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ORIGINAL PAPER

A Case Study of the Influence of Urban Morphology on Aircraft Noise

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Abstract Aircraft noise is a very important environmental problem that has been addressed in many ways over the years. Many strategies have been developed to mitigate aircraft noise exposure. To help identify the problem, computer simulations with mathematical models for aircraft noise have been developed. However, those models do not consider urban morphology effects on aircraft noise propagation. Urban morphology contains a set of features that modify noise, and it is necessary to be aware of its effects as it can be a factor that can potentially increase sound pressure levels to which the general population is exposed. This paper evaluates different aspects of urban morphology and determines the impact of street topologies, line of sight angles of buildings, façade positions, façade heights, and the combination of street topologies and LOS angles on aircraft noise. Measurements in front of the façade and in free field conditions were performed around buildings that make up educational facilities near Madrid Adolfo Suárez Barajas and Pisa Galileo Galilei airports. With the experimental work, it was demonstrated that front façades, U topologies, and greater LOS angles result in higher levels on façade as all these factors contribute to the transmission of noise in an urban environment. Correction factors for measurements made in façades with and without direct transmission with similar surroundings to the ones measured in this study and within a 95% confidence level were proposed for extrapolating the levels of aircraft noise events in free field conditions.

Keywords Aircraft noise · Urban morphology · LOS · Façade

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1 Introduction

Aircraft noise is a very important problem for health and the environment. It can cause annoyance, sleep disturbance, low work performance, irritability, and other health effects [1]. ICAO with its balanced approach proposes guidelines with different levels of action for mitigating aircraft noise [2]. Buildings have been soundproofed, airports have developed a system of fees against carriers that do not fulfill the noise emission curfews established by the authorities, and several maneuvers for landing and taking off have been established to reduce the aircraft noise levels in communities near airports [3].

The balanced approach states that an important part to mitigate aircraft noise is to identify the problem at the airport. Aircraft noise models help understanding the problem by assessing the evolution of noise climate at the airport and its surroundings according to statistical data. They predict aircraft noise emissions for regions close to an airport by calculating the noise contours produced. The predictions of aircraft noise models are based on two different approaches; one of them is based on the shortest distance between the aircraft and the assessment point. The second approach is based on calculations of noise exposure units around an airport at any point of noise control. Some examples of aircraft noise modeling tools are FLULA2 and AEDT 2b, which simulate aircraft performance in space and time to predict noise contours basing their calculations on the first and second approaches respectively [4,5]. However, both models only calculate sound pressure levels produced in free field conditions without considering buildings. According to Attenborough et al. [6], buildings can block the direct transmission of sound, the edges can cause diffraction effects on noise, and reflections can be present. However, in an urban area buildings are surrounded by streets, and other features that altogether as a whole modify noise levels. In the surroundings of an urban environment, features like buildings, streets and parks contribute to the modification of aircraft noise levels, and they make up urban morphology [7].

Urban morphology intervenes in the transmission of sound by modifying its levels. Studies demonstrate that in urban areas many factors modify the sound pressure levels of noise sources. An example of how urban morphology changes noise levels can be found in an experiment done by Ariza-Villaverde et al. [8]. They analyzed the influence of urban morphology on the total noise pollution. It was determined that in urban areas in which the spatial distribution was regular, a positive correlation could be found between the building height, street width and the noise pollution. Through the analyses performed to these variables, it was determined that they have an influence on noise propagation. Urban morphology has different effects on noise propagation depending on the type of noise source. Road traffic noise has been widely studied along with its cross relations with urban morphology. Oliveira and Silva [9] did a study in which a relationship between different building configurations and road traffic noise propagation was found. It was demonstrated that traffic noise levels diminish with greater heights of buildings. The influence of urban shape, construction density, the existence of open spaces and the shape and physical position of buildings on road traffic noise was studied by Guedes et al. [10,11]. It was demonstrated that cities have features that concentrate or disperse road traffic noise. Traffic noise was simulated in two cities with different densities by Wang and Kang [12]. They concluded that streets from different cities with diverse features influence noise attenuation before reaching a façade. All these studies demonstrate that buildings altogether with their configuration affect traffic noise propagation.

The influence of urban morphology on traffic noise has been investigated and all the previous studies mentioned demonstrate that the urban forms modify sound pressure levels produced by traffic. Aircraft noise is also affected by urban morphology, but its propagation differs from that of traffic noise as the source is elevated and the distance from source to receiver is larger than that of traffic noise. Some investigations show the influence of certain features of urban areas on aircraft noise. Pande and Lyon [13] demonstrated the shielding and amplifying effects of buildings as well as their contribution toward aircraft noise reverberation. Donavan [14] made an experiment in which he demonstrated the impact of urban geometry on aircraft noise and the amplification effects on its sound pressure levels.

Given the relevance of aircraft noise, standards have been developed to further study its propagation. The standard ISO 20906 states the configurations with which measurements must be performed in places with aircraft noise exposure [15]. These measurements help determining general noise levels of aircraft noise in communities near airports and in building noise maps.

Retrieving levels in free field conditions is not always possible because there are reflecting surfaces that modify the levels measured. Standard ISO 1996-2 helps determining aircraft noise levels in free field conditions through extrapolation. This standard enunciates the amplification that will be obtained in front of a reflecting surface with a noise source of the linear type [16].

The urban morphology within a city contributes to the shielding and amplifying effects of noise. Another configuration of buildings in urban areas is a street canyon. A street canyon, or U-shaped street, can modify the sound pressure levels of a noise source due to a variety of wave phenomena that take place during noise propagation [17]. These streets are a common feature in urban areas and noise behavior through them has been modeled to determine its impact on sound pressure levels [18].

