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Turbopropeller noise model assessment in CARMEN

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ABSTRACT

The Technological Evaluator of CleanSky, which presents the context for this study, aims at estimating the environmental impact of several new concepts developed in CleanSky, including turbopropellers. Over the last years a propeller noise model has been developed and implemented in CARMEN, the acoustic module of the IESTA platform, an ONERA tool making it possible to calculate acoustic footprints around airports. This model is based on semi-empirical formula and ATR data. It is assessed against measurement data, provided by the ANIBAL (Abaissement du Niveau de Bruit des Avions Légers) measurement campaign performed in 2008, during which an innovative 5-blade propeller was tested on a small commercial aircraft. Comparisons between calculation and measurement are shown for the ANIBAL propeller as well as the reference 2-blade propeller, which is originally mounted on the aircraft. At the same time the problem of emission noise tones is addressed, since the engine frequencies partially overlap with the blade passing frequencies. The accuracy of the prediction is evaluated and ideas for improvement are discussed. This work was financed by The Technological Evaluator of CleanSky.

Keywords: Propeller Noise, CARMEN I-INCE Classification of Subjects Number(s): 13.1

1. INTRODUCTION

The challenge for the European Air Transport System is to accommodate the forecast increase in air traffic as well as reduce the impact of aviation, with respect to noise and chemical emissions. This requires the ability to evaluate the benefit of innovative concepts and technologies through a set of complex and performance criteria.

IESTA (Infrastructure for Evaluating Air Transport Systems) is an efficient tool in the design and modelling of innovative air transport systems through a global evaluation platform, developed by Onera. One application of IESTA is dedicated to the environmental impact of the air traffic surrounding airports, including noise and chemical emissions. The acoustic model CARMEN implemented in IESTA makes it possible to predict the sound pressure level footprint during the whole aircraft trajectory simulation, in the perspective of modelling the noise impact of a whole aircraft fleet on airport surroundings. It is also expected to take into account new technologies and acoustical sources, such as the shielding effect and CROR, and to simulate the noise prediction within a short CPU time. To meet these conditions a specific process of modelling and assessment is developed. The CARMEN model dedicated to aircraft noise prediction is composed of three modules: the acoustic source models, the installation effects and the atmospheric propagation. As a tool aiming to model the physical insights of aircraft noise, CARMEN is complementary to the well-known INM code (Integrated Noise Model) based on an important data base.

One goal of the Technological Evaluator of CleanSky is to estimate the environmental impact of several new concepts developed in CleanSky, including turbopropellers. Over the last years a turboprop model has been developed at ONERA (1,2), based on semi-empirical formula, and was implemented in CARMEN. The present paper offers an assessment of the model against measurement results from ANIBAL (Abaissement du Niveau de Bruit des Avions Légers, (5)) campaign performed in 2008, during which a new propeller was tested.

2. TURBOPROP NOISE MODEL IN IESTA - CARMEN

CARMEN, the acoustic module of the IESTA platform, is an ONERA tool, making it possible to calculate acoustic footprints around airports. It includes noise source modeling based on semi-empirical data, the calculation of installation effects and the propagation to the ground through a ray-tracing method. The structure of CARMEN is based on modules. According to aircraft type and flight configuration, different noise sources are calculated. The focus of this study is the turboprop noise source module.

Turboprop noise is dominated by propeller noise. The semi-empirical model implemented in CARMEN is presented in reference (1). It is derived from a comprehensive paper on V/STOL rotary propulsion systems (3). The noise of a free-air propeller consists of tonal noise and broadband noise. A graphical procedure is done to evaluate the different noise sources and for estimating the third octave band spectra. For rotational noise, the graphical procedure can be replaced by an analytical formulation including thickness noise and loading noise. Thickness noise, being a monopole term, is caused by the displacement of the air by the blade and depends on the cross-section of the blade. Loading noise, being a dipole term, is composed of steady and unsteady loading noise. They are due, respectively, to the blade lift and to the non-uniform inflow resulting from the installation or the impact of the wake. The formulas implemented in CARMEN, are partly based on a GEMINI geometrical propeller data (4), and have been tested on an ATR72 configuration.

