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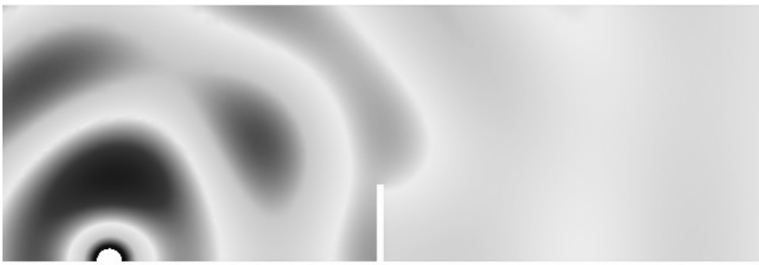
Sound Phase Change over Barriers



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2009

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Thesis submitted for completion of Master of Science in Mechanical Engineering with emphasis on Structural Mechanics at the Department of Mechanical Engineering, Blekinge Institute of Technology, Karlskrona, Sweden.

Abstract:

Noise barriers are used for cancellation of sound from roads. Sound of different frequencies travel differently over the top of the barriers. Design of barriers differ. Sound phase change can play an important role in noise cancellation. The aim of this thesis is to simulate the source, noise barrier, receiver environment by software and investigate the sound phase change for different designs of the top of noise barriers. Linear Acoustics and Wave Theory is used for wave propagation.

Keywords:

Noise Barriers, Sound Phase Change, Room Acoustics, Wave Propagation, Sine Wave, Comsol Multiphysics, MATLAB.

Acknowledgement

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Karlskrona, August 2009

Mehmet Yalcin YAGCI

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1 Notation

c	Speed of sound
e_a	Mass Coefficient
f	Frequency
L	Length
p	Sound Pressure
s	Second
T	Time Period
t	Time
u	Physical property
Δp	Sound Phase Change
∇^2	Operator
∂^2	Partial Differentiation Operator
λ	Wave Length

Indices

xx	Partial Differentiation in x direction
yy	Partial Differentiation in y direction
zz	Partial Differentiation in z direction
tt	Partial Differentiation for time

2 Introduction

Noise is one of our daily life problems. Noise pollution is a kind of pollution which we must reduce as we do in air pollution, sea pollution, etc. Different methods were developed to reduce or cancel the noise in many different areas. The method to control and to reduce the traffic noise coming from highways or railroads are noise barriers.

Traffic noise barriers are usually concrete walls 3-5 m high built along the highways. The barriers block the direct path from the noise source (traffic) to nearby communities. A shadow zone is created behind the barrier, in which listeners are protected from the noise (Figure 1.1).[1] However sound can still reach into the shadow zone by a variety of physical mechanisms. One of the most important mechanisms is called diffraction: Sound travels from roadway vehicles to the top edge of the barrier: There the edge scatters, i.e., diffracts, the sound in all directions. Some of the scattered sound reaches listeners behind the barrier. It is as though the sound arriving at the edge energizes it to be a new source of sound.[1]

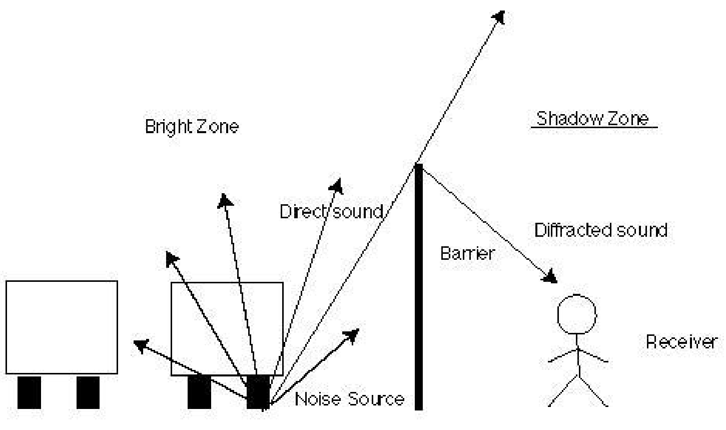

Figure 2.1. The barrier blocks the direct path from the noise source to the receiver. A shadow zone is created behind the barrier, in which listeners are protected from the noise. However, sound can still reach the receiver by sound diffraction at the top edge of the barrier.

Diffraction is the change in the direction of the propagation of sound waves passing the edge of the obstacle as illustrated in the following figure.[2]

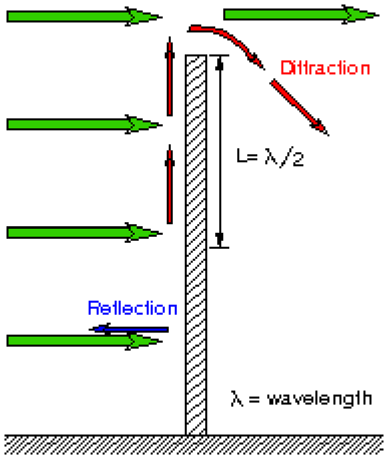

Figure 2.2. Diffraction

Diffraction phenomenon depends significantly on the ratio of the wave length of the sound to the size of the obstacle. The longer the wave length the stronger the sound diffraction. Diffraction effect happens to the sound transmitted through openings as well.[2]

An other example of diffraction is shown in Figure 2.3 [3] It can be observed how the sound wave propagates over an obstacle and how the edge of the obstacle acts as a new sound source. In Figure 2.3 [3], the upper-right edge of the obstacle acts as a sound source.

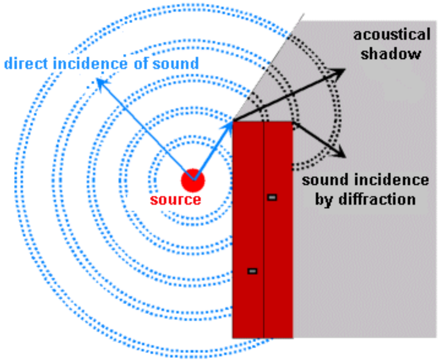

Figure 2.3. Wave Propagation by Diffraction.

In this work I attempt to investigate the sound phase change over the noise barriers for different top designs for different frequencies and to show the importance of phase in noise barrier designs and in other noise cancellation applications An environment, where the sound source, receiver and the wall are located, is simulated by software and the phase change is observed. By the sound phase change, I mean, for different frequencies, the difference between the starting times where the sound reaches the receiver. Sound phase change is good for noise barriers because occurance of sound phase change makes possible the sound cancelled according to the design in Figure 2.4.

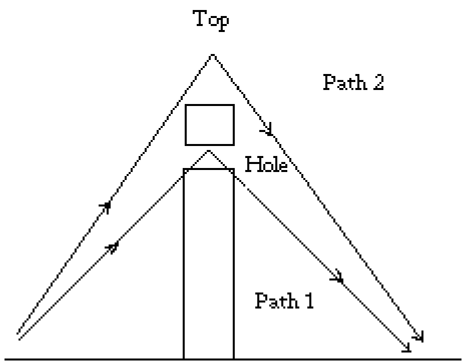

Figure 2.4. Noise Barrier Design.

Sound phase changes of waves going through the hole and waves going over the hole are Δp_1 and Δp_2 respectively.

The comparison should be made like in the following equation;

$$\Delta p = \Delta p_{Tops} - \Delta p_{Holes} \tag{2.1}$$

$$\Delta p = \Delta p_1 - \Delta p_2 = \pi = ideal!$$

In this work I investigate and calculate the phase changes, Δp for different top and hole designs.

Phase Change is good for noise barriers but phase change is not good in an other noise work area, concert halls. Phase change should be same for different frequencies. This should be considered in designing of pillars to keep the phase same for good sound quality.

$\Delta t_2 = \Delta p_1$ = constant (as of frequency)

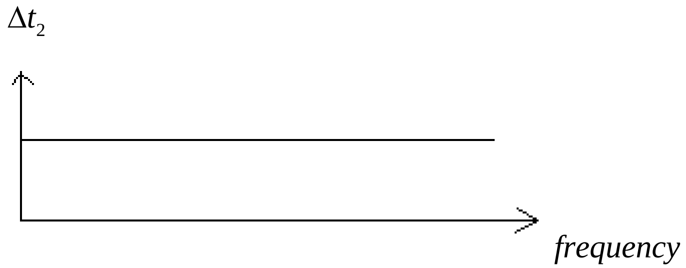

Figure 2.4. Phase Change vs frequency should be as in this figure for a good sound quality.

The sound you hear in a room is a combination of direct sound and indirect sound. Direct sound will come directly from the stage the other sound you hear is reflected off of various objects in the room.[4]

Good and Bad Reflected Sound

Have you ever listened to speakers outside? You might have noticed that the sound is thin and dull. This occurs because sound is reflected, it is fuller and louder than it would if it were in an open space. So when sound is reflected, it can add a fullness, or spaciousness. The bad part of reflected sound occurs when the reflections amplify some notes, while cancelling out others, making the sound distorted. It can also effect tonal quality and create an echo-like effect.[4]

Previous Works

Two previous works related to the subject of this thesis work are “Diffraction on sound from a point source against screens with periodical edge profiles”[6] by Ivan Pavlov and “Theoretical studies of acoustic waves with consideration of non-linearity, dispersion, dissipation and diffraction”[7] by Henrik Sandqvist.

3 Approach

The aim of this work is to investigate the sound phase change for different noise barrier designs for different frequencies. Therefore, I set seven simulation geometries for different top and hole designs. Dimensions are set realistic. A railroad is considered as a sound source and a point is considered as a receiver, that can be microphone or human ear. Comsol Multiphysics Software is used to build the geometries and to do the simulation.

3.1 Model and Geometries

Geometries are set according to the design in Figure 2.4. Basic model and the dimensions are shown in Figure 3.1.1. This model and the dimensions are used as a basis to build the geometries.

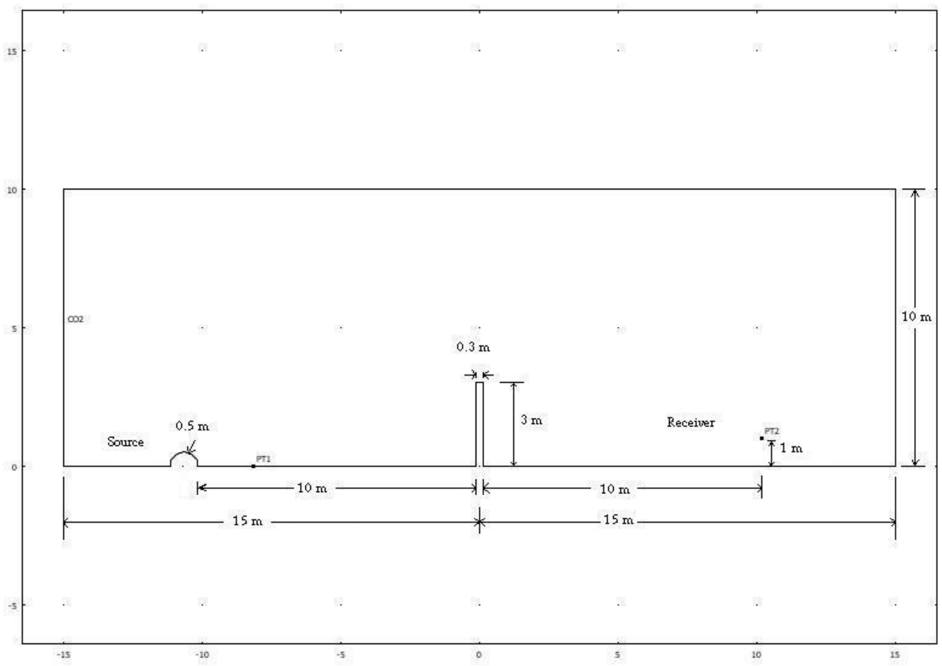

Figure 3.1.1. Basic Model.

Both the sound source and the receiver is 10 m away from the noise barrier. Sound source is 0.5 m high and the receiver is 1 m high. Noise barrier is 0.3 m wide and 3 m high.

Three geometries are built for top design and four geometries are built for hole design. In this work, the hole design geometries are in some parts called mirror geometries, because the upper part and the down part of the hole is same. (Figure 3.1.4 and 3.1.5)

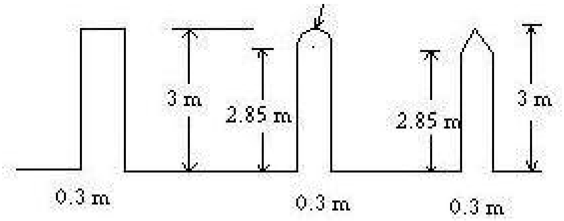

Figure 3.1.2. Top Designs.

A bigger geometry is built to see the wave propagation for smaller frequencies after two periods. Basic model can be seen as a subdomain of this bigger model at the bottom part.

The bigger geometry is as shown in Figure 3.1.3.

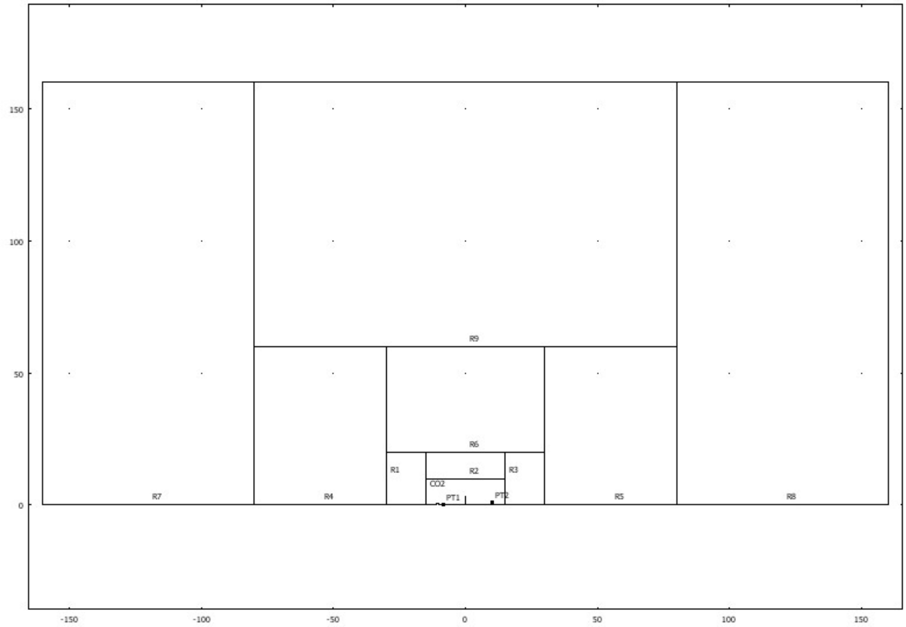

Figure 3.1.3. Bigger Model for Tops.

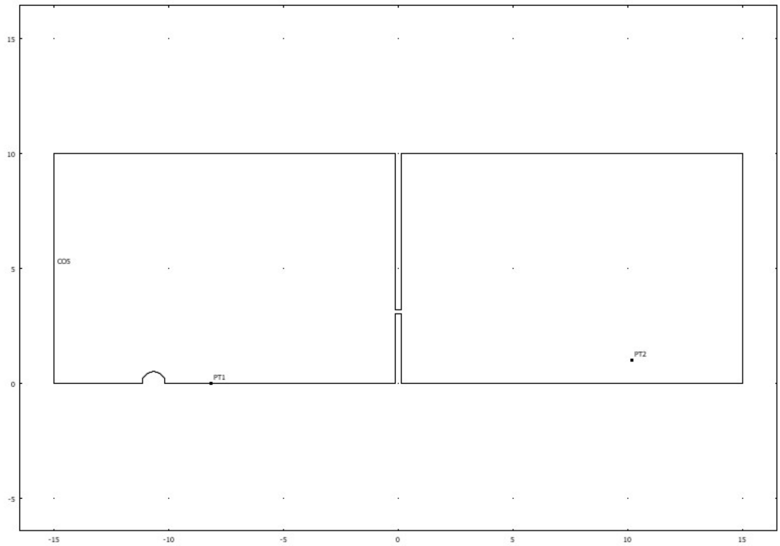

Figure 3.1.4. Basic Model for Holes.

