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AUDITORIUM ACOUSTICS PREDICTION USING BINAURAL TENTH-SCALE MODELLING

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1. INTRODUCTION

The desire to be distinctive and innovative in every new auditoria design project is obviously attractive. However, it unavoidably introduces new uncertainties into the design process and, consequently, implies potential risks for acoustic success. Nevertheless, the architect's favourite tools – pencil and paper – may help him intuitively, tracing some early reflections in determining hall shapes at the early stage of the design process, but a more elaborate study of acoustic behaviour in advance of building an auditorium can hold some promise of acoustic success. Two approaches have essentially been followed: physical modelling and computer modelling. Recently, the desire for objective and especially subjective predictability of acoustic properties in auditoria has prompted a rapid development of so-called **binaural room simulation** [1]. This development should be credited to the fundamental research [2] reveالling that human external ears play an important role with regard to spatial hearing and the subjective assessment of auditorium acoustics. The binaural room simulation takes the sound-transfer properties of the human external ear into account in modelling sound fields. The 'results' of such a modelling process, besides a set of objective parameters, are audible sound samples for binaural evaluation. The binaural room simulation opens up the possibility for a listener to obtain an auditory impression which is as close as possible to the one he would have in the real auditorium after completion. This is of great importance, since e.g. the music performance in an auditorium will ultimately be heard by listeners with their two ears. Although several important correlations between objective measures and subjective judgements of sound spaces have been found based on many successful auditoria, in the end, only listening in to the 'real auditorium' in advance, what is nowdays is called '*auralization* of auditoria'[3], will provide a reliable prediction of how an auditorium will really sound after completion.

One of the principal considerations in the binaural room simulation is that a normal listening situation in a room, particularly for one listener, can be modelled by a linear time-invariant transmission system with two outputs and probably several inputs. Consider a point at the eardrum of the listener as an output of this system, such a system then includes the transfer properties of sound source(s), the room under consideration and the external ears of the listener involved. Therefore, the binaural listening situation under consideration can be described by so-called *binaural room impulse responses* [4]. After determining binaural room impulse responses, this acoustic environment can be reconstructed at any time by performing the linear convolution between anechoic acoustic signals and binaural room impulse responses. The binaural room simulation for auditorium acoustics prediction can be carried out by both physical and computer modelling. They differ from each other in the way of obtaining binaural room impulse responses. This paper presents 'state of the art' binaural room simulation using tenth-scale modelling technique. The emphasis will be placed on some new developments such as miniaturized dummy head and advanced computer-aided procedure involved in this technique (Refer to [4] for more details).

2. TENTH-SCALE MODELLS

A scaled-down model provides an inherently correct boundary condition of the sound field if it possesses both geometrical and acoustic similarity to the original auditorium. The selection of a scale factor 10 may be an appropriate compromise between modelling cost and level of accuracy. At the same time, it is for the time being realistic with respect to achieving a sufficient bandwidth of the whole modelling system, since considerable difficulties in the development of modelling instrumentations can be more effectively overcome than that with a higher scale factor.

