Musical Acoustics - Topics and Aims
(„Was ist und zu welchem Ende studiert man Musikalische Akustik")

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Introduction

If the old Greek philosopher Aristoteles once said: The beginning of all science is the surprise, that things are as they are", this seems to be true particularly for musical acoustics. It is not only the fact that musical instruments work with a high degree of nuances, even if they had been developed empirically without any knowledge of their physical function. There are also the aesthetic aspects like the ranking of quality. Just this interaction between physical processes and the human sensation affects the particular appeal of musical acoustics – a research field that is comprised of much more than only the physics of musical instruments. However during his research, the author often has been asked "Why or for whom are you doing that?" That might be reason enough to comprehend the topics and aims of musical acoustics. And it might be allowed to express the title in German according to Friedrich Schiller's inauguration lecture at the University of Jena "Was ist und zu welchem Ende studiert man musikalische Akustik?" Schiller has spoken about the interdisciplinary aspects of history, and interdisciplinary aspects of musical acoustics shall be the focal point of this paper.

Historic Overview

Looking on the history of music-related acoustics, it is interesting to see, that in different epochs, people had different points of view for research and application (Meyer, 1987). It is unavoidable to start with Pythagoras, the more as we just have an anniversary: He died in 496 BC, exactly 2500 years ago. It corresponded to the mentality and the view of life that the old Greeks attached great importance to harmony. Basing on the common idea that there exists a connection between natural harmony and simple ratios of numbers, among others Pythagoras made experiments with strings and came to the well known result, that simple ratios between sections of a string lead to harmonic intervals.

From the classical antiquity, one can move directly to the renaissance time, as in the Middle Ages, there doesn't exist a scientific interest in music. Only the spirit of the renaissance reminded the people the heritage of the old Greek and Roman culture and revived the interest in natural processes. Thus it corresponds with the view of the world during the 16th and 17th century, that acoustic studies are intended to describe the generation of sound and the listening to music as exactly as possible , but only qualitatively by using visible and audible effects. Scientific questions have been oriented only to practical problems. Like this already Leonardo da Vinci (1452 – 1519) made several proposals for improving musical instruments, for example for tunable timpany. And certainly, it is no accident that two of the well known scientists of the 17th century have been sons of musicians, namely Galileo Galilei (1564 – 1642) and Christiaan Huygens (1629 – 1695).

To the essential results of acoustic studies during this period belonged the findings that pitch depends on the frequency of vibrations – even if frequency could not be measured – , that musical intervals depend on frequency ratios and that overtones affect the timbre – a knowledge which lead to the invention of overtone stops in organs. In particular, it might be mentioned, that Marin Mersenne (1599 – 1648) discovered the dependence of string resonances on tension and diameter of the string. And Isaac Newton (1643 – 1727) detected that the length of an open organ pipe equals a half wave length of the radiated sound.

After this period of experimental search for practically oriented results, during the 18th century follows on an epoch of mainly theoretical research with less or even no relation to musical reality. Based on the differential and integral equation systems that mainly have been developed by Gottfried Wilhelm Leipnitz (1646 – 1731), the interest was focused to questions like the calculation of the eigenfrequencies of vibrating structures. Musical instruments mainly have been used as appealing subjects for demonstrating the laws of physics and there haven't been any consequences on musical instrument making.

As some important examples of this research might be mentioned, that Brook Taylor (1685 – 1731) derived the formula for the eigenfrequencies of string vibrations, Leonard Euler (1707 - 1783 developed - among others - the differential equation for vibrating membranes and bares, considering different kinds of edge clamping. Joseph Louis Lagrange (1736 – 1812) derived the wave equation for horns with any cross section. One of few scientists, who combined theoretical and experimental studies at that time, was Daniel Bernoulli (1700 – 1782) – by the way, he had musical experiences too - . He explained complex vibration processes as superimposition of several vibration modi and described them by the so-called motion equation.

This mathematical kind of considering vibration problems required essential simplifications of the boundary conditions and drifted apart from the reality of musical instruments. It allowed the description of the vibration behaviour of simple structures in principle, but lead to a renunciation of all details that affect the musical appeal. Therefore it doesn't surprise that about the end of the 18th century, another phase of experimental research was entered. It included extensive attempts of quantitative descriptions of sound and vibration. At the begin of this epoch, the experiments of Ernst Friedrich Chladni (1756 – 1827) should be mentioned, who showed the vibrating patterns of plates; as well known, he excited the plates by a violin bow and made the knot lines visible by sand. And it may be characteristic for the varied view of the world that his demonstrations inspired not only the physicists, but proved very popular in scientific evening circles; and even in the ladies' saloons, these performances physical brought him great success. By the way, Chladni patterns are used by violin makers for tuning the plates even in our times.

