International Journal of Technology (2018) 2: 246-256
ISSN 2086-9614

OPTIMIZATION OF ARCHITECTURAL ELECTROACOUSTICS DESIGN FOR THE INTERIOR MEZZANINES OF VERTICAL BUILDINGS

FX Teddy Badai Samodra[1*]

[1]*Department of Architecture, Institut Teknologi Sepuluh Nopember, Campus ITS Sukolilo, Surabaya, 60111, Indonesia*

(Received: December 2017 / Revised: February 2018 / Accepted: February 2018)

ABSTRACT

The science that deals with the transformation of electrical energy into acoustic energy or vice versa, electroacoustics, generates an increased intensity and loudness of sound by mechanical and/or electrical means. It should be designed simultaneously with the consideration of room acoustics. A vertical building is usually designed separately from the architectural aspect and other technical considerations. An interior mezzanine has unique sound propagating characteristics because its balconies could be an element of the room acoustic reflectors and absorbers, shelters from noise and barriers to sound propagation. For optimum music and speech activities, a hybrid active design strategy using electroacoustics combined with a passive method is used. This research optimizes the room acoustic criteria of different building models as building systems integrated with loudspeakers. Ecotect Analysis and additional audio programming determine the overall process by simulating all potential variables. The results show that 5 m is the recommended minimum distance of column-loudspeaker placement for mezzanine floors. With the same loudspeaker power and frequency specifications, the vertical structure, as the armature of electroacoustic orientation, and the interior materials are the most critical variables in determining reverberation time optimization.

Keywords: Architectural electroacoustics; Interior mezzanine; Loudspeaker design; Reverberation time; Vertical buildings

1. INTRODUCTION

Currently, the relationships between passive and active systems, room acoustics and electroacoustics involve many issues, even if it is a fact that in room acoustics, modern techniques for its measurement could not exist without the aid of sound system components such as loudspeakers, microphones and electronic controllers. Whatever the characteristics of the type and purpose of an amplification system, there is a close interface between the system and the room in which it operates. Its performance depends on the high point of the attachment on the acoustical properties (Kuttruff, 2009). Therefore, the component installation and use of the system should involve careful acoustical design, both technically and aesthetically. In the relationship with architectural elements, room geometry, represented by the dimensional aspect of room acoustics, plays an important role in sound propagation control. According to Zhao et al. (2017), in a large building, whatever its internal activities, length and height have the ability to control sound pressure levels.

In a model of acoustical path representing the physical world, Kleiner (2013) suggests that it

*Corresponding author's email: fxteddybs@arch.its.ac.id, Tel: +62-81-232508454
Permalink/DOI: https://doi.org/10.14716/ijtech.v9i2.1080

should use acoustical components in order to simplify understanding of the process of the paths. The hybrid design of acoustics and electroacoustics provides a more reliable and complete characterization of a system than either one of these spectroscopes separately. A vertical building is usually designed separately from the architectural aspect and other technical considerations, such as building utility. As mentioned by Spaeth (2015), the design of acoustic spaces is an equal challenge for both architects, architecturally and aesthetically, and for engineers, in the technical sense, because of the complexity of the many interconnected factors. Furthermore, it is difficult to estimate how adaptations effect the various designs of the overall acoustic properties as the architectural design progresses, and acoustic design on vertical spaces should serve as starting points for architectural design solutions.

Interior mezzanines have unique sound propagating characteristics because their balconies could be an element of room acoustic reflection and absorption. When loudspeakers, as electronic devices, are distributed evenly and sufficiently, the particular reproduction of the pressure field on the bounding surface of the control volume clearly provides an effective method of reproduction. Most of similar findings have analyzed many hybrid factors technically (Poletti, 2011; Shin et al., 2016; Zhao et al., 2017) or for small or non-vertical spaces (Spaeth, 2015; Iswati, 2016; Lu et al., 2016; Shih et al., 2016;). However, there were no specific results of them related to the requirements for architectural acoustics, especially for vertical mezzanines. Therefore, in this research, in relation to the optimization of music and speech activities, a hybrid design of an active strategy using electroacoustics, combined with a passive method, is used. The research optimizes the room acoustic criteria of different vertical building factors as a building system integrated with loudspeakers. The results are expected to make recommendations to the practical work of architectural design related to sound systems or the active method of acoustics.

