Acoustics of the Lecture Theatre in ECA Main Building (E22)

Exam number: B275354

University of Edinburgh

December 2024

Figure 1 Room Overview

List of Contents

I. Introduction and Background

This study investigates the acoustic properties of the lecture theatre in the ECA Main Building, E22, with a particular focus on speech intelligibility (see Figure 1 for the room overview). The motivation stems from personal experiences of acoustic challenges in the space, where hearing speech was reported to be difficult both with and without the use of the public address (PA) system. By examining the lecture theatre's acoustic response, this study evaluates whether the PA system improves speech intelligibility and analyzes its spatial interaction with the room's acoustics.

By comparing the room's acoustic response with and without the PA system, it explores how the PA influences sound transmission and distribution and affects speech clarity across different locations. Additionally, the use of the Neumann KU100 Binaural Head enables the study to examine interaural differences, shedding light on directional and spatial perceptions of sound within the room.

Two methods are employed to measure the impulse response (IR) of the space: the impulsive method (using a balloon pop to excite the room) and the sine sweep method. These approaches are compared to assess their advantages and disadvantages, as well as the similarities and differences in the resulting data. Measurements at six evenly spaced positions across the lecture theatre capture the spatial variability of the room's acoustics.

Equipment used:

Neumann KU100 Binaural Head: To capture binaural recordings of the impulse response

GENELEC 8030A (mono): To play the sine sweep tones.

Sauter SU 130 Sound Level Meter: For measuring sound pressure levels (SPL).

Leica Disto X310 Laser Measure: For measuring the dimensions of the lecture theatre.

Audio Interface and Audacity: For recording and storing the audio data.

The IR of the swept sine was derived through deconvolution in MATLAB, while data analysis, including calculation and evaluations of acoustic parameters, was conducted using Room EQ Wizard (REW). This study aims to provide insights into the spatial distribution of sound and practical implications for improving speech intelligibility in similar environments.

II. Description of the Studied Space

The lecture theatre is large compared to regular classrooms, measuring 19.41m in length and 8.67m in width. It features raised ground levels at the stage and the back, resulting in variable ceiling heights: 7.00m at the stage, 5.77m in the front rows, and an average of 6.27m in the back rows. With its flat ceilings and spacious design, the room has significant potential for reverberation (see Figure 2 for the layout).

The PA system consists of two front speakers (left and right, positioned 4.52m from the front and 2.29m in height) and two back speakers (11.19m from the front and 2.95m in height). To assess the spatial distribution of sound and variations in the PA's effect, the GENELEC speaker was placed on the podium at a height approximate to the lecturer, and the microphone was positioned across three rows, with six marked locations: (1,1), (1,2), (2,1), (2,2), (3,1), and (3,2). The layout is illustrated in Table 3, and detailed distance measurements are included in the Appendix.