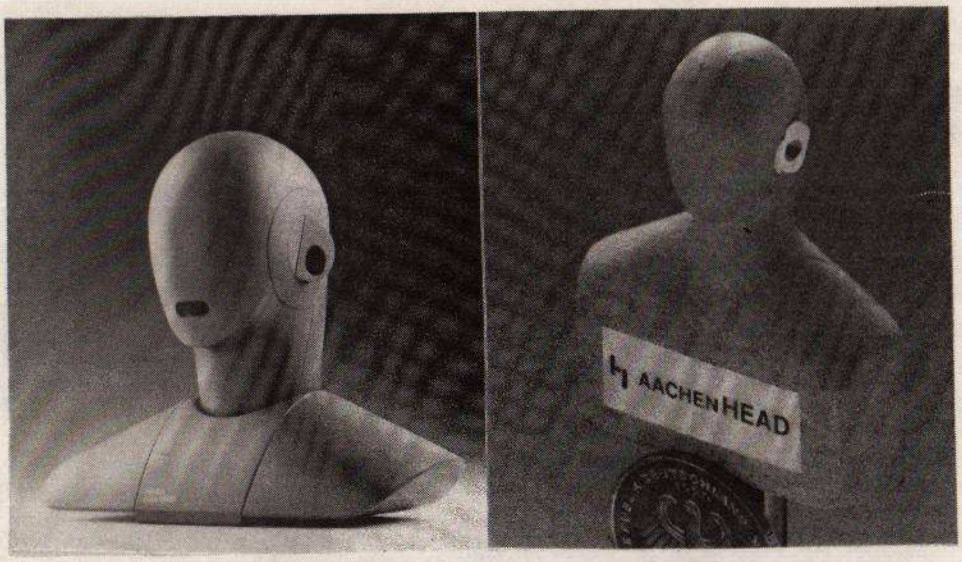
The geometrical similarity to the origninal auditorium may be achieved in the stage of building up a rough model while the acoustic similarity apparently implies a correct sound propagation medium and correct surfaces of the sound space and requires a careful adjustment within the elevated model-frequency range. The achievement of acoustically correct surfaces in a tenth-scale model is easier than might be supposed, since most surfaces in auditoria are acoustically hard, being easily reproduced. Only the surface of the floor, e.g during the performances, is covered by audience. It was suggested [5], for tenth-scale model testing, that a simplified form of auditors should be convenient for the purpose of model simulation. Taking this form, a number of single model auditors was built. The adjustment of absorption properties of these model auditors was undertaken according to the method and the data derived from [6] in a specially constructed model reverberation chamber.

The simulation of sound propagation medium can be achieved by creating dehumidified or nitrogen atmospheric conditions [7]. Both methods require the airtightness of scale models and are sometimes time-consuming. In spite of this complication, it is appropriate that the excessive air absorption in the model-frequency range should be compensated in this way. More reliable results from model measurements of binaural room impulse responses, with respect to the achievable signal-to-noise ratio, can be obtained than in air.

3. MINIATURE DUMMY HEAD

The efforts to build a model sound receiver in a form as close as possible to a human head extend back about 30 years. At first individual groups only produced model 'heads' of a crude nature, but from the 80s onwards, the development of model dummy heads became a real hope. The first prototype of a tenth-scaled dummy head was initiated by Els [8] 1984. He miniaturized not only the head but also the pinnae. Later the present authors [9] continued this development. Fig 1 shows this miniature dummy head. A pair of cast pinnae miniaturized in details is attatched on both sides of the head at correct position. This miniature dummy head was constructed corresponding to a 'typical' subject selected among numerous subjects using the criterion of minimal deviation of the monaural transfer functions [9]. However, the human external ear shows difference from individual to individual. With the aim of finding the 'average' external ear, great efforts have been made

Figure 1: Miniature dummy head with detailed cast pinnae.



(a) (b)

Figure 2: Dummy head microphone system with simplified, mathematically definable external-ear geometry, (a): dummy head in real size; (b): tenth-scale replica of (a).

over recent years. As the results show [10], the relevant parts of an 'average' external ear can, in fact, be approximated by a relatively simple, mathematically definable geometry. A dummy head designed according to this principle is shown in Fig. 2 (a).

For achieving as good a simulation of the receiving end as possible, miniaturization of such a dummy head for binaural tenth-scale modelling technique is apparently of importance, since a comparison between the binaural recording in a real hall and their binaural model simulation will become more realistic in this way. Fig. 2 (b) demonstrates such a simplified, mathematically-definable dummy head in tenth-scale. Similar to the miniature dummy head in Fig. 1, this tenth-scale head contains two 1/8-inch condenser-microphone capsules inside the head. The adapter between the ear-canal entrance and the microphone membrane is optimized to keep the sensitivity over the whole frequency range as high as possible. This allows a bandwidth up to 160 kHz. Details related to the tenth-scale dummy head can be found in [9].

