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Assessing the Impact of Building Shape on Aircraft Noise Attenuation: Comparison between Geometrical Acoustics Simulation and In-situ Measurements

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Abstract

Analyzing the impact of aircraft noise on urban areas requires specific consideration of sound propagation over long distances, which is not typically covered by tools designed for indoor acoustics. Although it is unclear to what extent existing parametric tools that combine 3D modeling and acoustic simulation can accurately replicate these spatial scales, they provide a valuable means of exploring design options and optimizing performance. One such tool, Pachyderm, a numerical model based on geometrical acoustics, was used to simulate a field lab near Schiphol Airport to assess its applicability for urban acoustics simulation. The simulation results were compared to in-situ measurements, with a focus on differentiating the effect of air noise attenuation based on varying building shapes and the accuracy of the resulting sound pressure level values. The most decisive factors in reducing noise in the courtyard were found to be the building's orientation and slope relative to the sound source. However, as the design complexity increased with the addition of features such as shielding, the accuracy of the simulation results decreased.

Highlights

- The effect of building shape on aircraft noise attenuation is evaluated using both in-situ measurements and numerical models.
- The geometrical acoustics method is used to simulate the propagation of aircraft noise in the courtyard building.
- The differences in sound pressure levels detected at various points within the courtyard is analyzed.

Introduction

Aircraft noise is a major source of nuisance in areas close to airports. Prolonged exposure to severe noise levels not only erodes the quality of such areas, but also the health and wellbeing of people living in such areas (Brown and van Kamp (2017)). To prevent people from living too close to airports, ICAO advocates for the so-called 'balanced approach' (Boucsein et al. (2017)). Besides guidelines related to flight procedures and routing, the balanced approach also includes guidelines for land-use planning and zoning based on noise levels. These noise levels are in most cases based on noise prediction methods such as INM, AEDT and doc.29 (ECAC (2016), Arntzen (2014)). The noise footprint of airports is the summation of all individual flights over a specific period, traditionally based on heuristic data (Arntzen (2014)). To balance computational overhead and accuracy, aircraft noise prediction models omit the built environment. Recent studies have shown that buildings do affect aircraft noise (see e.g. Krimm et al. (2017); Flores et al. (2017)). This can lead to substantial variances in local sound levels depending on the geometry of streets and buildings, and the position of the airplane.

The influence of building shape on sound in street canyons has been studied with various simulation methods, varying from scale models to numerical models. The applicability of numerical models depends on the spatial scale and time constraints (Hornikx (2016)). Wave-based models are normally used for indoor spaces, or to study sound propagation inside a single street, or between a small number of (adjacent) streets. Geometrical acoustical models, based on ray-tracing and image source algorithms, are traditionally used when either the distance between a source and receiver is relatively great, or for mesoscale studies, or for cases in which it is important to study sound dispersion in a three-dimensional setting. Previously, a handful of studies used (geometrical) numerical models to predict aircraft noise levels in street canyons (see e.g. Hao and Kang (2014); Ismail and Oldham (2002)). Most studies have only simulated sound for low-flying aircraft (less than 200m altitude). However, the results were not backed up with measurements, leaving the question of how valid these methods are for real streets. Moreover, most studies used license-based models or models that are not open-source or publicly accessible.

In this paper, the applicability of an open-source geometrical numerical model (Pachyderm) is examined. The study has two objectives, namely, to examine if,

1. the model can be used to compare the acoustical performance of different (urban) designs, based on the shape of buildings,
2. the model accurately predicts the relative differences between shielded and non-shielded receiver positions.

Results from an in-situ experiment are compared with output generated by the computational model. First, the paper presents the research methods, including the in-situ experiment and the computational model. Second, presents the

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Figure 1: Field Lab in Hoofddorp.

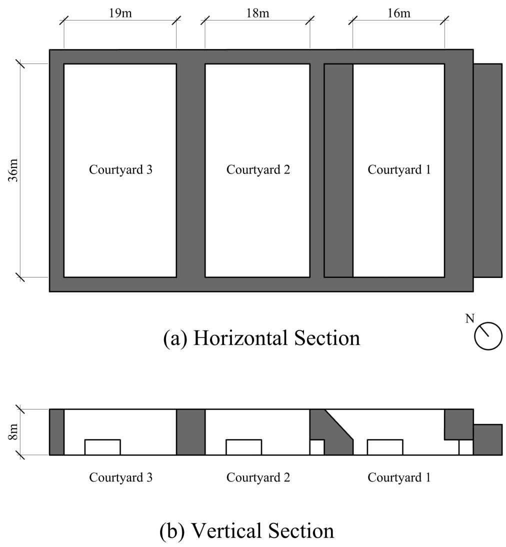

Figure 2: Field Lab configuration.

results of the comparisons made between measurements and simulations. Finally, the conclusions are presented and discussed.

