Acoustics and Hearing

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With 58 Figures

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Part I

Head-Related Sound from Two Loudspeakers

Preface and General Introduction

In a good concert hall, a big orchestra can evoke remarkably spacious sounds. The concertgoer is surrounded by the physical sound waves, and out of these waves the subjective sound impressions are created ***in the listener's head***. This biological "measuring device" organized itself during childhood. With no special effort—and quite continuously—it performs parallel data processing and makes no distinction between complex or simple analysis.

Imagine that the orchestra, after complete silence, strikes a load, abrupt chord. In that moment we can watch the immediate response of the hall. The phenomenon is called the *onset of reverberation*. During this process the listener's auditory system has to evaluate the *direct sound* of each particular musical instrument along with portions of sound reflected from the walls or the ceiling. If those sound reflections arrive at the listener's ears less than 50 ms later than the direct sound, they are called *early reflections*. All these amounts of sound make up such an intricate mixture that the ear is unable to resolve it as a series of separate events. From a favourable seat in the auditorium the listener receives only one complex impression, which can be wide and yet very detailed and appears abruptly in the front. This subjective impression may briefly be named a *sound image*. Its width and its depth, its facets and the weights or contrasts of its different parts characterize "the acoustics" of the concert hall and also the orchestra.

The onset of reverberation is followed immediately by a slow decay process, in which we can also perceive directional and spatial effects. This works very well after a distinct flourish of the orchestra when clouds of sound, floating over the listener's head, can be perceived. The duration and timbre of the reverberation and our impressions of width and depth are substantial for the acoustical quality of a room. As mentioned, this holds just the same for the onset of reverberation and depends on the music presented. However, in the decaying reverberation no directional details can be distinguished because the sound is now mixed stochastically after many reflections.

For this short description of the sound phenomena we started with orchestral music. In fact, when judging a concert hall we have to consider the style of music and even its separate passages because the acoustical quality of a room depends on these aspects. In a good hall we may be surprised by extremely nice glitters of sound in just one striking part of a particular piece of music, even in a single chord.

Exciting sounds often give rise to discussions of acoustical issues just *because* subjective impression comprises a fan-like variety of topics. However, when using physical methods to investigate the acoustics of a concert hall, we dismantle the maze of interconnected problems as much as possible and then clear each question step by step.

Indeed, we do not need the full orchestra for our investigations. For example, the orchestra may be replaced by the simple sound of a “peaceful” shot fired on the stage. A microphone, placed at a selected seat in the hall, receives the *impulse response* which is recorded for later analysis. A non-physicist might think it rather strange to replace an orchestra by a pistol, thus ignoring the richness of acoustical problems. Yet, if applied by experienced persons and with restraint, the sophisticated methods and devices of physics are excellent tools. Spectral analysis and the oscilloscope are typical examples.

However, powerful measuring techniques should not be allowed to mislead us to forget that acoustical quality is basically defined by *subjective sound impressions*. Moreover, data gathered by technical equipment can be so complex that their relevance to the listening experience will be unclear. The aforementioned impulse response of a room is a very good example: How is it to be interpreted, since it contains the complete, intertwined acoustical information? We know, for example, that the early reflections do substantially determine the sound image, whereas many of the later reflections are *inaudible*. Their unimportance is thus out of the question: they are redundant [1]. This makes the proper interpretation of measured physical data a difficult job.

On the other hand, direct comparison tests with many subjects are a time-consuming effort right from the start. Such experiments demand careful preparation and skilful execution in order to allow meaningful and reliable conclusions. All physical parameters have to be kept constant during the experiments, possibly for several months in extreme cases. This is a good reason for further preferring purely physical measuring techniques in room acoustics.

The foregoing discussion shows that relations between the data measured by technical devices on the one hand and subjective sound effects on the other should be analyzed carefully. Do we know sufficiently well, for example, how the sound image changes if one of the important early reflections is made stronger by 2 dB, or if it arrives 4 ms earlier at the listener's ears? Could we reduce the measuring redundancy right away with the use of technical models of characteristic properties of the human ear? In this book we shall devote our attention to questions of that kind.

