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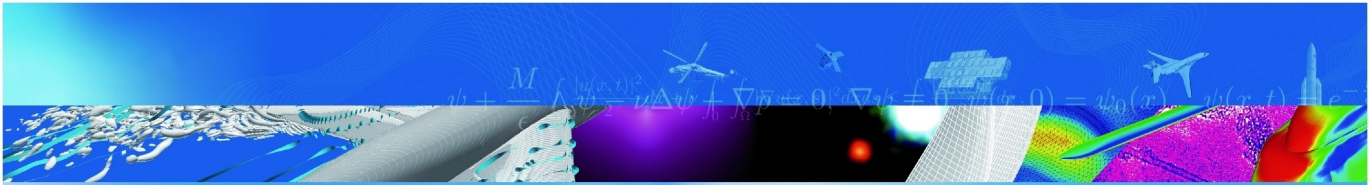
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CAPABILITIES OF IESTA-CARMEN TO PREDICT AIRCRAFT NOISE

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CARMEN is a tool to predict aircraft noise on the ground all along its trajectory during landing, take-off and cruise flyovers. It includes the acoustical source description, the installation effects and the sound propagation from the aircraft to the ground. The present paper illustrates the capabilities of the acoustic model CARMEN to take into account new technologies, such as contra-rotative propellers. A semi-empirical model describing the acoustical sources has been implemented in CARMEN. The simulation of the sound radiated by a mid-distance aircraft type motorized with a contra-rotative propeller is performed, predicting time dependent frequency spectra radiated on the ground. Temporal synthesis of the simulated spectra obtained with CARMEN together with an appropriate auralization procedure offer realistic signatures used in PARASOFT, a project dedicated to the perception of both existing and future aircraft noises.

1. Introduction

One challenge for the Air Transport System is to accommodate the forecast increase in air traffic, reducing the impact of noise. Since few decades a tremendous amount of researches and studies devoted to numerical simulations, wind tunnel and flyover experiments are performed in the aero-acoustics field aiming at the understanding of the acoustical sources, the control and the reduction of aircraft noise. Accurate physical insights, established through CFD and CAA modelling, experiments at reduced and full scales, are necessary to allow reducing the noise intensity but does not account for the comprehension of the noise impact on population, this impact being strongly correlated by the perception and the annoyance of the aircraft noise. Psychoacoustic studies are then performed where measured and synthesis sounds are listening by a cohort of participants and rated according to various scoring methodologies. Such an approach on the noise impact including both physical insight of the noise and psychoacoustic studies are increasingly developed. Due to its very strong influence on the air traffic growth, acoustics is now earlier integrated in the elaboration of new aircraft concepts. To reach this objective a two-step approach is required: the first one is the prediction of the noise radiated using semi-empirical, numerical predictions and experiment tools, and the second step deals with psycho-acoustics studies to take into account the influence of noise on human factors. The objective of this paper is to illustrate the capabilities of the IESTA-CARMEN to operate the first step of this approach and to provide data for the second step.

Section 2 summarizes CARMEN methodology to predict aircraft noise, Section 3 provides the noise sources description of the CROR with emphasis on its specification and Section 4 illustrates the prediction of the CARMEN calculation of the flyover simulations of a mid-aircraft motorized with CROR.

