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DOI
10.2514/6.2016-2769

Publication date
2016

Document Version
Accepted author manuscript

Published in
Proceedings of the 22nd AIAA-CEAS Aeroacoustics Conference

Analysis of landing gear noise during approach

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Airframe noise is becoming increasingly important during approach, even reaching higher noise levels than the engines in some cases. More people are affected due to low flight altitudes and fixed traffic routing associated with typical approaches. For most aircraft types, the landing gear system is a dominant airframe noise source. However, this element can only be modeled in an approximate manner in wind tunnel experiments. In this research, flyovers of landing aircraft were recorded using a 32 microphone array. Functional beamforming was applied to analyze the noise emissions from the landing gear system. It was confirmed that for some aircraft types, such as the Airbus A320 and the Fokker 70, the nose landing gear is a dominant noise source during approach. The correlation between the noise levels generated by the landing gear and the aircraft velocity was found to be significant, explaining about 70% of the variability found in the noise levels, which is in good agreement with all known theory. Moreover, the experimental results for the Airbus A320 measurements were compared with those obtained using the DLR system noise prediction tool PANAM. Whereas the total aircraft noise levels were in good agreement, the measurements indicate a higher contribution from the nose landing gear noise compared to the predictions.

I. Introduction

For decades, aircraft noise has been a continuous nuisance for residents living in the surroundings of airports. This problem also affects the aerospace industry, because noise regulations are becoming stricter leading to the limitation of the capacity of airports, night curfews and penalties to the airlines. All these facts occur in a situation with a continuous growth of air traffic (around a 5% rate per year up to 2013[1]), which is expected to aggravate the problem even more in the near future.

Engine noise has been reduced significantly on modern aircraft thanks to the implementation of high bypass ratio turbofan engines and acoustic lining around the 1970s [2, 3]. The reduction is such that, during landing, engines are not always the dominant noise source anymore and airframe noise, namely the noise produced by the interaction of the aerodynamic surfaces with the surrounding turbulent flow [4], is becoming more relevant, generating in some cases higher Sound Pressure Level (SPL) values than the engines. The dominant airframe noise source in most cases is the landing gear system [3, 5], followed by the leading edge and trailing edge devices, if deployed.

To determine the relative noise contributions of the aircraft elements, microphone arrays can be employed. Beamforming algorithms are applied to the array acoustic data to estimate the location and amplitude of

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sound sources at a selected frequency. Flyover tests with microphone arrays are the only feasible method to accurately measure the sound sources of an aircraft in real flight conditions, which are very difficult to represent in a precise way in wind tunnel experiments or numerical simulations [6]. For the case of landing gear noise, the study of small scale models in wind tunnels is usually not accurate enough due to the lack of geometrical detail in these models and the violation of the Reynolds similarity condition [3, 5, 7]. For instance, the presence of parasitic noise sources, which can contribute significantly to the overall airframe noise signature, may be overlooked [3].

In this research, 115 flyovers were recorded using a 32 microphone array to determine the main aircraft noise sources and their relative contributions for a variety of aircraft types under operational conditions. This paper focuses on 7 Airbus A320 and 23 Fokker 70 flyover measurements. Special emphasis was placed on the nose landing gear noise, studying its behavior in terms of frequency and aircraft velocity. Moreover, a correlation analysis was performed as an attempt to relate the observed variations in the noise levels from the landing gear to other factors, such as the aircraft velocity.

In addition, the experimental frequency spectra were compared with the results provided by an aircraft system noise prediction tool.

II. Experimental setup

The experimental campaign took place at Amsterdam Airport Schiphol, where 115 landing flyover measurements were recorded using a 32 microphone array arranged in a spiral distribution, see Fig. 1(a). The array has an effective diameter of 1.7 m and uses band filters for the frequency range from 45 Hz to 11,200 Hz. The sampling frequency employed was 40 kHz. Moreover, an optical camera was integrated in the center of the array at a fixed angle facing straight up, allowing the use of video footage synchronised with the acoustic data. The measurements were taken during two days with similar weather conditions and low wind speed [8].

Flight trajectories during landing are usually more regular than the ones for take-off, because all aircraft follow the Instrument Landing System (ILS) approach. In addition, the main reason for recording landing aircraft is because the engines are usually at approach idle or low fan rotational speed, so engine noise is less dominant and, thus, it is more likely to identify airframe noise sources. Hence, the microphone array was located 1240 m to the South of the threshold of the Aalsmeerbaan runway (36R), mainly used for landing, as illustrated in Fig. 1(b).

(a) (b)

Figure 1: (a) 32 Microphone array configuration, (b) Experimental setup located 1240 m to the South of the threshold of the Aalsmeerbaan (36R) Schiphol airport runway.

To be able to properly correct the propagation and Doppler effects, the trajectories of the aircraft need to be precisely determined. To that end, three different approaches [9] were used: The ADS-B (Automatic Dependent Surveillance-Broadcast), the ground radar from air traffic control, and the extrapolation of the optical camera images. The agreement between the results from the three methods is satisfactory. The optical camera data are preferred due to its availability and because it is easier to overlay the beamforming source plots to the optical frames. The other methods were used as a validation for the trajectory estimations. The average flight altitude and average aircraft velocity above the array were determined to be 67 m and

271 km/h, respectively. For such close distances to the threshold, small variations of velocity and altitude can be expected along the standard ILS approach.

The recorded acoustic data correspond to 13 different aircraft families, depending on the type of engine installed, see table 1. For this paper, only the Airbus A320 (7 flyovers) and Fokker 70 (23 flyovers) cases are further investigated. The Airbus A320 type was separated in two different categories because they were equipped with different engines. However, because this research focuses on airframe noise, both categories were analyzed together.

