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Technical Note

Experimental and Numerical Investigations of Acoustic Variations in a Classroom Environment

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The acoustic behaviour of a classroom is vital for an effective teaching-learning process. The present work aims to experimentally determine the acoustic performance of a typical classroom. The full-scale experiment was conducted at the Seminar Hall, the Department of Applied Mechanics, MNNIT Allahabad, Prayagraj, using a method with limited resource requirements. The Seminar Hall was divided into four planes by threads, and the sound pressure level (SPL) was measured at 30 coordinates in each plane for the specified sound source location. Data were collected from three different sound source locations. The study revealed that the sound source location and frequency significantly influence the sound pressure levels in the classroom, impacting its acoustic performance. The broader implications of interior materials, such as wall material and the position of elements like the teaching board, door, and podium, are highlighted as critical considerations for future classroom acoustic optimization. Furthermore, a numerical model was developed to predict the variation in the SPL with change in the sound source locations and frequencies. The collected data validated with the finite element (FE) model. The verification experiments for the modeling results were performed for each plane. The results of the FE model and experiments were found consistent across all four planes of the seminar hall and the various sound source locations.

Keywords: acoustic measurements; finite element method; room acoustics; sound pressure level; sound source location.

1. Introduction

Comfortable acoustic conditions are essential in the workplace, as is intensive verbal communication for improved efficiency. Classrooms are often noisy and reverberant, making learning difficult (MEALINGS, 2023a). Specific classrooms are used for students to convey better acoustics and comfort (RABELO *et al.*, 2014). The acoustic parameters such as the sound pressure level (SPL) and the speech transmission index directly impact the audience's intelligence present in the classroom. Noise decreases the information sent from the source in the classroom (MEALINGS, 2023b; PENG *et al.*, 2016; RABELO *et al.*, 2014). The research community has conducted various studies to achieve the acoustic comfort of the classroom. PENG *et al.* (2016) investigated the background noise level and speech SPL for the Chinese word recognition test and found that high SPL could not guarantee good Chinese word recognition score for children present in the classroom because of its dependency on the background noise level. VISENTIN *et al.* (2018) used speech intelligibility, response time, and rating scales to analyze the effect of acoustic changes in the room. ZHANG *et al.* (2019) used two classrooms and conducted listening tests at different SPLs. The interaction effect of the sound types and the SPL was found to have practical significance for different noises. GRAMEZ and BOUBENIDER (2017) measured the ambient noise and interior sound insulation for a conference room compared with the guidelines available in the literature. Poor room acoustics was found due to the low insulation and high reverberation time. Mealings *et al.* (2024) measured the acoustic performance of 166 rooms and found that reverberation time and noise level (SPL) are the two significant factors that impact the room's performance.

It is reported that the superior signal-to-noise ratio is significant in addition to reverberation time (Bradley, 1986; Bradley *et al.*, 1999; 2003; Yang, Bradley, 2009). Budzyński (1986) mentioned that early reflections coming from sidewalls are responsible for increasing auditory distance localization. Installing sound-insulating material may help, but speech transmission quality could be better and more cost-effective. Increasing sound-absorbing material leads to a lower signal-to-noise ratio and a decreased speech intelligibility, specifically for distant listeners. Interestingly, the acoustic ceiling tiles used for the sound insulation absorb consonant sounds higher than the vowel sound, as vowels have lower frequencies (Nábělek *et al.*, 1989; Nijs, Rychtáriková, 2011). The optimum configurations of absorptive treatment for improved acoustical conditions using computer-based and numerical models were reported in (Bistafa, Bradley, 2000; Mir, Abdou, 2005; Reich, Bradley, 1998; Smirnowa, Ossowski, 2005). The authors reported the FE model, which effectively predicted the acoustic behaviour of a room in their previous work. The presented model was validated for a rectangular room made of laminated glass (Vedrtnam, Pawar, 2018). Many standards are reported in the literature, which provide reference values for the different parameters that may influence acoustic comfort (World Health Organisation, 1999; Newman, Sabine, 1965). The studies on designing and measuring the acoustic properties of interiors, especially for small rooms and primarily SPL (Vorländer, 1998; Weyna, 1996) problems in estimating the acoustic behaviour of interiors, the effect of source directivity (Vigeant *et al.*, 2006), and acoustical designing of classrooms (Bradley, 1986; Bradley *et al.*, 1999; 2003; Gramez, Boubenider, 2017; Jerlehag *et al.*, 2018; Peng *et al.*, 2016; Rabelo *et al.*, 2014; Visentin *et al.*, 2018; Yang, Bradley, 2009; Zhang *et al.*, 2019) are already available.

Numerous studies have explored the influence of room geometry, materials, and sound source locations on classroom acoustics. For example, Visentin (2023) study explores how background noise, including student interactions, impacts task performance and listening comprehension in classrooms. The research highlights the critical role of signal-to-noise ratio and emphasizes designing acoustic environments that account for real-world noise levels beyond typical reverberation time measurements. Hongisto *et al.* (2023) compared two classrooms, one acoustically refurbished with enhanced sound-absorbing materials and reduced reverberation times. The study demonstrated significant reductions in noise annoyance and improved speech intelligibility, particularly during activity-based lessons. This reinforces the importance of targeted interventions in classroom design. Van Reenen and Manley (2023) focused on the implementation of classroom acoustic standards globally. It discusses the effectiveness of mandatory standards accompanied by detailed design guidance in achieving optimal learning environments and identifies cost and accessibility as barriers to adoption.

