Study of the Effect of Splaying Wall to Modify Acoustic Modes Distribution in Small Room

H Gunawan¹ and T Aditanoyo¹
¹ALTA Integra (Jakarta, Indonesia)

Email: info@vokuz.com

Abstract. Modes are known as ones of the important acoustical issues in small room. These phenomena could drastically change the spectral and temporal characteristic of sound. Studies have been done in optimizing rectangular room dimension, optimizing source and listener position, and optimizing low frequency with acoustic panel. To follow the best room ratio, a built room has to be cut a lot. This paper is studied the effect of splaying wall in attempt to shift the modes without trimming too much space. Axial room modes from different room ratios – including random, splay wall, Bolt, Louden, Cox – were calculated and compared. Low frequency characteristic of small rooms were observed aided by FEM simulation so that SPL result could be graph and statistically analyzed. It was found that splaying some walls from the random room dimension could distribute the modes evenly, similar with Cox’, though the SPL standard deviation was raised. Further research will be continued through psychoacoustic evaluation.

Keywords: Room Modes, Room Ratio, Splay Wall, Modes Distribution, FEM

1. Introduction

Room modes add acoustic distortion that could drastically change the spectral and temporal characteristic of sound in critical listening space. Studies have been done in optimizing rectangular room dimension, with the essence of method is to avoid degenerate modes by evenly distributing modal frequencies. Design criteria suggested is (1) to avoid multiple modal in one third octave (2) to avoid the absent of modes at every one third octave.

Bolt [1] using design charts method that determine the average modal spacing and evenly spaced modes in a room. Ratios of 2:3:5 and 1:2.33:4.33 and 1:1.26:1.59 are suggested consecutively.

Louden [2] calculated the modal distribution for a large number of room ratios and published a list of preferred dimensions based on a single figure of merit with the lowest the standard deviation of the intermodal spacing. One of the room ratio is 1:1.4:1.9.

Bonello [3] developed a criterion that the modal density in one third octave frequency band should never decrease when going up from a band to the next higher band. Modes with coincidental frequency are only tolerated in one third octave band with five or more modes.

Cox et al. [4] continue Louden research by developed computer algorithm using image source modelling to find the best room ratio. The computer algorithm can go through thousands of variations with more precise calculation. The calculated result was compared to Bolt, Louden, IEC room ratio and showing that Cox’ room ratio has the lowest standard deviation.
In practice, it is difficult to have the room comply with ideal room ratio suggested above since the listening room usually has to be designed in a room that already built. To follow the best room ratio, a room’s one or more dimensions have to be shortened and it will reduce a lot of space. To save room space and cost, this paper suggests an alternative method to evenly distribute modal frequency by splaying wall or ceiling instead of preserving the shoebox shape room. Bolt [5] said boundary irregularities may produce interactions and consequent spreading of energy among modes, resulting in greater sound diffusion throughout the room. Thus the fewer shape symmetries a room possesses, the greater will be the energy mixing and sound diffusion. In contrast, D’Antonio [6] said that making the room non-rectangular does not make modes disappear and does not make the modal behavior less pronounced than in an equivalent rectangular room, just different.

This paper is to study the effectiveness of splaying wall in attempt to evenly distribute the modal frequency and reduce peaks and dips due to the presence of modes. The contradiction of Bolt’s and D’Antonio’s statement is also discussed.

2. Comparison of Established Shoebox Room Ratios
Assumed we have random room with dimension 6.583-meter length, 4.888 meters width and 2.732-meter height. This random room does not comply with any ratio recommendation according to Bolt, Louden, or Cox. Table 1 show that if the random room wants to follow Cox ratio for small listening room [7], the space will be reduced from about 87 m³ to about 60 m³. Space loss due to reducing dimension is expensive considering expensive land cost at big city.

| Room Ratio       | Dimension       | Volume (m³) |
|------------------|-----------------|-------------|
| Random (1:1.79:2.41) | Length (m) | Width (m) | Height (m) |
| 6.583           | 4.888           | 2.732       | 87.909     |
| Bolt (2:3:5)    | 6.583           | 3.950       | 2.633      | 69.466     |
| Louden (1:1.4:1.9) | 5.191           | 3.825       | 2.732      | 54.245     |
| Cox (1:1.56:1.86) | 5.082           | 4.262       | 2.732      | 59.174     |