Table 1: Aircraft types with their correspondent engine and the number of recorded measurements for each type. The measurements analyzed in this paper are shown in bold.

Aircraft type	Amount	Engine type
Airbus 300	1	CF6-80C2A5
Airbus 320 (CFM)	**4**	**CFM56-5B5/P**
Airbus 320 (IAE)	**3**	**IAE V2500-A1**
Airbus 380	1	GP7270
Boeing 737 (series 300, 400 and 500)	9	CFM56-3C1
Boeing 737 (series 700, 800 and 900)	50	CFM56-7B
Boeing 747	4	CF6-80C2B1F
Boeing 767	1	PW 4060
Boeing 777	6	GE90-94B
Embraer 145	1	RR AE3007A1
Embraer 190	11	GE CF34-10E5
Fokker 70	**23**	**RR TAY 620**
McDonnell Douglas 81	1	PW JT8D-217C

III. Beamforming method

A. Data preprocessing

Several preprocessing considerations need to be taken into account for the case of flyover measurements. To perform these corrections, the aircraft flight trajectories need to be accurately estimated, as was mentioned in Sec. II.

1. First of all, to avoid amplification errors, the background noise needs to be considered, such as the noise generated by the microphone array electronics or the ambient noise. Thus, all the SPL values in the spectrograms under a 30 dB threshold value were neglected [8].

2. Secondly, the Doppler effect due to the relative motion of the aircraft with respect to the observer needs to be corrected to determine the emitted frequencies. A resampling of the data is required, as stated by Howell *et. al.* [10]. Moreover, the effect of the moving source also affects the time delays considered for the beamforming algorithms [6, 9].

3. Lastly, the propagation effects (namely the geometrical spreading and the atmospheric absorption) have to be considered for obtaining the actual SPL values at the source location [2, 8].

B. Functional beamforming

Functional beamforming is a novel technique recently developed (2014) by Dougherty [11, 12]. This method is based on the conventional frequency domain beamforming (CFDBF) algorithm, also known as delay-and-sum, which is the most widely used method for aeroacoustic experiments [6, 13–18]. The performance of functional beamforming depends on an exponent parameter ν which needs to be set by the user.

The source autopower (A_ν) expression for the functional beamformer is based on the eigenvalue decomposition of the cross-spectral matrix $\boldsymbol{C}$. For the general case of a N-microphone array and for a general grid point $\boldsymbol{\xi}_j$ in the scan plane:

$$A_\nu\left(\boldsymbol{\xi}_j\right) = \left[\boldsymbol{w}_j^* \boldsymbol{C}^{\frac{1}{\nu}} \boldsymbol{w}_j\right]^\nu = \left[\boldsymbol{w}_j^* \boldsymbol{U} \boldsymbol{\Sigma}^{\frac{1}{\nu}} \boldsymbol{U}^* \boldsymbol{w}_j\right]^\nu \tag{1}$$

where an asterisk $(\cdot)^*$ denotes the complex conjugate transpose, $\boldsymbol{U}$ is a unitary matrix whose columns are the eigenvectors of $\boldsymbol{C}$, $\boldsymbol{\Sigma}$ is a diagonal matrix whose diagonal elements are the eigenvalues of $\boldsymbol{C}$, and $\boldsymbol{w}_j \in \mathbb{C}^{N\times 1}$ is the normalized steering vector, $\boldsymbol{g}_j \in \mathbb{C}^{N\times 1}$, for that grid point $\boldsymbol{\xi}_j$. The steering vector accounts for the phase shifts and change in amplitude between the source and each microphone [6, 9, 19]. Different steering vector normalizations are found in the literature [20], but none of them is able to provide the exact source location and the correct source strength at the same time, although the errors are typically small for acoustic sources close to nadir, as considered in this paper. In this research, two different normalizations were employed. The first one provides the correct source position [Eq. (2)] and the second one the correct source strength [Eq. (3)].

$$\boldsymbol{w}_{j_{pos}} = \frac{\boldsymbol{g}_j}{\|\boldsymbol{g}_j\|} \tag{2}$$

$$\boldsymbol{w}_{j_{str}} = \frac{\boldsymbol{g}_j}{\|\boldsymbol{g}_j\|^2} \tag{3}$$

A compromise solution is to first calculate the source plot with the correct source positions using Eq. (2) in Eq. (1) and later correct the SPL values of the whole source plot according to the ones obtained when using Eq. (3) in Eq. (1). In this way, a satisfactory combination of estimating both source strength and location is achieved.

With functional beamforming, the Point Spread Function (PSF) factor is now powered to the exponent ν [11]. Therefore, powering the PSF at a sidelobe will lower its level, leaving the true source value identical. For ideal conditions, the dynamic range (the difference in decibels between the main lobe and the highest sidelobe [6]) for the functional beamforming should increase linearly with the exponent value, ν [11]. Thus, for an appropriate exponent value the dynamic range is significantly increased. The beamforming peak will also be sharpened, improving the array spatial resolution (width of the main lobe 3 dB under the peak [21]) to some extent. The computational time for the functional beamforming is basically identical to the CFDBF, because the only relevant operation added is the eigenvalue decomposition of $\boldsymbol{C}$, which is typically faster than the rest of steps involved in the beamforming process. Notice that the case with $\nu = 1$ corresponds to the CFDBF formula.

