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Influence of mesoscale urban morphology on the spatial noise attenuation of flyover aircrafts

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Abstract: The influence of urban morphology of low-density built-up areas on spatial noise level attenuation of flyover aircrafts is investigated at a mesoscale. Six urban morphological parameters, including Building Plan Area Fraction, Complete Aspect Ratio, Building Surface Area to Plan Area Ratio, Building Frontal Area Index, Height-to-Width Ratio, and Horizontal Distance of First-row Building to Flight Path, have been selected and developed. Effects of flight altitude and horizontal flight path distance to site, on spatial aircraft noise attenuation, are examined, considering open areas and façades. Twenty sampled sites, each of 250m*250m, are considered. The results show that within 1000m horizontal distance of flight path to a site, urban morphology plays an important role in open areas, especially for the buildings with high sound absorption façades, where the variance of average noise level attenuation among different sites is about 4.6 dB^2 at 3150 Hz. The effect of flight altitude of 200ft-400ft on average noise level attenuation is not significant, within about 2 dB at both 630Hz and1600Hz in open areas. Urban morphological parameters influence the noise attenuation more in open areas than that on façades. Spatial noise attenuation of flyover aircrafts is mainly correlated to Building Frontal Area Index and Horizontal Distance of First-row Building to Flight Path.

Key words: aircraft noise; urban morphology; noise attenuation; low-density area; flight altitude

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1. Introduction

The concerns on the impacts of air transport on noise, air quality, water quality and the ecology are increasing, especially for the higher density population European regions [1]. The annoyance of the population who had been living near a big European airport for at least 5 years caused by aircraft noise has been raised over recent years and the annoyance ratings due to aircraft noise were higher than predicted by the EU standard curves [2]. Aircraft noise has been an important cause for the degradation of soundscape in the adjacent areas of airports, especially for the regions that have strong connections between noise annoyance and local outdoor life [3,4].

Conventionally, the research on aircraft noise mapping and assessment is based on the standard conditions of constant flight speed and flat terrain without reflecting objects [5]. At present, much attention is still paid to large-scale aircraft noise modelling [6,7] and mapping with an emphasis on aircraft flight performance, rather than the effects of built-up obstacles on noise attenuation [8-10]. While many prediction tools mainly focus on the noise from taking offs and landings, noise mapping tools for aircraft taxing have also been developed [11]. On the other hand, with the expansion of air transport and injection of airports and heli-pads into or close to city areas, the effects of morphology of urbanised areas, for instance, the effects of urban street pattern [12,13], have become a concern on aircraft noise distribution near airports. It is indicated through modelling that noise from an aircraft passing overhead in a city street is enhanced compared to that heard in an open area [14]. Kinney et al [13] carried out a series of field experiments which confirmed the enhancement and explained the phenomenon. It has been demonstrated that relative Effective Perceived Noise Level increases with the ratio of building height to flying altitude, but the street width has little influence [12]. While the above research demonstrated the importance of considering the influence of urban morphology, there are further important research questions: are there any other parameters of urban morphology which influence aircraft noise attenuation, considering the mesoscale of urban morphology with a group of buildings, rather than a street?

The aim of this study is therefore to explore whether and how urban morphology parameters influences noise attenuation of flyover aircrafts. Low-density residential areas are considered, because they have relatively low noise resistance and they are more common near airports. The study focuses on flyover landing aircrafts or helicopters, of which the noise is prone to be loud, lasting and annoying [12, 15-18]. In particular, this study aims to find out (1) the effects of horizontal distance between a site and flight path; (2) the effects of altitude of flight path. Given the needs for quiet rooms for people to relax, sleep and restore and an impact of quiet side on the aircraft noise annoyance ratings [2], besides open areas, the noise attenuation on façades is also considered.

2. Methods

2.1 Site selection

To select study sites with diverse urban morphologies from low-density residential areas, Assen in the Netherlands was considered which has a long history of province capital since 1258. It is the fastest-growing city in the North of Netherlands and has an increase of 5,000 residential buildings per 10 years since 1960 [19], resulting in a mixture of various urban morphologies generated in different historical periods, representing typical European sub-urban morphologies which can often be found near airports. According to a GIS database of 763 grids of Assen built-up areas, less than 10% grids are used for industry and commercial purposes, and the main function of the built-up areas is residence and mixed-use (residential and commercial). More than 70% of the residential buildings are low-rise terraced and detached buildings [19]. Twenty sites, each of 250m*250m, were sampled by using Simple Random Sample (SRS) method from the GIS database. Figure 1 shows the figure-ground diagrams of the sampled sites.

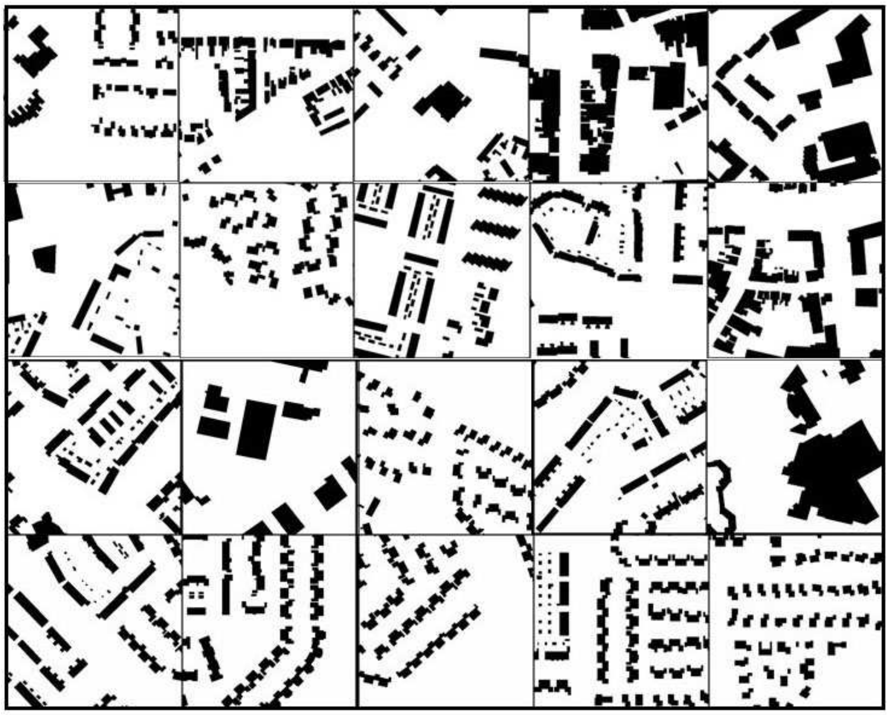


Fig. 1. Figure-ground diagrams of the 20 sampled sites, each of 250m*250m, where buildings are in black, and open areas are in white.

