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Good Acoustics

What is the meaning of "good acoustics"?

GOOD ACOUSTICS is perhaps the most presupposed and most loosely used term by the musical/architectural world. Everybody from music critics to music listeners use "Good Acoustics" freely in their vocabularies without stopping to think about what it really means. "Good Acoustics" is not as "cut and dry" as it appears on the surface. Its parameters are based upon subjective musical tastes, which are then translated into the "physical domain," and are then finally defined scientifically. It is the object of this short review article to give us a perspective of the field of acoustics, including some background information, so that we may better understand and appreciate the term "Good Acoustics."

Jesse Klapholz is a contributing editor for db Magazine as well as guest editor for this particular issue.

OUR FOREFATHERS' FOREFATHERS

It has often been said of acoustics that the basic theory was laid down early, and that all that was needed was its implementation by the necessary analysis and its application to new problems as they arose. The basic theory of the production, propagation, and reception of sound was postulated by the ancient Greeks in substantially the same form as we accept it today.

While the theory of pitch was conceived by the Greeks, it was not until the time of Galileo Galilei (1564-1642) that acoustics as a science really developed. The great scientists and mathematicians of that period—Mersenne, Hooke, Taylor, Bernoulli, D'Alembert, Euler, Wallis, and Sauveur—were the most prominent to work on the mathematical and physical relationships of vibrating bodies. Perhaps Joseph Sauver's most recognizable contribution was that he first suggested the name acoustics for the science of sound. Acoustics actually comes from the French word "acoustique," which was derived from the Greek word akoustikos, meaning "of or for hearing," which is from the word akouein, "to hear."

OUR FOREFATHERS

In 1853, a Boston physician, J.B. Upham, wrote several papers concerning the "multiple reflections" of sound from all the surfaces in a room and how they could be treated so the room's reverberation time could be reduced. In 1856, Joseph Henry made a study of auditorium acoustics, although his suggestions were all of a qualitative nature. In 1895, Wallace Clement Sabine, a professor at Harvard University, developed a theory that reverberation could quantitatively be measured as the time it takes a sound in an enclosed space to decay 60 dB, and is directly proportional to the room's volume and inversely proportional to the area of its absorbent surfaces. In 1900, Sabine served as the acoustical consultant for Boston Symphony Hall, making it the first music hall designed according to scientific principles. The only instrumentation available to Sabine at the time was his stop watch and his ears. Ironically, according to many critics it is still one of the best concert halls in the world.

Sabine's work marked a new era in acoustics—an age of reverberation. For the next half century, the theory of reverberation, as first developed by Sabine, was to be the "golden rule" as well as the "buzz-word" of much discussion and conjecture for acousticians. Although during the vaudeville era, rooms were being designed empirically (Radio City Music Hall in New York City was the last such theatre to be built during this time), the early '20s saw the growth and development of a more scientific approach. Watson's "Acoustics of Building" (1923), was a milestone "single-source" on the subject for architects and engineers. In the '30s, Frederick V. Hunt, using the new electronics of broadcasting to the measurement of reverberation times and sound fields, perfected an apparatus for accurately tracing sound-decay curves. Professor Hunt engaged in continual discussions with his students (among whom were L.L. Beranek and T.J. Schultz) on the meaning of sound diffusion in auditoriums, direct-to-reverberant sound energy, optimum reverberation times for different sizes and purposes of auditoriums, and so on. A source of reverberation criteria still used can be found in Vern O. Knudsen and Cyril M. Harris' book published in 1931, *Acoustical Designing in Architecture, The Hearing of Speech in Auditoriums*, published by Knudsen in volume #1,1929, of the *Journal of the Acoustical Society of America*. This endures as an important work in which he discusses the causes and effects of percentage of articulation, signal-to-noise ratio, reverberation, and the shape of the auditorium on speech communication in rooms.

ROOM ACOUSTICS

When a sequence of sounds is produced in a room, the original sound reaches a given listening point, plus a multiplicity of reflected versions that may reinforce and embellish the original or may distort and blur it beyond recognition. Room acoustics is a study of the influence of the room on the end product reaching each listening position. Rather than attempt to analyze such a complex phenomenon in one "view," several different idealized models may be used, which are often categorized under the headings of "geometrical acoustics," "statistical acoustics," and "wave acoustics." Simply stated "geometrical acoustics" is the application of geometrical optic techniques to acoustical investigations. The basic method is a graphical ray-tracing process from a source, through reflections from various surfaces in a hall, to their ultimate arrival at a listening/observation point. The application of geometrical acoustics to design is ingeniously demonstrated by W.C. Sabine's paper, "Theatre Acoustics." It illustrates his very successful use of an optical-acoustical pulse technique for studying the propagation of wave fronts in auditoriums. Variations of Sabine's approach were later developed by A.H. Davis, Takeo Satow, and the team of R. Vermeulen and J. de Boer. As in geometrical optics, there are limitations: for specular reflection a surface must be comparable in size to a wavelength, and smooth compared to a wavelength. Another complication of the acoustical analogy is that the various direct and reflected versions of a brief sound may arrive at a listening point at noticeably different times, with a resultant distortion of the original. The acoustician must therefore consider both the spatial and temporal distributions of sounds. Thus, it can be said that geometrical acoustics provides a way of examining the direct sound plus the first few reflections.