2. THE CARMEN PREDICTION METHODOLOGY

2.1 Acoustical modelization in CARMEN

IESTA (Infrastructure for Evaluating Air Transport Systems) is a tool developed by ONERA to design innovative air transport systems through a global evaluation platform [1]. The application of IESTA to the environmental impact of the air traffic surrounding airports deals with noise and chemical emissions. To reach this application several physical models are integrated in the IESTA platform: ground planning, aircraft, engine, acoustics and chemical dispersion, as shown in Figure 1. The acoustic model CARMEN is connected with the engine module in order to provide, all along the trajectory, the inputs required for the propulsion noise sources and also, with the aircraft module, to give the trajectory, the attitude of the aircraft, the high lift devices and the landing gear configurations. The aircraft and its fly mission being preliminary defined, CARMEN can predict the noise footprint around airport within a short CPU time, on existing and future aircraft. It describes the main acoustical phenomena encountered during aircraft flyover summarized by the sound pressure level prediction around the aircraft and also computes the propagation effects such as Doppler frequency shift, spreading loss, atmospheric attenuation. This prediction is of interest for the design of new technologies compared to reference aircraft, in order to provide faithfully gain in multi-disciplinary optimization studies. The time varying aircraft noise spectra can also deliver a realistic input for psycho-acoustic studies, using an efficient temporal synthesis, as done in the National PARASOFT project.

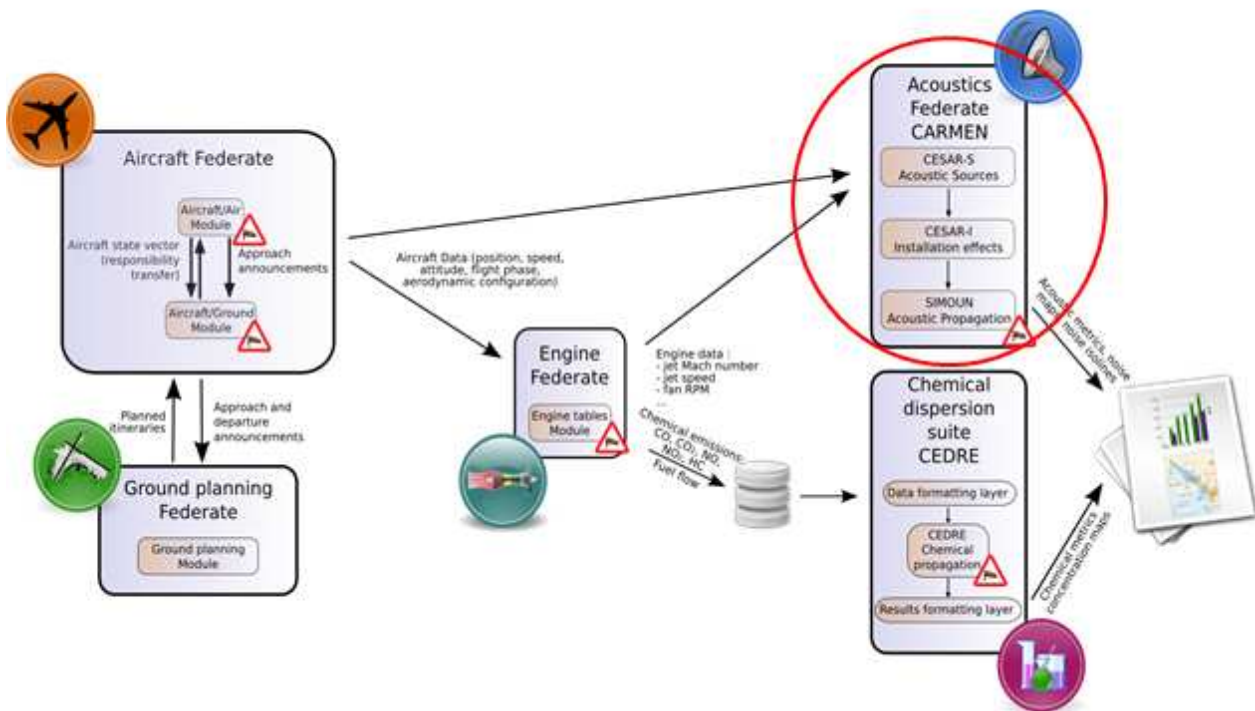


Figure 1: Physical models implemented in the IESTA platform.