Another characteristic of noise propagation is the line of sight. The line of sight (LOS) refers to a direct propagation path from source to receiver. However, along the propagation path there will be obstacles acting as barriers which will reduce the line of sight. Noise reductions are present when a barrier is located between source and receiver. Its effectiveness depends on its acoustic properties and on how far beyond the line of sight the receiver lies [19]. An example of the influence of line of sight on aircraft noise can be seen in an experiment by Lugten et al. [20], in which measurements were performed near an airport in façades with and without direct transmission in buildings located 700 m away from the runway. Through the results of this experiment, it was determined that during takeoffs and landings, buildings cause high attenuations as the direct transmission is obstructed.

Flights with their configuration and setups can modify the levels on façade. In a study by Hao and Kang [21], computer simulations determined that the shielding effects of buildings are reduced with higher altitudes. Therefore, aircraft noise is not only modified by urban morphology. Flights with their different altitudes, trajectories and distances modify the levels measured on façade.

Certain features present in an urban environment such as U or L topologies, LOS angles and façade positions modify aircraft noise levels. The goal of this investigation is to determine whether street topologies at distance from flight paths and directly overhead, heights from the ground, and line of sight angles affect the average façade levels of aircraft noise and to propose correction factors for front and back façades that can help extrapolating aircraft noise levels in free field conditions.

2 Methodology

Measurements were performed in schools located near Madrid Adolfo Suárez Barajas airport and a library in Pisa near the airport Galileo Galilei. Both airports have daily traffic that leads to noise exposure of the general population living nearby and noise action plans have been made to mitigate aircraft noise [22,23]. All the measurements were performed outside, near the schools and the library mentioned. The choice of considering these types of buildings is motivated by their geographical position with respect to flight paths as well as by their shapes and configurations in space (i.e., street topologies, line of sight angles and façade positions), which reflect those sought for the purpose of the present work. Furthermore, getting the permissions to carry out the measurements in these particular locations was easier due to a higher interest of the decision-makers in evaluating noise-sensitive receivers' exposure.

It must be highlighted that aircraft noise may vary due to both operational and meteorological parameters affecting flight settings and aircraft performances even considering the same aircraft models. As a consequence, each event has a set of features that could cause fluctuations in the measured noise levels adding dispersion. Each flyover has its own flight path and altitude; in order to minimize all these effects, measurements in free field conditions were also performed and were considered as a reference.

In fact, a reference noise-level value is necessary to determine any significant differences among the sound levels measured on the different façades. The fluctuations related to these levels, in particular the difference between the sound level recorded on the reference and the sound level measured on each façade, are mainly due to wave phenomena (reflection, absorption and diffraction) taking place during noise propagation. Noise emission and propagation of an aircraft can also vary due to its own operational settings and meteorological issues, but the difference between the noise level measured in the reference point and that measured in the façade point can be considered independent of these variations. In order to study deeply this situation and to understand how they affect the results, two possibilities for reference values were considered: One was a microphone that measured sound pressure levels of each event in free field conditions, and the other consisted on an average façade noise level calculated from the events measured on façade per building. Both possibilities determined a difference of levels, but each one evaluated a different variation. One evaluated the variations between free field and on façade positions while separating the influence of each aircraft and flight. The other just evaluated the variation of levels in façade with the mean value of all events measured on each building as a reference without separating the variability introduced by flights.

The surroundings of the places on which measurements were performed were very similar. The schools and the library were located inside the cities. All those complexes had a playground and sometimes they consisted on more than one building. On the U topologies measured, it was found that the distances between the façades that formed them were 7–8 and 20 m. The widths of 7–8 m were found in buildings within the same complex, whereas the one of 20 m was found between buildings of the complexes under study and buildings located outside. The altitudes of the flight paths over the schools were between 700 and 1140 m and those of the library were of 500 m, but with smaller horizontal distances, which caused higher elevation angles. In some of the schools, there were façades that had plastic canopies, which influenced the line of sight angles to flight paths. However, façades with elements that influenced line of sight angles were discarded.

$L_{eq,A,1s}$ of each event was measured simultaneously with three microphones. Two of them were located at different heights on façade and the other one measured levels in free field conditions, as seen on Fig. 1. It can be noted from Fig. 1 that the microphones on façade are prone to be affected by reflections with the walls on which measurements are performed.

All the events measured in Madrid were compared to B&K's Adolfo Suárez Madrid Barajas airport Webtrak application, which allowed visualizing events and their flight paths. Once the events were identified, the single event level $L_{E,A}$ was calculated for each aircraft event according to the criteria stated in ISO 20906, which states that events must be discriminated from background noise with a 10 dBA difference from the peak level as seen on Fig. 2. While performing

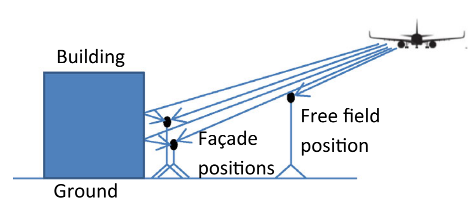

Fig. 1 Reference position in free field conditions

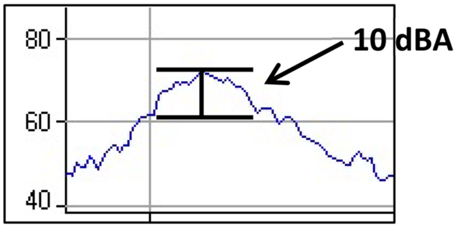

Fig. 2 Example of an aircraft event measured and the selection of a 10 dBA decay

the measurements, notes were taken on background noise so that events from other sources could be ignored.

