Room Acoustics Modeling Using Ray-Tracing Method

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Abstract

The main task in this project was to model the room acoustic using the ray tracing and then to compare the performance of the ray tracing method in estimating some important parameters like RT60 and SPL to the values obtained using theoretical calculations. To complete this task a programing code was developed using MATLAB to implement the ray tracing method, based on the equations describing this method. The created model was simplified by using some assumptions regarding the reflections inside the room, and the room shape was assumed to be a simple rectangular shape. The obtained results and the comparison shows that the ray tracing model is consistent with the theoretical results.

Ray Tracing method

Ray tracing is one of the geometrical acoustic modeling method, in which, a large number of rays are emitted from the sound source each with a given initial energy, the initial energy is the same for all rays if an omnidirectional sound source is assumed. Then each ray is traced as it travels inside the room and possibly reaching the receiver. During this process the energy for each ray will be decreasing because of the wall and air absorption effects. When a given ray intersect with the receiver, the intensity at the receiver is obtained at that time, and at the end of the process the room impulse response is obtained.

Approach and model information

In this experiment, there is one omnidirectional sound source and three receivers were used all of which assumed to be omnidirectional. Also, the receivers are assumed to be of a spherical shape, the volume of the receiver can be calculated using equation (1), the spherical shape was chosen because its easier to model and it requires less computation to determine if the ray intersect with the receiver or not and afterwards in acquiring the intersection length inside the receiver.

$$Vreceiver = 10 * \frac{Vroom}{Nray} \qquad (1)$$

The total number of rays ($Nray$ = 100352), uniformly distributed in spherical coordinates and having the same initial energy.

According to [1], the following equation can be used to calculate the sound intensity at the receiver.

$$I(t) = E' * \frac{dcell}{Vreceiver} \qquad (2)$$

$$E_0 = 10^{\frac{Lw}{10}} * \frac{10^{-12}}{Nray} \qquad (3)$$

$$E' = E_{0*} e^{-h*d} * \prod_{i} (1 - \alpha i) \qquad (4)$$

Where

E_0 Initial energy of each ray

αi the sound absorption coefficient of a wall

h sound absorption coefficient of air

Lw sound power level of the source

d total distance traveled by each ray

$dcell$ length of intersection of each ray with the receiver

In addition, according to [1], using ray tracing the SPL at the receiver and at each frequency band can be estimated using equation (5).

$$\text{SPL} = 10[\log(E) + 12] \qquad (5)$$

Where E is, the total energy sensed by the receiver

Also, according to [2], the sign of the received impulse depends on the number of reflections for each ray when traveling from the source to each receiver. In such a way that the sign will be positive for even number of reflection and negative for odd number of reflection. For example, the direct traveling ray without any reflection will have a positive sign, whereas a ray that has reflected one time before reaching the receiver will have a negative sign. Also, the impulse response a discrete time delta, where delta was chosen to be 1/fs and fs =44100 Hz which is used to represent frequency bandwidth up to 22050 Hz which is what needed to cover the entire hearing range [~20Hz to ~20kHz]

After getting the frequency response for each receiver at different frequency bands, the overall frequency response can be obtained for each receiver [2], by combining the DFT from each octave bands after filtering according to the frequency bandwidth of each band.

In addition to the results and procedures used for the ray tracing model as mentioned above, to evaluate the accuracy and consistency of the model, the following theoretical calculation was performed.

First, the manual calculation for RT60 was performed using Millington-Sette Equation (6), because some of the sound absorption coefficients > 0.2, and also this equation takes into account the air absorption effect, which was considered in the ray tracing model, Therefore, Its more suitable for the model and the sabine equation.

$$T_{60} = \frac{0.161 * Vroom}{\sum_i \ -Si * Ln(1 - \alpha i) + 4 * h * Vroom} \quad (6)$$

Also, SPL at each receiver (Lp) was calculated using equation (7). [4]

$$Lp = Lw + 10 * log10(\frac{Q}{4*pi*r} + \frac{4*(1-\alpha^{\sim})}{S*\alpha^{\sim}}) \quad \text{(dB)} \quad (7)$$

where $\alpha^{\sim}$ is the average absorption coefficient of all surfaces in the room.