The CARMEN model dedicated to aircraft noise prediction is composed of three modules [2, 3]: the acoustic source models, the installation effects and the atmospheric propagation. Each of these modules is assessed against reference results from experiments, analytical solutions or cross-checking simulations. The acoustics source model includes propulsive noise generated by the engine: the fan and the jet noise, and the airframe noise generated by the slat, the flap and the landing gear. Most of these models are based on semi-empirical model derived from the literature. Prior to their implementation in CARMEN, these models are assessed against experimental results obtained by ONERA within several National and European projects (VITAL, TYMPAN, LAGOON, SILENCER, AWIATOR, etc.). The module on installation effect is based on the ray-model, allowing

to perform direct and reflected rays, and scattered field by the whole aircraft. The aircraft surface is described with NURBS (Non-Uniform Rational Basis Splines) instead of a mesh surfaces, saving significant CPU time in the computation of the reflected rays. Propagation in the atmosphere model is based on the ray-model taking into account wind and temperature gradients, and atmospheric absorption along the rays. During the CARMEN simulation both static (aircraft geometry and meteorology) and dynamic variables (acoustical aircraft sources) relative to the trajectory scale time are considered. To save CPU time, shielding effects and long range sound propagation in the atmosphere, requiring more heavy computations, are pre-computed, while acoustical sources derived from semi-empirical models are supplied in “real time”, as function of the aircraft configuration.

It is to notice that CARMEN is quite complementary to the Integrated Noise Model developed by the Federal Aviation Administration, based on a very large experimental database. INM is well suited to predict the footprint generated by a fleet of existing aircraft over a long duration period under mainly conventional procedures, while CARMEN can give the acoustical gains on modified and new aircraft concepts, vs reference aircraft. CARMEN methodology is similar to ANOPP and the PANAM ones developed since many years by NASA [4] and DLR [5], respectively. The alive cooperation between the three research centres, based on benchmarking for reference aircraft configurations, will reinforced the assessment of the tools.

2.2 CARMEN assessments

Complementary to the individual evaluation of the three models, a continuous overall assessment of CARMEN is performed against experimental results measured from aircraft in flight tests. Such a comparison requires gathering a tremendous amount of information on the aircraft itself to feed the CARMEN modules (engine type, high-lift devices configurations) and also on the meteorological conditions to account for the wave propagation in the low atmosphere. Flyovers concerning A340 during landing and A320 during take-off performed in the European projects AWIATOR and SILENCER, respectively, offer such a huge and well-documented data base.

It is to notice that such an amount of data is subject to variations and uncertainties, especially the meteorological conditions. A sensitive analysis on the CARMEN prediction has been done on the meteorological conditions varying the wind velocity and the wind profile, for the AWIATOR and SILENCER flyovers [6]. A good agreement is obtained with the AWIATOR measurement for both the OASPL and the spectrum on the ground during the aircraft flyover. For these flyovers where the aircraft-microphone distance varies from a few hundred meters to a few kilometres, the CARMEN prediction found few decibels difference between the homogeneous and log-profile wind velocity. Such a sensitive study is of interest on the whole data to determine the accuracy of the prediction, *i. e.*, to plot a global error margin on the results.

The CARMEN assessment performed on the turbo-jet engine aircraft A320 at take-off, using a modified fan noise modelisation was presented during ICSV22 [7]. This paper shows a quite a good agreement between the CARMEN prediction and the experiment performed by Airbus on a A320 in the framework of the SilenceR program and demonstrates the fan noise improvements, including the Buzz Saw Noise description and the implementation of the liner treatment covering the nacelle intake.

During the PARASOFT project, CARMEN spectra of the A320 and A340 flyovers were synthesized, providing predicted temporal signatures. Listening to both the predicted signatures and experimental measured signal shows the realism of the simulation, reinforcing its relevance, in addition to the comparisons of the directivity pattern and spectra shape.

