FLY-OVER SOURCE LOCALISATION ON A BOEING 747-400

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ABSTRACT

Fly-over measurements with several Boeing 747-400 aircraft of Lufthansa were performed on the airport of Parchim in September, 2008 in the framework of the German national research project FREQUENZ. The Engine Acoustics department of the DLR Institute of Propulsion Technology performed array measurements using a microphone array with 238 microphones that were arranged in a multi-arm spiral. The array had an elliptical shape with the major axis in the direction of flight and covered an area of 42 by 35 m. The trajectory of the aircraft was measured with an array of laser distance meters on the ground and with additional GPS systems on board the aircraft. An extensive data set of over 80 flyovers in different flight configurations has been acquired during the three test days. The results of the beamforming analysis for one fly-over with extended landing gears will be presented together with a description of the experimental set-up and the methods employed during the data reduction.

1 INTRODUCTION

In the year 1999, Lufthansa and DLR started a cooperation on the analysis of noise sources on commercial aircraft. During several measurement campaigns, fly-over measurements have been performed with large microphone arrays.

In the framework of the German national research projects LAnAb [6] and FREQUENZ [2], extensive array measurements of the A319, the MD-11, and the B747-400 aircraft have been performed. During these tests, a large set of acoustic data has been acquired for these aircraft. The purpose of these measurements was to localise and identify the noise sources and to create a data base for the development of noise models. Results of the beamforming analysis for the Airbus A319 have been presented in [3, 9], results for the MD-11 in [10]. In the project LAnAb, a noise model for the A319 was developed and integrated into the DLR noise prediction code SIMUL. This tool can be used to simulate the acoustic footprint of different

Figure 1: A Boeing 747-400 passing over a microphone array at Parchim airport (DLR, 2008)

flight trajectories during take-off and landing. The fly-over measurements with the Boeing 747-400 were performed in order to extend these models to a commonly used wide-body aircraft type with four engines.

On three days in September 2008, fly-over tests were performed at the airport of Parchim in the German state of Mecklenburg-Vorpommern. The test matrix consists of 8 different flight configurations for engine noise and 16 different configurations for airframe noise. Each configuration was repeatedly flown so that altogether, data was acquired for over 80 different fly-overs.

While the major part of the data still waits for being processed, a preliminary analysis of selected fly-overs has been performed in order to check the quality of the data. This paper presents the results for one flyover with extended landing gears, the slats and flaps in clean configuration, and with the CF6-80C2 engines running at 83% N1. At this stage, the results can only be presented in qualitative form and no absolute levels will be given.

2 EXPERIMENTS

2.1 Array set-up

The microphone array was arranged east of the landing strip at Parchim airport (see figure 2). The array was a multi-arm spiral array that was stretched by 25% in the direction of flight in order to increase the resolution in this direction to compensate the reduced aperture at emission angles other than 90°. Altogether, 238 microphones were arranged over an area of 42 by 35 m.

The array actually consisted of two microphone arrays: an inner array with 112 microphones for the higher frequencies and an outer array with 126 microphones for the low frequency range. The inner array was placed on a hard concrete surface, which can be seen in figure 1, in order to ensure a defined acoustic boundary condition. The outlying microphones were mounted on square wooden boards of 80 by 80 cm that lay flat on the ground. While the inner array was set up with condenser microphone capsules (type MK301 manufactured by Mikrotech-Gefell), microphones with Sennheiser KE4 electret capsules were used in the outer, low-frequency array.

The array microphones were calibrated at least once per day of measurements using pistonphones. The calibration data were saved for later reference.

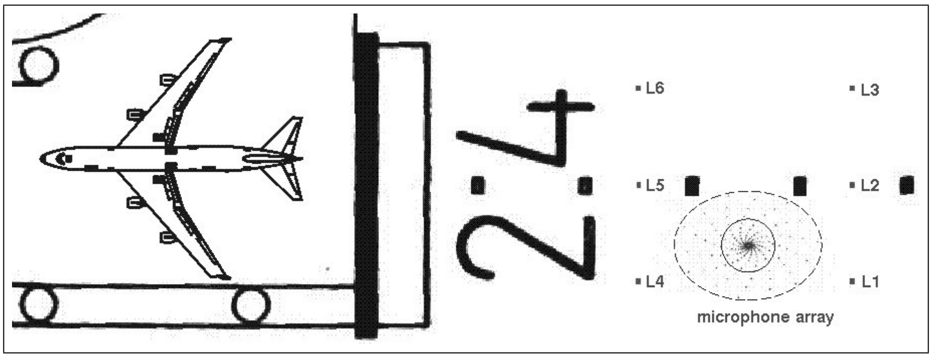

Figure 2: The set-up of the 42x35 m multi-arm spiral array for the B747-400 fly-over measurements of DLR and Lufthansa at Parchim airport, 2008; the aircraft on the runway is shown in order to indicate the relative size, the points L1–L6 mark the locations of the laser distance meters