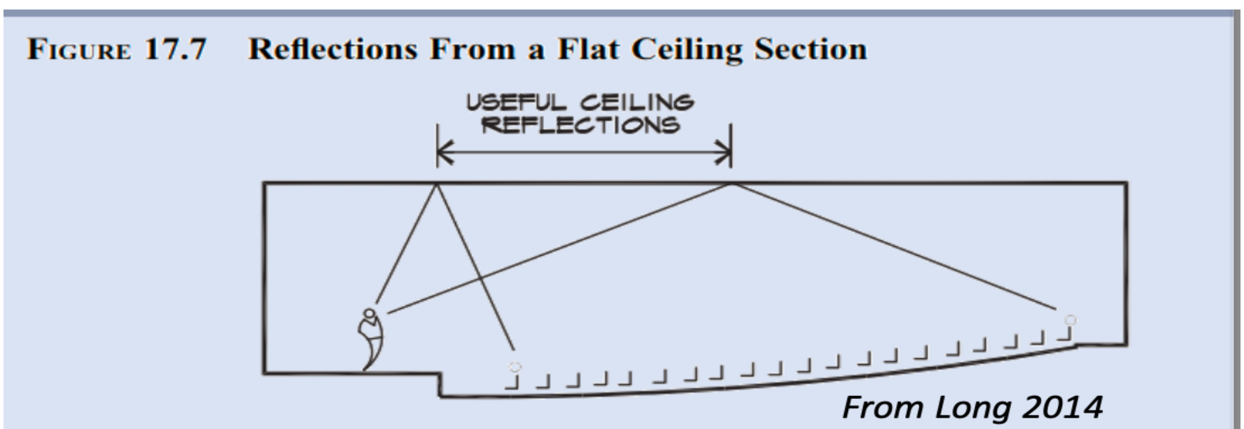


Figure 2 Room Shape

R A I S E D	S T A G E
PODIUM (SOUND SOURCE)	
(1,2)	**(1,1)**
(2,2)	**(2,1)**
(3,2)	**(3,1)**

Table 1 Microphone Positions

III. Experimental Procedures Used

The impulsive method involved popping a balloon to generate a short, sharp sound to excite the room. To simulate a quiet and empty space, all people except the person popping the balloon vacated the area. Due to the variability of balloon pops, two impulse response (IR) recordings were taken at each receiver position, allowing for either the exclusion of an outlier or averaging the two samples. Additionally, sound pressure level (SPL) measurements were taken at each receiver position and 5 times at the source position. Table 2 summarizes these measurements.

Balloons SPL(dBA) - 5 times @ 1m

Test 1	Test 2	Test 3	Test 4	Test 5
102.8	102.3	106.0	104.9	105.8

SPL of Different position when using impulsive method(dBA)

Position	1.1	1.2	2.1	2.2	3.1	3.2
SPL (dBA)	93.4	95.7	90.8	89.8	88.5	87.4

Table 2 Balloon's SPL

With an average source SPL of 104.36 dB, the balloon IR exhibits a nonlinear decay as it propagates through the room. The most significant reductions occur in the first row, where the SPL decreases by 10.96 dB at position (1,1) and 8.66 dB at position (1,2). This significant drop in energy at the first row may be attributed to obstruction by the podium, although further investigation is needed to confirm this hypothesis.

The sine sweep was measured with the GENELEC speaker positioned at the same location as the balloon, under identical conditions. The source SPL was recorded at 90.1 dB at 1 kHz. Table 3 presents the peak SPL values calculated from the unnormalized raw IR, derived through deconvolution with the inverse sine sweep and adjusted using a spectrum roll-off operation to balance energy distribution.

Position	SPL without PA	SPL with PA	Position	SPL without PA	SPL with PA
(1, 2)	*R: 54.83* L: 53.11	R: 43.03 *L: 44.79*	(1, 1)	R: 37.58 *L: 46.53*	*R: 53.57* L: 43.01
(2, 2)	R: 42.72 *L: 43.42*	*R: 50.16* L: 46.04	(2, 1)	R: 33.55 *L: 42.25*	*R: 49.68* L: 43.27
(3, 2)	R: 38.07 *L: 39.43*	R: 45.43 *L: 45.52*	(3, 1)	R: 37.93 *L: 39.53*	*R: 49.26* L: 42.48

Table 3 SPL of Swept Sine (*the greater value is highlighted in red and italic*)

The data highlights that the PA system significantly increases the overall SPL at most positions, with the ipsilateral side (same side as the PA speaker) consistently perceiving greater loudness than the contralateral side (except for (2,2) where the contralateral side is higher), indicating a directional dispersion pattern. Despite the PA system's effect, the distance decay pattern remains evident, with SPL decreasing as the distance from the source increases. Notably, position (1,2) records the highest SPL without the PA system, likely due to its proximity to the source and direct orientation toward it, which allows for localized reinforcement from direct sound waves and favorable reflections. This exception underscores the influence of spatial positioning and orientation on SPL distribution.

Both the impulsive method (balloon burst) and the swept sine method effectively captured the distance-related energy decay across rows in terms of SPL measurements. Notably, position (1,2) consistently registered the highest volume. However, due to the extremely short duration of the balloon sound, its impulse response (IR) exhibits a higher noise floor, resulting in a significantly lower signal-to-noise ratio (SNR) compared to the 10-second swept sine result.

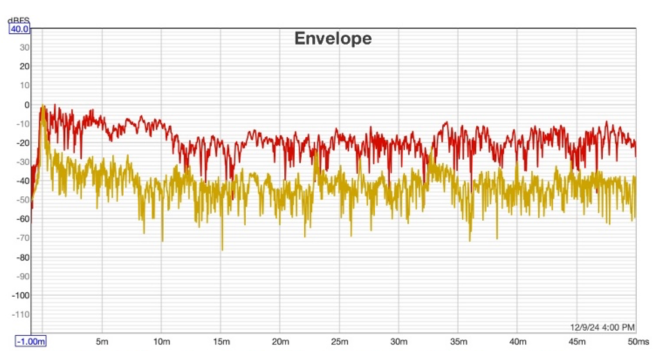


Figure 3 ETC: Balloon vs Sine Sweep

Figure 3 overlays the Energy Time Curve (ETC) for the first 50 ms of the two methods, with the red graph representing the balloon IR and the yellow graph representing the sine sweep IR. As expected, the balloon IR demonstrates a much slower decay, supporting the analysis of differences in SNR and energy decay between the two methods. This distinction is further highlighted in the Impulse Response graphs shown in Figures 4.