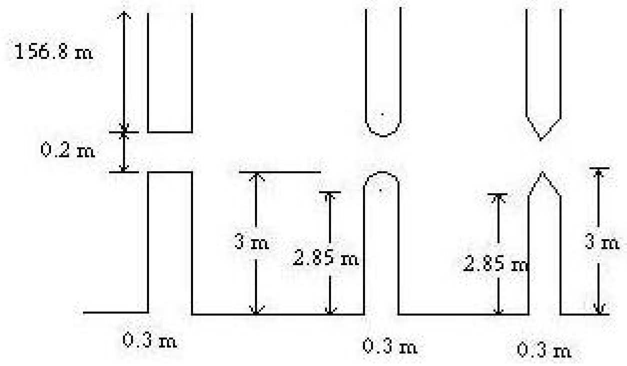

Figure 3.1.5. Hole Designs.

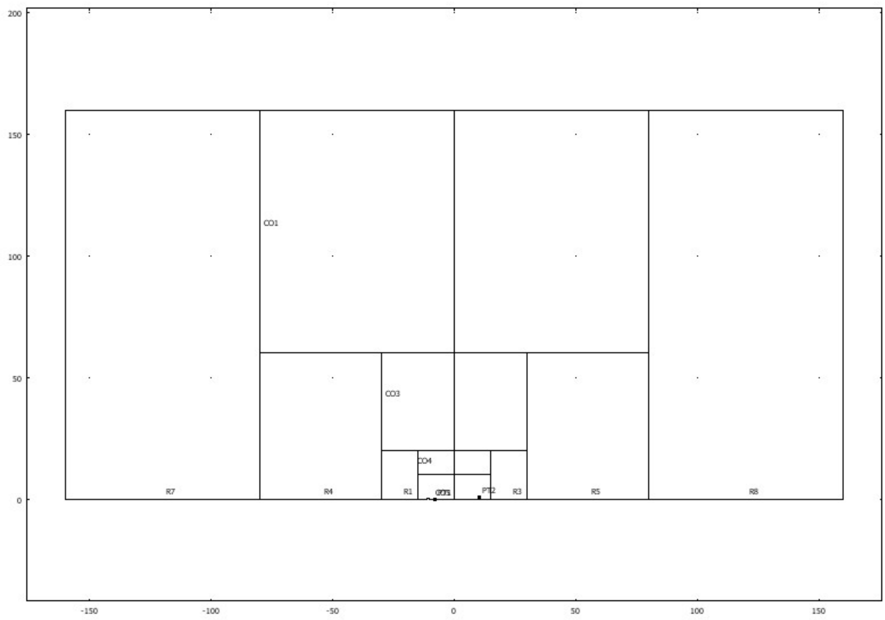

Figure 3.1.6 Bigger Model for Holes.

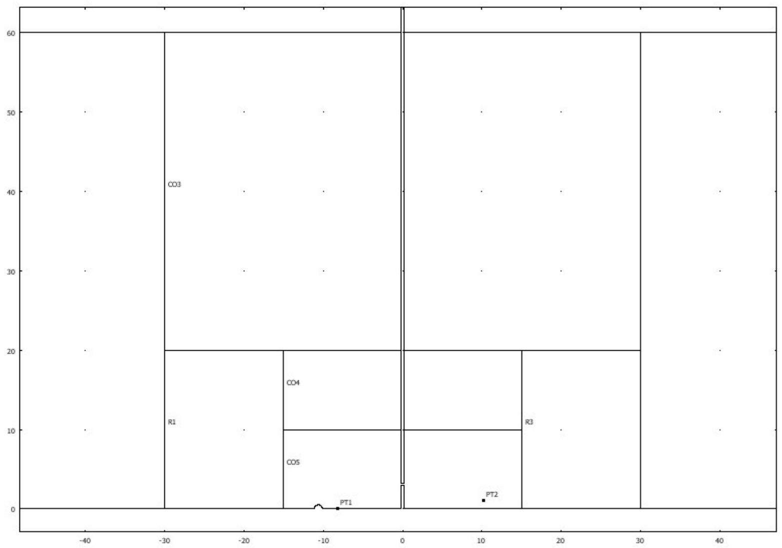

Figure 3.1.7. Bigger Model for Holes (Closer View).

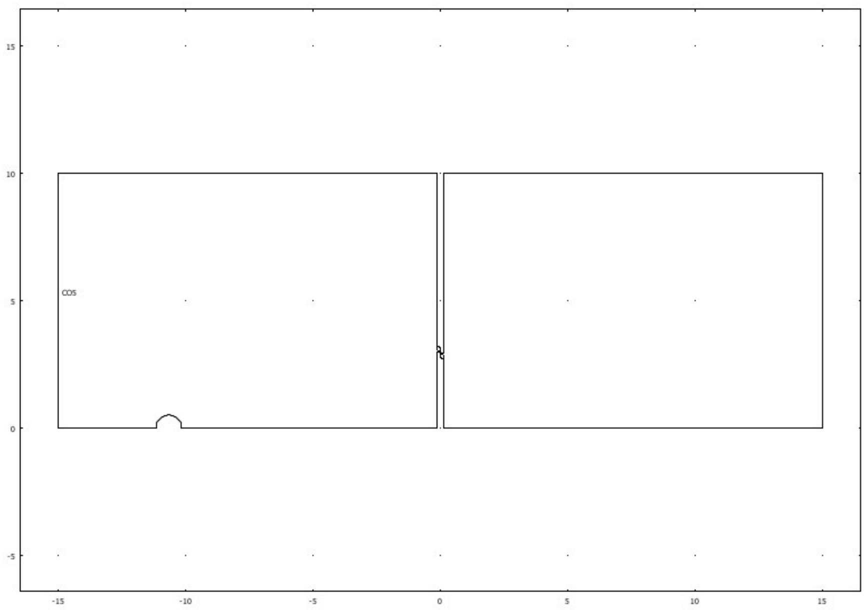

Figure 3.1.8. Model for S-Shape Hole.

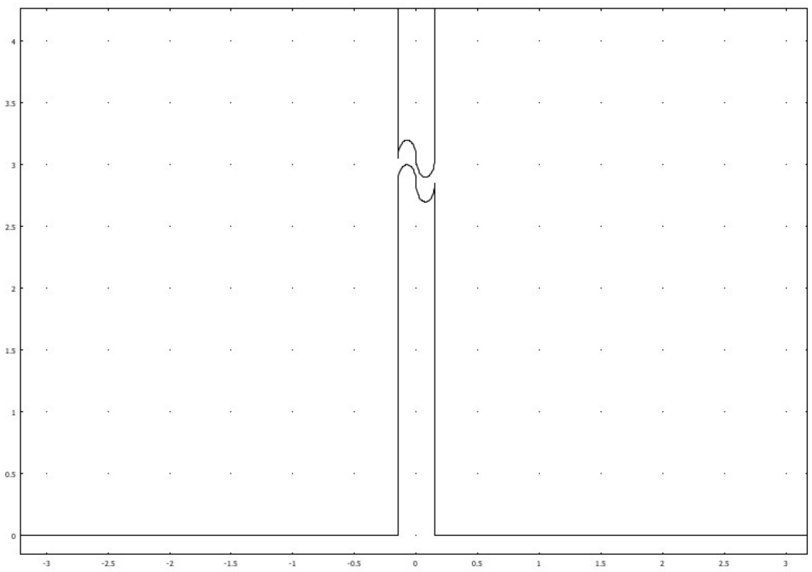

Figure 3.1.9. Model for S-Shape Hole (Closer View).

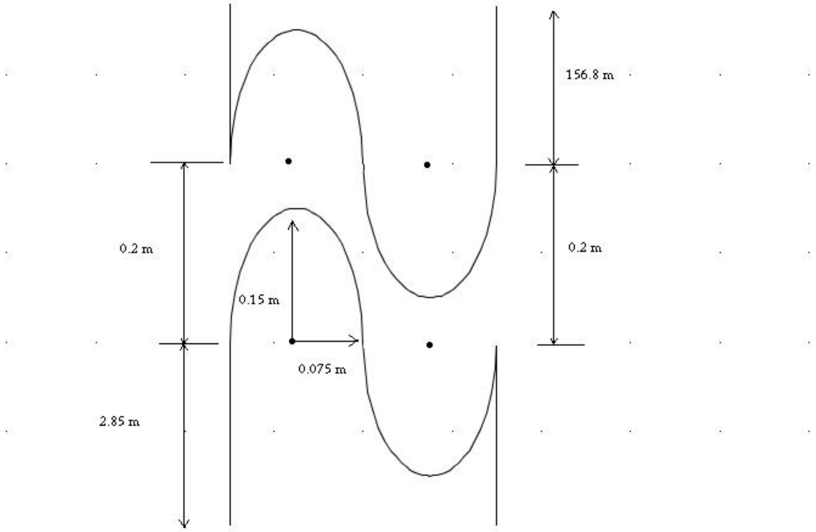

Figure 3.1.10. S-Shape Hole Design.

3.2 Method

As shown in Fig.3.1.1. source is a half circle with radius of 0.5 m . The boundary condition of this half circle is set as a sound pressure source. Sine wave is set as a sound source and propagates by wave equation.

Source;

$\sin\left(f \cdot 2\pi \cdot t \right)$

f : frequency

An idelization of many types of wave motion is embodied mathematically in what is called the wave equation.[5]

$$c^2\nabla^2 u - u_{tt} = 0 \qquad (3.2.1)$$

Where u is a physical property associated with the disturbance or signal, the operator ∇^2 is defined by[5]

$$\nabla^2() = ()_{xx} + ()_{yy} + ()_{zz} \qquad (3.2.2)$$

c is a constant representing the speed at which the wave travels, and x, y, z and t are rectangular spatial coordinates and time, respectively. Independent variables used as subscripts denote partial differentiation, for example, u_{tt} means $\partial^2 u / \partial t^2$.[5]

Wave Equation used in the simulation;

$$e_a \, \partial^2 p / \partial t^2 - c\nabla^2 p = 0 \qquad (3.2.3)$$

p : sound pressure [Pa]

t : time [s]

e_a : mass coefficient

c :speed of sound [m/s]

$c = 343$ m/s (air)

The simulation is done for eight frequencies for each model. The frequencies used in simulation are 5, 10, 20, 40, 60, 80, 100, 120. I let the wave propagate and after reaching the receiver, I let the wave propagate two periods more and plot the time signal of the receiver point for further sound phase change calculations.

An example of time-signal and the important values are shown in Fig.3.2.1.

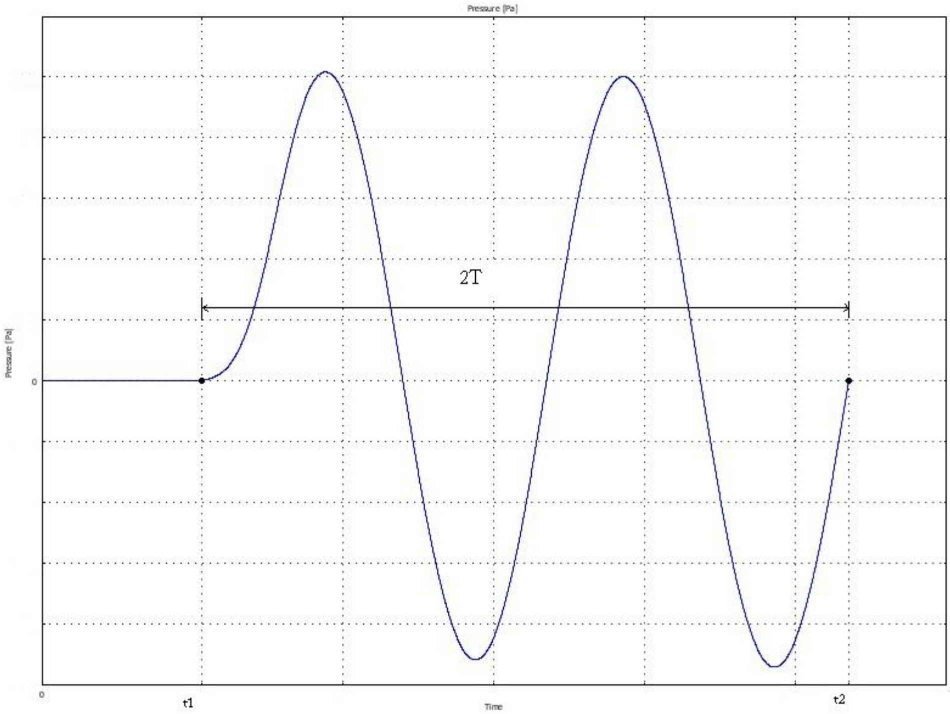

Figure 3.2.1. Time Signal for the wave propagating between the source and the receiver.

t_1 : starting time where the sound reaches the receiver

t_2 : end time after two periods

T : period, $T = 1/f$

Time range used in simulations is $t = 0:0.0001:t_2$.

Time signals are plotted for t_1 and $t_2 - 2T$. Then phase change is calculated for both t_1 and $t_2 - 2T$ for different frequencies for each model.

Phase Change Calculation

A time shift is equivalent to a phase shift. Time shift is the time difference between the sound reaching times(t_1) to the receiver for different designs and for different frequencies.

The sound phase change (Δp_1) and so the time shift(Δt_1) for the smallest frequency (f_1 = 5 Hz), is accepted as 0.

$$\Delta p_1\left(f_1\right) = \Delta t_1\left(f_1\right) = 0 \tag{3.2.4}$$

$$\Delta t_1(f_2) = t_1(f_2) - t_1(f_1) \tag{3.2.5}$$

$$\Delta p_1(f_2) = \Delta p_1(f_2) - \Delta p_1(f_1) \tag{3.2.6}$$

Sound phase change for each frequency is calculated as shown in the following equations.

$$\Delta p_{1_5} = 0 \tag{3.2.7}$$

$$\Delta p_{1_{10}} = 2\pi \frac{\left(t_{1_{10}} - t_{1_5}\right)}{T_{10}} \tag{3.2.8}$$

$$\Delta p_{1_{20}} = 2\pi \frac{\left(t_{1_{20}} - t_{1_5}\right)}{T_{20}} \tag{3.2.9}$$

$$\Delta p_{1_{40}} = 2\pi \frac{\left(t_{1_{40}} - t_{1_5}\right)}{T_{40}} \tag{3.2.10}$$

$$\Delta p_{1_{60}} = 2\pi \frac{\left(t_{1_{60}} - t_{1_5}\right)}{T_{60}} \tag{3.2.11}$$

$$\Delta p_{1_{80}} = 2\pi \frac{\left(t_{1_{80}} - t_{1_5}\right)}{T_{80}} \tag{3.2.12}$$

$$\Delta p_{1_{100}} = 2\pi \frac{\left(t_{1_{100}} - t_{1_5}\right)}{T_{100}} \tag{3.2.13}$$

$$\Delta p_{1_{120}} = 2\pi \frac{\left(t_{1_{120}} - t_{1_5}\right)}{T_{120}} \tag{3.2.14}$$

4 Results

In this section, simulation results are presented. Time signal examples, wave propagation examples are given as figures and sound reaching times to the receiver $t_1, t_2 - 2T$, end time after two periods, t_2 and sound phase change values for $t_1, t_2 - 2T$ are given as data for each geometry model.

4.1 Time Signals

Time signals for square top design for different frequencies are shown in the following figures.