2.2 Data acquisition

A data acquisition system developed by DLR was used that can record 256 channels simultaneously. The sampling frequency was 48192 Hz and data was recorded for 35 seconds. Additionally to the 238 microphone channels, a GPS time code in the IRIG/B format, and trigger and data signals from the six laser distance meters were recorded. For every fly-over, 1.7 GByte of data were recorded.

2.3 Flight path estimation

One of the greatest practical difficulties in fly-over measurements with microphone arrays is the synchronisation of the acoustic data with the trajectory of the aircraft. For the present investigation, several systems were used in parallel. Their output data was combined and evaluated with respect to the optimal beamforming result. This, of course, is a time consuming task.

The systems for flight path estimation included an array of laser distance meters, a camera, the flight recorder on board the aircraft, and the two additional GPS systems on board of the aircraft.

The array of laser distance meters consisted of six range finders that were arranged in two lines crossing the flight path up- and downstream of the array (see figure 2). The laser devices trigger whenever an object passes the ray and measure the distance to the object. The trigger times and distance readings can be used to compute the fly-over altitudes at the trigger times and the velocity components in the forward and upward directions. However, the offset to the side can only be inferred from the number and the position of the devices that were triggered and it is not known, which part of the aircraft triggered. The results are in some cases ambiguous, i.e. when different parts of the aircraft trigger sensors at the same span-wise position.

A camera operated by the DLR Institute of Aerodynamics and Flow Technology was used to calculate fly-over altitudes on the basis of triangulation and it also generated trigger signals.

The flight log system of the aircraft recorded all relevant parameters, e.g. engine speeds, slat, flap, and spoiler settings, landing gear status etc. as well as the flight path. However, the spatial resolution of the position data from the flight log is not accurate enough for array measurements.

The GPS measurements from the two additional systems installed on the aircraft gave more accurate readings and were used as the starting point of the iteration of the aircraft position for the beamforming calculations.

2.4 Flight matrix

The fly-over measurements were aimed at analysing both aerodynamic and engine noise sources. The flight test matrix was designed so that a very large number of configurations could be tested in the restricted time frame of three days of measurements. The test plan allowed for at least one repeat fly-over for every configuration.

3 DATA REDUCTION

3.1 Method

The data analysis method used by DLR is based on the classical beamforming algorithm in the time domain that has been adapted for moving sources. This technique has been developed at DLR in the late eighties of the last century. First applications were on high-speed trains [1]. Later, the method was extended to aircraft in flight [5] and has been improved since by better and larger microphone array arrangements, data acquisition hardware, flight trajectory tracking, and analysis techniques. Examples for applications in European research projects are given in [7] and [8]. These experiments were aimed at diagnosing noise sources and the development of noise reduction measures for aircraft already in service.

The data analysis was taken one step further by the development of a deconvolution method for moving sound sources at DLR [4]. Because the source distributions that are calculated by the beamforming algorithm are the result of a convolution of the actual source distribution and the imaging properties of the array, a deconvolution greatly improves the results. The spatial resolution and the dynamic range of the noise maps increase and a quantitative analysis of the source levels becomes possible. The sources can be ranked for different flight configurations and quantitative noise models for the different aerodynamic sources and the engine-related sources can be developed.

3.2 Application

In preparation for the beamforming analysis, the microphone data was first checked for validity. Defective tracks were isolated and removed, and the valid data were calibrated. The IRIG time code signal was analysed and the matching data sets from the different sources of flight trajectory data were selected.

From the trajectory data, the position of the aircraft in three coordinates relative to the array centre and the velocity in three coordinates were determined at a reference time. This linearised flight path was used to determine the aircraft position and velocity when the aircraft was at emission angles of $\theta = 60°$, $\theta = 90°$, and $\theta = 120°$. For these angles, first de-Dopplerised frequency spectra were calculated in order to check the accuracy of the flight trajectory data. When the results were satisfactory, beamforming maps were calculated by scanning a plane of 80 by 80 m at the fly-over altitude at the three emission angles with a spatial resolution of

0.7 m. The scan plane was aligned with the aircraft by taking the pitch, roll, and yaw angles into account.

