Gazi University Journal of Science
Part B: Art, Humanities, Design And Planning
GU J Sci Part:B
1(3):49-56 (2013)

Use of Scale Modeling for Architectural Acoustic Measurements

Ferhat ERÖZ[1,♠]

[1] *Atılım University, Department of Interior Architecture & Environmental Design*

Received: 09.07.2013 Accepted:01.10.2013

ABSTRACT

In recent years, acoustic science and hearing has become important. Acoustic design tests used in acoustic devices is crucial. Sound propagation is a complex subject, especially inside enclosed spaces.
From the 19th century on, the acoustic measurements and tests were carried out using modeling techniques that are based on room acoustic measurement parameters.
In this study, the effects of architectural acoustic design of modeling techniques and acoustic parameters were investigated. In this context, the relationships and comparisons between physical, scale, and computer models were examined.

Key words: Acoustic Modeling Techniques, Acoustics Project Design, Acoustic Parameters, Acoustic Measurement Techniques, Cavity Resonator.

1. INTRODUCTION

In the 20th century, especially in the second half, sound and noise concepts gained vast importance due to both technological and social advancements. As a result of these advancements, acoustic design, which falls in the science of acoustics, and the use of methods that are related to the investigation of acoustic measurements, became important. Therefore, the science of acoustics gains more and more important every day.

It is known that the first numerical observation and the invention of a sound measurement device were made by Pythagoras (580 – 500 B.C.). Aristotle's "Sounds and Hearing" contains impressively accurate physical concepts about sound propagation. Also, Euclid's studies on sound still maintain their value. The second numerical observer seems to be Theophrastus. Later, there were no experimental studies until Galileo Galilei (1564 – 1642). However, the dawn of acoustics is accepted to be the date when Newton (1642 – 1727) defined the speed of sound. Newton indicated the speed of sound in gases almost accurately. With Rayleigh's (1877) "Theory of Sound", acoustics was born as a science [1].

A scientific context began to take shape with the theoretical sound studies of Prof. Wallace C. Sabine, who laid the foundations of architectural acoustics, between 1898 and 1905. Modern acoustics started with studies that were conducted by Sabine and auditory quality was related to measurable and calculable parameters.

In the 1900s, he devised the human voice localization theory by using Interaural Time Differences (ITD) and Interaural Level Differences (ILD) of sounds that reach each ear. The time and level differences between two ears make it possible for humans to detect sounds sources in space.

Architectural acoustic studies are mainly related to the artificial environment. In other words, in order for a study to be in the context of architectural acoustics, the structure needs to be reinforced with structural elements. Acoustics, the science of sound, is the motion

♠Corresponding author, e-mail: erozferhat@yahoo.com

and results of motion of sound waves propagating through air. At this stage, wave motion in fluids and related definitions come into play. From an acoustic point of view, we are interested in longitudinal waves, which propagate in a medium of air that we define as sounds waves and their motions and actions. In the field of architectural acoustics, wave motion is the fundamental data.

Architectural acoustics creates the criteria for either the existing or designed volumes within the structure. This is considered in two stages. These stages are defined as noise control and room acoustics. In volumes, where sound is important, such as a concert hall or theatre, the fundamental factor is a homogeneous distribution of sound and keeping energy loss under control. In this study, fundamental acoustic concepts, acoustic wave motion properties (propagation, absorption, reflection), and acoustic design modeling and measurements and related definitions are mentioned. Reverberation time is the most well-known and oldest parameter. Although other methods are being investigated, today, the Sabine equation and its improved form are still used to explain volume acoustics and its principles. The accuracy of acoustic design and calculations are examined by using architectural acoustic modeling.

2. MODELING

In recent studies, with the advancement in acoustic design and measurement tools, the importance of modeling has increased. Within this subject, two-dimensional modeling is done firstly by using a ripple tank in order to relate sound propagation in nature. Scale modeling has been in use for acoustic design, where sound is important, in places such as concert halls, opera and theatres, since 1930s. In this modeling method, frequency increases proportionally with scale. In Room acoustics, the development of parameters occurred parallel to the development of modeling. Modeling is one of the major methods to control sound from its early days.