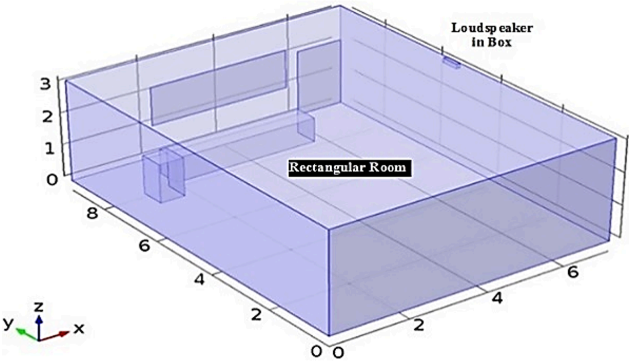
Several standards for the acoustical property measurements, i.e., ISO 10534-2, ASTM E2611-09, ASTM E1050-98, JIS A1409, ISO 354-2003, ASTM C423, ISO 140-3, SAE J1400, ISO 140-4, and ASTM E90 are also available. The architect's job nowadays should essentially involve meeting the measurable standards set for designing acoustically comfortable living rooms, classrooms, workshops, laboratories, concerning halls, lecture halls, fictional rooms, dining halls, drawing rooms, factories, sports halls, mechanical rooms, hotels, restaurants and every enclosed space of human intervention including sound and noise. The minor changes in frequency, room dimensions, materials, goods, and interiors affect the SPL in the rooms.

Numerous studies have explored the acoustic performance of classrooms, focusing primarily on reverberation time (RT), speech intelligibility indices (STI), clarity (C50), noise reduction coefficients. However, the influence of spatial variability in SPL across different loudspeaker locations in a classroom using controlled frequency tones, such as 4000 Hz (a frequency crucial for speech clarity), has been underexplored. Also, many of these studies rely heavily on generalized assumptions and computational simulations, often needing to integrate detailed experimental validation. In this work, a method to determine SPL variation due to sound source (SS) location, directivity, and objects in the room is proposed. A numerical model is also proposed for predicting SPL variation as a function of SS location, frequency, and object.

2. Materials and methods

Figures 1a and 1b show the photograph and schematic diagram of the seminar hall. The dimensions of the seminar hall were 9.25 m × 7.23 m × 3.14 m. This seminar hall had tiles on the floor, concrete walls, a door, a teacher's desk, a podium made of wood, and a teaching board made of Balsa wood. The dimensions of the board, door, podium, and teacher's desk were 3.6 m × 1.2 m, 1.20 m × 2.05 m, 0.62 m × 0.62 m × 1.20 m, and 3.68 m × 0.62 m × 0.76 m, respectively. An air-conditioner was also mounted on the wall. The speaker was placed in three different positions.

a)



b) c)

Fig. 1. Schematic diagram (a) and photograph (b) of seminar hall, photograph of the room used for verification experiment (c).

Four different planes (Fig. 2) in the seminar hall were created using the mesh of treads for accuracy and repeatability of a particular location while recording the SPL. The SPL was recorded at 30 points (six along the x-axis and five along the y-axis) in each plane. The coordinates were marked on the threads for the accuracy of the location while noting the SPL. The sound signal was produced using a directivity-controlled SS mounted in a cubic cabinet. The omnidirectional microphones were used. A filling of bonded acetate fibre significantly increased the effective volume of a sealed-box loudspeaker. An amplifier was used to enhance the amplitude of an electrical signal produced by the source. The amplifier was connected in between a sound-generating laptop and the 2-in electrodynamic loudspeaker. The horizontal and vertical input loudspeaker coverage are 50° and 30°, respectively. The directivity index of the loudspeaker is 18.9 dB at 2000 Hz.

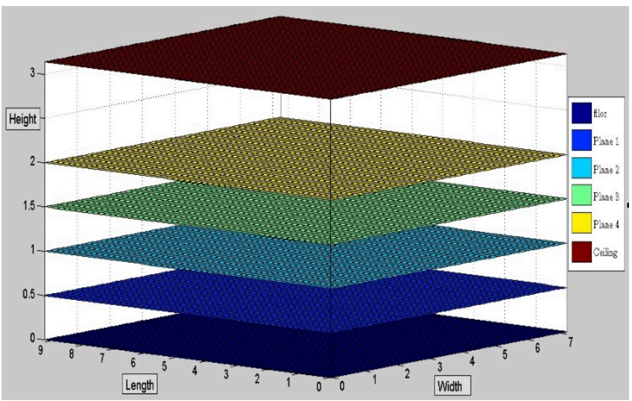


Fig. 2. Position of different planes selected for the work.

The speaker sensitivity rating is 85 dB – 1 W – 1 m, i.e., 85 dB sound is produced at 1 m away from the speaker if 1 W input is given. The loudspeaker with a 50 mm driver was mounted on the front, attempting to block the sound backward, utilizing sound-insulating materials. The Indi 6182 Multifunctional Sound Level Meters were used to measure the SPL at different locations in the room. The SPL was measured by the sound level meters in L_{eq} (equivalent continuous sound level) mode. The Laser Distance Meter (Leica DISTOTM X310, Swiss technology by Leica Geosystem) was used for the distance measurement. The pure tone of 4000 Hz (sine wave) was generated following the authors' procedure in their earlier work (Vedrtnam, Pawar, 2018).

The typical frequencies under consideration for room acoustics are 125 Hz–4000 Hz, octave bands. Thus, the SPL was measured at 1000 Hz, 2000 Hz, and 3000 Hz at the selected coordinates of different plains for comparison purposes. To systematically analyze the variation of SPL at different frequencies, separate controlled experiments were conducted using pure sine wave signals at 1000 Hz, 2000 Hz, 3000 Hz, and 4000 Hz. The SPL measurements reported for each frequency correspond to independent experimental runs rather than being derived from a single 4000 Hz excitation. This approach ensures accurate assessment of frequency-dependent acoustic behaviour in the classroom environment. Further, the experimentation was repeated in a different room to verify the effect of frequency change on the SPL (Fig. 1c). The FE model was constituted using the acoustics module, pressure acoustics, and frequency domain of COMSOL 5.4. The actual dimensions of the seminar hall and other objects were considered for the geometry model (Fig. 1b). The SS geometry was taken from experimentation for simulation. The meshing was performed using a physics-controlled mesh with the extra fine element size. The full mesh comprises 103 811 domain elements, 6146 boundary elements, and 390 edge elements. The parametric sweep of coordinates for the speaker (similar to the experiment) was performed to compute the speaker's results for three locations. The standard material properties were utilized for the different materials present in the seminar hall (Vedrtnam, Pawar, 2018). The SPL of four virtual planes (Fig. 2) at similar locations to experiments were obtained from the FE model.

