Honor's Paper

Concert Hall design

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On the Design of Concert Halls

Concert halls are not created equal. Once a rectangular structure with clearly delineated dimensions, concert halls exist today in diverse shapes and sizes, some of which are highly acclaimed for the rich listening experience they offer, while others are sharply criticized for failing to achieve this elusive quality. Regardless, each hall has its own unique acoustic environment (McCandless 1990, 7), also called the hall's "signature"; its own predominating frequency range, volume, and tone, mainly due to the architecture of the hall itself (Jaffe 2010, 15). Concert hall design, is both an art and a science, and as such, it lends itself to being analyzed from both perspectives.

As a musician and electrical engineer considering specializing in the field of acoustics, I am excited about exploring this topic in some detail. Although we have not covered the subject of acoustics specifically in University Physics 1 or 2, we do touch upon the study of waves at the end of both courses, of which the phenomenon of sound is a subset. In this paper, I will discuss the nature of sound waves and some of the physics preliminary to a broader understanding of concert hall design. I will analyze the evolution of the concert hall, from humble but time-tested "shoebox" beginnings to the ultra-modern design halls such as the Sydney Opera Theater or the Walt Disney concert hall, while investigating the physics behind what makes for a superior concert or performance hall. Finally, I will conclude with some brief remarks on the auditory system of human beings and psychoacoustics.

The joint collaboration of many experts make possible the establishment of those traditional edifices of high culture known as concert halls, such as designers, acoustical consultants, project architects, and specification writers (McCandless 1990, 7). Acoustic consultants are charged with the critical task of maximizing the pleasing effect of the way sound travels through a particular hall. One of the principle means they employ for engineering an ideal acoustical setting is through the utilization of noise control methods designed to minimize undesirable sounds both from sources internal and external to the structure (McCandless 1990, 7). This is accomplished in a variety of ways: from a careful consideration of the design of the physical structure itself, to the meticulous selection of absorptive and reflective materials with which to build and furnish it, and even the location on which the hall is to be built. (Mehta et al. 1999, 170-180)

Despite many technological advancements in recent years contributing to the modern engineering of concert halls, a clear-cut formula for reliably capturing the legendary characteristics of the ideal acoustical space—warmth, dimensionality, clarity—has not yet been devised, and perhaps never will, due to the inherent subjectivity involved in a listener's definition of an ideal acoustical space. Generally, the structure of the concert hall itself and the elements within it should be not only functional in terms of controlling or directing the sound, but aesthetically tasteful as well. While an appealing visual structure is certainly a consideration for those responsible for its creation, it is the intangible acoustic qualities that are primarily sought after by those involved in concert hall design and production. After all, they are providing a valuable service, and if the critics and patrons are not pleased with the result, their poor reputation will precede them, preventing them from procuring further contractual work.

Many people have attended a symphony, opera, or some other type of auditory entertainment at a concert hall or performance venue. However, it is a truism that most people are not cognizant of the feat of engineering that is the structure itself and all that accompanies its production, from its conception in the mind of the designer and preliminary modeling (Jordan

1980, 62) to its physical construction. Speaking from my own experience, when I had the opportunity to attend a modern adaptation of Pucini's opera, "La Boheme", at the Los Angeles Opera years ago, I did not consider all these subtle complexities. Fortunately, a lack of a deeper knowledge of the physics and engineering involved did not detract from my appreciation of the performance, whereas if the opera house had had a poor acoustical environment, it certainly would have dampened my enjoyment of that evening. Our ears are sophisticated instruments, and are capable of quickly assessing the acoustical quality of an environment.

