VIRTUAL SOUND AIRCRAFT SIMULATION IS NOW REALITY

J Périsse 01dB-Metravib, Limonest, France
P Chevret 01dB-Metravib, Limonest, France
C Thirard 01dB-Metravib, Limonest, France
R Maier EADS-Deutschland GmbH, Munich, Germany
JM Nogues Snecma Moteurs, Moissy-Cramayel, France

1. INTRODUCTION

Within the European funded project SEFA (Sound Engineering For Aircraft) a method generating a synthesis sound targeting the noise signature of a flying aircraft was created.

The purpose of this article is to describe this method and to demonstrate its quality level through a sound demonstration on a test-aircraft.

First the noise sources as the different physical effects composing an aircraft noise signature are enlisted. Then, the methods used to synthesize these components and these effects are detailed. What brings each of these steps to approach the global noise signature of the test-aircraft is illustrated thanks to a “progressive” sound demonstration. To establish the quality of the method, the synthesis sound is finally compared to a real noise measurement of the test-aircraft.

2. METHOD FOR THE NOISE SYNTHESIS OF ENGINE SOURCES

2.1 General procedure for aircraft noise simulation

Engine noise is decomposed into distinct types of sources. Each source has its own frequency spectrum and directivity, which depends on the engine speed.

Based on the spectrum for each noise component, a common source classification can be established according to:

1. Harmonic noise including the *fan noise*, the *compressor noise*, the *turbine noise*,
2. Broadband noise, corresponding to the background spectrum of contributions from jet and combustion noise.

The method for the noise synthesis is directly linked to the class the source to be synthesized belongs to [1]. The harmonic and broad band sources are treated independently in a different way (described below), the synthesis depending on the flight parameters (engine speed, directivity, etc). Then, the sources are summed and finally used as inputs to the time varying propagation filters (see section 4).

It has to be noted that the aerodynamic noise of the aircraft is not considered in this paper but in that case, the approach would be similar to the broad band synthesis.

2.2 Synthesis of Harmonic noise

The method for tonal components synthesis (including harmonic noise) consists in calculating at each time the sound pressure *P(t)* from the amplitude and the phase (if provided) of each harmonic – for a given engine speed – which make up the harmonic noise spectrum. The expression for the computation of acoustic sound pressure by summation of all harmonics contribution is:

$$P(t) = Re\left\{ \sum_{n=1}^{N} \left[a_n(t) \times \exp\left(jn\alpha(t) \right) \right] \right\} \quad (1)$$

where a_n are the complex amplitudes of harmonic n and $\alpha(t)$ is the instantaneous engine shaft angle which is expressed in stationary condition as $\alpha(t) = \Omega \times t$, where Ω is the engine speed.

The amplitude and phase information may come from measurements at static conditions or computations from numerical models. Then, when changing the engine speed for instance, harmonic values are interpolated in the Nyquist plane (Figure 1).

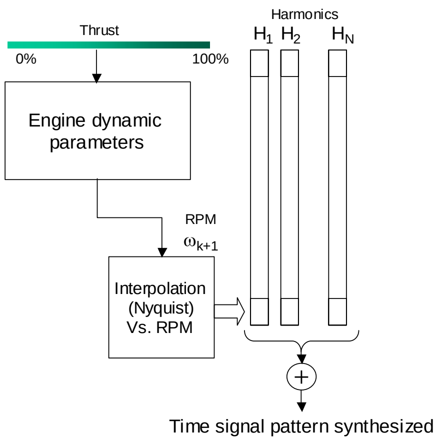

Figure 1: General layout of harmonic noise synthesis.

For non-stationary condition the computation of the shaft angle at each instant t_k (where $t_k = k \times \Delta t$) is performed by a time dependent numerical integration of the engine speed:

$$\alpha(t_k) = \left(\frac{1}{2}\Omega_0 + \sum_{i=1}^{k-1} \Omega_i + \frac{1}{2}\Omega_k \right) . \times \Delta t \quad (2)$$

where Ω_i is the engine speed at instant t_i (computed by interpolation from the time history of the engine speed).