While acoustic performance is typically assessed using multiple parameters, including RT, STI, and C50, this study focuses specifically on SPL variations. The SPL is a critical factor in classroom acoustics as it directly influences speech intelligibility and sound distribution. By analyzing the SPL across different source locations and frequencies, this study provides valuable insights into the spatial acoustic behaviour of the classroom. Future work will extend this analysis to incorporate additional acoustic metrics for a more comprehensive assessment. The SPL was measured up to the height of 2 m from the floor since the maximum range of height of humans for listening belongs to this region. The controlled harmonic tone 4000 Hz sine wave frequency was selected as a test signal in the mid to high-frequency range. It plays a significant role in understanding consonants due to its critical importance in speech intelligibility. It provides preciseness and repeatability for evaluating the frequency-dependent SPL distributions without neglecting the confounding effects of other variables, such as mixed-frequency content or background noise.

The SPL at 70 dB refers to the pressure value of 0.063 Pa and intensity of $1\ \text{W/m}^2 \times 10^{-5}\ \text{W/m}^2$, and at 80 dB, the SPL refers to the pressure value of 0.2 Pa and intensity of $1\ \text{W/m}^2 \times 10^{-3}\ \text{W/m}^2$ (Smirnowa, Ossowski, 2005). Sound intensity as a "sound energy quantity" can be related to sound power (acoustic power) as $I \approx p^2$ (for progressive plane waves) (Vedrtnam, Pawar, 2018).

The SPL was measured at 30 coordinates in every plane, and the results were plotted using MATLAB. Table 1 shows the locations of the loudspeakers used in the experiments. These positions were selected to represent different typical loudspeaker placements in a classroom environment. The loudspeakers were placed at varying distances and orientations from key room features (e.g., the teacher's desk, podium, and walls) to assess how the sound source location influences the SPL distribution. These positions were not based on any pre-existing loudspeakers in the room but were experimentally chosen to cover a variety of configurations that might be encountered in real-world classroom setups. Thereafter, the results for all three fixed positions of the loudspeaker (Table 1) in each plane are discussed.

Table 1. Location of the loudspeaker and their coordinates.

Loudspeaker location	x	y	z
First fixed position	4	0	3.14
Second fixed position	1.5	3.5	0.76
Third fixed position	5.5	3.5	0

3. Results and discussions

3.1. Measurement of SPL in seminar hall at first fixed position of the loudspeaker – $(x, y, z) = (4\ \text{m}, 0\ \text{m}, 3.14\ \text{m})$ – in different planes

Figure 3 shows the variation of the SPL in plane 1. It is found that the effect of source directivity plays a significant role in the SPL distribution curve (Fig. 3a). The higher SPL values (red colour) were on an axis parallel to the source as plenty of direct sounds reached that axis. The low SPL was measured below the speaker. The minimum SPL was measured behind the podium because sound waves could not reach

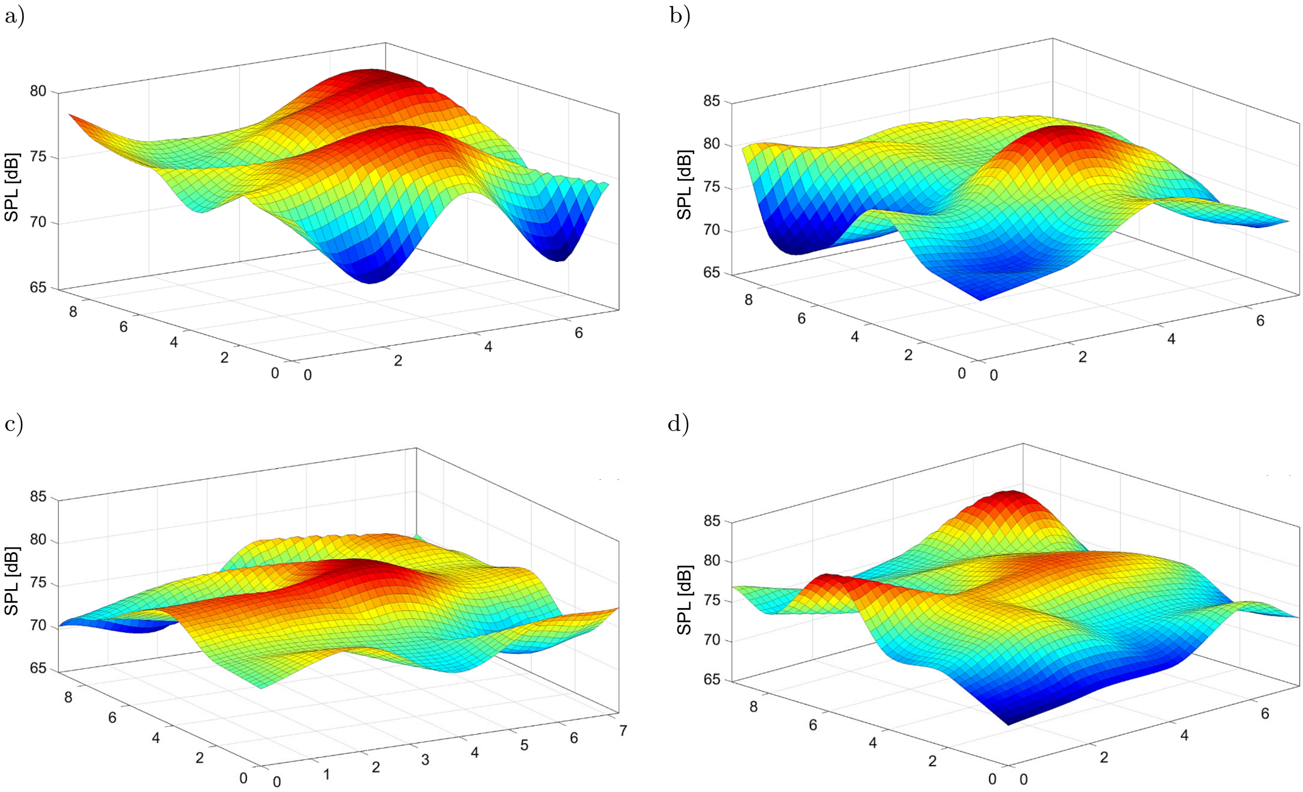


Fig. 3. Variation in SPL at first fixed position of the source in: (a) plane 1; (b) plane 2; (c) plane 3; (d) plane 4.

there directly. The lower reflection and lack of direct sound waves have resulted in the lowest SPL behind the podium. The sound waves coming toward the podium first struck it, then absorbed and partially reflected. The lowest values of the SPL (blue colour) were found beside the teacher's desk because of the lack of reach of direct sound waves.