3. ACOUSTICS OF THE CONTRA-ROTATIVE PROPELLER

The interest of the CROR and its theoretical acoustical background is briefly illustrated below from considerations in [8]. The efficiency of counter-rotating open rotors is better than that of turboprops and of conventional single propfans: it reduces the fuel consumption. In comparison with the

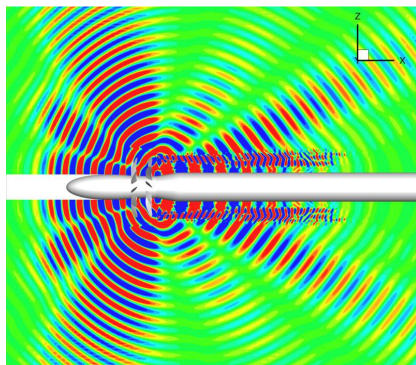
single propfan, a 10 % reduction of fuel consumption can be obtain with the counter-rotating open rotor (CROR), where the swirling flow is recovered by the aft of counter-rotating blade row. CROR can motorize mid-distance aircraft at cruise Mach number of 0.7 to 0.8. As a consequence, the passion on this propulsive technology strongly depends on the fuel cost and was extensively studied to power aircraft in the 80s. As an example, Figure 2 illustrates the CROR designed by GE UDF mounted on a McDonnell-Douglas MD-80.



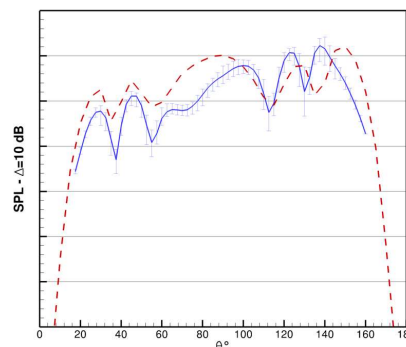
Figure 2: UDF[®] de General Electric mounted on a McDonnell-Douglas MD-80.

It was shown that CROR can give rise to an acoustic issue, the noise being generated, on the one hand by the two isolated rotors operating with high tip speed and, on the other hand, by interactions between the two blade rows. In addition, in the open rotor configuration the noise can radiate freely unlike the ducted engines where the nacelle acts as a noise guide (low-pass filter regarding the azimuthal modes and high-pass filter in frequency) and allows the insertion of acoustic liners to reduce the noise. In the free field conditions of CROR, the sound waves can radiate towards the fuselage, an unfavorable configuration to the passenger comfort, and towards the ground around airport. Only an appropriate positioning of the engines may limit the noise, using the airframe as a shield, the so-called acoustical installation effects. It is therefore mandatory to properly predict the acoustic radiation of such systems, first to assess the noise directivities of an isolated engine and then to offer an optimal noise installation solution.

Since the last years, counter-rotating is again a subject of interest for the aeronautics industry while the acoustical issue could still prevent its development. A large amount of recent results are available especially thanks to progress in numerical simulations. Most of the numerical methodologies are based on hybrid methods, combining Computational Fluid Dynamics (CFD) simulations of the propulsive system with Computational AeroAcoustics (CAA) methods, allowing propagation in the far field [9] (Figure 3). Analysis taking into account the presence of solid boundaries such as a pylon, wing and fuselage, can now be performed thanks to advanced numerical simulations [10].



a) CFD/CAA prediction of the sound pressure field radiated by a CROR



b) Z08 averaged experimental results (—) and CFD/CAA (- - -).

Figure 3: Numerical prediction and comparison with scaled model experiment, from [9].

This study does not aim to accurately describe the CROR noise with a numerical solution, but to show the capabilities of the CARMEN prediction to operate a new concept, by use of a simplified CROR description. Future works are planned to chain CARMEN with existing numerical simulation or experimental results. The CROR model implemented in CARMEN is derived from the Hanson model [11] and the propeller theory described by Goldstein [12] for the tones noise, and on the Blandeau model [13], for the broadband emission.

