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Publication date
2016

Document Version
Final published version

Published in
23rd International Congress of Sound and Vibration

DETERMINATION OF AIRCRAFT NOISE VARIABILITY USING AN ACOUSTIC CAMERA

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Nowadays, aircraft noise is one of the major problems to be dealt with by the aerospace industry and especially suffered by the residents living in the vicinities of airports. The enforcement of noise control environmental laws around airports is hindered due to the large variability observed in the noise levels for flyovers of the same aircraft type. These variations are not properly considered by the current assessment tools, such as the Noise-Power-Distance tables. In this paper, a measurement campaign was performed in Amsterdam Schiphol Airport using a 32 microphone array, where 115 flyovers of landing aircraft were recorded in order to determine these variations for various aircraft types and investigate the causes. It was assumed that the main cause of this variability are the differences in the emitted aircraft noise, since previous experience confirmed that the effect of the variable atmosphere (for the distances considered) is negligible. A strong correlation was found between the noise levels and the fan rotational speed (determined from the spectrograms), with almost 40% of the observed total noise variation explained by the engine settings variation. The use of a microphone array allows for acoustic imaging, thus discerning the noise of the aircraft elements from those of other sound sources. It was shown that for many aircraft types the turbofan engines were the main noise sources. After applying functional beamforming to the acoustic data focusing on the engines location, this correlation is even higher, explaining over 62% of the noise level variability.

1. Introduction

Noise pollution from aircraft is an issue of paramount importance for the aerospace industry and is especially annoying for the population in the surroundings of airports. This phenomenon can provoke severe health problems, such as sleep depravation, cognitive effects and hypertension [1]. Despite the significant reduction in the noise produced by individual aircraft achieved over the last decades, the continuous growth of air traffic (approximately at a 5% rate per year [2]) is expected to worsen the situation even more in the following years.

Therefore, stricter noise regulations and night curfews are being implemented, which constrain the increasing airport capacity. Most airports use noise level assessment models, such as the Integrated Noise Model (INM) [3, 4], which employ the so-called Noise-Power-Distance (NPD) tables. These tables include the Sound Pressure Level (SPL) values for different aircraft types for predefined distances and flight procedures. Hence, these models only offer one noise level value for a given aircraft type flying in a certain flight phase and at a given position. Nonetheless, measurements [5] confirmed that variations in the noise levels as large as 12 dB are observed for the same aircraft type, flight procedure and location. This variability is considered to be due to the combined effects of the changing atmosphere and the fluctuations of the emitted noise at the source. Previous experience [6] showed that the contribution of the varying atmospheric conditions to the total variability is negligible for distances between source and observer of up to 100 m, as considered in this paper. Thus, the changes of the noise source emissions (i.e. the aircraft) were assumed to be the main cause of variability in this research. Aircraft noise emissions depend on several parameters, such as the engine settings, aircraft velocity and flight configuration, which are not properly taken into account by the NPD tables. Enforcing environmental laws for noise control around airports is, therefore, a burdensome task due to this large noise level variability.

In order to analyze the variability of aircraft noise levels, 115 flyovers were recorded using a 32 microphone array in this research, which enables the application of beamforming algorithms to the acoustic data. Therefore, source plots can be obtained, which depict the location and SPL of the sound sources on the aircraft. The selected method for this paper was functional beamforming [7, 8], which provides better spatial resolution than conventional beamforming methods. This is highly beneficial for aircraft flyover measurements, due to the relatively large distances between the sound source and the observer. Also, the effects of background noise and ground reflection are largely reduced [6], allowing the noise emissions of single elements from the aircraft to be separated and studied in terms of frequency.

2. Experimental set-up

A measurement campaign was held at Amsterdam Airport Schiphol using an acoustic camera with a 32 microphone array with a spiral distribution, see Fig. 1 (a). Previous experience [9] showed that this microphone configuration provides acceptable results over a considerably wide frequency range, in terms of dynamic range and spatial resolution. This microphone array has an effective diameter of 1.7 m, uses a band pass filter for the frequencies between 45 Hz and 11,200 Hz and employs a sampling frequency of 40 kHz. The array was placed 1,240 m to the South of the threshold of the Aalsmeerbaan (36R) runway (see Fig. 1 (b)), which is a smaller distance than the recommended by ICAO for validation measurements during landing (2,000 m) [10]. This was done for availabilty reasons and in order to decrease the distance to the sound source to obtain better results. Using this device, the sound of 115 aircraft flyovers during landing was measured. The two dates when the measurements were performed presented very similar weather conditions and low wind speeds [11]. Parameters such as the sound speed or the atmospheric absorption coefficient require to take into consideration any variation in the atmospheric conditions.