For the following calculations, we suppose the propeller incidence to be zero. The propeller efficiency is set to 0.8 and rotational speed and traction were recorded during measurement.

3. MEASUREMENT CAMPAIGN ANIBAL

The project ANIBAL was commissioned by the Direction of Aeronautic Programs and Cooperation (DPAC) of the DGAC (Direction Générale de l'Aviation Civile) and performed with the partners CGTM, STAC, SEFA, FFVV and DUC Hélices. The goal of this project was to define, manufacture and characterize through static and flight tests a prototype propeller which is to be mounted on a DR400 glider towplane. It has to be certifiable by the JAR-P standards and low cost, and present a noticeable reduction in noise emission without tempering with flight performance (5). The first part of the project consisted in the design and validation of the new propeller. In the second part, a measurement campaign was performed on the airfield of Aire sur l'Adour (Figure 1) in 2008.

Figure 1 – Google Earth® view of Aire sur l'Adour airfield, red dot represents microphone position

Figure 2 shows on the left hand side the 2 blades Sensenich reference propeller which is currently mounted on the DR400 plane which will serve as reference propeller in the following comparisons. The right hand side shows the new 5 blades propeller developed in the ANIBAL project. Its design is of no interest in this study, details can be found in reference (5).

Figure 2 – Sensenich (left, reference) and ANIBAL (right) propellers mounted on a DR400 – 180R FGICU

The measurements were done with free-field microphones. One take-off and one overflight at 2700 min^{-1} are studied in this paper. Those configurations being done for both propellers, we obtain 4 configurations.

Several flights were done for every configuration. These repetitions showed very similar noise measurement results. Since meteorological conditions varied for each flight, only those configurations which are the less influenced are kept for the following study, i.e. the configurations where the wind speed is the lowest.

4. ASSESSMENT

4.1 Remarks on measurement data

The ideal comparison would imply measurements done on an aircraft producing solely propeller noise, which is never the case. Exhaust noise is not negligible on this kind of small aircraft. If the engine turns at a rotation frequency N, the exhaust will produce tones at 2*N Hz, since the engine mounted on the DR400 is a two stroke four cylinder Lycoming engine. The propeller emits tones at B*N Hz, where B is the number of blades. Therefore the spectra will show coinciding tones for exhaust and propeller noise.

The reference propeller Sensenich has two blades. It is therefore impossible to distinguish between the exhaust and the propeller tones, as can be seen in Figure 3, where all tones are multiples of 90 Hz (N = 45 Hz = 2700/60 Hz).

