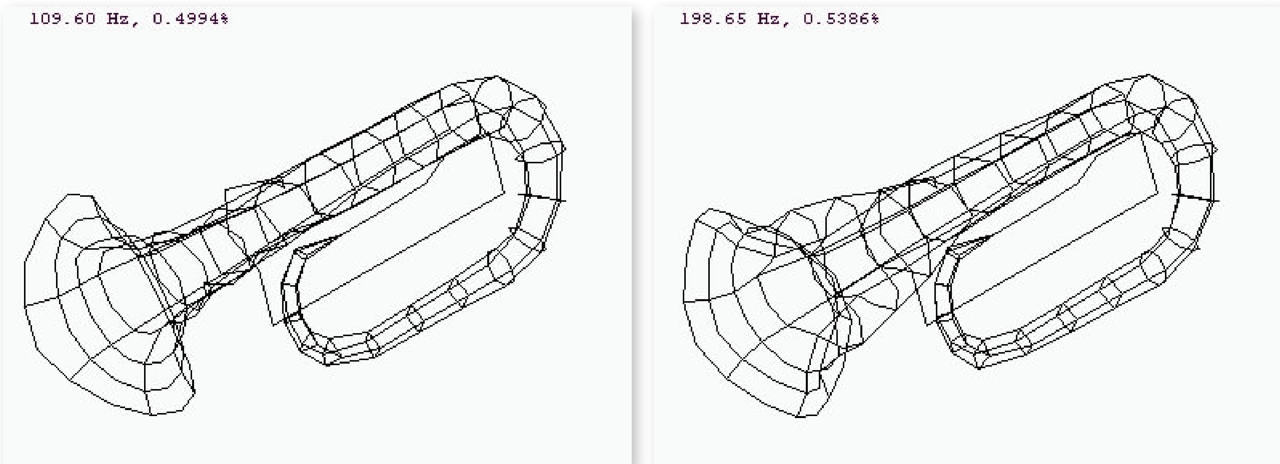


Fig. 11: Third vibrating system: the instrument as a combination of levers including longitudinal/axial vibration. The vibration frequencies of the instrument in its entirety are defined by the sizes of the instrument, its mass and the location of the braces and typically have no relation to the frequencies of the played notes. But if they (sometimes) match or interfere with resonance frequencies of the air column, they can cause reponse problems for particular notes. (Screenshots of a modal analysis movie made by Klaus Wogram).

Woodwind Instruments

Toe crucial factors in the case of woodwind instruments are the excitation mechanism and, to some extent, the properties of the tone holes. Arthur H. Benade‘s contributions in the 70s and 80s (Benade 1969, 1977, 1983) set the basis for today‘s research.

Special attention has recently been paid to the nature of the air jet of flutes/recorders and the behavior of single and double reeds (Chatziioannou et al. 2012, Kühnelt 2003). Simulations with 3- dimensional fluid-dynamic models using, for example, the Lattice Boltzmann Method give new insights into the aero dynamic phenomena of the air jet and brought up interesting results on losses due to vortex shedding and the influence of the edge shape and the mouth cavity on the sound.

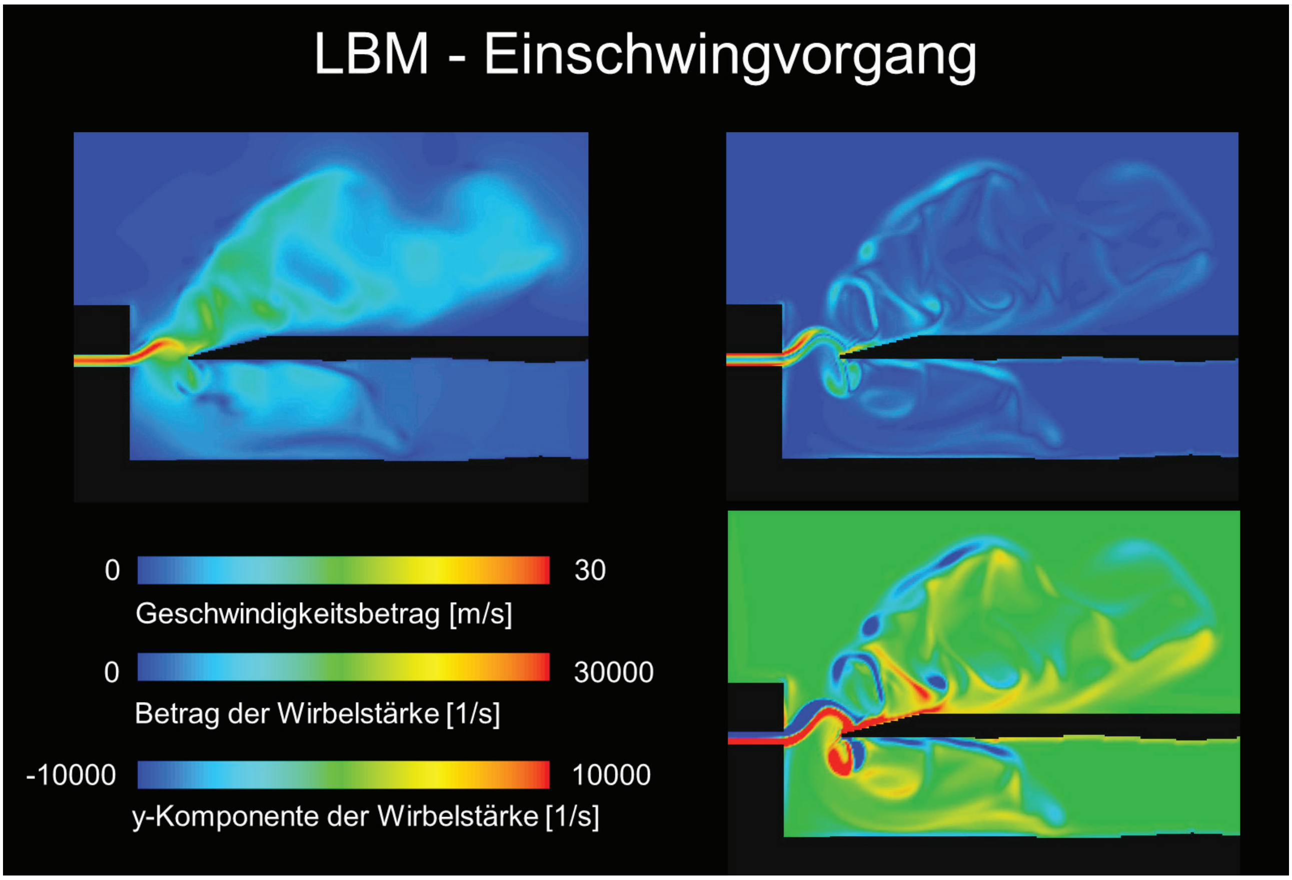


Fig. 12: Vortex sound power in a transverse flute. Simulation with Lattice Boltzman Method by Helmuth Kühnelt. Contribution of the velocity (top left), vorticity (top right) and y-component of the vorticity (at the bottom right).