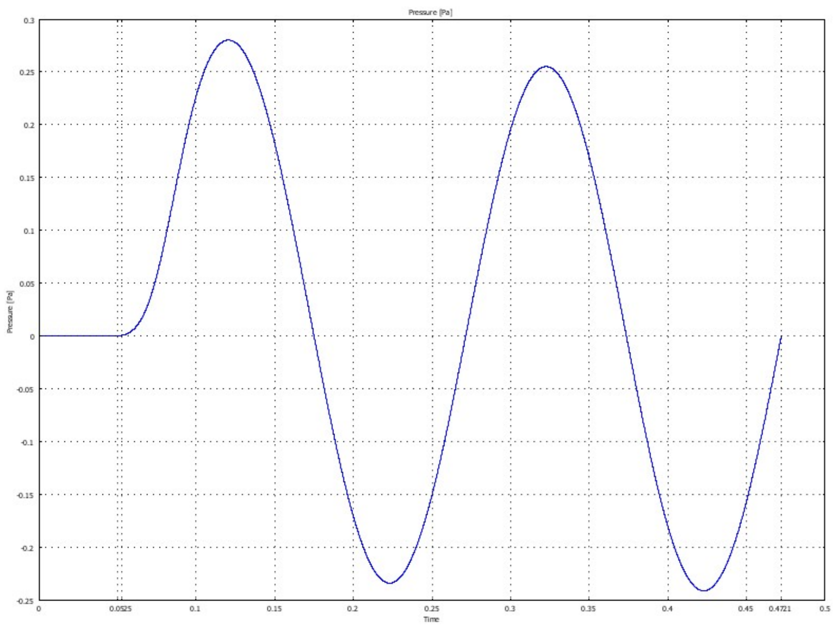

Figure 4.1.1. Time Signal for Square Top Design (5 Hz).

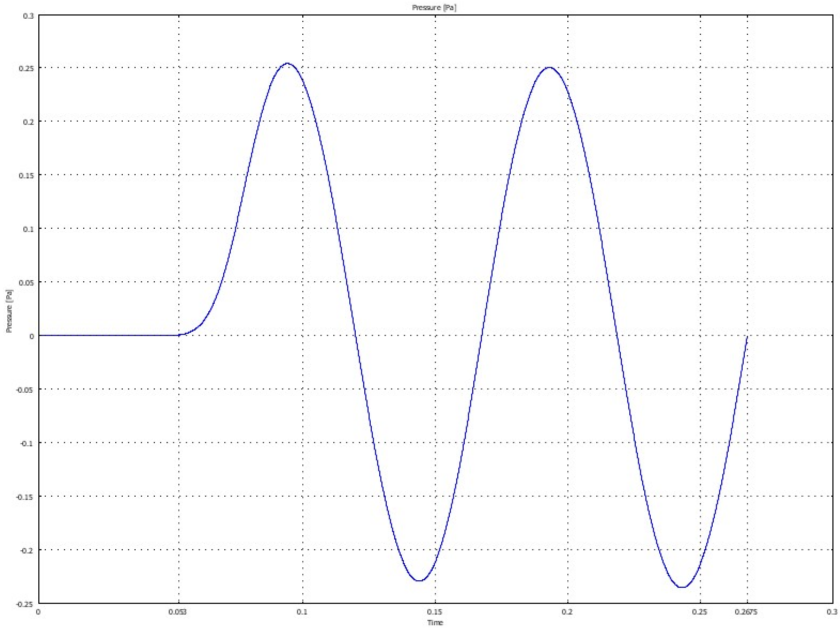

Figure 4.1.2. Time Signal for Square Top Design (10 Hz).

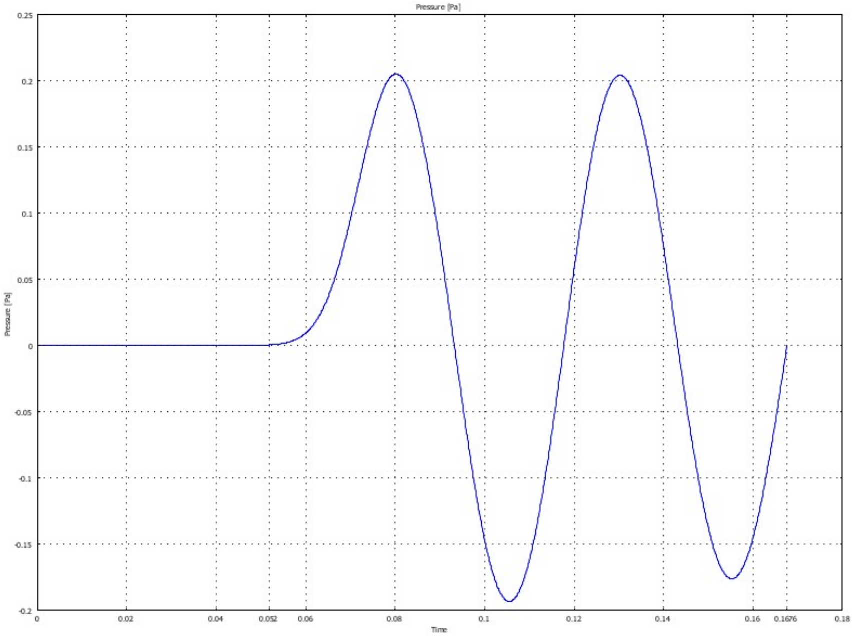

Figure 4.1.3. Time Signal for Square Top Design (20 Hz).

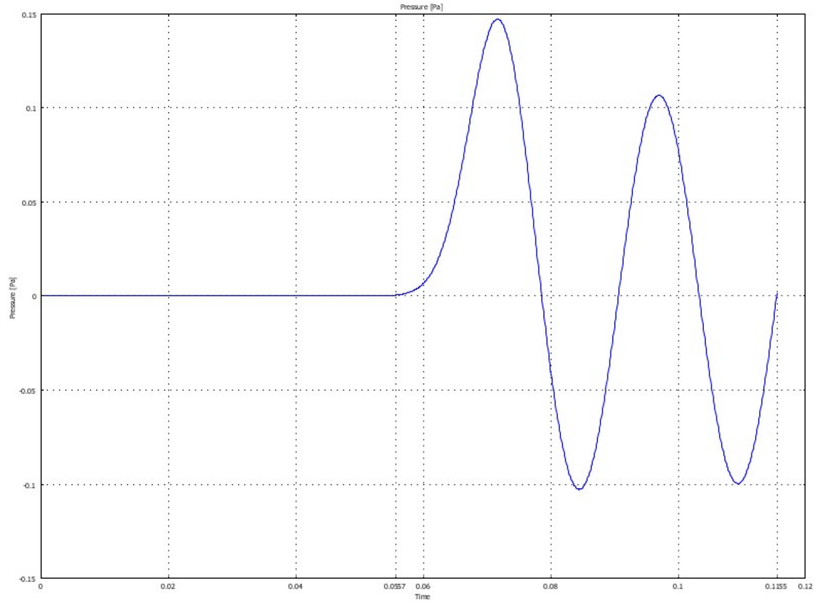

Figure 4.1.4. Time Signal for Square Top Design (40 Hz).

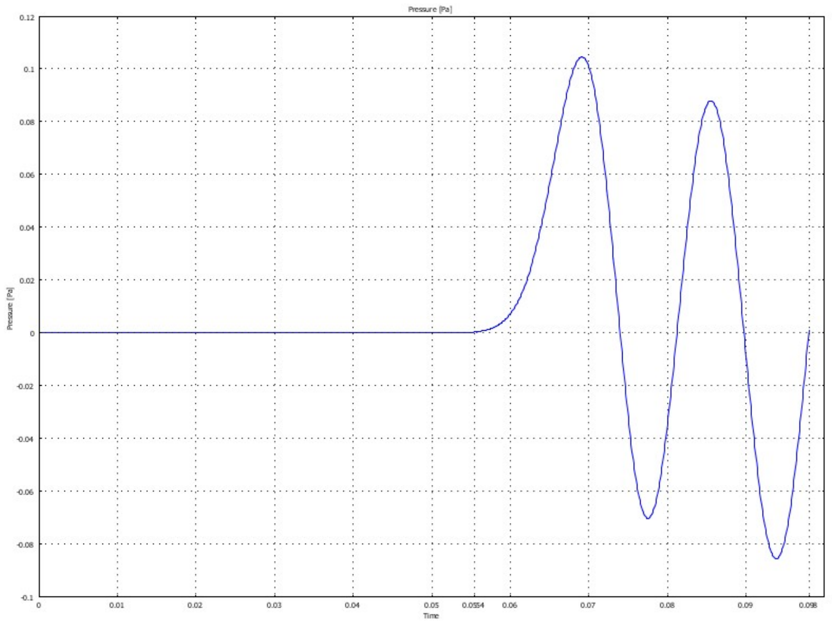

Figure 4.1.5. Time Signal for Square Top Design (60 Hz).

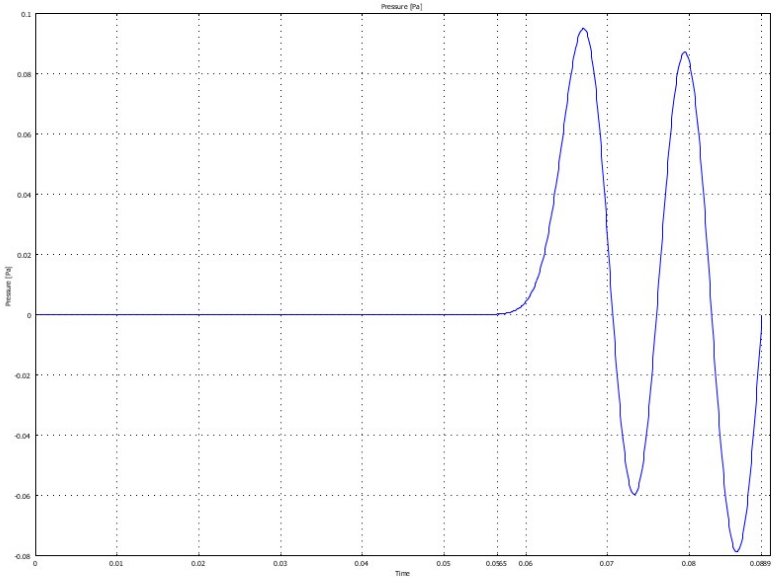

Figure 4.1.6. Time Signal for Square Top Design (80 Hz).

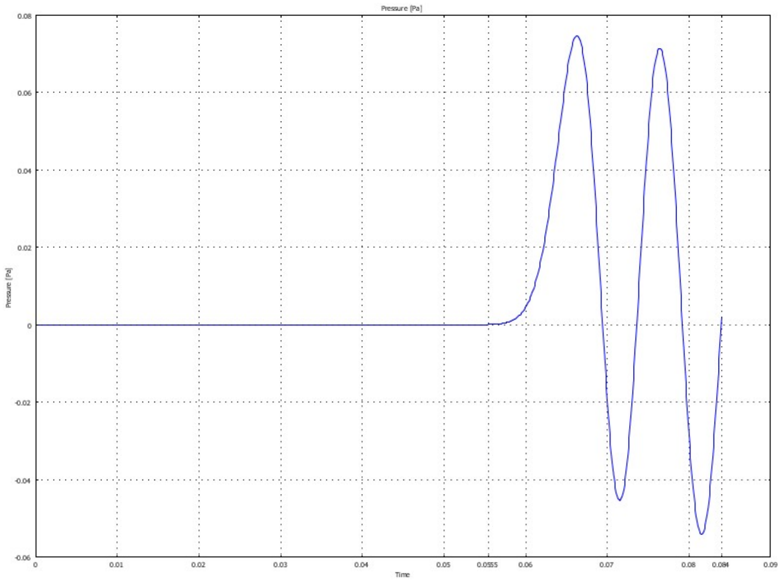

Figure 4.1.7. Time Signal for Square Top Design (100 Hz).

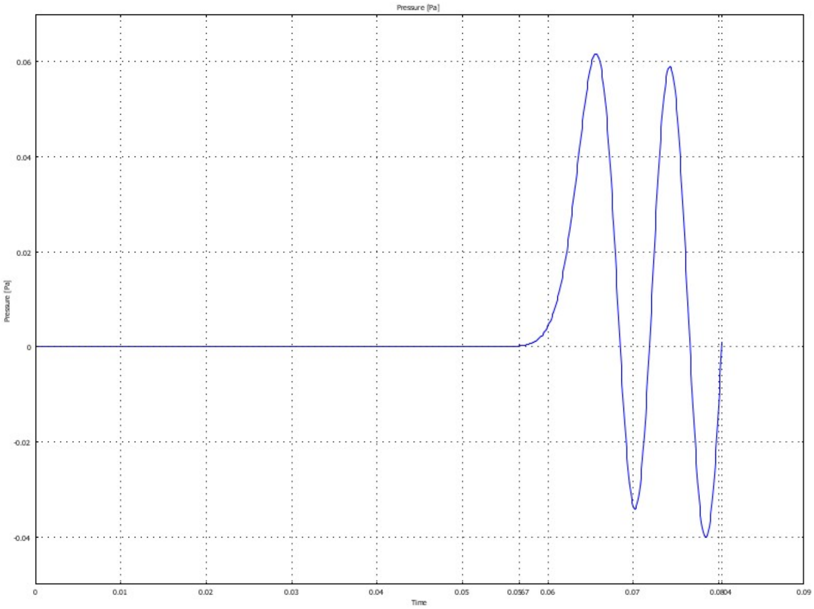

Figure 4.1.8. Time Signal for Square Top Design (120 Hz).

Because the time signal visually looks almost same for other models, t_1 and t_2 values are given as data for other models in the following sections. The values for the square top model are given as data as well.

In the following section, the wave propagation can be seen. Because of the same reason; as the wave propagation is visually almost same, only the wave propagations for square top model design is given in the figures.

4.2 Surfaces and Wave Propagation

Surface condition and wave propagation at time, t_2, for square top design for different frequencies are shown in the following figures.

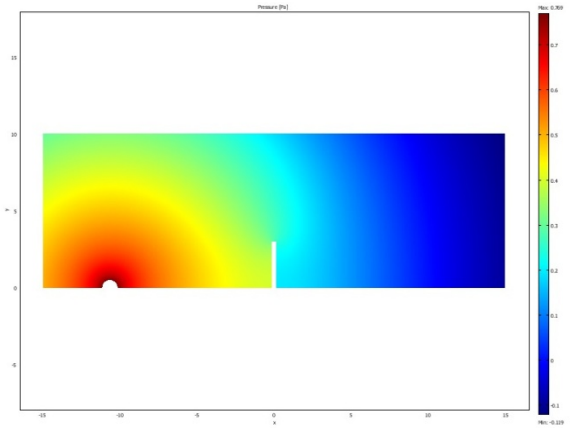

Figure 4.2.1. Wave Propagation for Square Top Design (5 Hz).

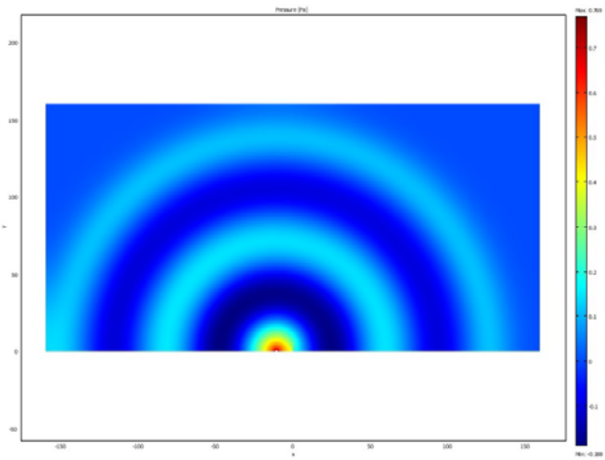

Figure 4.2.2. Wave Propagation (5 Hz).

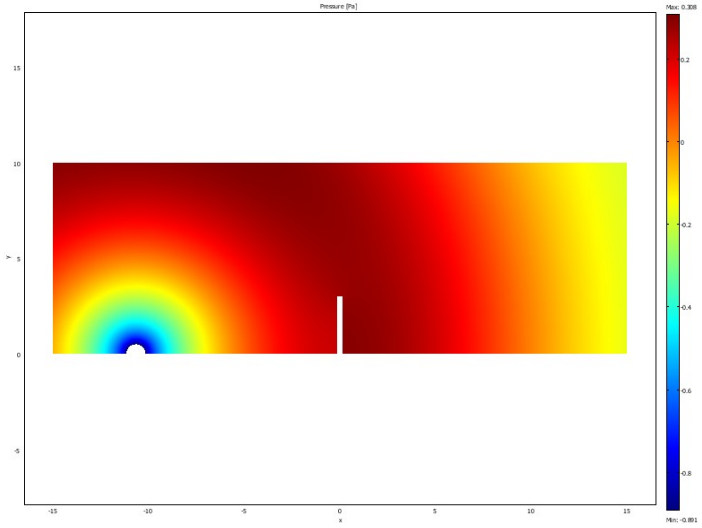

Figure 4.2.3. Wave Propagation for Square Top Design (10 Hz).