Table 1. Established room ratios, dimension, and volume

The formula for determining the frequency of each mode inside a room, $f$, is

$$f = \frac{c}{2} \sqrt{\left(\frac{n_x}{L}\right)^2 + \left(\frac{n_y}{W}\right)^2 + \left(\frac{n_z}{H}\right)^2}, \quad n = 1, 2, 3, ...$$

with $c$ is the speed of sound; $L$, $W$, $H$ are consecutively length, width, and height of the room; $n$ is the index of the room modes. Primary axial modes frequency of length (1,0,0) is 26 Hz; primary axial modes frequency of width (0,1,0) is 35 Hz; and primary axial modes frequency of height (0,0,1) is 63 Hz. Table 2 shows the distribution of axial modes based on one third frequency propose by ISO 266 axial modes of experiments room. Primary axial modes of Random room is absent on the 3rd and 4th one third octave. In our experience, the absent of modes for 2 of one third octave bandwidth give the feeling of lack of bass in this room. Bolt, Louden, and Cox show more evenly spaced modes compared to the random room.

FEM (Finite Element Method) was utilized to predict the SPL (Sound Pressure Level) in a point inside a room. Each room was drawn based on the dimension in Table 1. The air inside the room had density 1.2 kg/m³ and speed of sound 343 m/s. All of the surfaces were defined as totally reflective boundaries to emphasize the effect of standing wave inside the room. The room then was broken down into elements of tetrahedral. The maximum size of each element was 0.5 m so the calculation duration did not take too much time while the observable valid frequency still maintained below 343 Hz. Then, mode shapes could be calculated.
Table 2. Distribution of primary axial modes of various room ratios

| ISO 266 | Axial Primary Modes (Hz) |
|---------|--------------------------|
|         | 1/3 Octave | Freq (Hz) | Random | Bolt | Louden | Cox |
| 1<sup>st</sup> | 22.1 – 27.8 | (1,0,0) 26 | (1,0,0) 26 |
| 2<sup>nd</sup> | 27.8 – 35.1 | (0,1,0) 35 | (1,0,0) 33 | (1,0,0) 34 |
| 3<sup>rd</sup> | 35.1 – 44.2 | (0,1,0) 43 | (0,1,0) 40 |
| 4<sup>th</sup> | 44.2 – 55.7 | (0,1,0) 45 |
| 5<sup>th</sup> | 55.7 – 70.2 | (0,0,1) 63 | (0,0,1) 63 | (0,0,1) 63 |

The source was defined as monopole point source at a corner of room. Monopole point represents omnidirectional behavior of speaker when exciting low frequency sound. The corner was chosen to nullify the speaker-boundary interference effect. The acoustic power excited by the source was $1 \times 10^{-6}$ Watt and flat throughout the whole frequency band. The SPL probe was located at the 3D diagonally opposite corner of the source. At a mode frequency, the dimensional corner is the location with highest pressure fluctuation hence resulting highest SPL among other locations. Each simulation was run from 20 Hz to 200 Hz with 1 Hz increment.

Figure 1 shows SPL calculation results of 4 different room ratios. The SPL standard deviation and average is provided in Table 3. It is shown that Cox room ratio has the lowest standard deviation with high average. Considering that the room’s SPL response with low standard deviation is preferable [4], it indicates Cox room ratio may be the best room ratio with less coloration and more powerful bass sound. Meanwhile, the random room comes out as the second best despite of not complying with any established room ratio.

Table 3. SPL standard deviation and average of various room ratios

|         | random | bolt | louden | cox |
|---------|--------|------|--------|-----|
| Stdev (dB) | 11.66612 | 13.70007 | 15.21464 | 11.32772 |
| Average (dB) | 74.47975 | 72.78577 | 75.24404 | 74.25697 |

Figure 1. Sound pressure level of various room ratios with both source as well as receiver at corner and 3D diagonally opposing each other.
3. Splay Wall Room Experiment
Splaying walls may be the solution to balance between minimizing reduced room volume and achieving room with less modes degenerate problems. The splay room illustration can be found at Figure 2. According to Table 4, cutting volume from random room to splay room is a half compared to the cox room ratio.

![Figure 1](image)

**Figure 1.** Sound pressure level of various room ratios with both source as well as receiver at corner and 3D diagonally opposing each other (continued)

![Figure 2](image)

**Figure 2.** Splay room (a) 3D view, (b) top view, (c) rear view, (d) left-side view; blue dot is the source, red dot is the receiver

| Room Ratio   | Dimension | Volume (m³) |
|--------------|-----------|-------------|
|              | Length (m) | Width (m)   | Height (m) |          |
| Random (1:1.79:2.41) | 6.583 | 4.888 | 2.732 | 87.909 |
| Cox (1:1.56:1.86)   | 5.082 | 4.262 | 2.732 | 59.174 |
| Splayed (1:1.56:1.79:1.86:2.41) | 5.082~6.583 | 4.262~4.888 | 2.732 | 72.274 |