The desk influences sound wave distribution by reflecting and diffusing the sound waves, with minimal contribution from material absorption. Hence, the SPL values were little higher in front of the teacher's desk. At the front wall, the SPL was measured lower near the air conditioner's presence. Generally, air conditioners are designed with sound-absorbing materials to dampen the sound. The front panels of the air conditioners act as barriers and help reflect and absorb sound waves. However, the SPL suddenly rose at the corners of the front wall because of constructive interference due to the intersection of two walls.

Figure 3b shows the variation of the SPL in plane 2. A similar trend was observed in plane 2.

The lowest SPL value was found on the wall, exactly below the speaker. The SPL was found most stable near the source directivity field (yellow colour). The area near the door (at the origin) had a lower SPL primarily due to the positioning and interaction of the sound waves with the wooden door, rather than significant absorption by the material itself. Additionally, due to the formation of destructive interference, the SPL values were low. The trends observed in Fig. 3c and 3d were almost similar, with minimum variations because of the absence of obstructions in their planes. The comparison of the SPL for all four planes is shown in Fig. 4.

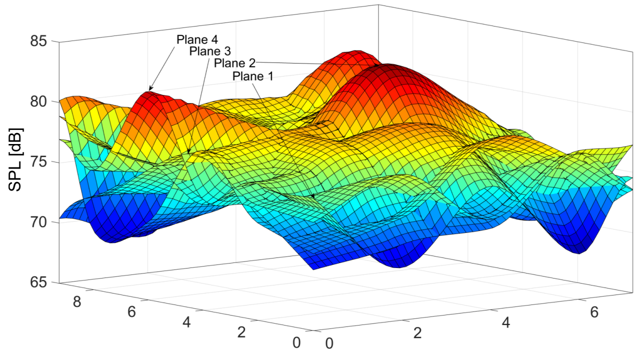


Fig. 4. Comparison of SPL at first fixed position of the source in all planes.

3.2. Measurement of SPL in seminar hall at second fixed position of the loudspeaker – $(x, y, z) = (1.5\text{ m}, 3.5\text{ m}, 0.76\text{ m})$ – in different planes

In the second case, the loudspeaker was placed 0.76 m above the floor, facing the larger space in the opposite direction as the board. The SPL was measured and plotted in a similar manner to the previous. Figure 5a shows the variation in the SPL in plane 1 and the effect of source directivity on the SPL distribution,

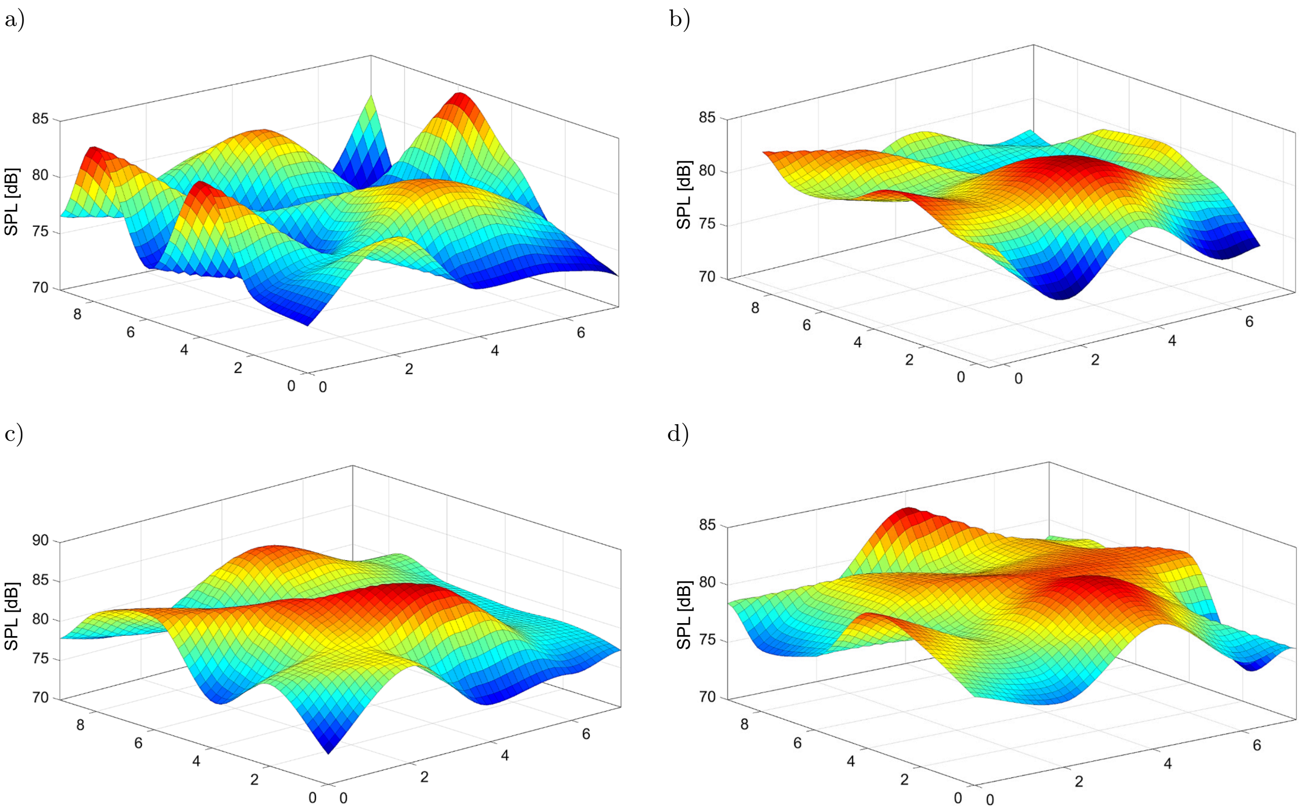


Fig. 5. Variation in SPL at the second fixed position of the source in: (a) plane 1; (b) plane 2; (c) plane 3; (d) plane 4.

which remains highly variable. Higher SPL values (red colour, near 6 m, 7.23 m, 0.5 m) were measured in the far-field region of the lower plane. This far-field region has a significant amount of space without interfering with room interiors, so a lot of direct sound reaches it. The average SPL values were measured on the same wall where the speaker was mounted, because the side walls were closer in this case.