For quantifying the impact of urban morphology on aircraft noise, two analyses were performed. One of them was a façade noise variations analysis. To determine how noise changed on façade, two variables were defined: $L_{E,AB_x\text{average}}$ and $\Delta L_{E,\text{Afaçadej}}$. $L_{E,AB_x\text{average}}$ is the mean value of façade SEL values in the xth building as defined on Eq. 1. Where n is the total number of events during the measurements carried out in the xth building. $\Delta L_{E,\text{Afaçadej}}$, as shown on Eq. 2, is the difference between $L_{E,AB_x\text{average}}$ and $L_{E,\text{Afaçadej}}$, which are the mean value of SEL data measured on façade in the xth building and the SEL of the jth event measured on façade, respectively.

$$L_{E,AB_x average} = \frac{\sum_i^n L_{E,\text{Afaçadej}}}{n} \quad (1)$$

$$\Delta L_{E,\text{Afaçadej}} = L_{E,AB_x\text{average}} - L_{E,\text{Afaçadej}} \quad (2)$$

The analysis was performed according to the following variables:

– LOS angle: The angles between the flight path and the lines described by every façade under assessment were defined to quantify the direct exposure.
– Height: The outdoor noise propagation was evaluated at certain heights to determine how noise behaved at different distances from the ground.
– U or L topology: A U topology refers to a street located between two buildings within a maximum space of 20m, whereas an L topology refers to a street by the side of a building.
– Front and back façades: Front façades are those in which the slant distance is free of obstacles and back façades are those in which obstacles are present at the slant distance.
– LOS angle and street topology: Street topologies modify sound pressure levels by inducing reflections and other wave phenomena, they also imply greater LOS. The greater the LOS is, the higher the sound pressure levels are expected to be as a greater fraction of the flight path will be in direct transmission.

The other analysis performed consisted on an evaluation of the free field variations of SEL values measured in façade. The differences between free field SEL values and on façade SEL values were determined for front and back façades, a correction factor that could help extrapolating the free field conditions SEL values from the SEL noise events measured on façade was determined. To determine the difference between free field and façade measurements, a parameter called ΔL_{Ej} was calculated. As shown on Eq. 3, ΔL_{Ej} is the arithmetic difference of $L_{E,Aj}$, the free field SEL value of the jth event, minus $L_{E,\text{Afaçadej}}$, which is the SEL value measured in façade of the jth event.

$$\Delta L_{Ej} = L_{E,Aj} - L_{E,\text{Afaçadej}} \quad (3)$$

3 Experimental Setup

Adolfo Suárez Madrid-Barajas Airport is located on the outskirts of Madrid with many suburbs surrounding it. Coslada and Mejorada del Campo are two of the most affected cities by aircraft noise, mainly landings. Therefore, those sites were selected as appropriate for collecting samples of aircraft noise events. With permissions from the authorities of each city, five schools were analyzed, being one from Coslada and the other four from Mejorada del Campo. In Pisa, Italy, all measurements were performed in a library located nearby to the Airport Galileo Galilei as seen on Fig. 3.

The façade measurements were performed with two microphones at different heights which were 1.5 m and the other ranged from 4.0 to 6.6 m from the ground. For Madrid, B&K 2260 and 2250 were used with half inch microphones for free field and on façade measurements respectively, and in Pisa Solo 01dB were used for both free field and on façade measurements, being all of them type 1 certified sound level meters. The microphones had their outdoor kits and windscreens. The A-weighted equivalent continuous sound pressure level $L_{eq,A,1s}$ was measured for façade and free field conditions measurements.

Different trajectories were measured in all cities. For the flight paths of Madrid, the application Webtrak of Brüel and Kjaer was used to retrieve the information of trajectories. Tracking information related to flight movements of Pisa airport was obtained by means of ADS-B data signals emitted by the aircraft's transponder. On Figs. 4, 5, and 6 the most frequent flight paths measured are shown for Coslada, Mejorada del Campo and Pisa, respectively. In the case of sites 2 and 3, the most frequent flight path passed near both locations, but on different days, which was noted while retrieving the flight information from Webtrak. The measurements were performed in a period of four months. During the measurement sessions, the mean temperature and wind speed of Madrid were 16.4 °C and 1.9 m/s and those of Pisa were 12° C and 2.7 m/s. The geo-coordinates of all sites are shown on Table 1.

Fig. 3 Location of airports Adolfo Suárez Madrid-Barajas and Galileo Galilei

Fig. 4 Flight path of site at Coslada

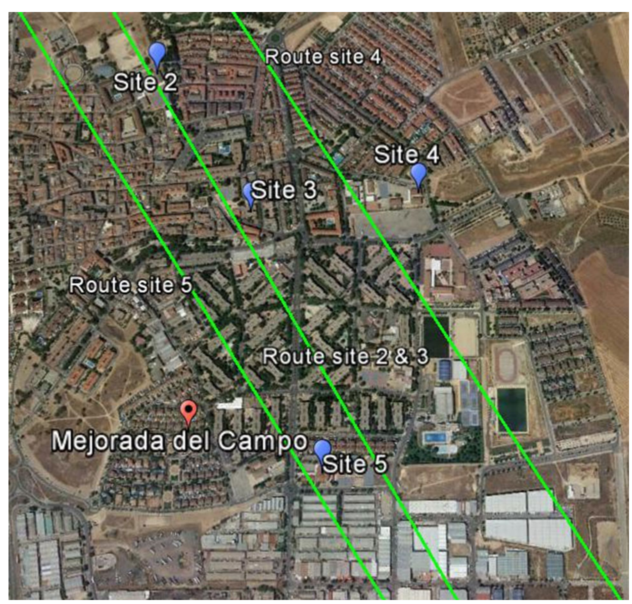

Fig. 5 Flight paths for each site at Mejorada del campo

Fig. 6 Flight paths for site at Pisa

Table 1 Geo-coordinates of measurement sites

Site	Geo-coordinates
1	40°26′15.47″N; 3°31′53.90″W
2	40°23′59.09″N; 3°29′18.35″W
3	40°23′47.02″N; 3°29′7.52″W
4	40°23′47.87″N; 3°28′51.57″W
5	40°23′26.16″N; 3°28′58.44″W
6	43°42′22.47″N; 10°25′5.43″E

The line of sight angles were classified from the information retrieved about flight trajectories. Each trajectory formed an angle with the line described by the façade, and it was expressed with a resolution of the degrees measured. Seven line of sight angles were measured, and data were grouped in clusters of the angles shown on Fig. 7.