2. METHODOLOGY

In this study, a numerical method using calculations of formulation, architectural design and acoustical software is employed. An architecture design program, as conducted by Shih et al. (2016) and Iswati (2016), *Ecotect Analysis* software, and the audio programming developed by Horvath (2016), determine the overall process by simulating all the potential variables. The evaluation method is based on the following comprehensive analysis. (1) *acoustical analysis:* an evaluation of sound propagation with critical speaker placement on the mezzanine floor and surrounding the balconies; this part describes room acoustic performance for vertical building areas such as large rooms, by using software simulation, and the sound propagation decay could be considered as initial design. (2) *loudspeaker design:* the main analysis of electroacoustic components with architectural consideration and a technical approach related to their requirements and interior geometry; some technical aspects such as the directivity of the devices focus on providing design deliberation. (3) *optimization of the architectural electroacoustic:* determination of the dimensional requirements for the acoustical comfort of room acoustics, such as building volume and the maximum loudspeaker (LS) distance to receiver relationship, and interior panel weight and its frequency effect on sound propagation.

The study model is based on minimum of two mezzanine floors, with a height of 2.5−3.0 m per floor, as shown in Figure 1. Compared to a smaller space, on the classroom scale (Iswati, 2016), in which the reverberation time is better, when changing the room dimension to that of a mezzanine, the model is feasible as the representative object. In fact, there is no specific building typology or function, but this study focuses on more critical needs such as speech activities. Consequently, a level of 500 Hz for the LS is set for the initial design as the electroacoustic component. The building height will be simulated with some main general calculations of (a) the requirements of distance between loudspeakers; (b) maximum distance to the receiver to comply with the required reverberation time (RT); and (c) recommended room height. In general, the independent variables are the number of mezzanine floors, RT, sound frequency, building/room volume, and panel weight. The dependent variables are distance between loudspeakers and receivers, recommended ceiling height, and panel resonance frequency.

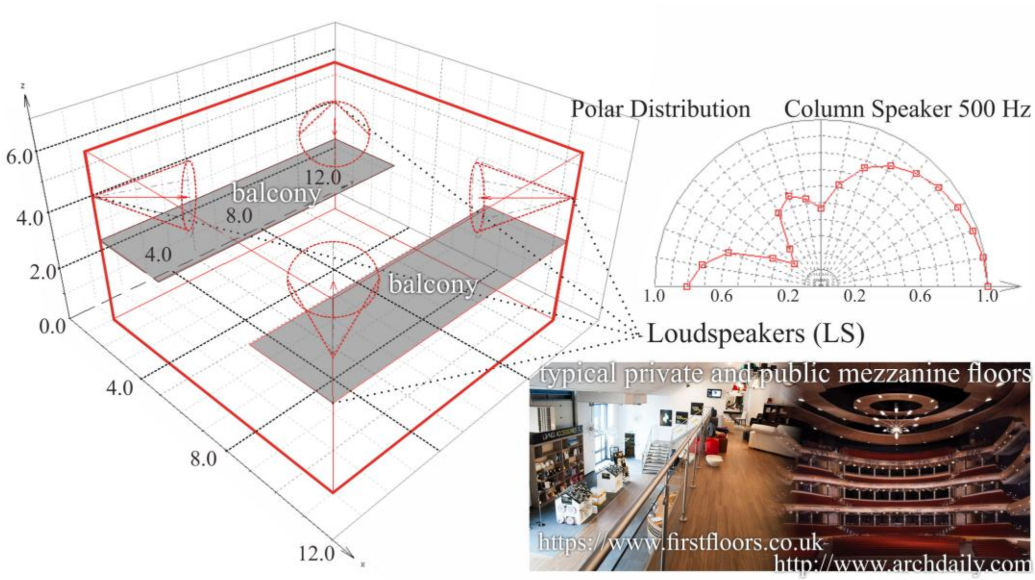


Figure 1 Building model

The section on the optimization of the architectural electroacoustics explains the architectural context of room acoustic design. Therefore, numerical equations (1 to 5) below are used to establish the spatial aspect and the interior elements in the building design. Developed from Egan (2007) and Satwiko (2009), formulation of the distance between loudspeakers is achieved by the difference between the ceiling and the average sitting reference height, with the additional calculation of the cavity height if the room uses masking elements. The recommended ceiling height from the floor is determined directly by the reverberation time, while the maximum loudspeaker distance to the receiver is calculated by the directivity of the loudspeaker and the room volume, as additional factors. The panel resonance frequency is directly based on its weight and the air depth behind it.