Similar efforts can be observed in the investigation of the sound generation of single or double reed instruments. In these cases the problem is the anisotropic structure of the reeds. Various research teams have investigated the behavior and the suitability of reeds depending on the parameters density, humidity, stiffness, structure and shape (Dalmont et al. 2003, Guillemain 2004, Hofmann et al. 2012). Figure 13 (next page) shows the difference in playing range between various reeds, Figure 13 a the interaction between the players tongue and the reed.

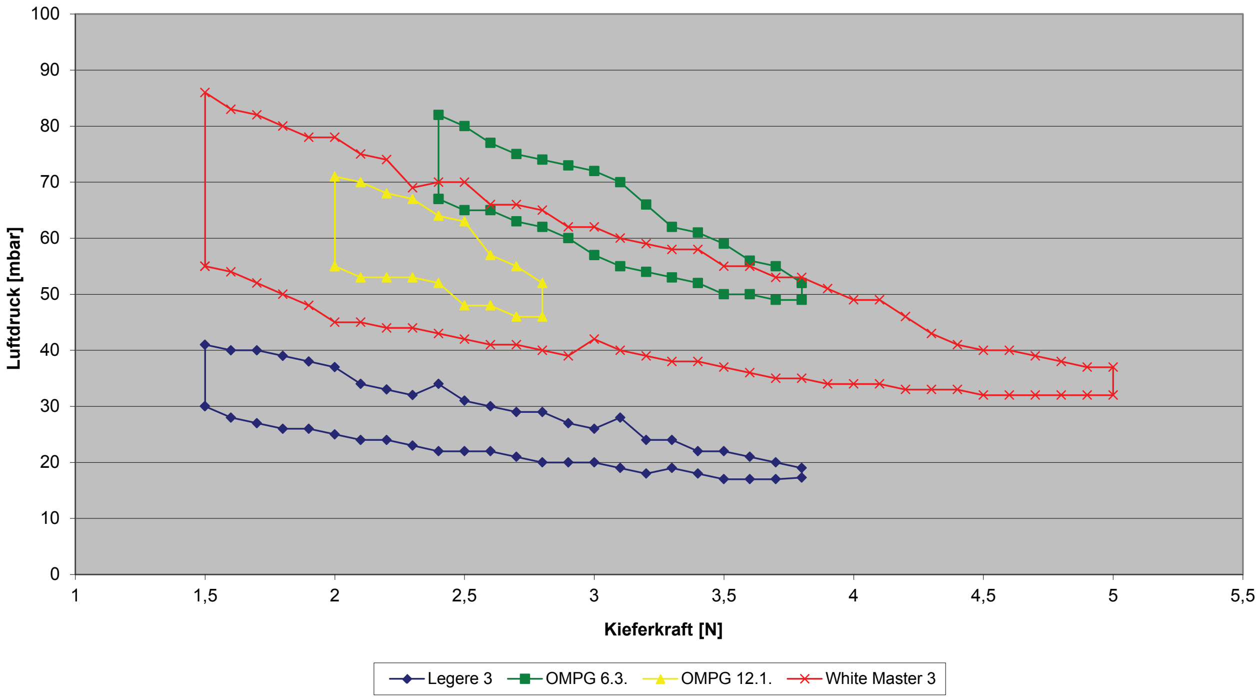


Fig. 13: Operating range of Arundo Donax and plastic reeds.

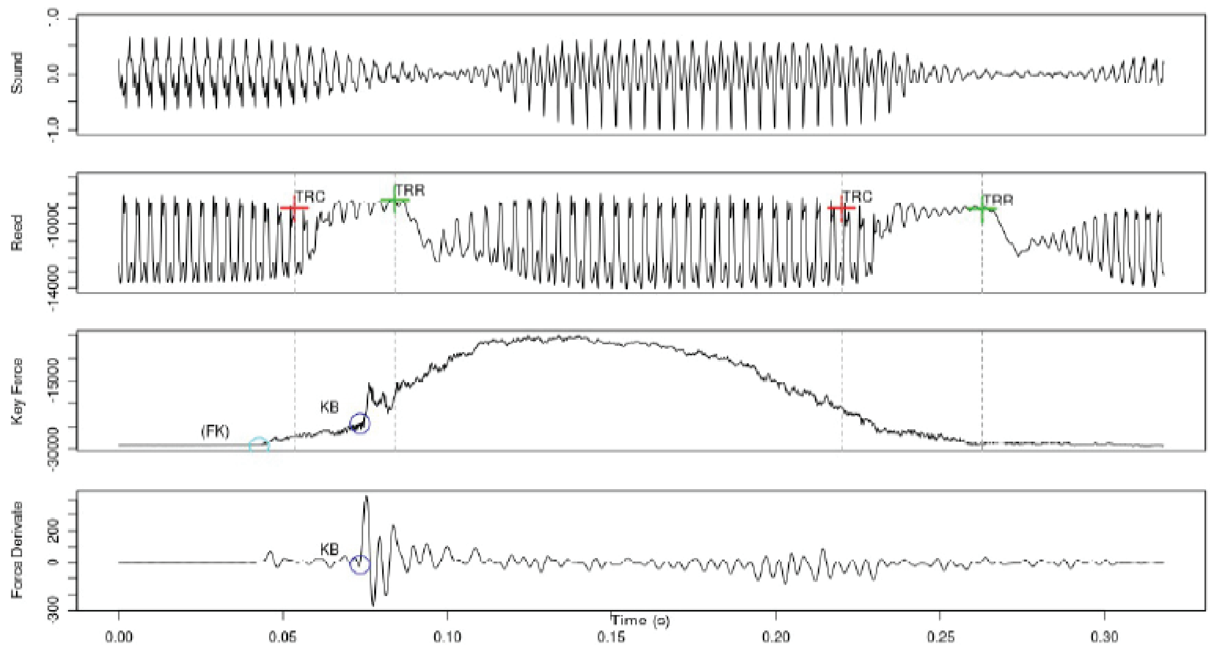


Fig. 13a: Recorded data for the tone „g3“: Audio signal from 1 m distance (top panel), sensor reed (middle panel) and key sensor and its derivate (bottom panel). Tongue-reed (TR) landmarks are indicated by a cross in the reed signal and key bottoms (KB) by circle in the force data.