The high-frequency array with the Microtech microphones and the low-frequency array with the Sennheiser microphones had to be calculated separately due to the different phase response of both microphone types.

After the beamforming analysis, the deconvolution analysis was performed. On a 2.6 GHz AMD Opteron CPU, the calculation of the 11 one-third-octave bands for the high-frequency array lasted about 18 hours.

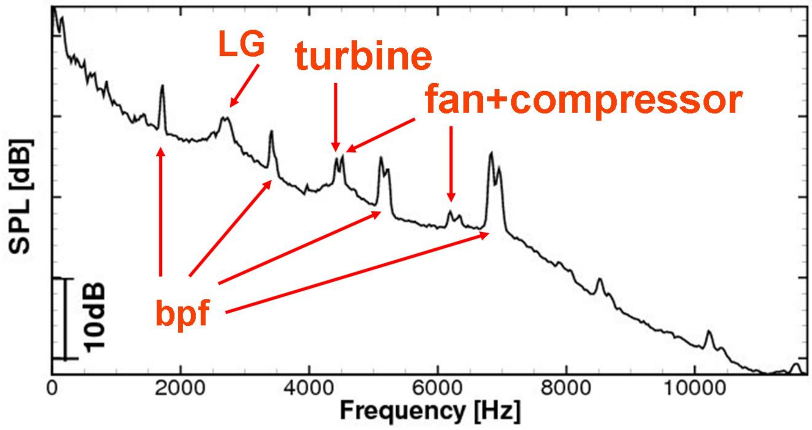

Figure 3: De-Dopplerised spectra for a fly-over with extended landing gears for an emission angle of $\theta = 90°$

4 RESULTS

4.1 Classical beamforming

Figure 3 presents the de-Dopplerised narrow-band spectrum for a fly-over with the landing gear extended. The B747 passed over the array at an altitude of 177.5 m with a speed of 117.3 m/s. The engines were running at 83% N1 and the high-lift devices were in the clean configuration. The spectrum shows the engine blade passing frequency (bpf) of 1730 Hz and its harmonics, engine tones between the 2nd and 3rd and also between the 3rd and the 4th bpf harmonic, and a source from the fuselage near the main landing gear around 2700 Hz.

The beamforming maps for this fly-over in selected one-third-octave bands are shown in figures 4, 5, and 7. They show that in this configuration, the strongest noise source over a wide frequency band at low frequencies is the outer main landing gear. At high frequencies, the engines can be clearly identified as noise sources.

The microphone array was designed for a relatively constant beamwidth over different one-third-octave bands. This was ensured by inceasing the distance between the microphones proportionally with the distance from the array centre and by introducing shading factors that progressively compensate the higher density of microphones in the centre of the array. For the