(a) (b)

Figure 1: (a) 32 Microphone array configuration in spiral distribution. (b) Experimental set-up located 1,240 m to the South of the threshold of the Aalsmeerbaan (36R) Schiphol airport runway.

In addition to the acoustic data, the flight trajectories of each flyover need to be precisely determined and synchronised with the time signal of the microphones, in order to account for the moving source and acoustic propagation effects (see subsection 3.1). One of the reasons why only landing aircraft were considered is that their flight paths are usually more regular than during take-off, since all aircraft follow the Instrument Landing System (ILS) approach. The aircraft position and velocity were calculated using three different methods [12]:

- The Automatic Dependent Surveillance-Broadcast (ADS-B).
- The Air Traffic Control ground radar.
- The extrapolation of the images taken by an optical camera attached to the centre of the array, facing straight up.

In general, the three methods provided very similar results, with an average flight overhead height and aircraft velocity of 67 m and 271 km/h, respectively. The last method is preferred due to its availability and the ease of overlay the beamforming plots on to the optical images. The collected acoustic data correspond to 21 different aircraft types, from which the Boeing 737 “Next Generation” is the most frequently ocurring with 50 flyover measurements available.

3. Data processing

3.1 Propagation effects

Before applying any beamforming algorithm, the acoustic data requires several corrections, which need accurate estimations of the aircraft trajectories, as mentioned in section 2:

- The background noise, such as the ambient noise or the noise generated by the acoustic camera electronics, should be minimized in order to avoid amplification errors. To that end, all the SPL values in the spectrograms under 30 dB were neglected.
- Since the aircraft are moving with respect to the observer, the Doppler effect has to be corrected as explained by Howell et al [13].
- To obtain the SPL at the source, the corresponding geometrical spreading from the source location to the observer needs to be added to the recorded SPL.
- Even if the variability due to the effect of the variable atmosphere is neglected in this research, the consideration of the atmospheric absorption of the sound is required to obtain the absolute SPL values. It depends on the sound frequency and the atmospheric temperature, static pressure and relative humidity [14, 15].

3.2 Beamforming method

Most beamforming algorithms are based on the phase delays between the sound signal emission and the received signals at each microphone. The Conventional Frequency Domain Beamformer (CFDBF), also known as delay-and-sum, is one of the simplest and most robust methods and is widely used for aeroacoustic experiments [16, 17]. This technique requires considerably low computational resources and allows for the performance of a frequency analysis.

However, the CFDBF presents a dynamic range (i.e. the difference in dB between the main lobe and the highest sidelobe [16]) and a spatial resolution (i.e. the width of the main lobe 3 dB below its peak [17]) which are not sufficient for aircraft flyover measurements, due to the large distance between source and observer. Therefore, a novel method called functional beamforming [7, 8] was employed. The performance of this technique depends on an exponent parameter, ν, which needs to be set by the user. For an appropriate exponent value, the dynamic range and spatial resolution are significantly improved with respect to the CFDBF. Setting $\nu = 1$ provides the CFDBF method.

One of the main advantages of functional beamforming is that it preserves sound sources of lower amplitude than the strongest source. This can be observed in Fig. 2, which shows the results for a simulation with two different sources: one 100 dB source at (0, 0) m and one 90 dB source at (0.875, 0.290) m, both emitting sound at 3 kHz and situated 1 m away from the array. The array considered in this simulation has the same microphone distribution as the ones used in the experimental set-up, see Fig. 1 (a). It can be seen that the weaker source cannot be properly identified bt CFDBF, due to the abundance of high sidelobes of approximately the same SPL, while functional beamforming succeeds in separating both sources clearly at the correct source locations and with the correct strengths.

