BUZZ-SAW NOISE SPECTRA AND DIRECTIVITY FROM FLYOVER TESTS

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A fly-over noise test with an Airbus A319 was conducted jointly by DLR and Lufthansa with support from Airbus and Snecma. The signals of a large array of 238 electret microphones were recorded. In a first test, the noise emission of each engine was studied by running the other engine with flight-idle power. De-dopplerised narrow-band frequency spectra averaged over a large number of microphones were used. Alternatively, the noise emission from the inlet of each engine was evaluated with both engines at take-off power with the aid of a phased microphone array focused on each moving engine inlet. The results show as expected that buzz-saw noise is mainly radiated in the forward arc. The peaks at multiples of the shaft frequency can easily be identified in the de-dopplerised narrow-band spectra. The directivity of a number of frequency components is evaluated. The characteristics of buzz-saw noise are seen to vary between individual engines and even, for the same engine, between different fly-overs. The resulting directivities also indicate that mode scattering has a large influence on the radiated buzz-saw noise field.

Introduction

The present paper is a by-product of a flight-test that was jointly carried out by DLR and Lufthansa with support of Airbus and Snecma. The test flights were performed on the 9th and 10th of October 2001 with an Airbus A319 equipped with the CFM56-5A5 engine which is a low-thrust version in the CFM56-5A family with a bypass ratio of 6.2 and a dual stream nozzle. The experiment was aimed at testing the effects of modifications to the airframe and to one of the engines on the noise emission of the aircraft. The modifications of the engine consisted of taping the casing liner immediately in front of the rotor (proposal by Snecma) and of replacing the core nozzle by a serrated nozzle designed by DLR and manufactured by Lufthansa Technik. Another objective was to acquire noise data for the validation of semi-empirical prediction schemes for airframe noise sources, for which first results are reported by Pott-Pollenske et al.[1] The influence of the engine modifications on the noise emission will be reported later.

Apart from these intentions, the resulting data showed interesting results with respect to buzz-saw noise, an aeroacoustic problem of practically all modern aero-engines with high bypass ratios.

The test set-up on the ground included a large phased array of microphones consisting of 238 relatively cheap electret microphones for the localisation of the noise sources on the flying aircraft. These microphones were also used to determine the de-dopplerised narrow-band frequency spectra for a range of emission angles. It were these spectra that revealed the large contribution of buzz-saw noise.

Fig. 1 Microphone array installed on the test site

”Buzz” consists of tones at multiples of the shaft frequency f_s of the fan. Origins of these tones are a series of nonuniform shock waves and expansion fans that develop upstream of the fan rotor whenever the relative rotor tip Mach number is larger than one.

The mechanism of buzz-saw noise was first investigated and reported in the 1970s. A recent comprehensive description can be found in McAlpine & Fisher[2] together with a new numerical prediction method. The problem is studied there with the assumption of a uniform flow in a hard-walled circular cylindrical duct. Under these conditions, the pressure field in front of the rotor is stationary in the rotor frame of reference and can be decomposed into azimuthal Fourier components of order m which rotate together with the rotor. As a result, each component will radiate sound from the inlet with a frequency of $f_m = m\ f_s$ if the component can propagate in the duct.

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Aero-engines are fitted with liners. The influence of lining was studied by McAlpine & Fisher.[3] Since the effectiveness of lining depends primarily on frequency and flow speed, certain buzz-saw noise components are more attenuated than others. a result that is shown to depend on the flow speed in the inlet.[3]

The situation in aero-engines differs from the assumptions made by McAlpine & Fisher.[2,3] The first difference is the presence of liner splices which permits the manufacture and installation of the liner in sections. The consequence of these splices is that the rotating pressure field in the inlet is no longer stationary in the rotor frame of reference. The acoustic influence can be determined with the theory of Tyler & Sofrin[4] and yields scattered modes. As a result the buzz component emitted at a frequency of $f_m = m\ f_s$ will contain duct modes of many orders $m + ks$, where s is the number of (assumed to be uniformly spaced) splices and $k = \ldots, -1, 0, 1, \ldots$ is an integer.