2.3 Synthesis of a broadband noise

The principle for the broad-band noise synthesis is the time convolution of the impulse response calculated from the noise power spectral density (expressed either as a narrow band or a third octave band spectrum) with a white noise of zero average and 1 variance [2]:

$$P_{BB}(t) = \mathrm{FIR}_{BB}(t) \otimes S_{WN}(t) \quad (3)$$

FIR_{BB} is the finite impulse response of the broadband noise and S_{WN} is a white noise signal.

The variation of the broad-band noise versus the engine speed is performed by a linear interpolation between two spectra of known noises (according to engine speed) or, if existing, by interpolation according to simple physical law (

Figure 2).

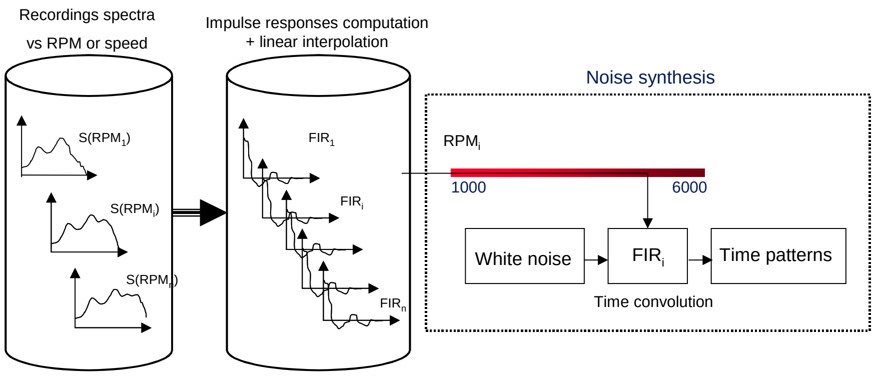

Figure 2: General layout of broad-band noise synthesis

3. VALIDATION IN STATIC TEST BENCH CONDITIONS

In this section, we apply the synthesis method presented above from measurement made on real engine at static bench conditions. First, the sound pressure field (in the form of a temporal signal) is measured at different angles around the engine (at a fixed engine speed). Typically, a 10° sampling is performed. Then, from the computed spectra at each angle, the harmonic energy and background noise are extracted.

The synthesis finally consists in applying, first the method presented in section 2.2 for harmonic components and then, the one presented in section 2.3 for background noise. A listening comparison between the measured signal and the synthesized one shows the relevance of the approach at all the angles.
Moreover, from this static data some simulations can be performed. For example, a person walking around the engine and the perception of sound all along the path is simulated. The obtained sounds are judged as very realistic.

At this stage, the synthesis was applied only for an engine lying on the ground. The challenge is to extrapolate from this ground data to in flight signals, including a simulated flight path and propagation transfer function. This is the aim of next section.

4. IN-FLIGHT NOISE SYNTHESIS INCLUDING MODELLING OF PROPAGATION EFFECTS

For the conversion of static noise data into flight a couple of effects have to be considered. For aircraft noise prediction all these effects are considered usually in the frequency domain by applying deltas in 1/3rd octave band data. An overview of the effects relevant for aircraft noise prediction are visualised in Figure 3.

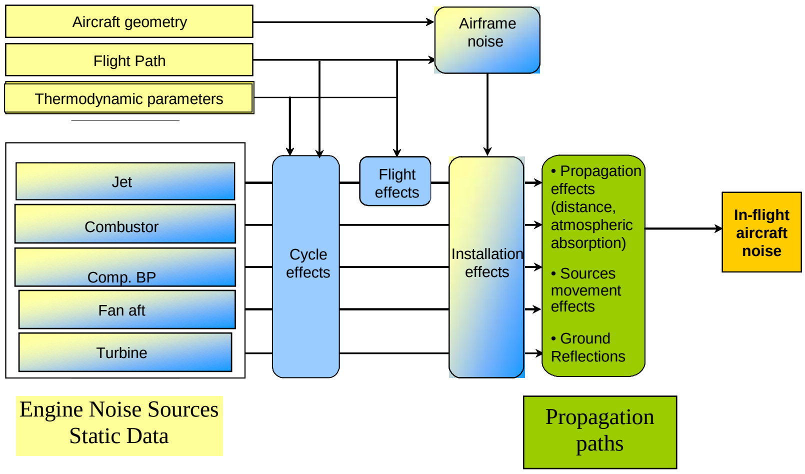

Figure 3: Typical aircraft noise prediction scheme

In a first step flight effects have to be taken into account, i.e. mainly impacts on the source itself due to :

- thermodynamic effects on noise sources (atmospheric conditions, altitude)
- cycle effects
- installation effects (e.g. wing shielding)
- flight effects on noise sources (*e.g*. Doppler amplification)

Flight effects modify the source strength. So it is possible to consider the impact of flight effects on noise sources in the frequency domain also within a sound simulator for audible sounds. For effects occurring on the propagation paths, like Doppler shift and ground reflection, phase information is important. These effects must be therefore simulated in the time domain.