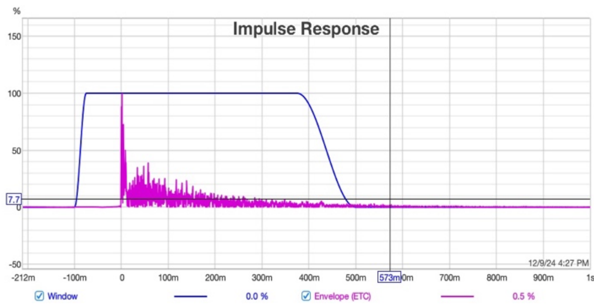


Figure 4(a) Ballon's IR.

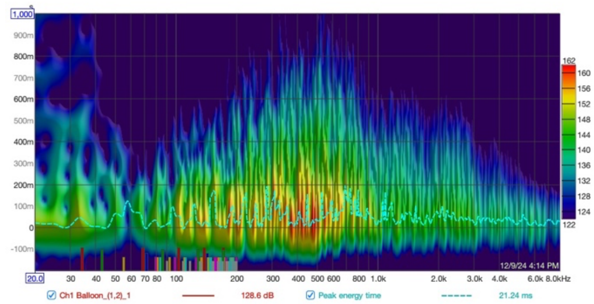


Figure 5(a) Ballon's FR

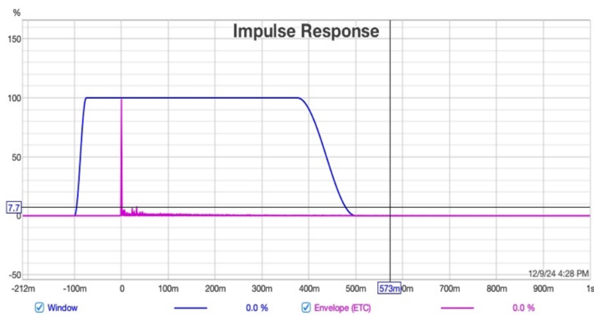


Figure 4(b) Swept Sine's IR

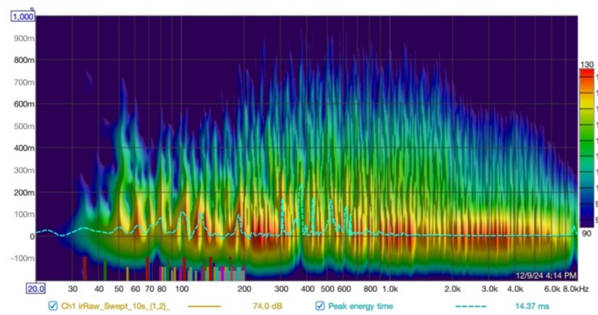


Figure 5(b) Swept Sine's FR

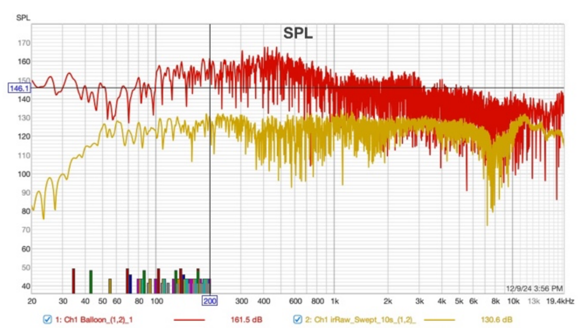


Figure 6 SPL: Balloon vs Swept Sine

Aside from the temporal differences in energy decay rates, the frequency response also reveals a significant distinction. Figures 5 illustrate that the sine sweep's frequency response (FR) exhibits a flatter and more even energy distribution compared to the balloon's.

Therefore, the sine sweep method has proven to be more robust than the impulsive method, offering finer resolution and accuracy in both the time and frequency domains. This results in a better representation of the IR, FR, and EDC. On the other hand, the impulsive method is still useful for providing a rough overview, such as identifying the energy distribution in space and pinpointing the location of maximum energy.