The situation in an aero-engine in flight is further complicated by the nonuniform flow in the inlet due to the flow angle between the engine axis and the flight stream and/or the inlet droop. In this case the shock system in front of the rotor blades is modulated during each rotation. The result is an increase of buzz-saw noise which can be noticed by passengers in the front rows of an aircraft when the aircraft rotates at the end of the take-off run. This increase is caused by additional modes of order $m + l$ for each frequency $f_m = m\ f_s$, where $l = \ldots, -1, 0, 1, \ldots$.

Any experimental investigation of buzz-saw noise requires a narrow-band analysis with a band-width equal to a small fraction of the shaft rotation frequency. This can be performed quite easily on a static test bed with a fan model or a real aero-engine. The effects of fan speed, blade geometry, inlet acoustic liner design, etc., can be studied.

However, the effect of inlet flow angle and the influence of flight speed can not easily be tested on static test beds and requires fly-over tests for its investigation. The situation is much more difficult in the fly-over case because the frequencies observed on the ground are Doppler-shifted and change considerably during a fly-over. A de-dopplerisation of the microphone data has to be performed which requires a precise knowledge of the aircraft's position as a function of time.

No studies with de-dopplerised narrow-band spectra of buzz-saw noise in flight are known to the authors. It is shown in this report how this can be done. The experimental set-up and the data processing are described first followed by a presentation of some experimental results.

Experimental set-up

New 256 channel data-acquisition hardware developed at DLR was used for the first time in this measurement campaign. It features analogue-to-digital converters with a resolution of 24 bits and a measured signal-to-noise ratio of 108 dB, making the self-noise of the microphone capsules the limiting factor. The analogue signal cable length is minimised by positioning the analogue-to-digital converters close by the microphones, while the long cables connecting the array microphones to the data acquisition computer carry only digital signals. The large dynamic range makes it unnecessary to use microphone amplifiers. This and the digital transmission of the signals reduces signal distortion, system costs, and complexity. The computer stores the data into memory and subsequently writes it to hard disk. Currently, the maximum sampling rate is 78 kHz, independent of the number of up to 256 channels used, and the recording time is only limited by the memory size of the computer.

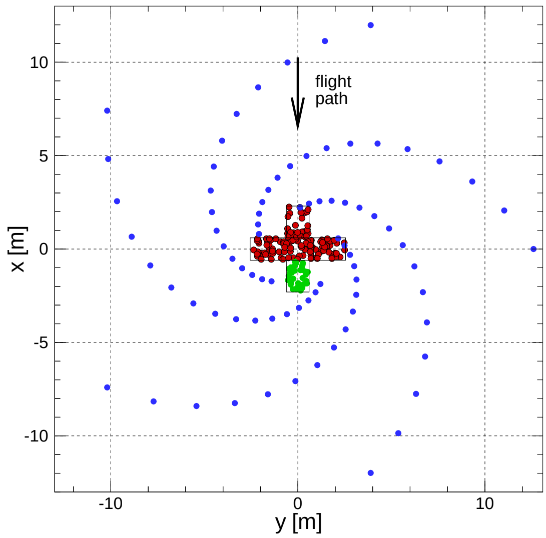

Fig. 2 Microphone array with 78 microphones in spiral arms and 160 microphones in 5 plates

The microphones used were Sennheiser KE4 electret capsules. They were arranged into a large microphone array with a diameter of 25 meters (see figure 2) consisting of two sub-arrays of different shapes. A large array consisted of 78 microphones located on 5 logarithmic spirals. 5 microphones were located on a circle. The diameters of the circles decreased with a factor $10^{-1/20} = 0.891$ which makes it possible to keep the beam-width for one-third-octave bands constant by reducing the array size by two radial steps with a resulting diameter ratio of 0.794 for neighbouring frequency bands. The beam-width can also be adjusted for different fly-over altitudes in steps of 11% by changing the diameter of the largest circle used. (See discussion on beam pattern in Piet et al.[5])

The microphones were mounted with grazing incidence on 1 m by 2 m moisture resistant wooden plates laid out on the grass of the test site shown in Fig. 1. The microphones were connected to cabinets containing 32 analogue-to-digital converters. The positions of the cabinets were chosen such that the cables carrying analogue signals were as short as possible. All 32 digitised microphone signals are transmitted to the computer via a single CAT 5 shielded twisted pair computer network cable.