The Physics behind Acoustics

For a deeper understanding and appreciation of acoustics, let us briefly consider a few fundamentals of the subject. The nature of sound seems an obvious place to begin. When we speak of sound, we are referring to sound waves, which are really pressure waves in flux that create an invisible disturbance of the surrounding air molecules, transmitted—directly and indirectly—from some sonorous body to our ears (Egan 1972, 3). $k = \frac{\omega}{c} = \frac{2\pi f}{c} = \frac{2\pi}{\lambda}$, where we designate k the *wave number*, with wavelength $\lambda = \frac{c}{f}$ (Beranek 1954, 7, 26). In acoustics, c represents the speed of sound, and *f* is the frequency in units of s^{-1}. $\nabla^2 A + k^2 A = 0$ gives the relation between the wave number and the amplitude of the wave in the elliptic partial differential equation (Tippner). Richard Feynman gave us the partial differential equation for sound traveling in one dimension: $\frac{\partial^2 p}{\partial x^2} - \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} = 0$ (Feynman et al. 2010, 48.10). The general solution to the wave equation in one dimension is of the form *p* = − − , where and are two equations, twice differentiable and whose derivatives are continuous. The first term represents the contribution of the outgoing wave itself, while the second term denotes its identical reflection back to the source (Beranek 1954, 22-25). Assuming standard conditions, the pressure flux is goverened by the partial differential equation of a three-dimensional wave: $\nabla^2 p = \frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2} + \frac{\partial^2 p}{\partial z^2}$ in rectangular coordinates, or more concisely: $\nabla^2 p = \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2}$ (Beranek 1954, 22).

Galileo Galiei (1564-1642) saw deeply into the nature of sound. He is quoted as saying: “[sound] waves are produced by the vibrations of a sonorous body, which spread through the air, bringing to the tympanum of the ear a stimulus which the mind interprets as sound.” (Tippner) Galileo was highly accurate in all these assertions, and his insight points the way to what today is called psychoacoustics, which studies the subjective perception of sound (Beranek 1954, 416). On a purely physical level, the pressure waves of sound causes our eardrum— “the tympanum of the ear”—to vibrate, and these vibrations are multiplied by the tiny bones in the middle ear, and then transported via fluid to the auditory nerve which leads directly to the brain (Egan 1972, 18). These vibrations are converted into electrical signals which the brain finally organizes into meaningful sounds, whether the source is the spoken word or Beethoven’s fifth symphony. It is often taken for granted, but without nature’s marvelous invention of the ear, we could not experience the sound of an orchestra, an oration, or an opera. Both figuratively and literally, there is more to the ear than meets the eye. What we see of the external ear, is actually a very small part of its overall structure, and the least significant.

Sound waves are examples of *mechanical waves,* whose source is some external agent and which is carried through a medium, such as water or air. Every mechanical wave is characterized by two general characteristics: they carry energy and momentum (Mazur 2007, 426). From this we can see that any acoustical occurence satisfies three criteria: it emanates from a source, it propagates through a medium along a certain path, and at the last stage, it is perceived by a receiver (Doelle 6). Sound waves traveling through air are primarily longitudinal, rather than transverse, which means that their displacement is in tandem with the direction of the wave is travelling (Mazur 2007, 429).

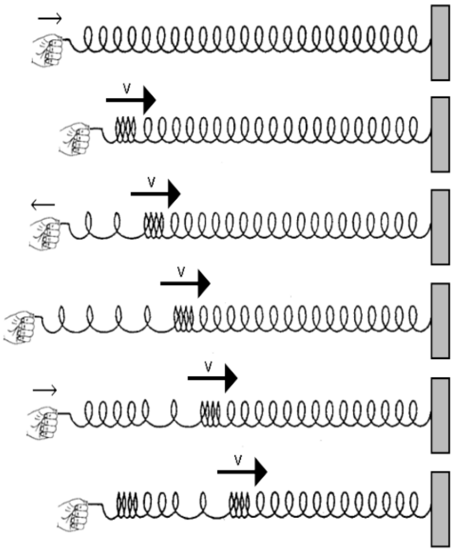
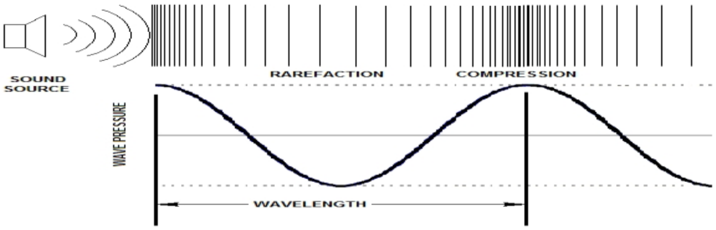