Method

To investigate the effects of building shape on aircraft noise attenuation, the field lab setup is replicated in Pachyderm acoustic simulation setup. However, applying the physical distance between the field lab and the aircraft directly to Pachyderm's spatial scale, which is typically used for room acoustics, may lead to inaccuracies. Therefore, adjustments are made to the modeling to produce more precise results that facilitate a comparative analysis with the in-situ measurements.

In-situ Measurements in Field Lab

Field lab environment

The field lab, as shown in Figure 1, is located near Amsterdam Airport Schiphol, specifically close to a flight path frequently used for departures in the south-western direction. The lab comprises three courtyards surrounded by three-storey building blocks made of stacked shipping containers on concrete block paving. Each courtyard represents a distinct building form, as illustrated in the section of Figure 2. Courtyard 3 features a building with a straight wall, courtyard 2 has a building with an inset wall, and courtyard 1 has a building with an inset and slanted wall. A total of ten microphones are mounted on the facades, facing either towards or away from the nearby flight path. This setup allows for an analysis of how building and street designs impact the propagation of aircraft noise.

Receiver points based on building shape

The positions of the microphones are shown in Figure 3. Receiver point 4 and 8 face the sound source, whereas receiver point 1, 2, 3, 5, 6, and 7 are located on the opposite side of the sound source. The receiver points are placed each 1.5 meters above the ground surface, except for microphone 2 and 6 which are each 3.9 meters above the ground surface. Class II microphones (NP2 series) were used, equipped with a porous water repellent windscreen, and the acoustic data was stored as WAV files on a flash drive on site and remotely on a cloud server through 4G. Sound Pressure Level (SPL) in third octave bands were recorded every 0.125 seconds and uploaded to the cloud server with a time stamp linked to a clock at the server.

Processing Benchmark flights

The sound source points were set up by recording the sound levels around the probe continuously, which were matched with radar data from the airport and meteorological data from a weather mast at the airport, managed by the Dutch Met Office (KNMI). For the analysis of the in situ measurements, only flyovers recorded at hours during which the average wind speed was 0 m/s were selected for further analysis, resulting in a subset of 32 flyovers that flew past the test site between November 2021 and March 2023. The final benchmark route consisted of the three flyovers corresponding to the mean (M), first (Q1), and third (Q3) quartiles of the dataset. For each flyover, a point with the maximum SPL was selected, and the xyz coordinate system was used as the data point. These data points are shown in Figure 4.

Numerical Model (Geometrical Acoustics)

Pachyderm Acoustic Simulation

Pachyderm Acoustic is a software based on geometrical acoustics, developed by Arthur van der Harten since 2008. The software is available as a plugin for Rhinoceros 3D and Grasshopper 3D. This study utilized Grasshopper, a parametric modeling tool that is suitable for processing multiple data points and modifying shape parameters. Additional information about the software and its installation can be found in Food4Rhino (van der Harten (2020)). The workflow of Pachyderm simulation involves specifying the receiver and source positions and setting param-

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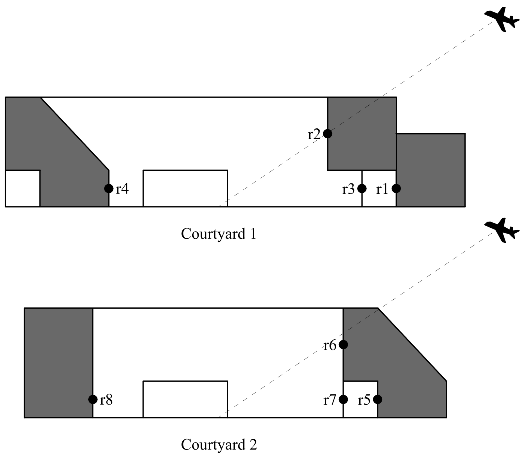

Figure 3: Receiver Positions.