The main specifications of CROR noise are briefly reminded in terms of directivity patterns, tonal and broadband noise. The main parameters governing acoustic radiation are the number of blades in each rotor, B_1 and B_2 , their tip speeds and the blade loadings. In the case of rotors rotating at the same speed, sound spectra are dominated by the harmonics of each blade passing frequency, $f_1 = |n_1 B_1 N|$ and $f_2 = |n_2 B_2 N|$, and by the interaction tones between the two rotors at frequencies $f_{12} = |n_1 B_1 N + n_2 B_2 N|$, where N is the rotation speed, and n_1 and n_2 are integers.

3.1 Directivity patterns

In the Hanson model, the directivity of tones is mainly determined by a Bessel function. While the rotor alone rows mainly radiated in the plan of the propeller, interaction tones can strongly radiate near the centerline due to low-order Bessel functions, as illustrated by Woodward [14] in Figure 4. This can significantly increase the duration of the perceived sound levels and penalized the EPNL (Effective Perceived Noise Level) for the certification. The overall sound intensity varies as the thrust to the power 3 due to the dipolar type of the main sources.

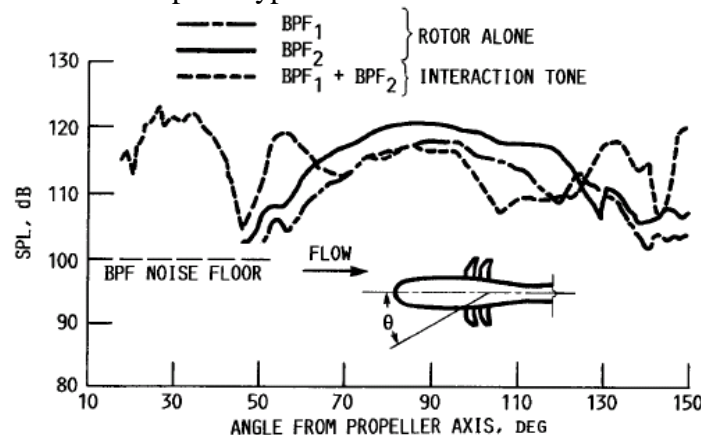


Figure 4: Directivity pattern of a CROR, from 14.

3.2 Tones noise

The model is based on decomposition of the rotational Mach and the loads repartition along the blade wingspan. According to Hanson, the circumferential mode m at the interaction tone frequency $f_{12} = (n_2 B_2 + n_1 B_1) \Omega$ is $m = n_2 B_2 - n_1 B_1$. The tones which are efficiently radiated have a supersonic circumferential phase Mach number. It is the reason why interaction tones are noisy at low advancing speed of take-off and approach and can exceed the sound levels due to each rotor. Tones due to each rotor only radiate efficiently at cruise speed when the helical tip Mach number $M_{rot} = 2\pi RN/c_0$ (c_0 is the speed of sound, R is the rotor radius) becomes supersonic.

3.3 Broadband noise.

Two mechanisms of broadband noise are identified: (i) the interaction noise of the turbulence with the blade, generated when the wake of the upstream propeller impacts the downstream one, (ii) the self-noise of the blade profile located at the trailing edge, radiating for the two rotors. The semi-analytical model implemented in CARMEN is derived from Blandeau, using logarithmic laws to establish the acoustical level as function of the frequency. Broadband noise level is relative, while the level of the tonal noise, straightforwardly depending on the propeller thrust, is absolute. The

broadband level is tuned to the tone noise, in order that the latter one sufficiently emerge, according to conventional single propeller noise measurements.