fig. 1 example of a longitudinal wave

In a vacuum, no sound can exist. Even if there is a sound producing agent or mechanism, there is no medium that is available to transmit the sound to a receiver. We can liken the air molecules to so many springs, which “slinkys” the sound away from its source at roughly 345 m/s (Beranek 1954, 10). Aristotle over two thousand years ago, described accurately the behavior of air when disturbed by sound as "…falling upon and striking the air which is next to it.” (Tippner) In the parlance of acoustics, we talk about a time-varying compression and rarefaction—regions of high and low pressure, respectively—of the pressure waves.



. **Rarefaction and Compression of Sound Wave** fig. 2

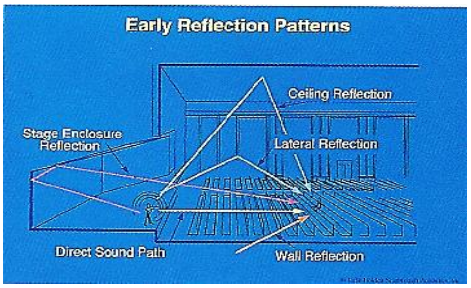


fig. 3

A History of Acoustics

Before the 20th century, concert halls were consistently long and narrow, with elevated ceilings. It was not aesthetics, or conformity to tradition that caused this uniformity of design, but a very simple reason: they were narrow because the timber would deflect and potentially collapse under their own weight if the width were extended by too great a degree. (Jaffe 2010, 11) This physical restriction imposed by the materials of early concert halls actually contributed to their superior acoustics, for, in addition to the direct radiation of sound toward the audience it caused many early reflections, principally the lateral ones, to reflect off of the side walls and reach the listener's left and right ear very slightly out of phase, bestowing a rich binaural texture to the music sound and enhancing the audience's listening pleasure.

. Composers such as Haydn, Vivaldi, and Mozart had the acoustics of these halls in mind as they were composing (Jaffe 2010, 14-15). Although these so called "shoebox" halls had their own drawbacks, primarily visual—those who were seated farther toward the back of the hall couldn't recognize the performers distinctly (Jaffe 2010, 11), but also auditory: they were not in an positioned so as to hear the fullness of all the early reflections, such as the lateral, stage enclosure, and ceiling reflections which had their focal point near the front of the hall (Jaffe 2010, 11).

In the early 1900s, access to low-cost, mass-produced steel made possible the inclusion of reinforcements that provided greater stability to the structure of the hall, and some architects began experimenting liberally with the traditional concert hall design (Jaffe 2010, 15-17). Those who sponsored the construction of the halls were pleased, as the accommodation of more people within the hall meant higher profit margins. Around the same time, special materials became available that would dampen the reverberations and unwanted echos (Jaffe 2010, 22). Some designers increased the width of the halls dramatically, causing a delay of the lateral sound reverberations from the walls to the listener’s ears, which resulted in much consternation among critics and many of those in attendance. Because of the complex patterns of early and later reflections that resulted from this early experimentation, there evolved a distinct qualitative (and quantitative, though not quantifiable at that time) difference from one concert hall to another (Jaffe 2010, 15). Modern designers can actually convincingly mimic the traditional acoustical effect of attending a “shoebox” hall, by creating a similar pattern of sound reflection, while exercising liberally the freedom to alter the shape itself (Jaffe 2010, 19).