IV. Analysis of Results Obtained

Research has shown that reverberation time alone is insufficient for characterizing a classroom's acoustic response (Nilsson, 2013). Instead, C50 and sound strength (G) are commonly proposed by researchers as more effective metrics for reflecting speech intelligibility (Harvie-Clark, 2014). However, due to the lack of calibration during the measurement process, comparing G may not be valid. Therefore, C50 will be treated as the primary metric for speech intelligibility, with RT60 used as a secondary reference.

Table 4 lists the C50 and RT60 values at all positions, both with and without PA. The C50 values for each condition are compared binaurally at each position, with the higher value in each pair marked in red. It can be observed that at positions (1,1), (2,1), and (3,1), PA yields better results than without PA, marked with a highlighted average value at each row. Additionally, PA's "binaural effect," where the ipsilateral channel outperforms the contralateral channel (except at position (2,2)), is again observed, consistent with the findings in Table 3 with the SPL data.

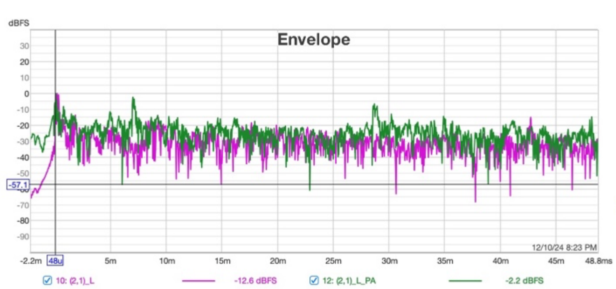
The finding that PA has a stronger impact on C50 on the far side of the source (positions 1,1; 2,1; 3,1) compared to the near side (positions 1,2; 2,2; 3,2) suggests that PA systems are more effective in improving speech intelligibility in areas farther from the sound source. On the far side, the greater acoustic challenges—such as increased distance, lower direct sound energy, and higher reverberation—lead to a degraded signal-to-noise ratio (SNR) and prolonged reverberation times (RT60). PA compensates for these issues by reinforcing the direct sound, reducing the masking effects of reflections, and improving clarity. This indicates that PA systems are particularly beneficial in environments where listeners are positioned farther from the source, where natural acoustics result in weaker direct sound and more prominent room reflections.

Position	Room Acoustics without PA		Room Acoustics with PA	
(1, 1)	**C50**	**RT60**	**C50**	**RT60**
	R: 1.64	R: 1.432	*R: 7.94*	R: 1.349
	L: 5.32	L: 1.419	L: 1.81	L: 1.344
	A: 3,48	A: 1.426	A: 4.88	A: 1.347
(1, 2)	**C50**	**RT60**	**C50**	**RT60**
	R: 12.55	R: 1.325	R: 0.54	R: 1.354
	L: 12.07	L: 1.319	*L: 2.69*	L: 1.365
	A: 12.31	A: 1.322	A: 1.62	A: 1.360
(2, 1)	**C50**	**RT60**	**C50**	**RT60**
	R: 0.81	R: 1.391	*R: 5.01*	R: 1.367
	L: 4.75	L: 1.358	L: 2.20	L: 1.366
	A: 2.78	A: 1.375	A: 3.61	A: 1.367
(2, 2)	**C50**	**RT60**	**C50**	**RT60**
	R: 4.72	R: 1.354	*R: 4.23*	R: 1.354
	L: 4.65	L: 1.306	L: 2.09	L: 1.368
	A: 4.69	A: 1.330	A: 3.16.	A: 1.361
(3, 1)	**C50**	**RT60**	**C50**	**RT60**
	R: 2.66	R: 1.369	*R: 4.69*	R: 1.333
	L: 3.76	L: 1.318	L: 1.99	L: 1.368
	A: 3.21	A: 1.346	A: 3.34	A: 1.351
(3, 2)	**C50**	**RT60**	**C50**	**RT60**
	R: 2.58	R: 1.430	R: 2.33	R: 1.386
	L: 3.83	L: 1.398	*L: 2.74*	L: 1.474
	A: 3.21	A: 1.414	A: 2.54	A: 1.430

Table 4 Spatial variation of C50 and T20

a. PA's contralateral effect: Ex (2,1) _Left

To illustrate the PA system's impact at position (2,1) left channel, Figure 7(a) compares the Energy Time Curve (ETC), and Figure 7(b) shows clarity (C50) values with and without PA across 250 Hz to 8 kHz.