Statistical acoustics deals with the reverberant sound resulting from many reflections from the room boundaries. The multiplicity of reflected sounds is treated statistically to relate the average level of reverberant sound in the room and the rate at which it decays to the absorption properties of the room surfaces. The first such scientific revelation was Sabine's famous formula $T\ 0.049V/A$, where T is the reverberation time in seconds, V is the room volume in cubic feet, and A is the room's absorption expressed in sabins. The assumption upon which Sabine's theory is based is that the growth, steady-state, and decay of sound in a room may be treated as continuous processes, with equilibrium at all times between the energy density in the room, the power being added to the room, and the power being lost by transmission or absorption. Implicit in this is the assumption that the sound field is diffuse; i.e., that on the average it looks the same everywhere, with equal probability of waves traveling in all directions. Sabine recognized these limitations, but he found that in many rooms his theory described the reverberation processes with adequate accuracy.

Indeed it still does. Sabine's formula has the defect that it yields a finite reverberation time in the limit when all surfaces are perfectly absorptive. Attempts were subsequently made to eliminate this defect and provide a formula that gives more accurate results. The most successful of these is the formula developed simultaneously by K. Schuster, R.F. Norris, and Carl Eyring. The two more prominant presentations form an interesting contrast: the Norris version is simple and brief, while Eyring's is an exhaustive analysis using image theory. Both lead to the same formula, quite widely used today, which agrees with Sabine's formula when room absorption is low. Of the various reverberation theories, the Sabine theory remains the most satisfactory, when restricted to highly reverberant rooms. The other approaches involve certain assumptions about transit times between successive reflections and the use of ray-tracing concepts that cannot easily be pushed to the statistical limit. These difficulties were examined later in some detail by F.V. Hunt, L. Batchelder, and W.B. Joyce.
However, for the accuracy needed in design, the Sabine formula provides the basis of a method for measuring absorption coefficients of materials; and depending on the parameters, either the Sabine or the Norris/Eyring formula can be used to calculate the reverberation properties of a hall. Wave acoustics is based upon wave theory as developed by Lord Rayleigh, who published wave equations and the expressions for normal modes in rooms and applied them to "room resonance" control methods. In the mid '20s, E.T. Paris, who invented the stationary-wave tube for measuring normal-incidence absorption and impedance of materials, further developed the concept of acoustic impedance and its relation to sound absorption. The application of wave theory to room acoustics really took off in the mid '30s as a result of research by P.M. Morse and his co-workers. It was believed at the time that all the phenomena of room acoustics would soon be explained by wave theory.

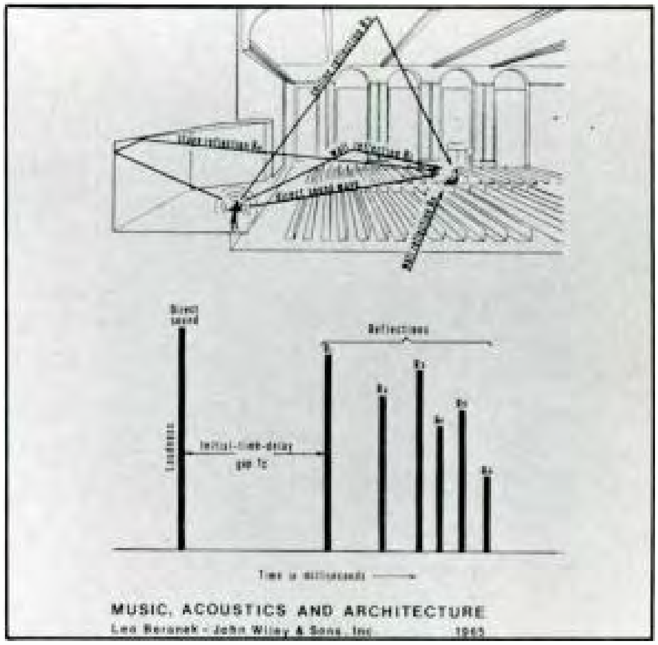
As the story unfolds, however, sound fields in most rooms are far too complicated to be described by wave acoustics alone. However, these studies have given us yet another view of the behavior of sound in rooms and of the physics of the absorption process. Although it is beyond the scope of this writing, a comprehensive look at the applications of wave acoustics to rooms may be found in a review paper by P.M. Morse and R.H. Bolt. (*Sound Waves in Rooms, Review of Modern Physics*—#16:69-150, April 1944.)