4. CROR Simulation in IESTA-CARMEN

4.1 CROR configuration

The take-off configuration is the noisier and more annoying due to the presence of tones generated by the interactions between the two rotors radiating in the whole space, compared to the single propeller, mainly radiating in the propeller plane. This configuration has been studied in CARMEN for a mid-distance aircraft type motorized with two CRORs, with propellers upstream to the pylon supporting the engine. A standard take-off trajectory is considered, with a rising slope of 5.5° from altitude 200 to 300 m, that is a covering distance on the ground of 1450 m. The airframe noise is not modelled, being significantly lower than the propeller one. Two listening points are studied: the *Flyover* point, directly above the trajectory, and the *Sideline* point, beside the trajectory.

Figure 5 plots the tonal and the broadband contributions at the three moments of the trajectory, for *Flyover* and *Sideline* locations. The *Flyover* point being closer from the aircraft than the *Sideline*, 5 more decibels expected are observed for the flyover location in Figure 5b, when the aircraft is directly above the microphone (assuming an acoustical radiation independent of the azimuth). Levels are also more intense when the aircraft approach the *Flyover* point. However, when the aircraft moves away, levels at *Flyover* and *Sideline* are closed, the Doppler effect being more intense for the *Flyover*, but balances out by the distance. The spectra show the heavy density of the tone due to the interaction of the two rotors. It is to notice that the level of each tone may vary at the different moments of the flyover, which is a worry behavior for the annoyance, while the broadband noise remains almost constant.