4. A COMPUTER-AIDED MEASURING SYSTEM

The binaural room impulse responses play a central role in the binaural room simulation, because both objective and subjective evaluations of acoustics of the auditorium under consideration can be essentially carried out according to them. Among various methods for the measurement of room impulse responses, the method using binary periodic maximal-length sequences (in short M-sequences) provides an efficient approach. Binary M-sequences have a number of useful properties, e.g., their two-valued auto-correlation function and the minimal crest factor in one period make it possible for the evaluation of room impulse responses to be broadband and to have high noise immunity. It is obvious, that such kinds of sound signals contain significantly more energy in one period for a given dynamic range than impulsive sound signals. In particular, the evaluation of impulse responses is based on the cross-correlation principle [11], this can efficiently suppress uncorrelated noises. Due to the fact that the binary M-matrices are permutationally similar to the Sylvester-type Hadamard matrices, room impulse responses can be evaluated efficiently by carrying out two permutations and the Fast Hadamard-Transforms known in the literature [11] as Fast M-sequences Transforms.

The algorithm of the Fast M-sequences Transforms is effected on a personal computer (IBM or compatible) along with a specially developed transient recorder so that the measuring system is easily transportable. The algorithm is effected for the length of M-sequences up to $2^{18}-1$ points. The transient recorder has been designed to have a variable sampling frequency up to 1 MHz. The resolution of the A/D and D/A converters is 14/16 bits. The possibility of averaging data over a number of periods is also included in the host computer to additionally increase the SNR of the measurements. Special kinds of model sound sources [4] have to be used for radiating binary M-sequences into the model space. After recording responses to the M-sequence stimulation in the model space, the Fast M-sequence Transform is then applied to the recorded responses, directly resulting in room impulse responses. The auralization of the model sound space can then be achieved in terms of carrying out the digital linear convolution between anechoic sound signals and binaural room impulse responses being measured. Moreover, objective prediction of acoustic qualities in the form of physical paramaters can also be carried out on the basis of the room impulse responses obtained from tenth-scale models. The measurement system described here is also suitable for evaluating room impulse responses in rooms of 'real size', since the sampling frequency of this system can be selected as required in the range from several kHz up to 1MHz.

5. COMPARISON WITH DIRECT RECORDING OF BINAURAL SIGNALS

In contrast to measurement of binaural room impulse responses and linear convolution, auralization of a scale model space for subjective evaluations could be carried out in fact by the so-called 'speed-up' recording method as done in several groups [7]. Today, techniques even allow a better approach through digital recording [4].

Two major disadvantages of this direct-recording method make the binaural room simulation by measuring binaural room impulse responses and linear convolution preferable. First, direct recording restricts trying out many kinds of input signals, especially subsequent to recording, while the binaural room simulation allows the listening situation under consideration to be reconstructed *at any time* by performing the linear convolution between acoustic input signals *arbitrarily* selected and the binaural room impulse responses. Finally, direct recording is, at present, strongly affected with respect to the signal-to-noise ratio (SNR) due to the limited sensitivity of the miniature dummy head. The very small size of microphone capsules being selected and the very thin adapter between the ear-canal entrance and the microphone membrane are responsable for this. In the case of binaural room simulation by means of measurement of binaural room impulse responses, several possibilities for improving sound quality of resulting binaural samples with respect to the SNR can be exploited.

Selecting efficient evaluation methods for room impulse responses is one step towards improvement as discussed in section 4. In addition, an appropriate number of averaging and even long M-sequences (e.g. $2^{17}-1$) can be selected in the measurement procedure for further improvement of SNR. An SNR of measured binaural room impulse responses usually ranges between 30 dB and 45 dB, depending on the number of averagings, the length of M-sequences selected in measurement and the distance between the sound source and the miniature dummy head.

Furthermore, this SNR figure must be evaluated relatively. Room impulse responses generally consist of a direct sound portion, an early-reflection portion and a reverberation tail, the latter relating to the decay behaviour of sound energy in a room being of random or quasi-random nature. The direct sound and the early reflections, under a given SNR (taking the worst case of an SNR about 30 dB as an example), will certainly suffer from slight distortions, while reverberation tails are partly or entirely obliterated in noise. From a psychoacoustic point of view, the sound samples resulting from convolution between such binaural room impulse responses and an anechoic sound signal with a sufficient SNR will sound more reverberant than the correct one, while localization and the other attributes of spatial hearing may not be significantly affected. The precision of the simulation, however, is certainly related to the SNR achieved. For auralization of the room under consideration, this distorted auditory impression may be compensated to a certain extent by means of modification of reverberation tails of room impulse responses in an appropriate fashion as discussed in [9].