2.2 Set-up of calculation parameters for noise mapping

Noise mapping techniques [20-22] were employed with the software package of Cadna/A [23] in this study. The accuracy in noise mapping calculation depends more on the quality of input data rather than specific modelling program [24]. It has been stated that the results of calculation and measurement can generally reach a rather good agreement [24, 25, 26]. For instance, when considering both traffic noise and fountain sounds in urban areas, the inaccuracy is within around 2dB [25]. The 2D polygon maps of the sampled sites were obtained from the web of Zoning Plan [27] and TOP10NL of Kadaster [28], which include the 3D information of buildings. As the aim of this study is to examine the influence of urban morphology, the atmospheric effect is not taken into account, and generic source conditions were considered. The flyover aircraft was set as a line source, considering five horizontal distances from a given site, namely 0m, 100m, 300m, 600m and 1000m, and two flight altitudes, namely 60.96m (200ft) and 121.92m (400ft), according to previous studies [12, 13]. The receiver height was set as 1.6m. The calculation configuration is shown in Fig. 2. Based on the research by Khardi [29], three main frequencies of aircraft noise, 630Hz (low), 1600Hz (medium), and 3150Hz (high), were selected for calculation. The absorption coefficient was assigned as 0.3 across frequencies, considering the mixture of windows and masonry façades, and the ground absorption was assigned as 0. The reflection order by buildings was set as 3, based on a previous study [24], and comparison was also made by considering no reflections so that the shielding effects as well as the effectiveness of absorptive building façades like green walls can be examined.

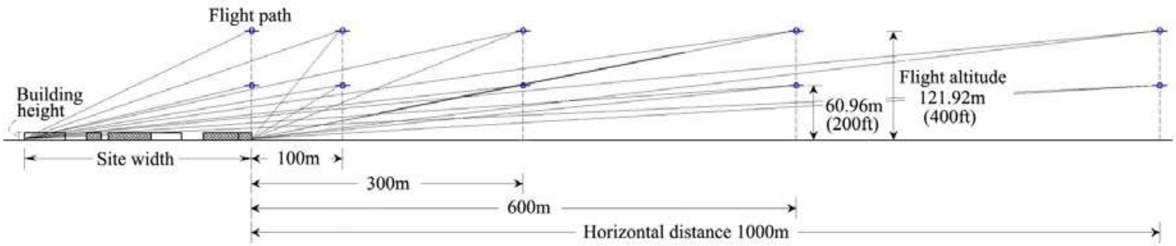


Fig. 2. Cross-section of the calculation configuration, showing the location of flight path.

2.3 Matlab processing

To transform the RGB raster noise maps into the matrices of spatial noise level values, a Matlab program has been developed. The program can arrange all the spatial noise level values in a descending order to obtain the indices of spatial L_n, where for example, L_{max} represents the highest value in the ranking, L_{min} represents the lowest value, and L_{10} is the top 10% value [30]. In this study, L_{10}, L_{90} and L_{50} were chosen to indicate the high, low and middle spatial levels, respectively. In addition, L_{avg}, the mean of all the spatial noise levels of a given site, was calculated. The sound level values on building façades and in open areas were separately processed.

2.4 Calculation of urban morphological parameters

A set of urban morphological parameters have been developed and employed in different domains of environmental studies including environmental performance, atmospheric and wind environment and traffic noise [31-34]. To consider various acoustic effects such as distance, barrier and street canyon, [24,35], in this study six parameters were selected or developed, including Building Plan Area Fraction (BPAF), Complete Aspect Ratio (CAR), Building Surface Area to Plan Area Ratio (BSAPAR), Building Frontal Area Index (BFAI), Height-to-Width Ratio (HWR) and Horizontal Distance of First-row Building to Flight Path (HDFBFP), as listed in Table 1, where the first three parameters are independent from the source condition, whereas the other three are related to sound source locations. In this paper, they are grouped as independent and dependent parameters, respectively. Calculations of the 20 sites show that BPAF is evenly distributed from 0.13 to 0.38, CAR from 1.17 to 1.53, BSAPAR from 0.36 to 0.88, BFAI from 0.04 to 0.15, and HWR from 0.09 to 0.62. When the horizontal distance between site and flight path is 0, HDFBFP covers a range of 3.4m to 116.2m.

Table 1. Calculations of the six urban morphological parameters used in this study.

Parameter	Definition	Formula	Notes
Building Plan Area Fraction (*BPAF*)	The ratio of the plan area of buildings to the total surface area of the study region	$BPAF = \frac{A_p}{A_T}$	A_p is the plan area of buildings at ground level and A_T is the total plan area of the region of interest.
Complete Aspect Ratio (*CAR*)	The summed area of roughness elements and exposed ground divided by the total surface area of the study region [36]	$CAR = \frac{A_C}{A_T} = \frac{A_W + A_r + A_G}{A_T}$	A_C is the combined surface area of the buildings and exposed ground, A_W is the wall surface area, A_r is the roof area, A_G is the area of exposed ground [37].
Building Surface Area to Plan Area Ratio (*BSAPAR*)	The sum of building surface area divided by the total surface area of the study region	$BSAPAR = \frac{A_r + A_W}{A_T}$	A_r is the plan area of rooftops, A_W is the total area of non-horizontal roughness element surfaces (e.g. walls) [37].
Building Frontal Area Index (*BFAI*)	The total area of the façade areas parallel with the flight direction (A_{para}) divided by the total surface area of the study region	$BFAI(\theta) = \frac{A_{para}}{A_T}$	θ is the flight path direction.
Height-to-Width Ratio (*HWR*)	The average of the building heights (H_{avg}) is divided by the average of the horizontal distances between two adjacent buildings on the direction vertical to the flight direction (S_{avg})	$HWR(\theta) = \frac{H_{avg}}{S_{avg}}$	θ is the flight path direction.
Horizontal Distance of First-row Building to Flight Path (*HDFBFP*)	The mean of the horizontal distances from the frontal façades of the first-row buildings to the flight path	$DFBR = \frac{1}{n}\sum_{i=1}^{n} d_i$	n is the total number of first-row buildings, and d_i is the distance from the first-row building to the flight path.

3. Results

3.1 Effects of the horizontal distance between site and flight path

Figure 3 shows the maximum, minimum, and mean aircraft noise attenuation (re. source power level) among the 20 sampled sites, in terms of L_{avg} at 630, 1600 and 3150Hz, with a range of horizontal distance between site and flight path, when the flight altitude is 200ft. In the figure the noise attenuation of each site is also shown. It can be seen that the difference between the maximum and minimum values among the 20 sites in open areas generally increases with horizontal distance between site and flight path, and reaches 7.9dB at 1000m, at 3150Hz (see Fig. 1-c). It is also interesting to note that from 300m to 600m, namely when the horizontal distance between site and flight path is doubled, the mean L_{avg} difference among the 20 sites in open areas reduces by 6.9dB at 630Hz, 7.5dB at 1600Hz, and 16.1dB at 3150Hz, as shown in Fig. 3a, 3b and 3c, respectively, demonstrating the significant influence of urban morphology.

In general, the sound level variations among the 20 sites are larger in open areas than those on façades. For example, by comparing Fig. 3b and 3e, it can be seen that at 1600Hz at 1000m, the difference between the maximum and minimum values is 7.7dB in open areas and 4.5dB on façades. However, the façades have higher noise attenuation than that in open areas, in terms of the mean L_{avg} of the 20 sites.

For example, by comparing Fig. 3a and 3d, it can be seen that at 630Hz at 1000m, the value is 54.0dB on façades and 49.2dB in open areas.