Figure 5b shows the variation of the SPL in plane 2. The highest SPL values (red colour, near 2 m, 4 m, 1 m) were measured near the speaker field. The absorption of sound was maximum at the front wall location (9.25 m, 2 m, 1 m) and near the air conditioners (9.25 m, 6 m, 1 m), but the source's directivity to the receiving place was also maximum. As a result, the SPL in these areas is approximately average. Comparing Figs. 5a and 5b reveal that both curves have higher and lower values at the same locations and follow a nearly identical pattern while only varying in SPL intensity. Figure 5c shows the variation of the SPL in plane 3. The SPL was measured lower near the origin coordinates (0 m, 0 m, 1.5 m) because of the presence of a door, as sound absorption was maximum at that location due to the presence of wood material. The higher and lower points in Figs. 5a–c are almost identical. Figure 5d shows the variation of the SPL in plane 4. Since the sound distribution is more uniform in the presence of more free space, and there is less interruption of interiors, this plane had the fewest variations in the SPL distribution curve compared to all other planes.

The highest SPL value (near 2 m, 4 m, 2 m) is found in the near field region and on-axis to the source. The SPL values at the speaker's backside, as well as the corners of walls near the podium (0 m, 7.23 m, 2 m) were lower due to source directivity and the presence of absorbing materials. The comparison of the SPL for all four planes is shown in Fig. 6. The comparison shows that the plane 4 has the most stable SPL values because of the higher source directivity and least absorptivity. The corners of the room also helped in maintaining the SPL values at the far end by forming constructive interferences.

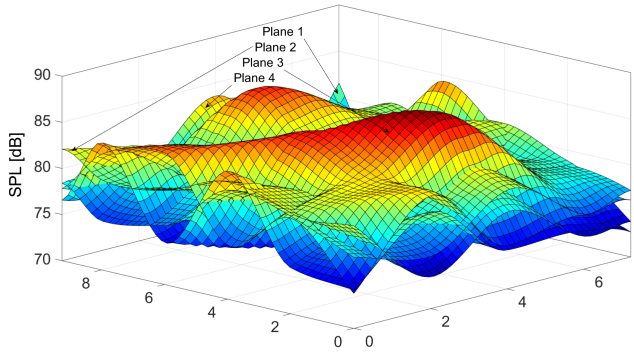


Fig. 6. Comparison of SPL at second fixed position of source in all planes.

3.3. Measurement of SPL in seminar hall at the third fixed position of the loudspeaker – $(x, y, z) = (5.5\,\text{m}, 3.5\text{m}, 0\,\text{m})$ – in different planes

In the third case, the loudspeaker was positioned at ground level (near the center of the room), away from the origin, and facing the teacher's desk and board.

Figure 7a shows the SPL variation and the source directivity effect in plane 1. This plane had the most significant variation in SPL values due to speaker location, less free space, and maximum interruption from interiors. In Figs. 7a and 7b, the highest SPL (red colour, near 4 m, 4 m, 0.5 m, and 4 m, 4 m, 1 m, respectively) were measured near the field region, speaker location, and on-axis to the source. In Fig. 7b, the SPL drops abruptly between the podium and the teacher's desk (2 m, 6 m, 1 m) due to the maximum amount of sound-absorbing material surrounding this area. Figures 7c and 7d show the variation of the SPL in planes 3 and 4, respectively. SPL distributions were relatively uniform due to the significant free space and minimal interruption of interiors. The area from the front to the speaker location was measured as the high SPL. Figure 7d shows the variation of the SPL in plane 4, which has a similar distribution to plane 3 with some apparent changes.

Figure 8 shows a comparison of the SPL across all four planes. The SPL behaviour was found most stable compared to the other two loudspeaker locations. The area near the speaker showed the maximum SPL in all four planes, whereas the SPL was found lower at the corner backside of the SS location.

After analyzing all speaker locations, it was found that the first plane had the most variations when compared to the other planes. The most apparent reason is the presence of objects in the room on this plane, such as air conditioners, the teacher's desk, and the podium. Because the material absorption coefficients of these interiors (beyond the scope of this study) can vary, the reverberant field may influence the value of SPL at different coordinates. The third speaker location, in the third and fourth planes, was constantly compared to the other two speaker locations because the speaker was placed in the center of the room, at ground level. As a result, the sound distribution was more uniform than the other speakers' locations.

Figure 9 shows the surface plot of the SPL obtained after solving the FE model using COMSOL for the different planes. However, as it was ambiguous to demonstrate the experimental results with the simulation results using this plot, a few verification experiments were also performed, and line graphs were plotted. The line graphs were plotted along the line parallel to the Y-axis at $X = 4$ m in four different planes as described previously, and results were compared to those obtained from the experiment. For comparison, 20 SPL readings from the investigation were collected