The sound quality of the samples resulting from convolution, *with respect to noise*, is essentially governed by anechoic signals, so that the recording of such sound signals must be carried out with a high resolution while the requirement on the resolution of an A/D converter only for evaluating binaural room impulse responses can more easily be met, since a resolution of 12 or 14 bits is sufficient for achieving room impulse responses with an SNR as high as 50 dB.

6. APPLICATION IN AUDITORIUM ACOUSTICS DESIGN

In March 1991, we were fortunately able to participate in an acoustic design project of a hall in the Kyoto School of Computer Science in Japan. During the architectural design, this binaural scale modelling technique was applied to the room acoustic design of the hall. A tenth-scale model of the hall possessing a geometrical similarity to the first architectural design had been put at our disposal for model experiments when we arrived at the school with the portable equipment transported from Germany. Besides the model hall, a great number of model auditors and suitable seating had been built. Some absorption materials, determined only for tenth-scale models, had also been selected. Before the measurements,

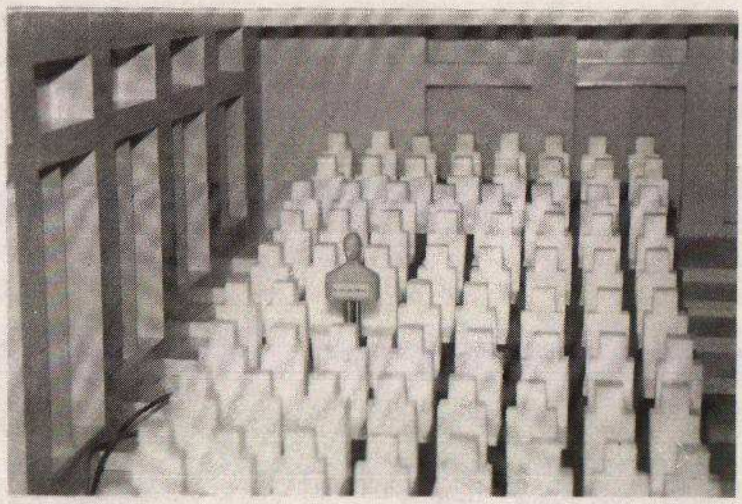


Figure 3: View of the tenth-scale model hall of the Kyoto School of Computer Science with a tenth-scale miniature dummy head sitting in the audience area.

nitrogen was put into the model space for simulating the sound propagation medium. Fig. 3 gives a view of the model hall.

Both binaural and monophonic room impulse responses were measured at some 'strategic' positions in the audience area by using both the miniature dummy head and a 1/4-inch microphone with a nose cone. The sampling frequency was set to be 441 kHz per channel. The room responses to the M-sequence, radiated through a specially developed ultrasonic sound source were averaged ten times after recording. The averaged result was then transformed by the Fast M-sequence Transform into room impulse responses. To complete auralization of the hall, the binaural room impulse responses measured in different cases were convolved with some anechoic music and speech signals. All measurements with the model and the calculations were completed within two weeks. After only 10 days, a hearing test with a number of subjects took place directly at the experimental site.

7. CONCLUSION

Acoustic scale modelling of auditoria has proved to be very valuable as a design and research aid for quite some years. Although this technique has undergone a half century of its development, it has only recently acquired a certain level of maturity. As the instrumentation of binaural tenth-scale modelling, an aurally-adequate miniature dummy head, in addition to the conventional modelling method, has been developed in our group. A computer-aided procedure supports model evaluation of binaural room impulse responses and provides for further digital signal processings facilitating both objective acoustics prediction and subjective auralization.

In the near future, systematic comparisons between modelled and real halls are expected. Wir are optimistic that more and more applications of the technique will be found in real acoustic design projects of auditoria. We confidently believe that this binaural scale modelling technique, in addition to fully computer-aided room simulation, may help acousticians reduce risks in the acoustic planning phase to a minimum.

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