$$s = 1.4(h\text{-}hr) \tag{1}$$

$$s = 1.4((2hc)+h\text{-}hr) \tag{2}$$

$$hrec = 6.1Tr \tag{3}$$

$$d = 0.18\left(\frac{QV}{Tr}\right)^{0.5} \tag{4}$$

$$Fr = \frac{207.4}{(w.dp)^{0.5}} \tag{5}$$

where:

s : distance between loudspeakers (m)
h : ceiling height from the floor (m)
hr : average sitting/standing reference height (m)
hc : ceiling cavity height (m)
hrec : recommended ceiling height from the floor (m); covered chairs and attenuated sound by the back wall
Tr=RT : reverberation time (s)
d : maximum loudspeaker distance to receiver (m)
Q : directivity of loudspeaker (2−15); a higher value, a more directional distribution (voice is 2 at 500Hz)
V : room volume (m^3)
Fr : panel resonance frequency (Hz)
w : panel weight (kg/m^2)
dp : air depth behind the panel (m)

3. RESULTS AND DISCUSSION

3.1. Acoustical Analysis

In the analysis of the acoustic field, the subjective properties will be combined with a quantitative approach. Therefore, *Ecotect Analysis* simulation highlights that passive design in designing the building acoustical materials plays an important role in the integration with the active method, electroacoustics. As shown in Figure 2, the balcony effect reduces or deflects sound propagation. The close distance sound distribution of a loudspeaker is very useful, even though the further area should be considered in relation to loudspeaker distribution. According to Samodra (2017), decreasing sound propagation works in step with noise reduction. The sound decay due to balcony design could be higher than 10 dB and the shadow below will have a potential effect on interior zoning if there is differentiation between room activities with their specific acoustical standards. However, in the case of an auditorium or concert hall, different treatment by placing additional sufficient LS distribution should be applied. This is useful not only for generating power level potential, but also for creating the expected atmosphere. Therefore, LSs, both in terms of the number, placement and classification, work in line with quantitative and qualitative predictions.

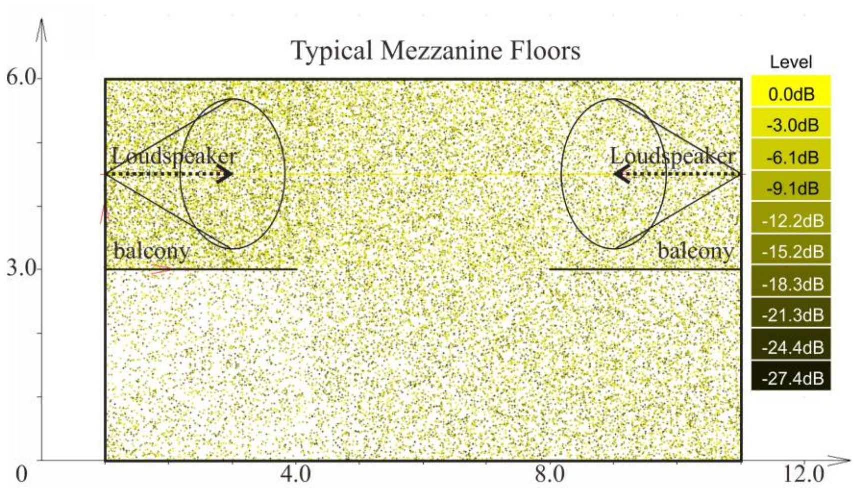


Figure 2 Acoustical rays

The main characteristic of an interior mezzanine is the way in which a building provides one room with several floors. Whatever its function, reverberation is confirmed as the main parameter, because to improve sound quality in a closed environment, it is quite important to make predictions (Quartieri et al., 2010). Moreover, in that vertical rooms, it will be easier when making non-intimate speech actions such as making announcements than it should achieve intimate quality activities. Based on the standard results from Egan (2007), the reverberation time (RT) is 0.8−1.2s for intimate speech, and a little higher for music activities. In fact, building typology suggests that vertical buildings with interior mezzanines are usually dominant for commercial buildings such as hotels, offices and business centers. Therefore, speech is more frequent than music activities. These findings emphasize the need to adapt not only to reverberation time, but also other acoustic requirements, such as clarity and noise control (Ansay et al., 2016; Samodra, 2017). For clarity, and better and clear distribution, an intimacy setting for speech activity standards should be implemented. When the critical setting for closer actions is established, the open space will be easier to design.