An important mile stone in the development of acoustic measure techniques was the determination of the frequency as an absolute number of oscillations per second, as in earlier times, it was only possible to evaluate intervals (as frequency ratios) or beats (as frequency differences). It was Thomas Johann Seebeck (1770 – 1831) , who reduced the higher numbers of oscillations to lower rotation numbers that are easier to be determined – by using sirens and cogwheel transmissions.

In 1858, Jules Antoine Lissajous (1822 – 1880), who is well known by his oscillation figures, investigated the tuning forks used in 24 European orchestras (Leipp, 1976). The background for this comparison was the ascending tendency of the "standard pitch" during the preceding hundred years. He got an interesting result: only 4 forks had a frequency below 440 Hz, most orchestras tuned between 440 Hz and 450 Hz and one exception was found with 455 Hz. Please remember, that for frequencies about 440 Hz, an interval of 4 cent equals a frequency difference of 1 Hz. In order to stop the ascending tendency, the commission decided on a standard frequency of 435 Hz (the lowest that was found). But with very small success: most orchestras continued with their traditional tuning, and even today, most orchestras tune on a basis of 442 or 443 Hz.

The most important scientist of the 19th century who worked in the field of acoustics was undoubtedly Hermann von Helmholtz (1821 – 1894). He was not only a physicist, but also a physician, and – by the way – he was a friend of the famous violinist Joseph Joachim, to whom Brahms dedicated his violin concerto. Therefore it isn't surprising, that his research was not only focused on physical questions like the motion of the bowed string or the overtone structure of sounds, but included also perceptive aspects. In 1852, he held his inauguration lecture at the Königsberg University "on the nature of human sensation". And in 1863 appeared the 1st edition of his well known book on the sensation of sound, followed by four new editions during the 19th century. So he can be called "the father of psychoacoustics". Moreover being the 1st president of the Physikalisch-Technische Reichsanstalt, he executed - as first official calibration service - the frequency determination of a tuning fork. That might be seen as the begin of musical acoustics research in this institution.

After Helmholtz, the most essential event was the invention of the microphone. It opened the wide field of sound analysis by electronic means. From this basis, a variety of possibilities for interdisciplinary research and applications of musical acoustics developed during the 20th century and the contemporary state of these connections shall be the content of the second part of this paper.

Acoustics of Musical Instruments

Naturally, the physics of musical instruments including the singing voice has to be the centre of attention when speaking on musical acoustics. For after the research done during the last century, there exists now an extensive knowledge of the physical processes of sound generation as well as of sound radiation (Fletcher and Rossing, 1991, Sundberg, 1987, Meyer 1999). Even these days, the physical processes play an important role in the education of physicists as the different kinds of the excitation of vibrations as well as of the resonance systems are clear and impressive examples for processes as they are to found everywhere in acoustics. That includes still experimental and theoretical considerations, the latter based on much better known boundary conditions than in earlier times. On the other hand naturally the instrument makers benefit from the modern state of science. And even musicians can learn something about the interaction of their playing technique with the sound production. I will go into some details later.

The teaching of pure physics can be completed by aspects of sound radiation. But the main interest in sound radiation is to be found in adjacent areas of acoustics like psychoacoustics or sound engineering as well as with persons who don't belong to the close section of acousticians but need the results for their profession like architects and musicians. In this connections, four aspects of the radiated sound have to be presented:
The spectral structure of sound, i. e. the number and strength of overtones that lead to the impression of timbre,
The temporal fine structure of sounds, particular the tone onsets, that form the tonal character even more than the steady state spectrum,
The radiated sound power and its spectral distribution and last not least
The directivity, i. e. the dependence of the radiated sound level on the direction.
Also about this, I will go into some details later.