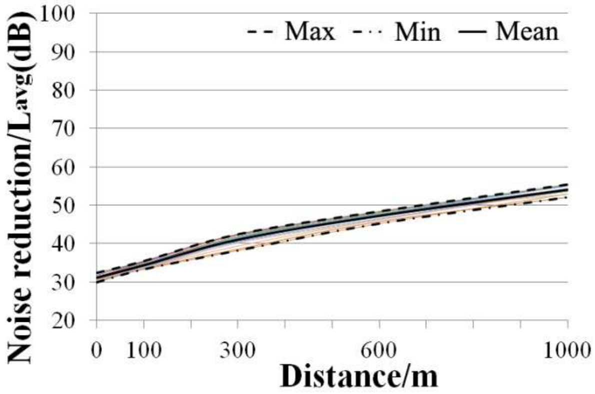
Fig. 4 and 5 show the variances of the aircraft noise attenuation L_{avg} among the 20 sites, in open areas and on façades, respectively. It can be seen in Fig. 4 that generally speaking, with the increase of distance, the variances at all the frequencies go up. Corresponding to Fig. 3, the variances at 1000m are the largest, where at 3150Hz and altitude of 200ft the variance is 4.6dB^2, higher than that at 1600Hz and 630Hz (see Fig. 4a, 4b and 4c). By comparing Figs. 4 and 5, it can be seen that the variances of noise attenuation on façades, mostly below 2dB^2, are lower than those in open areas.

In Fig. 4 and 5 two conditions, with a reflection order of 0 and 3, are considered. Compared with the condition without reflections, the variances with 3 reflections are lower at almost all the distances, which means that sound reflections by buildings reduce the influence of morphology on the noise resistance. At a large horizontal distance between site and flight path, say 1000m, the differences in variances between reflection order of 0 and 3 can be neglected, in open areas and also on façades.

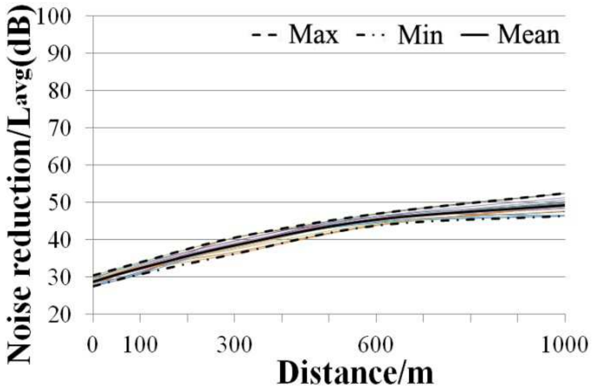
The variances in terms of L_{10}, L_{50} and L_{90} are shown in Table 2. It can be seen that the variances of L_{50} and L_{90} are generally higher than those of L_{10}, and the variances in open areas are higher than those on façades, suggesting that urban morphology may have more influence on the noise attenuation at the middle level and the quiet level in open areas. The highest variance occurs for L_{50} at 1600Hz at 1000m, which is 19.7dB^2.

Table 2. Variances of the aircraft noise attenuation among the 20 sites in terms of L_{10}, L_{50} and L_{90}, both in open areas and on façades.

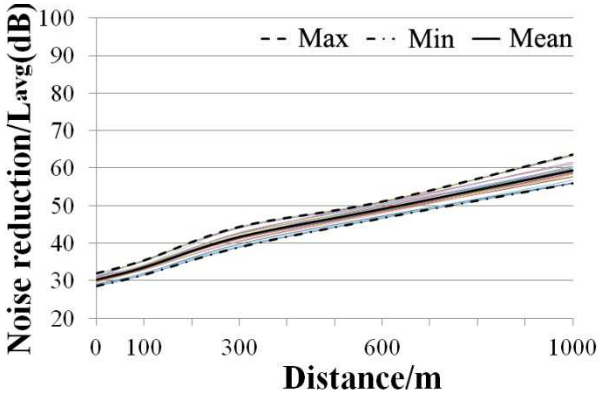
Frequency(Hz)		**L_{10}**			**L_{50}**			**L_{90}**		
		630	1600	3150	630	1600	3150	630	1600	3150
	Distance(m)									
Open Areas	0	1.4	2.6	0.0	0.6	1.2	3.8	1.8	1.0	5.7
	100	0.8	1.4	2.0	4.6	5.2	8.1	0.0	3.4	1.2
	300	3.0	0.5	3.0	3.6	7.6	3.8	2.2	0.9	3.3
	600	6.8	2.1	5.8	2.1	5.3	1.6	1.0	1.6	2.2
	1000	0.0	0.8	1.2	8.6	19.7	8.9	1.8	6.2	3.2
Façades	0	0.4	0.9	0.4	0.2	0.8	1.2	1.7	6.0	6.4
	100	1.2	0.5	1.0	0.6	1.0	0.6	7.4	9.0	4.2
	300	1.0	0.4	0.8	4.6	0.8	1.0	5.0	3.3	3.6
	600	3.3	0.4	0.4	1.0	1.6	2.0	2.2	6.1	8.5
	1000	1.0	1.6	2.4	1.0	1.2	4.6	3.7	0.9	0.8