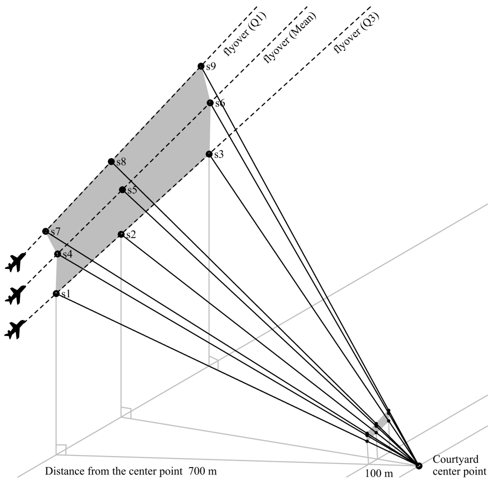

Figure 4: Source Positions.

eters, such as sound power level and material properties, according to the purpose of the model. Next, a combination of direct source, image source, and ray tracing components is used to calculate results such as reverberation time and SPL.

The ray tracing algorithm in Pachyderm Acoustic casts rays in all directions from a point in space and traces the energy of many paths that sound may take from the source to the receiver. Each ray is split into its constituent parts of specularly reflected energy, scattered energy, and transmitted energy every time it encounters a surface, as shown in the following equation:

$$I_0 = I_{specular} + I_{scattered} + I_{transmitted} \qquad (1)$$

$I_0$is the intensity (energy) of the ray after reflection, and its intensity of the ray decreases with number of bounces. Reflection tree that is sampled by the algorithm results in the end nodes, that is final intensity of ray I that is detected by the receiver point. The intensity of the specularly reflected ray, represented by $I_{specular}$, is calculated using the following equation:

$$I_{specular} = I_{incident} * (1-\alpha) * (1-\tau) * (1-s) \qquad (2)$$

Here, $I_{incident}$ is the intensity of a ray incident on a surface, a is the absorption coefficient, t is the transmission coefficient, and s is the scattering coefficient. The incident angle of the ray and the material properties of the surface are the primary factors determining sound attenuation in the ray tracing method.

A Monte Carlo method is used in Pachyderm Acoustic, where the amount of wavefront represented by a ray is proportional to the number of rays being cast (van der Harten (2022). A large enough sample size with many rays yields relatively small amounts of error. In this study, the spatial scale of the model is large, but the area of the surface where the ray hits is relatively small. Even if the number of rays is increased exponentially, the computing load required for modeling becomes irrelevant. Therefore, the ray tracing method is an efficient modeling technique for distinguishing the difference between receiver points.

Simulation Model Settings

The study's input parameters are presented in Table 1. To ensure stable results across all receivers and maintain reasonable simulation time, the number of rays was set at 1+E8. For the sound power level of the sound source, an estimated value of approximately 140 dB (flat over octave frequency) was used for the noise outside the aircraft engine during takeoff. The environmental factor is set to follow Pachyderm's default settings. The material properties for the shipping container and concrete block were obtained from the absorption coefficient used in a previous study conducted by Christensen (2002).

The receiver points were positioned at the same locations as the microphone positions depicted in Figure 3. Any rays passing within one meter of a receiver point are recorded in Pachyderm, along with the time of arrival and sound power. The power embodied in the ray at a given point in time is attenuated based on the air absorption coefficient, as calculated in ISO standard 9613-1, and weighted according to the proximity of the ray to the actual receive point.

The sound source positions in Pachyderm correspond to the data points for aircraft noise used in the in-situ measurements. However, accounting for the actual distance between the source and receiver, which is approximately 700 meters as shown in Figure 4, would cause the ray to take a significant amount of time to reach the receiver. Since Pachyderm has a cutoff time limit of 15000 ms, which is typical of software primarily used for room acoustics, the ray may not arrive at the receiver within this time frame, making it impossible to measure the SPL. Therefore, it is necessary to control the distance between the source and receiver. However, changing the distance while maintaining the elevation angle between the sound source and receiver affects the sensitivity to the same sound between the receiver points, as illustrated in Figure 5. Receiver 4, which faces the sound source, maintains

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Table 1: Input Parameters

Simulation Parameter			
Number of Source Points		9	
Number of Receiver points		8	
Number of Bounces		1	
Number of Rays		1E+8	
Distance Source, Receiver		100 m	
Cutoff Time		15000 ms	
Sound Power Level		140 dB	
Environmental Factors			
Air Temperature		20 °C	
Relative Humidity		50 %	
Static Air Pressure		1000 hPa	
Material Property			
		Concrete	Steel
Absorption Coefficient	63 Hz	0.36	0.05
	125 Hz	0.36	0.05
	250 Hz	0.44	0.05
	500 Hz	0.31	0.05
	1 kHz	0.29	0.06
	2 kHz	0.39	0.04
	4 kHz	0.25	0.02
	8 kHz	0.82	0.02

a constant SPL difference from receivers 1 and 3, which are not facing the source. Receiver 2, located at a relatively high position, fluctuates depending on the source's position. As the purpose of this study is to obtain the relative SPL difference between the receiver points, the sound source was placed at the 100-meter distance point where the differences between the receiver points are noticeable.