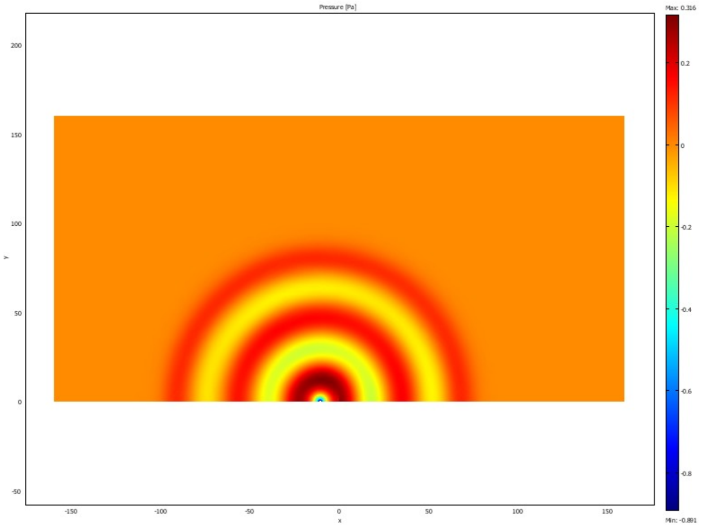

Figure 4.2.4. Wave Propagation (10 Hz).

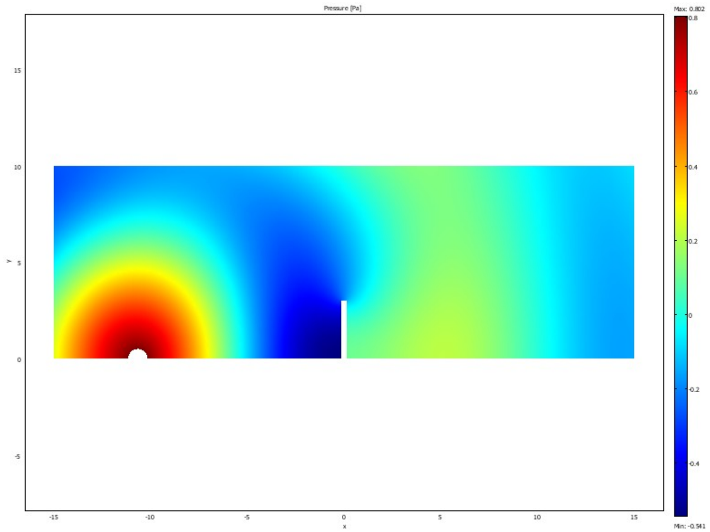

Figure 4.2.5. Wave Propagation for Square Top Design (20 Hz).

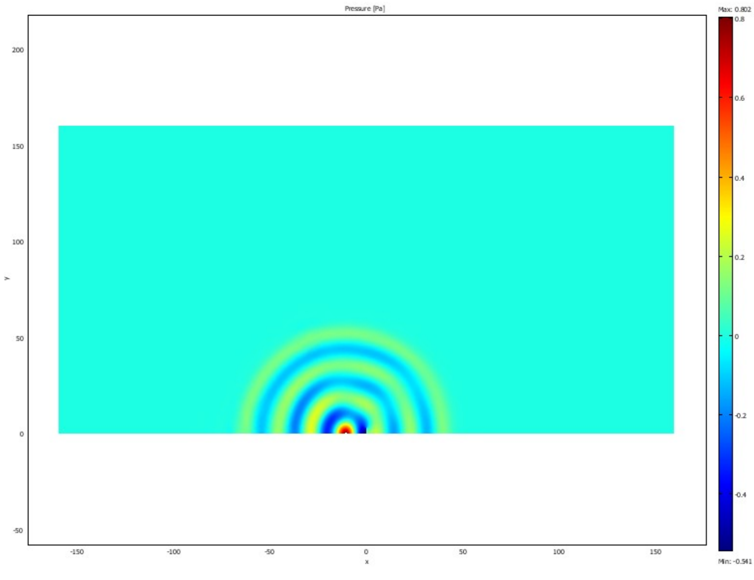

Figure 4.2.6. Wave Propagation (20 Hz).

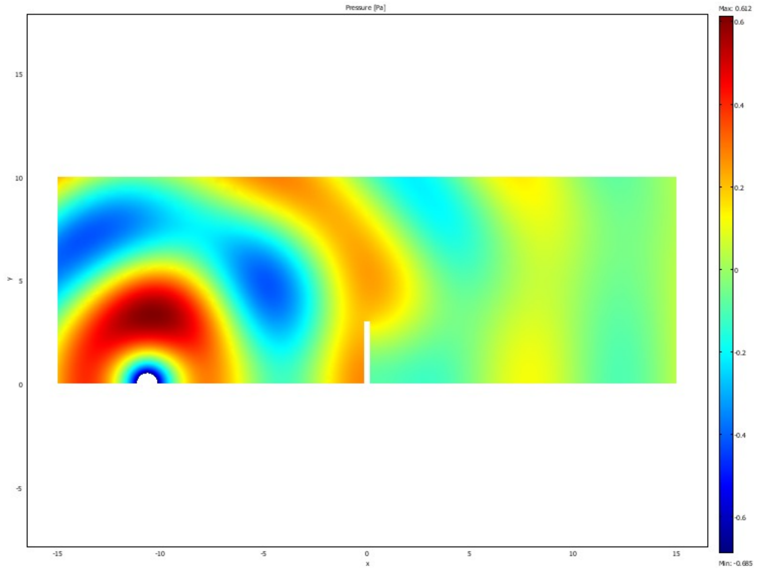

Figure 4.2.7. Wave Propagation for Square Top Design (40 Hz).

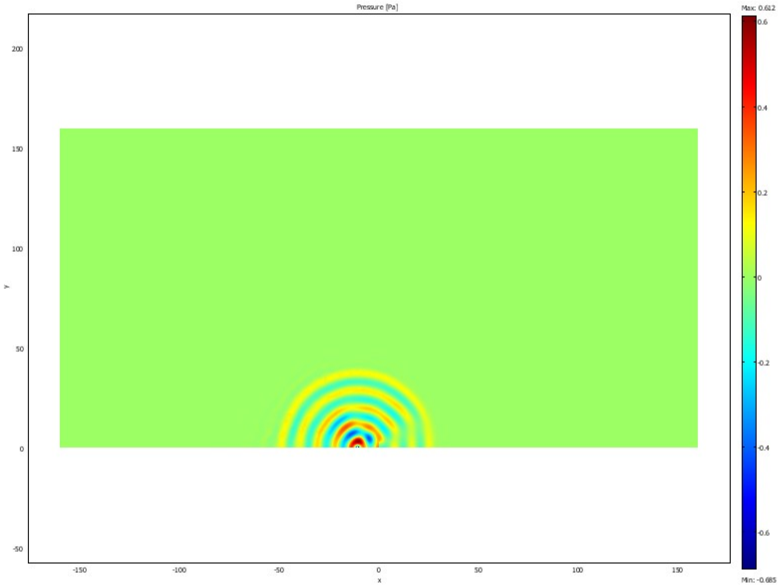

Figure 4.2.8. Wave Propagation (40 Hz).

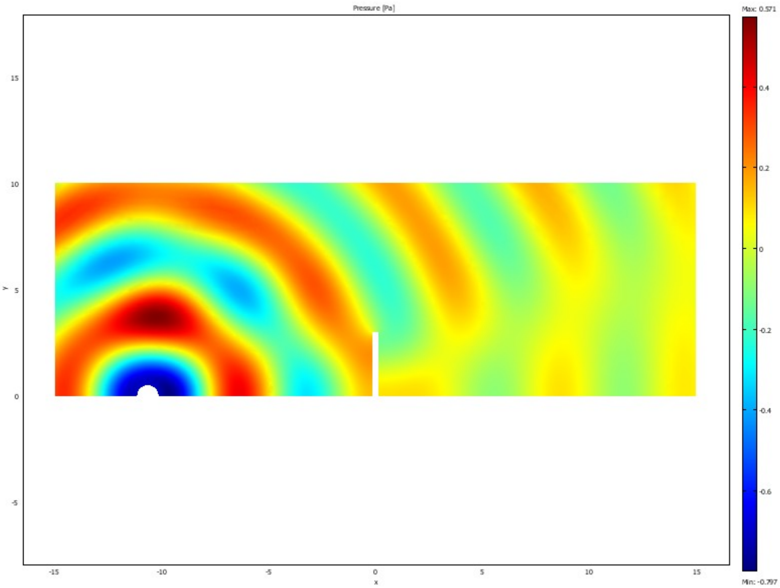

Figure 4.2.9. Wave Propagation for Square Top Design (60 Hz).

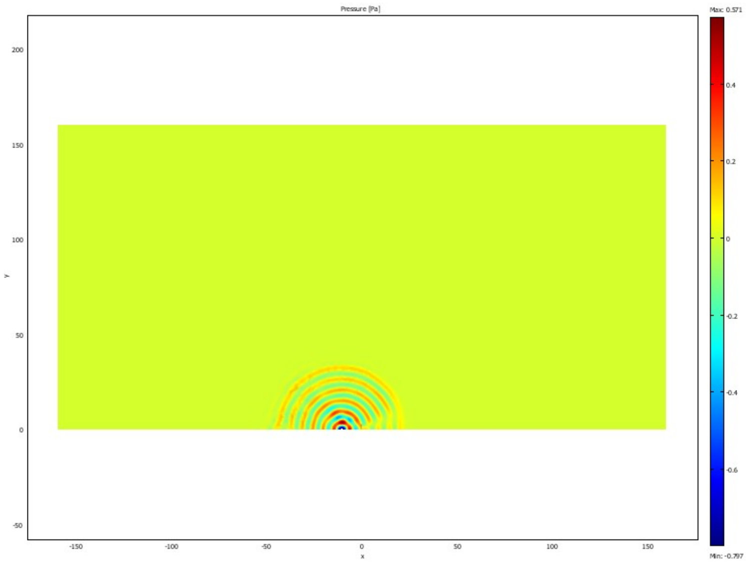

Figure 4.2.10. Wave Propagation (60 Hz).

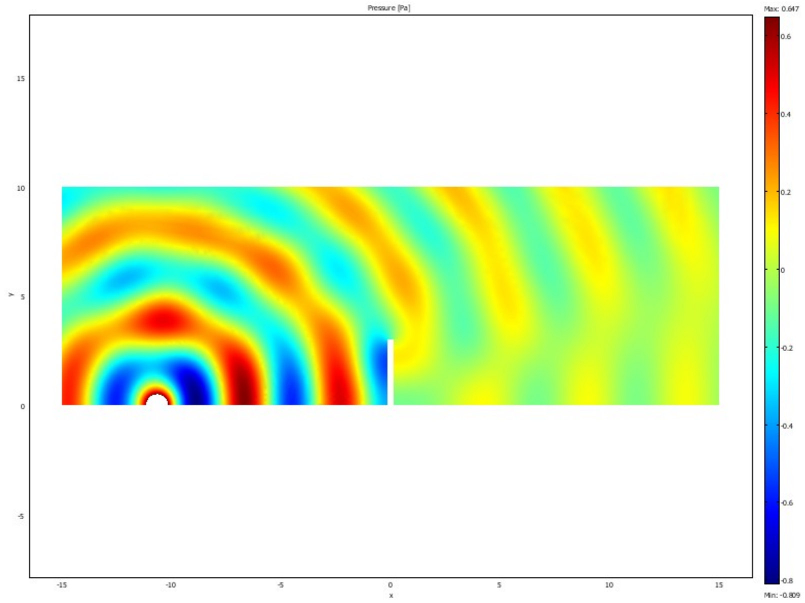

Figure 4.2.11. Wave Propagation for Square Top Design (80 Hz).

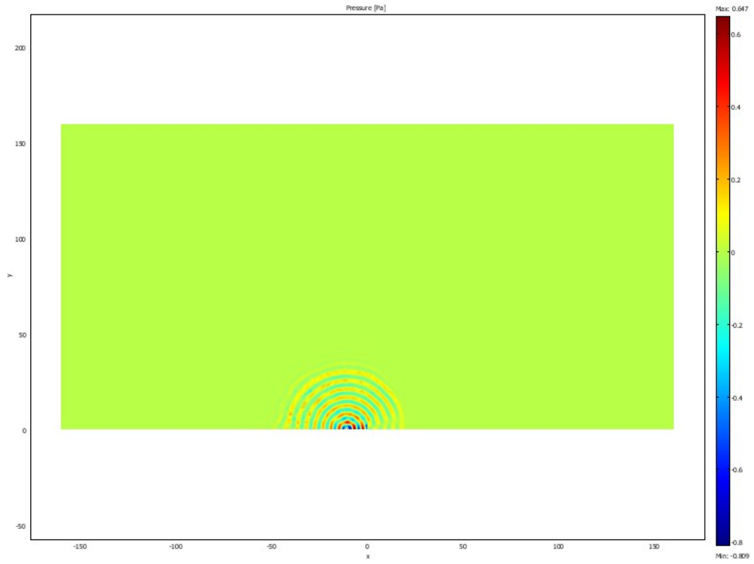

Figure 4.2.12. Wave Propagation(80 Hz).

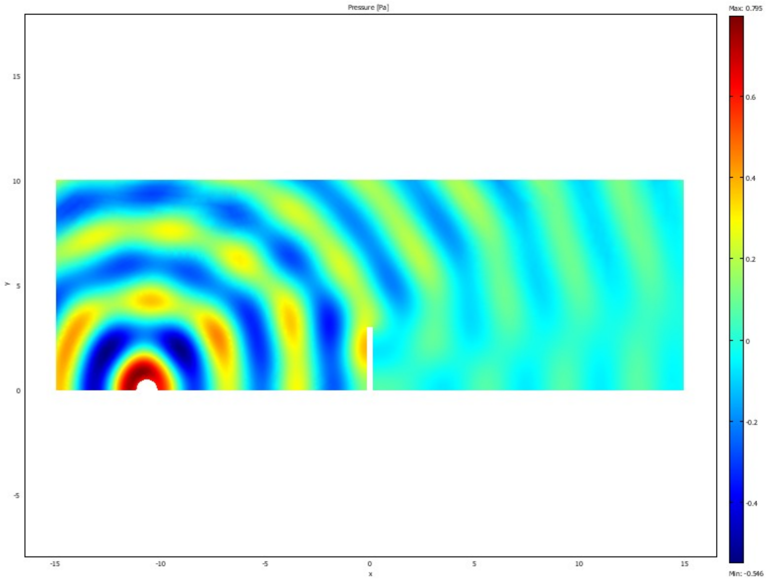

Figure 4.2.13. Wave Propagation (100 Hz).

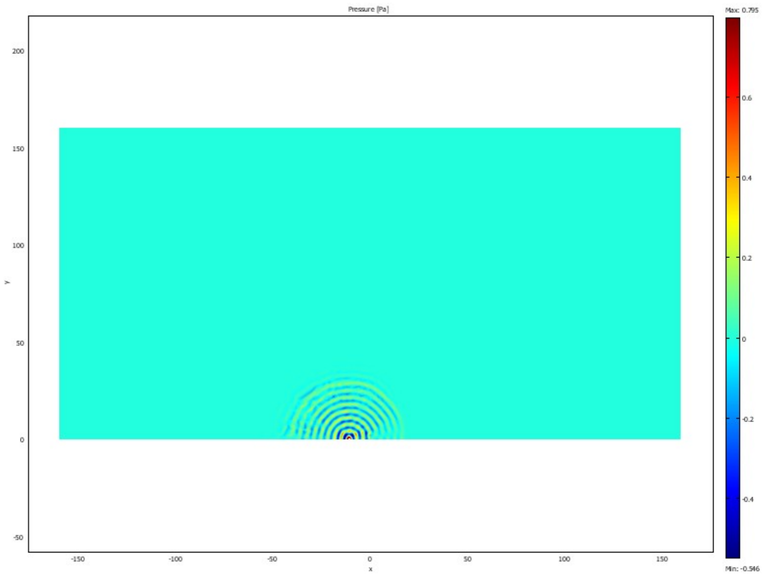

Figure 4.2.14. Wave Propagation (100 Hz).