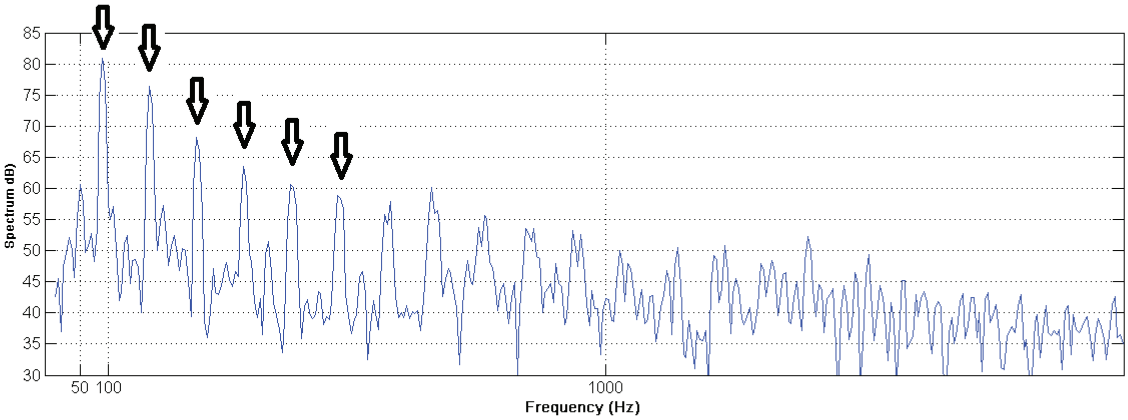

Figure 3 – DR400 overflight at 2700 min^{-1}, with **Sensenich** propeller

The ANIBAL propeller however has 5 blades. Only a few tones coincide with the exhaust frequencies, as can be seen in Figure 4, where the red arrows point to the exhaust tones (multiples of 90 Hz), the green arrows to the propeller tones (multiples of 225 Hz = 5*45 Hz) and the black ones to the combination of both.

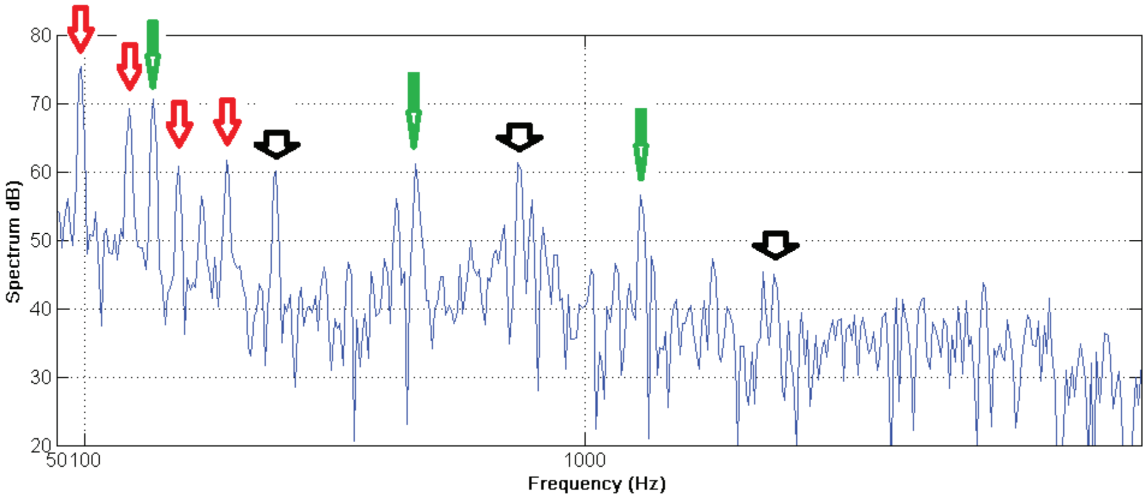

Figure 4 – DR400 overflight at 2700 min-1, with **ANIBAL** propeller

(red arrow: exhaust; green arrow: propeller; black arrow: both)

The most interesting comparison between our semi-empirical model and the experimental data will concern the tones multiples of 225 Hz for ANIBAL configurations, since they are the only data not polluted by exhaust noise.

It is at the point where the aircraft is right above the microphones that the best comparison is done between measurement and calculation. In fact, exhaust noise is rather omnidirectional, whereas propeller noise, and more precisely the tonal contribution, is maximum in the propeller plane. Therefore at the point where the aircraft is above the microphone, propeller noise is predominant and the total noise is less polluted by exhaust noise. The fact that the ANIBAL propeller is designed to reduce noise radiation doesn't work in favor of the comparison, since then, even at the point specified before, propeller noise doesn't cover exhaust noise anymore. For this reason and for informative purposes, global values and spectra will still be shown for both propellers.