Stringed Instruments

Musically-inclined scientists have often been fascinated by the famous Old Italian violins and have tried to unlock their reputed secrets. Felix Savart (1791-1841) disassembled such violins and investigated the vibration modes of top plates and back plates with the method of his friend Ernst Chladni. His findings about the relationship between the main modes of the top and back were interesting but not sufficient enough to explain the outstanding quality. Luthiers carried on with the ‚trial and error‘ method. A big step forward was made by Heinrich Dünnwald in the late 1960s by his Transferfunction method. Based only on the measured transfer function, he clearly could differentiate between Old Italian, luthier-made and industrially produced violins (see Figure 14). Almost the same information can be obtained by an admittance measurement where the instrument gets excited by a short impulse at one edge of the head of the bridge. The measurement sensor is mounted at the opposite edge of the bridge (see Figure 15 and Figure 16).

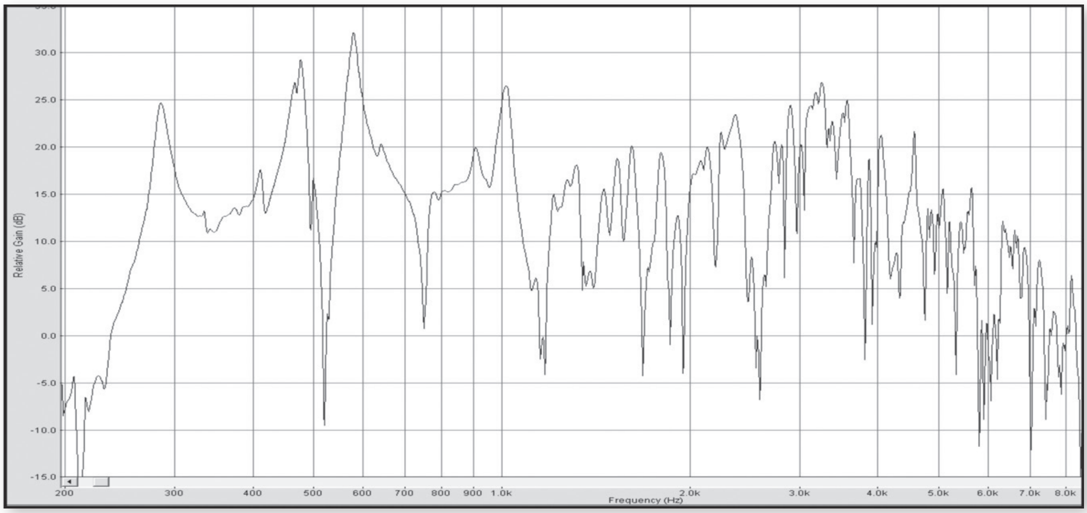


Fig. 14: Transfer function of a violin (Joseph Curtin, Luthier, 2009).

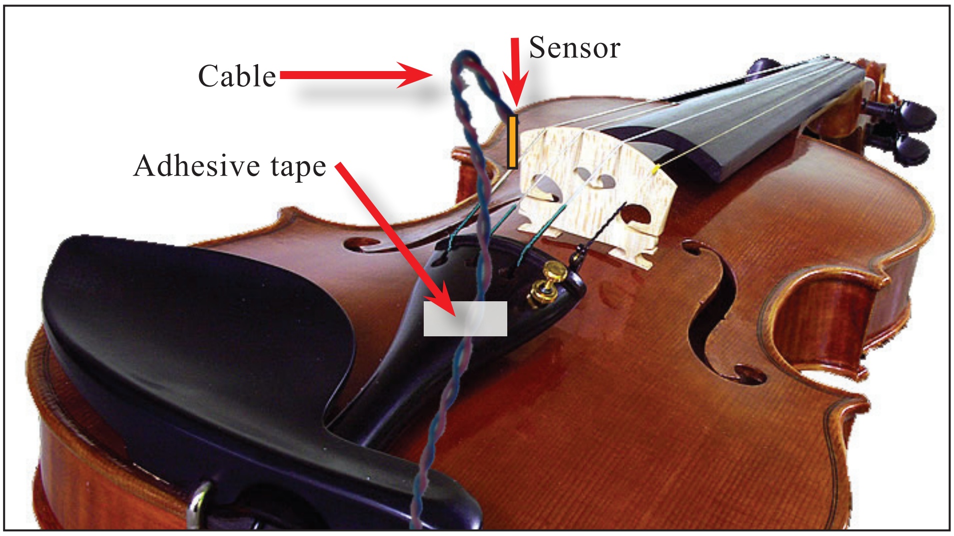


Fig. 15: Setup for an admittance measurement. The instrument gets excited at the right upper edge of the bridge by an impulse hammer. A sensor at the left side of the bridge records the reaction of the instrument.