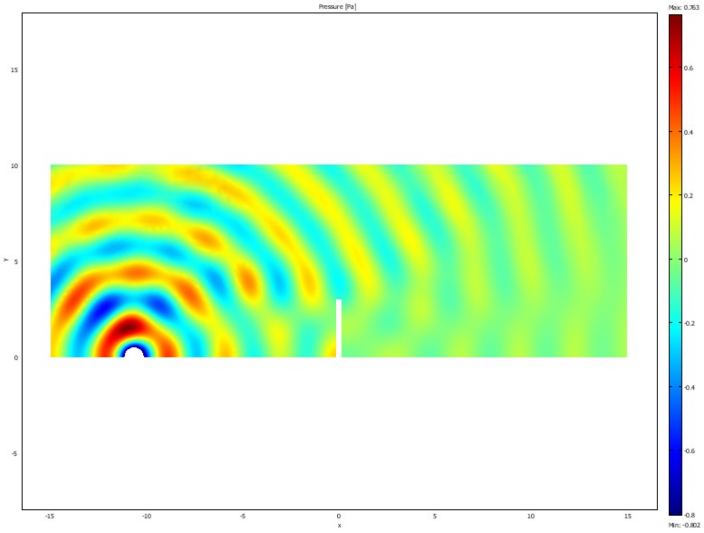

Figure 4.2.15. Wave Propagation (120 Hz).

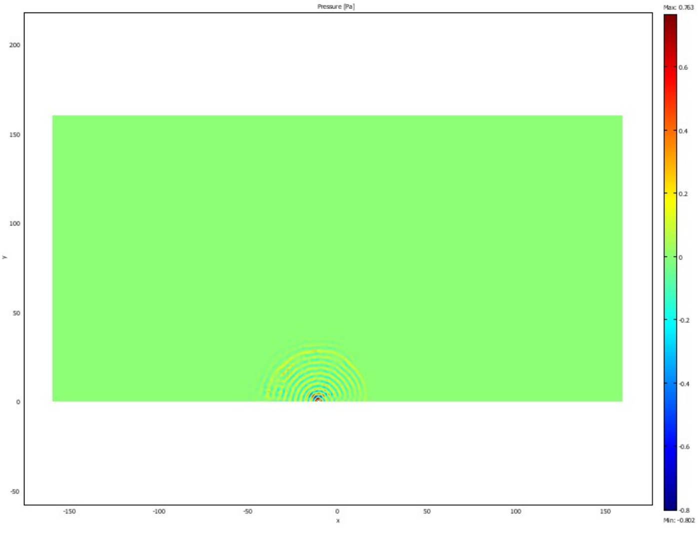

Figure 4.2.16. Wave Propagation (120 Hz).

4.3 Starting Time for Each Geometry (t_1)

In this section, starting times (t_1), which means the time where the sound reaches to the receiver, are given as data.

Time values are in [s].

Table 4.3.1. Starting times(t_1) for square top design.

Square Top	**5 Hz**	**10 Hz**	**20 Hz**	**40 Hz**
	0.0525	0.0530	0.0520	0.0557
	60 Hz	**80 Hz**	**100 Hz**	**120 Hz**
	0.0554	0.0565	0.0555	0.0567

Table 4.3.2. Starting times(t_1) for circular top design.

Circular Top	**5 Hz**	**10 Hz**	**20 Hz**	**40 Hz**
	0.0525	0.0530	0.0521	0.0557
	60 Hz	**80 Hz**	**100 Hz**	**120 Hz**
	0.0552	0.0564	0.0557	0.0567

Table 4.3.3. Starting times(t_1) for triangular top design.

Triangular Top	**5 Hz**	**10 Hz**	**20 Hz**	**40 Hz**
	0.0525	0.0533	0.0520	0.0557
	60 Hz	**80 Hz**	**100 Hz**	**120 Hz**
	0.0553	0.0571	0.0553	0.0566

Table 4.3.4. Starting times(t_1) for square mirror hole design.

Square Mirror Hole	**5 Hz**	**10 Hz**	**20 Hz**	**40 Hz**
	0.0531	0.0503	0.0498	0.0542
	60 Hz	**80 Hz**	**100 Hz**	**120 Hz**
	0.0532	0.0555	0.0564	0.0559

Table 4.3.5. Starting times(t_1) for circular mirror hole design.

Circular Mirror Hole	**5 Hz**	**10 Hz**	**20 Hz**	**40 Hz**
	0.0538	0.0525	0.0593	0.0514
	60 Hz	**80 Hz**	**100 Hz**	**120 Hz**
	0.0520	0.0530	0.0562	0.0562

Table 4.3.6. Starting times(t_1) for triangular mirror hole design.

Triangular Mirror Hole	**5 Hz**	**10 Hz**	**20 Hz**	**40 Hz**
	0.0531	0.0526	0.0515	0.0548
	60 Hz	**80 Hz**	**100 Hz**	**120 Hz**
	0.0537	0.0562	0.0551	0.0562

Table 4.3.7. Starting times(t_1) for S-Shape mirror hole design.

S-Shape Mirror Hole	**5 Hz**	**10 Hz**	**20 Hz**	**40 Hz**
	0.0495	0.0520	0.0522	0.0525
	60 Hz	**80 Hz**	**100 Hz**	**120 Hz**
	0.0534	0.0546	0.0565	0.0565

4.4 Starting Time for Each Geometry (t2-2T)

In this section, starting times ($t_2 - 2T$), which means the time where the sound reaches to the receiver, are given as data.

Time values are in [s].

Table 4.4.1. Starting times(t_2-2T) for square top design.

Square Top	**5 Hz**	**10 Hz**	**20 Hz**	**40 Hz**
	0.0721	0.0675	0.0676	0.0655
	60 Hz	**80 Hz**	**100 Hz**	**120 Hz**
	0.0647	0.0639	0.0640	0.0637

Table 4.4.2. Starting times(t_2-2T) for circular top design.

Circular Top	**5 Hz**	**10 Hz**	**20 Hz**	**40 Hz**
	0.0724	0.0676	0.0680	0.0656
	60 Hz	**80 Hz**	**100 Hz**	**120 Hz**
	0.0652	0.0643	0.0641	0.0642

Table 4.4.3. Starting times(t_2-2T) for triangular top design.

Triangular Top	**5 Hz**	**10 Hz**	**20 Hz**	**40 Hz**
	0.0719	0.0673	0.0673	0.0653
	60 Hz	**80 Hz**	**100 Hz**	**120 Hz**
	0.0645	0.0638	0.0638	0.0639

Table 4.4.4. Starting times(t_2-2T) for square mirror hole design.

	5 Hz	10 Hz	20 Hz	40 Hz
Square Mirror Hole	0.0751	0.0728	0.0659	0.0644
	60 Hz	**80 Hz**	**100 Hz**	**120 Hz**
	0.0636	0.0629	0.0630	0.0629

Table 4.4.5. Starting times(t_2-2T) for circular mirror hole design.

	5 Hz	10 Hz	20 Hz	40 Hz
Circular Mirror Hole	0.0742	0.0719	0.0657	0.0656
	60 Hz	**80 Hz**	**100 Hz**	**120 Hz**
	0.0641	0.0641	0.0630	0.0632

Table 4.4.6. Starting times(t_2-2T) for triangular mirror hole design.

	5 Hz	10 Hz	20 Hz	40 Hz
Triangular Mirror Hole	0.0736	0.0714	0.0656	0.0644
	60 Hz	**80 Hz**	**100 Hz**	**120 Hz**
	0.0637	0.0628	0.0630	0.0632

Table 4.4.7. Starting times(t_2-2T) for S-Shape mirror hole design.

	5 Hz	10 Hz	20 Hz	40 Hz
S-Shape Mirror Hole	0.0783	0.0760	0.0666	0.0654
	60 Hz	**80 Hz**	**100 Hz**	**120 Hz**
	0.0638	0.0639	0.0630	0.0632

4.5 Ending Time After Two Periods (t_2)

In this section, ending times (t_2), which means the time where the wave propagation ends after two periods, are given as data.

Time values are in [s].

Table 4.5.1. Ending times after two periods(t_2) for square top design.

Square Top	**5 Hz**	**10 Hz**	**20 Hz**	**40 Hz**
	0.4721	0.2675	0.1676	0.1155
	60 Hz	**80 Hz**	**100 Hz**	**120 Hz**
	0.0980	0.0889	0.0840	0.0804

Table 4.5.2. Ending times after two periods(t_2) for circular top design.

Circular Top	**5 Hz**	**10 Hz**	**20 Hz**	**40 Hz**
	0.4724	0.2676	0.1680	0.1156
	60 Hz	**80 Hz**	**100 Hz**	**120 Hz**
	0.0985	0.0893	0.0841	0.0809

Table 4.5.3. Ending times after two periods(t_2) for triangular top design.

Triangular Top	**5 Hz**	**10 Hz**	**20 Hz**	**40 Hz**
	0.4719	0.2673	0.1673	0.1153
	60 Hz	**80 Hz**	**100 Hz**	**120 Hz**
	0.0978	0.0888	0.0838	0.0806

Table 4.5.4. Ending times after two periods(t_2) for square mirror hole design.

Square Mirror Hole	**5 Hz**	**10 Hz**	**20 Hz**	**40 Hz**
	0.4751	0.2728	0.1659	0.1144
	60 Hz	**80 Hz**	**100 Hz**	**120 Hz**
	0.0969	0.0879	0.0830	0.0796

Table 4.5.5. Ending times after two periods(t_2) for circular mirror hole design.

Circular Mirror Hole	**5 Hz**	**10 Hz**	**20 Hz**	**40 Hz**
	0.4742	0.2719	0.1657	0.1156
	60 Hz	**80 Hz**	**100 Hz**	**120 Hz**
	0.0974	0.0891	0.0830	0.0799

Table 4.5.6. Ending times after two periods(t_2) for triangular mirror hole design.

Triangular Mirror Hole	**5 Hz**	**10 Hz**	**20 Hz**	**40 Hz**
	0.4736	0.2714	0.1654	0.1144
	60 Hz	**80 Hz**	**100 Hz**	**120 Hz**
	0.0970	0.0878	0.0830	0.0799

Table 4.5.7. Ending times after two periods(t_2) for S-Shape mirror hole design.

S-Shape Mirror Hole	**5 Hz**	**10 Hz**	**20 Hz**	**40 Hz**
	0.4783	0.2760	0.1666	0.1154
	60 Hz	**80 Hz**	**100 Hz**	**120 Hz**
	0.0971	0.0889	0.0830	0.0799

4.6 Sound Phase Change

In this section, sound phase change (Δp_1) calculated for t_1 values are given as data.

Sound phase changes are in [rad].

4.6.1. Sound Phase Change for t_1 (Δt_1)

Table 4.6.1.1. Sound phase change(Δp_1) for square top design for t_1 values.

	5 Hz	10 Hz	20 Hz	40 Hz
Square Top	0	0.0314	-0.0628	0.8042
	2π .0	2π .(0.0050)	2π .(-0.0100)	2π .(0.1281)
	60 Hz	**80 Hz**	**100 Hz**	**120 Hz**
	1.0933	2.0106	1.8850	3.1667
	2π .(0.1741)	2π .(0.3202)	2π .(0.3002)	2π .(0.5043)

Table 4.6.1.2. Sound phase change(Δp_1) for circular top design for t_1 values.

	5 Hz	10 Hz	20 Hz	40 Hz
Circular Top	0	0.0314	-0.0503	0.8042
	2π .0	2π .(0.0050)	2π .(-0.0080)	2π .(0.1281)
	60 Hz	**80 Hz**	**100 Hz**	**120 Hz**
	1.0179	1.9604	2.0106	3.1667
	2π .(0.1621)	2π .(0.3122)	2π .(0.3202)	2π .(0.5043)

Table 4.6.1.3. Sound phase change(Δp_1) for triangular top design for t_1 values.

Triangular Top	**5 Hz**	**10 Hz**	**20 Hz**	**40 Hz**
	0	0.0503	-0.0628	0.8042
	2π .0	2π .(0.0080)	2π .(-0.0100)	2π .(0.1281)
	60 Hz	**80 Hz**	**100 Hz**	**120 Hz**
	1.0556	2.3122	1.7593	3.0913
	2π .(0.1681)	2π .(0.3682)	2π .(0.2801)	2π .(0.4922)

Table 4.6.1.4. Sound phase change(Δp_1) for square mirror hole design for t_1 values.

Square Mirror Hole	**5 Hz**	**10 Hz**	**20 Hz**	**40 Hz**
	0	-0.1759	-0.4147	0.2765
	2π .0	2π .(-0.0280)	2π .(-0.0660)	2π .(0.0440)
	60 Hz	**80 Hz**	**100 Hz**	**120 Hz**
	0.0377	1.2064	2.0735	2.1112
	2π .(0.0060)	2π .(0.1921)	2π .(0.3302)	2π .(0.3362)

Table 4.6.1.5. Sound phase change(Δp_1) for circular mirror hole design for t_1 values.

Circular Mirror Hole	**5 Hz**	**10 Hz**	**20 Hz**	**40 Hz**
	0	-0.0817	-0.5655	-0.6032
	2π .0	2π .(-0.0130)	2π .(-0.0900)	2π .(-0.0960)
	60 Hz	**80 Hz**	**100 Hz**	**120 Hz**
	-0.6786	-0.4021	1.5080	1.8096
	2π .(-0.1081)	2π .(-0.0640)	2π .(0.2401)	2π .(0.2881)

Table 4.6.1.6. Sound phase change(Δp_1) for triangular mirror hole design for t_1 values.

Triang. Mirror Hole	**5 Hz**	**10 Hz**	**20 Hz**	**40 Hz**
	0	-0.0314	-0.2011	0.4273
	2π .0	2π .(-0.0050)	2π .(-0.0320)	2π .(0.0680)
	60 Hz	**80 Hz**	**100 Hz**	**120 Hz**
	0.2262	1.5582	1.2566	2.3373
	2π .(0.0360)	2π .(0.2481)	2π .(0.2001)	2π .(0.3722)

Table 4.6.1.7. Sound phase change(Δp_1) for S-Shape mirror hole design for t_1 values.

S-Shape Mirror Hole	**5 Hz**	**10 Hz**	**20 Hz**	**40 Hz**
	0	0.1571	0.3393	0.7540
	2π .0	2π .(0.0250)	2π .(0.0540)	2π .(0.1201)
	60 Hz	**80 Hz**	**100 Hz**	**120 Hz**
	1.4703	2.5635	4.3982	5.2779
	2π .(0.2341)	2π .(0.4082)	2π .(0.7004)	2π .(0.8404)

4.6.2. Sound Phase Change for t_2-2T ($\Delta(t_2 - 2T)$)

In this section, sound phase change (Δp_1) calculated for $t_2 - 2T$ values are given as data.

Table 4.6.2.1. Sound phase change(Δp_1) for square top design for t_2-2T values.

Square Top	**5 Hz**	**10 Hz**	**20 Hz**	**40 Hz**
	0	-0.2890	-0.5655	-1.6588
	2π .0	2π .(-0.0460)	2π .(-0.0900)	2π .(-0.2641)
	60 Hz	**80 Hz**	**100 Hz**	**120 Hz**
	-2.8023	-4.1218	-5.0894	-6.3083
	2π .(-0.4462)	2π .(-0.6563)	2π .(-0.8104)	2π .(-1.0045)

Table 4.6.2.2. Sound phase change(Δp_1) for circular top design for t_2-2T values.