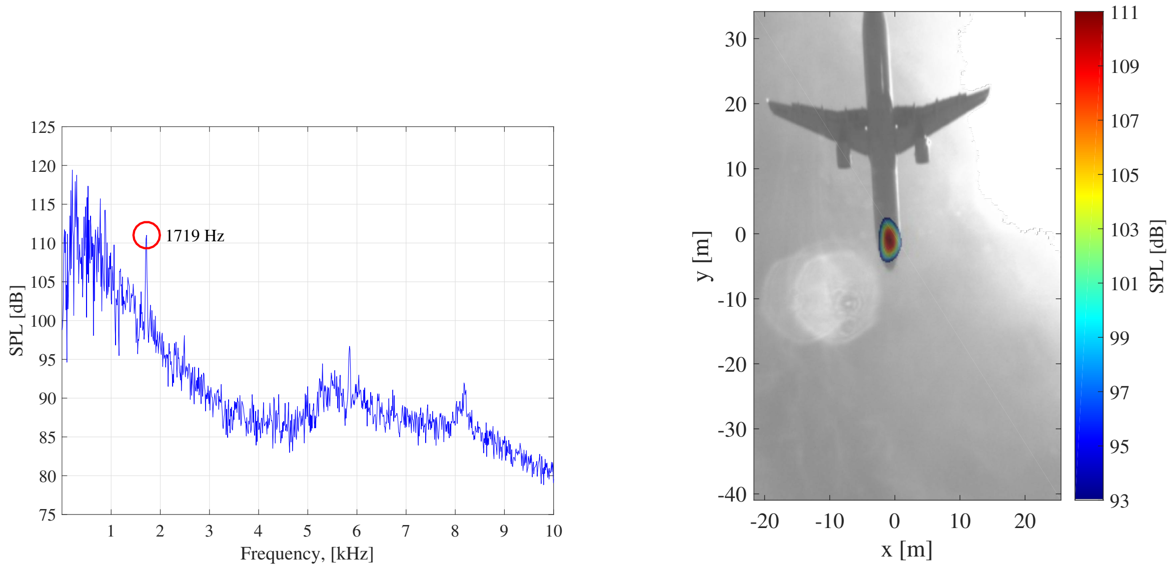
In previous work, functional beamforming has been applied for numerical simulations [9, 11, 12], idealized cases with speakers as experimental noise sources, and controlled experiments with components in a laboratory [11, 12]. This algorithm was also tested recently [9, 19] for practical aeroacoustic experiments on full-scale aircraft during operational conditions indicating a dynamic range (in decibels) approximately 30 times larger and an array spatial resolution 6 times better than the CFDBF. Thus, this algorithm is more suitable for flyover measurements.

IV. Experimental results

Henceforth, all the presented results refer to emission angles of 90°, i.e., the direction perpendicular to the aircraft, pointing down and at the source position. The azimuthal angle was considered to be 0°, i.e., within the aircraft symmetry plane.

A. Analysis of the Airbus A320 nose landing gear noise

After analyzing the acoustic frequency spectra from each flyover, it was observed that all the measurements from the Airbus A320 family present a high tonal peak in a frequency range between 1500 and 1750 Hz, see Fig. 2(a). The source plots after using functional beamforming with $\nu = 100$ at those peak frequencies showed that the tonal noise is generated at the nose landing gear position, see Fig. 2(b). Interestingly, analogous frequency peaks and source location were found by Michel and Qiao [5] for a single-aisle aircraft. The main landing gear system (both bogies) was not a dominant sound source at this particular frequencies, but it usually has a similar contribution than the nose landing gear [3, 22], as will be shown later in Sec. IV.B. However, it is more difficult to isolate the noise coming from the main landing gear, due to the proximity to the engines in most aircraft types, which can obscure the beamforming source plots. This is a problem especially at low frequencies, due to the Rayleigh criterion [5, 23].



(a) (b)

Figure 2: (a) Frequency spectrum at the source position for an Airbus A320 flyover during the time overhead, (b) Beamforming source plot for the same Airbus A320 flyover at the peak frequency of 1719 Hz. Functional beamforming was applied with $\nu = 100$.

It is interesting to notice that the frequency of the aforementioned tonal peaks for all the seven Airbus A320 in this research does not seem to have a significant correlation with the aircraft velocity (see Fig. 3) because the correlation coefficient, $\rho \approx 0.16$, is considerably low and the p$-$value ≈ 0.73 is much larger than the 0.05 threshold typically used for determining whether a correlation is significant or not [22]. This fact indicates that these tones are likely to be caused by a flow-induced cavity resonance in the landing gear system, as suggested by Michel and Qiao [5] and Dobrzynski [3]. This cavity noise depend on both the geometry of the orifice and the local flow conditions [3]. For sound waves with a frequency of around 1700 Hz and a sound speed of $c = 340$ m/s, the approximate value of the half-wavelength is 10 cm. This length is of the same order of magnitude as the dimensions of some of the many components of the nose landing gear for this aircraft type [24], such as the towing fitting width, which would explain the presence of the tonal peaks found in the spectra.

B. Relative contribution of the landing gear noise

The relative contribution of the landing gear noise was initially studied for two different aircraft types: the Airbus A320 and the Fokker 70. These vehicles have been selected for this initial assessment due to their prominent airframe noise [22] and their market share and, hence impact on community noise. Figure 4 contains an example of a source plot for each aircraft, which depicts the Overall SPL (OASPL) when the nose landing gear is above the array. Functional beamforming with $\nu = 100$ and a time interval of 0.1 s were used to obtain these results. It can be observed that for the Airbus A320 [Fig. 4(a)], the nose landing gear is a dominant source, as well as what it seems to be a combination of flap noise and main landing gear noise, with possible contribution of the engines exhaust as well. As mentioned before, it is difficult to separate the individual noise contribution of the main landing gear with the current setup. On the other hand, the engines of the Fokker 70 [Fig. 4(b)] are mounted at the back of the fuselage, further away from the main landing gear than for the Airbus A320 case. This allows for a separation of both sources, as performed by Snellen *et. al.* [22], showing that the whole main landing gear has a contribution approximately 4 dB larger than the nose landing gear.

