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RESEARCH METHODS IN AUDITORIUM ACOUSTICS

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This paper concerns research methods in auditorium acoustics, and contains observations from my particular perspective, that of a practitioner at Artec Consultants Inc, acoustics and theatre consultants of New York City.

Research methods in our branch of acoustics are the means by which acoustical principles of auditorium design are discovered. The methods we apply in our quest for this knowledge range from the simplest act of listening to live music to the most complex analysis with a computer. It is important not to lose sight of how much can be learned from listening to music in a variety of performance spaces; there is a certain glamour in the newer computer techniques and applications of higher mathematics in research that can easily mislead us, causing us to place perhaps too great a reliance on an as yet imperfect science. Human ears are, in many ways, our most reliable guide, and they are the means for final judgement of a completed auditorium.

Research into auditorium acoustics undertaken world-wide in the last three decades has lead to exciting new concepts in auditorium design springing from a better understanding of human hearing. Of particular note are the "discoveries" of early sound energy (for perceived "clarity") and early lateral sound energy (for perceived "envelopment" and "clarity").

Our science has certainly progressed, and some of the myths of acoustics have been dispelled. Our knowledge has increased sufficiently that we know there is no single "prime measure" of acoustics, as Reverberation Time was once viewed. But with the plethora of measurements available today, who can tell us which ones to use and how to use them?

We are a long way from finding full scientific explanations for all aspects of auditorium acoustics. In common with most other practitioners I rely heavily on my own listening experience and the collective experience in our firm to fill the enormous gaps in scientific knowledge. In this respect I am particularly indebted to Mr. Russell Johnson who has completed more than 200 auditoria over the last 30 years.

It is always sobering to remind oneself that if our research is valid and if we can find the proper ways to apply our knowledge, then we can help produce successful buildings. But, if we are wrong, we can mislead a community that is spending perhaps $60 million on a new concert hall. In these circumstances we must rely heavily on practical experience; we more often employ research methods to study trends rather than absolutes, and to confirm design proposals rather than to generate them.

One principal reason for slow progress in acoustical science is the great difficulty of validating acoustics research through what would seem to be the most direct route, that of feedback from a finished building. The connection is simply too tenuous. First, there are many different parties involved: The acoustical researcher is usually a scientist, the acoustical practitioner often an architect, and the judges of acoustics are frequently musicians and conductors. Second, the nature of research itself is conceptual: for feedback to come from a finished building the concept must be embodied in a design proposal, preserved during the design development, and finally constructed in a building. Third, the time taken to design and construct a building is measured in years (decades in some cases), so prompt results are not readily obtained. The length of time between conceptual design and feedback is further increased because comments from musicians and other critical listeners in a new building are distinctly unreliable: the excitement generated by the newness of a building often imparts an impression of overall satisfaction, which is sometimes erroneously translated to satisfaction with the acoustics.

Another handicap to researchers in auditorium acoustics is that most, if not all, of the standard text books in this subject contain statements that are clearly opinions rather than documented facts (but are not identified as such). Perhaps these opinions stand out in the texts so clearly for me because my own prejudices and opinions are usually different!

With these difficulties slowing progress of acoustical science we cannot be surprised that the public and our clients frequently ask us if acoustics is not an art rather than a science. We reply that historically acoustics was called a philosophy. Perhaps we need to be philosophers to identify the truth in the standard text books on acoustics!

As practitioners involved in auditorium acoustics research, our firm, Artec Consultants, is well placed to overcome at least some of these problems. We wear the hats of practitioners and of researchers, and as designers we can ensure the results of acoustical research are incorporated in the designs for real buildings. With several new buildings opening each year, we have a good opportunity to learn as promptly as possible from our successes (and mistakes).

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Our research is in the "private sector", in that it is usually funded by fees related to specific design projects. Thus we generally have to direct our research towards actual buildings and models of actual designs as part of the design process for a new facility. Although such research is less likely to break new ground in discovering concepts underlying psychoacoustics (where most of the advances of recent years have been made), it places us in as good a position as any to break new ground in the application of research results to auditorium design. Indeed, this will be the subject of my second paper, later this afternoon.

The particular research methodologies we practise are perhaps unusual; our rationale is as follows. If we describe acoustical design (somewhat simplistically) as the process of selecting particular building materials and positioning them in relation to one or more sound sources and listeners, our research, then, is often directed toward determining appropriate locations for the sources, listeners and room boundary surfaces.

One of our research projects, conceived with this description of acoustical design in mind, concerns the acoustical effects of altering the angle between two side walls in a hall (that is varying the room from fan shaped to rectangular to reverse-fan shaped). The results were presented to the Acoustical Society of America in 1983 at the meeting in San Diego, and are described in the August 1984 issue of Architectural Record.

Technically fluent readers of that article may be disappointed to find no numerical comparisons between the various conditions presented. There were a number of reasons for this, including respect for the interests of that magazine's readers. For me, however, the most important lesson in this research project is not a numerical analysis but a better understanding of how room shape affects the sound field within a room.