The black dot represents the microphone position on façade and the green lines represent different flight paths. For the case of Madrid, the flights were landings and those of Pisa were takeoffs. From Fig. 7, we can consider the angles greater than 45° as angles of front façades and the ones lower than 45° as those of back façades. A greater line of sight angle means that there will be a greater fraction of the flight path in direct exposure to the aircraft noise event. But noise incidence can change if there are other features of flight paths that modify noise incidence like the elevation angle. As seen on Fig. 8, the elevation angle is formed by the horizontal distance to the aircraft and the vertical of the microphone to the flight path. When the aircraft flies over an L topology near the vertical of the microphone, the horizontal distance from the microphone to the flight path is reduced and the elevation angle gets close to 90°.

In the U topology, there are flight paths with an elevation angle close to 90°. But the obstruction caused by the building in front of the façade reduces the LOS angle. In the U topologies measured, most buildings were located at distances of 7–8 and 20 m. For the first range of distances, the angle formed is 45° and for distances up to 20 m, the LOS angle is 60°.

From Figs. 8 and 9, we can consider that the line of sight angle depends on features like building orientation, and in

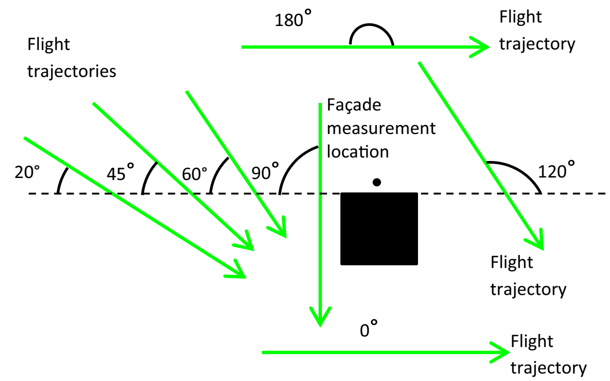

Fig. 7 Classification of LOS angles

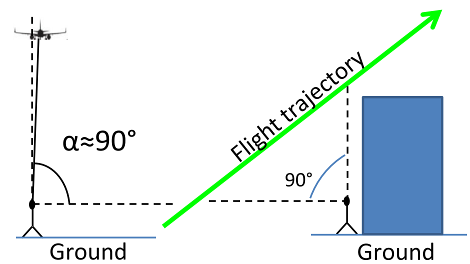

Fig. 8 Elevation angle close to 90°

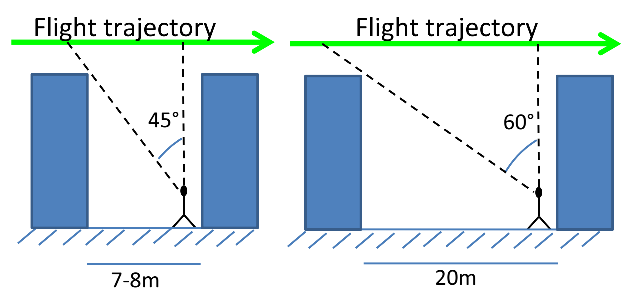

Fig. 9 U topologies with elevation angles close to 90°

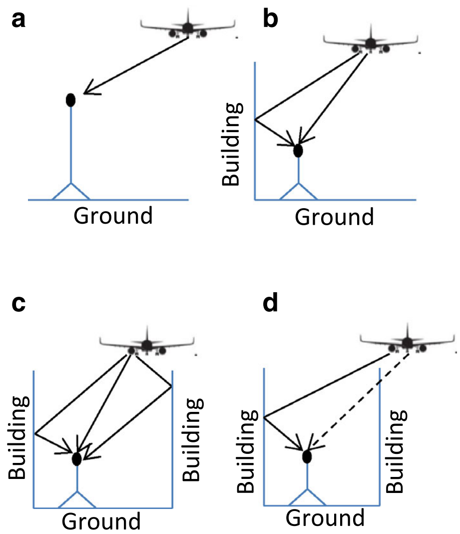

Fig. 10 Aircraft noise transmissions in different conditions. **a** Free field conditions. **b** L topology. **c** U topology direct transmission. **d** U topology indirect transmission

the case of a street canyon, on its width. However, there are different wave phenomena that take place according to the street topology on which noise incidence occurs. To be able to understand which behavior of noise is expected, in Fig. 10, a graphical representation of noise incidence on different conditions can be seen. In Fig. 10a, the scenario of transmission in free field conditions is depicted. This represents a situation in which no obstacles are present, and therefore, the only sound pressure levels present will be those of direct transmission. It is expected to have greater SEL values on façade than on free field conditions as the façades present on a particular topology will add reflections.

From the cases observed, it can be considered that on façades that are directly exposed to aircraft noise, the SEL values will be greater than on façades located behind aircraft trajectories. The different heights at which façades may be located are also expected to influence the aircraft noise modifications as there will be different façade elements that will interact with noise propagation, especially when noise reaches a façade by diffraction effects. The elevation angle is expected to change the conditions in which the incidence of noise takes place as it will cause direct transmission. In a U topology, there are induced reflections, as well as diffraction effects that generate high sound pressure levels on façade. Therefore, we can consider that in a U façade with greater LOS angles, as there is a greater fraction of the flight path in direct transmission and a greater reflection order, the SEL values registered on façade will be greater than those measured on U façades with lower LOS angles. An L topology will also be expected to have greater SEL values than the ones registered in free field conditions because reflections are produced with the wall and wave phenomena take place. However, as there is only one wall, the levels produced on an L street are expected to be lower than those produced on a U street because L shaped streets produce less reflections. On an L topology with greater LOS angles, the SEL values are expected to be greater than on those with smaller LOS angles. On that account, street topologies and façade positions toward flight paths change line of sight angles and, therefore, the SEL values registered on façade.