3.2. Loudspeaker Design

Although all electroacoustic components should be designed better, loudspeakers play a role as the main actor in capturing the user's needs. In general, the system could consist of one or more devices. There is a very wide range of applications for sound output devices, which may be assumed as serving some grouping for the primary purposes, such as communication, amplification systems or sound reinforcement, sound production, and sound reproduction.

This research makes loudspeaker analysis by generating a correlation between sound frequency and its sound pressure level as a directivity index. It is useful to check the speaker radiation, the ideal performance, and the beaming directivity on varying loudspeaker frequencies. Figure 3 illustrates the electroacoustic design which is focused on the LS analysis. The evaluation of the LS directivity index is important to create not only the required RT, but also the quality (clarity) of the produced sound, especially for speech activities in vertical buildings. Based on the development of an audio program by Horvath (2016), the case of 10 cm LS produces in mid to high range frequencies for ideal results, being around 3000 Hz to 4000 Hz. When the lower sound frequencies are propagated evenly around the building, the higher ones have too narrow a directivity. This indicates that the recommendation for LS installation is that frequency or its combination with another LS frequency should be considered to create better room acoustics. As discussed by Aoki et al. (2017), by setting the parametric loudspeaker 5 degrees to the right, the sound localization path moves approximately 20 degrees in the same direction. This condition will have consequences for electronics device placement, as an additional strategy for instrument selection.

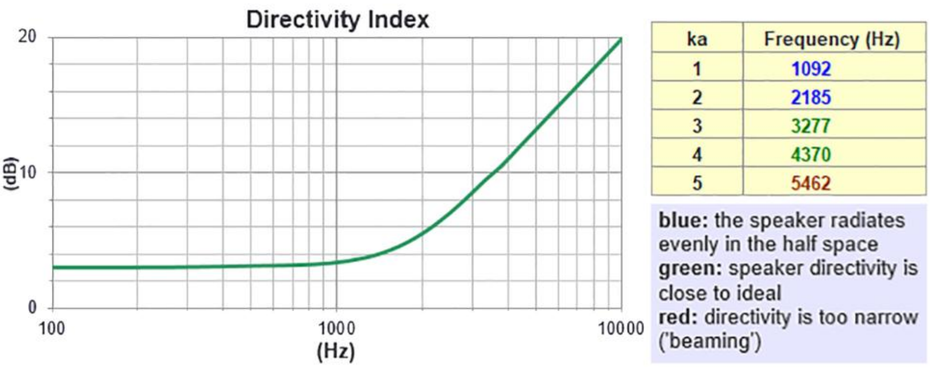


Figure 3 Loudspeaker analysis

In addition to previous similar findings by Kleiner (2013), this study identifies that directivity is the scheme used to describe the distribution of irregular and angular intensity for an LS as a transmitter and the uneven angular sensitivity generated by a receiver. The directivity of an LS can be achieved using two techniques: by the appropriate geometrical properties as a distribution of sound sources and receivers; and by a change in the sound vibration or sensitivity to the vibration phase and its amplitude. For wider directivity, Figure 4 shows an alternative LS chart that could be adopted for LS selection in room design. For lower decay, the building should use a higher wavelength or low-frequency LS; if an instrument with a frequency lower than 1545 Hz LS is installed, only 2.5 dB of sound distribution is reduced. This could save more electrical energy, which can be used for the active method of LS work. Meanwhile, the lower sound decay at lower frequencies has consequences for the noise problem for low frequency (LF) loudspeakers. Therefore, it is recommended that the number of LS should be less than high frequency (HF) frequency. HF is intentionally installed more, which suggests a gradual increase in LS numbers with higher frequencies.