With the present state of knowledge, there are no numerical criteria to which we can design auditoria. Research has posited the important trends, such as a monotonic relationship between lateral energy and listener preference, but the practical optimum values and necessary tolerances of the various potential criteria are not yet established. With the advance of technology enabling auditorium designers to more readily create audible simulations of sound fields it is perhaps less essential to use objective criteria: after all, ears will be the final judge; why not the designer's tools also?

Our research methods build on the use of simulations. In fact, we produce the raw material for simulations (impulse responses) in each area of our research including:

- from computer models,
- from impulse responses measured in real rooms,
- from impulse responses measured in scale models

These research methods each have particular strengths and weaknesses:

- computational models help us learn how sound behaves in rooms;
- scale models help us study those effects of diffraction that we cannot yet compute;
- measurements of impulse responses in existing halls allow us to evaluate and validate our computational and scale models, and to evaluate proposed objective measurements.

I will describe each of these research methods in outline.

Computational Models

Two of our computational models are concerned primarily with the early sound up to about 300 ms. One is an image-locating algorithm called IMAGES while the other is an advanced sound beam-tracing and audible simulation program called GODOT. These programs are described in detail elsewhere; here I shall discuss only their methods of operation.

Images

The IMAGES program, written in Applesoft Basic and implemented on an Apple II computer, locates the virtual sources (or "images" of a sound source) associated with reflecting surfaces. Although the program is slow in operation, we have found that it can be left running happily overnight to find all reflections up to fourth order for a room consisting of approximately twenty surfaces (walls, soffits, ceiling, stage floor etc.). Of particular interest to the designer, the IMAGES program produces a graphical output in which the propagation paths associated with each sound arrival are shown. Thus we can study which room surfaces are particularly effective (or ineffective) at producing lateral sound, or any other acoustical phenomenon, at a listener's position.

The great advantages of this modeling technique for us are that it is relatively quick, and its graphical output helps us better understand the interrelationships of room shape and acoustics.

Godot

GODOT is, as its name implies, a developmental project which draws together sound beam (equivalently pencil or ray bundle) tracing with audible simulation.

A major goal of the project, initiated in 1978, is to deal efficiently with the geometric databases of arbitrary complexity, specifically those which will be produced by the next generation of computer-aided architectural design geometric modeling packages. The beam tracing portion has also proved useful in resolving the hidden surface problem in computer graphics, an area in which the group in Vancouver, led by John Walsh, has made significant contributions in recent years.

The beam tracing algorithm follows a finite-sized beam from one of a number of source positions, checking for interference with boundary elements, and generating reflections as appropriate (splitting beams when necessary, preserving cross-section shape). The program clearly "knows" which edges can contribute diffracted beams, and early versions of the program incorporate the uniform geometrical theory of diffraction. Any number of receiver positions can be incorporated, and GODOT keeps track of the beams which are most likely to strike any of these in the time interval of interest.

The simulation sub-system uses linear least-squares prediction (with finite error prediction order estimation) to derive minimum-phase filters for each path; a tapped delay line is then driven with anechoically-recorded music to simulate the desired conditions.

The GODOT system, written in Pascal with some special microcode, currently runs on a PERQ workstation with custom-built 16-bit AD/DA converters. While work on the portion of GODOT devoted to beam tracing is nearing the point where it will be of great practical benefit to Artec's projects, the simulator has been in place for some time, and we discuss the use of this for some recent experiments next.

Simulation Examples

We have prepared a tape, which can be heard today, that contains simulations derived from impulse responses output from the IMAGES program, processed with the GODOT simulator. The program material is the ubiquitous anechoic recording of Mozart's Jupiter Symphony. The impulse responses from the IMAGES program are for fan shaped, rectangular, and reverse-fan shaped rooms (as described in reference (3)). The tape illustrates a number of the subjective effects of increased lateral energy, similar to those reported by Dr. Barron in his thesis, which occur when the room shape changes from fan, to rectangular, to reverse-fan shaped. These effects include enhanced envelopment, apparently increased bass response, and improved intimacy. Listeners who have already heard this tape also report greater ease in identifying the individual instruments in the orchestra for the results with higher levels of lateral energy.

One advantage that both these computational models have over the measurements we can make in real rooms and models is that the full directional information concerning the impulse response is made available to us. The models are limited at present to studies of the early sound. We use other computational models to predict the behaviour of the late sound.

Prediction of decays in partially coupled volumes

We have employed partially coupled volumes in many of our auditorium designs and have found them particularly effective for achieving designs that possess both clarity <u>and</u> reverberance.

In some ways, we have had more difficulty with the theory than with the practice: we know from experience what will and what will not work, yet our computational models do not indicate this distinction as clearly as we would like.

One of the two computational models we use looks at the energy decay in one room, taking into account the transfer of energy from the partially coupled volume, by solving a pair of coupled differential equations. The other computational model is a stochastic process model that "passes" sound intensity from one surface to the next, in accordance with the degree to which that surface is "visible" from the first (i.e. what solid angle it subtends). Despite the substantially different mathematical approaches, the models have predicted similar results.