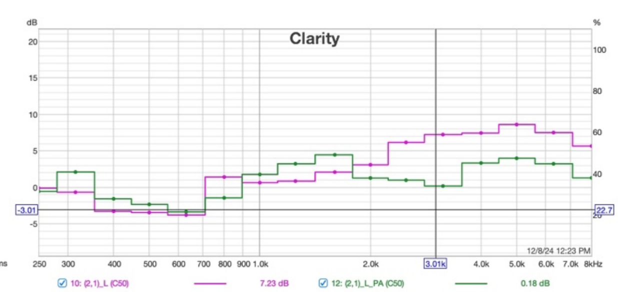


Figure 7(a) PA's Contralateral Effect in Time.

Figure 7(b) PA's Contralateral Effect on Frequency

Energy Time Curve (ETC):

With PA, the ETC indicates a *slower* energy decay compared to without PA, highlighting enhanced early reflections and sustained energy. This suggests the PA reinforces the sound field but may increase the masking of subsequent sounds.

Clarity (C50):

C50 values below 2 kHz are generally higher with PA, reflecting improved clarity in the lower speech frequency range for vowels. Above 2 kHz, C50 decreases with PA, likely due to increased high-frequency reflections or dispersion, reducing clarity critical for consonant intelligibility.

Conclusion:

The comparison underscores the dual effects of the PA system: it enhances energy and clarity at lower frequencies while potentially compromising high-frequency clarity. Reducing high-frequency clarity poses a significant challenge for understanding non-tonal languages like English, where consonant perception is more critical for speech recognition than vowel perception (Fogerty, 2009). This highlights the importance of careful PA calibration to balance energy reinforcement with speech intelligibility across the frequency range.

b. PA's ipsilateral effect: Ex (2,1) _Left

Contrarily, the ipsilateral impact of PA demonstrates a direct sound dominant pattern with rapid energy decay in the early reflections, which presumably is a good sign for enhancing speech clarity.

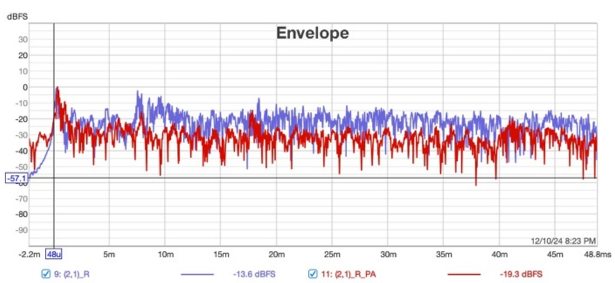


Figure 8 PA's Ipsilateral Effect in Time

Now let's analyze the near-side positions with examples (1,2) and (2,2) presented below.

c. Addressing PA Ineffectiveness: Frequency Perspective at (1,2) _R and (2,2)_L

At the near-side positions, the interaural difference in PA performance diminishes, but clarity degradation above ~2 kHz remains dominant, limiting high-frequency intelligibility. Figures 9 and 10 illustrate this for positions (1,2)R (contralateral) and (2,2)L (ipsilateral), comparing (a) C50, (b) SPL across 250 Hz–8 kHz, and (c) ETC. Both positions show stronger early reflections with PA, with contralateral (1,2)R stronger than ipsilateral (2,2)L, aligning with the contralateral effect observed on the far side. Figure 11 averages across all positions, revealing PA's impact on raised low frequencies below 40 Hz, reduced highs above 3 kHz, and midrange peaks ~70 Hz–2 kHz. This highlights how PA hinders speech clarity at near-side positions by amplifying low frequencies and early reflections while degrading high-frequency intelligibility.

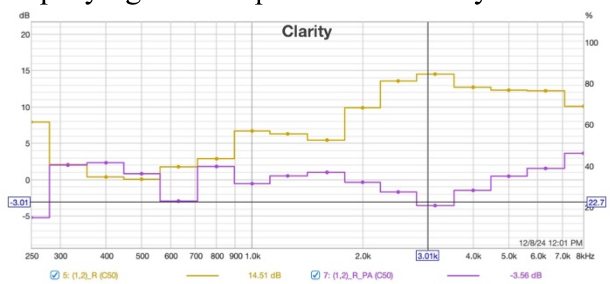


Figure 9(a) C50 at (1,2) R: PA vs without PA.