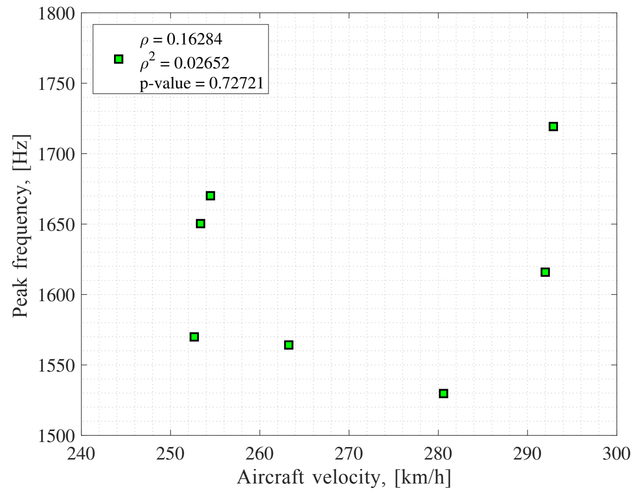


Figure 3: Peak tonal frequencies found for the Airbus A320 measurements emitted at the nose landing gear plotted versus the respective aircraft velocities.

The boxplots in Fig. 5 present the relative contribution, as well as the variability in the noise levels, of the landing gear noise for the seven Airbus A320 and the 23 Fokker 70 flyovers. These results were obtained by extracting the maximum OASPL values from the landing gear positions, as depicted by the black boxes in Fig. 4). The Airbus A320 nose landing gear average OASPL is only 4 dB lower than the average total OASPL of the whole aircraft, confirming the importance of this noise source. The variability of the total OASPL (4.6 dB) is smaller than the variability of the nose landing gear OASPL (6.9 dB). This fact indicates that other noise sources of similar magnitude are present as well. For the Fokker 70 the main landing gear is the strongest noise source presenting an average OASPL approximately 4 dB lower than the average total OASPL, whereas the nose landing gear presents average values 8 dB lower than the total. The variability of the total OASPL (7.5 dB) is now slightly larger than those of the different sources: main landing gear (6.4 dB) and nose landing gear (6.2 dB). The variabilities for both aircraft types are of the same order of magnitude. A correlation analysis for these variabilities is presented in the following subsection.

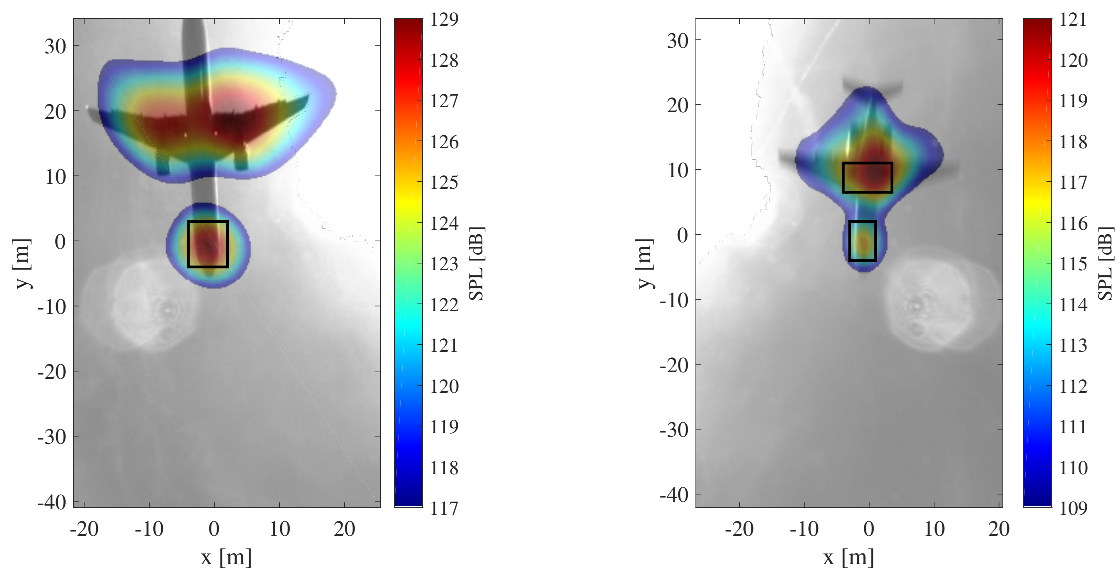
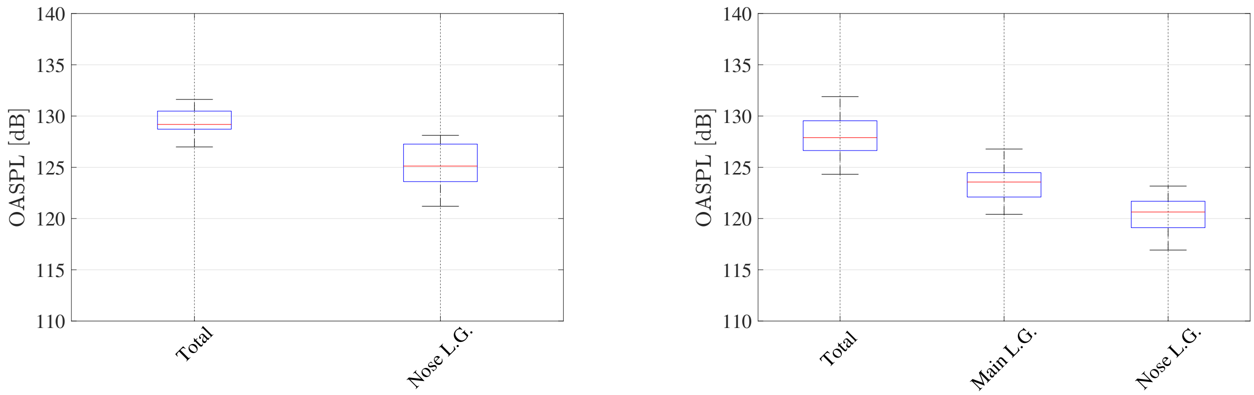


Figure 4: Beamforming source plots for example flyovers. The OASPL using functional beamforming with $\nu = 100$ is indicated. The black rectangles show the areas of study for the variability analysis.