Table 2 Descriptive statistics of façade noise levels (SEL) per measurement site

Façade measurements									
Site	Building	Number of façades measured	Back façades	Front façades	Number of events	Min (dBA)	Max (dBA)	Mean (dBA)	SD (dBA)
1	1	4	1	3	30	79.1	86.9	83.7	2.5
1	2	4	2	2	47	81.8	86.5	84.3	1.3
1	3	4	2	2	44	80.9	89.8	85.1	2.1
2	4	2	1	1	132	76.2	87.2	81.7	2.4
2	5	2	1	1	227	76.7	88.7	83.2	2.7
2	6	2	1	1	170	79.2	89.4	83.9	2.5
3	7	4	3	1	164	79.0	88.9	84.2	2.6
3	8	4	2	2	104	78.3	89.7	83.2	2.4
4	9	3	0	3	199	72.8	87.0	81.6	2.9
4	10	3	2	1	143	75.8	86.3	81.3	2.9
4	11	3	3	0	92	75.5	86.0	81.4	2.8
5	12	3	1	2	234	74.3	87.7	81.0	2.7
6	13	4	1	3	94	81.8	91.3	87.4	2.2

4 Results and Discussion

Analyses were performed for evaluating noise variations on façade. There were 324 positions measured with 1680 events. The main statistic parameters were obtained to determine the general dispersion of noise for each building as seen on Table 2. Each overflight was classified according to the street topology, LOS angle and façade position. It can be noted on Table 2 that the number of front and back façades is shown. The latter was named as “Back” or “Front” in separate columns by taking into account the position of the façade compared to the backbone track of the majority of events measured at each façade. The mean value of the façade levels or $L_{E,AB_X\text{average}}$ of each building was considered as the reference. First, the variations of $\Delta L_{E,\text{Afaçadej}}$ were analyzed according to the variables proposed with hypotheses tests such as *t*-student, Welch, Kruskal Wallis, or linear regression analyses. Afterward, correction factors were proposed with measurements made in free field conditions for the façade positions.

4.1 Façade Noise Variations

4.1.1 Height Influence

Measurements were performed around the perimeter of each building. Most buildings consisted of two storeys, one of which was located at 1.5 m and the others were between 4.0 and 6.6 m. A linear regression analysis was performed for the values of $\Delta L_{E,\text{Afaçadej}}$ at the different heights for the front and back façades to see if height has an influence on $\Delta L_{E,\text{Afaçadej}}$. For the front façades, there were 498 events measured at 1.5 m and 478 events measured between the heights of 4.0 and 6.6 m. For the front façades, the Pearson correlation of the covariance and variances of $\Delta L_{E,\text{Afaçadej}}$ and height was calculated obtaining a value of −0.002. Afterward, the residuals between the predicted values, and the real values of $\Delta L_{E,\text{Afaçadej}}$ were determined and they did not belong to a normal distribution. An *F*-ratio test for the sum of the squares gives a value of 0.004 with a significance level of 0.949, which means that this model provides an adjustment equal to that of the intercept only model. Homoscedasticity was also tested, and the variances of $\Delta L_{E,\text{Afaçadej}}$ and the height were not homogeneous. For the back façades, there were 371 events measured at 1.5 m and 334 events measured between the heights of 4.0 and 6.6 m. The Pearson correlation of the covariance and variances of $\Delta L_{E,\text{Afaçadej}}$ and height was calculated and it was 0.047. The residuals between the predicted values and the real values of $\Delta L_{E,\text{Afaçadej}}$ were determined, and they did not fit a normal distribution and homoscedasticity was not found as the variances of the residuals and real values of $\Delta L_{E,\text{Afaçadej}}$ were not homogeneous. The *F*-ratio test for the sum of the squares gives a value of 1.574 and a significance level of 0.210, which means that this model provides an adjustment equal to that of the intercept only model. As seen on Figs. 11 and 12, the values of R^2 on both regressions are close to 0. This means that they have different variances and there is not a linear relationship between the heights and $\Delta L_{E,\text{Afaçadej}}$ because the values of $\Delta L_{E,\text{Afaçadej}}$ are not uniformly distributed around the lines described by the equations.

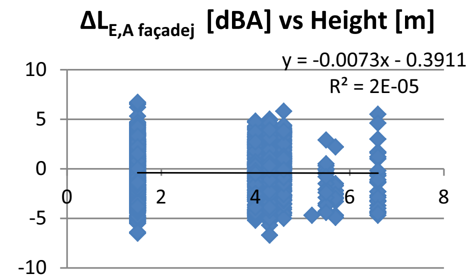

Fig. 11 Linear regression analysis between $\Delta L_{\text{Eifaçade}}$ and height from front façades

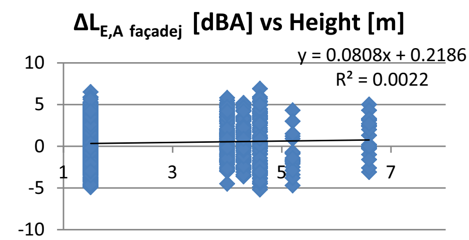

Fig. 12 Linear regression analysis between $\Delta L_{Eifaçade}$ and height from back façades

4.1.2 Façade Position

The shortest perpendicular distance between flight path and the microphone is the slant distance. When there are no obstacles between the flight path and the façade at the slant distance, the façade is considered front, and when they are present, the façade is considered back. Each flight was classified as front/back, and afterward, they were analyzed. There were 22 front façades and 20 back façades, with 975 events measured in the front façades and 705 events measured in the back façades. Noise data from both categories did not come from normal distributions, and hypotheses tests were applied. The variances of the data were not equal, and therefore, the Welch test was performed to check whether the mean values were equal. The mean values of $\Delta L_{E,\text{Afaçadej}}$ for front and back façades were −0.4 and 0.5 dBA, respectively. After calculating an *F* ratio of 9.715 with a significance level of 0.002, a Welch test shows that the values measured in front and back façades belong to different distributions with a *p* value of 0.00 for a *t* statistic of −6.998 yield-

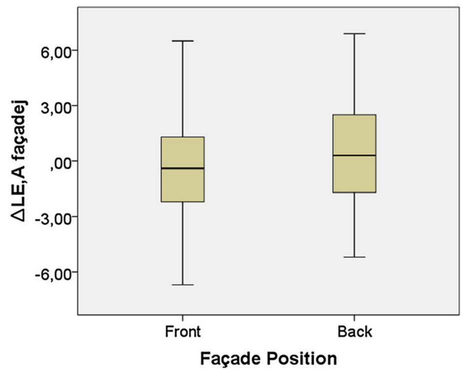

Fig. 13 Box plot of front and back façades

Table 3 Mean and standard deviation for street topologies

Topology	Mean (dBA)	SD (dBA)
L	0.1	2.7
U	−0.3	2.3

ing significant differences between front and back façades (Fig. 13).