A second array with 160 microphones consisting of five pre-fabricated plates was placed into the centre of the spiral. The latter array was designed and built for an investigation of the noise from the wake vortices of aircraft. The plates were equipped with 32 flush mounted microphones each and had built-in analogue-to-digital converters. A cover of acoustic foam reduced the influence of wind noise.

The aircraft attitude, airspeed, engine data, GPS position, aircraft cockpit time, and computed wind vector were recorded in steps of one second using an on-board system. The GPS (not DGPS) position was recorded with an uncertainty of one half of a second. Therefore, the position information as function of time of the aircraft could only be used as a hint for the data reduction. Additional ground based equipment was used for more precise estimates. The aircraft ground speed was determined by two line cameras positioned before and after the array on the flight path with a known distance. The altitude of the fly-over was determined by an array of three laser distance meters separated by 15 m perpendicular to the flight path. These distance meters scanned for a target with a frequency of 500 Hz and created a trigger signal when they acquired a target during a fly-over. The analogue signals of the line cameras and the trigger pulses of the distance meters were recorded together with the microphone signals. In addition, colleagues from DLR Braunschweig (Institute of Aerodynamics and Fluid Technology) determined the fly-over altitude with a photographic method.[1]

Data processing

The original data, sampled at 38095 Hz, are first re-sampled with a multiple of the engine's shaft frequency f_s,

$$f\text{res} = f\text{s}\,\frac{2048}{6}$$

for the position of a moving engine inlet on the aircraft. See Piet et al.[5] for details of the de-dopplerisation procedure. This ensures that buzz related peaks appear at integer multiples of the shaft frequency at every 6th line in the discrete frequency spectrum.

A time series of 12288 samples is then used for the further frequency analysis using a Fast Fourier Transform for 11 time segments with 2048 samples with an overlap of 0.5, windowed with a Hanning function. The length of the time series corresponds to an averaging time of 0.3 s. For a typical fly-over with a ground speed of 80 m/s and an altitude of 200 m, the aircraft moved about 25 m in 0.3 s. The maximum change of the emission angle θ occurs when the aircraft is directly over the array at $\theta = 90°$ and is in the order of $\Delta\theta = \pm 3.7°$.

The data are processed using two different methods:

- **De-dopplerised frequency spectra** require the computation of the power-spectral density of an unspecified number of de-dopplerised microphone signals followed by an averaging over these microphones.
- **Focused frequency spectra** require a beam-forming algorithm consisting of an averaging in the time domain of the de-dopplerised time series of the microphones in a phased array and subsequent computation of the power-spectral density of the resulting averaged time series.

The 160 microphone signals from the five plates were used for the computation of de-dopplerised frequency spectra because the signals were free of wind noise.

The 78 microphone spiral-arm array was used for the focused frequency spectra. The here applied array signal processing is a delay-and-sum beam-forming approach.[6] The array processing procedure for moving sources with application to aircraft fly-over measurements and its limitations are described in detail by Piet et al.[5]

The data-reduction software of DLR had to be extended for a perfect de-dopplerisation to include the influence of the average wind vector.

Experimental results

Directivity of buzz-saw noise

In order to investigate the sound characteristics of both engines individually, fly-overs were performed with one engine running at 93 % NLC and the other in flight idle. For one of these flights, Fig. 3 shows the evolution of the narrow-band spectra of the unmodified engine as a function of the emission angle θ. Ten instances of the sound-pressure level for emission angles $45° \leq \theta \leq 90°$ rel. to the flight direction are shown in one plot offset relative to each other by 10 dB, starting from the spectrum at $\theta = 90°$. Smaller angles could not be studied because of a too late start of the data acquisition. The frequency axis is scaled with the engine shaft frequency so that the peaks in the spectra can be associated with the engine order. The blade-passing frequency is at EO = 36, its first harmonic at EO = 72, and buzz tones show at integer multiples of the engine order. Tones that do not scale with the engine order are not buzz-related, e.g. the peak at EO $\approx$ 18.5 that first appears at $\theta = 70°$, until it stands out alone at $\theta = 90°$. This tone results from an aerodynamic noise source.