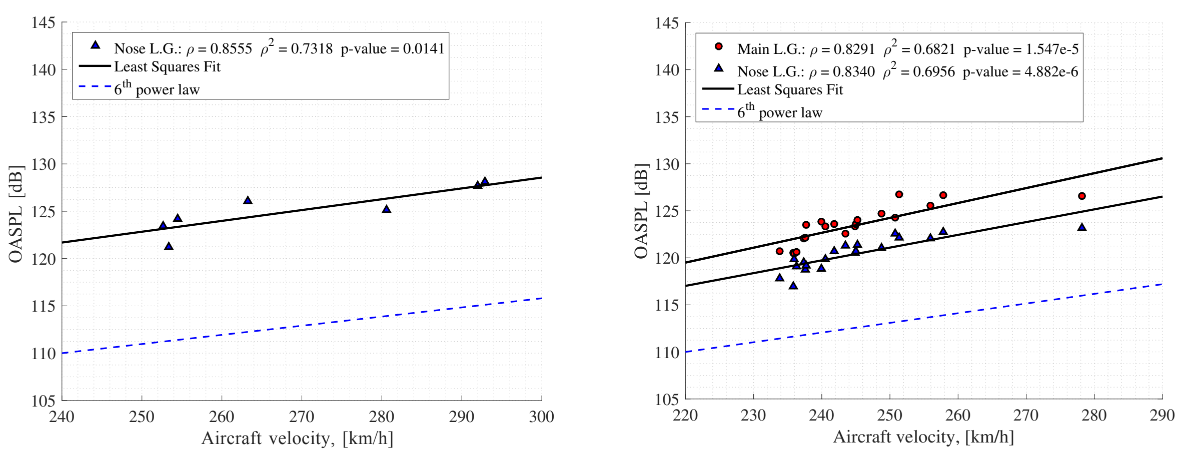
(a) Airbus A320 (b) Fokker 70

Figure 5: Boxplot of the measured total OASPL and the OASPL at the landing gear system. On each box, the central mark is the median, the edges of the box are the 25^{th} and 75^{th} percentiles and the whiskers extend to the most extreme data points.

C. Correlation analysis with the aircraft velocity

A correlation analysis was performed to determine the dependency of the noise levels generated by the landing gear with the aircraft velocity. Previous studies in similar conditions [25, 26], showed that the effect of the variable atmosphere on the sound propagation in the noise level variability for distances up to 100 m is negligible. As mentioned in Sec. II, the measurements were taken during two days with similar weather conditions. Therefore, the variability in the noise levels is assumed to be mainly caused by changes in the sound source, i.e., the aircraft.

Figure 6 shows the variability of the OASPL generated by the nose landing gear for the Airbus A320 case [Fig. 6(a)] and for the Fokker 70 case [Fig. 6(b)]. Both aircraft types present a high and significant ($p-$values < 0.05) correlation between the OASPL at the landing gear and the aircraft velocity. This correlation is compatible with the expected theoretical prediction by Curle [27], which states that the acoustic power approximately follows a 6^{th} power law (also included in the graphs in Fig. 6) with the airflow Mach number. For both aircraft types, coefficients of determination ρ^2 of around 0.7 are obtained, meaning that approximately 70% of the variability of the noise levels from the landing gear can be explained by changes in the aircraft velocity. Once again, a similar behavior was observed by Michel and Qiao [5] in their flyover experiments.



(a) Airbus A320 (b) Fokker 70

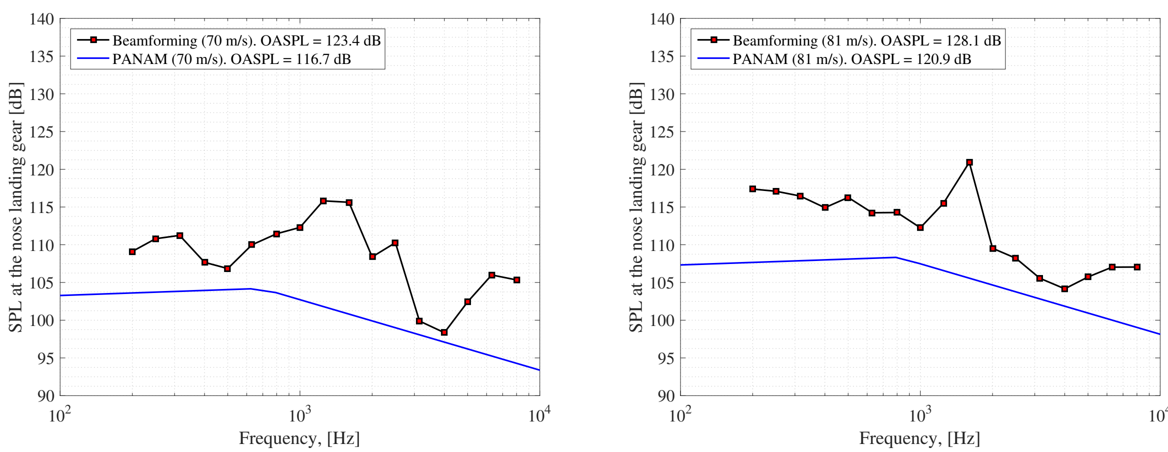
Figure 6: Correlation analysis between the OASPL at the nose landing gear and the aircraft velocity.