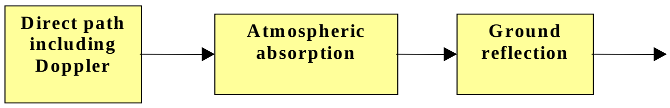

Figure 4: Modeling of propagation path

For the sake of simplicity all effects occurring along the propagation paths have been treated in the time domain assuming a simple point to point propagation. In a 1st step the direct path is modelled, by considering the distance and Doppler effect. The Doppler effect can be considered by retarded time, i.e. a nonlinear transformation of time from emission to arrival at the receiver point must be carried out:

$$t_i = \tau_i + r_i/c \quad (4)$$

In this expression, t_i:is the arrival time for theh trajectory point i, r_i: is the distance from the source to the receiver, τ_i is the retarded time and *c* is the sound speed.

The nonlinear transformation of time is done by interpolation and re-sampling of the sampled audio data. Atmospheric absorption is also considered in the time domain by applying time varying filtering on the audio data. Due to atmospheric absorption higher frequencies are significantly damped in particular for large distance of the source [3]. Other atmospheric effects like wind and turbulence are currently not taken into account. In a final step ground reflection is modelled. The basic principle is illustrated in Figure 4. Due to the ground surface between source and receiver, sound is reflected against the ground and is thereby affected by a complex impedance. This leads to interference phenomena with the direct sound path at the receiver. The phenomena can be described analytically for single frequency analysis, provided that the ground impedance is known.

In order to assess the mean effect on sound pressure level it is possible to use *e.g*. a statistical approach with an octave band or third octave band frequency bandwidth as usually done for aircraft noise prediction. For simple geometries like flat terrain, the two paths (r_2, r_1, see Figure 5) can be treated independent and superimposed. In the path r_2 the magnitude and phase change due to reflection can be approximated by a filter. The required filter characteristic can be calculated from the Weyl-Van der Pol equation [4]:

$$p = p_D + p_R$$

$$p_D = \frac{e^{-ikr_1}}{kr_1}$$

$$p_R = [R_p + F(1-R_p)]\frac{r_1}{r_2}e^{-ik(r_2-r_1)}p_D$$

k is the wave number, $R_p(\omega)$ is the reflection coefficient, Z is the ground impedance, $F(\omega)$ accounts for ground waves relevant for Θ near zero (mathematically complex error function of "numerical distance").

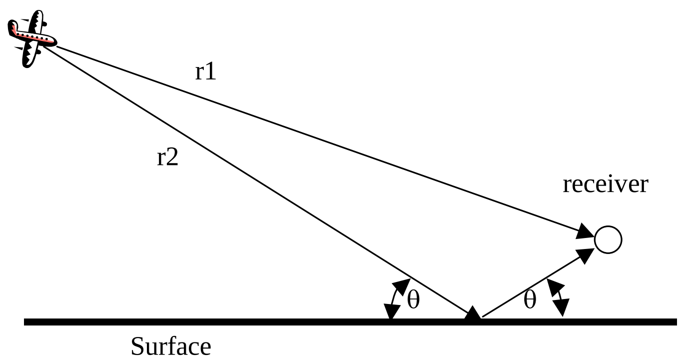

Figure 5: Visualization of ground effect

An example for the required filter characteristic is shown in Figure 7. The required filter characteristic depends on the aircraft position versus the receiver. This means that the filter characteristic must be changed permanently during the simulation of a flight. In addition to the reflection filter a time delay caused by the different path length (r_2-r_1) has to be taken into account as illustrated in Figure 6. An example for the total effect of ground reflection on the perceived sound is shown in Figure 8.