Data Comparison Protocol

In the study, eight receiver points were utilized to measure the SPL at nine source points, resulting in a total of 72 data points. The SPL measurements were obtained across a broadband spectrum and the results were reported in A-weighted sound level (dBA), which offers an overall representation of the sound level across the entire frequency range. The comparison dataset consisted of in-situ measurements for courtyard 1 and 2, as well as simulation data for courtyard 1 and 2, resulting in four sets of data for analysis.

The comparison in this study was made based on the SPL difference between receiver positions within the courtyard, instead of using the absolute SPL for each receiver position. This is because the way the sound source is set up in in-situ measurements differs from simulation results. In in-situ measurements, the sound power level of the aircraft at the time of measurement is unknown, so only the sound source positions are matched with radar and meteorological data. Due to this uncertain factor, a flat spectrum for the sound power level 140 dB was used for all

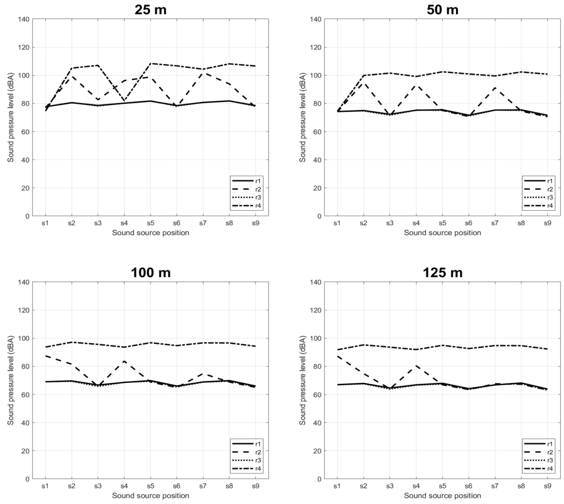

Figure 5: Distance between receiver and source.

sound source positions in the simulation. There is another inconsistency in how the sound source is modeled. Aircraft flyovers are fast-moving point sources, whereas in simulation, the sound sources are set to be discrete omni-spherically emitting monopoles. When sound waves are in motion, the relative movement between the source and the observer generates the Doppler effect, which causes a shift in frequency that is observed by the receiver. Results from the simulation model, where all sound sources are stationary relative to the receiver, are not filtered or corrected for Doppler, which was seen as an a priori shortcoming of the method in this article. Hence, aside from A-weighted results, data was also compared for two octave bands (250Hz and 1000Hz), and these results are included in the appendix of this paper.

Results

Effect of Direct Sound

Figure 6(a) illustrates the average SPL value at the source location in courtyard 1. A comparison between in-situ measurements and simulation results revealed that the simulation results had a considerably larger error bar, indicating a a significantly larger variance around the mean. By examining the maximum error bar ranges, it could be observed that the in-situ measurements have an error bar range of 10 dB(A) at source position 8, while the simulation results have a range of up to 28 dB(A) at source position 3.

SPL for each receiver point is plotted in Figur 6(b). The simulation results have shown that the SPL at receiver 4 is considerably higher than that at receivers 1, 2, and 3. This observation implies that at receiver 4, direct sound is being detected. Generally, direct sound has a higher SPL than reflected sound because it travels straight from the sound source to the receiver without being dispersed or absorbed by obstacles or surfaces.