Q is the directivity factor

The value of Q are chosen according to table (1).

Situation Directivity factor	*Q* Directivity Index	*DI (dB)*
free space	1	0
centered in a large flat surface	2	3
centered at the edge formed by the junction of two large flat surfaces	4	6
at the corner formed by the junction of three large flat surfaces	8	9

Table1. Directivity factors for a simple source near reflecting surfaces [4]

Room information

All the surface assumed to be flat and smooth, and thus all reflections are assumed to be specular reflections.

The room has the following dimension in meters.

Length = 12, width= 10, Height = 3

Omnidirectional sound source was used with Lw = 90 dB, and three omnidirectional spherical receivers were used, the source and receiver's locations are shown in figure (1).

Source = (2, 6, 2); R1 = (6, 6, 1.5); R2 = (6, 10, 1.5) ; R3=(8, 10, 1.5)

Octave Band Hz	125	250	500	1000	2000	4000
Side walls	0.22	0.2	0.2	0.2	0.15	0.15
Ceiling	0.2	0.2	0.22	0.2	0.2	0.1

Floor	0.15	0.15	0.1	0.1	0.1	0.05
Air attenuation	0.445	1.32	2.73	4.66	9.86	29.4

Table 2. Sound absorption coefficients for the room surfaces

Octave Band Hz	125	250	500	1000	2000	4000
Air attenuation	0.445	1.32	2.73	4.66	9.86	29.4

Table 3. Energy attenuation coefficients for air (dB/Km) at frequencies for temperature 20^0C and relative humidity 50% [3]

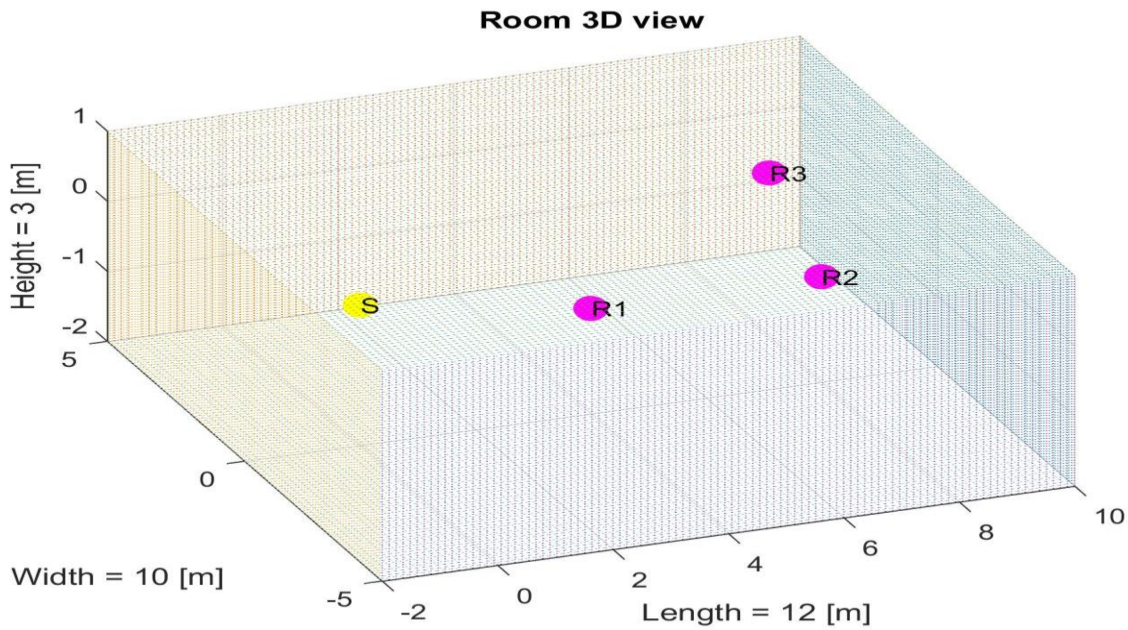

Figure 1. 3D view of the room with the source and receiver's locations

Results

1-Figure (2) shows the impulse response obtained from each receiver for 1KHz band. Also, the impulse response for the rest of frequency bands was obtained as well but only the 1KHz case is shown below.