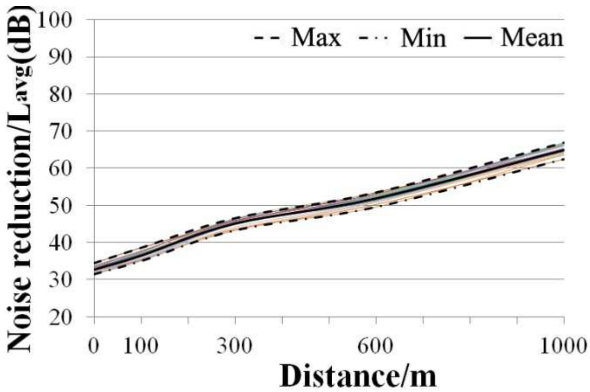
(a) 630Hz, open areas



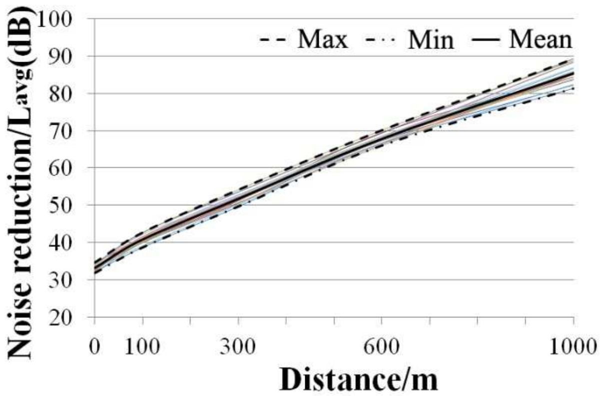
(d) 630Hz, façades



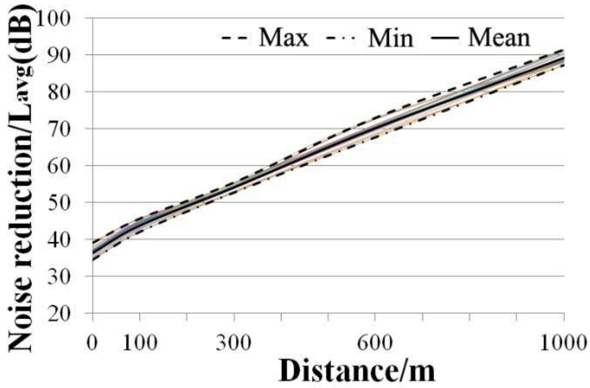
(b) 1600Hz, open areas



(e) 1600Hz, façades

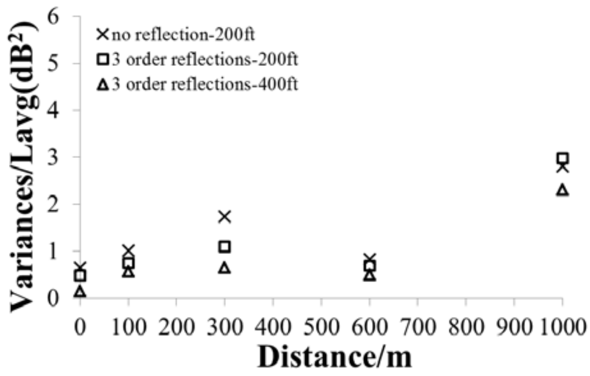


(c) 3150Hz, open areas

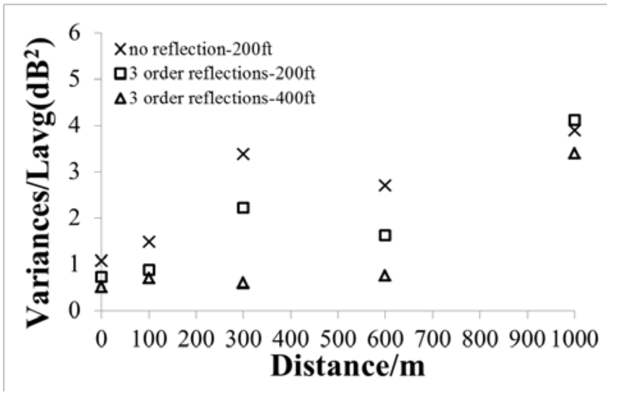


(f) 3150Hz, façades

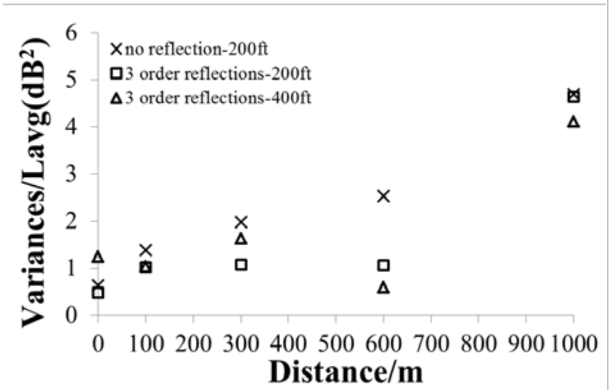
Fig. 3. The maximum, minimum, and mean aircraft noise attenuation (re. source power level) among the 20 sampled sites, in terms of L_{avg} at 630, 1600 and 3150Hz, with horizontal distances between site and flight path of 0m, 100m, 300m, 600m and 1000m, where the flight altitude is 200ft. In the figure the noise attenuation of each site is also shown, although individual sites are not identified.



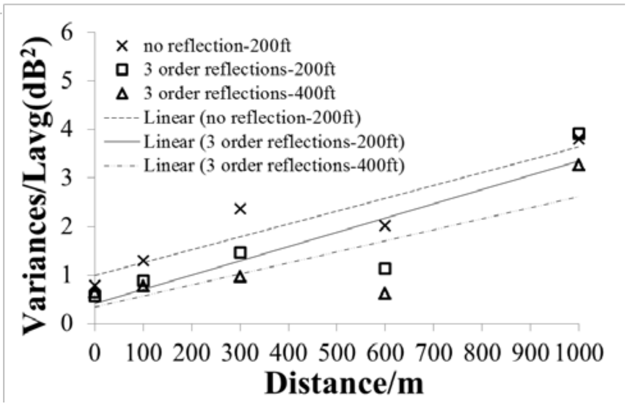
(a) 630Hz



(b) 1600Hz

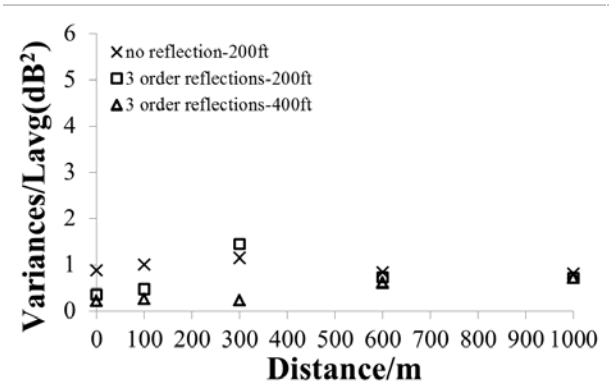


(c) 3150Hz

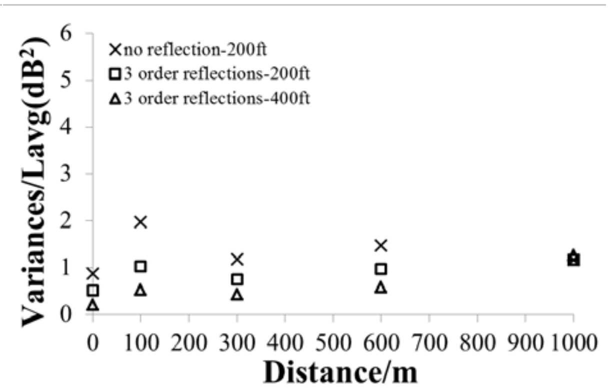


(d) Average of 3 frequencies

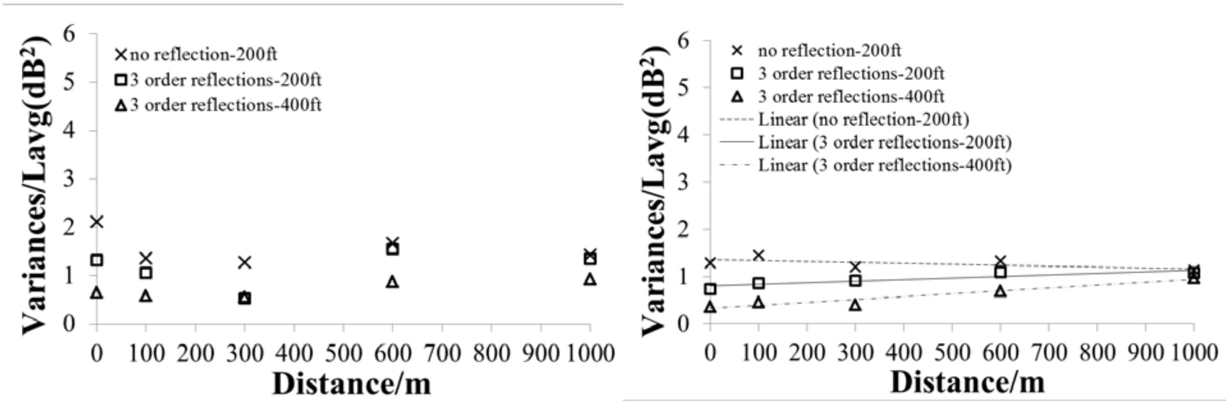
Fig. 4. Variances of the aircraft noise attenuation L_{avg} in open areas among the 20 sites, with increasing horizontal distance between site and flight path of 0m, 100m, 300m, 600m and 1000m.