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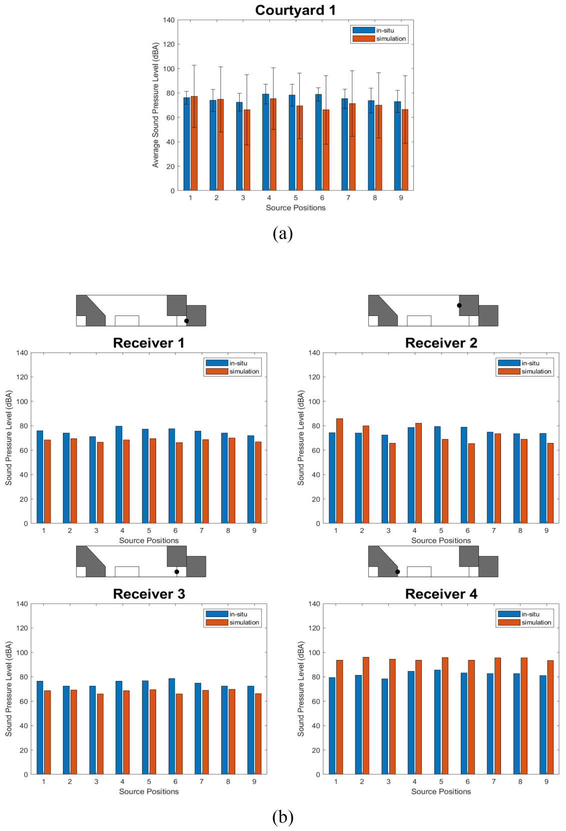

Figure 6: SPL Courtyard 1 (dBA).

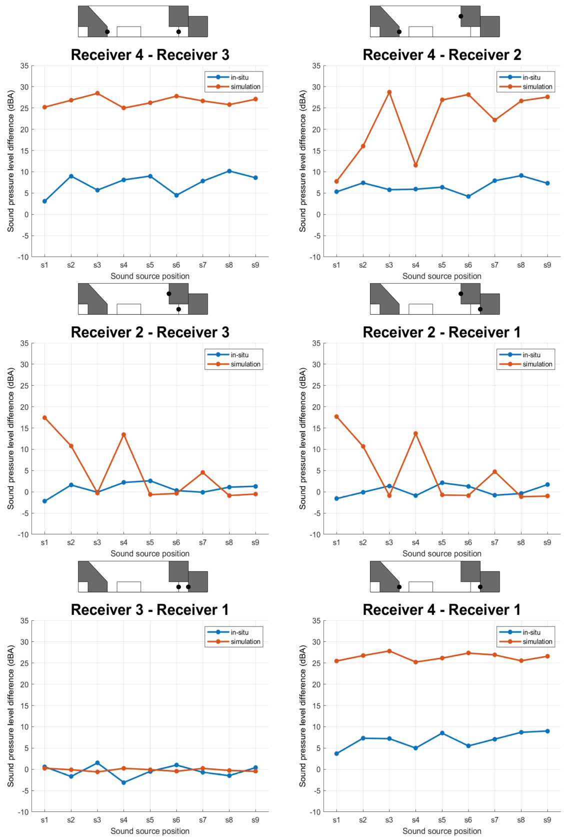

Figure 8: Difference in SPL Courtyard 1 (dBA).

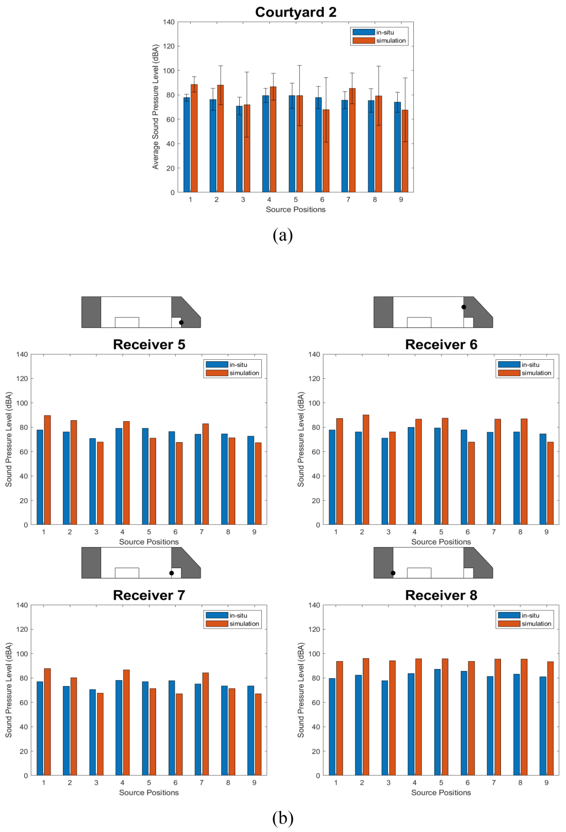

Figure 7: SPL Courtyard 2 (dBA).