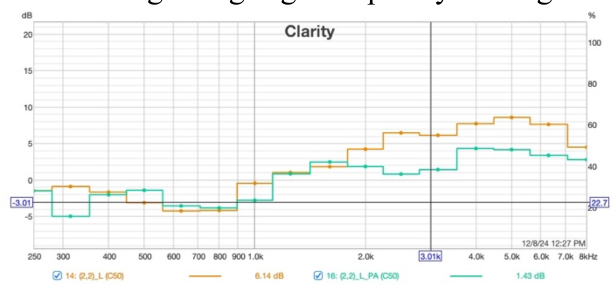


Figure 10(a) C50 at (2,2) L: PA vs without PA

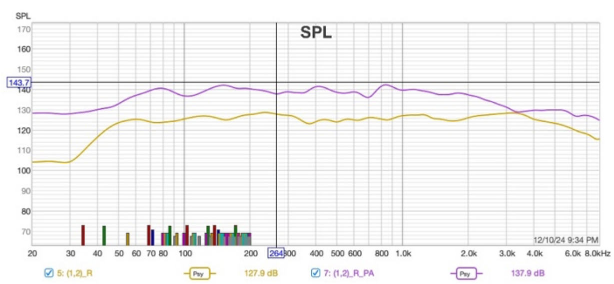


Figure 9(b) SPL at (2,2) R: PA vs without PA

Figure 10(b) SPL at (2,2) L: PA vs without PA

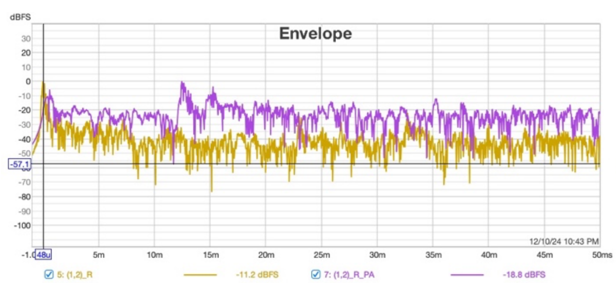


Figure 9(c) ETC at (1,2) R: PA vs without PA

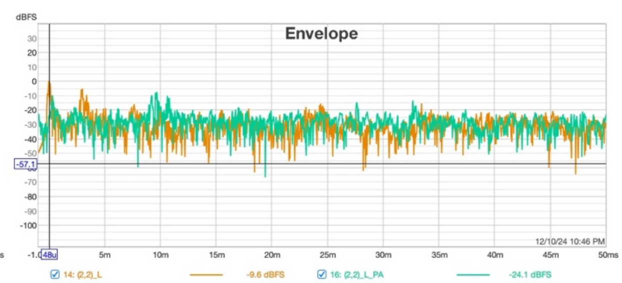


Figure 10(c) ETC at (2,2) L: PA vs without PA

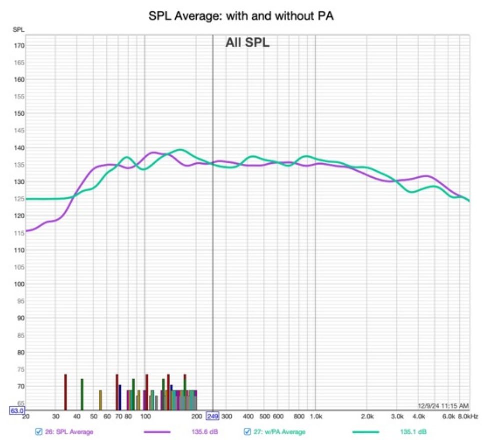


Figure 11 SPL Average: PA vs without PA

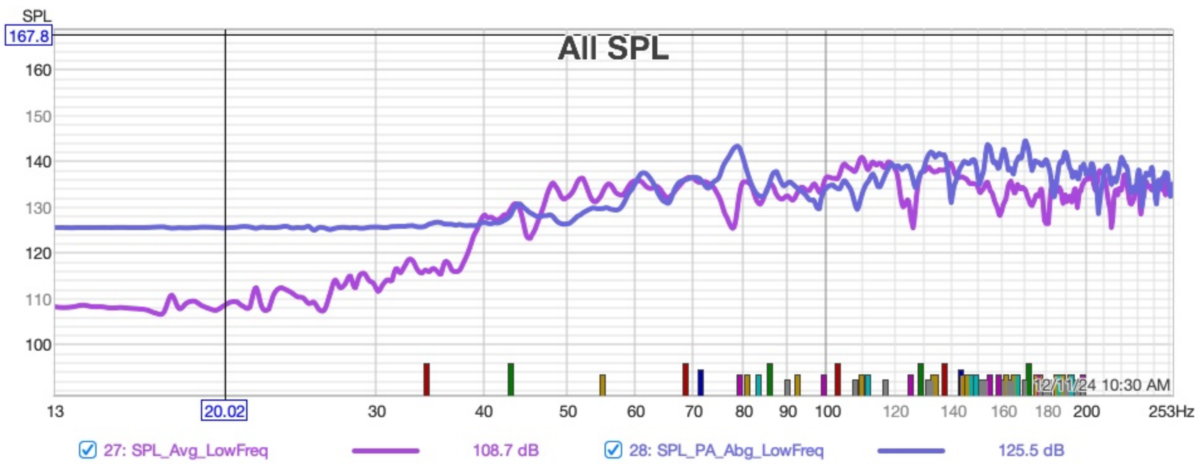


Figure 12 SPL at low frequency: PA vs without PA

The SPL graph below 250 Hz (Figure 12) shows that PA amplifies low-end frequencies and introduces peaks at modal frequencies, emphasizing its impact on low-frequency resonance.

V. Conclusions and Recommendations

This study assessed the acoustic performance of the studied space with and without a public address (PA) system, focusing on key metrics such as speech intelligibility (C50), sound pressure levels (SPL), and early-to-late energy distributions. The findings highlight both strengths and areas for improvement in the acoustics of the space:

a. Comparisons with Theoretical Predictions or Standards:

The recommended C50 value for classroom settings is typically around 3 db. The study found that most positions with the PA system met this criterion, except near-side positions (1,2) and

(3,2), which did not achieve the desired C50 levels. While RT60 values generally aligned with theoretical expectations, deviations in C50 emphasized inconsistent intelligibility, particularly at near-side locations. The PA system's amplification of low frequencies and degradation of high-frequency clarity, essential for consonant perception in English, contributed to these issues.

b. Overall Evaluation of the Space's Acoustics:

The space demonstrated uneven acoustic performance. The PA system improved intelligibility at far-side positions, but adversely affected near-side positions by boosting low frequencies and reducing clarity above 2 kHz. Although SPL coverage was generally adequate, high-frequency intelligibility remained insufficient in some areas, especially near the speakers.