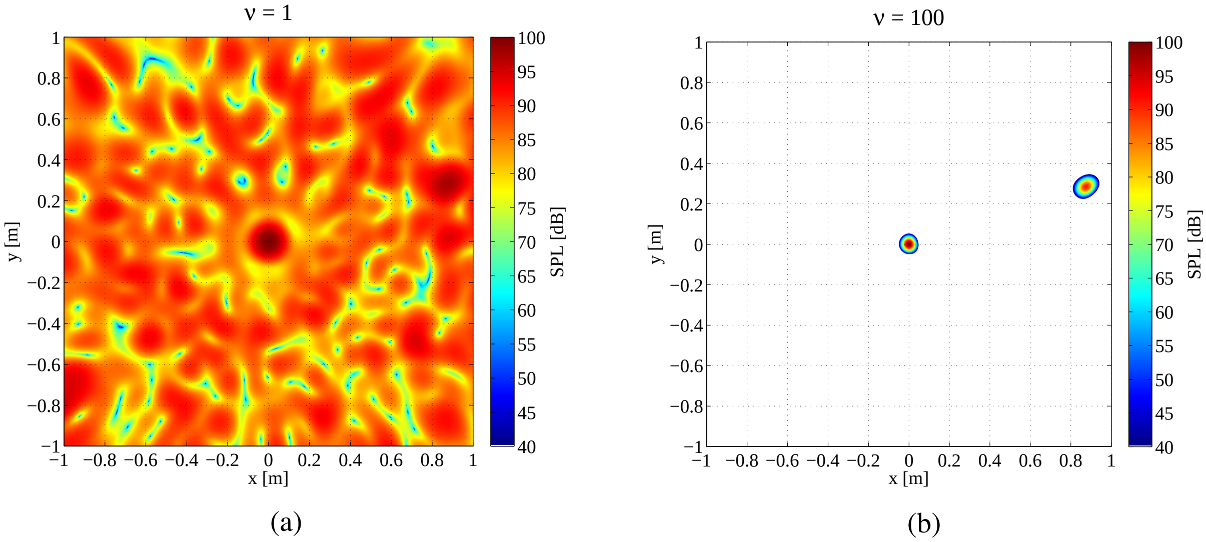


Figure 2: Comparison between the results of (a) CFDBF and (b) functional beamforming with $\nu = 100$ for two simulated sources: one 100 dB source at (0, 0) m and one 90 dB source at (0.875, 0.290) m, both emitting at 3 kHz and situated 1 m away from the array.

This algorithm has been tested in numerical simulations, idealized cases with speakers as experimental noise sources and controlled experiments with components in a laboratory [7, 8]. Furthermore, it was also applied very recently to full-scale aircraft during operational conditions with satisfactory results [12, 18]. It was found that the dynamic range achieved was approximately 30 times larger (in dB) and the spatial resolution was 6 times better than the CFDBF.

In addition, when applying beamforming to a moving source, an additional correction needs to be performed for calculating the time delays between the signal at the source and each microphone of the array [12, 18].

3.3 Engine fan settings determination

Turbofan aircraft noise during landing is usually dominated by the fan noise, especially in the forward direction [14]. Fan noise is mainly generated by the interaction between the fan blades and the stator vanes and it often presents a strong tonal component. The fundamental tonal frequency, f_1, also known as the Blade Passing Frequency (BPF), can be calculated using:

$$BPF = f_1 = \frac{B\,n}{60} \tag{1}$$

where B is the number of fan blades and n is the fan rotational speed in revolutions per minute. Typically, higher harmonics of the BPF are also present in the spectrograms. Their frequencies (f_k) are multiples of the BPF (f_1):

$$f_k = k\,f_1, \quad k = 1,\, 2,\, 3\ldots \tag{2}$$

The fan rotational speed, n, can be divided by the maximum fan rotational speed, n_{max} (100%), in order to obtain the relative fan speed percentage $N1\% = 100\,n/n_{max}$. The variable $N1\%$ is typically called the engine fan settings, since it refers to the low pressure spool.

Hence, to calculate the engine fan settings, the fan BPF of each flyover needs to be determined first by using the spectrograms. Since fan noise is more dominant in the forward direction, it is easier to detect the BPF and its harmonics in the forward arc spectra, i.e. the sound when the aircraft is approaching the array. Once the desired time interval has been selected, the Doppler corrected spectra in this interval are averaged over time. Then, a 10^{th} degree polynomial fit, which represents the broadband noise, is subtracted from the averaged spectrum. The difference is then squared to show the tonal peaks in a clearer way.

After selecting all the peaks over a threshold amplitude, different methods [11] were used to determine the BPF value and, therefore, the engine fan settings of each flyover. These methods are mainly based on least squares regressions between the considered peaks and the maximum correlation with a synthetic noise model. The selected BPF candidate is the one which presents the highest correlation with the measured data and that coincides with the largest number of harmonics. It is necessary to confirm that the obtained frequency values are realistic. The engine fan settings ($N1\%$) determined in this research range from 40% to 70%, which are common values for commercial aircraft during landing.

