Architectural Acoustics

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Since the earliest civilizations, music has been an integral part of our lives as humans. Music has been used throughout the ages as a supplementary form of communication, a way to stimulate the mind, as well as for pure entertainment value. Because music has become such a vital component to our society, it should come as no surprise that humans have been working for millions of years to create environments more conducive to musical performance. Science has lent itself to the study of acoustics to accommodate this need for such an environment. This has become a continuous effort because of the nature of music and the act of listening. Sound quality is a subjective assessment. What we consider positive aspects of a sound varies from person to person and also varies over time periods in our history. Design criteria needed to evolve to accommodate these trends. Aspects of architectural design have also developed to accommodate for the changing purposes for these structures; the ancient Greeks and Romans needed a way to project the voice for performances of the great tragedies, whereas now we are concerned with performance of popular music and theatre. As technology and our knowledge of acoustics expand, architects and physicists continue to modify the designs for concert halls and theatres to achieve the optimum acoustic experience for today's audience.

To fully understand and appreciate the design elements of these structures, a basic knowledge of physics, materials science, and architectural design is necessary. One of the most essential of these topics is the physics involving the path of a sound wave from source to receiver. An enclosed space, like a theatre or a concert hall, provides an infinite number of different paths for the longitudinal sound wave to take in traveling from source to receiver. Depending on the properties of a surface, a sound wave will experience reflection, diffraction, diffusion, or absorption when contacting the surface. The reflection of a sound wave is simply the sound wave "bouncing" off of a surface while retaining most of the sound wave's original energy. The diffraction and diffusion of a sound wave occurs when the wave bends or scatters to move around some obstruction, again while retaining the wave's original energy level. When a sound wave encounters certain surfaces, the material will actually absorb some of the energy. An absorption coefficient is used to evaluate the amount of sound absorption of a particular material. The absorption coefficients of some common materials with sound waves of various frequencies are included in Table 1. As the table indicates, the most absorbent materials are the theatre patrons themselves and any fabric materials. Theatres and other listening environments are carefully designed to balance the amount of reflection and absorption of energy to create an appropriate sound.

Table 1: absorption coefficients for various materials; larger coefficients indicate a more absorbent material

Material	Frequency in Hertz		
	250	1000	4000
Marble	0.01	0.01	0.02
Acoustical Plaster	0.45	0.92	0.87
Concrete	0.01	0.02	0.03
Audience Member	4.3	7.0	6.0
Cloth Seats	2.8	5.0	4.4

Another factor of a structure which greatly affects the quality of a sound is the reverberation time. Reverberation occurs when sound energy remains after the energy source has stopped producing sound. The reverberation time is the time necessary for this remaining sound to decay; for practical purposes a sound is considered to have decayed to 60 dB. The value of the reverberation time depends on the room volume and the area of absorptive materials as shown in the equation:

$$R_{Time} = 0.016 \times V/A$$

where:
0.016 is a constant of proportionality
V is the Volume of the room (m^3)
A is the Area of absorption (surface x coefficient of absorption m^2)

The purpose of the space is very important to consider when deciding what reverberation time is ideal for a listening environment. Sound energy that lingers for a prolonged period of time, having a great reverberation time, can be problematic for the production of spoken words; the clarity of a sound is compromised, as the long reverberation time blends the sounds together. However, a long reverberation time might be desirable for music from the romantic period, which is known for blended tones and swelling dynamics.

Resonance is an additional concept that applies to the science of architectural acoustics. Resonance occurs when an object is vibrating at its natural frequency. Everything has a natural frequency, which causes it to vibrate at different modes, which is called its resonant frequency. A theatre can be thought of as a giant resonator. When sound energy stimulates a surface of the structure with the resonant frequency, the sound quality will be affected. One of the most interesting applications of this idea is in the construction of domes as resonators to specifically distort or channel a sound.