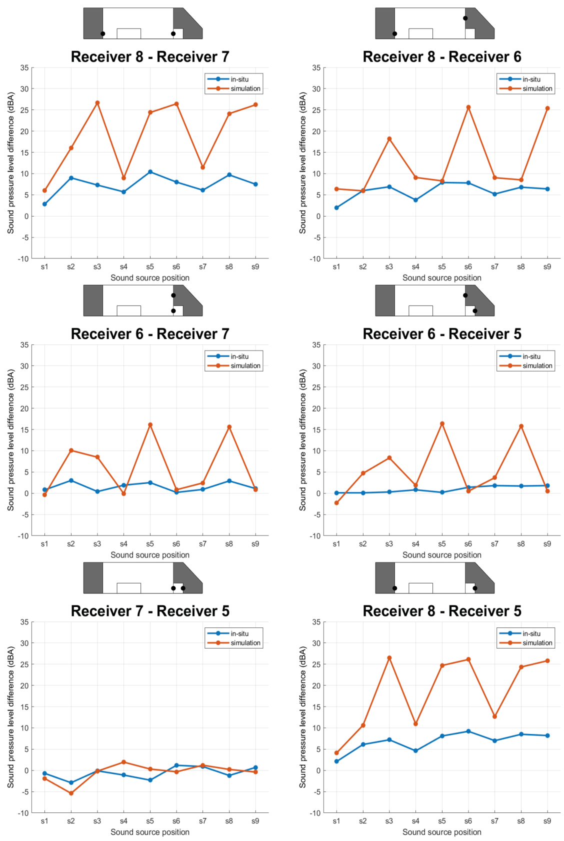

Figure 9: Difference in SPL Courtyard 2 (dBA).

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Effect of Slanted Roof in Courtyard

The effect of a slanted roof in a courtyard could be observed by comparing the SPL at different points in courtyards with slanted and without slanted walls (straight walls). The results of the SPL of receivers 1,2,3,4 in Courtyard 1 and receivers 5,6,7,8 in Courtyard 2 are shown in 6(b) and Figure 7, respectively.

The results from both in-situ measurements and simulations indicated that the largest difference in SPL value was observed at receiver 2 in Courtyard 1 and receiver 6 in Courtyard 2. Receiver 2 was located opposite to the slanted wall, while receiver 6 was located opposite to the straight wall. The lower SPL value at receiver 2 suggests that noise entering the courtyard was reflected by the slanted wall, resulting in attenuation of the sound at the opposite building facade.

The simulation results showed an average difference of 17 dB(A) between the courtyards, indicating that the slant angle of the building significantly influenced the sound distribution in the courtyard. Moreover, the ray tracing method, which uses specular reflection in the algorithm, proved to be sensitive in detecting the effect of the slanted roof.

Effect of Building Shape

The building shape's effect was assessed by comparing different receiver points within the courtyard, each representing distinct building shape characteristics. Figure 8 compares the SPL between the four points of Courtyard 1, while Figure 9 compares the SPL between the four points of Courtyard 2. Receivers 4 and 3 differ in their orientation to the direct source, while receivers 2 and 3 differ in their elevation relative to the ground. Receiver 3 and 1 differ in how far they are inset from the reference plane.

The differences in SPL between the receivers demonstrate the impact of design variables like "facing" "elevated," and "inset" on sound attenuation. The differences between receiver 4 and 1 demonstrate the mixed effects of "facing" and "inset", the differences between receiver 2 and 1 indicate "elevated" and "inset," and the differences between receiver 4 and 2 show "facing" and "elevated" sound attenuation.

To determine which design variable has the most significant effect on sound attenuation, the difference in SPL values between receiver points were added and plotted on a radar chart in Figure 10. While the simulation results yielded higher absolute SPL values compared to in-situ measurements, it produced the same results for identifying the design variable with the most significant effect. The analysis shows that facing a sound source is the most decisive factor in sound attenuation, followed by the height difference and inset degree. The results also suggest that height difference and inset degree have a similarly less influential effect.