4. Experimental results

4.1 Assessment of OASPL variations using a single microphone

As a first glimpse of the total aircraft noise variability observed, the average Overall Sound Pressure Level (OASPL) at the source for each flyover was calculated. The OASPL time series at the source (obtained from the corrected spectrograms) were averaged over a time interval ranging from 2 seconds before the overhead time to 2 seconds after the overhead time. All the flyovers were divided in different aircraft types depending on the turbofan engine they are equipped with. Variations as large as 7 dB for the same aircraft type were observed. After studying the flyover sound frequency spectra, the presence of this variability was confirmed, and it was observed that the level variation for single frequencies can be even larger. An example of these spectra for the case of the Boeing 737 “Next Generation” (series 700, 800 and 900) is depicted in Fig. 3. The time interval chosen for this spectral analysis was 1.5 second to 1 second before the time overhead.

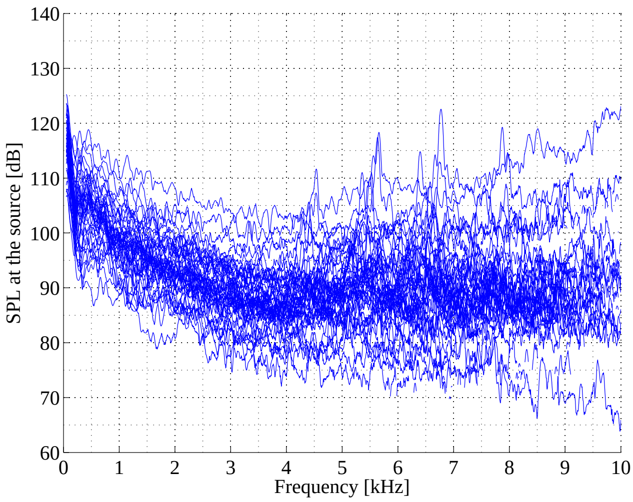
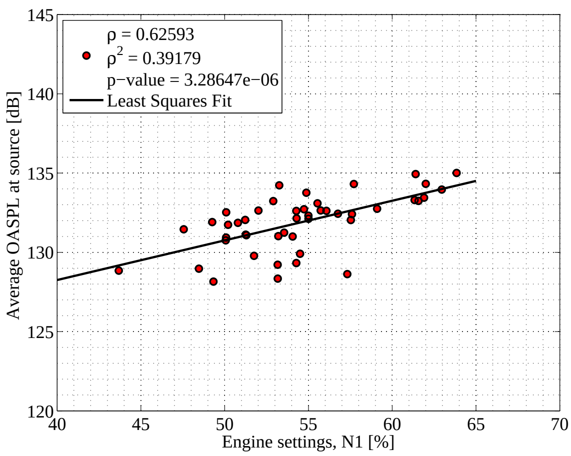
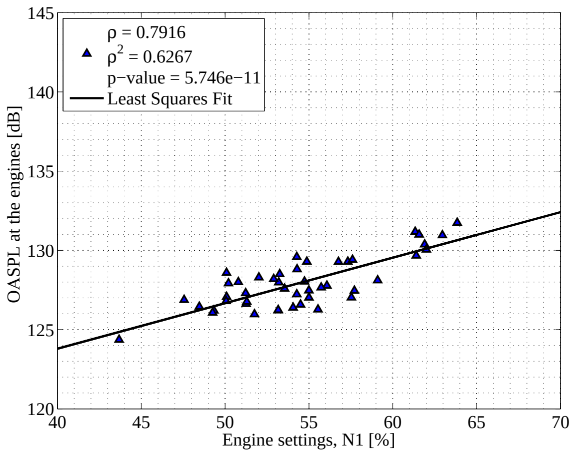


Figure 3: flyover spectra at the source for the Boeing 737 (series 700, 800 and 900). The time interval selected was 1.5 to 1 s before the time overhead.