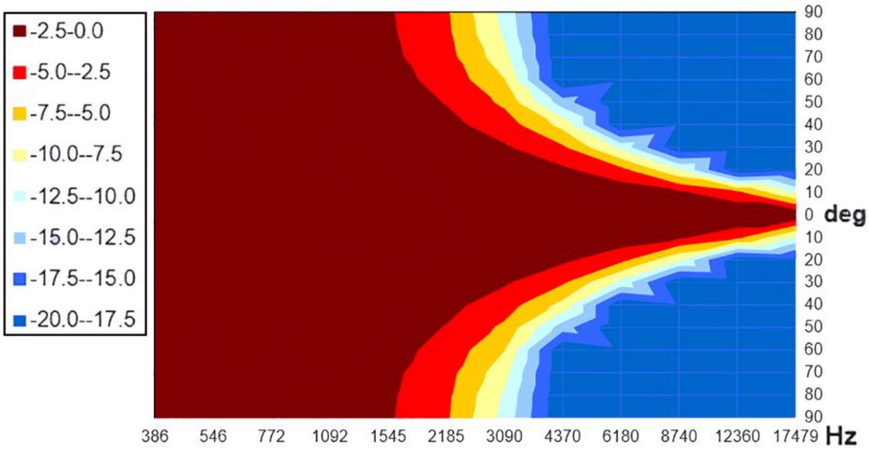


Figure 4 Loudspeaker directivity

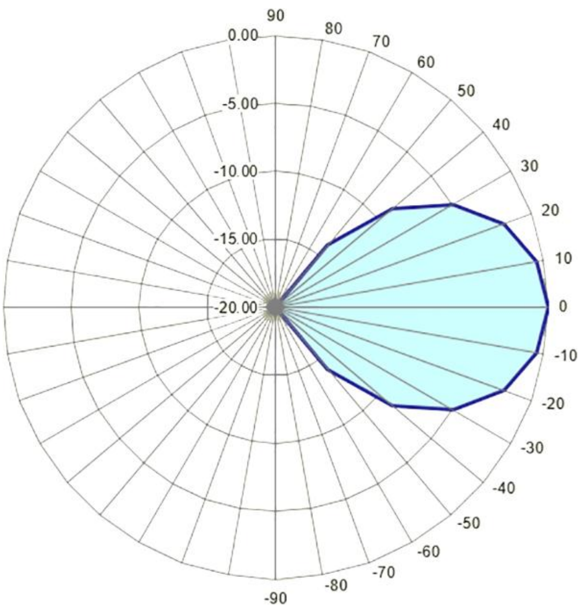


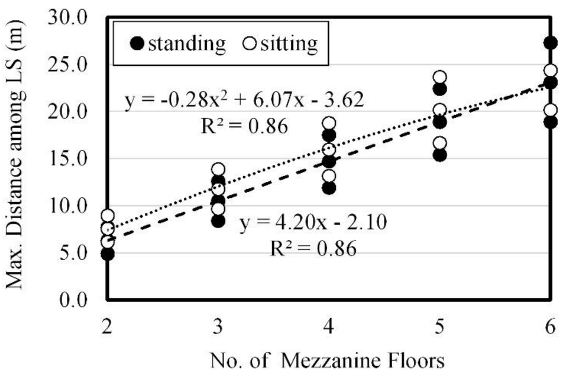
Figure 5 Loudspeaker performance

In detail, LS performance design explores the ideal LS (4360 Hz), which is not too wide to maintain the optimum quality of sound for 40-degree directivity (Figure 5). The evaluation recommends 7.9 cm for the wavelength of an ideal LS and designs which avoid beaming or too narrow results, because in this condition, the room will be too noisy. The single direction type of column LS will be followed by the strategy of its distribution, both horizontally and vertically. All the detailed analysis of the devices still does not change the architectural aspect, which concerns study of the space for better occupancy in the building. Therefore, in the following section, the discussion of architectural electroacoustics will center on optimization of the performance of the physical aspect discussed in this section.

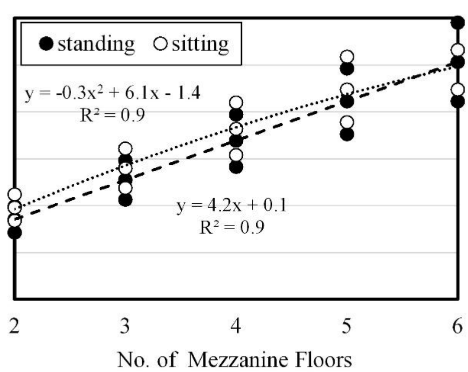
3.3. Optimization of Architectural Electroacoustics

For varying numbers of mezzanine floors, Figure 6 shows two maximum distances between LS, with and without background masking (ceilings, which are usually applied as absorbers/reflectors), based on Equations 1 and 2. By accommodating all human activity reference heights, standing and sitting, two types of regular user actions have consequences on the specific distance. In general, without background masking, a closer distance is needed, of around 5 m. Above a height of six floors, the sitting activities need a closer distance when in a lower vertical building, a short distance is required for the standing reference height. The sitting and standing graphs are quite similar generally, but they have different trends. This means that there is no significant occupant activity effect on LS placement, even though there are consequences for the number of LS, as indicated by the typical trend difference. For optimum results, the materials used are also well known to be a strategic aspect in the interior design related to acoustic studies. In addition to the requirement of distance and number, the hidden design of loudspeakers has the capability of creating an illusional image to help the audience feel comfortable in the room.