2.1. Ultrasound-Schlieren Photography

Schlieren, in its singular form “schliere” means “line or trace” in German. Schlieren is used to investigate wave motion in fluids and to determine acoustic field properties.

For quite a long time, optical methods have been used to investigate wave motion in non-homogeneous media. In 1670, Robert Hooke (1635 – 1703) demonstrated a simple method, which is known today as the shadowgraph method, in order to show Royal members the smoke created by a candle.

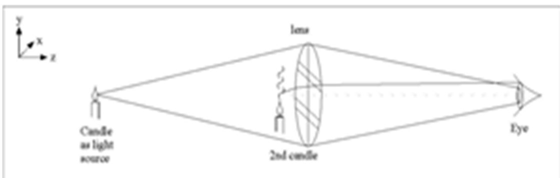


Figure 1. Hooke’s original schlieren system, using two candles, a lens, and the human eye [2].

The invention and usage of schlieren photography method is generally tied to August Toepler (1836 – 1912).

In 1913, a study regarding the use of ultrasonic waves and schlieren photography method was published by Sabine, and reflection in the walls and ceiling were observed on a two-dimensional model. These wave reflections are merely the smoke, which is diffused into the media, made visible by a strong light source and be photographed. Here, wave front density is greater than the surrounding air, and light waves are refracted.

Refraction is the change in direction of the light while passing to another transparent medium. The refraction of light while passing through different media also causes differences in its speed. The speed of light in a vacuum is greater than other media. The speed of light for a specific medium is constant. The refraction index for a medium (n) is the ratio speed of light in air (c) to the speed of light in the considered medium (c_0). (n) is a dimensionless constant, which is greater than one.

$$n = \frac{c}{c_o} \qquad (1.1)$$

where; c: speed of light in air (m/s)
c_o: speed of light in medium (m/s)
n: refraction index (n>1 and is a dimensionless constant)
n2>n1

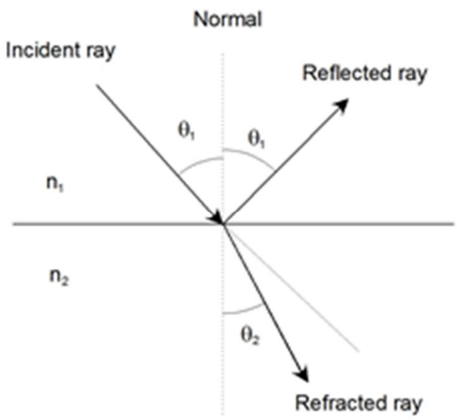


Figure 2. Refraction of Light

Patterns emerge as a result of refraction. In this photography method, low-density and high-density zones in a fluid exhibit differences (Figure 1-3). As a result, compression and expansion zones differ from each other.

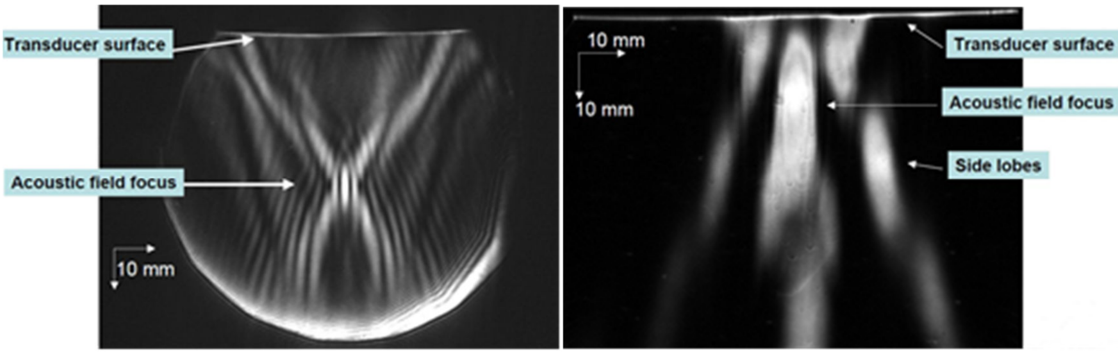


Figure 3. (a) High frequency-compression zone, (b) Low frequency-expansion zone, schlieren image [3].