**Table 4.** Random, cox, and splay wall room ratios, dimension, and volume

Table 5 shows better distribution of axial modes in splay wall room with absent of axial modal only at 4th one third octave; compared to the random room with absent of axial modal at 3rd and 4th one third octave. The splay wall room has the same axial modes pattern with the cox room ratio. The axial modes shape of random, cox, and splay wall room are depicted in Figure 3 in isosurfaces plot. Surfaces with different color indicates different pressure with blue color means the lowest sound pressure that lay below zero and red color means the highest sound pressure that lay above zero. As the sound pressure oscillates periodically, both blue and red surfaces imply the area with the highest sound pressure level and known as antinodes. Green yellowish surfaces indicate zero sound pressure which means no sound at the area and known as nodes. Irregularity in boundary surface like splayed wall can undermine the modes shape in a shoebox room. This disruption is preferable as the sound field is more diffuse.

To analyze the sound pressure level of splay wall room in frequency response, FEM with similar configuration was applied and the result can be found at Figure 4. The differences with previous FEM depicted in Figure 1 are position of both monopole sound source and receiver probe that were set at 1
m height above floor while were remained opposing each other 2D diagonally (see **Figure 2**). This configuration is implemented to make the result practically relevant for ear level of a sitting person is around 1 m. Splayed room showing highest peak at 55 Hz at 107 dB and lowest dip at 106 Hz at 0.3 dB. Statistical calculation of SPL from these three different rooms can be seen at **Table 6**. Curiously, SPL standard deviation in splay wall room comes as the highest with its average is marked as the lowest among random room and cox ratio room.

**Table 5.** Distribution of primary axial modes of random, cox, and splay wall room

| ISO 266 | Axial Primary Modes (n,n,n) Hz |
|---------|--------------------------------|
| 1/3 Octave | Freq (Hz) | Random | Cox | Splayed |
| 1st | 22.1 – 27.8 | (1,0,0) 26 |
| 2nd | 27.8 – 35.1 | (0,1,0) 35 | (1,0,0) 34 | (1,0,0) 29 |
| 3rd | 35.1 – 44.2 | (0,1,0) 40 | (0,1,0) 38 |
| 4th | 44.2 – 55.7 | |
| 5th | 55.7 – 70.2 | (0,0,1) 63 | (0,0,1) 64 |

**Figure 3.** Axial modes shape of random (left), cox (center), and splay wall room (right)

**Figure 4.** Sound pressure level of random, cox, and splay wall room with both source as well as receiver at corner with 1 m height and 2D diagonally opposing each other
4. Conclusion

Splaying the wall of small room can shift the axial modes and make more even distribution without cutting too much space compared to resizing room while maintaining the shoebox room shape. The splay wall room also shows more diffuse sound field inside the room. Some of the peaks and dips in SPL in the splay wall room are become more extreme. Hence, this room is recommended to take further treatment such as considering the source and listener position or applying sound absorption panel that tuned at halved boosted peak frequencies.

After all of the applied treatment to the small room, it is still unknown which kind of character is preferred; whether it is with evenly distributed modes rather than modes with coincidence frequency, or with lowest SPL standard deviation rather than ignoring this parameter. In practice, some people go for the room that a bit colorized with peak in some frequencies.

References

[1] R. H. Bolt, ‘Note on normal frequency statistics for rectangular rooms’, J. Acoust. Soc. Am., vol. 18, no. 1, pp. 130–133, 1946.
[2] M. Louden, ‘Dimension-ratios of rectangular rooms with good distribution of eigentones’, Acta Acust. United Acust., vol. 24, no. 2, pp. 101–104, 1971.
[3] O. J. Bonello, ‘A new criterion for the distribution of normal room modes’, J. Audio Eng. Soc., vol. 29, no. 9, pp. 597–606, 1981.
[4] T. J. Cox, P. D’Antonio, and M. R. Avis, ‘Room sizing and optimization at low frequencies’, J. Audio Eng. Soc., vol. 52, no. 6, pp. 640–651, 2004.
[5] R. H. Bolt, H. Feshbach, and A. Clogston, ‘Perturbation of sound waves in irregular rooms’, J. Acoust. Soc. Am., vol. 14, no. 1, pp. 65–73, 1942.
[6] P. D’Antonio, ‘Minimizing acoustic distortion in project studios’, Disponivel Em Httpwww Rpginc Comegi-Binbyteserver PlnewslibraryPS AcD Pdf Acesso Em, vol. 5, 2004.
[7] ‘University of Salford | A Greater Manchester University’. [Online]. Available: http://www.acoustics.salford.ac.uk/acoustics_info/room_sizing/?content=best. [Accessed: 12-Sep-2017].