Using terms like "tonal impression" or "character", we leave the field of pure physics by including the human peculiarities of sound sensation. We enter the area of psychoacoustics and one can say that nowadays musical acoustics cannot be managed without research in the field of hearing sensation. For example, that concerns aesthetic aspects of musical sounds: Which details make a sound beautiful and pleasant or - on the other side - unpleasant? Which components are typical for high-quality instruments? Such questions only can be answered by listening tests and subjective comparisons. And in this connection, the masking effect plays an important role: Which components are audible when a single instrument plays or when it is integrated in a larger ensemble – playing in a concert hall or church?

Moreover, psychoacoustics are asked for determining the thresholds of distinguishibility for quantities like pitch, loudness and timbre or reverberation time and early sound reflections in rooms. All these quantities can be measured much more exactly than they can be distinguished by listening. Therefore in many cases, the question arises which degree of accuracy is sensible or necessary for practical applications.

Talking about aesthetic aspects of sound, leads to the instrument makers' sphere of interest. For ages, the instrument makers tried hard to build instruments of high quality due to the playability as well as to the sound quality. Therefore, finding quality criteria is as important as developing measuring methods for the evaluation of the quality. Particularly with the more or less industrial production of musical instruments, it is necessary to use methods that are independent from individual and subjective judgements. Furthermore, the modern instruments makers expect specific advice for the construction of their instruments and for the possibility of detail variations that improve the quality – derived from a scientific basis of the way instruments work. The following three examples shall give an impression of such practical applications.

First, I would like to present two results from my former colleagues who worked in the Laboratory for musical acoustics in the PTB in Braunschweig. For testing drums, modal analysis is a well suitable method to make the vibrations of drum and tripod visible. The problem, Ingolf Bork was confronted with by the instrument maker, was the following: played by one musician, the drum had a pleasant long decay, played by a different musician, the decay was unpleasantly short. This could be explained by a coupling effect between drum and tripod: In the main mode, both membranes vibrate in phase, i.e. in the same direction. As the centre of gravity of the whole drum has to be constant, the body of the drum vibrates in the opposite direction as the membranes. If the resonance frequency of the drum-tripod-system matches with the main membrane mode, vibration energy is transmitted by the feet to ground and withdrawn from the drum affecting a short decay. Only by shifting the drum a little on the side arm, the resonance frequency of tripod and drum can be varied so that it doesn't interact with the membrane vibrations. The result is a longer decay. It seems, that the different musicians had fixed the drum at different positions on the arm of the tripod (Bork, 1988).

The second example concerns the tuning of brass instruments. If a musician plays a tone on a brass instrument, the fundamental frequency of the blown tone isn't determined by only one resonance, but follows the condition that as many partials of the harmonic spectrum as possible match as well as possible with the – mostly not exact – harmonic resonances of the instrument. These resonances depend on the standing waves in the air column of the partly cylindrical, partly conical tube as well as on the impedances at the bell and at the players lips. For an individual trumpet, the deviation of the resonance frequencies from the correct values can be measured by an artificial blowing device. The main problem of finding the right way for corrections of these resonance frequencies is based on the fact that a shape correction done at one position influences all resonances but with different effects. For example, increasing the shape diameter close to a sound pressure maximum of the standing wave lowers the related resonance frequency, a diameter reduction increases the frequency. Close to a node, it is vice versa. Using extensive experience with numerical results of such corrections, Wogram developed a computer program for optimised corrections by combining shape variations at different positions – with the result that these instruments have a much more better intonation when blow by a player (Wogram, 1998).

As an example for developing new instruments, I would like to mention Carleen Hutchin's "New Violin Family" that consists of 8 instruments of different tonal range. The origin of this concept may be found in Michael Praetorius' "Syntagma Musicum", published about 1620, when he was orchestra chief at the Court of the Duke of Brunswick. He proposed a complete set of stringed instruments, the highest one tuned an octave higher than a normal violin; towards lower pitch, instruments follow tuned alternately a fifth and a fourth lower down to the "Bas-Geig". This system has been realised in the States during the second half of the 20th century, likewise with the highest one an octave above the violin and the lowest one tuned like a double bas. The construction of these new instruments follows some acoustic rules, for example the cavity resonance corresponds with the fundamental frequency of the second string, and the first corpus resonance corresponds with the third string, because investigations of famous old-Italian violins showed similar tuning of the body resonances (Hutchins, 1992).