D. Comparison with aircraft system noise prediction

In this section, the measured frequency spectra and OASPL values are compared with simulation results. In previous studies [30], the predictions from the methods of Fink [31] and Guo [32] were compared with wind tunnel measurements using a scaled-model Boeing 777 main landing gear. However, as it was mentioned before, it is difficult to scale these results to obtain accurate full-scale predictions, since, for example, parasitic noise sources may not be detected in wind tunnel experiments [3]. Therefore, the comparison of the prediction models with flyover data of aircraft under operational conditions is of great interest.

The simulations are carried out with a so-called scientific prediction tool. The German Aerospace Center (DLR) has developed this aircraft system noise prediction tool, i.e., the Parametric Aircraft Noise Analysis Module (PANAM) [28]. PANAM models the overall aircraft noise as a sum of individual noise components on-board and their interactions. Specific noise source models are applied to simulate the major noise sources, i.e., airframe and engine contributions, and ultimately to obtain the ground noise impact of the whole aircraft. These noise source models are parametrical, hence allow to modify the underlying parameters of each source. As a consequence, the parameters which refer to the operational and geometrical data can be optimized for minimal noise contribution (within predefined limits). This tool is mainly used to assess the impact of low-noise modifications to individual components on-board of existing aircraft or for the design of new low-noise aircraft [29].

In the context of this paper, prediction results are generated for the Airbus A320 experimental test cases aforementioned. For the different flights, the frequency spectra for the nose landing gear and for the whole aircraft on a reference sphere of 1 m are predicted and compared to the measured spectra after beamforming. For illustration purposes, only the two cases with lowest (70 m/s) and highest (81 m/s) aircraft velocities available are presented here. The same analysis was repeated for measurements with different velocities, showing similar results. The comparisons of the experimental and predicted one-third octave frequency spectra for the nose landing gear noise are presented in Fig. 7. The frequency range for the experimental data is restricted to $200 - 8000$ Hz due to the limitations of the current microphone array geometry.



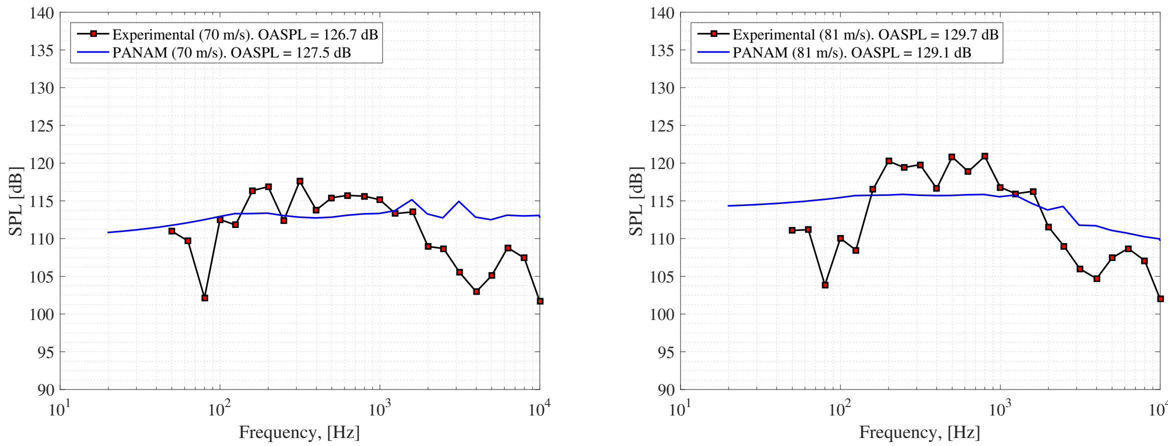
(a) $V = 70$ m/s (b) $V = 81$ m/s

Figure 7: Comparison between the experimental and predicted frequency spectra of the nose landing gear noise for two Airbus A320 flyovers.

Results in Fig. 7 show a considerable difference between experimental and predicted spectra in both cases. It is seen that the measured data consistently indicate higher noise level values, with OASPL values approximately 7 dB higher than those predicted. The maximum A-weighted levels are present in the frequency range between 500 and 3000 Hz, as observed by Dobrzynski [3, 7] in wind tunnel tests with (original) full-scale landing gears. It can be observed that the predicted frequency spectra present no tonal contribution because only classical noise sources can be accounted for by PANAM. This is a strong indicator that the measured tonal peaks do indeed originate from a parasitic noise source, e.g. a cavity on the nose landing gear as mentioned before. In case the tonal peak would not be present, the observed OASPL for the nose landing gear would be approximately 2 dB lower, obtaining a closer agreement with the modeled data.

The frequency spectra for the whole aircraft is also compared for the same flyovers, as depicted in Fig.

8. In this case, the experimental data considered refer to the sound signal of a single microphone corrected for the propagation effects mentioned in Sec. III.A. Because the whole aircraft is considered now, the noise contribution from the engines and all other modeled airframe sources is also included. The corresponding engine fan settings (N1%) of each flyover were calculated from the spectrograms [8]. For the cases shown in Fig. 7 they were found to be 48% for the flyover with a 70 m/s velocity and 43% for the one with 81 m/s. Furthermore, the geometric parameters for airframe and engines, and, most importantly, the engine performance data are required. All these necessary input data was not directly recorded during the experiments, and, therefore, had to be derived from the sound signals [8] and additional simulation results.