Acoustical/architectural advancement came to a grinding halt after the Greek and Roman era, which had made significant strides in outdoor amphitheaters, some that were enclosed, and some that were not. Cathedral acoustics were horrible because of echoes and unwanted reverberations. The late, great American Concert hall designer W.C. Sabine, produced a renowned replica of a European style “shoebox” concert hall at the turn of the twentieth century with his Boston Symphony Hall, with one unique exception (Jordan 1980, 35-37). Sabine, apparently by intuition alone, placed the orchestra in a separate semi-enclosed section from the main hall, contributing to the early reflections of the hall, although the term “early reflections” did not exist at the time (Jordan pg. 37). The general idea of early reflections is that the aural reverberations that occur very quickly after the notes themselves give a feeling of spaciousness and richness to the music. If they are extended even a fraction of a second too long, they become late reflections, and the two sounds will be perceived as separate, and referred to as delay.

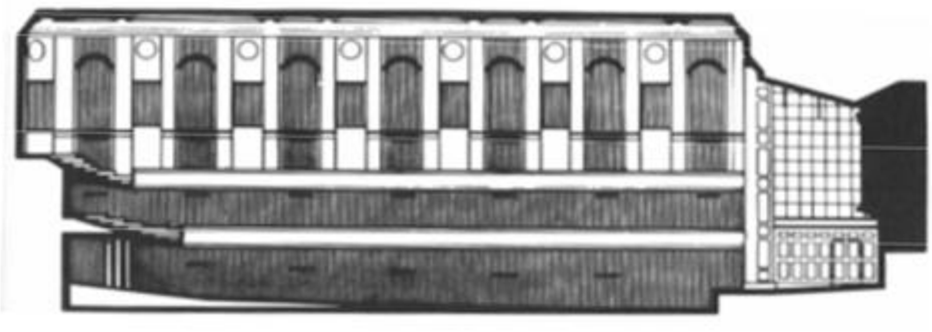


Fig. 4 Boston Symphony hall—section

In addition to bequeathing to Americans one of the finest example of a “classical” concert hall, easily competing with the finest Europe had to offer, Sabine single-handedly elevated the credibility of acoustics to a science from an intuitive art-form, through a collection of seminal papers on the topic (Beranek 1954, 1).

In researching this topic, there is a two letter combination of prime importance in concert hall design: RT (Jordan 1980, 107). RT stands for reverberation time, and intuitively, we can understand why it would be such an important value. In a large enclosure, if you are hearing sounds from .2 or .3 seconds ago, it can seriously detract from the appreciation of what is currently being heard. In the extreme, all that can be perceived is a torrential downpour of noise (Mehta et. al. 1999, 27). In an irregular shaped enclosure, such as the Sydney Opera Theater, it can be hard to predict how the sound field will behave.

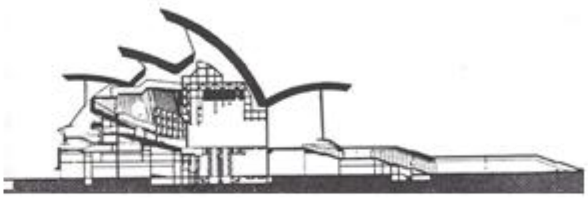


Fig. 5 interior layout of the final design of the Sydney Opera Theater

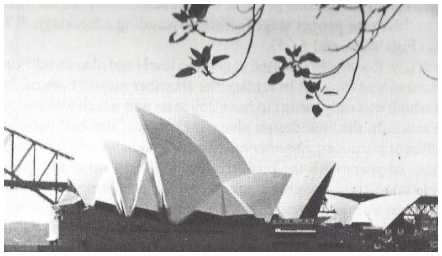


Fig. 6

Sydney Opera Theater

Modern concert halls like the Sydney Opera Theater often implement amplification systems, also known as electronic enhancement systems, which are used to make possible congress, or human speech, in addition to enhancing it with sparse special effects (Jordan 1980, 112). Through the use of tiny delays in the signal, the sound department of a concert hall can actually closely mimic, if not replicate, the experience of hearing the lateral reflections that helped to secure the fame of early concert halls. Usually, amplification is used to correct for some defect in the natural acoustics of a concert hall, not simply to boost the sound level. Interlinked speakers are placed in strategic positions throughout the building and are often used to support the particular type of production that is being performed (Kai 2001).