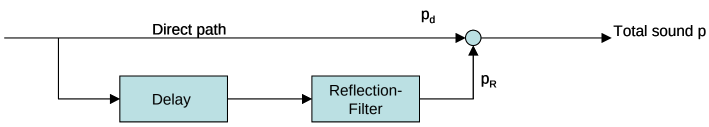

Figure 6: Simulation of ground reflection

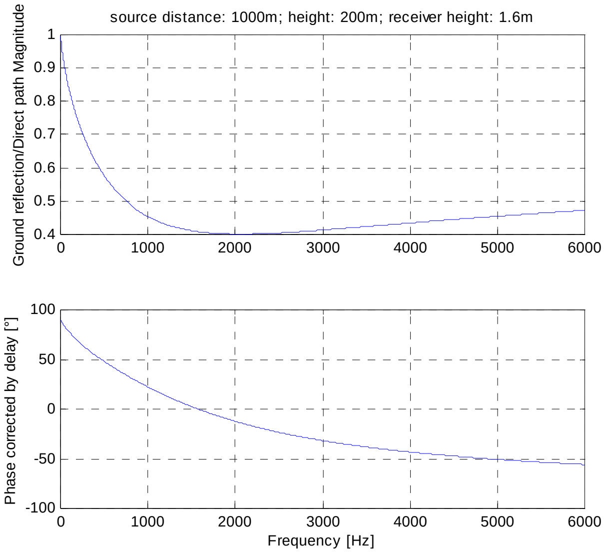

Figure 7: Magnitude and phase change due to reflection for flat terrain with grass (flow-resistivity $300*10^3$ Pa-s/m²)

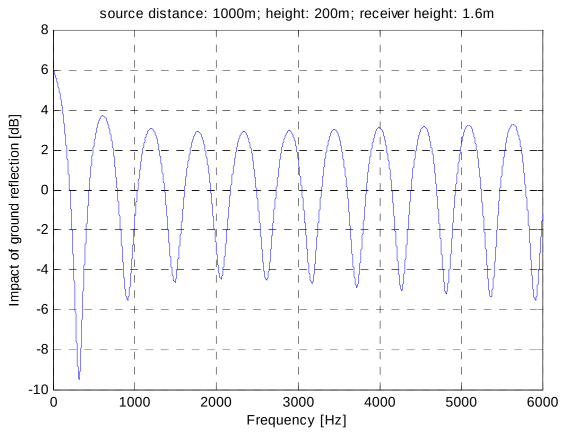

Figure 8: Simulated impact of ground reflection for flat terrain with grass (flow-resistivity $300*10^3$ Pa-s/m²)

5. TESTS SYNTHESIS OF AIRCRAFT ENGINE NOISE AND IN FLIGHT CONDITIONS

Synthesis of aircraft sound has been performed for several test cases related to certification measurements. In all cases the receiver is positioned at a height of 1.2m above ground. In a first step static engine noise has been synthesised considering the directivity according to varying view angle during flight path. After that the propagation effects as described in section 5 are applied. Changes of the sound for cutback condition are illustrated by the following waterfall diagrams showing the frequency spectrum versus time after each step of the simulation process.

Figure 9a shows the variation of source strength along the flight path due to directivity Figure 9b illustrates how the sound changes due to direct path propagation. The sound is attenuated according to the distance of the source and the Doppler shift changes significantly the frequency, which becomes very obvious for tonal noise components. Figure 9c shows the impact of acoustic absorption on the sound.