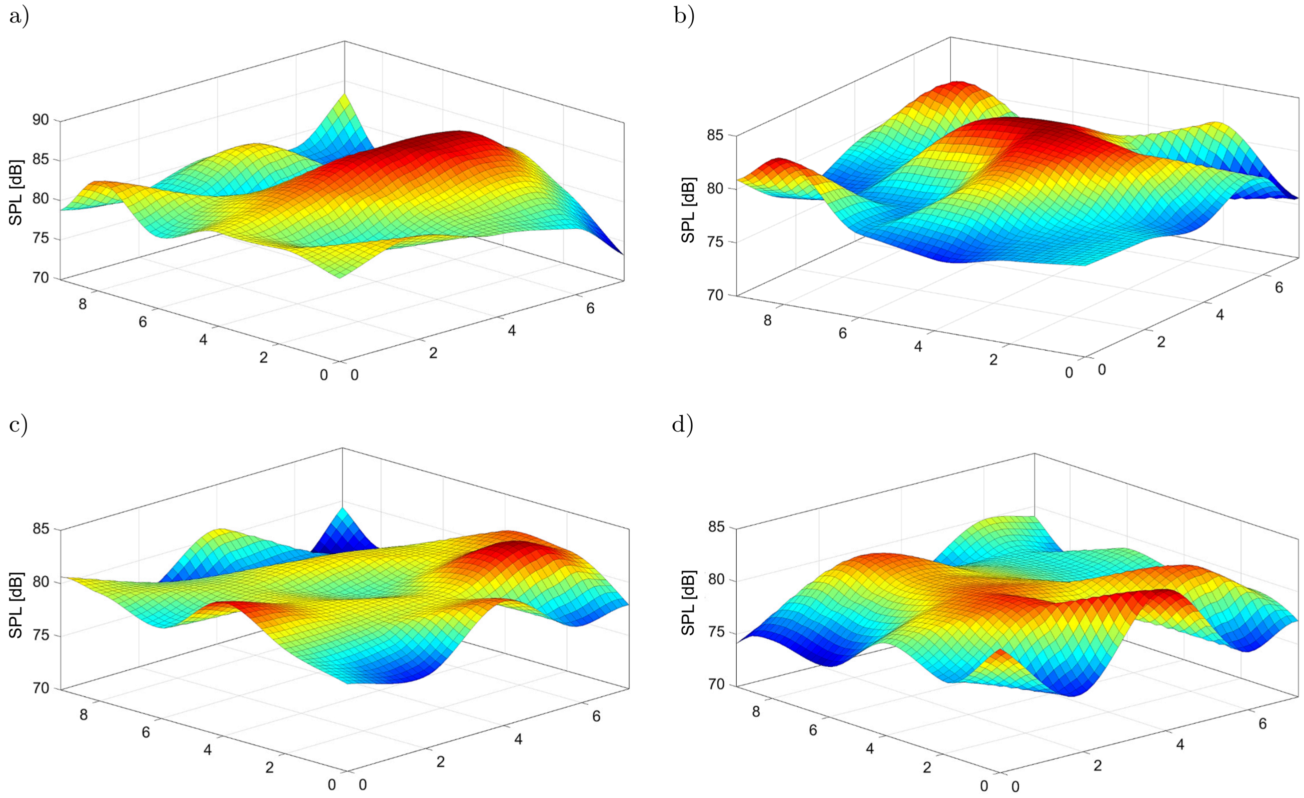


Fig. 7. Variation in SPL at the third fixed position of the source in: (a) plane 1; (b) plane 2; (c) plane 3; (a) plane 4.

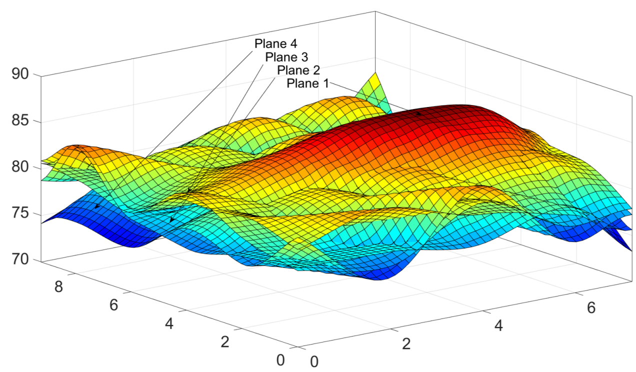


Fig. 8. Comparison of SPL at the third fixed position of the source in all planes.

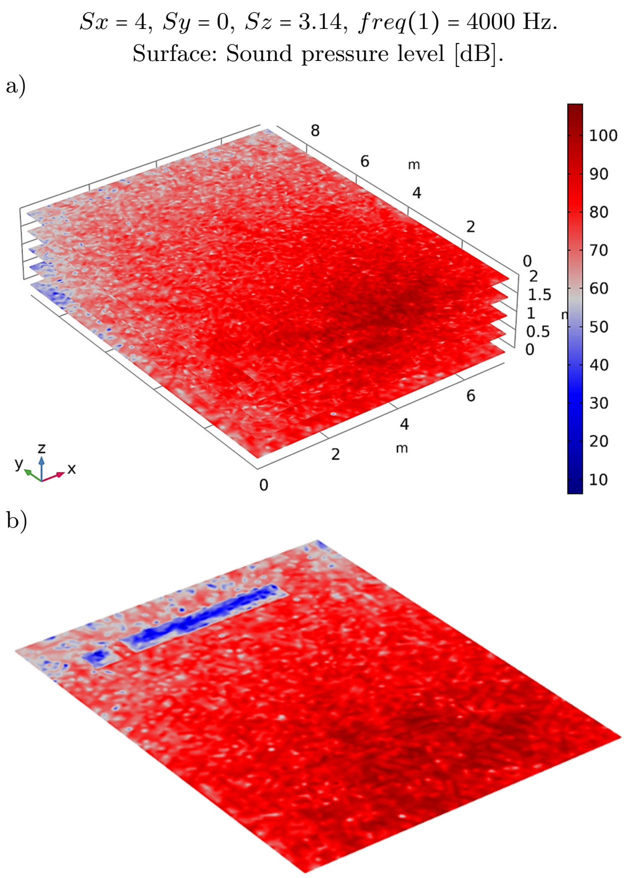


Fig. 9. (a) Surface plots of SPL (sample modeling results) and (b) surface plot of plane at $y = 0$.

for the first and third locations of the SS in four different planes, and the results were compared against the simulation results.