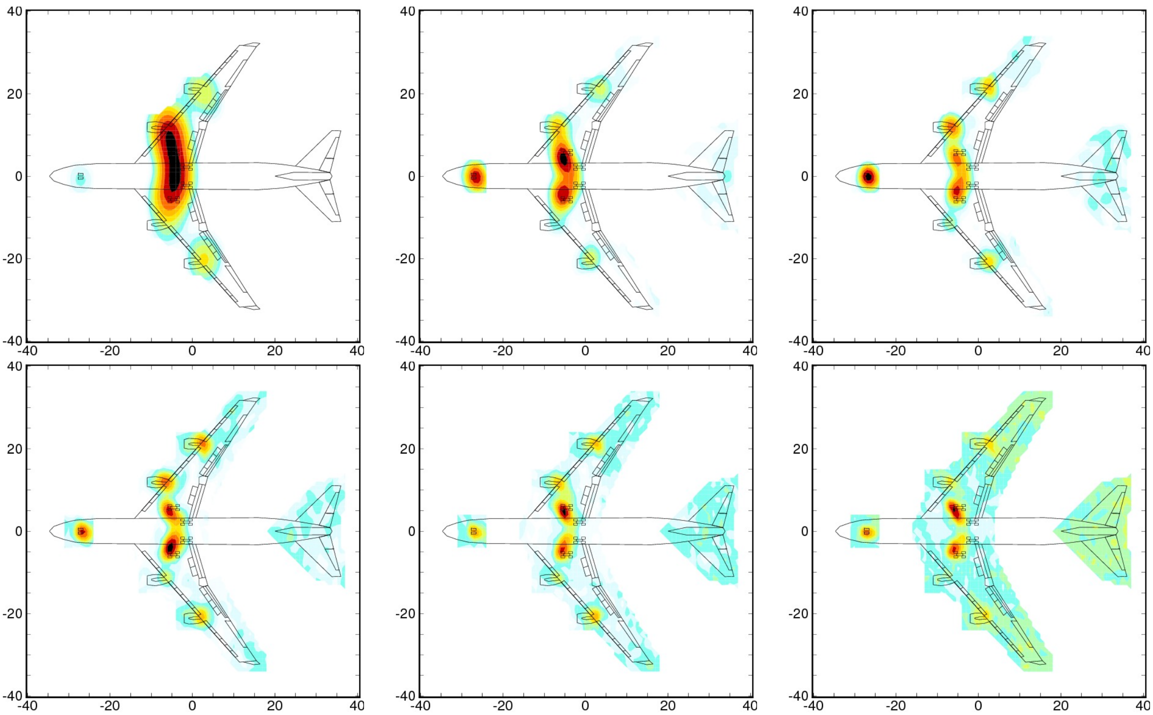

Figure 4: Results of the classical beamforming analysis for a fly-over with extended landing gears from the low-frequency array; $\theta = 90°$, 10 dB dynamic range, from left to right, top: 200 Hz, 315 Hz, 400 Hz; bottom: 500 Hz, 630 Hz, and 800 Hz

analysis of lower frequency bands, the outer microphones would contribute more while the inner microphones would be attenuated by the shading. For high frequencies, the microphones near the centre would be preferred while the outer microphones, which have a reduced coherence at high frequencies, would be suppressed.

The low-frequency maps in figure 4 show that the array has a good spatial resolution and a relatively constant beamwidth. For the two lowest frequency bands at 200 Hz and 250 Hz, the two landing gear sources cannot be separated, but from 315 Hz on, the maps show the proper sources.

The low-frequency and the high-frequency array overlap in the frequency range between 1000 and 1250 Hz. The results from both arrays for these frequency bands are shown in figure 5. Here, the low-frequency array gives a better spatial resolution, but lower dynamic range.

Figure 6 shows on the left-hand side the map for the 2500 Hz one-third-octave band, which includes the source near 2700 Hz which can be seen in the de-Dopplerised spectrum in figure 3. The source is either in the wheel-well of the outer main landing gear, or it might be the outflow from a vent on the fuselage. The right-hand side of figure 6 shows the narrow band map at 4422 Hz with the turbine tone between the 2nd and the 3rd bpf harmonic.

The high frequency array results are presented in figure 7. From 1600 Hz on, the resolution is improved and from 3150 Hz on, the engine noise becomes more and more dominant.