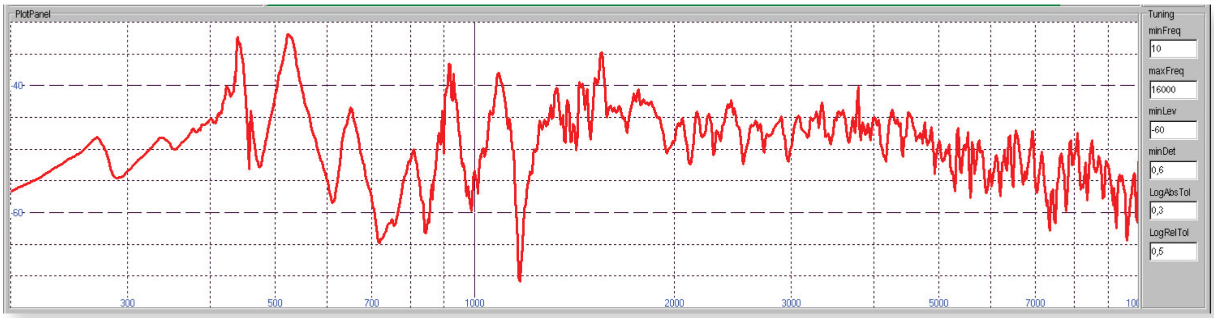


Fig. 16: Admittance curve of a Stradivari (Ex Benvenuti) violin.

Although a transfer function contains all information on the radiated sound of an instrument, it gives no information on the involved parts of the instrument. As string instruments (also pianos) consist of a multitude of parts which can influence the sound and response, a further method is required to clear up which part influences which of the radiated frequency.

The solutions are measurements by Laser Hologram Interferometry or Electronic Speckle Pattern Interferometry. Both methods show which parts of the instrwnent are involved, and how much. In the early 70s, E. Jansson et al. were the first to carry out this work (see Figure 17), and subsequently, Laser Holography, Interferometry or ESPI methods have commonly been used for all musical instruments, especially for pianos (Fig. 17a).

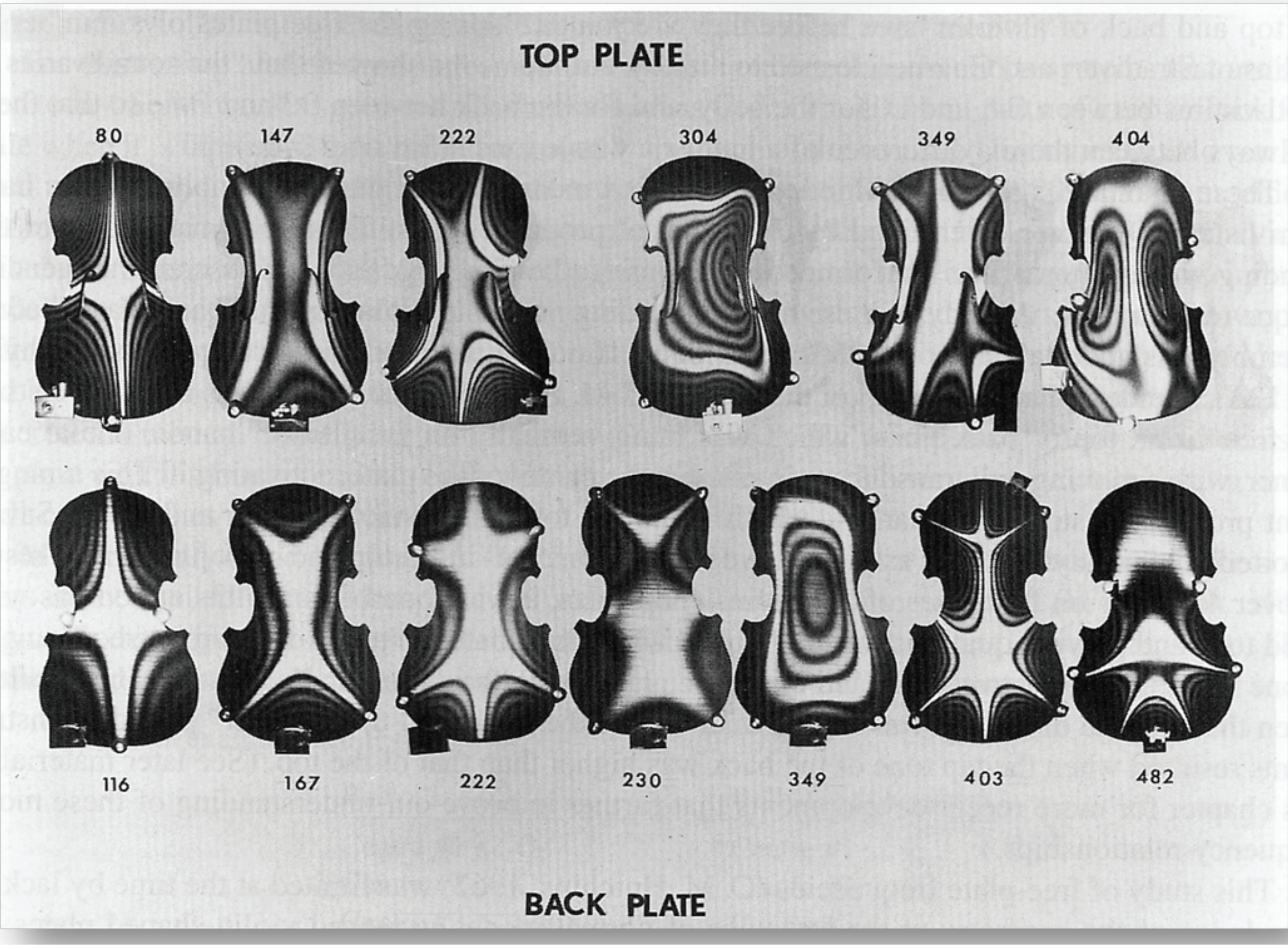


Fig. 17: Some vibration modes of a violin top and back plate by Erik Jansson et al. 1970.