Sound waves are subject to acoustic diffraction when they pass the human head with its funny-shaped pinnae. In this process the amplitudes as well as the phases of the waves are affected to a relevant degree. These changes depend on the frequency as well as the direction of the sound waves, and are of basic importance to our directional perception. However, where is the sepa- rating line between the external physical world and the subjective world of perception? Instead of seeking that line at the diaphragms of microphones placed somewhere in the sound field, we can better find it at the eardrums. We should take advantage of this fact and push the application of well-developed physical methods up to this limit.

Toward that end, the first chapter of this book describes a special stereophonic 2-channel system. The system uses the human head as an important acoustic object in the sound field. The idea is realized by a dummy-head that has two built-in microphones, allowing binaural recordings. The recordings are manipulated electronically and then reproduced by two loudspeakers in a living room. The result is a perfect surround transmission.

The second chapter deals with the onset of reverberation caused by the direct sound and some early reflections. The process can be simulated in an anechoic chamber. For a series of six early reflections we measure their respective *drift threshold*. This threshold is defined by a criterion which is sharper than that of the well-known Haas effect [2, 3]. If the sound pressure levels of all the successive reflections are adjusted to their drift threshold, the onset of reverberation has surprising properties. The resulting sound images are investigated with groups of subjects.

In the third chapter, we carefully examine these measured directional sound distributions. From those examinations, we arrive at a definition for a sound image's subjective *diffuseness*. Thus, the diffuseness can be characterized by a numerical value. A few detailed comparisons show that the known directional *diffusity* [4, 5], as measured with a unidirectional microphone, has hardly any meaning for the subjective impression of diffuseness. The auditory space perception requires binaural data processing which does not agree with the application of only one microphone.

The fourth chapter shows the drift thresholds to be computable with an astonishing accuracy. The calculations are realized by applying a loudness model described by A. Vogel and E. Zwicker [6, 7], and thus the close relations between the loudness and the drift thresholds become obvious.

Actually, time functions of the loudness even allow a quantitative distinction between the clear effect of the direct sound on the one hand, and the diffuse directional impressions created by some early reflections on the other hand. This discussion is presented in the fifth and last chapter of the book. It also reveals that the cross-correlation process involved in directional analysis might be combined with loudness analysis.

During the long reverberation a large multitude of reflections are received by the ear, and it tries hard to perform an analysis which is as precise and as fast as possible. The results presented here throw some light upon the permanent overstrain of the auditory system which, in reaction, creates diffuse and spacious sound impressions.

We necessarily repeat some information in the introductions to the chapters, so that each chapter is comprehensible in itself. The mutual relationship between the five chapters and thus the intention of the book is to emphasize the important part of the head and the auditory system in acoustics. The circle is closed by the head-related stereophony which allows the nice space effects—for example, the diffuse onset of reverberation—from concert halls to be replicated in a living room.

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The measurements described in this book, especially those with groups of subjects, were carried out in Göttingen up to 1972. Later on, some experiments and advancements were continued in my private home in Goslar. This work covers a period of many years, because my personal energy had to be concentrated on my teaching employment as master of a Gymnasium. The

scientific results are published here for the first time. However, the contents were partly presented in a few papers given in Germany, Canada, and Japan.

I am also grateful to my wife, Christiane, who for several decades supported me in her friendly manner. She always followed the ideas and can sometimes explain some important points better than the author himself. Even the mess of cables in our living room did not cause grumbles, except after several months. I thank my children, Martin and Bettina, as well as Stefan Fricke for their stimulating criticism, and I wish to express my extra special thanks to Bettina again, who talked with so much patience to a silly dummy-head. I am thankful to the whole family for accepting so many subjects in our home, and I am equally thankful to all the persons in Göttingen and Goslar—might it be a few hundred?—who took part in the listening sessions. Finally, my thanks to Kenneth Allard for skilfully polishing the English translation.

Goslar, January 2008 *Peter Damaske*

Contents

Part II

The Hearing Process in Concert Halls