Other fields of application can be found with architectural acoustics. For solving problems of sound insulation in some cases such as rooms for music rehearsals or individual practise, it is necessary to know the radiated sound power of the instruments. In particular cases it might be helpful to know even the spectral distribution of the radiated sound power. Since the sound power depends not only on the dynamics but also on pitch, it is difficult to combine the radiated power levels into one numerical value. Therefore we have measured averaged levels for fast played scales covering a compass of two octaves as well as individual levels for very soft and very loud tones. The dynamic range for scales is essentially smaller than that for individual tones, not least as both the lower and the upper limit of the playable dynamic range increase with pitch. Averaging once more, one can combine all results in a single value for an averaged *forte*: these sound power levels lie between 87 and 93 dB for the strings, 91 and 93 dB for the woodwinds and 101 and 104 dB for the brass instruments.

Room Acoustics and Musical Performance

For room acoustic design as well as for auralisation it is necessary to take the directivity of instruments and singing voice into account. The directivity plays a major role in the strength of the direct sound reaching the audience, but it is just as important for the strength of early lateral reflections that generate the space impression of orchestral sound. The space impression gives the audience the feeling of a broadening of the apparent source width and an increased tonal "volume", if the music becomes louder. It is a very important criterion for the quality of concert halls.

Undoubtedly, the most essential application of the directivity is to be found in the field of audio recording. The directivity is the basis for microphone positioning and thus for the quality of records. Furthermore sound engineers need the knowledge of the radiated sound power of whole ensembles for designing of sound reinforcement and loudspeaker systems.

Finally, the directivity should be considered also by the musicians, as it influences the sound impression of the audience. But there are other aspects of the application of musical acoustics for the musicians which I would like to talk about first. For players and their teachers, but even for composers, it is useful to know how and between which limits they might vary the different parameters of playing technique and how that influences the tonal character.

As an example, this might be explained with the violin. There exist three bowing parameters: bow velocity, bow force and distance between bow and bridge, the so-called point of contact.

For a steady sound, i.e. for a steady Helmholtz-motion of the string, by the bow force two limits should not be surpassed. Simplified one can say that the lower limit is determined by the condition that the energy losses effected by radiation and friction have to be compensated by the bowing energy. As these losses increase with increasing vibration amplitude and again this amplitude increases with declining bow-bridge-distance, the required bow force is the higher the closer the bowing point is to bridge. The upper limit is determined by the condition that in the moment when the string has to leave the bow and to move back, the friction force must not be stronger than the reversing force of the string. Once more there is an ascending tendency for bowing points closer to the bridge. Between these limits, the player can vary loudness and timbre. Outside these limits, the tone becomes rough or the fundamental is interrupted or even missing (Meyer, 1978).

A further parameter of violin playing is the vibrato. By moving his finger, the player primarily generates a frequency modulation. But because of its rather sharp resonances, the body of the violin adds an amplitude modulation too. Comparing the sound received by the player and by the audience, an essential difference can be detected. Close to the instrument, i.e. in the direct sound, a clear frequency modulation of the partials is to be seen, combined with an amplitude modulation. As the loudness of a amplitude-modulated tone (with typical vibrato frequencies of 5 to 7 Hz) is determined by the maximum amplitude of the temporal oscillation, for the player, the tone – if played with vibrato - becomes louder. For the audience, about 90 % of the sound energy arrive as reflections with different delay times. Thus, nearly no frequency modulation can be detected in the temporal fine structure of the spectrum: The listener hears at one moment what the instrument has radiated at different moments ago. Consequently, the loudness will be determined by the total (i.e. temporal-averaged) sound energy. Compared with a tone without vibrato, the tone doesn't become louder, but as the single partials are formed to frequency bands, the tone gets more "volume" (Meyer, 1992).

The awareness of the directivity is also important for conductors. Two aspects should be mentioned: the balance of the orchestral voices at the conductors point and the influence of the seating arrangement on the sound impression of the audience. As the latter topic very often has been explained and even demonstrated by the author, it shall be renounced in this paper. The sound pressure at the conductors point it determined more or less by the direct sound, i. e. by the radiated energy, the directivity, and particularly by the distance of the different instruments or instrument groups. On the other hand, one can assume that the loudness in the audience area is determined more or less only by the sound power. That leads to the effect that for example the conductor hears the front player of the violins (by some dB) louder than the oboe, whereas in the audience area, the same violin is (by some dB) softer than the oboe. That is important for finding the right dynamic balance for the audience.