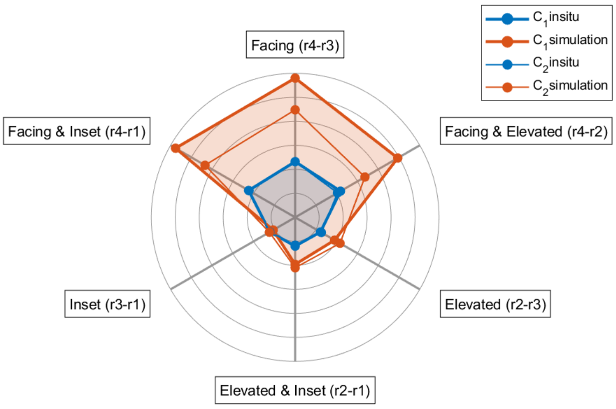

Figure 10: Noise attenuation effect of design variables.

Conclusions and Discussion

Aircraft noise prediction models typically do not consider the impact of buildings, particularly the effect of building shape on aircraft noise attenuation at a local level. This study presents a methodology that uses both in-situ measurements and a numerical model to establish the correlation between building shape and aircraft noise.

The study assesses the applicability of the geometrical acoustics simulation tool for two purposes: (1) evaluating the acoustic performance of different building shapes in urban designs, and (2) accurately predicting the relative differences between shielded and non-shielded receiver positions. The results indicate the following:

1. The simulation tool shows a clear difference in SPL between receiver points with different building shapes, consistent with in-situ measurements. It was observed that different building shapes in the courtyard had a mutual effect on noise attenuation. Specifically, the slanted roof facing the sound source reflects the sound towards the courtyard, reducing noise, particularly on the façade opposite the slanted roof.
2. However, the simulation tool tends to underestimate SPL values for shielded areas. These areas are characterized by receiver points that face away from the sound source and are either inset or elevated. The receiver points in shielded areas exhibited discrepancies in both dB(A) and SPL for two analyzed frequencies when compared to other parts of the courtyard. These discrepancies can be attributed to the limitations of geometrical acoustics modeling. While geometrical acoustics modeling effectively captures ray-conforming attributes such as direct sound and specular reflection, it falls short in accurately representing non-geometric wave behaviors, such as edge diffraction. The omission of accounting for edge diffraction in the simulation is expected to have resulted in the underestimation of the detected SPL in the shielded areas.

This study examines the direct relationship between an aircraft (sound source) and a courtyard building (receiver), without modeling the surrounding urban context. By creating this controlled environment, we can assess the im-

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pact of different flight altitudes and horizontal flight paths on the propagation of aircraft noise within the courtyard. However, due to the considerable distance between the source and receiver, the rays take longer to reach the courtyard, which reduces the receiver's sensitivity to the sound source. To address this limitation, we moved the source to a distance of 100 meters from the receiver while maintaining the same slant angle. This approach revealed a need for future research: determining the correction factor for SPL when it is moved closer to the field lab. A better identification of the aircraft sound source (sound power level along frequencies, accounting for the Doppler Effect) will improve the simulation model and add validity to the absolute SPL values of the simulation results. This, in turn, will enable further research into the effects of distant sound sources on sound propagation in local areas.