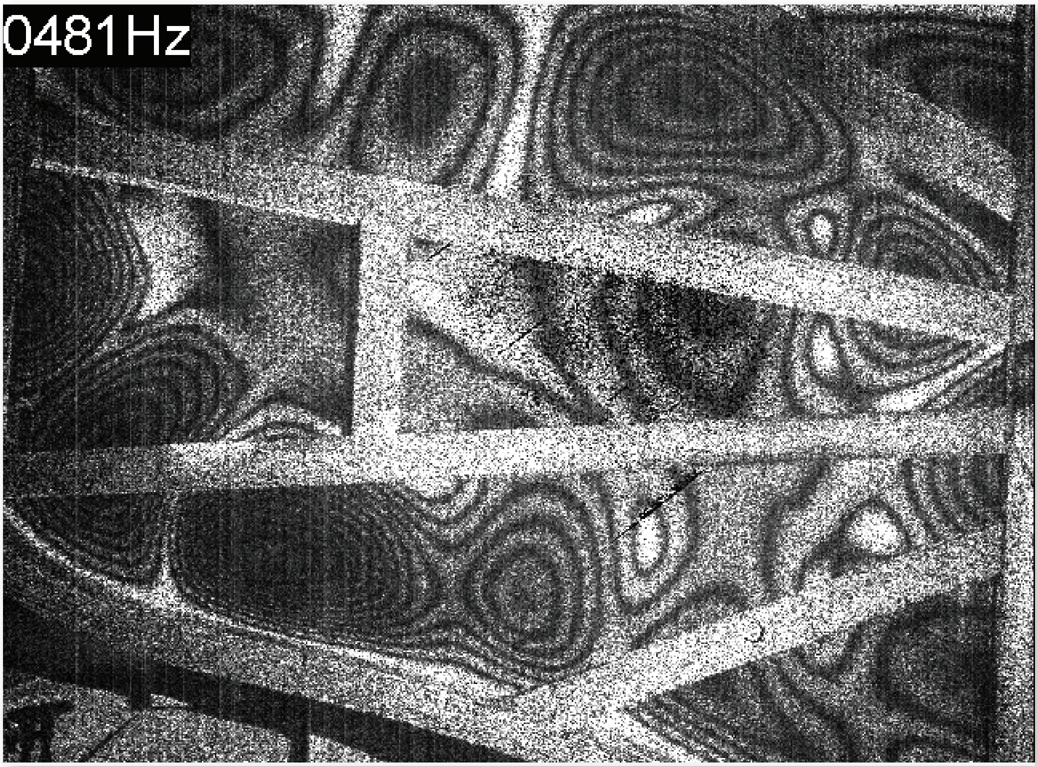


Fig. 17a: Screenshot of an ESPI analysis (movie) of the soundboard of a grand piano.

Significantly greater computing power now enables us to use the Finite Element Method for investigating or improving stringed instruments. The figure below shows an early example by Antoine Chaigne (2003) for an acoustic guitar body (see Figure 18).

Fig. 18: Screenshots from the top plate movement of a guitar. Finite Element Simulation by Antoine Chaigne.

Today‘s state of knowledge enables any interested instrwnent maker to produce top class instruments, provided that he is willing to forget traditional myths and is open-minded enough to use the tools of our times and not those of the 19th century. Monitoring the international musical instrument maker scene shows that brass wind instrument makers and companies with mass production tend to accept and use new findings (about 100 BIAS systems are in use worldwide), whilst luthiers seem to be immune to new knowledge and modem tools. An explanation could be that in case of the violin, the number of parts with an influence on the timbre and response is much higher than in the case of brass instruments. Contrary to wind instruments, at least two different measurement methods are required.

Physiological Acoustics

The human ear, as the most important interface between the player and his instrument, can confidently be named as the world's most perfect microphone - but sometimes it has a will of its own and for musicians, the answer to the question: ‚Can I trust my ears?' is: ‚Yes and No'!

For example, in some cases we hear sounds which do not exist, and conversely, existing sounds are not perceived. Additionally, the perception of pitch is influenced by the loudness, and the impression of the loudness of a musical sound is not based (as one would think) on the sound level, but primary on the timbre!

Our knowledge today about the function of the human ear is based on the investigations of the famed Georg von Bekesy (1899-1972) and was significantly deepened in the last ten years by industrial cochlear implant research (see Figure 19). Basic information on the function of the human ear can be found here: http://www.neuroreille.com/promenade/english/
and http://www.cochlea.eu/en.