Circular Top	**5 Hz**	**10 Hz**	**20 Hz**	**40 Hz**
	0	-0.3016	-0.5529	-1.7090
	2π .0	2π .(-0.0480)	2π .(-0.0880)	2π .(-0.2721)
	60 Hz	**80 Hz**	**100 Hz**	**120 Hz**
	-2.7269	-4.0715	-5.2150	-6.1575
	2π .(-0.4342)	2π .(-0.6483)	2π .(-0.8304)	2π .(-0.9805)

Table 4.6.2.3. Sound phase change(Δp_1) for triangular top design for t_2-2T values.

Triangular Top	**5 Hz**	**10 Hz**	**20 Hz**	**40 Hz**
	0	-0.2890	-0.5781	-1.6588
	2π .0	2π .(-0.0460)	2π .(-0.0920)	2π .(-0.2641)
	60 Hz	**80 Hz**	**100 Hz**	**120 Hz**
	-2.8023	-4.0715	-5.0894	-6.0067
	2π .(-0.4462)	2π .(-0.6483)	2π .(-0.8104)	2π .(-0.9565)

Table 4.6.2.4. Sound phase change(Δp_1) for square mirror hole design for t_2-2T values.

Square Mirror Hole	**5 Hz**	**10 Hz**	**20 Hz**	**40 Hz**
	0	-0.1445	-1.1561	-2.6892
	2π .0	2π .(-0.0230)	2π .(-0.1841)	2π .(-0.4282)
	60 Hz	**80 Hz**	**100 Hz**	**120 Hz**
	-4.3480	-6.1324	-7.6027	-9.1735
	2π .(-0.6924)	2π .(-0.9765)	2π .(-1.2106)	2π .(-1.4607)

Table 4.6.2.5. Sound phase change(Δp_1) for circular mirror hole design for t_2-2T values.

Circular Mirror Hole	**5 Hz**	**10 Hz**	**20 Hz**	**40 Hz**
	0	-0.1445	-1.0681	-2.1614
	2π .0	2π .(-0.0230)	2π .(-0.1700)	2π .(-0.3442)
	60 Hz	**80 Hz**	**100 Hz**	**120 Hz**
	-3.8202	-5.0768	-7.0372	-8.2687
	2π .(-0.6383)	2π .(-0.8084)	2π .(-1.1206)	2π .(-1.3167)

Table 4.6.2.6. Sound phase change(Δp_1) for triangular mirror hole design for t_2-2T values.

Triang. Mirror Hole				
	5 Hz	**10 Hz**	**20 Hz**	**40 Hz**
	0	-0.1382	-1.0304	-2.3122
	2π .0	2π .(-0.0220)	2π .(-0.1641)	2π .(-0.3682)
	60 Hz	**80 Hz**	**100 Hz**	**120 Hz**
	-3.7448	-5.4287	-6.6602	-7.8163
	2π .(-0.5963)	2π .(-0.8644)	2π .(-1.0605)	2π .(-1.2446)

Table 4.6.2.7. Sound phase change(Δp_1) for S-Shape mirror hole design for t_2-2T values.

S-Shape Mirror Hole				
	5 Hz	**10 Hz**	**20 Hz**	**40 Hz**
	0	-0.1445	-1.4703	-3.2421
	2π .0	2π .(-0.0230)	2π .(-0.2341)	2π .(-0.5163)
	60 Hz	**80 Hz**	**100 Hz**	**120 Hz**
	-5.4789	-7.2382	-9.6133	-11.3600
	2π .(-0.8724)	2π .(-1.1526)	2π .(-1.5308)	2π .(-1.8089)

5 Analysis and Discussion

In this section, the results are analysed and discussed. To compare and and to investigate the phase change four graphs, “t_1 vs frequency”, “$t_2 - 2T$ vs frequency”, “sound phase change (for t_1) vs frequency” and “sound phase change (for $t_2 - 2T$) vs frequency” are plotted. MATLAB is used for analysis.

5.1 Analysis

5.1.1 t_1 vs Frequency

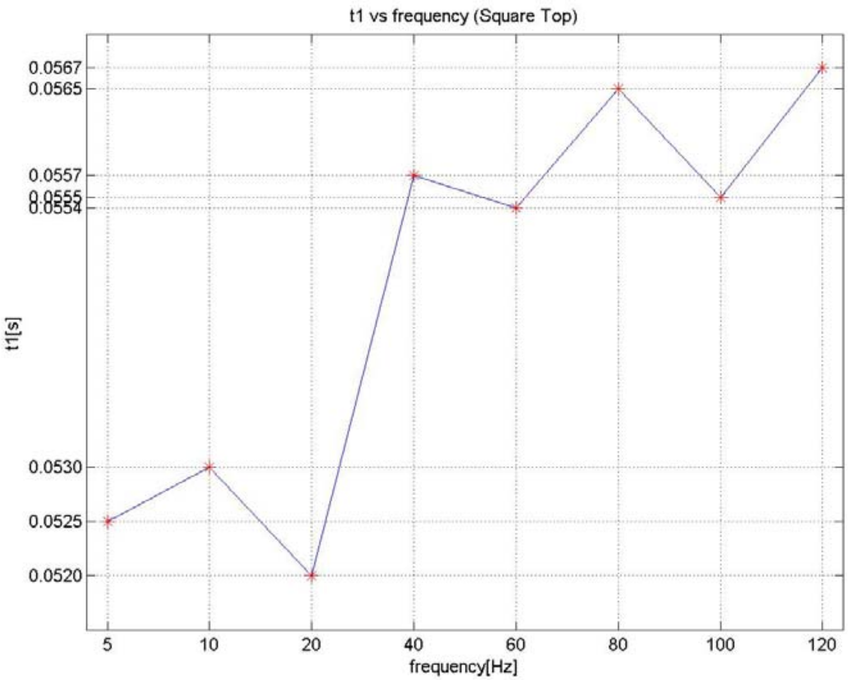

Figure 5.1.1.1. t_1 vs frequency (Square Top).

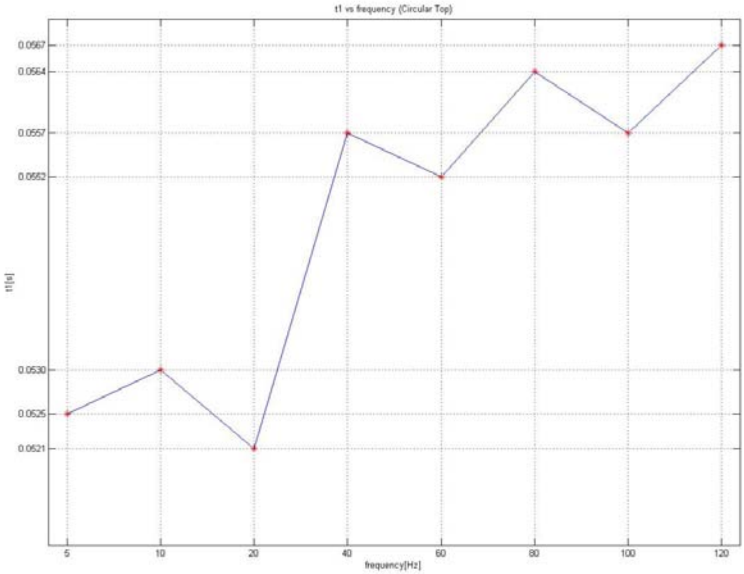

Figure 5.1.1.2. t_1 vs frequency (Circular Top).

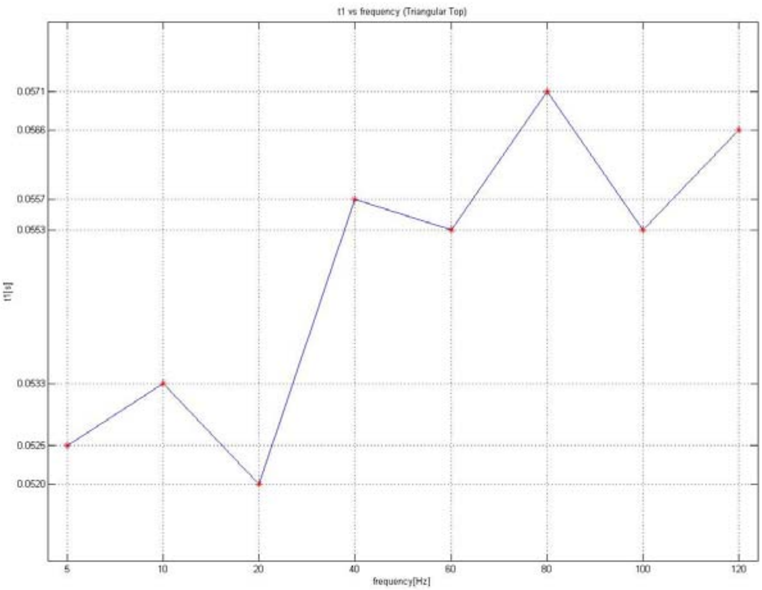

Figure 5.1.1.3. t_1 vs frequency (Triangular Top).

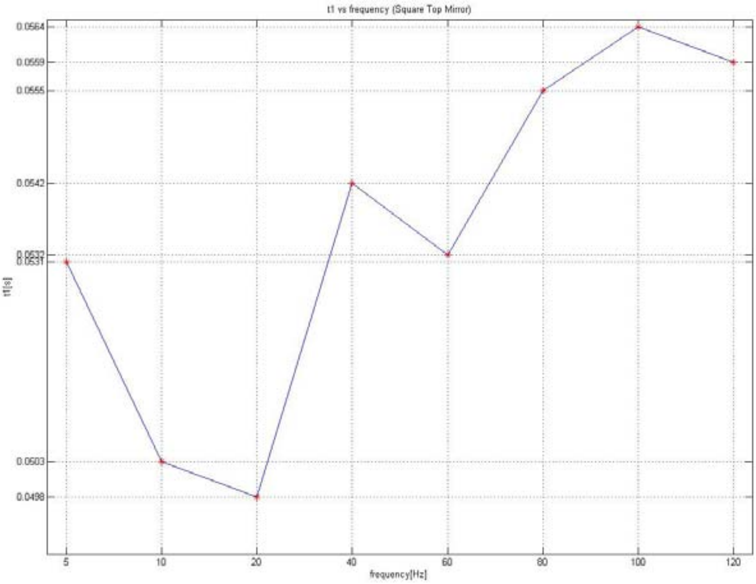

Figure 5.1.1.4. t_1 vs frequency (Square Mirror Hole).

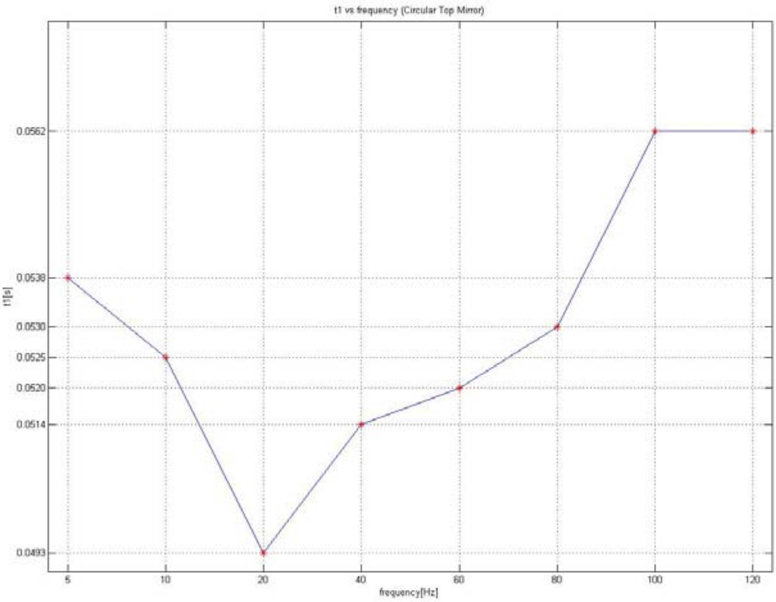

Figure 5.1.1.5. t_1 vs frequency (Circular Mirror Hole).

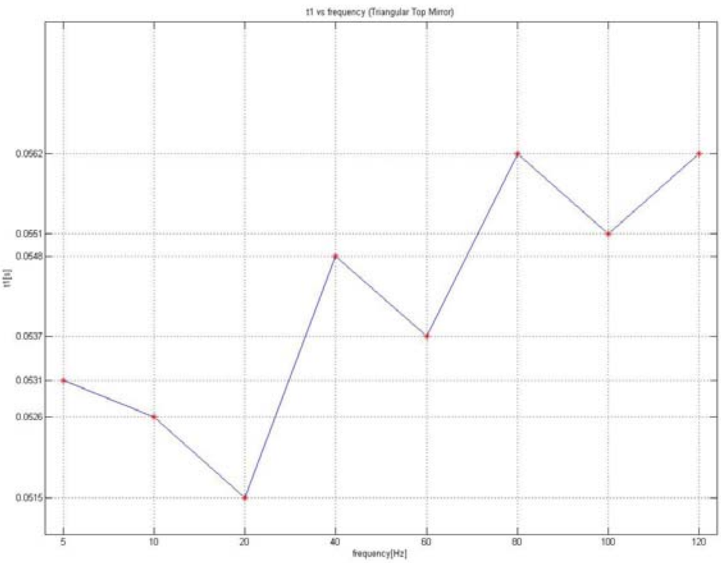

Figure 5.1.1.6. t_1 vs frequency (Triangular Mirror Hole).

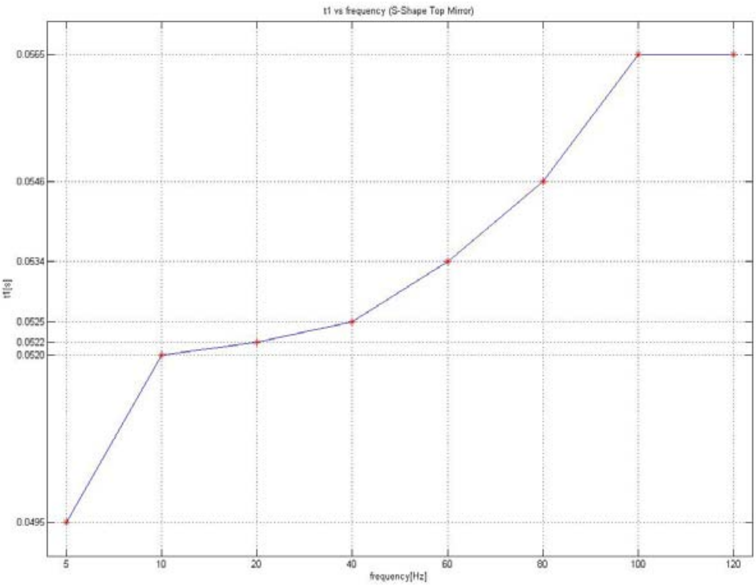

Figure 5.1.1.7. t_1 vs frequency (S-Shape Mirror Hole).

5.1.2 t_2-2T vs frequency

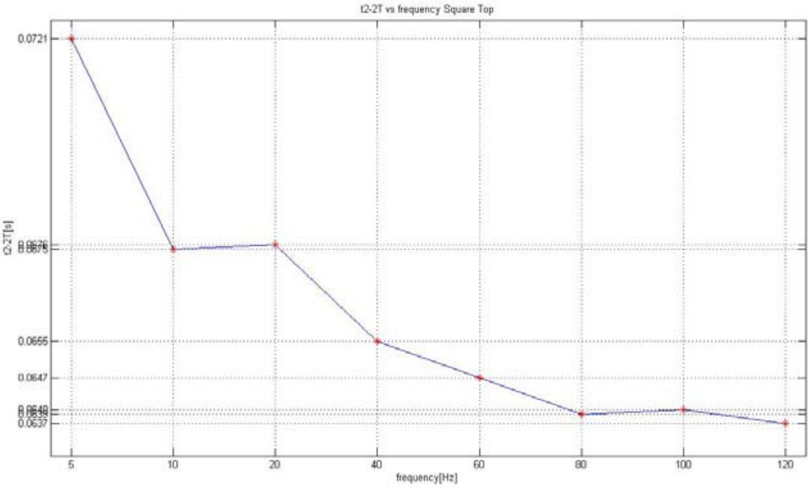

Figure 5.1.2.1. t_2-2T vs frequency (Square Top).