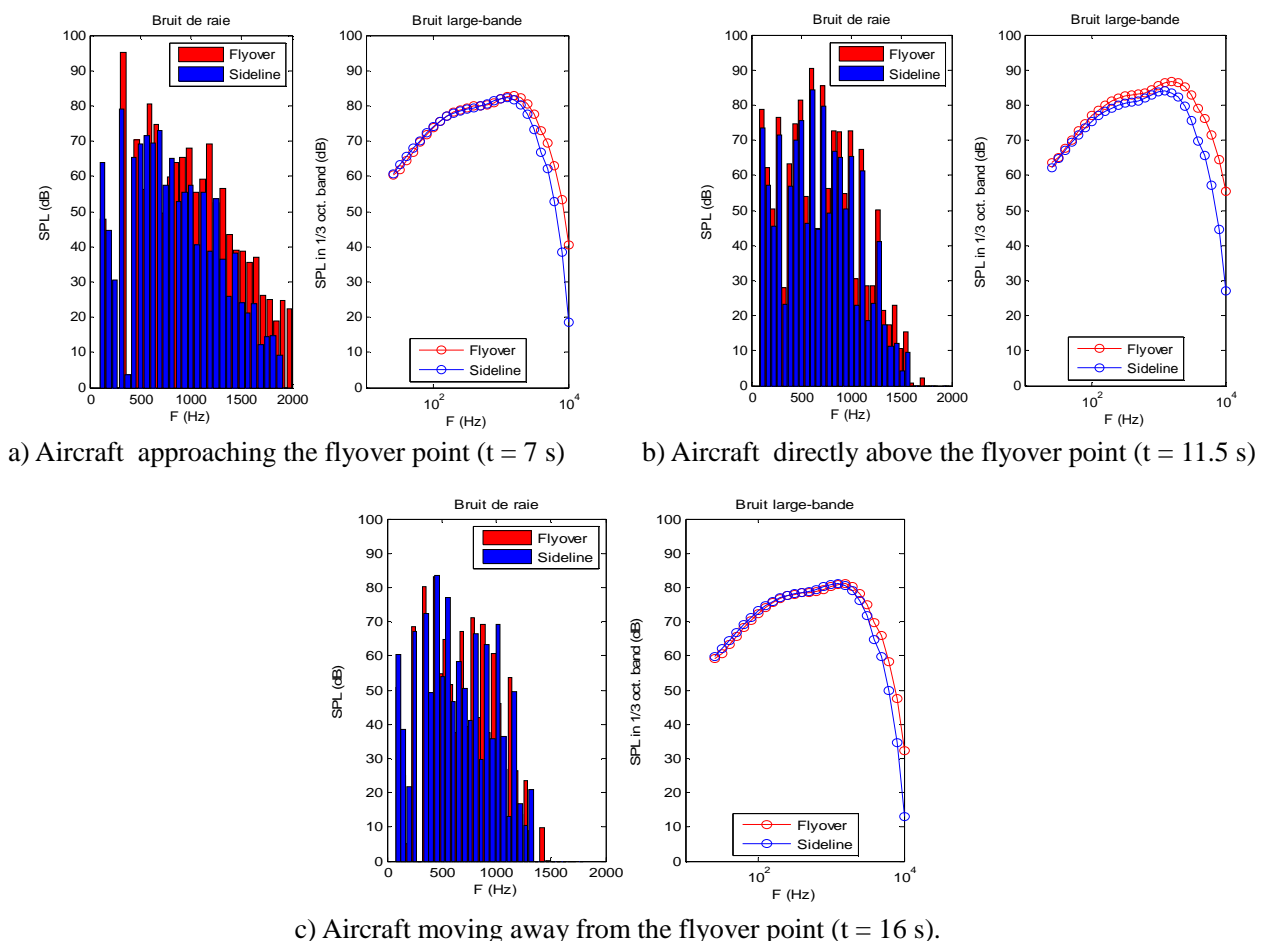


Figure 5: Noise predicted by an aircraft motorized with a CROR. Tone noise (left) and broadband noise (right).

4.2 CARMEN output to generate synthesis sound for psycho-acoustic studies

Test using real aircraft flying over the subjects is very challenging because it is not known precisely what each listener is hearing, the same flyover can never be reproduced exactly and in particular flight tests are expensive. Flyover recordings or syntheses are then preferred for evaluation of perception and annoyance using loudspeakers in laboratory listening situations.

In the past, laboratory experiments on psycho-acoustic of advanced turboprop aircraft with CROR were conducted using a specific Aircraft Noise Synthesis System [15]. CARMEN tool is used in PARASOFT (Psycho-Acoustic Research Aiming at Assessing Sonic Unpleasantness of Aircraft Flyovers) to provide CROR signatures. This national project funded by FRAE is devoted to the perception of both existing and future aircraft noises. University of Cergy Pontoise is responsible of the influence of temporal aspects of aircraft sound on flyover unpleasantness, INSA-Lyon is in charge of the spectral influence of the aircraft signature on unpleasantness, GENESIS performed measurements around airport, auralization and head tracking procedure to provide realistic temporal signature for listener in Labs. Predicted spectra varying in time along the trajectory are synthesized by Genesis, generating very realistic audio simulations [16]. Within PARASOFT, in addition to the CROR, tests have been performed on existing mid-distance aircraft with modified signatures, particularly varying the contribution between broadband noise and tonal noise from the Buzz-Saw-Noise generated by the fan when operating at full power during take-off. Results on psycho-acoustics are described in [17, 18].

5. Conclusion

Accurate predictions of the usual physical acoustics remains a priority to reduce the noise level, while perception and annoyance studies are more and more pertinent to design the aircraft noise in order to be complied by residents around airport. As illustrated, CARMEN can favourably respond to the physical insight of acoustical issues and provides realistic data for the second purpose. In this context it can be a powerful and efficient tool for emerging new concepts such as, flying wing, buried engines and, more generally, concepts where shielding effects are expected to lower the sound level.

Existing sources, such as jet noise, fan, flap, slat, landing gear, etc. are more and more accurately predicted thanks to semi-empirical model tuned from dedicated wind tunnel experiment on isolated model. But in practice, the main and hard-unavoidable limitation of the prediction for non-existing concepts remains the accuracy of the source modelization. Nevertheless, CARMEN allows modifying the broadband and tone noises of each source, as well as the relative contribution of these sources and, which is of interest for perception and annoyance studies. As a further step, coupling CARMEN with experimental results or CFD computations should improve the overall prediction for both insight of the physical acoustics and the sound design for perception studies.

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