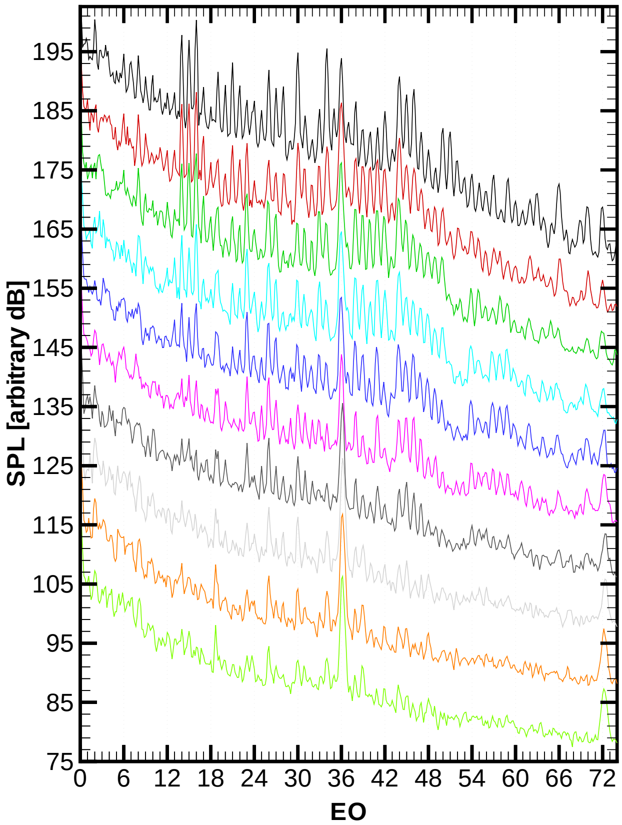

Fig. 3 Flyover with the unmodified engine at 93 %NLC and the modified in flight idle; de-dopplerised narrow band spectra for increments of $\Delta\theta = 5°$ shifted by 10 dB each from bottom ($\theta = 90°$) to top ($\theta = 45°$). SPL is defined with the same arbitrary reference in all figures.

Fig. 3 shows that buzz-saw noise is mainly radiated in the forward arc. The intensity of buzz-saw noise decreases from $\theta = 45°$, the smallest values of θ that could be evaluated, until $\theta = 80°$.

The directivity of the radiated noise is different for the buzz related peaks (at multiples of rotor shaft frequency) and for the blade passing frequency and its harmonics. Fig. 4 shows that the maximum at the blade passing frequency (EO = 36) occurs at $\theta = 85°$, with another weaker local maximum at $\theta = 50°$. The strong appearance of the blade passing frequency in the far field cannot be explained as a buzz-saw noise component but indicates a strong interaction noise between the non-uniform flow field in the inlet and the rotor. The rotor-stator interaction noise of this engine is cut off at the blade passing frequency . The first harmonic of the blade passing frequency has a maximum at $\theta = 90°$ (see Fig. 4).

The Doppler-amplification in the forward arc is not removed in any of the figures. A proper correction would reduce the levels in the forward arc (angles smaller than 90 degrees). Also, no correction due to attenuation in the atmosphere was applied. This would increase the levels in the forward arc, especially at higher frequencies.