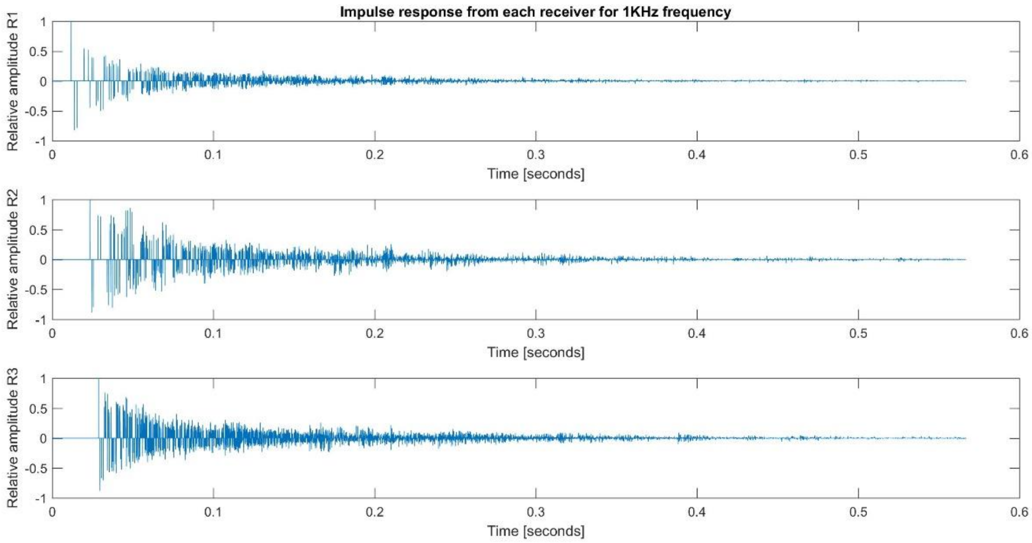

Figure 2. Impulse response from each receiver at 1KHz frequency

2- Figures (3 - 5) shows the relative sound intensity level decay for each receiver at 4KHz frequency. The same procedures were followed for other bands. Then, the RT60 time was estimated from these plots.