SHORT-TERM ROOM CHARACTERISTICS

The techniques of statistical acoustics and reverberation time provides us with room characteristics which may be described as the long-term transient behavior of sounds in rooms. Reverberation, though, is only part of what we experience in listening to sounds being transmitted in rooms; equally important are the short-term transient characteristics of rooms. The sequence of reflected sounds in a hall is universally accepted to have a strong influence on a listener's acoustical assessment of a hall. Early systematic approaches concerning the short-term response of halls were carried out by C.A. Mason and J. Moir, and Erwin Meyer and his associates at Gottingen University in Germany.

While some investigators studied the directional distribution of arriving sounds, others have emphasized the timing and relative magnitudes of successive arrivals. A special objective of the early reflection studies was to investigate the relation between the timing of the various signals reaching the listener and the apparent location of the source. The effect, in how it relates to electronic reinforcement systems, was known at least as early as 1935, when two papers were independently presented by R.D. Fay and W.M. Hall at the fourteenth meeting of the Acoustical Society of America.

In 1951, a more complete study was made by Meyer's student, Helmut Haas—hence, the term "Haas-effect" Shortly thereafter, Bolt and Doak proposed a transient response criterion for auditorium design purposes. In the '50s a worldwide study of many of the better known concert halls was undertaken by Leo L. Beranek, including interviews with conductors, musicians, and music critics. This study resulted in his book, *Music, Acoustics, and Architecture*. Two of the most important design



Architecturally developed early reflections.

parameters, as described in Beranek's book, were the initial time-delay gap at a listener's position (defined as the difference, usually measured in milliseconds, between the direct sound from the source and the first reflection), and the values and shape of the curve of the reverberation time versus frequency.

Later, researchers at Bolt Beranek and Newman, Inc., (BBN) of Cambridge, Massachusetts, set up an electroacoustical experiment in Philharmonic Hall which simulated the sound field perceived by a main floor listener in terms of three components: direct sound; the reflection from the ceiling panel array; and the reverberant sound. Through being able to electroacoustically alter the above-mentioned sound components, they were able to demonstrate the effects of changing spectral content in the early and late sound fields. At the BBN laboratory, Schultz and his co-workers demonstrated that it is not important that early reflections have a full complement of low-frequency energy. Like telephone circuits, the "musical intimacy" and "definition" functions depend principally on clear "consonants." They further showed, that the perception of "warmth" (or rich bass sound), though apparently independent of the spectrum of the early sound, is lost when the late arriving reverberant sound is deprived of its low-frequency energy. The ear seems to judge spectral-balance in terms of an integration over several hundred milliseconds; it is willing to wait for the reverberant energy before making its evaluation of musical warmth. One of Schultz's conclusions was that the reverberant field can stabilize the overall spectral balance despite low-frequency deficiencies in the early sound.

CONDITIONS FOR GOOD HEARING

Let's take a moment to review what we have discussed so far. Starting immediately after the initial-time-delay-gap (whose duration establishes the "size" of the hall), we hear a number of individual reflections that perceptually "cue" us for our determination of the hall's characteristics that include articulation, definition, spatial imaging of the source(s), intimacy, presence, and ambience/spaciousness.

Subsequent to the early arrivals, the later reflections' density increases as time squared, so the density of reflections becomes extremely high after a short time. Therefore, for clarity's sake alone, we are primarily concerned with the statistical properties of the late-field and not its detailed structure. The quantity of RT60 is just that, a number—not the definition of what reverberation is. The balance of energy between the early- and late-field is the critical acoustical parameter that determines a hall's liveness, clarity, and warmth of sound. Simplistically, a hall's acoustical parameters are structured in terms of its components in the early-and late-field, and the balance between the two.

A concept that is most overlooked is the coupling of adjacent spaces—in fact, most tables of absorption coefficients include procenium openings. While a procenium may be absorbent for one space under consideration, it misleads us in that we overlook the effects of the reverberant energy of one space coupling to another. In most theaters the stagehouse may be larger than the auditorium, with a greater reverberation time which couples to the listening space. This may be used to the designers advantage by "fooling" the space into thinking it's bigger than it actually is. In designing musical performance spaces, one must satisfy the requirements of the source area, the listening area, and how the two interact with each other. While it is beyond the scope of this article, it must be understood that the acoustical requirements for performance/listening spaces include many aspects not discussed here, including site selection, noise criteria, room shapes, dynamics, ensemble for performers, and freedom from flutters and echos.

Acoustics is a science that constantly evolves around musical technology and musical trends. Musical instruments were developed empirically, and as they became reliable composers and musicians began using them in their works. As musical instruments grow, so do the requirements of room acoustics. It is the job of the acoustician to provide a "translation" system so that the musician may communicate his ideas to the listener. It is, therefore, the priority of the designer to accurately understand the requirements of the space, so that he can implement them into a physical design with good acoustics.

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