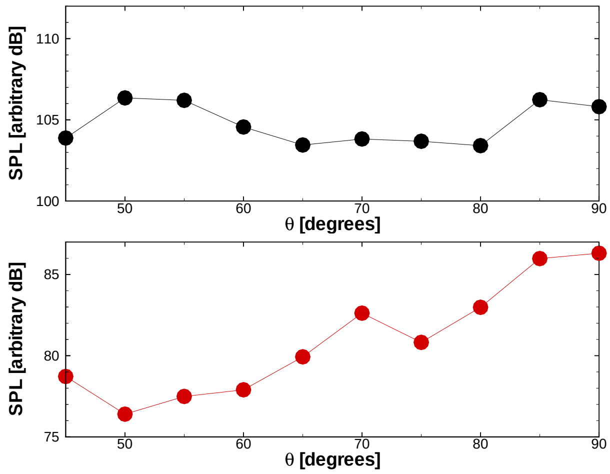

Fig. 4 Directivity of BPF and 2 BPF for the data shown in Fig. 3

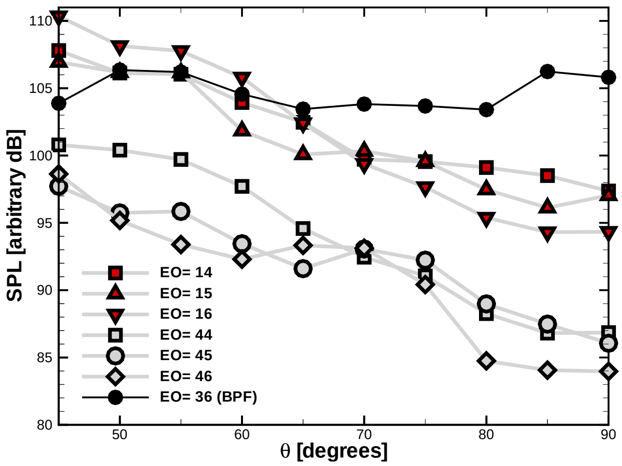

Fig. 5 Directivity of EO peaks 14 to 16 and 44 to 46 for the data shown in Fig. 3

The strongest buzz-saw noise peaks in Fig. 3 occur at engine orders 14, 15, and 16. Above the blade passing frequency, there is another group of three neighbouring strong peaks at engine orders 44 to 46. Fig. 5 shows the directivity of these peaks in comparison with the blade-passing frequency. At $\theta = 45°$, the peaks at engine orders 14-16 have higher levels than the blade passing frequency. These buzz related peaks show a strong decrease between $45° \leq \theta \leq 70°$, followed by a weaker decrease up to 90°. Smaller angles than $\theta = 45°$ could not be analysed due to the late start of recording.

The peaks at engine orders 30 and 34 (see Fig. 6) show a different behaviour: while they show higher levels than the blade passing frequency at $\theta = 45°$, they decrease rapidly by 10 dB between $\theta = 45°$ and $\theta = 55°$.

The directivities are more uniform for engine orders be-

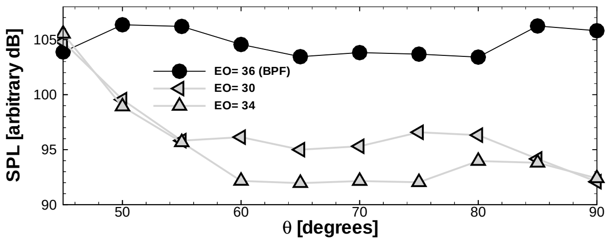

Fig. 6 Directivity of peaks for EO 30 and 34 for the data shown in Fig. 3

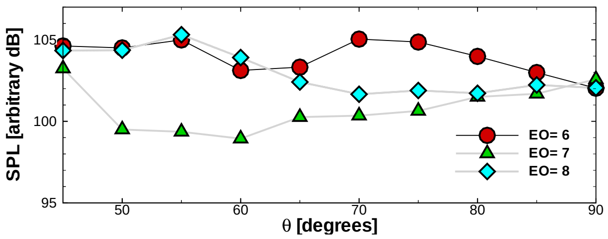

Fig. 7 Directivity of EO 6 and 8 peaks for the data shown in figure 3

tween 6 and 8 as shown in Fig. 7.

Influence of mode scattering

According to the theory for uniform mean flow and uniform acoustic wall impedance, one would expect that each buzz component would have a distinctive peak in the directivity at a certain emission angle. The peak angle of a radial duct mode would be expected close to the phase-normal angle of the propagating wave. The first few engine orders are cut-off according to this theory. The lowest cut-on mode for a hard-walled circular cylindrical duct should peak close to $\theta = 90°$ and this peak should move to smaller angles for increasing frequencies.

In contrast to this theory, the measured directivities generally show a smooth variation with emission angle which can only be explained if the radiation for each engine order consists of several azimuthal modes. This is most likely related to the scattering of buzz-saw noise in the engine inlet by the liner splices and the non-uniform inflow as described in the introduction. E.g., the casing liner immediately in front of the fan rotor consists of 6 pieces that are assembled with 6 wide splices and the inlet liner contains 2 splices.