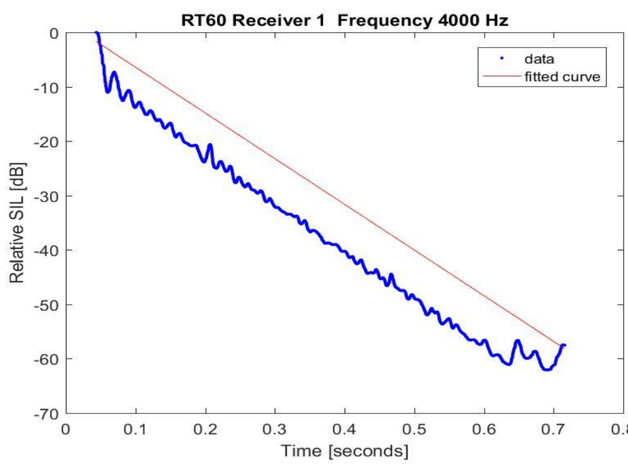

Figure 3. Receiver 1 sound intensity level decay at 4KHz frequency

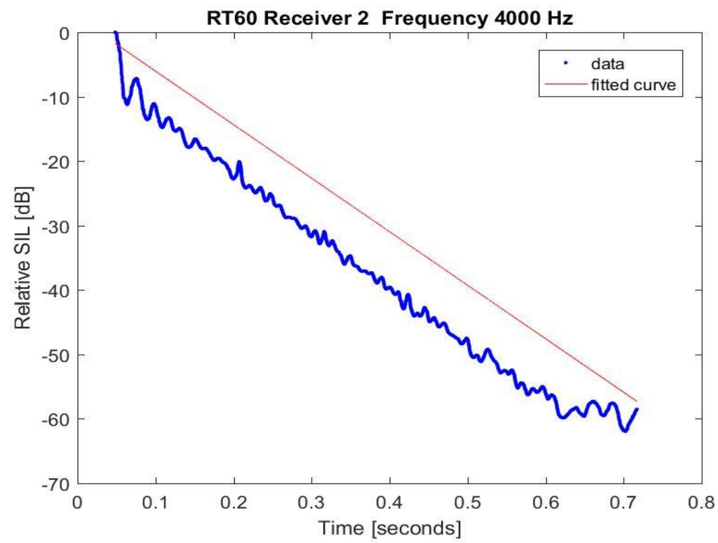

Figure 4. Receiver 2 sound intensity level decay at 4KHz frequency

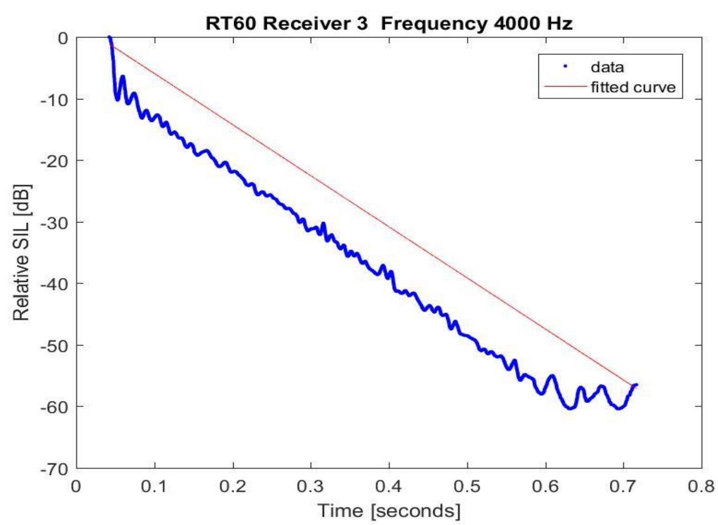

Figure 5. Receiver 3 sound intensity level decay at 4KHz frequency

4- comparison between the calculated T60 using equation (5) and the mean of the T60 obtained from the ray tracing models at different frequencies

Octave Band Hz	125	250	500	1000	2000	4000
Calculated	0.7271	0.7466	0.7642	0.7668	0.7721	0.7018
R1	0.7793	0.8141	0.8295	0.8269	0.8461	0.7138
R2	0.7784	0.8218	0.8358	0.8282	0.8442	0.7202
R3	0.7883	0.8288	0.847	0.8454	0.8607	0.7359
Mean	0.782	0.8216	0.8374	0.8335	0.8503	0.7233
Difference %	7.5564	10.0465	9.5856	8.6989	10.1364	3.0621