(a) $V = 70$ m/s, $N1\% = 48\%$ (b) $V = 81$ m/s, $N1\% = 43\%$

Figure 8: Comparison between the experimental and predicted frequency spectra of the total aircraft noise for two Airbus A320 flyovers.

In general, it seems that the experimental data in Fig. 8 present higher noise levels for frequencies between 150 and 1000 Hz and lower levels for lower and higher frequencies. The graphs for both velocities present similar trends in frequency. However the OASPL difference between the predicted and experimental results in this case is less than 1 dB. Even though there was a considerable difference in the nose landing gear predictions, the predicted total noise level at the source is in very close agreement with the experimental data. The observed differences can be partially attributed to one or a combination of the following facts:

1. The experimental results for the nose landing gear sound spectra (see Fig. 7) are obtained after applying beamforming, whereas the ones for the whole aircraft (see Fig. 8) are obtained using data from a single microphone.
2. Beamforming considers separated sound sources, whereas prediction models such as PANAM consider all the noise sources on an aircraft as a point source.
3. Apart from the inherent uncertainties of the experiments and models, the input data employed for the predictions was not directly recorded and had to be estimated or derived from additional data sources.

Finally, the observed ranking of the most dominant noise sources for these operational conditions was found to be the same as that predicted by the model.

V. Conclusions

In this research functional beamforming was applied to full-scale flyover measurements using a 32 microphone array. Special emphasis was placed on the noise emitted by the landing gear system due to its relatively high contribution to the total aircraft noise level during the approach stage. The analysis performed for the Airbus A320 measurements showed a strong tonal noise peak for frequencies around 1600 Hz generated at the nose landing gear. The frequencies where the peak is found do not scale with the aircraft velocity.

A detailed analysis of the noise emissions of the Airbus A320 and the Fokker 70 confirmed that the landing gear noise is a dominant source for both aircraft types during approach. Variations in the landing gear noise of around 6 dB were observed for flyovers of the same aircraft type. Around 70% of these variations can be explained by changes in the aircraft velocity, following the expected 6^{th} power law.

Finally, a comparison of the measured Airbus A320 frequency spectra with the results of the aircraft system noise prediction tool PANAM was performed. The measurements indicate higher noise levels for the nose landing gear, presenting OASPL values around 7 dB higher than those predicted. This difference may be partially explained due to the fact that the tonal peak found for the Airbus A320 is not modeled in the predictions, which provides evidence that this noise source may be generated by a cavity in the nose landing gear. On the other hand, the difference between the predicted and measured noise levels for the whole aircraft is less than 1 dB and the ranking of the dominant sources is the same for both cases.

This study will hopefully improve the insight of landing gear noise in terms of frequency and aircraft velocity. For the tonal peak example, a careful analysis should be performed to eliminate this kind of airframe noise, e.g. by closing any unnecessary cavity with pin-hole caps or the installation of vortex generators.

The observed differences between the flyover measurements and the predictions emphasize the necessity of recorded flight data for such comparisons. Further research is recommended, including the study of other aircraft components from different aircraft types under a wider variety of operational conditions, allowing a more detailed comparison with the current prediction models.

References

[1] Boeing Commercial Airplanes. *Current Market Outlook 2013-2032.* USA 2013.

[2] Ruijgrok, G.J.J., *Elements of aviation acoustics.* Second edition 2007. VSSD. Delft, The Netherlands. ISBN-10 90-6562-155-5.

[3] Dobrzynski, W.. "Almost 40 Years of Airframe Noise Research: What Did We Achieve?," Journal of Aircraft, Vol. 47, No. 2, pp 353−367. March−April 2010. DOI: 10.2514/1.44457.

[4] Lighthill, M. J., "On sound generated aerodynamically, I. General theory," Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences, Vol. 221, No. 1107, pp 564−587. 1952. DOI: 10.1098/rspa.1952.0060.

[5] Michel, U. and Qiao,W., "Directivity of Landing-Gear Noise Based on Flyover Measurements," 5^{th} AIAA/CEAS Aeroacoustics Conference, May 10−12 1999, Bellevue, Greater Seattle, WA, USA.DOI: 10.2514/6.1999-1956. AIAA Paper 1999-1956.

[6] Sijtsma, P., "Phased array beamforming applied to wind tunnel and fly-over tests," National Aerospace Laboratory (NLR), NLR-TP-2010-549. December 2010.

[7] Dobrzynski, W. and Buchholz, H. "Full-scale noise testing on Airbus landing gears in the German Dutch Wind Tunnel," 3^{rd} AIAA/CEAS Aeroacoustics Conference, May 12−14 1997, Atlanta, Georgia, USA. DOI: 10.2514/6.1997-1597. AIAA Paper 1997-1597.

[8] Snellen, M., Merino-Martinez, R., and Simons D.G., "Assessment of aircraft noise sources variability using an acoustic camera," 5^{th} CEAS Air & Space Conference. Challenges in European Aerospace. September 7−11 2015, Delft, Netherlands.

[9] Merino-Martinez, R., Snellen, M., and Simons D.G., "Functional beamforming applied to imaging of flyover noise on landing aircraft," Journal of Aircraft, June 2016. DOI: 10.2514/1.C033691.

[10] Howell, G.P., Bradley, A.J., McCormick M.A., and Brown J.D., "De-Dopplerization and acoustic imaging of aircraft flyover noise measurements," Journal of Sound and Vibration, Vol. 105, No. 1, pp 151−167. 1986. DOI: 10.1016/0022-460X(86)90227-0.

[11] Dougherty, R.P., "Functional Beamforming," Proceedings of the 5^{th} Berlin Beamforming Conference, BeBeC 2014-01, February 2014.