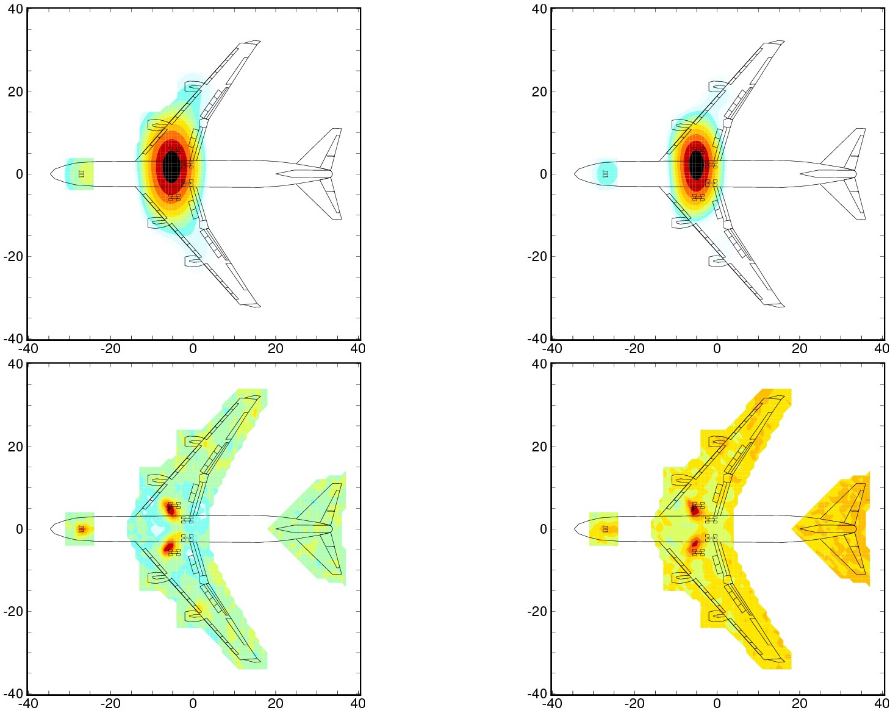

Figure 5: Results of the classical beamforming analysis for a fly-over with extended landing gears: overlap between the low- and the high-frequency arrays; $\theta = 90°$, 10 dB dynamic range, left: 1000 Hz, right: 1250 Hz; top: high-frequency array, bottom: low-frequency array

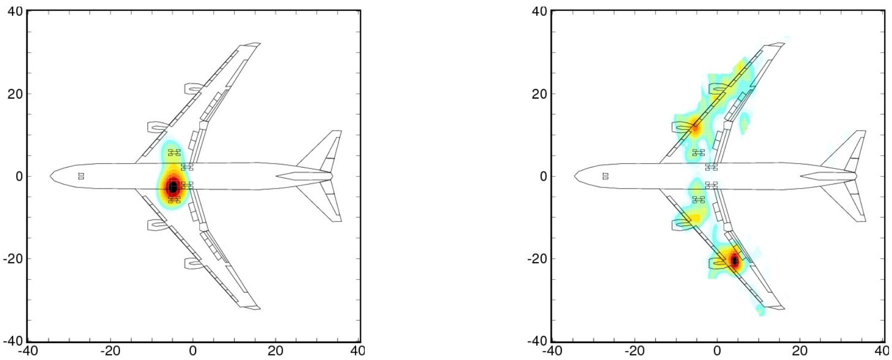

Figure 6: Results of the classical beamforming analysis for a fly-over with extended landing gears: left: tone in the 2500 Hz one-third-octave band; right: turbine tone in the 4420 Hz narrow band; $\theta = 90°$, 10 dB dynamic range