The quality and properties of the light source are important for the quality of the schlieren image. Usually, as the light source, white-hot lamps, light bulbs, or lasers are used. In the schlieren photography method with a laser light source, better results are obtained compared to other light sources.

In volumes, where sound is important, the schlieren photography technique is important in order to check the homogeneity of wave propagation and remove problems. This method is used to visualize acoustic, thermodynamic, and physical phenomena.

2.2. Ripple Tank Modeling

Water waves are extensively researched in hydrodynamics, other than acoustics. In particular, acoustic or electromagnetic waves exhibit complicated behavior. These waves move through fluids. A ripple tank is used for investigating the properties of an acoustic wave (reflection, refraction, interference, and diffraction).

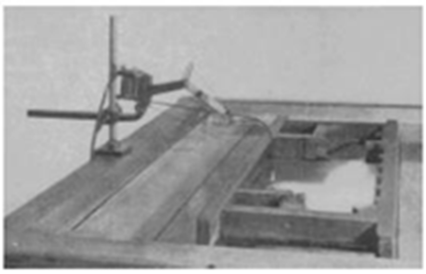


Figure 4. Ripple Tank [4].

Reflection: Sound changes direction by bouncing off the boundaries of the volume. This is important in sound-related volumes. Here, a model of a concert hall, which has a scale of 1/50, is placed into the ripple tank and a wave generator is located at the stage. The wave generator is being used as a sound source. In order for the reflection images to be understandable, the frequency (*f*) and amplitude setting of the light source, which will be used in the application, should be configured. A frequency of 20 Hz is suitable from the image efficiency point of view. As a result, reflection and influence area measurements should be verified by equations;

$$\theta = \theta' \tag{1.2}$$

where; θ: incident angle
θ': reflection angle

Refraction: In order to photograph the model, which is located in the ripple tank, a stroboscope-mounted light source is set to a frequency of 15 Hz or smaller. Measurements of the refracted waves are made. Furthermore, the measurements of influence area and refraction are verified by using the following equation;

$$\frac{1}{c_1}\sin\theta_i = \frac{1}{c_2}\sin\theta_r \tag{1.3}$$

where; c1: incident wave speed (m/s)
c2: refracted wave speed (m/s)
θ_i: incident angle
θ_r: reflection angle

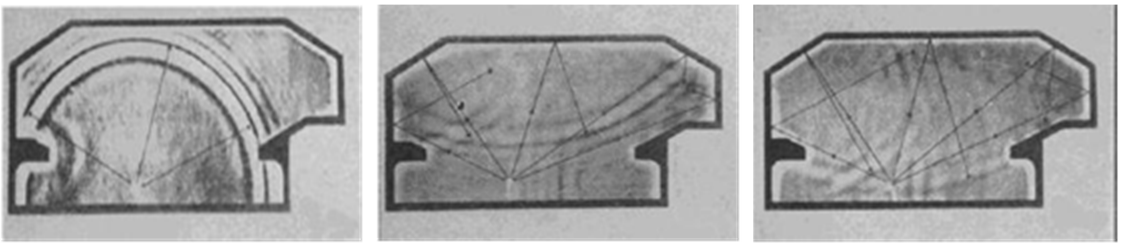
Diffraction: It is possible to test the forms that are used at the borders of the model. A wave generator is set to 20 Hz and half the amplitude. The propagation angle of the radial waves in the model, θ can be determined. Propagation graph width is verified by the following equation;

$$a\sin\theta = \lambda \tag{1.4}$$

where; a: the distance between the regulator and the reflected material, (Distance traveled by the wave)

λ: wavelength, (m)

A ripple tank is an important modeling method in order to achieve acoustic comfort. In addition to its benefits in structural acoustic design studies, it also provides the ability conduct experiments about the volume's geometry, form and shape.