As proposed by Urban et al. (2016), the application of micro-perforated foils in one of the mezzanine floors, the atrium, will not only significantly improve the noise levels and sound reverberation, but will also result in sufficient speech intelligibility, which can be achieved only by the combination of the vertical structure and acoustical placement of the absorptive material on the vertical structure as an armature. However, the study of the acoustics will be focused on providing sufficient space, and discussion of materials will be made separately, specific to the density of the interior mass to obtain the suggested frequency.



(a) without masking



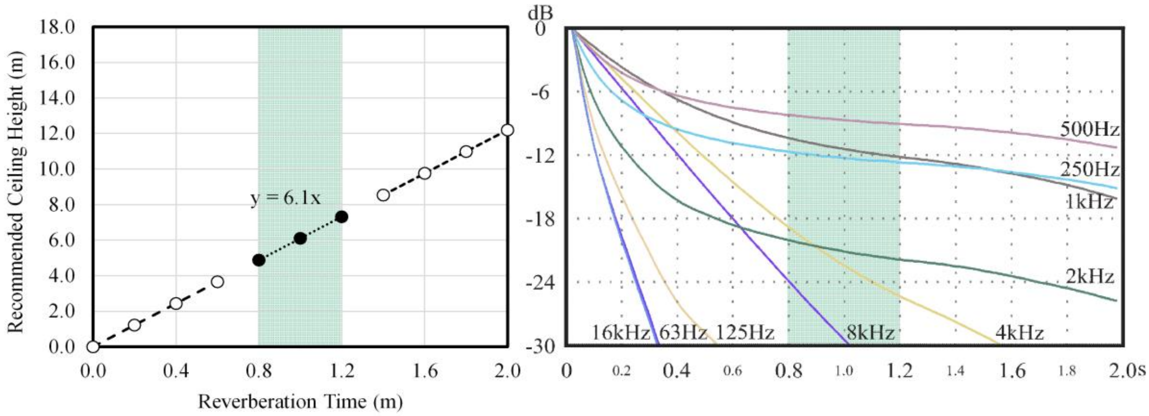
(b) with masking

Figure 6 Maximum distance between loudspeakers

For optimum results, the conventional space and ceiling height should be redesigned. With an increase in the room length or height, the average Sound Pressure Level (SPL) will decrease, and the tendencies of the curves will be logarithmic (Zhao et al., 2017). Moreover, for interior mezzanine floors or longer atria, the attenuation could become smaller than for a single floor or conventional interior. The attenuation model is still consistent when its length is doubled and the reverberation time increases significantly in a minor space. On the other hand, Zhao et al. (2017) also report a slight increase when the room length is more than 20 m. With an increase in height, the average SPL decreases, and the attenuation trend is also logarithmic. This result indicates that in a large space, when the height is greater, the attenuation decreases. As analyzed by Equation 3, the required RT suggests 4-8 m as the recommended range (Figure 7a). The intimacy impression effects of providing a lower ceiling height and the room geometry ensure the important role of electroacoustic design remains correlated to the architectural purposes.

The open area from the ground to upper floors is still not sufficient for the effective floor to floor height; it should meet the recommended height. The potency of the integrated building system fulfills the suggested height for effective space. For the threshold requirement, the hearing devices between the passive and electroacoustic transmission should pay attention to the attenuation function of the device and the duration of the signal (Lezzoum et al., 2016). Furthermore, the level and type of background noise are other elements, but they are still considered to enhance the accuracy of the evaluation. Essentially, for an evaluation of speech intelligibility, reverberation time will be the key to overcoming this constraint. However, by calculating background noise, speech intelligibility is also potentially accomplished. Contrary to Rychtarikova et al. (2016), the decay of sound values at a location away from the source is altered. This means that in a large room such as a hall, the modeling of the walls can have a substantial impact on the intelligibility of sound. When analyzing fractions of the lateral energy, the position of the stage is important when source performance takes place, as expected. In line with this, when the sound spreads and sound decay occurs, the RT requirement is obtained by a mid-range frequency (Figure 7b). This indicates that low frequency (LF) and high frequency (HF) LS design is recommended. The slow decrease in sound decay at 500 Hz indicates the required compliance of speech maintenance for the existing room.