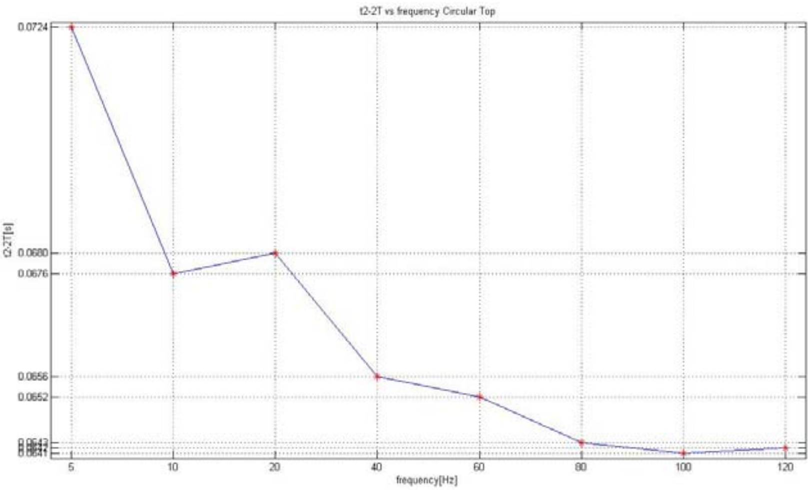

Figure 5.1.2.2. t_2-2T vs frequency (Circular Top).

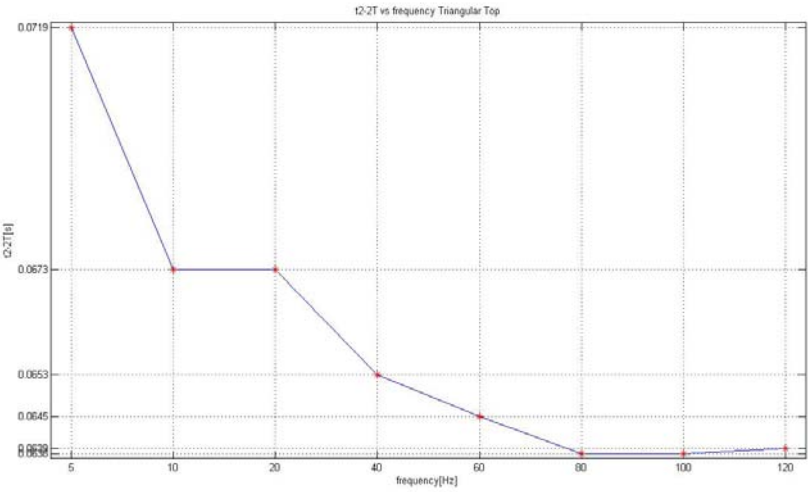

Figure 5.1.2.3. t_2-2T vs frequency (Triangular Top).

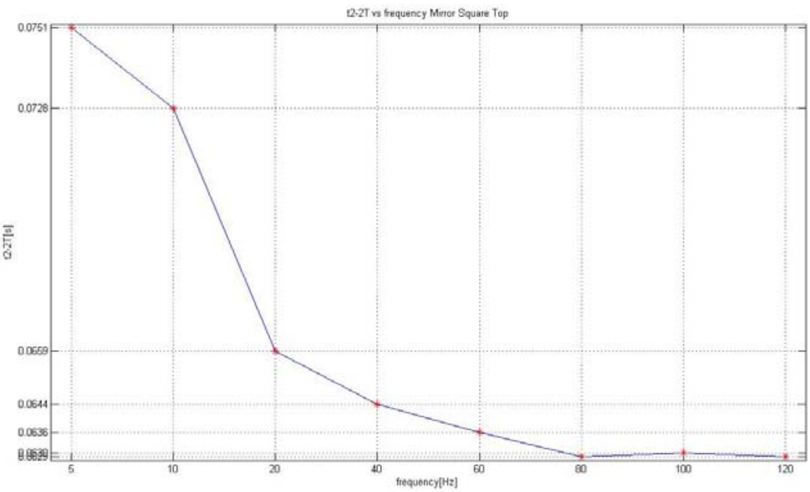

Figure 5.1.2.4. t_2-2T vs frequency (Square Mirror Hole).

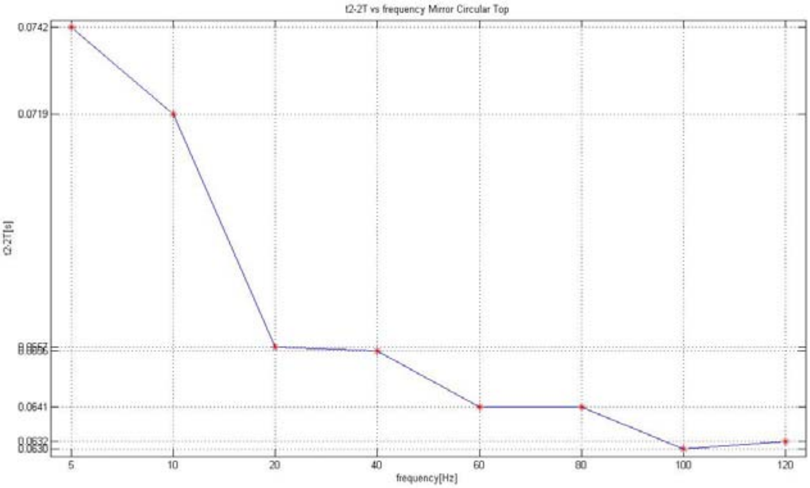

Figure 5.1.2.5. t_2-2T vs frequency (Circular Mirror Hole).

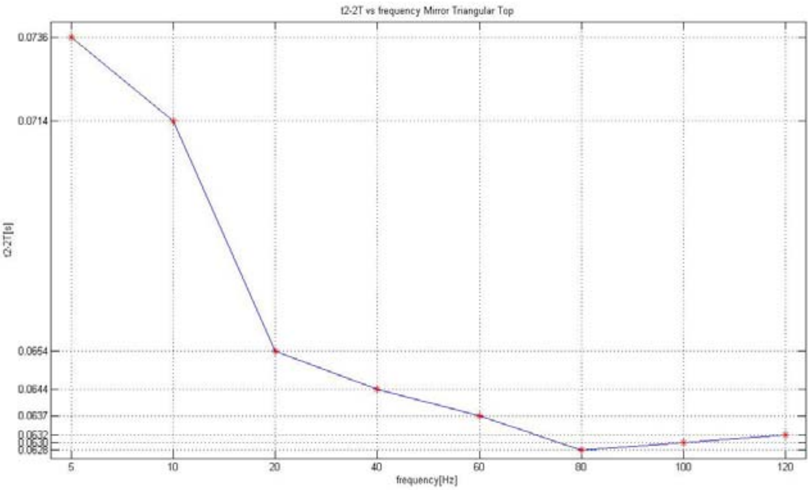

Figure 5.1.2.6. t_2-2T vs frequency (Triangular Mirror Hole).

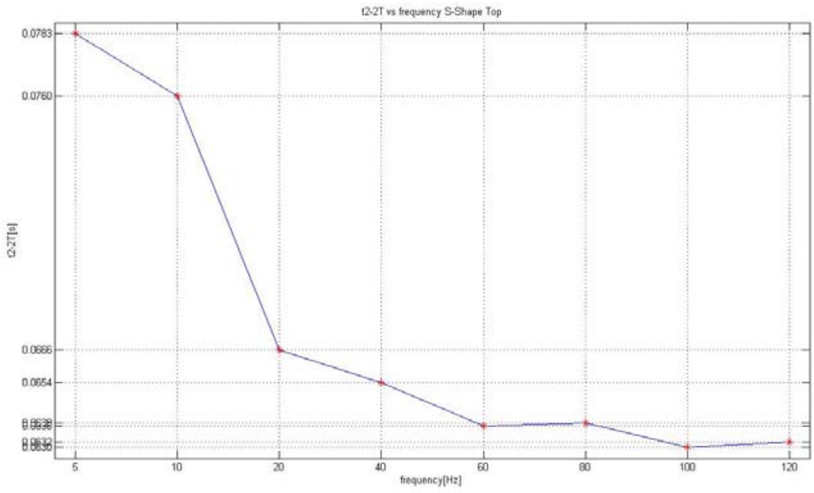

Figure 5.1.2.7. t_2-2T vs frequency (S-Shape Mirror Hole).

5.1.3 Phase Change vs Frequency

5.1.3.1 For t_1 Values

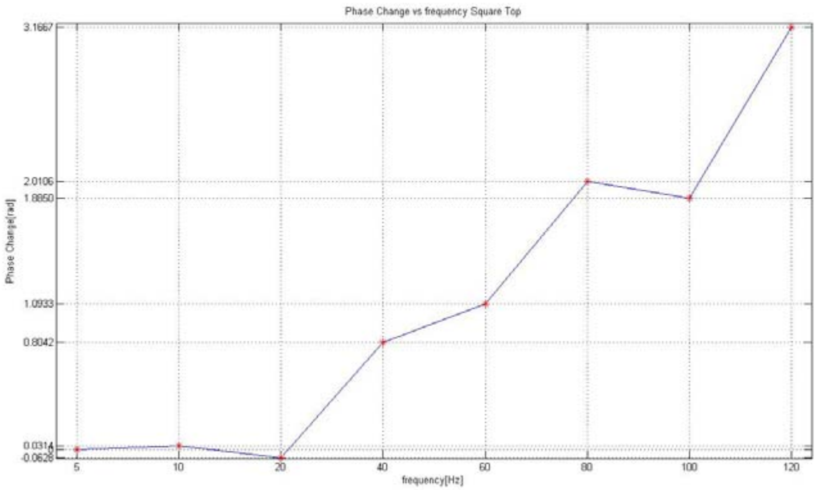

Figure 5.1.3.1.1. Phase Change(Δp_1) vs frequency (Square Top).

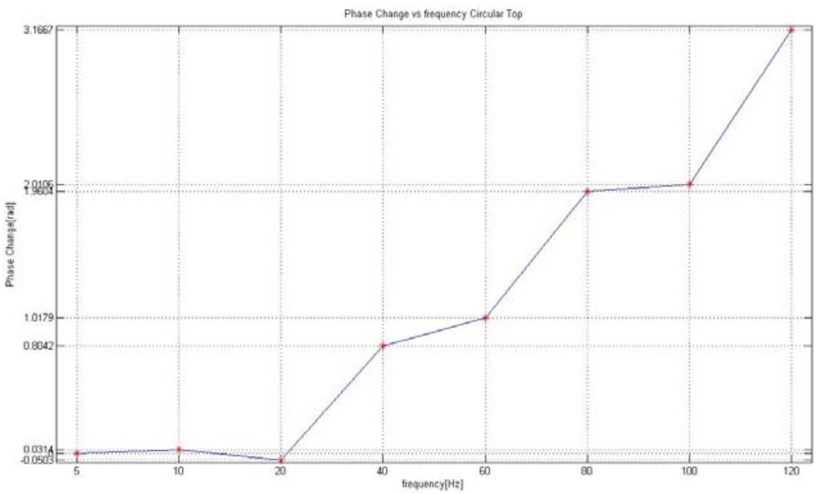

Figure 5.1.3.1.2. Phase Change(Δp_1) vs frequency (Circular Top).

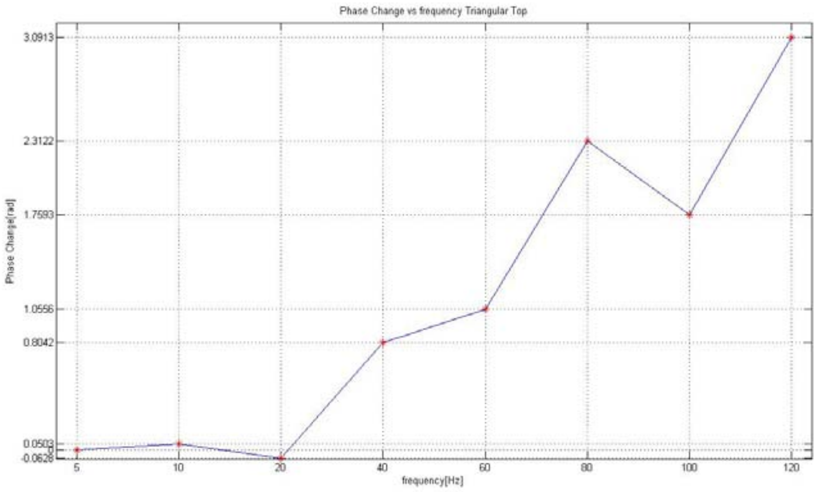

Figure 5.1.3.1.3. Phase Change(Δp_1) vs frequency (Triangular Top).

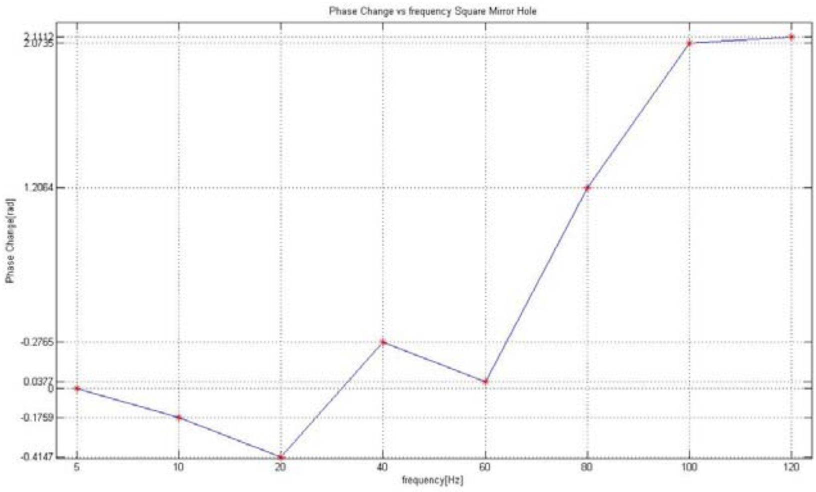

Figure 5.1.3.1.4. Phase Change(Δp_1) vs frequency (Square Mirror Hole).

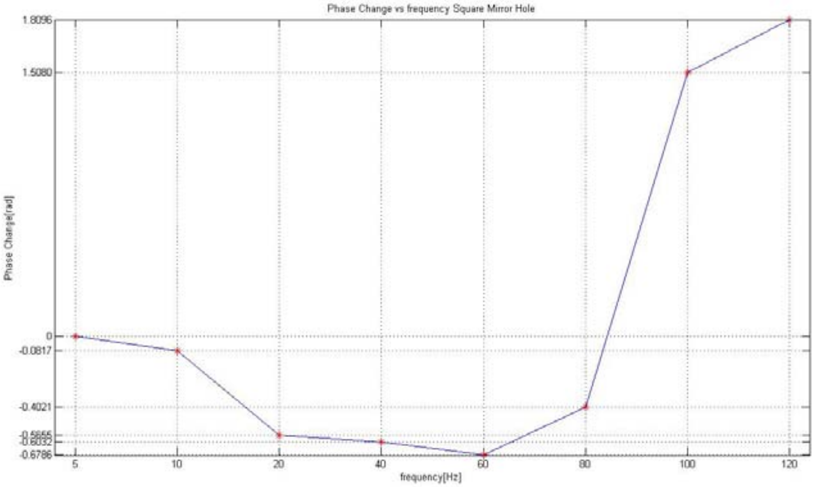

Figure 5.1.3.1.5 Phase Change(Δp_1) vs frequency (Circular Mirror Hole).