Verification of these two computational models is not complete. Neither are we satisfied that they are adequate representations of the essentially deterministic acoustical processes involved. However, both models confirm our casual listening observations. We are currently seeking funding to undertake more rigorous evaluations that will involve measurements in existing auditoria with coupled spaces.

Measurements

The occasions on which we undertake measurements in an auditorium come about either because we reporting to the client on the completion of a room or because we have been retained to seek the causes of pathological acoustical conditions.

In order to capture the impulse response of an auditorium we have designed and built an 8-bit digital data acquisition system based on an Apple II computer. The hardware supports a number of functions, such as sampling the signal from a microphone, placing the data directly in the memory of the computer, detecting threshold conditions (triggering), and variable trigger delay times. The data is stored on floppy disks for later analysis. Associated software allows control over most housekeeping tasks, and permits the operator to examine the captured data to verify that the full 42dB dynamic range of the system is being exploited.

For typical measurements in real rooms we operate the system with a 48 kHz sample rate and capture a 200 to 300 ms "window" of the impulse response. The maximum sampling speed is nearly 500 kHz, making the system suitable for acoustical model testing also.

For the sound source, we have had most success with a starter's pistol, and for the microphone, we have used standard B&K omni-directional microphones, AKG figure-of-eight microphones, or highly directional "shotgun" microphones.

The digital nature of the recordings allows ready integration of sound intensity in any particular time period. Comparing the data for otherwise identical recordings made with either omnidirectional or figure-of-eight microphones (facing laterally) allows us to compute "lateral energy fractions".

A range of standard software tools allow detailed examination of the data, such as constructing the decay curve by backwards integration of the impulse response. Software for editing of the recordings and for deconvolution allows computation of the "true" room impulse response from the recorded data.

The acquisition hardware can also be operated in a different software environment to sample, with less detail, several seconds of the sound decay. In this case a micro-coded routine sums the squares of a number of samples prior to storing the result in the memory. This software will be particularly useful in our studies of the decays in partially coupled volumes.

A paper on this data acquisition system was presented to the Acoustical Society of America at the 1983 meeting in San Diego (4).

Physical Scale Models

In some of our projects, the audible effects of diffraction are of particular concern. In this regard, physical models better current computational models, which either preclude diffraction effects or include approximations to them. The scale model will reproduce diffraction effects as accurately as we can build the physical model, and the digital techniques we employ to "capture" the impulse response afford us much of the flexibility of computational models, such as in editing the impulse response or in driving the model with a variety of program material.

Perhaps the simplest hybrid of acoustical modeling and simulation is one in which music is played into a scale model at a multiple of its normal speed appropriate to the scale. This method dates back at least to the 1950's when Lochner and Berger used it to evaluate speech intelligibility in auditoria. The difficulties of this method are well known, and are common to all acoustical scale modeling techniques: transducer inadequacies, excess air absorption at very high frequencies and imperfect modeling of boundary absorption at these very high frequencies.

We use a spark source to excite the model, and use the same 8-bit microcomputer based data acquisition system described above to sample the response of a miniature microphone. We have used 1:24 scale models and a sample rate of nearly 500 kilohertz to give an effective bandwidth of approximately 150 kHz, or a full-scale equivalent of 6.3 kHz. The responses of the source and the receiver need not be exceedingly flat, as we use a deconvolution method to extract the "true" room impulse response from the "raw" model response (i.e. the sampled data). The deconvolution process extracts the spark signature plus effects due to the microphone and electronics, leaving an estimate of the true impulse response of the model alone. Finally, we convolve this impulse response with digitized anechoic music and convert it back into the analog domain for listening on headphones.

The deconvolution process we use, recently developed by Walsh and Ulrich, uses pseudo-inverse filtering. Its great attraction is that, unlike the "spiking" techniques used by Berkhout (1) it makes no assumptions with regard to the true impulse response of the room.

Even though the data acquisition system is single-channel, we have made quite acceptable "stereo" simulations by capturing two room responses with the microphone pointing 45 degrees to the left and right of the line-of-sight to the source. The nature of deconvolution permits us to capture left and right channels at different times with different spark firings yet to obtain the true channel responses in each case.

This physical scale modeling and simulation system was described in an oral paper presented at the 1984 meeting of the Acoustical Society of America in Minneapolis (5).

CONCLUDING REMARKS

I have introduced, very briefly, some of the research methods we employ in our continuing studies of auditorium acoustics, and in our designs for performance spaces. We continue to refine these techniques and to develop new ones as the need arises for better understanding of some aspect of room acoustics.

We, like most of you I'm sure, raise more questions than we answer. Most pressing seem to be those questions related to the hearing and "human processing" of music in rooms. So I would like to end with an appeal to you all for a concerted effort towards approaching the fundamental psychoacoustics questions from an architectural perspective. We would be delighted to discuss any proposals for research you may be considering and to review how such research could be made more directly applicable to problems we see in auditorium design.

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