Introduction

Acoustics – the science of sound – is a very broad discipline. It has many links to other natural and human sciences and to electrical, mechanical and civil engineering. The glue of acoustics is "sound": Waves in fluid or elastic media, their generation, transmission, reception, cognition and evaluation. Acoustics thus involves aspects of physics, engineering and psychology. Ultrasound applied in physical acoustics, medical diagnosis or in material testing is an example where acoustics meets several other disciplines, such as solid-state physics and image processing for medical diagnosis or for material testing. Therefore it is in the nature of acoustics to deal with various methodologies. The physical side, of course, is best understood by applying linear and nonlinear wave theory in a straightforward way and especially in academic case studies where analytic calculations are possible. In engineering, more complex geometries or structures must often be considered and simplifications and approximations come into play, the limits of which are motivated from another area: psychoacoustics. Physical data are examined, evaluated and condensed to give meaningful information on the particular characteristics of acoustic impression perceived by humans. This description is indeed typical, although not generally applicable to all acoustical science.

The scientific methods used in acoustics are therefore based on mathematically well-grounded wave theory, on experimental methods and usage of high-standard instrumentation and analysis software. Today, theoretical analytical calculations are increasingly augmented by simulation tools. These tools are the result of tremendous progress in numerical mathematics. Either geometric methods, similar to those used in computer graphics, or wave-based methods similar to those applied in radar, microwave propagation or other electromagnetic waves for mobile communication, for instance, are used. Numerical methods of field problems also have great impact on scientific progress and innovation in engineering in mechanical engineering, heat conduction, flow dynamics and climate models.

Prediction of the acoustic behaviour of components or systems is called "modelling." Modelling acoustics is the everyday task of acoustic engineering. The areas of activity for acoustic engineers are extremely manifold. Accordingly, the methods and tools of acoustic engineering are, too,

Table 1. Examples of quantities for applied acoustics.

Problem	Quantity	Unit	Goal
Noise emission	L_w, directivity	dB, dB(A)	Noise limits for the source
Noise immission	L_{den}	dB(A)	Protection against noise (urban, traffic) at receiver
Sound insulation	D, TL, …	dB	Protection against excessive noise
Sound insulation	R, D, TL, …	dB	Protection against noise from neighbours
Auditorium acoustics	T, EDT, G, C_{80}, …	s, dB, …	"Good acoustics" for musical performances
Auditorium acoustics PA systems Communication systems	STI, AlCons	%	Speech intelligibility
Product Sound Quality	Loudness, roughness, tonality …	sone, asper, …	Acoustic comfort

very different in complexity and accuracy. One reason for this diversity is the necessity for a pragmatic approach to reduce the acoustical problem to a simple, one-dimensional scale of sound and noise levels expressed in global decibels which are linked to legal requirements, norms or other regulations of sound and noise effects. Another aspect might be the historical development of international standards[2] in acoustics, describing acoustics in relation to easily measurable quantities such as dB(A) levels, sound level differences, or any weighted level number of acoustic absorption, attenuation or insulation. Engineering models of acoustics are often described in standards, as listed in Table 1. They are related to real-world problems of daily life in which people are affected, entertained, informed or disturbed by acoustical phenomena.

If the acoustic behaviour of a component or a system is to be predicted by rather limited effort, we talk about "modelling." The result is a numerical quantity or a set of quantities. Numerical quantities, however, have a clearly limited descriptive meaning. Imagine you have to explain a painting to a person who does not see it. The verbal characterization will be based on descriptors such as size, colour, and brightness and maybe on

[2] International Standard Organization, ISO.

information about objects or resolution of details. A painting reproduced according to this verbal or numerical description will never be exactly such as the original. The reproduction will contain a lot of subjective interpretations, even if the descriptors are "objective parameters." How much easier and unambiguous would it be if we just looked at the painting instead of discussing its parameters! In acoustic problems, one might ask why we discuss numbers describing the character of sound instead of listening to the sound and evaluating its loudness, timbre, roughness, sharpness, character or quality directly.

If the behaviour of an acoustic object or system is described in a more complex way including the creation of acoustic signals in time or frequency domain, we talk about "simulation" and "auralization."

Auralization is the technique of creating audible sound files from numerical (simulated, measured, or synthesized) data.

Any sound, noise, music, or in general any signal generated, transmitted, radiated and perceived can more precisely be interpreted and compared by people if it is made audible instead of discussing "levels in frequency bands," "single number quantities" or "dB(A)."

Perception of sound signals has multiple dimensions, some of which are listed here: type of sound generation, direction of the event, movement of the source, listener movement, environment room (kind, shape and size). The auralization must cover all relevant cognitive aspects of the specific case.