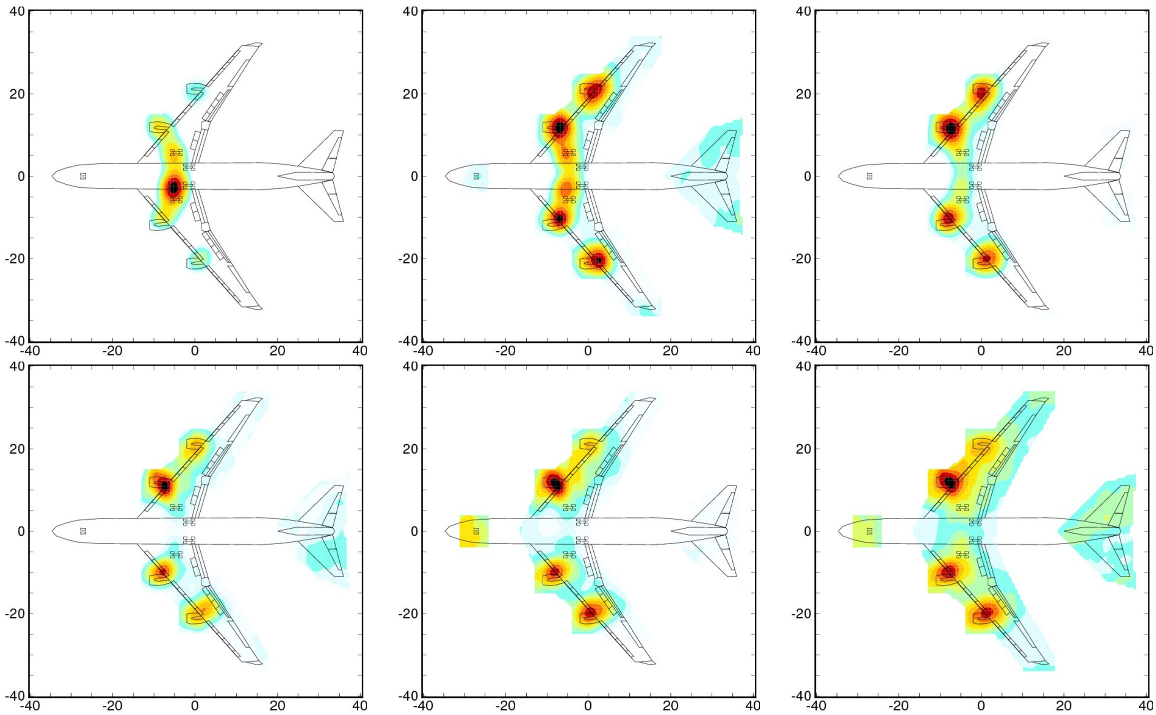

Figure 7: Results of the classical beamforming analysis for a fly-over with extended landing gears from the high-frequency array; from left to right, top: 3150 Hz, 4000 Hz, and 5000 Hz; bottom: 6300 Hz, 8000 Hz, and 10000 Hz

4.2 Deconvolution

The deconvolution increases the spatial resolution and the dynamic range of the maps. Figure 8 shows the maps calculated from the low-frequency array data for the one-third-octave bands between 315 and 1000 Hz. In this frequency range, the main landing gear, especially the outer, forward, landing gear, appears as the strongest noise source.

The deconvolution results for the higher frequencies are presented in figure 9. The tone on the fuselage is the dominating source in the 2500 Hz and 3150 Hz bands, in higher freqency bands, the engines are the loudest sources.

5 Conclusions

The large elliptical multi-arm spiral array set-up by DLR for the acoustic fly-over test with the Lufthansa B747-400 shows good spatial resolution over a wide frequency range. The landing gear sources can be separated from the 315 Hz one-third-octave band on upwards. The upper frequency range of the array extends well into the 10 kHz one-third-octave band. Because two different types of microphones were used, the array is separated into a large outer low-frequency array and an inner high-frequency array. Both arrays overlap in the 1000 Hz and 1250 Hz bands, where the low-frequency array gives a better spatial resolution, while the shading applied to the high-frequency array gives a better dynamic range at the expense of an increased beam-width.

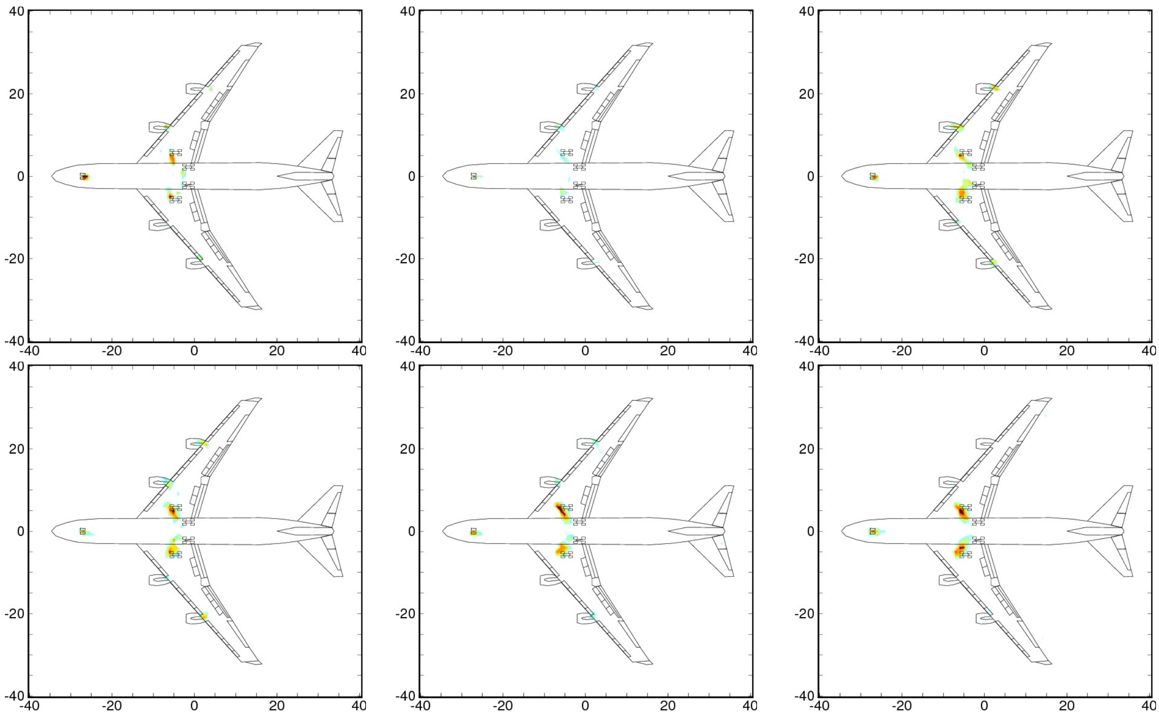

Figure 8: Results of the deconvolution analysis for a fly-over with extended landing gears from the lower frequency range; $\theta = 90°$, 12 dB dynamic range, from left to right, top: 315 Hz, 400 Hz, and 500 Hz; bottom: 630 Hz, 800 Hz, and 1000 Hz