(a) 1/34 seconds (b) 1/18 seconds (c) 1/15 seconds

Figure 5. 1/50 auditorium scale model, ripple tank test for reflection wave 1/34s, 1/18s, 1/15s [4].

In Figure 1-5, a 1/50-scaled model of an auditorium is photographed by using the Ultrasound – Schlieren technique in a ripple tank with fixed-duration reflections. The water depth of the experiment with reflections in 1/50-scaled model should not be less than 10 mm. When the wavelength in the model was 13 mm, it is observed that the wavelength in the 1/1-scaled auditorium is approximately 610 mm (at 560 Hz). [5]

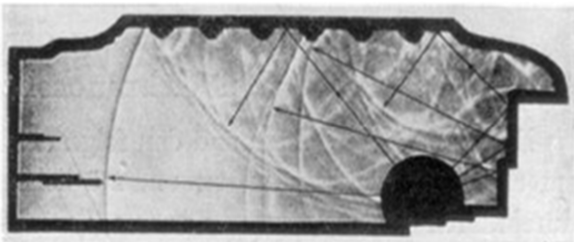


Figure 6. Schlieren photograph showing reflections of ultrasound wave fronts in a sectional model of the Gewandhaussaal in Leipzig [5].

Figure 7. Leipzig Gewandhaus (1835) was destroyed during World War II.

Sound propagates as waves and creates reflections. It is easy to create a series of waves that can be tracked within the ripple tank with the help of a hand motion. These waves generate a sound pattern with a continuous tone, which is called a standing wave pattern.

2.3. Optical-Light Beam Modeling

With the Optical-Light Beam Modeling, reflections that are related to function and function-related volume, in the ceiling of a two-dimensional model of Okuma Memorial Auditorium, Waseda University, were investigated.

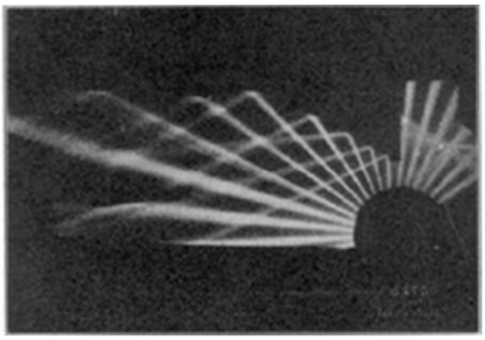


Figure 8. Light beam investigation of reflections in a sectional model of Okuma Memorial Auditorium [5].

Figure 9. Optical model of a hall with a concave ceiling. The energy distribution on the floor can be studied on a photographic plate [5].

In the study published in 1929, a cylinder, which has slits in it in order to allow light beams to pass through, was used as a sound source using this method and reflections were generated (Figure 1–8, 1-9). In other words, light and sound waves behave identically.

	Schlieren method	Ripple tank	Optical - light beams	Optical - distribution	Optical - laser beam
Earliest report	1913	1921	1929	1936	1985
Dimensions	2D	2D	2D	3D	3D
Physics	Ultrasound	Water	Light	Light	Laser
Wavefront	X	X			
Wavelength		X			
Typical scale	1:200	1:50	1:50	1:200	1:10
Early reflections	X	X	X		X
Energy distribution				X	
Surface absorption	X		((X))	((X))	((X))
Scattering effects	X	X			
Diffraction effects	X	X			

Table 1. Some characteristics of physical models. [5].

These methods are important tools for directing the sound in the structure and achieving functional acoustic parameters. We see that these methods contain different data collected by experiments that have been conducted (Table 1–1).

2.4. Acoustic Scale Modeling

Acoustic modeling techniques are a fundamental step of room acoustics and used for controlling and improving the homogeneous propagation of sound in volumes, where sound is of importance, for example, ensuring that sound is perceived perfectly by every single audience and speaker in a conference room.

Acoustic modeling enables alterations in acoustic design approaches and determining the volumetric acoustic parameters. It is a fast and an effective method to achieve acoustic comfort in a structure. Using the data, which is acquired during a model study, provides effectiveness to volumes that are related to sound.