In order to determine the cause of these variations in the noise levels, a correlation analysis was performed, taking the engine fan settings ($N1\%$) as the independent variable. The average OASPL at the source was considered, before applying any beamforming method to the acoustic data. The outcome for the Boeing 737 “Next Generation” is presented in Fig. 4 (a) as a representative example, since it was the most numerous aircraft type found in this research. The correlation coefficient, ρ, the coefficient of determination, ρ^2, and the p-value are calculated and depicted in the plot. The linear least squares fit is also included. It can be observed that there is a significant correlation (considering a threshold p-value of 0.05) and that almost 40% ($\rho^2 \simeq 0.39$) of the noise level variability is explained with the variation in the engine fan settings. A similar study performed with respect to the aircraft velocity showed a considerably lower correlation, although significant [11].



(a)



(b)

Figure 4: Correlation analyisis results for the Boeing 737 "Next Generation" between: (a) The average OASPL (without beamforming) and engine fan settings. (b) Engines OASPL (after applying functional beamforming) and engine fan settings.

4.2 Assessment of engine noise level variations using beamforming

For studying the fluctuations in noise levels at an aircraft component level, a similar correlation study as before was performed after applying functional beamforming to the acoustic data. This subsection focuses only on the noise sources located at the engines positions. The times selected range from 0.2 to 0.1 second before the time overhead. Since during those times the aircraft is within the field of view of the optical camera, it is possible to overlay the beamforming plots on to the optical images, as illustrated in Fig. 5, where it can be seen that the array has correctly located the source of the engine noise for a Boeing 737-900.

Figure 4 (b) shows the engines OASPL plotted against the engine settings for the Boeing 737 "Next Generation". A substantial increase in the correlation coefficient with respect to the engine fan settings can be observed, compared to the case without applying beamforming. This time more than 62% of the observed variation of the noise levels can be explained by the modification of the engine fan settings. This improvement can be explained due to the partial elimination of the contributions from other noise sources by selecting an adequate spatial area and frequency range when applying beamforming [6].

The correlation between the noise levels and the aircraft velocity was measured to be even lower than for the case without beamforming. This can be explained because an increase in aircraft velocity mostly increases airframe noise and, since the main contributors of airframe noise are the landing gear system and the high-lift devices, engine noise is affected to a lesser extent by the aircraft velocity.

A comparable study by Simons et al. [6] provided similar results. The remaining unexplained percentage of variability could be attributed to the source directivity, since the relative positions of each aircraft with respect to the array were not exactly the same.

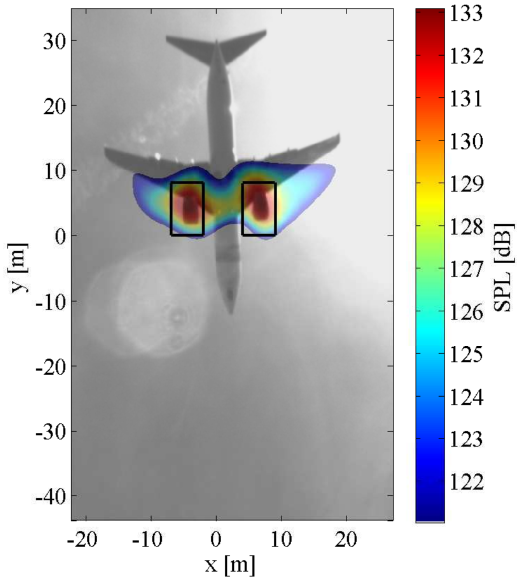


Figure 5: Beamforming source plot for a frequency range from 50 to 11,200 Hz using functional beamforming with an exponent parameter of ν = 100 of a Boeing 737-900 flyover. The black rectangles show the area of analysis for the variability analysis. The time interval ranges from 0.2 to 0.1 seconds before the time overhead.

5. Conclusions

This paper analyzes the issue of noise level variability for flyovers of the same aircraft type. Large SPL variations are observed at the source for the same aircraft type, hence hampering the assessment of noise levels around airports for the enforcement of environmental laws. The current assessment models normally rely on Noise-Power-Distance tables, which do not consider these variations properly and just provide fixed values of aircraft noise levels. In this research, the noise variability was considered to depend mostly on the emitted noise at the source, i.e. the aircraft itself, neglecting the effects of changing atmospheric conditions.

The noise signatures of 115 landing aircraft were recorded in a full scale experiment using a 32 microphone array at Amsterdam Airport Schiphol. After correcting the acoustic data taking into account the background noise and propagation and Doppler effects, the engine fan settings were estimated by analyzing the spectrograms.

The average OASPL variability observed directly under the flight path was approximately 7 dB for several landings of Boeing 737 “Next Generation” aircraft flyovers. A correlation analysis showed that the average OASPL variations are highly related to the fan rotational speed of the engines. Correlation coefficients of approximately 0.62 were obtained for the case of the average OASPL with the engine settings, meaning that almost 40% of the total observed variation can be explained by changes in the engine fan settings.