c. Recommendations for Improvements:

1. **Adjust PA Calibration**: Modify the PA system's frequency response to limit low-frequency amplification and enhance clarity above 2 kHz. This adjustment would improve intelligibility at near-side positions and contribute to overall speech recognition.

2. **Implement Acoustic Treatments**: Installing absorptive materials at strategic locations to control low-frequency resonance and mitigate early reflections would enhance speech clarity, particularly at near-side positions where low-frequency buildup was problematic.

3. **Reevaluate Speaker Placement**: Optimizing speaker placement to reduce interaural differences and improve sound distribution across seating areas is essential. Specific attention should be given to near-side positions, where PA-induced degradation was most pronounced.

d. Limitations of the Study and Suggestions for Future Work:

The study lacked calibrated measurements, limiting the evaluation of absolute sound strength (G). Future research should incorporate calibrated data to provide more accurate assessments. Additionally, exploring other metrics such as the Speech Transmission Index (STI) and conducting subjective listening tests would offer complementary insights into perceived intelligibility, enhancing the understanding of acoustic performance.

These recommendations aim to improve speech clarity and create a more balanced acoustic environment. Optimizing PA calibration, enhancing acoustic treatments, and refining speaker placement will help achieve consistent performance across the space and address intelligibility issues at near-side positions.

VI. Bibliography

1. Nilsson, E. (2013). Calculations and measurements of reverberation time, sound strength, and clarity in classrooms with absorbing ceilings. *Inter-noise*.

2. Harvie-Clark, J., Dobinson, N., & Larrieu, F. (2014). Use of G and C50 for classroom design. *Proceedings of the Institute of Acoustics*, 36, 550-560.

3. Daniel Fogerty, Diane Kewley-Port; Perceptual contributions of the consonant-vowel boundary to sentence intelligibility. **J. Acoust. Soc. Am.** 1 August 2009; 126 (2): 847–857. https://doi.org/10.1121/1.3159302