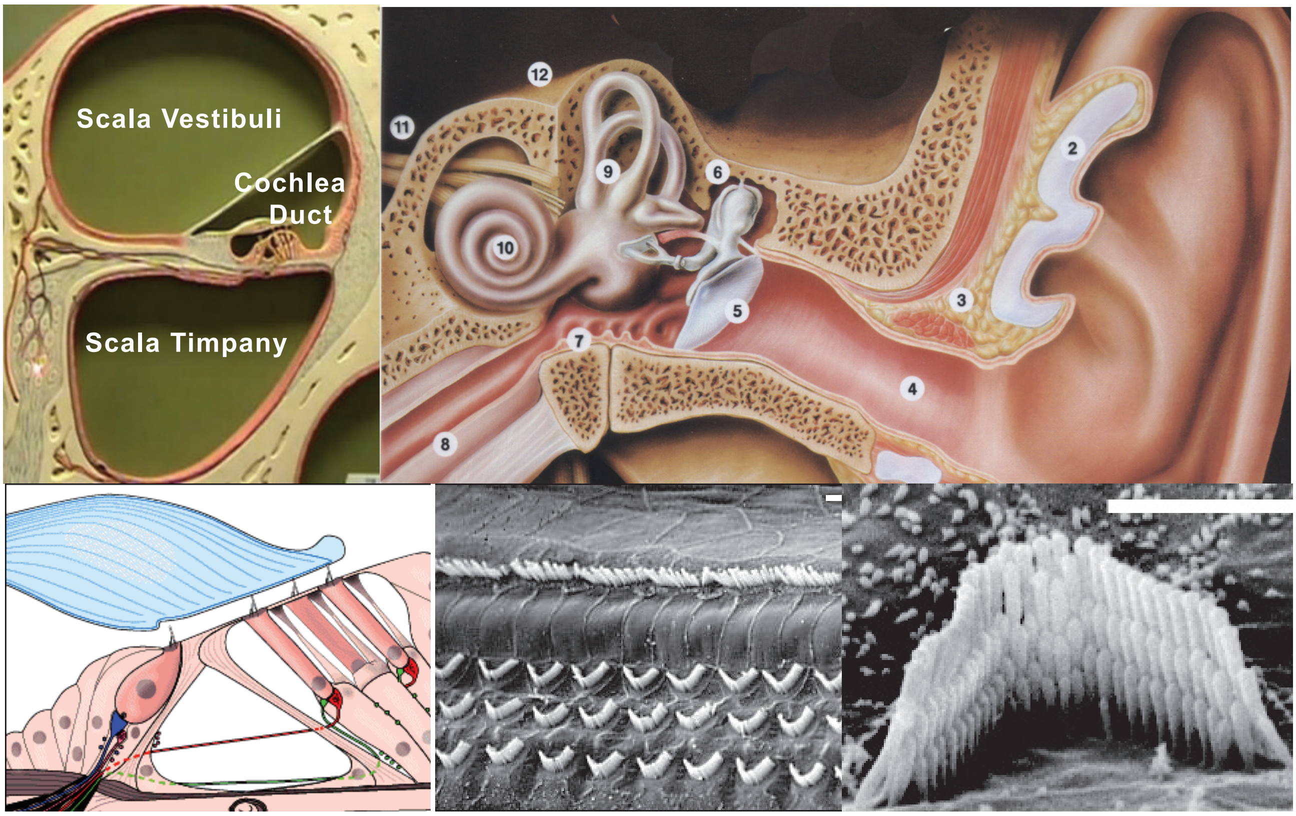


**Fig. 19: From left to right: upper part: cross section of the cochlea (left), the whole ear (right).
Lower part: Corti organ (left), outer and inner hair cells (middle), hairs of an outer hair cell (right).**

Psychoacoustics

Psychoacoustics is a sub-discipline of Psychophysics and investigates the relation between the perception of sounds and their acoustical properties. In other words: the relation between stimulus and sensation. As music exists only in our brain (before that, it is only patterns of various time-variant frequencies), psychoacoustics is an essential part of music acoustics and mainly deals with the data processing in our brains. On the journey from the cochlea to the brain, the digitally coded information passes various nodes consisting of a conglomeration of neurons (varying from -30,000-500,000 neurons) where various aspects are ‚preprocessed'; for example, the localization left-right-ahead at the Superior Olivary Complex. The first main stage in data processing is done by the Primary Auditory Cortex (~ 100 million neurons).

Although new discoveries are published nearly every month, more questions are still open than answered. Aside from some well-known hearing phenomena like ‚template matching' which results from efficiency reasons - the incoming neuronal patterns are not always analyzed but only compared to the stored templates in the cortex - we know that making music can cause significant changes in the brain.

Neuroplasticity

This phenomenon, well understood for ten years, occurs if one uses specific synapses many thousands of times, leading to the growth of new synapses and finally new neurons. For example, the brain region responsible for the movement of the fingers of the left hand of violin players is 1.5-3.0 ems larger than that of normal people. Additionally, all professional musicians have a significantly larger and better working Corpus Callosum (connects the left and right hemisphere). This is because playing music in a professional manner also involves the left (analytical) hemisphere, in contrast to laypersons where mainly the holistic right hemisphere is involved.

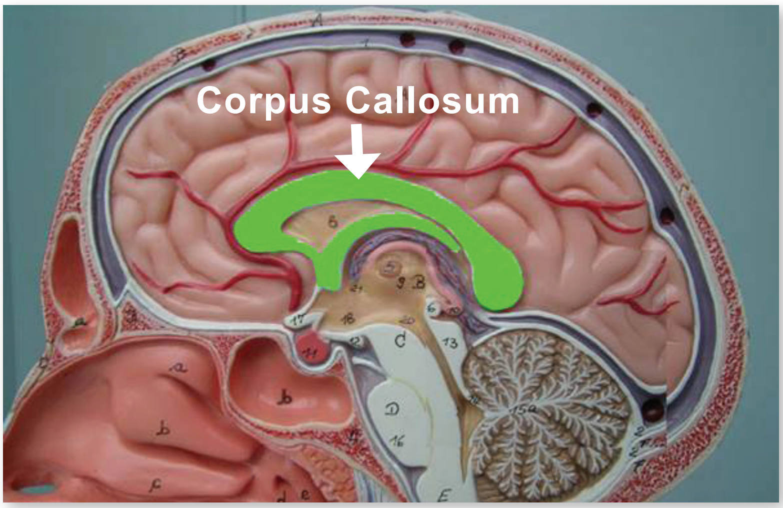


Fig. 20: An increased Corpus Callosum in the brain of professional musicians provides a significantly better crosslinking.

	Musician	Non-Musician
Male	12.2%	8.5%
Female	11.8%	7.2 %

Table 1. Percentage of left handed persons.

An interesting phenomenon where no satisfactory explanation has existed until now is the relationship between a low laterality and an increased ‚left handedness'.

Performance Science

Performance science is the latest discipline and started officially in 2007 with its first international congress in Porto (Portugal). As well as acoustical aspects it also covered medical topics like musicians‘ health and typical musicians‘ diseases (all sorts of focal dystonia, stage fright, and problems with the musculoskeletal system) as well as applied performance psychology and physiology.

It should be mentioned that research projects in Performance Science mostly require an increased expenditure for measurement equipment, because measured data using many diverse sensors have to be set into relationship and synchronized. In my presentation, I will discuss research results which predominantly outline acoustical aspects.

The following movie screenshots (see Figure 21 and Figure 22) are an example of realtime capturing of all of the parameters of violin playing as they are: involved string(s), bow position, bow angle, bow velocity and bow pressure as well as the movement of the shoulders, head, upper arm and forearm, wrist and position of the fingers. Such investigations require specific sensors and the application of a motion capture system. Besides the gain of new scientific insights, the application of such methods can be very useful in cases where a teacher can hardly explicitly identify the technical problems of students. Such a research project with violin players was done for the first time at McGill University (Canada) and at the KTH (Schoonderwaldt 2010).