4.1.3 Street Topology

Once the measurements were classified according to the topology, there were 326 events measured in U topologies and 1354 events measured in L topologies. The mean values of $\Delta L_{E,\mathrm{Afaçadej}}$ for U and L topologies did not come from a normal distribution. An F ratio value of 8.724 was calculated with a significance level of 0.003. Afterward, a Welch test was used, and it showed statistically significant differences between both categories with a t statistic of 2.408 and a p value of 0.016.

As seen on Table 3, the façade sound pressure levels on the U topology are higher than on the L topology because of the greater order of reflections.

4.1.4 LOS Angle

The analysis of front and back façades, shows that there are façades in which the slant distance between the assessment point and the flight path is in direct transmission. That happens because the line of sight is modified according to the orientation of the building. However, this does not imply that a determined façade will not have any portion of the flight path in direct transmission. The transmission through the entire flight is direct at 180°. Therefore, the value of $\Delta L_{E,\mathrm{Afaçadej}}$ will be expected to be lower because of the reflections. On the other hand, at 0° there is no fraction of the flight path in direct transmission and $\Delta L_{E,\mathrm{Afaçadej}}$ will be expected to have a greater value. Flight paths form different angles with the lines described by the façade under assessment, yielding different

Table 4 Mean values and SD of LOS angles

Angle	Number of events	Mean (dBA)	SD (dBA)
0°	206	0.8	2.8
20°	271	0.6	2.8
45°	156	−0.3	2.2
60°	184	−0.3	2.5
90°	50	0.1	2.0
120°	140	−0.2	2.5
180°	673	−0.4	2.6

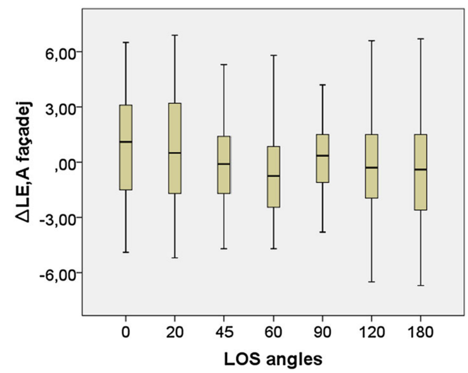

Fig. 14 Box plot of LOS angles

values of $\Delta L_{E,\mathrm{Afaçadej}}$. On that account, different fractions of the flight path will be in direct transmission according to the angle formed. In the measurements performed, there were seven clusters of LOS angles, whose mean values and standard deviations are shown on Table 4.

The nonparametric test Kruskal–Wallis was used because data did not fit a normal distribution. This test shows that all clusters belong to different distributions with a p value of 0.00 for an H statistic of 51.053. When the clusters are compared individually with a Welch hypothesis test, significant differences are found between certain clusters. For instance, when the clusters of 0° and 45° are compared, an F ratio of 17.243 with a significance level of 0.00 is obtained, then applying a Welch test, a t statistic of 4.413 results in a p value of 0.00 giving significant statistical differences. On the other hand, between the clusters from 45° up to 180° all tests gave p values of 0.00 showing no significant differences between the mean values except for the angle of 90°, which as seen on Fig. 14 has a greater mean value of $\Delta L_{E,\mathrm{Afaçadej}}$. When testing 0° and 20°, a Welch hypothesis test was applied resulting in an F ratio of 0.002 and a significance level of 0.968. The Welch test gave a p value of 0.644 for a t-statistic of 0.463.

As seen on Fig. 14, the LOS angle of 90° had positive values of $\Delta L_{E,A\,façadej}$. The cluster of 90° was analyzed separately to determine whether the elevation angle had influence on $\Delta L_{E,A\,façadej}$. The elevation angles were evaluated when their values were close to 90° and less than 90°. There were

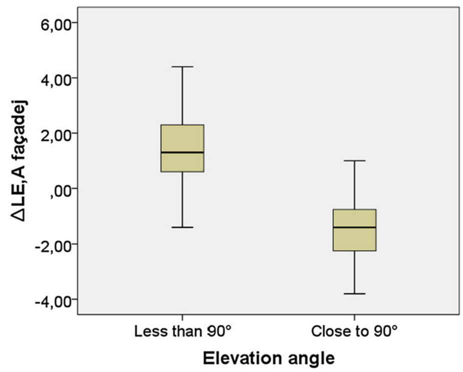

Fig. 15 Box plot of elevation angle

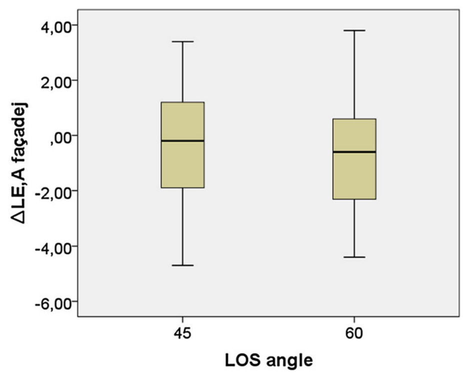

Fig. 16 Box plot of U topology with LOS angles of 45° and 60°

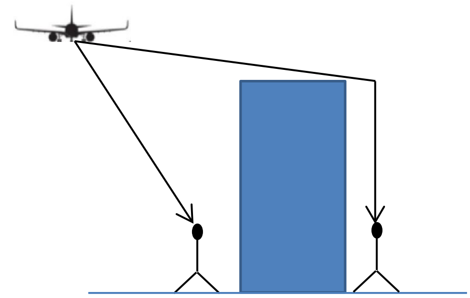

Fig. 17 Behavior of aircraft noise at 45°

Table 5 Mean and SD values of street topologies and LOS angles

Category	Number of events	Mean (dBA)	SD (dBA)
L < 45°	436	0.7	2.7
L > 45°	918	−0.3	2.6
U < 45°	194	0.1	2.4
U > 45°	132	−1.0	2.0