Comparison of different fly-overs

During the measurement campaign, four fly-overs were performed with only the left (unmodified) engine providing thrust and the right (modified) engine running in flight-idle. Table 1 lists parameters for these fly-overs and shows that the fly-overs were performed at reasonably comparable conditions. Fly-overs L-1 to L-3 were flown consecutively, while L-4 was performed after the aircraft had landed and taken off again providing the chance of different blade stagger angles.

fly-over	ground speed	altitude	glide angle	pitch	N1	acceleration
	[m/s]	[m]	[deg]	[deg]	[Hz]	[m/s^2]
L-1	88.9	203	0	3	73.6	0.6
L-2	94.3	204	0	3	73.6	0.4
L-3	92.4	204	0	3	73.6	0.7
L-4	93.2	206	0	3	74.0	0.5

Table 1 Overview of single-engine flights (fan spool of left engine running at $N_1 = 93$% NLC, right engine in flight idle)

Corresponding measurements were also made with the modified right engine and will be reported in a forthcoming paper.

Fig. 8 shows the power-spectral density at an emission angle of $\theta = 50°$ for the fly-overs listed in table 1. Although there is some variation between different fly-overs, the over-all sound characteristic of the engine remains fairly similar.

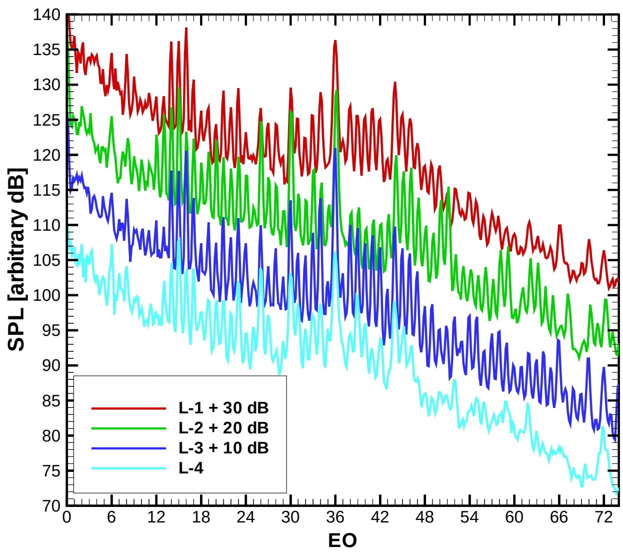

Fig. 8 Comparison of spectra at $\theta = 50°$ for single-engine fly-overs listed in table 1

Comparison of the two engines

The modifications on the airframe and engine were removed and the standard aircraft was then tested on the second day of the campaign. The single engine fly-overs were not repeated, assuming that the engines were identical. However, it turned out that the two engines of the test aircraft had different sound characteristics. (Is that really true? Please plot the differences and compare with Fig. 8) Retrospectively, this is not surprising, since the characteristics of buzz-saw noise depend on small variations in the fan.

The two engines had to be compared in the take-off configuration with both engines running with a speed of 88 % NLC. The fly-over altitudes were much higher in this case. The test method used for the single-engine fly-overs could not be used since the spectra would contain noise contributions from both engines. Therefore, the phased array was used to focus on the aircraft's two engine inlets and the narrow-band spectra were computed from the focused signals. Fig. 9 shows spectra of the spiral array focused on the engine inlets for an emission angle of $\theta = 65°$. This was the smallest emission angle that could be evaluated for the fly-overs in take-off configuration. The distribution of the buzz peaks and their strength differs for both engines. The difference of the right and left engine spectra is more obvious when they are displayed side by side as in figure 10, where the right engine data from figure 9 are incremented by 18 dB.

The spectra cannot be compared with those in the previous figures because the engines were run at different speed and the focussing results in a more rapid decrease of the levels with increasing frequencies in Figs. 9 and 10.

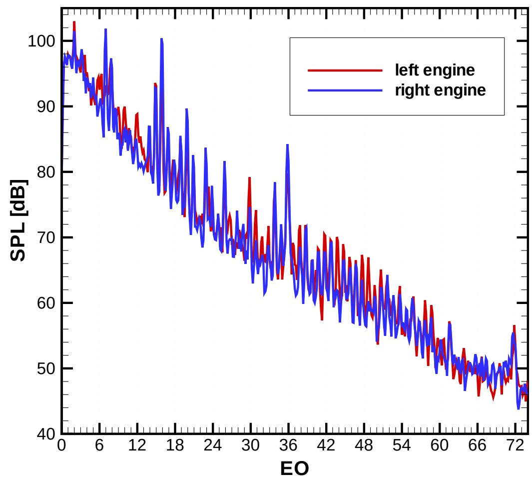

Fig. 9 De-dopplerised spectra of the spiral array focused on the engine inlets for a take-off at 88 % **NLC;** $\theta = 65°$

Contribution of buzz tones to the total noise level

The contribution of buzz-saw noise to the total noise level shall be estimated now by comparing the A-weighted sound-pressure level of the original spectra with the spectra obtained by reducing the sound-pressure levels of the buzz peaks to the broad-band levels in the adjacent frequency bands. The result is shown as a function of emission angle in Fig. ??. (Discussion.)