Church Acoustics

Specific acoustic situations can occur in churches, especially in historic ones. As during the last years, the author's work was related mainly to this field, at the end of this paper, some aspects of the interaction of organ sound and room acoustics shall be discussed. With this, the considerations shall be focused on a church in which Johann Sebastian Bach played the organ in the years 1707 and 1708: the Gothic hall church Divi Blasii in Mühlhausen /Thuringia. Looking from a position just in front of the organ into the room, mainly the compound pillars are to be seen. Thus for listeners seated in the nave, the influence of the pillars on the sound impression is particularly remarkable.

As the pillars act as reflectors with limited size, high frequencies are reflected diffusely into the nave with the result that every listener receives sound reflections from each pillar, whereas low frequencies are diffracted around the pillars. According to Cremer (1953), the limiting frequency for total reflection is determined by Fresnel zones: The detour of the sound path via the border of the reflector shouldn't be longer than a quarter of wave length compared with the sound path via the centre of the reflector. That means the limiting frequency is the lower, the larger the reflector, the steeper the sound incidence onto the reflector, and the smaller the distance of sound source and receiver. In the actual case of the church in Mühlhausen, the limiting frequency lies about 1300 Hz related to a sound source on the organ gallery and listeners in the nave. Typical values for other Gothic churches vary between 1000 and 1500 Hz, mainly depending on the diameter of the pillars. Below this limiting frequency, the reflected energy is attenuated by 6 dB / oct. If the frequency is lower by a factor of 4.5 than the limiting frequency, 95 % of the energy is bent around the pillar, that means there is nearly total diffraction. Usually this occurs below about 250 to 300 Hz.

This leads to an interesting reflection pattern that is very important for the listeners' impression of the organ sound. The diffuse high frequency reflections coming from the pillars reach the listeners with very short delay times and from lateral directions. As the with of the nave mostly doesn't exceed 8 to 9 m, typical delay times for these reflections are shorter than 10 ms. In contrast, first low frequency reflections arrive much later: For a sound source located on the organ gallery, first low frequency reflections arrive via the vaulting with a delay time in the order of 20 ms - depending on the distance of the organ gallery to the vaulting - and even later via side walls.

Concerning the typical organ sound, it should be mentioned that the main components of the so-called mixed voices like "Mixtur" or "Cimbel" fall into the range of high frequency reflections as well as the articulation noise (the so-called speaking) of all flue pipes, even in the low stops. That enhances the brilliance of the tutti sound and the clarity of the tone onsets very much. On the other hand, the later reflections of low frequency components lead – often together with an increasing reverberation time towards low frequencies – to a prolongation of the initial tone development, that gives the sound something like "gravity" as Bach liked very much. Additionally, the low frequency components seem to be softer caused by such a temporal fine structure of the reflections as we have learned from the clouds in the first New York Philharmonic Hall (Meyer and Kuttruff, 1963). That means, in Gothic churches, the loudness of low frequency components is not as high as to be expected when considering only the radiated sound power and the reverberation time.

Furthermore, the intensity of the vaulting reflections depends strongly on the vaulting shape. Mostly, Gothic churches have so-called groined vaults. With many of them, the top line in length direction of the church is more or less a straight line. By such vaultings, reflections are distributed more or less consistently over the whole nave. But there exist also different shapes of vaultings – the so-called “cambered vaultings” – that rise from the key stone to all sides into higher archs before drawn down to the transverse arch. For the organ sound, this leads to the effect, that the vaulting reflections are concentrated to the first bays, and the rest of the audience area doesn’t get any first order vaulting reflections. Such vaultings are to be found mainly in the northern German brick churches like St. Jacobi in Hamburg with the famous Arp Schnitger organ. It is fascinating to listen to the clear change of sound when passing the second pillar (Meyer, 2003).

Conclusion

The sound of an organ is a typical example in which way the sound impression when listening to music might be explained as interaction of instrument acoustics, room acoustics and psycoacoustics. Not only for church music with its large number of historic rooms and instruments, but also for historic concert halls and opera houses, the row of examples could be continued in order to discus authentic performance conditions. But this should be enough to give the reader an insight into the great variety of subjects investigated by musical acoustics even if it wasn’t possible to go more into details. Thus, the author hopes that the reader has got an impression of the innovation resources included in this field of acoustics. And last not least maybe, the readers awareness has been inspired for the role that musical acoustics are able to play for the conservation of the European cultural heritage.

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