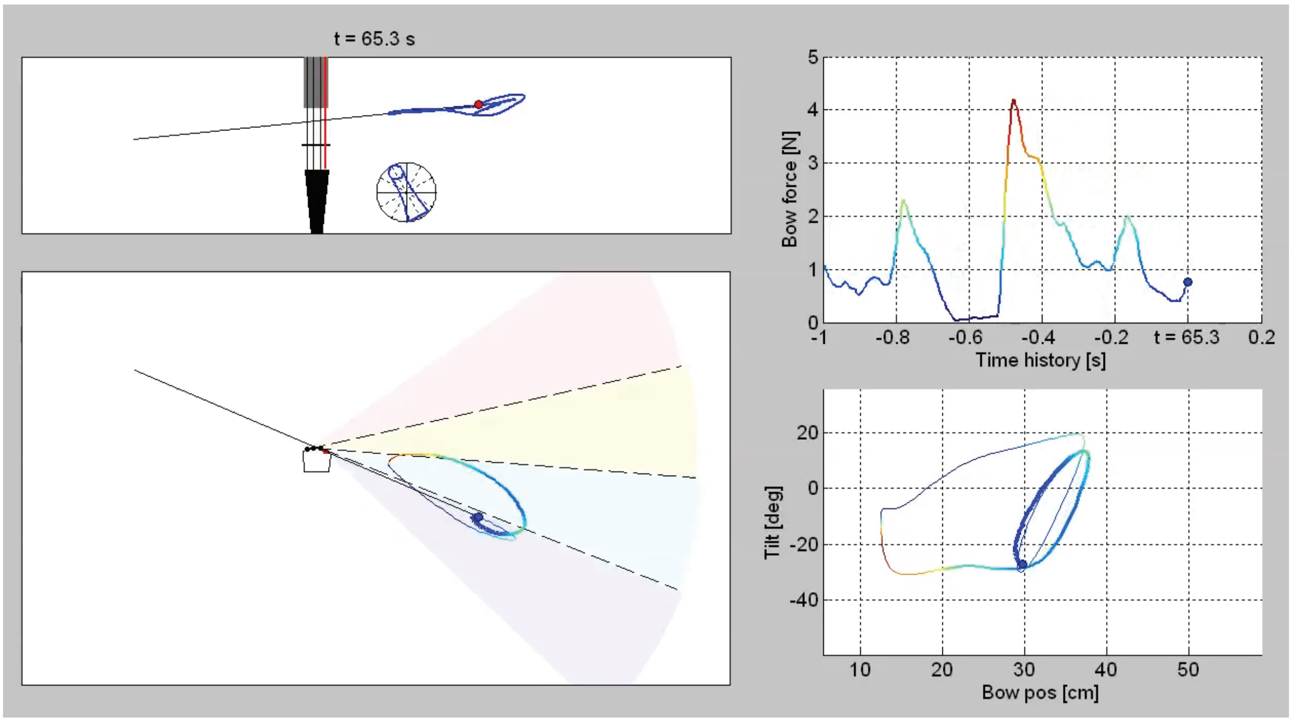


Fig. 21: Violin playing parameter (screenshot). Upper left: used string, bow angle at string contact point, bow position and angle in the horizontal plain; lower left: bow angle in the vertical plain; upper right: bow force in Newton versus time; lower right: bow position versus tilt.

Similar investigations concerning the piano playing took place in Montreal and Vienna (Goebl et al. 2009 and 2010), between 2006 and 2012. The main questions were: How do movement patterns change with performance rate? What are the consequences of different types of touch e.g. ‚struck‘ (from above) or ‚pressed‘ (finger resting at the surface)?

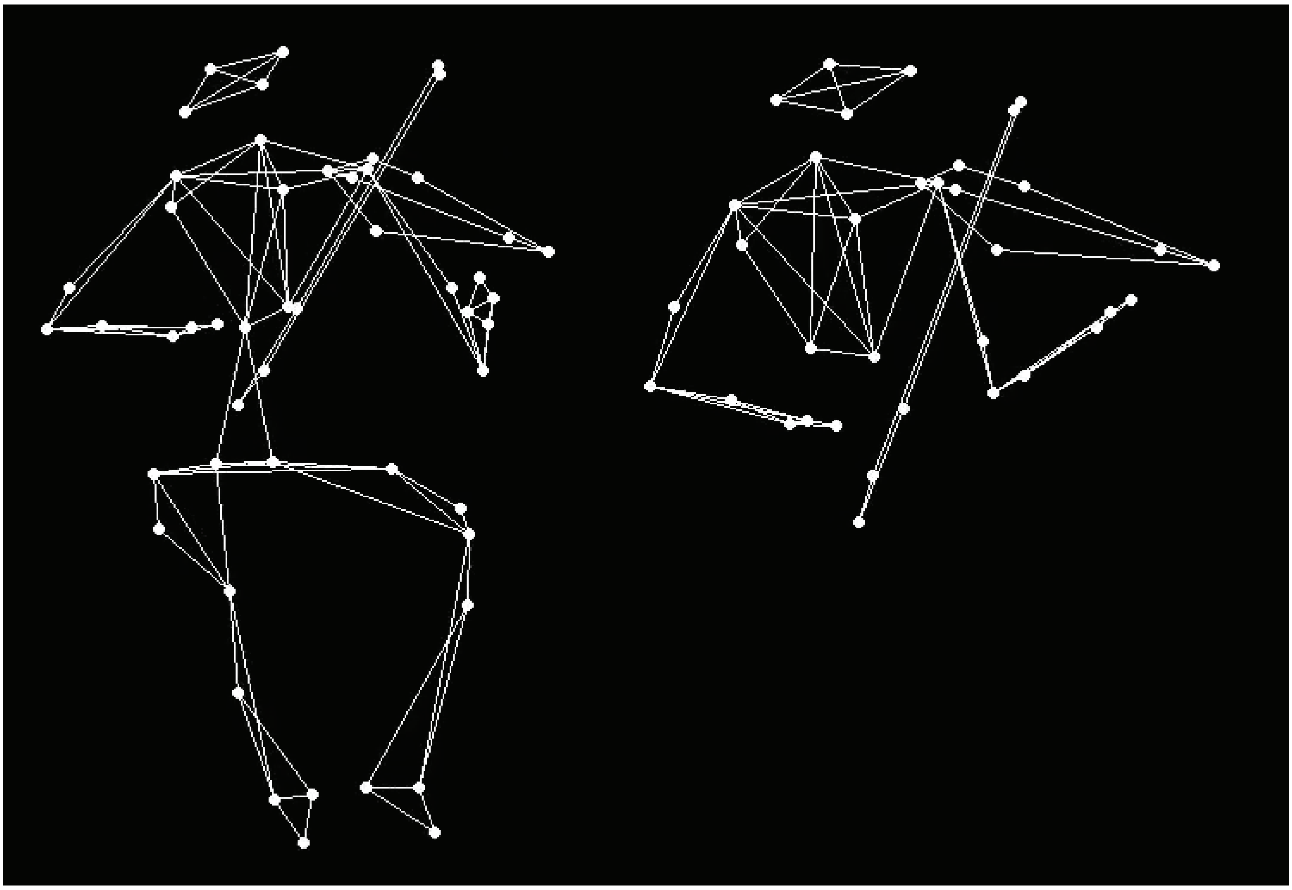


Fig. 22: Sensor arrangement of the motion capture system for violin playing.