[12] Dougherty, R.P., "Functional Beamforming for Aeroacoustic Source Distributions," 20^{th} AIAA/CEAS Aeroacoustics Conference, June 16−20 2014, Atlanta, GA, USA. DOI: 10.2514/6.2014-3066. AIAA Paper 2014-3066.

[13] Camier, C., Padois, T., Provencher, J., Gauthier, P.A., Berry, A., Blais, J.F., Patenaude-Dufour, M., and Lapointe, R., "Fly-over source localization on civil aircraft," 20^{th} AIAA/CEAS Aeroacoustics Conference, May 27−29 2013, Berlin, Germany. DOI: 10.2514/6.2013-2261. AIAA Paper 2013-2261.

[14] Dougherty, R.P., Ramachandran, R.C., and Raman, G., "Deconvolution of Sources in Aeroacoustic Images from Phased Microphone Arrays Using Linear Programming," 20^{th} AIAA/CEAS Aeroacoustics Conference, May 27−29 2013, Berlin, Germany. DOI: 10.2514/6.2013-2210. AIAA Paper 2013-2210.

[15] Sijtsma, P. and Stoker, R.W., "Determination of Absolute Contributions of Aircraft Noise Components using Fly-Over Array Measurements," 10^{th} AIAA/CEAS Aeroacoustics Conference, May 10−12 2004, Manchester, Great Britain. DOI: 10.2514/6.2004-2958. AIAA Paper 2004-2958.

[16] Sijtsma, P. and van der Wal, H.M.M., "Identification of Noise Sources on Civil Aircraft in Approach using a Phased Array of Microphones," National Aerospace Laboratory (NLR), NLR-TP-2004-166. April 2004.

[17] Michel, U., Barsikow, B., Helbig, J., Hellmig, M., and Schüttpelz, M., "Flyover noise measurements on landing aircraft with a microphone array," 4^{th} AIAA/CEAS Aeroacoustics Conference, 1998, Toulouse, France. DOI: 10.2514/6.1998-2336. AIAA Paper 1998-2336.

[18] Sijtsma, P., "Experimental techniques for identification and characterisation of noise sources," National Aerospace Laboratory (NLR), NLR-TP-2004-165. April 2004.

[19] Merino-Martinez, R., Snellen, M., and Simons D.G., "Functional beamforming applied to full scale landing aircraft," Proceedings of the 6^{th} Berlin Beamforming Conference, BeBeC 2016-D12, February 2016.

[20] Sarradj, E., "Three-dimensional acoustic source mapping with different beamforming steering vector formulations," Advances in Acoustics and Vibration. Vol. 2012, Article ID 292695. DOI: 10.1155/2012/292695.

[21] Mueller, T. J. (Ed.), *Aeroacoustic Measurements*. First edition 2002. Springer-Verlag Berlin Heidelberg. ISBN-978-3-642-07514-8.

[22] Snellen, M., Merino-Martinez, R., and Simons, D.G. Assessment of noise level variability on landing aircraft using a microphone array, Paper submitted for publication in the Journal of Aircraft (2016).

[23] Lord Rayleigh, F.R.S., "XXXI. Investigations in Optics, with special reference to the Spectroscope," Philosophical Magazine Series 5, Vol. 8, No. 49, pp 261−274. October 1879. DOI: 10.1080/14786447908639684.

[24] Airbus S.A.S. *Airbus A320 Aircraft Characteristics. Airport and Maintenance Planning.* Blagnac, France. 2005.

[25] Simons, D.G., Snellen, M., Midden, B., Arntzen, M., and Bergmans D.H.T., "Assessment of noise level variations of aircraft fly-overs using acoustic arrays," Journal of Aircraft, Vol. 52, No. 5, pp 1625−1633. September−October 2015. DOI: 10.2514/1.C033020.

[26] Bergmans, D., Arntzen, M., and Lammen, W., "Noise attenuation directly under the flight path," National Aerospace Laboratory (NLR), NLR-TP-2011-262. November 2011.

[27] Curle, N., "The influence of solid boundaries upon aerodynamic sound," Proceedings of Royal Society of London A, Vol. 231, No. 1187, pp 505−514. September 1955. DOI: 10.1098/rspa.1955.0191.

[28] Bertsch, L., Dobrzynski, W., and Guérin, S., "Tool Development for Low-Noise Aircraft Design," Journal of Aircraft, Vol. 47, No. 2, pp 694−699, March - April 2010. DOI: 10.2514/1.43188.

[29] Bertsch, L., Heinze, W., and Lummer, M., "Application of an Aircraft Design-To-Noise Simulation Process," 14^{th} AIAA Aviation Technology, Integration, and Operations Conference, 16−20 June 2014, Atlanta, Georgia, USA. DOI: 10.2514/6.2014-2169. AIAA Paper 2014−2169.

[30] Burley, C.L., Brooks, T.F., Humphreys Jr., W.M., and Rawls Jr. J.W, "ANOPP Landing Gear Noise Prediction Comparisons to Model-Scale Data," 13^{th} AIAA/CEAS Aeroacoustics Conference, 21−23 May 2007, Rome, Italy. DOI: 10.2514/6.2007-3459. AIAA Paper 2007−3459.

[31] Fink, M.R., "Noise component method for airframe noise," 4^{th} AIAA Aeroacoustics Conference, October 3−5 1977, Atlanta, Georgia, USA. DOI: 10.2514/6.1977-1271. AIAA Paper 1977−1271.

[32] Guo, Y., "A Semi-Empirical Model for Aircraft Landing Gear Noise Prediction," 12^{th} AIAA/CEAS Aeroacoustics Conference, 8−10 May 2006, Cambridge, Massachusetts, USA. DOI: 10.2514/6.2006-2627. AIAA Paper 2006−2627.