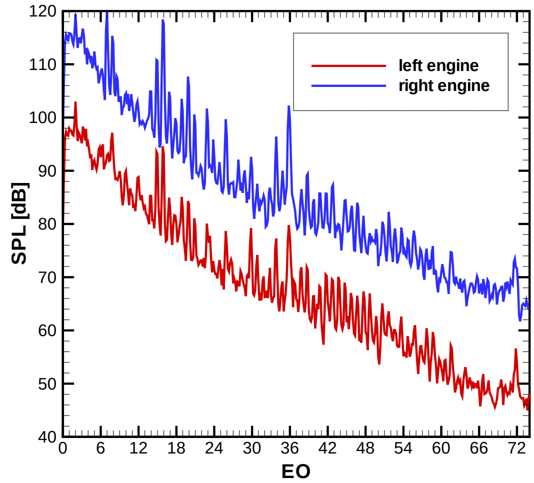

Fig. 10 The data from figure 9 with the right engine spectrum shifted upward by 18 dB

Conclusions

It can be concluded that fly-over noise tests are feasible for the investigation of buzz-saw noise. The influence of acoustic liner improvements or of any other changes to the engine inlet on buzz-saw noise can be tested in flight. A successful data reduction is only possible with a perfect de-dopplerisation of the microphone data and this requires an exact knowledge of the locations of the engine inlets as a function of time. The wind vector has to be considered in the de-dopplerisation process, although it suffices to use a constant wind vector for the whole distance between aircraft and microphones.

The results presented in this paper verify the observation that aero-engines in flight radiate buzz-saw noise mainly in the forward arc. The directivity of each radiated buzz component can be investigated separately. The levels of most buzz components decrease rapidly between $\theta = 45°$ and $\theta = 70°$. The directivity patterns of individual buzz tones change with frequency. They do not feature narrow peaks for a certain angle, a result that indicates that the radiated buzz-saw noise components are not dominated by a single mode, but are the result of an acoustic scattering by the splices in the acoustic liners and the non-uniform mean flow in the inlet.

The test procedure described in this report would be capable of studying the effect of a splice-less liner on the radiation pattern of each buzz component.

The contribution of the buzz tones to the total noise level can be estimated by reducing the levels of the buzz tones in the narrow-band spectra to the level of adjacent broadband level. This procedure shows that engine noise would be reduced by up to 5 dB(A) if buzz-saw noise could be eliminated. However, this reduction would only be achieved near the peak radiation angle of buzz-saw noise which is located at 45 degrees rel. the flight direction or smaller angles.

Acknowledgments

The tests were initiated by Dr. Frank Walle of Lufthansa and Prof. Heinrich Weyer of DLR in an effort to identify the noise reduction potential of the A319/A320/A321 fleet through retro-fits and to support the aircraft noise research at DLR. DLR and Snecma proposed the modifications which were designed with support and approval of Airbus. Lufthansa Technik manufactured and installed the devices and prepared the paperwork for approval by the German Federal Aviation Authority (Luftfahrt-Bundesamt) for measuring flights.

The efforts and motivation of all participants are appreciated who made it possible to carry out the flights only four months after the decision was made. Out of the many participants, Dr. Gerd Saueressig and Dr. Andreas Waibel of Lufthansa shall be mentioned as they had the immense task of organising the test campaign. The aircraft was flown with remarkable precision by the management pilots Raimund Müller, Jürgen Schadt, and Siegfried Wegeleben after practicing the procedures in a flight simulator.

The efforts of Airbus and Snecma in supporting the tests are also very much appreciated. The valuable discussions with Hervé Batard of Airbus concerning the scattering of buzz tones in the inlet are acknowledged.

It may be mentioned that the test was performed one month after the attacks of September 11, 2001 in spite of the dramatic financial situation of the airline industry. This shows how important noise reduction efforts are considered by Lufthansa.

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