Acknowledgment

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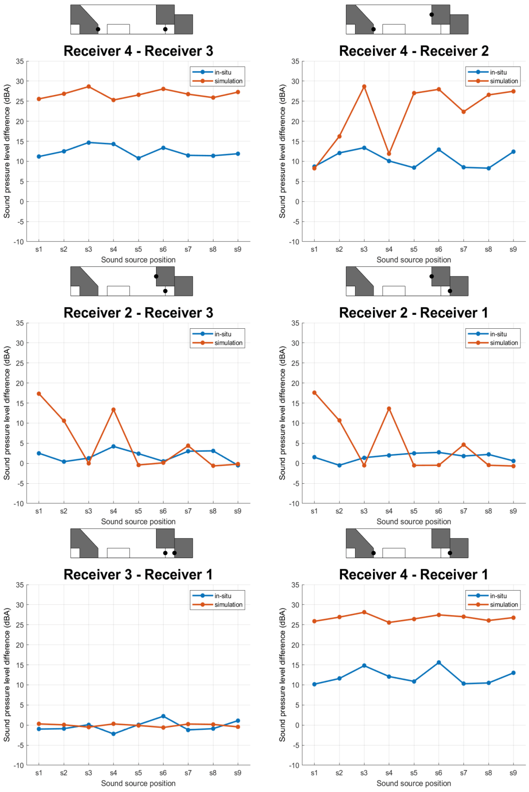
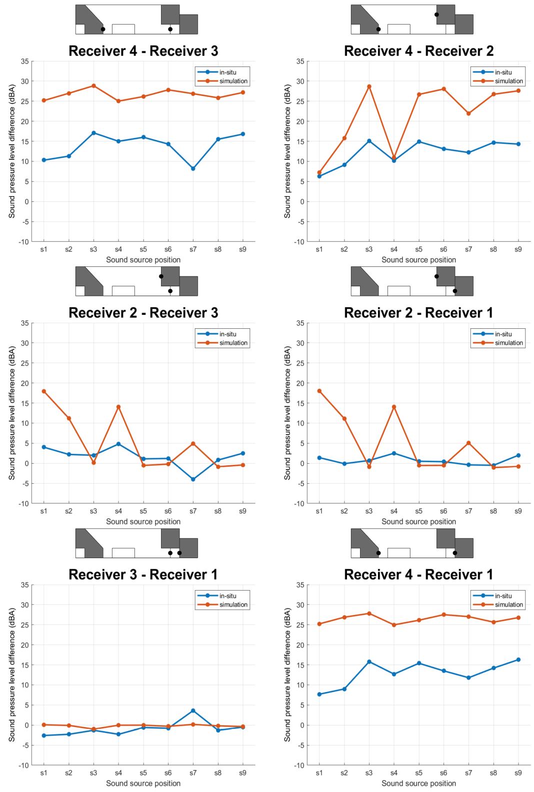
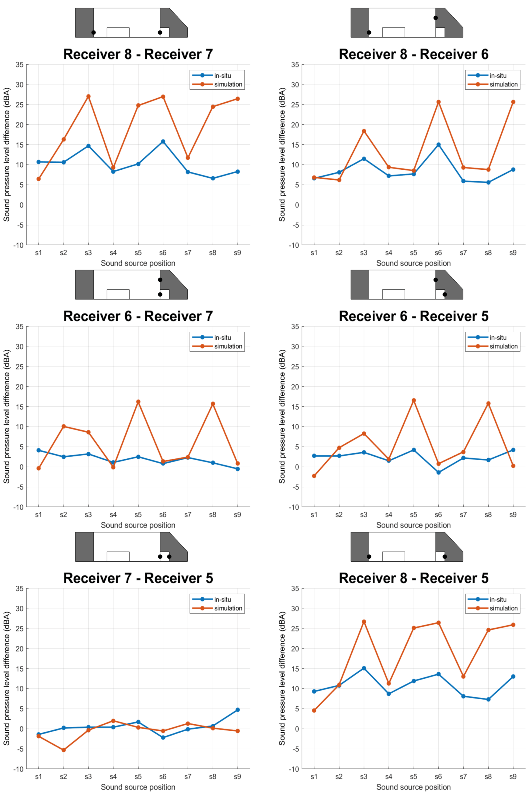
Appendix A



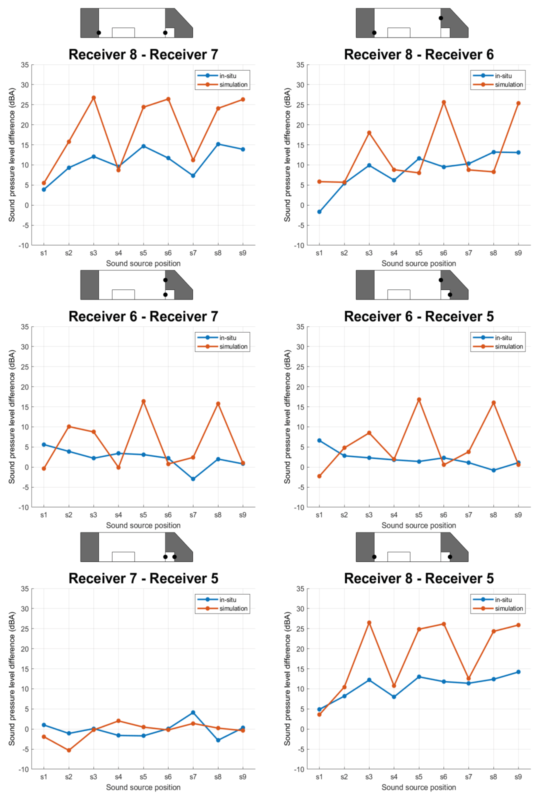
(a) Difference in SPL Courtyard 1 (250Hz).



(b) Difference in SPL Courtyard 1 (1000Hz).



(c) Difference in SPL Courtyard 2 (250Hz).



(d) Difference in SPL Courtyard 2 (1000Hz).

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