The deconvolution method developed by DLR [4] increases both the dynamic range and the spatial resolution.

In the near future, more individual fly-overs from this collection of acoustic data for the B747-400 will be analysed. The results will be used by DLR and Lufthansa to investigate the possibilities of retro-fit noise abatement measures for the B747-400. DLR will use the data to develop engine noise models for the CF6-80C2 engine.

For the fly-over shown with relatively high engine power and extended landing gear, but with retracted high-lift devices, the strongest noise sources in the low frequency range are the nose and the outer main landing gear, while the high frequency range is dominated by engine noise.

One aerodynamic source was identified on the fuselage near the main landing gear. The source is either located in the wheel-well or in a vent opening and might be treatable by a small modification.

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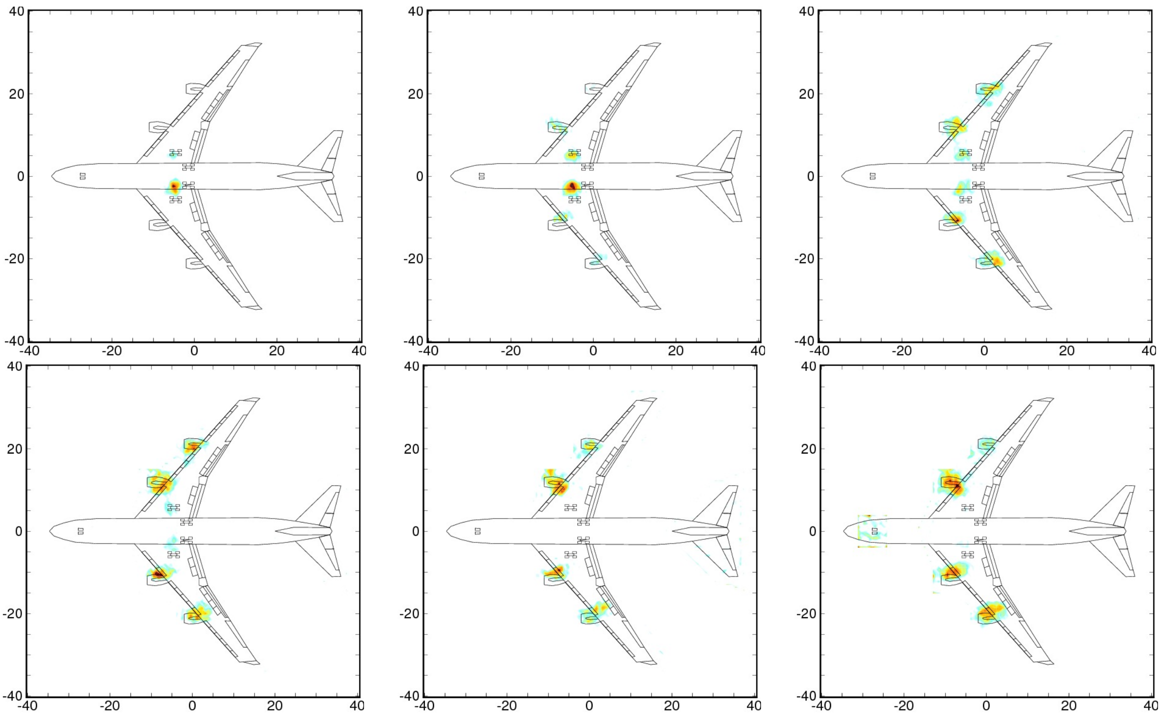

Figure 9: Results of the deconvolution analysis for a fly-over with extended landing gears from the high-frequency array; $\theta = 90°$, 12 dB dynamic range, from left to right, top: 2500 Hz, 3150 Hz, and 4000 Hz; bottom: 5000 Hz, 6300 Hz, and 8000 Hz

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