Table 4. T60 obtained from models and manual calculation

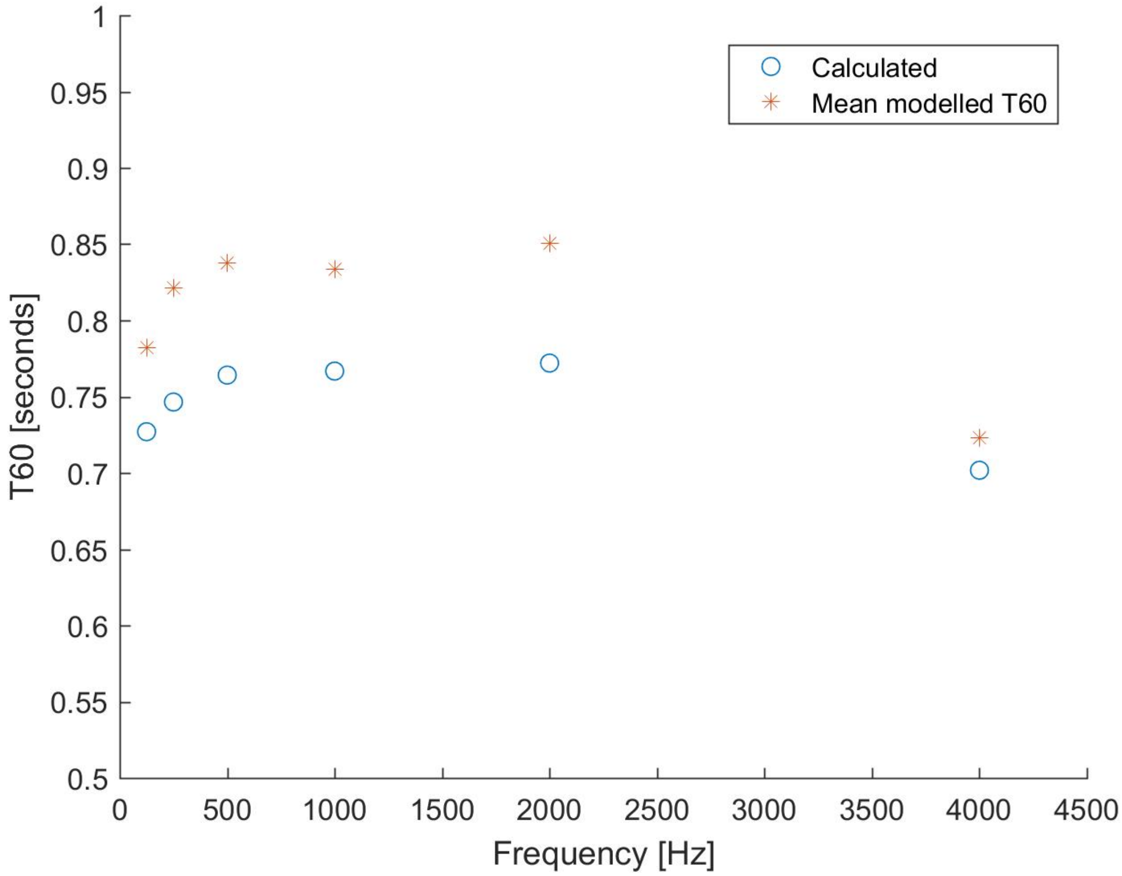

Figure 6. Calculated and modelled T60 for different Octave Bands

5- The SPL for each receiver at each Octave band was calculated from the model result using equation (5), and then the results were compared the manual calculation done using equation-7 with Q = 4. And the following results were obtained.

Octave Band Hz	125	250	500	1000	2000	4000
R1	76.1735	75.9985	76.0940	76.0816	76.079	75.5057
R2	74.7768	74.8686	74.9457	74.9042	74.9495	74.0812
R3	74.3361	74.442	74.5304	74.5	74.5484	73.7651

Table 5. SPL at each receiver for different Octave Bands

Receiver	R1	R2	R3
Mean modeled	75.9887	74.7543	74.3537
Calculated	78.2243	77.1437	77.0005
difference	2.2355	2.3894	2.6467