(a) 630Hz



(b) 1600Hz



(c) 3150Hz (d) Average of 3 frequencies

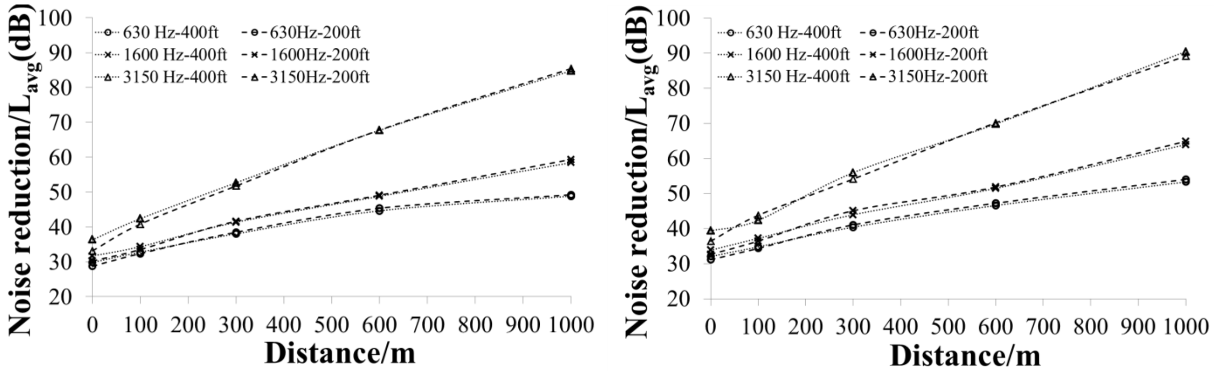
Fig. 5. Variances of the aircraft noise attenuation L_{avg} on façades among the 20 sites, with increasing horizontal distance between site and flight path of 0m, 100m, 300m, 600m and 1000m.

3.2 Effects of flight altitude

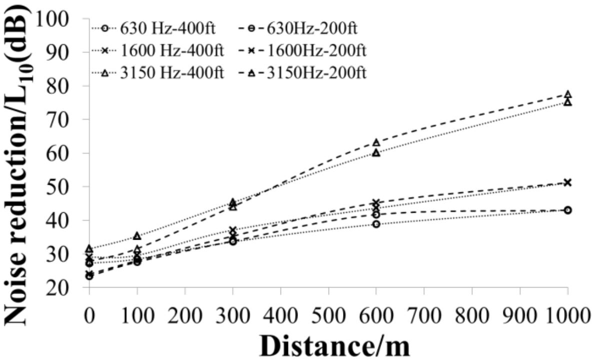
Fig. 6 compares the mean values of aircraft noise attenuation (re. source power level) of the 20 sites between the flight altitude of 200ft and 400ft, in terms of L_{avg}, L_{10} and L_{90}. It is interesting to note that the increase to 400ft from 200ft in flight altitude generally does not benefit the noise attenuation. This is perhaps because although the increase in flight altitude results in larger source-receiver distances, it also decreases the shielding effects of buildings. It was shown in a previous study that the enhancement of sound level by streets relative to that in the open field decreases with the increase of flight altitude, from 5.0dBA at 200ft to 2.0dBA at 400ft [13]. In Fig. 6 it can be seen that at 1000m, there is almost no difference in noise attenuation between the two altitudes.

In Figs. 4 and 5 comparisons of variances of spatial noise attenuation between the two flight altitudes are also shown. It can be seen that the increase of altitude does not significantly diminish the variances. In other words, the effect in the change of altitude on the influence of urban morphology on noise resistance is rather small, less than 1dB mostly.

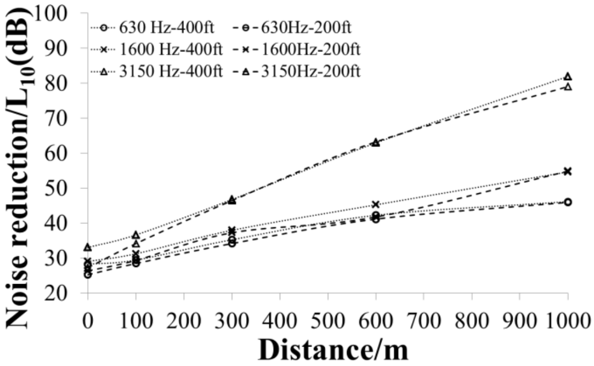
Compared with façades, the influence of altitude on noise attenuation in open areas is more significant in terms of L_{90}, as can be seen by comparing Figs. 6c and 6f, but surprisingly, the noise attenuation is generally higher at the altitude of 200ft than 400ft, which means that in certain situations, the increase of altitude does not decrease, but increase the sound levels in relatively quiet areas, of which the reason might be that the shielding effect that plays a key role in quiet area protection decreases with the increase of flight altitude.



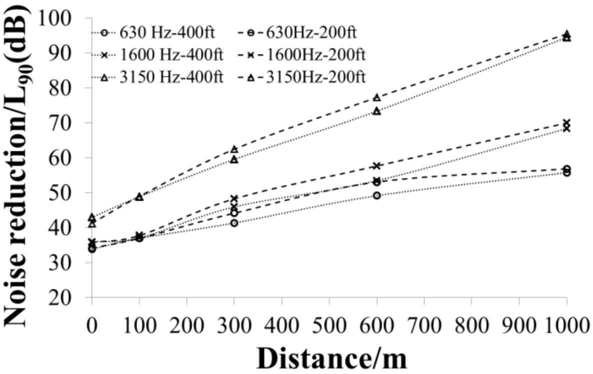
(a) L_{avg} in open areas (d) L_{avg} on façades



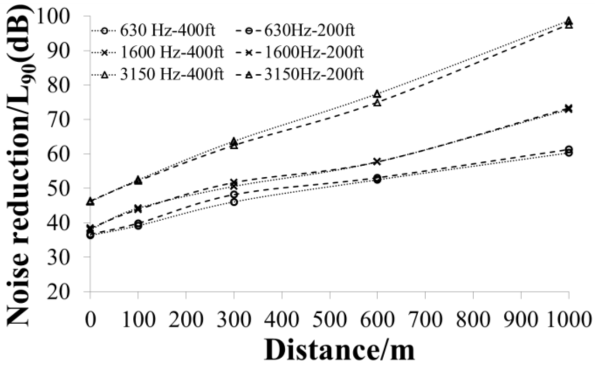
(b) L_{10} in open areas



(e) L_{10} on façades



(c) L_{90} in open areas



(f) L_{90} on façades

Fig. 6. The mean values of aircraft noise attenuation (re. source power level) of the 20 sites between the flight altitude of 200ft and 400ft, in terms of L_{avg}, L_{10} and L_{90}, with increasing horizontal distance between site and flight path of 0m, 100m, 300m, 600m and 1000m.