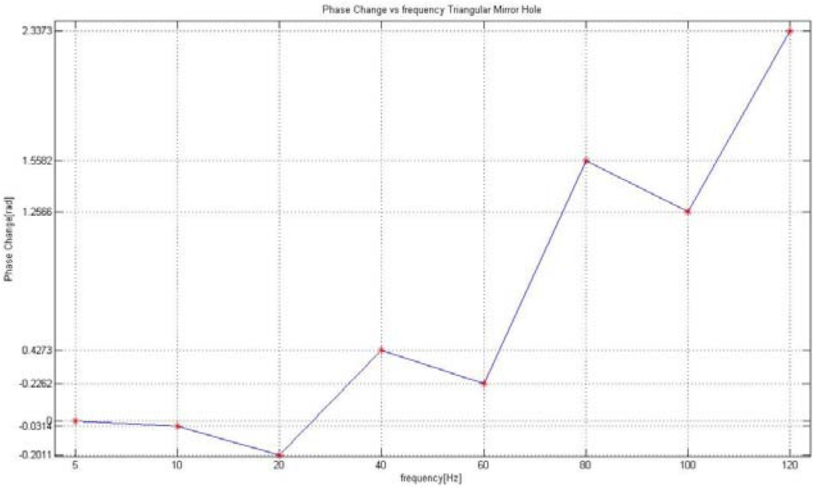

Figure 5.1.3.1.6. Phase Change(Δp_1) vs frequency (Triangular Mirror Hole).

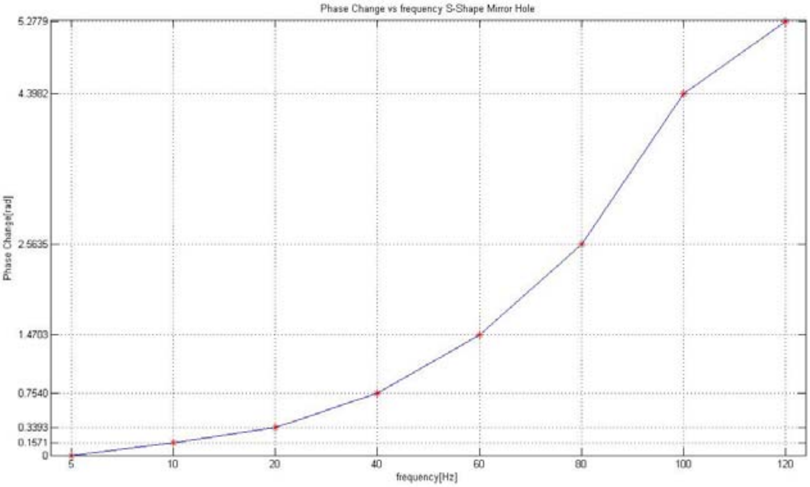

Figure 5.1.3.1.7. Phase Change(Δp_1) vs frequency (S-Shape Mirror Hole).

5.1.3.2 For t_2-2T Values

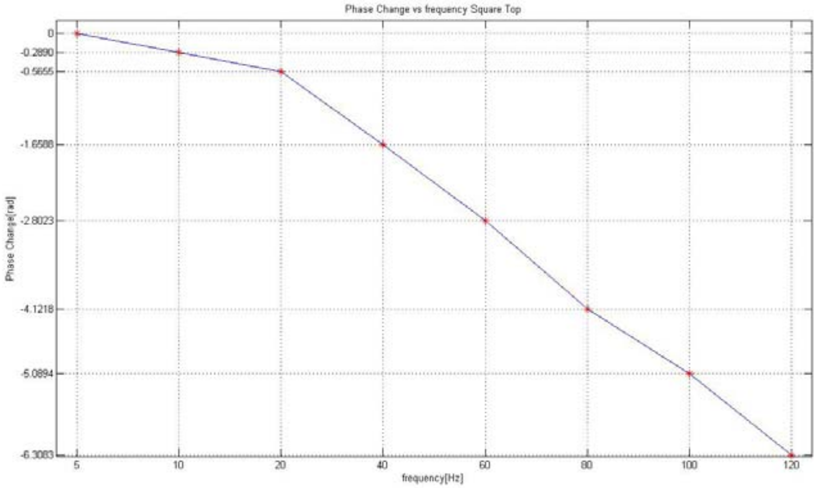

Figure 5.1.3.2.1. Phase Change(Δp_1) vs frequency (Square Top).

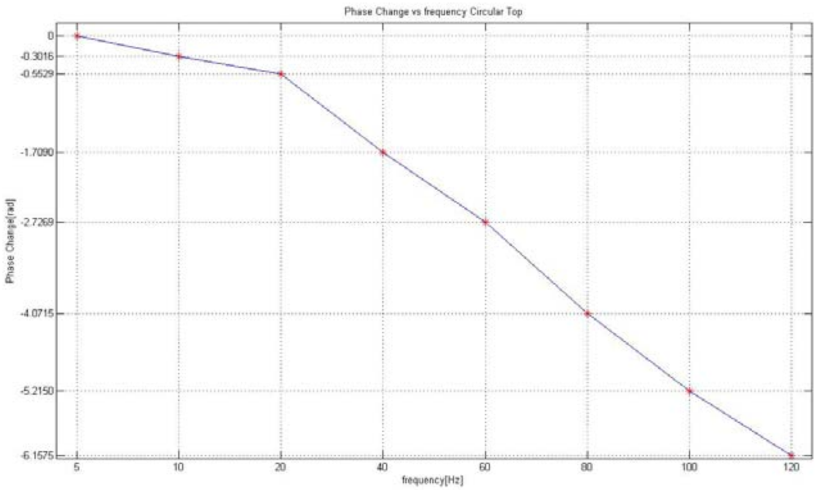

Figure 5.1.3.2.2. Phase Change(Δp_1) vs frequency (Circular Top).

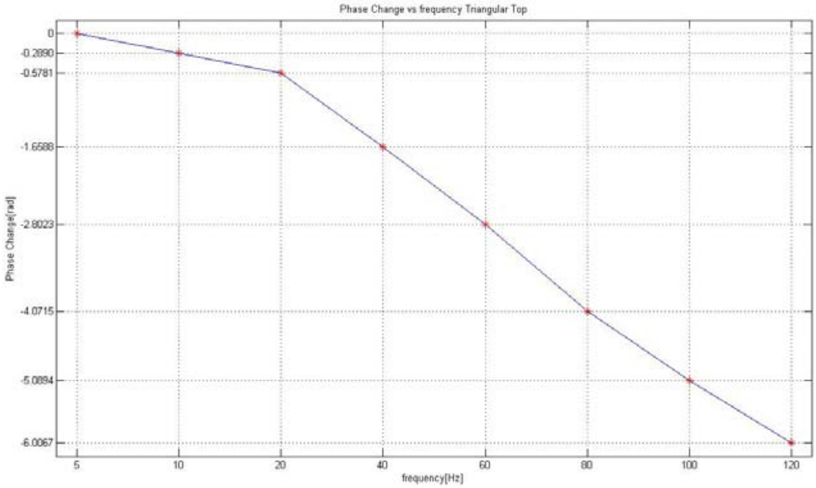

Figure 5.1.3.2.3. Phase Change(Δp_1) vs frequency (Triangular Top).

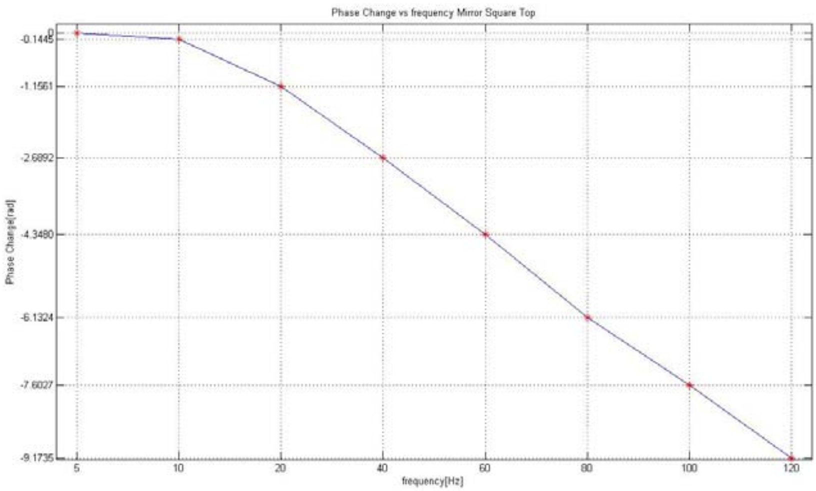

Figure 5.1.3.2.4. Phase Change(Δp_1) vs frequency (Square Mirror Hole).

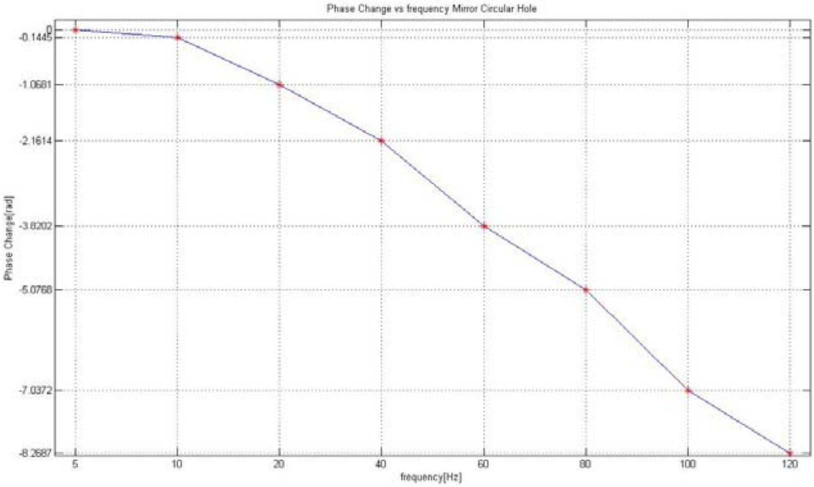

Figure 5.1.3.2.5. Phase Change(Δp_1) vs frequency (Circular Mirror Hole).

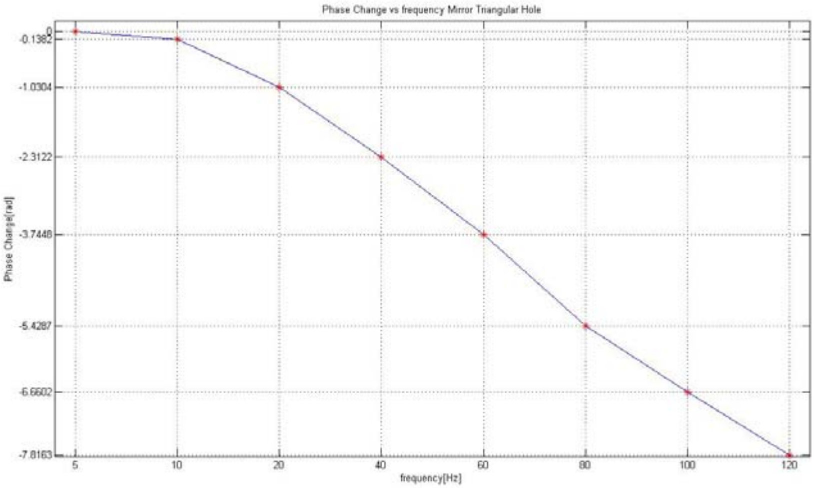

Figure 5.1.3.2.6. Phase Change(Δp_1) vs frequency (Triangular Mirror Hole).

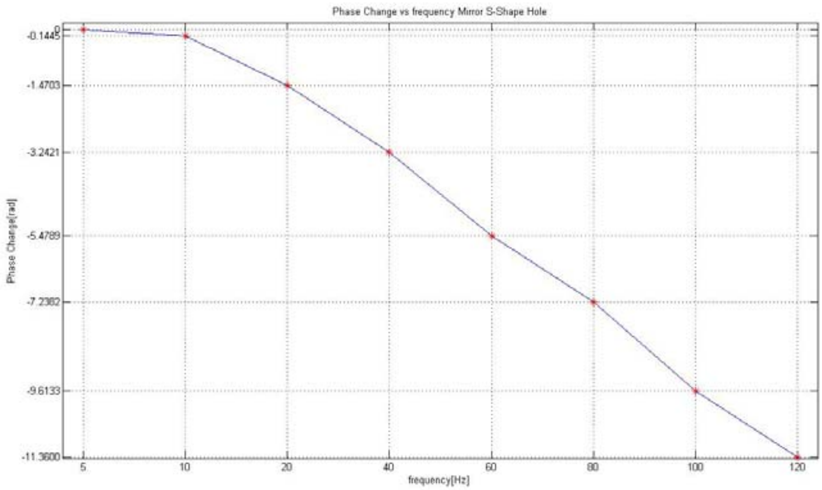

Figure 5.1.3.2.7. Phase Change(Δp_1) vs frequency (S-Shape Mirror Hole).

5.2 Discussion

After analysing the results, sound phase change can now be compared between the frequencies and the designs.

The phase change was compared between two frequencies, the minimum and the maximum frequency in this work, one of them is 24 times bigger than the other one. It is good to observe the phase change in such a range.

If we look at the results and analysis, we can observe the values close to the ideal phase change for different models and frequencies.

In figure 5.2 , phase change can be observed for different designs. For the same frequency (80 Hz in this figure), sound reaching times to the receiver differ for different models.

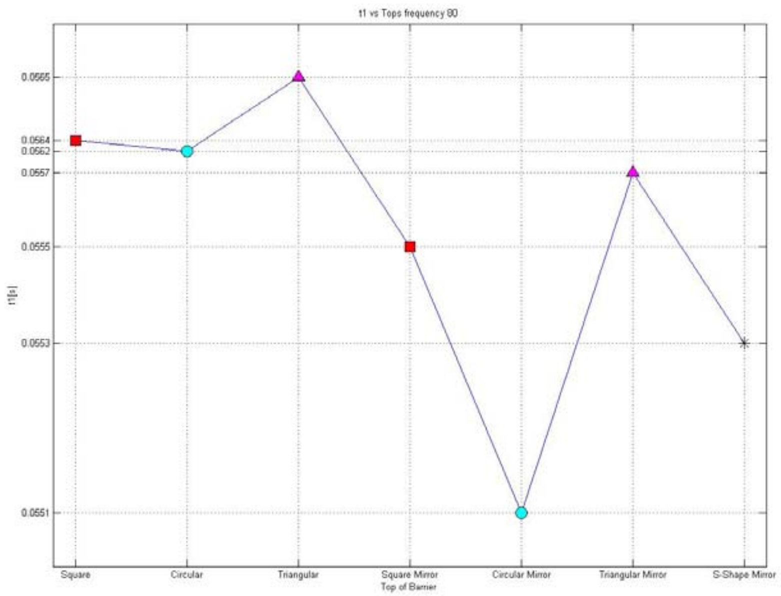

Figure 5.2. t_1 vs designs (80 Hz).

As an example of the phase change calculation according to the equation (2.1),

$$\Delta p = \Delta p_{Tops} - \Delta p_{Holes}$$

if we calculate the phase change between the square top and the s-shape mirror hole, for the frequency of 60 Hz, using the data in table (4.6.2.1) and (4.6.2.7),

$$\Delta p = \Delta p_{SquareTop} - \Delta p_{S-ShapeMirrorHole}$$

$$\Delta p = \left(2\pi.\left(-0.4462\right)\right) - \left(2\pi.\left(-0.8724\right)\right)$$

The phase change is,

$$\Delta p = 2\pi.\left(0.4262\right) = 0.8524\pi$$

which is close to the ideal value, π .

If we look at the figures (5.1.1.7), (5.1.2.7), (5.1.3.1.7) and (5.1.3.2.7), we can see that the s-shape geometry design model is more consistent in phase change than the others.

6 Conclusion

The aim of this work was to simulate the sound source, noise barrier, receiver environment and to investigate the sound phase change over the noise barriers. Sound phase change was observed and sound phase change occurred for different designs and different frequencies. That is what was expected before the simulations. Now it can be said that noise cancellation can be possible according to the design in this work and can be possible for other designs. The data and the plots can be used to find; which design and the frequency gives the best phase response for noise cancellation. This work aims to show the importance of the phase in noise cancellation. Phase is a property which should significantly be considered in noise cancellation, for noise barriers and also in other noise cancellation applications. This work can be used as a reference in designing noise barriers and for further works in this area.

7 References

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