Table 6. Comparison between modeled and calculated SPL at each receiver

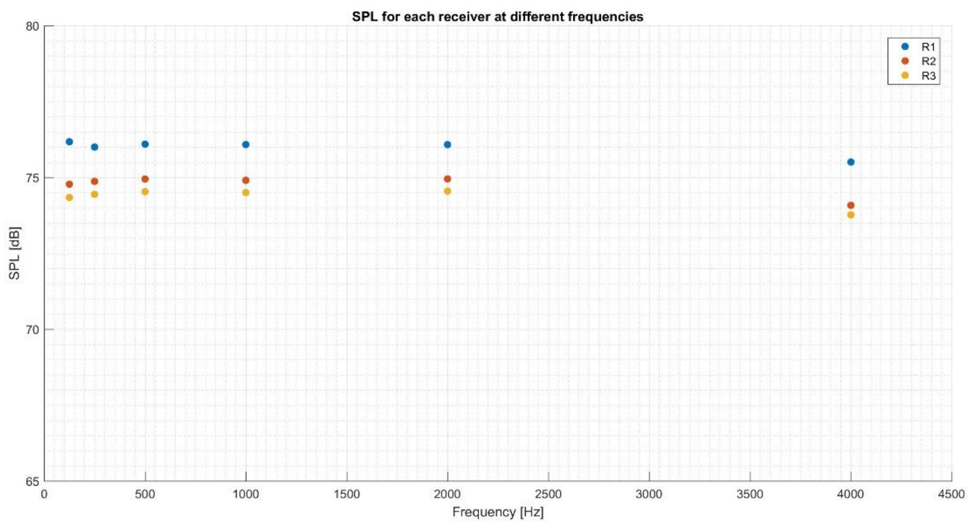

Figure 7. SPL for each receiver at each octave band

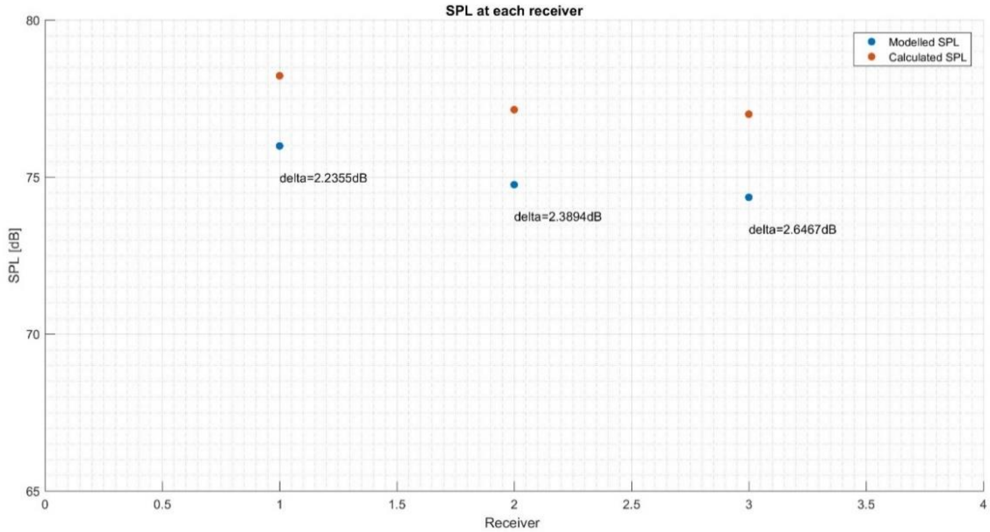

Figure 8. Comparison between modelled SPL and calculated at each receiver

6- After obtaining the impulse response for each octave band the corresponding frequency response was computed using DFT. Then the resulting DFT are filtered and combined according to the frequency bandwidth for each band figure-9 show the combined frequency response for each receiver. Finally, the overall impulse response was obtained by taking the inverse DFT. This process was repeated for every receiver and the final impulse responses are shown in figure-10