These basic ideas can be used to explain some of the more interesting acoustical phenomena found in architectural history. The following case studies demonstrate these principles of physics as applied to architecture throughout the ages:

CASE STUDY: The Classical Period- Epidaurus, Greece and Aspendos, Turkey

Greek Theatre at Epidaurus

The ancient Greeks and Romans were among the first known to create a structure for the sole purpose of creating a better listening environment. These people used these constructions to perform such famous works of theatre as *Oedipus the King* and *Lysistrata*. Two of the more renowned of these early structures are the Greek theatre at Epidaurus in Greece and the Roman theatre at Aspendos in Turkey. Epidaurus, built around 350 BC, and Aspendos, built around 24 AD, are both acoustical marvels. Speech is still intelligible from the furthest seats in Epidaurus, around 70 meters from the stage; the furthest seats in modern theatres are usually around 50 meters away from the source. Although somewhat primitive by today's standards, these structures were effective and are still used for performances.

Greek theatres generally seat patrons in a semi-circle, or fan shaped placement, while seating in classical Roman arenas exist in an elliptical or circular arrangement. Elliptical shapes in architecture produce some interesting acoustical properties. Sound waves emitted at one focus of the ellipse will be reflected off of the interior walls and converge at the other focus point. This is the same principle behind parabolic whispering dishes.

In both theatres, the seats were raked at a very steep angle, around 30° to 34°, to the horizontal. This steep angle was implemented to allow a clear view of the stage for each audience member. Consequently, this angle created favorable acoustic conditions. The steep raking creates a shorter path for the direct sound, with few interferences in that direct path from source to receiver. There are relatively few reflected sounds and a very short reverberation time in theatres of this design. The short time interval from source to receiver improves the clarity of the sound. This was absolutely necessary for the audience to understand the lines in the performances.

The steep raked seating at Aspendos

As shown in table 1, people absorb a great amount of sound energy. The presence of an audience has a major affect on the sound quality in any acoustic system. The presence of large absorbing material can reduce the intensity of the sound as it moves from source to receiver. The steeply raked seating in these amphitheatres helped to reduce this factor. The rows of people are arranged such that there is a clear path from the stage to each person; other audience members do not interfere with this path. The path is relatively free from absorbing agents.

Epidaurus sits atop a mountain

Another contributing factor to the acoustical properties of these theatres is the location. Background noise is another factor that can greatly influence the audiences listening experience. The Greek theatre at Epidaurus is located on a mountaintop, as is the theatre at Aspendos. As well as providing a breathtaking view, these locations were beneficial because they were located away from the noise of the main cities.

CASE STUDY: The Gothic Period- The Byzantine Church of Saint Mark's in Venice

Church if Saint Mark's, Venice

By the 9th and 10th centuries, during the gothic period of architecture, elements of acoustical design had changed to comply with the need for the performance of religious prayers and music in the church. The gothic period gave rise to many of the famous cathedrals found in Western Europe. The 9th century Byzantine church of Saint Mark's in Venice, Italy is one of these gothic cathedrals, which is notorious for its unusual acoustic properties.

Cathedrals are known for their large size and brilliant architectural detail. The huge volume of these buildings creates a great time period for the path of the sound wave from source to receiver, a large reverberation time. The reverberation affects the clarity of sounds. Spoken prayers in spaces with these large reverberation times would run together and become somewhat lyrical. As a result, over time some of the spoken prayers became chants that are used in services today.

The church of Saint Mark's houses a large Greek cross in the center. There are five domes on the top of the cathedral, one atop each end of the cross and one over the very center. It is the placement and the properties of the domes themselves, which create acoustic properties in Saint Mark's unlike any other. A dome focuses sound because of its interior parabolic surface. The sound waves are reflected off of the curved surface and the energy converges at the focus point of the structure. The qualities of a sound in a domed structure vary depending on the curvature of the dome and the coefficient of absorption of the material of the inside of the dome. Domes can be designed to control the echo affect, to either hinder it by using an absorbent material or to lengthen the reverberation time by using a more reflective material.

Five domes of Saint Mark's

The interior of the domes of Saint Mark's are marble, decorated with tile mosaics which do allow a considerable reverberation time. Each dome is fashioned a little differently and affects a sound in different ways. One of the domes is said to produce brassy tones while the opposite dome produces silver tones. Composers used to compose music especially for a specific cathedral to take advantage of the acoustical nuances of the building. Giovonni Gabrieli composed music specifically for Saint Mark's in Venice. He would have the audience sit under the main dome and have sounds projected from two of the domes on either side to experience the different affects of both domes.