An appropriately authentic model of the sound and vibration field is required to allow simulation of the psychoacoustically relevant features. Sound radiation models must therefore represent at least the correct sound propagation constant (distance law) and directivity. In complex coupled systems of sound and vibration, a further problem is the identification of relevant signal paths or vibration patterns, the degrees of freedom of motion in structural paths and the definition of interface line or planes between distributed velocity/pressure interaction effects or impedance coupling. In practice, the complexity of the vibroacoustic problem might be very challenging, maybe too challenging to be solved on the basis of tools and algorithms presented in this book. But even then the concept of auralization can be a valuable source of information and motivation for acoustic engineering. New numerical methods and new techniques of measurement and testing may be developed in the future, new materials and new constructions invented. Information on sound signals and sound transmission data of new sources and new materials can still be expected to be available. Hence the methodology to construct digital filters on the basis of computer data will be of interest in any case. The core of this book is accordingly formed by Chaps. 7, "Signal processing for auralization," 8, "Characterization of sources," and 9, "Convolution of sound sysnthesis."

Toward Virtual Reality

In the end, the goal is to achieve an auralization in real time, a dynamic interaction with the user, and the user's immersion and presence in the virtual scene. This most challenging auralization method arises when acoustics is integrated into the technology of "virtual reality." Virtual reality (VR) is an environment generated in the computer, which the user can operate and interact with in real time. One characteristic of VR is a three-dimensional and multimodal interface between computer and human. Besides vision and acoustics, more senses covering haptics (force feedback), tactiles and eventually others should be added. In several applications of science, engineering and entertainment CAD tools are well established. Visualization in CAD environments and VR is mostly the leading technology. Acoustics in VR (auralization, sonification) is not present to the same extent and is added often just as an effect and without plausible or authentic reference to the virtual scene.

The process of generating the cues for the respective senses (3-D image, 3-D audio, …) is called "rendering." Apparently, simple scenes of interaction, for instance, when a person is leaving a room and closes a door, require complex models of room acoustics and sound insulation. Otherwise the colouration, loudness and timbre of sound in and between rooms are not represented sufficiently. Another example is the movement of a sound radiating object behind a barrier or inside an opening of a structure, so that the object is no longer visible but can still be touched and heard. Sound also propagates by diffraction, one of the most difficult phenomena in general problems. The task of representing a realistic acoustic perception, localization and identification is therefore a big challenge.

Another particular difficulty in acoustic rendering can be explained by considering the large bandwidth and range of wavelengths involved. In acoustics, we must deal with three decades of frequencies (20 Hz to 20 kHz and wavelength from about 20 m to 2 cm). Thus it is necessary to model and simulate physical wave phenomena in environments of about the same dimensions as these wavelengths: The built environment has dimensions of several metres up to several tens of metres, while the objects of daily use, furniture, tools to finally the dimensions of humans are in the range of metres and fractions of metres. Wave physics is most difficult (and most interesting) when wavelengths are of the same order of magnitude as the objects in the sound path. Neither approximations of small wavelengths (such as in optics) nor large wavelengths (such as in radio broadcasting) can be made. This might be the reason for the delayed implementation of acoustic components in virtual environments. Personal computers have recently become capable of simulating acoustics in real time, although numerous approximations must be made to reach this goal. But in the end, the resulting sound need not be physically absolutely correct but only perceptually correct. Knowledge about human sound perception is, therefore, a very important prerequisite to evaluate auralized sounds and to set goals, too.

During the interaction with real scenes several senses are stimulated. Acoustics, besides vision, haptics and tactile cognition, yields important information about the environment and the objects in the environment. The cognition of the environment itself, external events and, very importantly, a feedback of the user's own actions are supported by the auditory event. If a high degree of immersion in virtual environments is to be obtained, all these sensory events must be matched in timing and magnitude. With respect to acoustics, various kinds of generations must be taken into account: Ambient speech, user's own speech, sounds from objects, sound from collision of objects, or simply loudspeakers are elementary examples. The total sound of these events is characterized by resonances in the generating and transmitting systems and by external signals. If the sound is bounded in a cavity, it will be reflected by walls, etc., and finally reaches the receiver's ears. Humans as recipients evaluate the diverse characteristics of the total sound, segregate it into its individual objects, and furthermore, evaluate the environment itself, its size and mean absorption (state of furniture or fitting). In the case of an acoustic scene in a room, which is probably the majority of VR applications, therefore, an adequate representation of all these subjective impressions must be simulated, auralized and reproduced.