Another focus can be the analysis of individual stylistic aspects of famous pianists and the comparison with other top international players (Goebl et al. 2009, Grachten et al. 2009) (see Figure 23 and Figure 24).

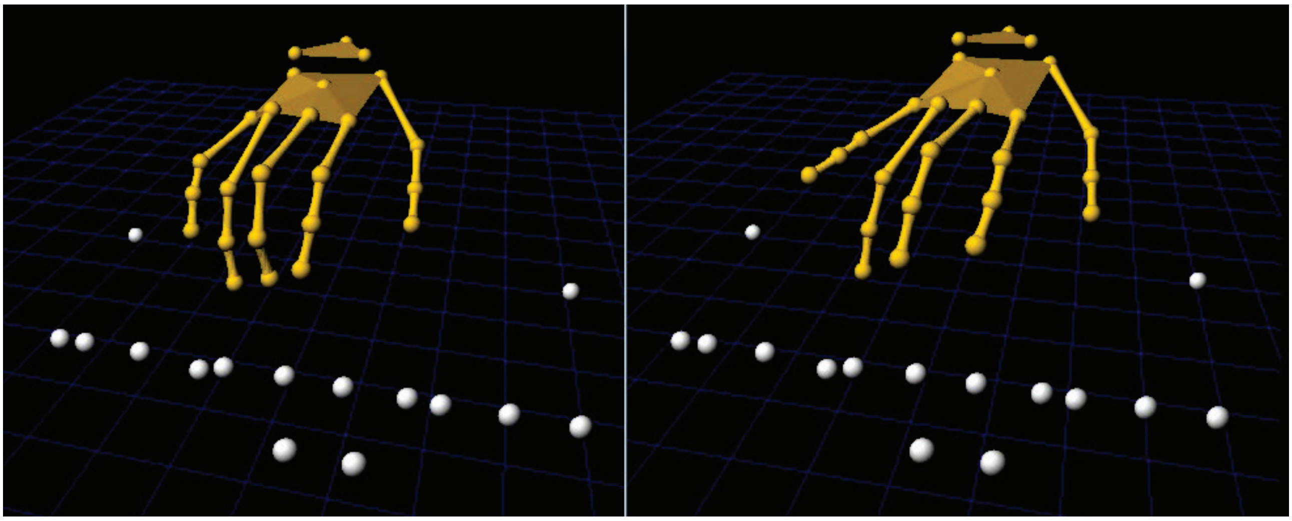


Fig. 23: Different types of touch. Left: pressed; right: struck.

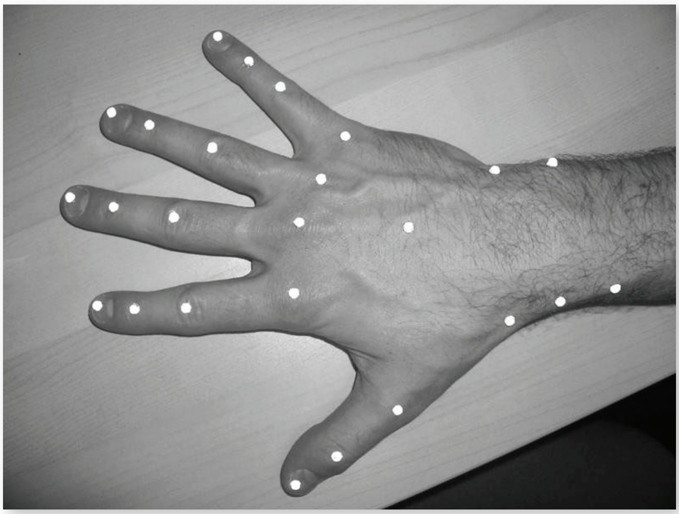


Fig. 24: Arrangement of the sensors for piano playing measurements.

Conclusion

Music Acoustics is a highly inter-disciplinary science. Depending on the object of research, its main focus can be physics, mathematics, physiology, psychology, neuroscience, brain research or even medical sciences.

Its target audience is accordingly diverse: it varies from scientists, musicians and teachers to health professionals.

The reasons for its relatively late establishment as an independent field of science were:

• the lack of adequate technical equipment
• insufficient computing power and
• too few people who understand both the language of scientists and artists

To achieve practice-oriented results, Music Acoustics often uses methods from other sciences and/or even depends on these results. Due to the fact that the objects under investigation are mostly new and unusual, it requires in the majority of cases new, unorthodox and often trans-disciplinary methods. Working in the field of Music Acoustics means to be highly communicative by nature. A side effect of that is the creation of many newly developed, particular and sophisticated software tools free for researchers of other sciences via open source libraries.

The growing interest in cooperation on the part of musicians is evident, whilst the behaviour of instrument makers is ambivalent: the majority of wind instrument makers are interested in new lmowledge and the use of modern tools, whilst luthiers react to the offer of music acousticians in general with anxiety and deprecation. There are two exceptions worldwide: the luthiers Martin Schleske (Germany) who studied physics, and Joseph Curtin (USA). They have done a lot of research themselves and use the methods described in this paper for their work with great worldwide success.

A survey of the entire area of research shows that Musical Instrument Research is the most advanced sub-discipline already producing commercial tools, as far as instrument customizing and cloning tools is concerned. Physiological Acoustics has been advanced by cochlear implant and hearing aid research while Psychoacoustics, depending on the success of brain research and caused by an extremely high level of complexity, has the greatest number of open questions. Performance Science is the ‚baby' of the sub-disciplines and is characterized by rapid progress.

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European Acoustics Association, TC Musical Acoustics, Work- group 2. http://www.eaa-fenestra.org/technical committees/ma/ workgroups/wg2/public/art

http://www.schleske.de/en/our-research.html
This website offers a complete bundle of lectures on all aspects of violin acoustics and instrument making.