Two configurations are presented, for the Sensenich (reference propeller) and the ANIBAL propeller. In order to compare data, all values are given in dB/Hz. The time step of the trajectory recordings are not the same as the measurement time step; the first being done with a 0.2 s time step, the other with a 0.3 s time step for 5 Hz bandwidth recordings. The CARMEN calculation follows the trajectory data, and is hence done with a 0.2 s time step. The only way to compare the simulation to measurement without having to interpolate the experimental data and hence smoothing out peak levels, is to do a comparison every 0.6 seconds.

4.2 Overflight at 2700 min-1

The first configuration under study is the overflight at 2700 min^{-1}. The aircraft trajectory with the microphone position where the measurements are taken from, are shown in the following Figure 5. This trajectory applies to both Sensenich and ANIBAL flights.

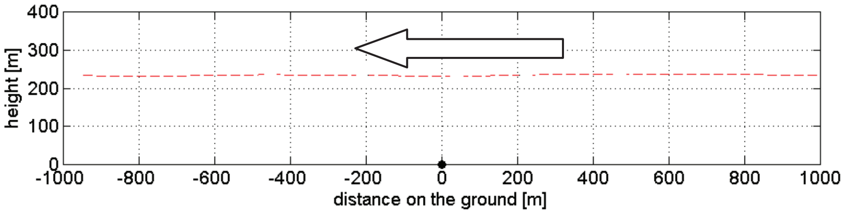

Figure 5 – Aircraft overflight trajectory and microphone position (black dot)

4.2.1 Overflight configuration Sensenich

The first comparison is done for the flight with the Sensenich propeller. The comparison of global levels between measurements and simulation will inevitably show lower levels for the latter, since exhaust noise is not included in the noise source model of CARMEN. Figure 6 shows the evolution of the global level of the power spectral density at the microphone position, the moment of overflight being at around 15 seconds after the beginning of measurement time on this graphic. It includes the broadband and tonal contribution. As said before, at the moment when the aircraft is right above the microphone, the exhaust noise is completely masked by the predominant propeller noise and the calculated levels approach closely the measured levels. Before and after, in time, the microphone is outside of the maximum propeller noise directivity and the exhaust noise becomes predominant. Since it is not modelled here, the simulation decreases more rapidly.

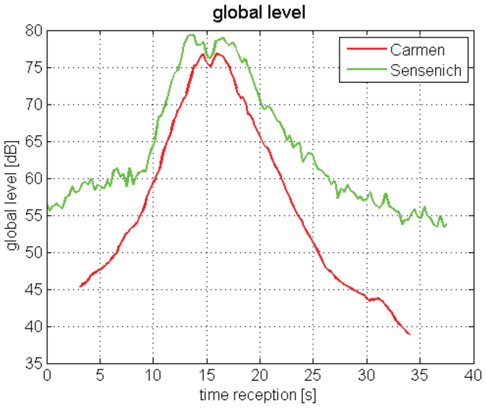

Figure 6 – Global level for overflight 2700 min^{-1}, **Sensenich** propeller

It appears that a drop in level happens around the moment where the level is supposed to be the highest, i.e. where the aircraft is right above the microphone, around 15 seconds. This drop can’t be explained neither by a trajectory variation nor specific weather conditions. Furthermore it is completely smoothed out when an A-filter is applied; therefore the cause probably resides in the specific tonal directivities.

Since the goal of this study is to assess the turboprop noise model, the real comparative interest lies in the tone levels at the blade passing frequencies which do not coincide with exhaust tone frequencies. For the Sensenich configuration, those do not exist since the propeller consists of two blades, but one can still have a look at the variations and levels of the first tones.

In the following figures the levels as well as the frequencies are compared between measurement and calculation. As a matter of fact, the above given blade passing frequencies (§ 4.1) are only recorded when the aircraft is exactly above the microphone position, so that no Doppler shift is applicable. Figure 7 shows that the Doppler effect is correctly applied, and that the calculated frequencies follow very closely the measured evolution. The apparently big steps in measured frequencies are due to the 5 Hz sampling frequency.