3.3 The relations between aircraft noise attenuation and independent urban morphological parameters

Relationships between aircraft noise attenuation and independent morphological parameters have been examined with the flight altitude of 200ft, since the variances are higher than those of 400ft. Three typical horizontal distances between site and flight path are considered, which are 0m, 300m, and 1000m.

Among the three independent urban morphological parameters, namely Building Plan Area Fraction (BPAF), Complete Aspect Ratio (CAR), and Building Surface Area to Plan Area Ratio (BSAPAR), at the distances of 0m, 300m and 1000m, BPAF is not significantly correlated to any of the acoustic indices, namely spatial L_n and L_{avg}, which suggests that building coverage has little influence on aircraft noise resistance, while CAR and BSAPAR have more significant correlations ($p < 0.05$) with the indices, as shown in Tables 3 and 4, respectively.

It can be seen in Table 3 that CAR is more correlated to the indices in open areas, mostly in terms of L_{90}, which means that the total surface area of building and ground may significantly influence the noise level in quiet areas. Fig. 7 further illustrates the tendencies of L_{90} at 630Hz (R^2=0.567) and 3150Hz (R^2=0.586) with a change of CAR, as examples. When CAR increases the regression line of either L_{90} of 630Hz or 3150Hz in open areas goes up and then becomes stable after CAR is higher than approximately 1.4. In other words, the importance of CAR on noise attenuation in open areas becomes less when CAR is higher than 1.4. The correlations also exist between CAR and the acoustic indices on façades, but they are not at a significant level statistically.

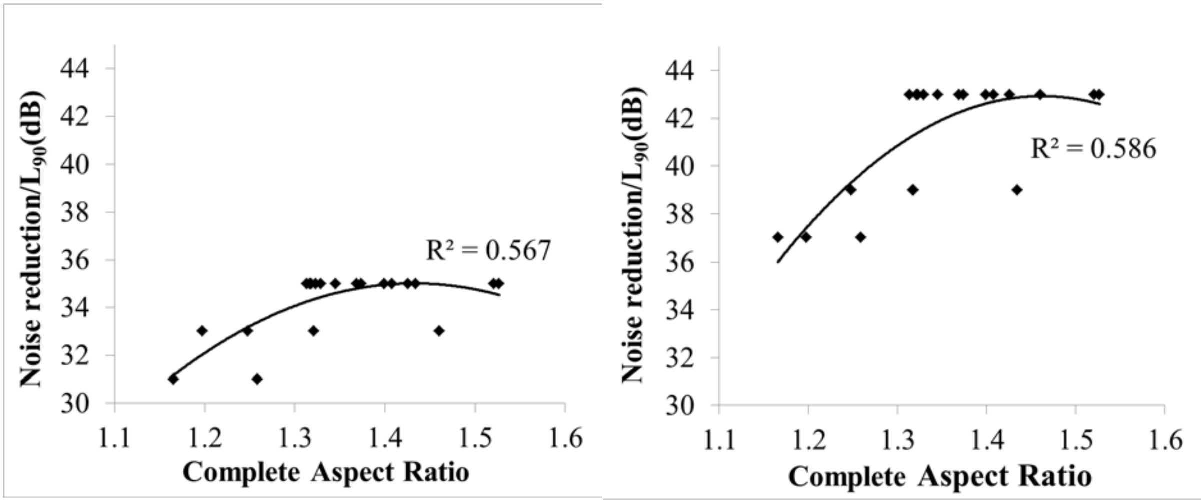
From Table 4 it can be seen that BSAPAR also tends to have high correlations with the acoustic indices, especially L_{90} in open areas. The tendencies of L_{90} in open areas at 630Hz (R^2=0.592) and 3150Hz (R^2=0.500) with a change of BSAPAR are further illustrated in Fig. 8. It can be seen in Fig. 8 that the noise attenuation in open areas at L_{90} increases before BSAPAR is about 0.7 and then decreases, both at 630Hz and 3150Hz, of which the reason might be that the increase of building surface area induces more sound reflections between buildings, so that further increases noise levels.

Table 3. Significances of the correlations between acoustic indices and Complete Aspect Ratio in terms of *p* values, where * indicates *p*<0.05 level (2-tailed), and ** indicates *p*<0.01 level (2-tailed) in Bivariate Correlation.

Distance(m) / **Frequency(Hz)**		**0**			**300**			**1000**		
		630	1600	3150	630	1600	3150	630	1600	3150
Open Areas	L_{10}	.721	.084	-	0.59	.148	.805	-	.449	.377
	L_{50}	.402	.371	.917	.272	.614	.199	.363	.627	.180
	L_{90}	**.005****	.151	**.001****	.082	.170	.477	**.008****	**.005****	**.037***
	L_{avg}	.070	.060	.536	**.036***	.169	.261	.100	.130	.222
Façades	L_{10}	.712	.121	.712	.072	.712	.072	.250	.060	.919
	L_{50}	.325	.757	.499	.061	.523	.061	**.040***	.081	.147
	L_{90}	.681	.779	.800	.741	.820	.741	.429	**.029***	.597
	L_{avg}	.150	.553	.565	.284	.806	.284	**.044***	.067	.168

Table 4. Significances of the correlations between acoustic indices and Building Surface Area to Plan Area Ratio in terms of *p* values, where * indicates *p*<0.05 level (2-tailed), and ** indicates *p*<0.01 level (2-tailed) in Bivariate Correlation.

Distance(m) / **Frequency(Hz)**		**0**			**300**			**1000**		
		630	1600	3150	630	1600	3150	630	1600	3150
Open Areas	L_{10}	.379	.140	-	**.019***	.143	.264	-	.373	.499
	L_{50}	.466	.470	.810	.453	.192	.322	.150	.520	.083
	L_{90}	**.021***	.297	**.022***	.173	.158	.966	**.027***	**.018***	.088
	L_{avg}	**.050***	.064	.883	.151	.101	.157	.064	.089	.264
Façades	L_{10}	.379	.108	.379	.051	.379	.051	.512	**.050***	.773
	L_{50}	.177	.854	.578	.115	.584	.155	**.039***	.106	.352
	L_{90}	.665	.695	.941	.691	.916	.691	.239	**.010****	.735
	L_{avg}	.260	.718	.758	.315	.504	.315	.071	.097	.319



(a) 630Hz (b) 3150Hz

Fig. 7. Relationships between L_{90} in open areas and the Complete Aspect Ratio.

3.4 The relations between aircraft noise attenuation and sound source dependent urban morphological parameters

Three sound source dependent parameters, including Building Frontal Area Index (BFAI), Height-to-Width Ratio (HWR) and Horizontal Distance of First-row Building to Flight Path (HDFBFP), have been also investigated. It has been shown that there is no significant correlation between HWR and the acoustic indices. This corresponds to a study by Ismail and Oldham on the effects of street canyon on noise from low flying aircraft [12], which shows that street width, which is indicated by HWR in the current study, hardly plays a role in the noise attenuation. The correlations between acoustic indices and BFAI and HDFBFP are shown in Tables 5 and 6, respectively. By comparing Tables 3&4 and 5&6, it can be seen that generally speaking, the sound source dependent parameters are more correlated to the acoustic indices than the independent ones.