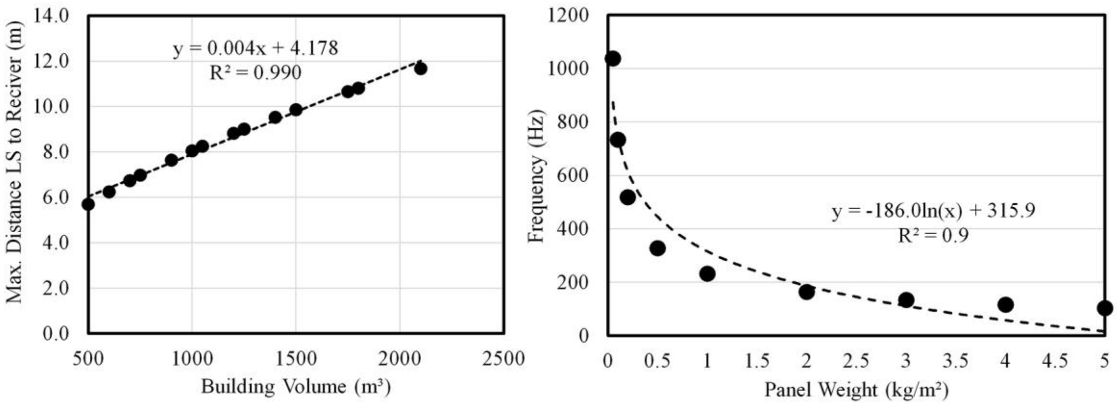
In terms of sound distribution for a large area, at all frequencies, and in line with Mei and Kang (2012), this study found a continuous decrease in sound pressure level by increasing the distance to the source, both vertically with increasing floor levels, and horizontally at each floor. The patterns of SPL will decrease with increasing source to receiver distance and are rather complicated, and will also fluctuate noticeably at different frequencies. In terms of reverberation, at all frequencies there is a continuous growth with increasing source to receiver distance, suggesting the non-diffuse features of such a distinctive atrium space. With a source at the ground floor, the RT variation could reach 100%, which is considerably greater than that of higher floors.



(a) recommended ceiling height (b) sound decay

Figure 7 Recommended ceiling height and sound decay

The building volume also effects the maximum LS distance to the receiver. As calculated by Equation 4, Figure 8a illustrates the linear relationships between the two variables. The direct formulation indicates three-dimensional room acoustical performance, which is greater than the effect of mezzanine or balcony design. Therefore, the depth of the interior mezzanine should be the essential factor. In addition to the interior design reference, the vibrating panel designed for the indoor element is useful for distributing sound. The appropriate frequency should be determined first and Figure 8b shows the analysis of Equation 5 in order to give comprehensive results. The key point in calculating panel frequency is its material density associated with its mass. With speech activities at 500 Hz, around 0.2 kg/m² should be provided to both reduce noise and distribute good quality sound from the source to receiver, by LS or naturally, while 0.05 kg/m² is used at 1000 Hz in music situations. A gradual decrease at higher frequencies means that a lightweight material or low porosity is very convenient for low wavelengths. The lowest frequencies, around 20 Hz, are still controlled in this way, but they need a very heavy panel (100 kg/m²). In general, sound propagation cannot be interrupted by the same technique, especially for frequencies higher than 200 Hz. As suggested by Yang and Cheng (2016), one of the designed panels, a micro-perforated panel, should be treated as an essential part of the room's acoustic design, more than a sound absorption boundary categorized by the surface impedance.



(a) maximum distance LS to receiver (b) vibrating panel frequency

Figure 8 Maximum distance LS to receiver and vibrating panel frequency

4. CONCLUSION

Generally, professional amplification systems can help to achieve the appropriate loudness and sound balance for audiences. Moreover, a stability of sound with an appropriate amount of echoing should be designed, and fine sound naturalness, consistent with room image, should be aimed for. In detail, the results show that 5 m is the recommended minimum distance of column-loudspeaker placement for mezzanine floors. At the same time, the required RT suggests 4–8 m to be the recommended range. With the same loudspeaker specifications of power and frequency, the vertical structure could be the armature of electroacoustic orientation, and the interior material is the most critical variable in determining reverberation time optimization. The combination of passive and active methods is recommended for better sound propagation in vertical buildings. Furthermore, implementation of electroacoustics as active systems should enhance either the stage or the audience sound, and provide the same control of sound as passive acoustic design. In the near future, this study will be extended to analysis of the integrated design of room acoustics, and thermal issues such as ventilation systems, as a thermo-acoustic analogy for high interior mezzanines. It will be very advantageous to obtain a more realistic approach to the combination of architectural and technical issues in buildings.