Figures 10a and 10d show line graphs that compare the experimental and numerical results. The line graphs in Fig. 10a represent the straight lines taken on plane 1. The graph showed that the variation in the SPL from modeling was uniform when compared to experimental results due to modeling data computed at continuous points on the line. After reaching a steady state, the sound level meter's equivalent continuous sound level mode provided the SPL without fluctuations. The SPL instability is visible in the simulation's steady state. The simulation fluctuations

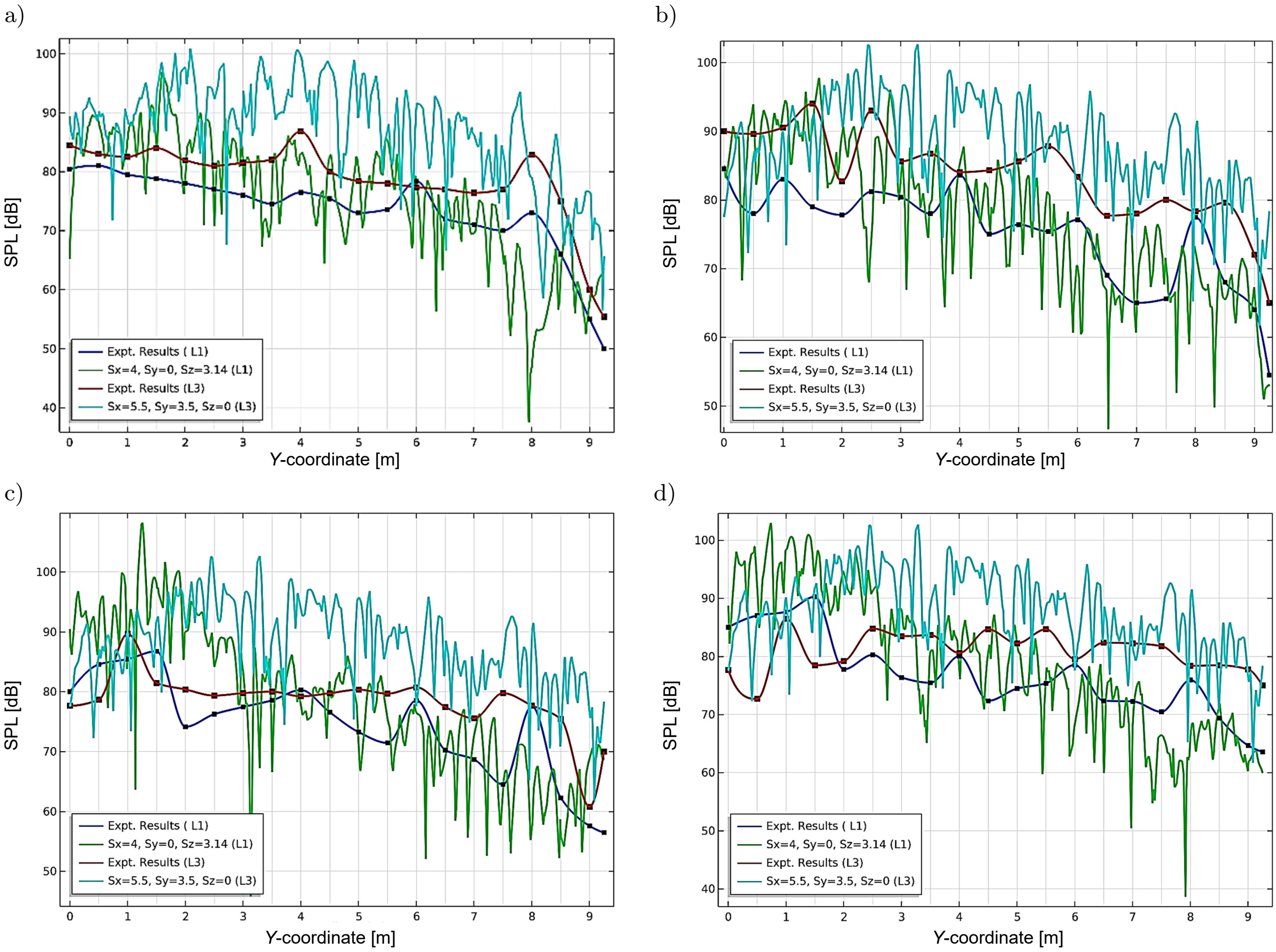


Fig. 10. Comparison of experimental and simulation results for: (a) plane 1; (b) plane 2; (c) plane 3; (d) plane 4.

show the values for each point in the room and do not vary with time.

Further, additional experiments are conducted to investigate the capability of a numerical model for predicting the SPL variation of any rectangular space for different frequency ranges with different objects and interiors if the velocity of sound and the absorption coefficient of the material are known. The additional experiments are conducted in the seminar hall and a different room. The SPL was noted for four randomly selected points.

Table 2 compares experimental and simulation results at different frequencies for the seminar hall. The SPL was reduced with the increment of frequency for the tested frequency values during the experiment. The numerical model captured this effect well, and the SPL was dropped in simulation results compared to the experiments. However, a slight variation in the SPL could be noticed; the SPL in simulation results is 3 %–5 % higher than the experimental results, possibly due to losses and unavoidable noise due to atmospheric factors present during the experiment. The trend of the SPL variation with frequency change was similar for experimentation and simulation.

Table 3 compares experimental and simulation results for a normal room at different frequencies. A similar observation was reported for the room and the seminar hall. The prediction of the SPL from the numerical model was in line with the experimentally evaluated SPL values for all randomly selected locations in the room for tested frequencies.

4. Conclusions

This study provides a comprehensive assessment of SPL distributions in a classroom environment, both experimentally and through FEM simulations. The findings demonstrate how the SPL varies with sound source location and frequency, providing critical insights for optimizing classroom acoustics. The results highlight the importance of considering spatial variability in the SPL for improving speech intelligibility, particularly in classrooms with complex geometries. This work also offers a replicable methodology for assessing classroom acoustics that can be extended to other indoor spaces, such as lecture halls and meeting rooms. It is concluded from the experiments that

Table 2. Comparison of experimental and simulation results at different frequencies for the seminar hall.