From Table 5 it can be seen that BFAI generally has more correlations with the acoustic indices than the independent parameters when the distance is 1000m (see Table 3, 4 and 5), suggesting that for aircraft noise attenuation, the barrier effect of urban morphology may play a more crucial role than the other effects when the distance is relatively large. However, when the horizontal distance between site and flight path becomes smaller, such as 300m, there is less correlation between acoustic indices and BFAI, since the barrier effects by building façades plays a less significant role.

HDFBFP has the most correlations among the six parameters, especially with the acoustic indices in open areas, as can be seen in Table 6. Unlike CAR, BSAPAR and BFAI, which have fewer correlations in terms of L_{avg} and L_{50} (see Table 3, 4 &5), HDFBFP is highly correlated to L_{avg} (e.g. p=0.000, at 1600Hz at 0m) and L_{50} (e.g. p=0.000, at 630Hz at 1000m) in open areas, although on façades it is almost not correlated with the acoustic indices, as shown in Table 6.

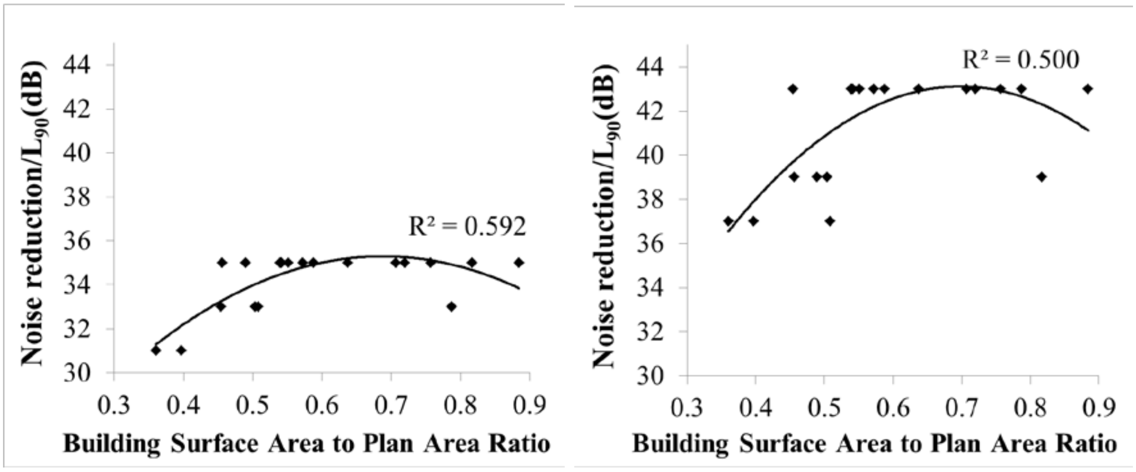
Figure 9 further illustrates the relationships between acoustic indices in open areas and HDFBFP. It can be seen in Fig. 9a that at 0m, the mean L_{avg} at 1600Hz decreases slowly with the increase of HDFBFP, which means if a given low-density site has a row of buildings that are close to the flyover aircraft horizontally, the average noise level in open areas might be considerably reduced, due to barrier effect. At 1000m, the noise attenuations in terms of L_{50} at 630Hz and 3150Hz both decrease constantly when HDFBFP increases, and the difference between the maximum and minimum level is rather high, at about 10dB, as can be seen in Fig. 9b and 9c. In other words, the distance between the first row buildings to flight path might play a rather significant role in the protection of quiet open areas in terms of L_{avg} and L_{50}.

Table 5. Significances of the correlations between acoustic indices and Building Frontal Area Index in terms of *p* values, where * indicates *p*<0.05 level (2-tailed), and ** indicates *p*<0.01 level (2-tailed) in Bivariate Correlation.

Distance(m) / Frequency(Hz)		0			300			1000		
		630	1600	3150	630	1600	3150	630	1600	3150
Open Areas	L_{10}	.640	**.027***	-	.160	.238	.583	-	.390	.265
	L_{50}	.258	.401	.778	.544	.221	.321	.065	.156	.013
	L_{90}	.159	.060	**.022***	.065	.239	.533	**.002****	**.002****	**.002***
	L_{avg}	.149	**.049***	.323	.110	.078	.328	**.018***	**.032***	**.029***
Façades	L_{10}	.640	**.016***	.640	.174	.640	.174	.181	.060	.421
	L_{50}	.601	.842	.918	.303	.158	.303	**.002****	**.020***	.067
	L_{90}	.839	.635	.868	.913	.399	.913	.662	.798	.187
	L_{avg}	.244	.638	.555	.551	.847	.551	**.029***	**.033***	.064

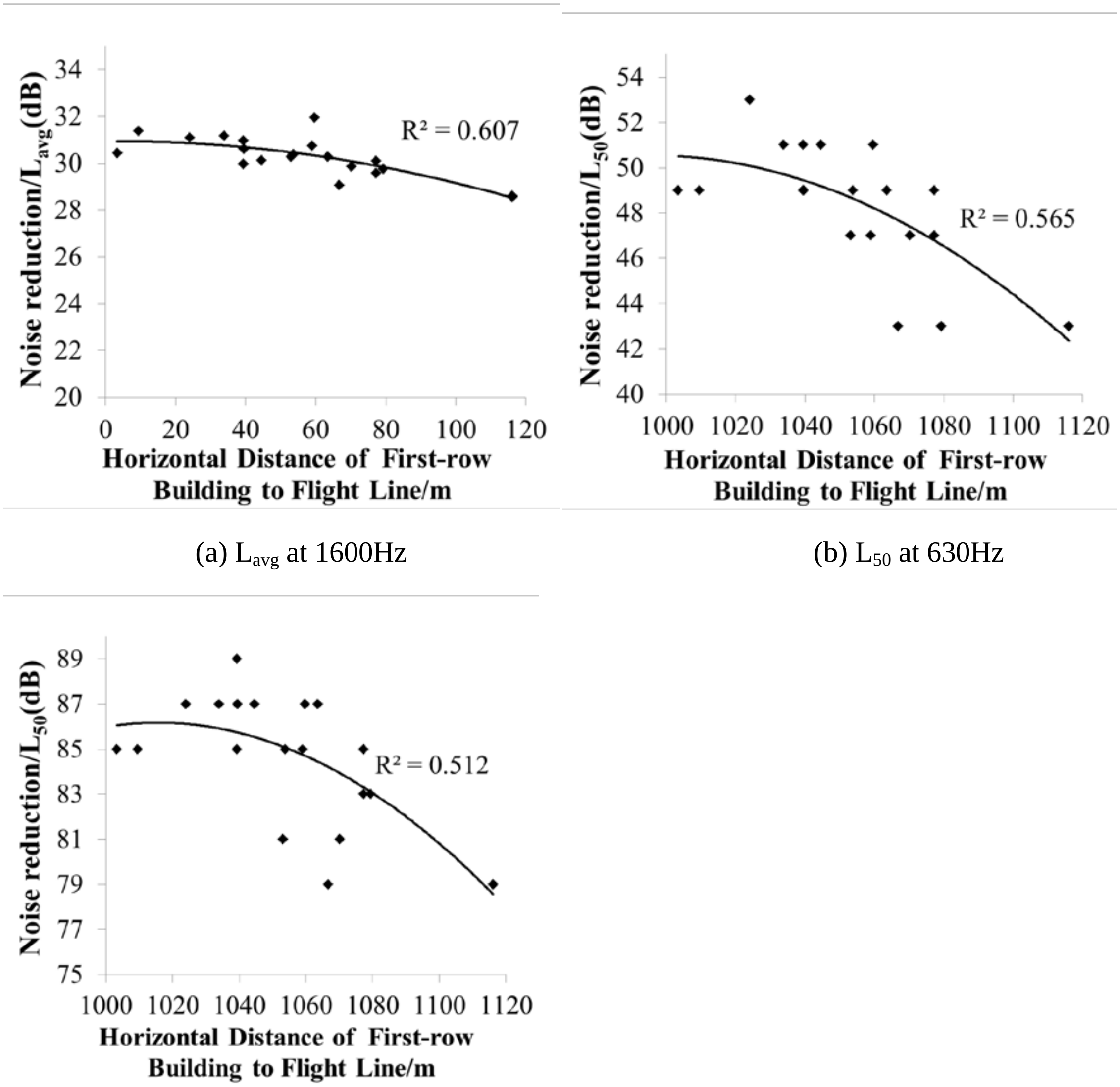
Table 6. Significances of the correlations between acoustic indices and Horizontal Distance of Building to Flight line in terms of *p* values, where * indicates *p*<0.05 level (2-tailed), and ** indicates *p*<0.01 level (2-tailed) in Bivariate Correlation.