CASE STUDY: The Renaissance- Teatro d'Argentina and Theatre Royale

The Renaissance and Post-Renaissance periods produced the great opera houses and playhouses of the seventeenth and eighteenth centuries for the performance of non-secular music and theatre. Architects created the final design elements of these opera houses by troubleshooting problems of the original designs. This method prompted creative engineering and some rather interesting solutions to common problems in acoustics. The renovations to the famous Teatro d'Argentina are particularly interesting.

The Teatro d'Argentina was built in Rome in 1732. It was typical of opera houses of that time period. It had seats arranged in a horseshoe pattern surrounding a central stage; the orchestra was placed in a section in directly in front of the stage. The Teatro d'Argentina also had problems typical of opera houses of the time; the audience had troubles hearing the performers over the orchestra. The sounds, particularly dialogue lacked intensity. This problem was exaggerated by the area of high absorption found in the opera houses; these theatres were decorated with a lot of cloth furnishings, which left too few reflective surfaces. The solution to this problem was very inventive as well as effective. The construction team dug a substantial trough underneath the stage and filled it with water. This provided a much highly reflective surface, which helped to project more sound to the back areas of the theatre.

Artist Giovanni Paolo Panini's depiction of the Teatro d'Argentina lavishly decorated in sound absorbent cloth

CASE STUDY: Modern Architecture- Philharmonic Hall, New York

There are many interesting examples of beautiful acoustics in modern architecture. One example, which includes many of the architectural elements common to more recent designs is the New York Philharmonic Hall, built in the 1950's. Recent research in the field of acoustics has become more focused on the audience experience. Scientists are concerned with the feelings that the listener experiences during a performance. Acoustic consultant for the construction of the Philharmonic, Leo L. Beranek, wanted the listener to feel a sense of intimacy, no matter where they are sitting relative to the performance. He made this one of the main criteria when designing the Philharmonic.

In his own research, Beranek found that actually the initial-time-delay-gap, and not the reverberation time determines the perceived amount of intimacy. The initial-time-delay-gap is the time between the source and the first reflection; supposedly, a smaller initial-time-delay-gap, like around 20 ms) would produce a more intimate experience for the listener. The way to achieve this result is to move surfaces closer to the source, so that the sound wave does not have to travel so far to reach the first reflective surface, decreasing the time delay. The surfaces need to be close to the source, but should not interfere with the sounds direct path to the receivers. The solution for the Philharmonic as in many other modern theatres and concert halls was to suspend reflective panels from the ceiling, angled so that the sound would project into the audience.

The delicate science of acoustics as applied to architecture is ever changing. As long as music continues to progress and evolve, the criteria of the listening environment will need to advance as well. The design process that began so many centuries ago will continue for as long as music remains indispensable in our culture.

Works Cited

Backus, John. The Acoustical Foundations of Music. New York: Norton, 1977.

Barron, Michael. Auditorium Acoustics and Architectural Design. New York: Chapman & Hall, 1998.

Brooks, Christopher N. Architectural Acoustics. Jefferson, NC: McFarland, 2003.

Cavanaugh, William J., and Joseph A. Wilkes, eds. Architectural Acoustics: Principles and Practice. New York: John Wiley & Sons, 1999.

Lord, Peter, and Duncan Templeton. The Architecture of Sound: Designing Places of Assembly London: Architectural Press Ltd., 1986.

Matthews, Kevin. Saint Mark's. Artifice Inc. 12/12/2003 <http://www.greatbuildings.com/buildings/St_Marks.html>.

Manta, Victor. Saint Mark Basilica. 12/29/02. 12/12/03 <http://www.values.ch/Venice/San%20Marco%201.htm>.

Price, John. Roman Theatres and Amphitheatres as a Model for the London Playhouses. University College Worcester. 12/12/2003 <http://www.pricejb.pwp.blueyonder.co.uk/Rome/Rome2.htm#CONCLUDING%20COMMENTS>.

Schaudinischky, L. H. Sound, Man, and Building. London: Applied Science Publishers Ltd., 1976.

Shea, Mike, and F. Alton Everest. How to Build a Small Budget Recording Studio From Scratch. New York: McGraw, 2002.