Integrated with attention to energy efficiency, this project intends to achieve a hybrid method as a compromise strategy for a better living environment.

5. ACKNOWLEDGEMENT

This research is part of Excellent Primary Research of Higher Education, *Penelitian Dasar Unggulan Perguruan Tinggi* No. 882/PKS/ITS/2018. The authors gratefully acknowledge this financial and technical support.

6. REFERENCES

Ansay, S., Henrique, P., Zannin, T., 2016. Evaluation of the Acoustic Environment in a Protestant Church based on Measurements of Acoustic Descriptors. *Journal of Building Construction and Planning Research*, Volume 4(3), pp. 172–189

Aoki, S., Shimizu, K., Itou, K., 2017. Study of Vertical Sound Image Control with Parametric Loudspeakers. *Applied Acoustics,* Volume 116, pp. 164–169

Egan, D., 2007. *Architectural Acoustics*. J. Ross Publishing

Horvath, C., 2016. *Speaker Polar Chart; Speaker Directivity Simulator*

Iswati, T.Y., 2016. Evaluation of Reverberation Time in the Classroom (Case of Classroom At Department of Architecture, Universitas Sebelas Maret). *DIMENSI − Journal of Architecture and Built Environment*, Volume 43(2), pp. 93–100

Kleiner, M., 2013. *Electroacoustics*. CRC Press, Boca Raton, FL

Kuttruff, H., 2009. *Room Acoustics.* Elsevier Science Publishers, New York, USA

Lezzoum, N., Gagnon, G., Voix, J., 2016. Echo Threshold between Passive and Electro-Acoustic Transmission Paths in Digital Hearing Protection Devices. *International Journal of Industrial Ergonomics*, Volume 53, pp. 372–379

Lu, S., Yan, X., Xu, W., Chen, Y., Liu, J., 2016. Improving Auditorium Designs with Rapid Feedback by Integrating Parametric Models and Acoustic Simulation. *Building Simulation*, Volume 9(3), pp. 235–250

Mei, H., Kang, J., 2012. An Experimental Study of the Sound Field in a Large Atrium. *Building and Environment*, Volume 58, pp. 91–102

Quartieri, J., Mastorakis, N.E, Guarnaccia, C., Iannone, G., 2010. Church Acoustics Measurements and Analysis. *In*: Proceeding AMTA'10 Proceedings of the 11th WSEAS International Conference on Acoustics & Music: Theory & Applications, pp. 216–224

Poletti, M.A., 2011. Active Acoustic Systems for the Control of Room Acoustics. *Building Acoustics*, Volume 18(3-4), pp. 237–258

Rychtarikova, M., Chmelík, V., Urban, D., Vargova, A., 2016. Acoustic Conditions in the Atrium of Slovak Philharmonic. *Procedia Engineering*, Volume 155, pp. 464–471

Samodra, F.X.T.B., 2017. Analysis of Resilient Design by Thermoacoustic Adaptation of Tropical Urban Model. *Journal of Architecture and Urbanism*, Volume 41(4), pp. 305–315

Satwiko, P., 2009. Building Physics *(Fisika Bangunan).* ANDI Offset, Jogjakarta

Shih, H-Y., Chou, Y-T., Hsia, S-Y, 2016. Improvement on Acoustic Characteristics of a Small Space using Material Selection. *Engineering Computations: International Journal for Computer-Aided Engineering and Software*, Volume 33(6), pp.1800–1809

Shin, M., Nelson, P.A., Fazi, F.M., Seo, J., 2016. Velocity Controlled Sound Field Reproduction by Non-uniformly Spaced Loudspeakers. *Journal of Sound and Vibration*, Volume 370, pp. 444–464

Spaeth, A.B., 2015. Acoustics as Design Driver. *Architectural Science Review*, Volume 59(2), pp. 148–158

Urban, D., Zrnekova, J., Zatko, P., Maywald, C., Rychtarikova, M., 2016. Acoustic Comfort in Atria Covered by Novel Structural Skins. *Procedia Engineering,* Volume 155, pp. 361–368

Yang, C., Cheng, L., 2016. Sound Absorption of Microperforated Panels inside Compact Acoustic Enclosures. *Journal of Sound and Vibration*, Volume 360, pp. 140–155

Zhao, W., Kang, J., Jin, H., 2017. Effects of Geometry on the Sound Field in Atria. *Building Simulation*, Volume 10(1), pp. 25–39