An acoustic modeling includes scaled models of functional volumes, of which acoustic design are completed. Small-scale models (scales of 1/50) usually are used in the early stages of acoustic design to assess the decisions about the size and shape of the volumes. Large-scale models (scales of 1/20 or 1/10) are used to evaluate the detailed acoustic design of the volume during the design process. Adequate sound propagation is achieved by electronic signals and amplifiers in the necessary zones within the volume as necessary. The main approach here should be avoiding electronic systems as much as possible to conduct measurements using scaled microphones at certain zones within the model on sounds acquired directly from the source, or from reflected and refracted sounds. Observed impulse responses are recorded on a computer with the assistance of an oscillator [6].

In the 1/10 scale model, materials and sizes used in the volume should be reduced to one-tenth of their actual values. The absorption coefficients of the materials that are used in the model should respond similarly for frequencies ten times higher than the actual values. For example, concrete has an absorption coefficient of 0.01 at 1000 Hz. In a model to simulate concrete, the material to be used should have an absorption coefficient of 0.01 at 10000 Hz. The frequencies generated by the sound source should be increased by the same ratio as the model's scale. If original size frequencies range between 125 and 4000 Hz, in a scale of 1/10, this range becomes between 1250 and 40000 Hz. Since frequency values increase according to the scale, the humidity within the model increases the absorption rate making it greater than original size values. Therefore, either less humid conditions (humidity < 3%) should be provided or absorption capacity should be manipulated mathematically in the computer programs when using small-scale models. In the studies of acoustic models, the necessary corrections and related development studies are done for 1/10-scale models. Scaling processes are built upon two main equations;

$$c = \frac{d}{T} = \lambda f$$

$$c = d / t = \lambda f \qquad (1.5)$$

where;	c: speed of sound	(m/s)
	d: distance	(m)
	t: time	(s)
	f: frequency	(Hz)
	λ: wavelength	(m)

	Technicolor models El. dynamic source	Technicolor models Impulse source	Half-tone models	Black & white models
Earliest report	1934	1956	1968	1979
Typical scale	1:8 - 1:20	1:8 - 1:20	1:8 - 1:20	1:50
Source	Loudspeaker	El. spark	El. spark	El. spark
Source directivity	X	(X)		
Microphone receiver	X	X	X	X
Dummy head receiver	X	X	(X)	
Surface absorption	X	X	(X)	((X))
Early reflections	X	X	X	X
Scattering effects	X	X	X	X
Diffraction effects	X	X	X	X
Impulse response	X	X	X	X
Reverberation time	X	X	(X)	(X)
ISO 3382 parameters	X	X	X	(X)
Auralization	X	X	(X)	
Time for construction	12-24 weeks	12-24 weeks	8-20 weeks	3 weeks
Time for measurements	4-8 weeks	4-8 weeks	3-8 weeks	1 week

Table 2. Some characteristics of acoustic scale models. [5].

2.5. Computer Modeling

The functional interior space should first be modeled in three dimensions virtually. Many computer programs and some computer-aided design programs' interface programs are capable of performing virtual acoustic modeling. In virtual space, it is assumed that the sound source is artificial and on the stage. Later on, the reflections of sound that is generated by the artificial sound source can be predicted at certain selected points within the space. Acoustic measurement can be calculated throughout the space as well as for a single point.

The direction and frequency characteristics of sound sources are listed in computer programs that can be found in the market. Virtual sources enable sound waves to propagate within the interior space. There are two main methods that are used in the computer model to improve a space's impulse response. These are the beam method and the image tracking method. In the beam tracking method, selected beams propagate from the source into the space. Radiated beams will reflect from the boundary surfaces of the space. Here reflected beams can be considered as sound waves. The amplitudes and arrival times of the sound waves will be recorded at selected points in the model. Within the octave band frequency range, space surfaces are assigned absorption coefficients. For auditorium acoustics, the approximate propagation and diffraction data of the sound can be obtained using several computer programs. Studies on this subject are being conducted. The space's acoustic impulse response and reflection predictions and results can be recorded. Some programs may not be able to calculate more than one reflection separately. On the other hand, the photography method works retrospectively. Reflections form computer-selected sources are again reflected from computer-selected receivers on the space's surfaces. The beams that propagate the surfaces of the interior space should be tracked from the source on the stage [6].