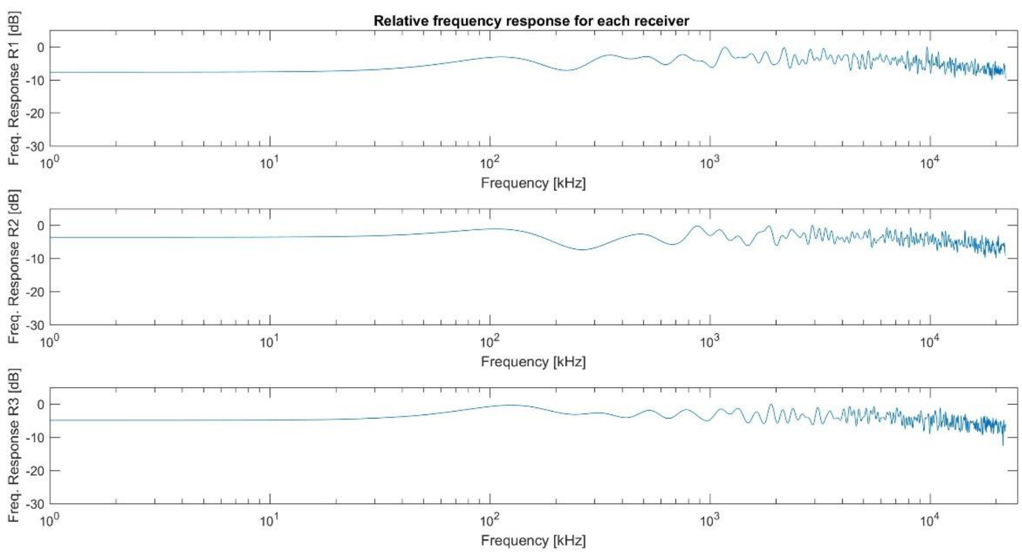

Figure 9. Frequency response for each receiver

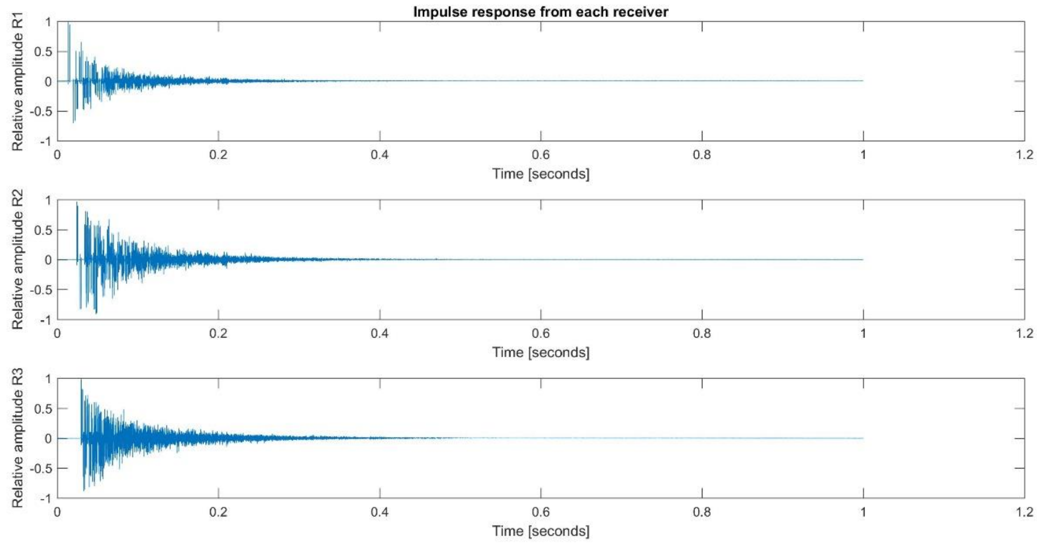

Figure10. Final impulse response for each receiver

Discussion

From figure (2) It can be clearly seen that the impulse response has the three parts, namely the direct sound, early reflection, and the reverberation. Also, it can be noticed that the time gap between the direct and the reflection parts are decreasing going from R1, R2 and R3. Where R2 & R3 are farther from the source and near the wall and corner respectively. In addition, the density of the reverberation and its amplitude increase in the same order.

The result in table (3) is consistent with what has been mentioned above, where It can be noticed that the reverberation time slightly increases, where it reaches its maximum at R3. Which is what is expected since R3 is close to the corner of the room. Also, comparing the results obtained from the model to the manually calculated results using equation (5), the difference was considerably small with a maximum of 10.1364%. In addition, figure (6) shows the correlation between the mean T60 from all receivers and the calculated results, for example at 4kHz both results decrease compared to other frequency bands.

The SPL results, figure (7) shows that the SPL at each receiver is approximately flat across different octave bands with the max difference being less than 1dB, and it shows that there are drop in SPL among different receivers where the SPL decreases as we go from R1, R2 to R3, which is what expected since their distant from the sound source increases in the same order, and in average the drop from R1 to R2 is about 1dB and the drop between R2 and R3 is about 0.5 dB. Also, from figure (7). It’s clear that the mean modeled SPL are very close to the calculated SPL where the maximum difference between them was about 2.6 dB.

Finally, the frequency response in dB figure (9) shows that its considerably flat with some fluctuations (comb filtering effects due to the reflections) but all the fluctuations are within 10dB. Most of the fluctuations appears at frequencies higher than 1 kHz.

Future Work

- This model can be further improved by not making the assumption that only a specular reflection is taking place. So, for example it could be improved by taking diffusion effects of the rays.
- To be able to create a real 3D virtual environment this model can be combined with the head related transfer function.

Programing Code

The created code can be found in the appendix

References

[1] Acoustic simulation of building spaces by raytracing method: Prediction vs. experimental

Results, by Mohammad Mahjoob and Sadeq Malakooti

[2] Computing Impulse Response of Room Acoustics Using the Ray-Tracing Method in Time Domain, by Adil ALPKOCAK, Malik Kemal SIS

[3] https://en.wikibooks.org/wiki/Engineering_Acoustics/Outdoor_Sound_Propagation

[4] FUNDAMENTALS OF ACOUSTICS Professor Colin H Hansen

Appendix

The Programming Code

All the programming for the model and the following analysis and comparison was done using MATLAB R2016a