The microphone array allows for the application of beamforming algorithms which provide valuable information about the noise sources location and amplitude on the aircraft. After applying a beamforming method called functional beamforming to the acoustic data and considering only the engines positions, it was found that the change in the engine fan settings now explains more than 62% of the variation of the engines SPL for the Boeing 737 “Next Generation”. The correlation with the aircraft velocity is considerably lower, since it does not affect engine noise in a considerable way.

In conclusion, in order to partly solve the problem of airport noise assessment due to the large noise level variations for same aircraft types, it is strongly recommended to implement more precise aircraft engine fan setting data into the current models for noise contour calculations around airports.

REFERENCES

1. Hansell, A., et al. Aircraft noise and cardiovascular disease near Heathrow airport in London: small area study, *British Medical Journal*, **347**, (2013).

2. Boeing Commercial Airplanes, USA., Current Market Outlook 2013-2032, (2013).

3. International Civil Aviation Organization (ICAO), Recommended method for computing noise contours around airports (ICAO Circular 205-AN/1/25). Montreal, Canada., (1988).

4. European Civil Aviation Conference (ECAC), CEAC Doc. 29. Report on Standard method of Computing Noise Contours around Civil Airports. Volumes 1&2. 3^{rd} edition, (2005).

5. Bergmans, D., Arntzen, M. and Lammen, W. National Aerospace Laboratory (NLR), Noise attenuation directly under the flight path. Anthony Fokkerweg 2, 1059 CM Amsterdam, P.O. Box 90502, 1006 BM Amsterdam, The Netherlands, (2011).

6. 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*, **52** (5), 1625–1633, (2015).

7. Dougherty, R. P. Functional Beamforming, 5^{th} *Berlin Beamforming Conference, February 19-20 2014, Berlin, Germany.*, February, GFaI, e.V., Berlin, (2014).

8. Dougherty, R. P. Functional Beamforming for Aeroacoustic Source Distributions, 20^{th} *AIAA/CEAS Aeroacoustics Conference. June 16-20 2014. Atlanta GA, USA.*, AIAA paper 2014-3066, (2014).

9. van der Goot, R., Hendriks, J., W., S. K. Y., Hermans, W., G.and van der Wal and Simons, D. G. A low cost, high resolution acoustic camera with a flexible microphone configuration, 4^{th} *Berlin Beamforming Conference, February 22-23 2012, Berlin, Germany*, February, GFaI, e.V., Berlin, (2012).

10. International Civil Aviation Organization (ICAO), ICAO Annex 16 Chapter 3. Environmental protection. Montreal, Canada, (2005).

11. 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*, (2015).

12. Merino-Martinez, R., Snellen, M. and Simons, D. G. Functional beamforming applied to imaging of fly-over noise on landing aircraft, *Journal of Aircraft*, paper accepted for publication., (2016).

13. Howell, G. P., Bradley, M. A., McCormick, M. A. and Brown, J. D. De-Dopplerization and acoustic imaging of aircraft flyover noise measurements, *Journal of Sound and Vibration*, **105** (1), 151–167, (1986).

14. Arntzen, M., *Aircraft noise calculation and synthesis in a non-standard atmosphere*, Ph.D. thesis, Delft University of Technology, (2014).

15. Ruijgrok, G., *Elements of aviation acoustics*, VSSD, Second edn., ISBN 1090-6562-155-5 (2007).

16. Sijtsma, P. and Stoker, R. Determination of Absolute Contributions of Aircraft Noise Components Using Fly-over Array Measurements, 10^{th} *AIAA/CEAS Aeroacoustics Conference, May 10-12 2004, Manchester, United Kingdom*, aIAA paper 2004-2958, (2004).

17. Sijtsma, P. National Aerospace Laboratory (NLR), Phased array beamforming applied to wind tunnel and fly-over tests. Anthony Fokkerweg 2, 1059 CM Amsterdam, P.O. Box 90502, 1006 BM Amsterdam, The Netherlands, (2010).

18. Merino-Martinez, R., Snellen, M. and Simons, D. G. Functional Beamforming Applied to Full Scale Landing Aircraft, 6^{th} *Berlin Beamforming Conference, February 29– March 1 2016, Berlin, Germany.*, (2016).