Table 6 Results from *t* student test to street topology and LOS angle

Category	*t*	*p* value
L<45° versus L >45°	5.308	0.00
U<45° versus U >45°	4.554	0.00
L<45° versus U>45°	5.884	0.00
U<45° versus L>45°	−3.081	0.00

27 events whose elevation angles were less than 90° and 23 close to 90°, whose mean values were 1.5 and −1.4 dBA respectively. The data came from normal distributions, and after obtaining an *F* ratio value of 2.405, a significance level of 0.128 was obtained. Then a *t* student test was applied obtaining a *t*-statistic of 7.530 with a significance level of 0.00 yielding significant differences as seen on Fig. 15.

The angles of 60° and 45° on the U topology were analyzed as seen on Fig. 16. There were 85 events measured in U topologies with 45° of LOS angle and 71 events in U topologies with 60°. The mean values for each cluster were −0.4 and −0.8 dBA, respectively. The data came from a normal distribution and were evaluated with a *t* student test, the *F* ratio was calculated, and a value of 0.223 with a significance level of 0.637 was obtained. Afterward, a *t*-student test was applied, and a *t*-statistic of 1.263 with a significance level of 0.209 was obtained, and no significant differences were found.

4.1.5 LOS and Street Topology

With the previous analyses made of the LOS angles, it was demonstrated that with direct transmission, the sound pressure levels on façade will be higher. Therefore, greater line of sight angles, are expected to have greater noise levels on façade. However, on U and L topologies, different wave phenomena take place. As a U street is prone to have more reflections than an L street, higher levels are expected to be obtained on a U street, whereas, in a U street with a large LOS angle, the sound pressure levels registered on façade are expected to be greater. The LOS angle analysis shows that there are no significant differences between the clusters of 0° and 20° and among those from 45° to 180°. As seen on Fig. 17, at 45° the transmission in slant distance stops being direct. Consequently, as sound pressure levels depend on wave phenomena like diffraction and direct path interference, the mean values of $\Delta L_{E,\text{Afaçadej}}$ should be positive from 0° to 45° and negative from 60° up to 180° as they represent back and front façades, respectively.

Four more cases have been evaluated to observe the influence of street shape and line of sight angles on the modification of $\Delta L_{E,\text{Afaçadej}}$. L with LOS smaller than 45°, L with LOS greater than 45°, U with LOS smaller than 45° and U with LOS greater than 45° and their mean values and standard deviations are shown on Table 5.

Kruskal–Wallis test was used to determine whether there were significant differences as the data did not come from a normal distribution. The results show that the four categories do not belong to the same distribution. When individual analyses are performed with Welch tests, significant differences are found between the angles greater than 45° and lower than 45° as seen on Table 6. This demonstrates that the street topology and the LOS angles altogether affect the direct transmission and modify noise levels as each topology has a certain order of reflections.

4.2 Free Field Noise Variations

In order to choose the correct free field position, there were some guidelines followed. The ideal free field position for any building was the rooftop because the noise from all aircraft could be retrieved with the lowest possible amount of obstructions. But it was not always possible to put the microphone on the rooftop. Therefore, it was necessary to find a clear space in which aircraft noise levels could be recorded. To assess correctly the sound pressure levels of aircraft noise, the conditions stated in standard 20906 were followed. Those are a minimum height of 6 m above ground to minimize the effect of ground reflections and a distance of at least 10 m from any reflecting surface. Therefore, free field positions with those guidelines were considered and measurements were performed in five buildings. Different positions were measured along façade on different days. In Fig. 18, the arrangements of the free field and on façade positions of the five buildings under analysis are shown.

In Fig. 18c, it can be noted that the microphone is located behind the building, which may imply that the building is obstructing the reference position from retrieving the levels properly. However, the microphone was located on a higher platform of 2 m that avoided the obstruction of the building. It was also located far enough from it so that reflections caused by the rooftop could be minimized. On the other hand, on Fig. 18e, the microphone was placed on the rooftop. For all the other buildings, the free field position microphones were placed between the flight trajectories and the façade positions.

The total events measured was 627, ΔL_{Ej} was calculated and a second analysis was performed. There were 254 events in front façades and 373 events in back façades. The events measured took place on different days. Every event had its own characteristic noise and certain features that could influence the measurements significantly. However, to make sure that all measurements were performed under the exact same