The difficulty is that the acoustic demands for a spoken word performance, an opera, and a symphony are drastically different. With speech, the aim of the acoustician is to reduce the delay from the time the speech is delivered to the time it reaches the audience's ears, because if the reverberations are in excess of 100 milliseconds, the sounds tend to get so convoluted that it is hard to decipher what is actually being communicated. An articulate, full-bodied delivery can degenerate to one that is muddy and obscured by too many echoes and reflections building upon one another. In the case of a symphony, the reverberation time can be extended to roughly two seconds, so that all parts of the orchestration can be appreciated in their totality. For an opera, a balance is sought between the two, since an opera blends speech and vocals with orchestration (Kai 2001).

The Hearing Mechanism

After all the proposals, designing, small-scale modeling, consulting, calculations and construction have been completed, and the work is complete, the final judge of the quality of the concert hall lies in the hands, or should I say ears, of the audience. The hearing mechanism encompasses not just the outer and inner ear, but the brain as well[1]. The ear is a marvel: not just a microphone, it acts as a multiple-band filter, revealing its discriminating nature. Moreover, it can discern sound pressures from 10^4 —— at its upper range to 10^{-4} —— at its lower range[1]. To provide a sense of scale this is, the displacement caused by these very small frequencies cause a displacement of the ear drum of less than — the diameter of a hydrogen molecule[1]! Although sound waves add by the principle of superposition, we do not hear that way[1]. The field of psychoacoustics, the study of the interplay between sound and one's perception of it is no less fascinating. Four speakers, identical to one another, each of which are placed in four identical rooms, will be ranked of different volume intensities[1]. In his masterful work, *Acoustics*, Belenuk writes, "if one selects his own components, builds his own enclosure, and is convinced he has made a wise choice of design, then his own loudspeaker sounds better to him than does anyone else's loudspeaker. In this case, the frequency response of the loudspeaker seems to play only a minor part in forming a person's opinion[1]."

[1] (Belenuk 1954, 389)

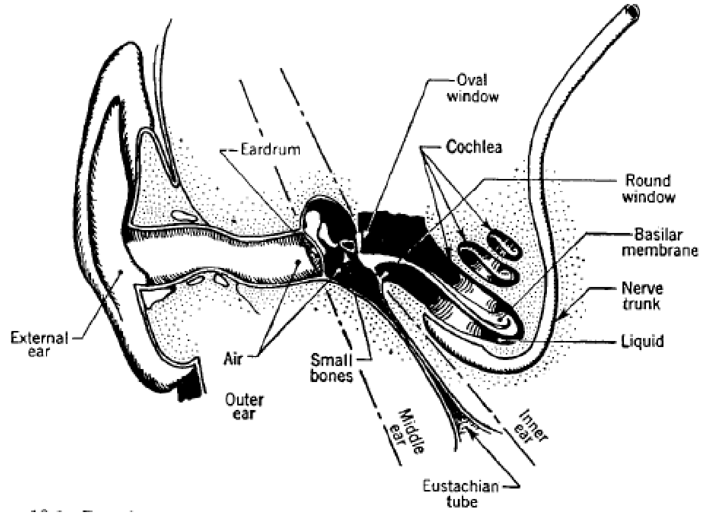


fig. 7 human ear—detail

Conclusion

In Conclusion, it has been gratifying to study the diverse spectrum of concert halls and the variegated uses to which they can now be put due to modern technology. Acoustics and psychoacoustics is a fascinating field of study to which I would like to devote more time to studying in the future. We have come a long way since the time of the shoebox concert hall, but some things do not change. High quality acoustics, for instance, are still just as important in as ever in concert hall design. I look forward to watching the development of concert halls as we move into the future.

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