Simulation no.	Location [m] (1st fixed position of the speaker)			Frequencies [Hz] used for experimentation results of SPL in seminar hall				Frequencies [Hz] used for simulation results of SPL in seminar hall			
	x	y	z	1000	2000	3000	4000	1000	2000	3000	4000
1.	2	4	0.5	90.1	87	85	79.44	92.8	90.6	89.5	83.1
2.	4	6	0.5	85.1	82.9	82.1	75.36	87.5	86.2	86.4	81.2
3.	6	2	0.5	83.7	81.8	80.9	73.84	84.2	84.3	84.7	79.2
4.	8	4	0.5	87	84.7	83.1	76.52	90.7	85.8	87.5	80.4
5.	2	4	1.0	88.2	86.1	84.1	77.8	90.2	91.5	87.5	83.1
6.	4	6	1.0	90.2	87	85.1	79.42	92.7	87.4	86.5	83
7.	6	2	1.0	82.1	80.2	79.3	72.56	87.1	82.1	81.2	75.2
8.	8	4	1.0	88	85.9	84	77.46	91.6	87.6	85.8	81.1
9.	2	4	1.5	83.8	82	81	74.14	88.6	87.5	83.1	80
10.	4	6	1.5	86.9	84.7	83	76.18	91.2	88.5	85.6	80.2
11.	6	2	1.5	83.1	81.9	80.6	73.5	87.5	85.7	84	78.1
12.	8	4	1.5	83	81.2	80.5	73.36	86.9	85	84.2	80.3
13.	2	4	2.0	84.7	82.3	81.4	74.76	87.7	84.2	83.1	79
14.	4	6	2.0	89.6	83.5	84.6	78.72	92.1	86.3	87.9	81.1
15.	6	2	2.0	86.4	84.4	82.6	75.12	88.2	87	83.5	79.2
16.	8	4	2.0	86.7	84.5	82.9	75.92	90	88.2	86	81.5

Table 3. Comparison of experimental and simulation results at different frequencies for a normal room.

Simulation no.	Location [m] (1st fixed position of the speaker)			Frequencies [Hz] used for experimentation results of SPL in normal room				Frequencies [Hz] used for simulation results of SPL in normal room			
	x	y	z	1000	2000	3000	4000	1000	2000	3000	4000
1.	2	4	0.5	93.2	91.2	88.1	84.7	94.2	92	89.1	86.1
2.	4	6	0.5	88.3	86.1	85.8	80.7	89.2	86.7	86.4	83.1
3.	6	2	0.5	86.8	85.4	84.2	78.1	88.4	83.2	82.1	82
4.	8	4	0.5	90.1	87	86.5	81.2	93.5	89.5	85	84.6
5.	2	4	1.0	91.3	89.6	87.2	82.4	95.1	90.5	87	83.2
6.	4	6	1.0	93.5	90.1	88.5	84.2	94.3	88.4	86.1	81.2
7.	6	2	1.0	85.1	83.2	82.7	77	86.7	85.1	80.2	74
8.	8	4	1.0	91.5	88.7	87.1	82.1	93.9	89.7	87.9	85.1
9.	2	4	1.5	87.2	86.1	83.9	79.5	89.5	86.5	85	82.5
10.	4	6	1.5	90.3	88	86.1	81.4	92.5	88.1	88	83.2
11.	6	2	1.5	86.5	85.1	83.9	79	88	86.9	84	83.1
12.	8	4	1.5	86.7	84.6	84.2	78.6	89.1	84.7	82.1	79
13.	2	4	2.0	87.9	85.2	84.6	80	90.1	84.1	81	80.1
14.	4	6	2.0	93	86.2	88.2	83.2	93.5	88.9	88	85
15.	6	2	2.0	90.1	87.5	85	80.3	92.1	88.1	84.5	81.9
16.	8	4	2.0	89.8	87.1	85.4	81	88.5	86.1	82	81.1

source directivity is a significant factor as an on-axis to the source. The SPL was comparatively found as a continuous varying curve, but SPL values varied considerably for other axes also. At the corners, the variations in the SPL were found maximum due to the higher absorption coefficient variation. As the material absorption coefficient varies at the corner because of the connection of two walls, the sound wave will get interrupted, and a discrepancy occurs. At the corners, the variation in the SPL was significant due to the source's directivity and construction or destruction of interference of waves. The SS location was also found as a significant factor in variation of the SPL behaviour. The SPL dropped for the tested sound frequency range with the increment in frequency. Changing the material in the interiors and surfaces of the room may alter the room's acoustic performance.

The FE model has predicted the SPL effectively and can be employed for the various concert halls, theatres, sports halls, and fictional rooms for the tested frequency range. The computation time has significantly increased for higher frequency ranges. These structures' acoustic performance can be analyzed after evaluating the speed of sound and absorption coefficient of different materials used in interior parts of the room. The application of the FEM in this study provides unique insights into the spatial variation of the SPL at a specific frequency, revealing non-uniformities that may not be captured by simpler models. This study also demonstrates the utility of the FEM in providing detailed spatial and frequency-specific insights into classroom acoustics, which are critical for designing learning environments optimized for speech intelligibility. While harmonic tones serve as a controlled experimental approach, future work should incorporate broader spectra and real-world sound sources to extend these findings. Further investigations incorporating other acoustic parameters, such as RT, STI, C50, etc., may also be considered for a more holistic evaluation. The selection of these frequencies (1000 Hz, 2000 Hz, and 3000 Hz) was based on previous studies emphasizing the importance of mid-to-high frequency bands in determining speech clarity in typical classroom settings. However, including lower frequencies (250 Hz, 500 Hz, and 750 Hz) would provide a more comprehensive understanding of speech intelligibility and can be considered as future work.

The results of this study can help in the design of classrooms and other educational spaces by optimizing sound source placement, material choices, and overall room geometry to enhance speech clarity and reduce acoustic discomfort. By providing both experimental and numerical insights, this study bridges the gap between theory and practical application, offering a more effective approach for achieving acoustically comfortable learning environments. Additionally, the hybrid methodology introduced here can be applied to a wide range of indoor spaces that require acoustic optimization. Future challenges that could be incorporated into the current FE model include modeling of source and boundary properties as well as frequency assessments.

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Declarations

All authors have guidance on competing interests, and none of the authors have any competing interests in the manuscript. All authors have read and approve this version of the article, and due care has been taken to ensure the integrity of the work.

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