Computer modeling studies are used to determine the interior space's sound pressure paths, certain paths between the source and the receiver, beam diagrams, acoustic impulse response predictions at certain locations and many acoustic design parameters. While the space is investigated virtually, by directly feeding the input, the results are used to create acoustic comfort.

	Statictically based equations	Wave equation models	Image source models	Markoff chain models	Particle tracing models	Ray tracing models	Cone tracing models	Radiosity models	Hybrid models
Earliest report	1900		1979	1975	1970	1968	1986	1993	1989
Low frequency model		X	(X)						
High frequency model	X		X	X	X	X	X		X
Point source		X	X	X	X	X	X	X	X
Line source						X		X	X
Surface source						X		X	X
Source directivity			X			X	X	X	X
Point receiver		X	X			(X)	X	X	X
Grid of receivers		X				X	X	X	X
Sound distribution						X	X	X	X
Volume average	X			X	X				
Surface absorption	X	X	X	X	X	X	X	X	X
Early reflections			X			X	X		X
Echo tracing in 3D			X			(X)	(X)		X
Scattering effects					X	X	X	X	X
Diffraction effects		X							X
Coupled spaces		X			X	X	X	X	X
Impulse response			(X)			(X)	(X)	X	X
Reverberation time	X			X	X	(X)	(X)	X	X
ISO 3382 parameters						(X)	(X)	X	X
Auralization			(X)			X	X	X	X
Time for modelling (1-5)	1	5	3	3	3	3	3	3	3
Time for calculations (1-5)	1	5	5	1	1	4	4	3	2

Table 3. Some characteristics of computer models [5].

3. CONCLUSION

Sound has great importance in human life. It has become first a subject of wonder and then a subject of research, and since the 20th century, it has taken its place as a branch of science in the world of science.

Modeling provides valuable data about early (C30) – late (C80) sound index and interactions of total sound levels from the geometric and acoustic design perspectives. Architectural acoustics' importance stems from the fact that it uses scaled, physical, or computer models in order to improve performance sound energy analysis of listener zones and achieve acoustic comfort. Studies from the 19th century provide guidelines on how the zones within a space will be formed and which materials will be used. At this point, it can be concluded that architectural acoustic modeling methods, which have a brief history, have room for improvement.

Architectural acoustic modeling (scale, physical, and computer modeling) generally provides the following results in and interior space:

1) Geometric design of the hall,

2) Vineyard designs (achieving the dynamic system rather than defined geometries, terracing the seating surfaces and relating the stage to the audience. Dynamic set-up obtained from the behavior of sound),

3) The reasons for low or total sound levels and high or insufficient clarity,

4) Uniformity of response throughout the auditorium,

5) Comparison of average behavior hall volume and reverberation time (RT),

6) Reinforced sound level zones (near the stage),

7) Early decay time (EDT),

8) Selection of construction materials and investigation of their application (ceiling, wall, hall rear wall, vicinity of the stage, mid-section, etc…),

Here, by investigating the scaled modeling, physical modeling and computer modeling, it is concluded that all three methods should be used together and it is understood that these methods provide valuable information on acoustic design. Geometric design, which has an important role on acoustic parameters, provides opportunities for analysis of the reflection paths and sufficient clarity. In addition to this, computer modeling takes its place in acoustic design by being an affordable and fast method. Physical modeling unites all of the properties of these two methods. On the other hand, acoustic design and measurements are equipped and defined with certain standards.

The analysis of the sound in the interior space, room acoustic effects, and acoustic sound fields provide data in various areas, such as source expansion and sound propagation. With modeling techniques, which enable us to perform sound measurements, the investigation of the analyses of acoustic parameters occurring within the space becomes possible

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