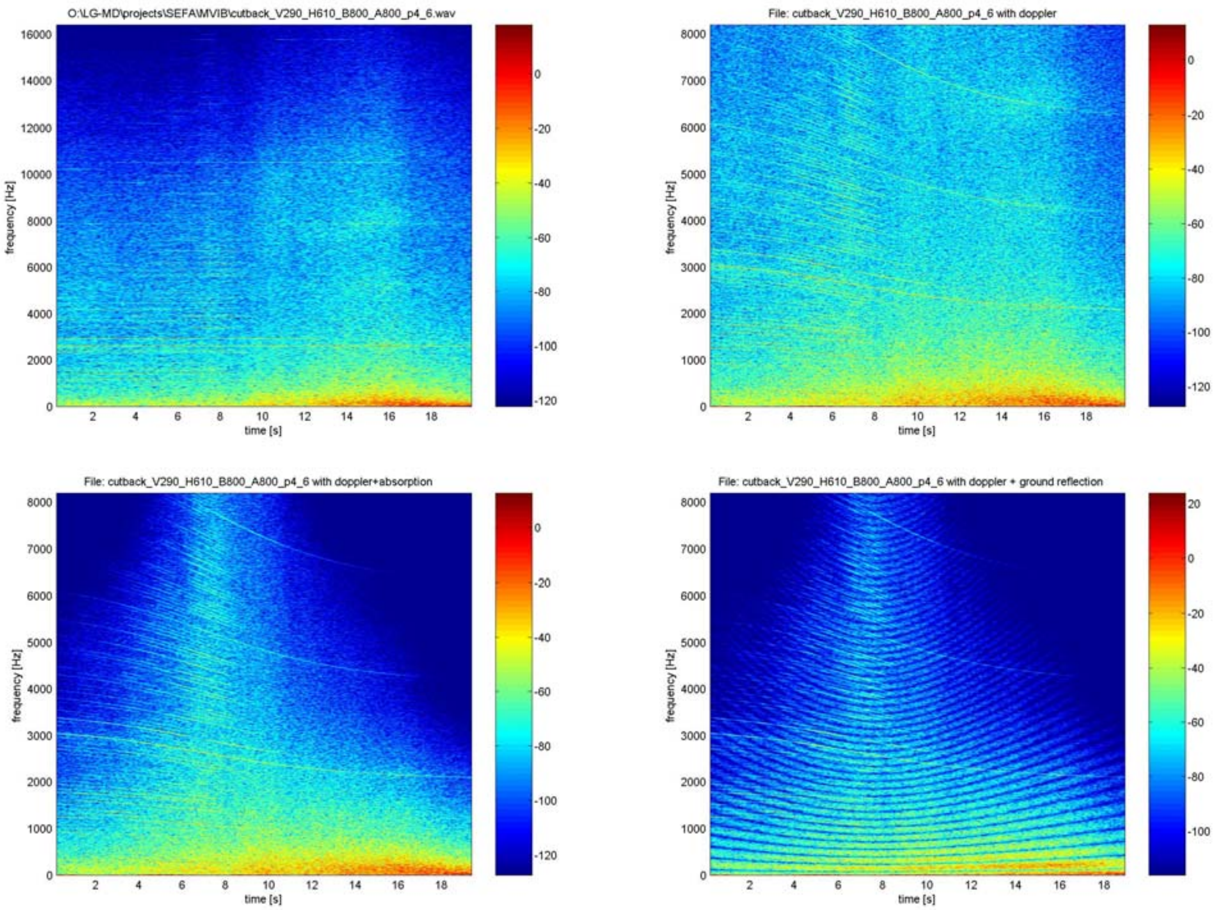

Figure 9: (a) Source strength including directivity along flight-path, (b) Uncalibrated sound pressure level at receiver due to direct path (without atmospheric absorption), (c) Uncalibrated sound pressure level at receiver due to direct path (including atmospheric absorption), (d). Uncalibrated sound pressure level at receiver including ground reflection

In particular for large distances (beginning and end of flight path) high frequency components are significantly reduced. All typical characteristics, which can be found in measured sounds for similar conditions are visible in Figure 9d. In particular, it becomes clear that the interference pattern due to ground reflection have a very important impact on the perceived sound.

6. CONCLUSIONS

In this paper, an original method for sound synthesis is presented. It is dedicated to aircraft noise modelling and specifically addresses the problem of aircraft noise disturbance. This method was built in the frame of SEFA European Project, which aims at developing a tool for the sound design of virtual aircraft. Two different synthesis methods are applied for tonal and broadband components, including accurate noise source decomposition. Then, by summing all components, time patterns synthesis of the noise sources is obtained including directivity along the real flight path. Afterwards, propagation effects are applied on the source time signal to achieve the final aircraft sound track as if measured at the ground.

The relevance of the approach was shown firstly through listening comparisons between static engine real measurements and synthesized sounds and secondarily thanks to listenings of synthesized sounds simulating a flying aircraft.

7. REFERENCES

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