Distance(m) / Frequency(Hz)		0			300			1000		
		630	1600	3150	630	1600	3150	630	1600	3150
Open Areas	L_{10}	.481	**.050***	-	.768	.110	.147	-	.909	.088
	L_{50}	.194	.062	.450	.650	**.003****	**.010****	**.000****	**.010****	**.002****
	L_{90}	.687	.513	.355	.334	**.032***	.861	.132	.091	**.034***
	L_{avg}	**.021***	**.000****	.774	.712	**.001****	**.007****	**.001****	**.002****	**.003****
Façades	L_{10}	.481	.936	.481	**.033***	.481	**.033***	.165	.253	.309
	L_{50}	.570	.360	.297	.991	.194	.991	.330	.401	.728
	L_{90}	.657	.643	.661	.994	.844	.994	.337	.833	.750
	L_{avg}	.530	.202	.321	.894	.797	.894	.922	.830	.583



(a) 630Hz (b) 3150Hz

Fig. 8. Relationships between L_{90} in open areas and the Building Surface Area to Plan Area Ratio.



(a) L_{avg} at 1600Hz (b) L_{50} at 630Hz

(c) L_{50} at 3150Hz

Fig. 9. Relationships between acoustic indices in open areas and the Horizontal Distance of First-row Building to Flight Path.

To overview the above results about the correlations between urban morphological parameters and acoustic indices, Table 7 shows the number of correlations according to the acoustic indices, and Table 8 gives the number of correlations according to the horizontal distances between site and flight path. It can be seen from Table 7 that L_{90} (15) and L_{avg} (13) in open areas are more correlated to urban morphological parameters than L_{10}, which indicates that control of urban morphological parameters can benefit aircraft noise attenuation for the relatively quiet areas and the whole area of a given site. Table 8 shows that when the distance is 1000m, urban morphology has greater influence on aircraft noise attenuation, both on façades and in open areas. Overall, two parameters, BFAI (14) and HDFBFP (17) have more correlations than the others.

Table 7. The number of correlations between urban morphological parameters and acoustic indices, according to the acoustic indices L_{10}, L_{50}, L_{90} and L_{avg}, both on façades and in open areas.

Urban Morphological Parameters	Open areas				Façades				Total
	L_{10}	L_{50}	L_{90}	L_{avg}	L_{10}	L_{50}	L_{90}	L_{avg}	
BPAF	0	0	0	0	0	0	0	0	0
CAR	0	0	5	1	0	1	1	1	9
BSAPAR	1	0	4	1	1	1	1	0	9
BFAI	1	0	4	4	1	2	0	2	14
HWR	0	0	0	0	0	0	0	0	0
HDFBFP	1	5	2	7	2	0	0	0	17
Total	3	5	15	13	4	4	2	3	49

Table 8. The number of correlations between urban morphological parameters and acoustic indices, according to the horizontal distance between site and flight path, at 0m, 300m and 1000m, both on façades and in open areas.

Urban Morphological Parameters	Open areas			Façades			Total
	0m	*300m*	*1000m*	*0m*	*300m*	*1000m*	
BPAF	0	0	0	0	0	0	0
CAR	2	1	3	0	0	3	9
BSAPAR	3	1	2	0	0	3	9
BFAI	3	0	6	1	0	4	14
HWR	0	0	0	0	0	0	0
HDFBFP	3	5	7	0	2	0	17
Total	11	7	18	1	2	10	49

4. Conclusions

This study aims to explore whether and how mesoscale urban morphology of low-density built-up areas influence the spatial noise level attenuation of flyover aircrafts. Six urban morphological parameters have been selected and developed in the study. The effects of horizontal flight path distance to site and flight altitude on aircraft noise attenuation are both considered.

The largest difference and variance of aircraft noise level attenuation are at 1000m, among the five horizontal flight path distances to site, i.e. 0m, 100m, 300m, 600m and 1000m. Sound reflections by buildings reduce the influence of urban morphology on noise attenuation. Compared with the distances of 0m and 300m, the acoustic indices have more correlations with the urban morphological parameters at 1000m. The increase from 200ft to 400ft in flight altitude generally does not benefit the noise attenuation significantly.

The façades have higher noise attenuation than open areas, but the variances of the acoustic indices on façades, including L_{10}, L_{50}, L_{90} and L_{avg}, are lower, and their correlations with the urban morphological parameters are less. In other words, urban morphology plays a more important role on aircraft noise attenuation for open areas than for façades. Moreover, the control of urban morphological parameters can benefit aircraft noise level attenuation more in quiet open areas and the whole area, rather than noisy open areas.

The urban morphological parameters tend to have considerable correlations with flyover aircraft noise attenuation in this study. Compared with the sound source location independent morphological parameters, the sound source dependent parameters may have greater influence. The general tendency is that the Building Frontal Area Index (BFAI) and Horizontal Distance of First-row Building to Flight Path (HDFBFP) correlate with noise attenuation most, while Building Plan Area Fraction (BPAF) and Height-to-Width Ratio (HWR) hardly influence the noise attenuation. The noise level attenuation in terms of L_{90} in open areas tends to increase with the increase of Complete Aspect Ratio (CAR) and then stays stable after CAR reaches approximately 1.4. The noise level attenuation in terms of L_{90} in open areas has a tendency to increase when the Building Surface Area to Plan Area Ratio (BSAPAR) increase before approximately 0.7 and it then decreases. The noise attenuation in terms of L_{50} and L_{avg} shows a constant upward tendency when HDFBFP decreases.

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