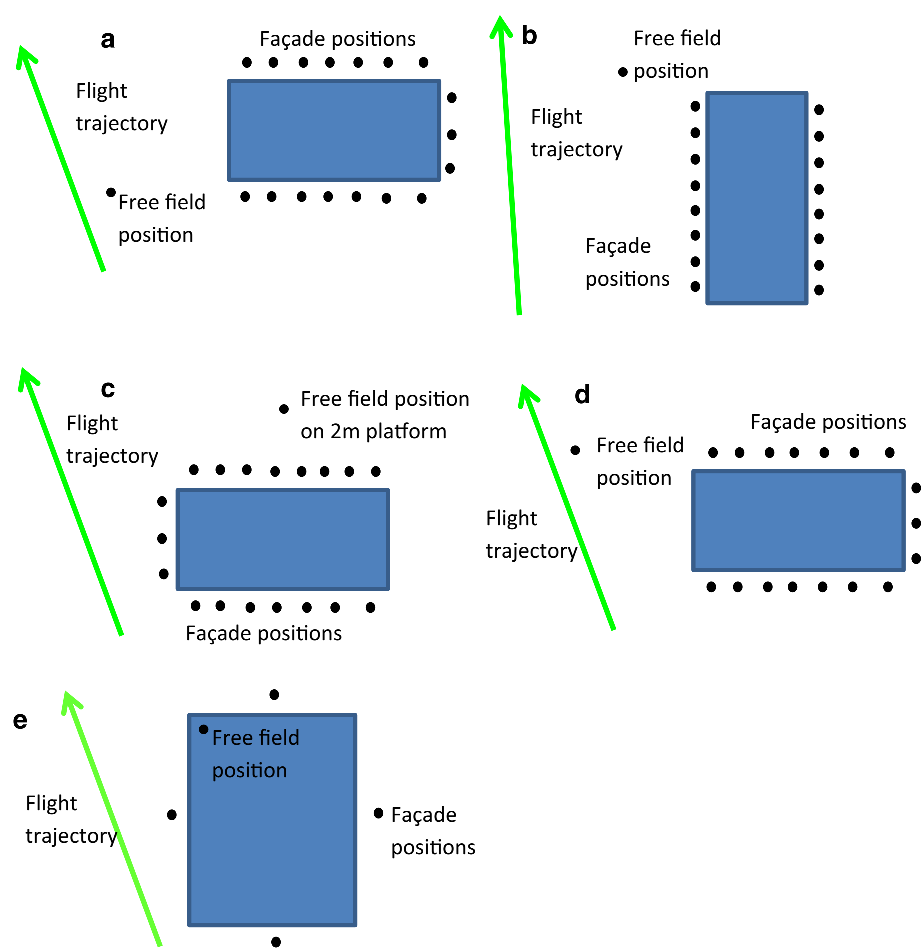

Fig. 18 Free field positions

Table 7 Mean and SD for front and back façades

Façade position	Mean (dBA)	SD (dBA)
Front façade	−0.4	1.3
Back façade	1.0	1.6

conditions, a t-student test was applied to the free field values measured for front and back façades. For the values obtained in free field conditions at the front façades, the mean value obtained was 82.9 dBA, and for those of the back façades, the mean value was 83.4 dBA. Normality tests were applied for them and none of the samples came from normal distributions. An F ratio of 24.415, and a significance level of 0.00 was obtained, and afterward a Welch test was applied. The t-statistic obtained was −1.601, and the significance level obtained was 0.110 which imply that there are no significant differences between the values obtained in free field conditions and hence, the data can be compared. The mean values of ΔL_{Ej} obtained for front façade and back façades were −0.4 dBA and 1.0 dBA, respectively. Both values came from a normal distribution, and with a t-student hypothesis test, it was proved that significant differences exist between these two clusters of data obtaining a p value of 0.00 for a t statistic of −6.998.

The mean values shown on Table 7 were obtained for front and back façades with a confidence level of 95%. This means that the correction factors to be applied to the SEL values measured on façade are located in the following intervals described in Eqs. 4 and 5 for front and back façades, respectively.

$$\text{Front façades} = -0.4 \pm 2\,(1.3)\,\text{dBA} \tag{4}$$

$$\text{Back façades} = 1.0 \pm 2\,(1.6)\,\text{dBA} \tag{5}$$

On that account, the highest SEL values within a 95% confidence level obtained on front and back façades will be free field SEL values amplifications of 3.0 and 2.2 dBA, respectively, as shown on Eqs. 6 and 7.

$$Front\ façades = -0.4 - 2\,(1.3) = -3.0\text{dBA} \tag{6}$$

$$Back\ façades = 1, -2\,(1.6) = -2.2\text{dBA} \tag{7}$$

5 Conclusions

The microphone heights at which the measurements were taken do not have a linear relationship with the difference of levels on façade at the heights on which measurements were performed in this study. Buildings located between the flight path and the façade at the slant distance affect aircraft noise propagation by attenuating aircraft noise levels as they obstruct the direct transmission. When no obstacles are located at the slant distance, buildings increase the sound pressure levels. This variable relates to another study made by Lugten et al. in which the influence of front and back façades was determined through measurements made by the side of a runway near Amsterdam's Airport Schiphol. Measurements were done simultaneously in front and back façades of buildings located at a horizontal distance of 700 m from the runway. The overall A-weighted sound pressure level of each event was compared between façades. It was determined that the differences between façades was about 14 dBA. The differences were larger than the ones obtained in this experiment because the altitude of the flight paths measured in this experiment was between 500 and 1140 m and those of Lugten et al. were of 70 m. Therefore, the shielding effects of the buildings decay when altitude increases. Both experiments demonstrate that the orientation of buildings toward flight paths influence sound pressure levels at the receivers. Whenever an obstacle is present in the trajectory of an acoustic wave, it will create a shadow zone, causing it to have a lower sound pressure level than the one it would have if it was located in front of the aircraft. Street topologies represent factors of urban morphology in aircraft noise propagation as they induce different orders of reflections. L topologies induce fewer reflections than U topologies, yielding lower levels on façade. Different façades have different amounts of LOS as they form an angle with the flight trajectories having certain fractions of the flight paths in direct transmission yielding different levels on façade. At 45°, a façade will be exposed half the time of an aircraft event. Street topologies add obstacles to noise transmission and modify LOS angles. The results obtained in this study were generally small because most of the flight paths had altitudes between 500 and 1140 m, which cause less shielding effects as aircraft fly close to overhead. The corrections proposed for front and back façades in this study could help in extrapolating the free field levels of aircraft noise events for LOS angles greater and lower than 45° found in urban areas with similar settings to the ones of this study with normal distributions and confidence levels of 95%. This study has proposed categorical criteria for classifying façades according to their topology, LOS angles and position. Although the overall estimates of corrections are valid for buildings and flight track configurations of the type considered in this study, the results of the statistical analysis should be considered as indicatives due to the large amount of parameters affecting the results that could vary depending on the situation considered. As future lines of investigation, the effects of the variables analyzed could be observed for buildings with greater heights and different wall and ground materials to determine whether those result in different attenuations.

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