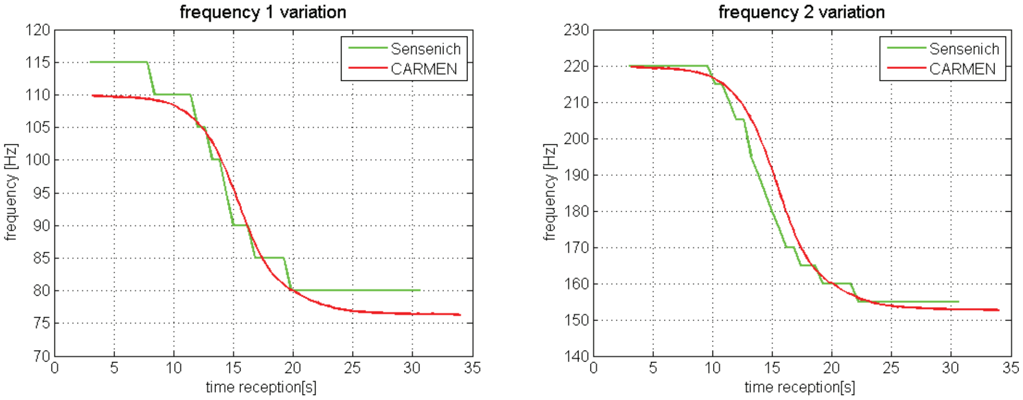

Figure 7 – Doppler shift on two first **Sensenich** propeller tones (90 Hz and 180 Hz), overflight 2700 min^{-1}

Figure 8 illustrates the levels of the first two tones. The first one, which is supposedly predominant, shows the same behavior than the global level in Figure 6. It is therefore reasonable to think that it explains the drop in global level. The reason for the appearance of the drop will have to be investigated further. The simulation doesn't catch this drop of the first tone. For the other harmonics (represented in this paper by the second harmonic only) the calculation reproduces very well the measured values at the angles of interest, which revolve around the moment when the aircraft is above the microphone.

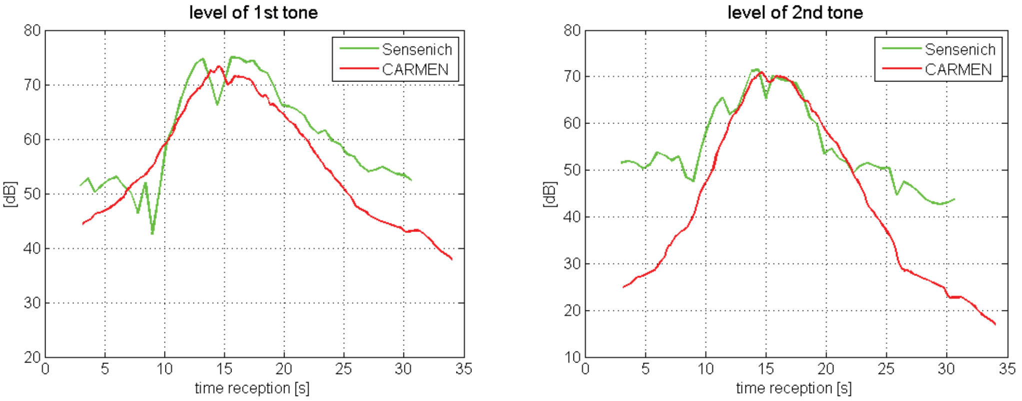

Figure 8 – Tone levels (**Sensenich** - 90 Hz and 180 Hz), overflight 2700 min^{-1}

4.2.2 Overflight configuration ANIBAL

The same comparison is done for a flight with the ANIBAL propeller. One of the goals for the development of the ANIBAL propeller was to reduce the radiated noise, which was a success (see reference (5)). Exhaust noise becomes therefore predominant at every reception angle, even in the propeller plane. The global levels shown in Figure 9 show that the simulation of propeller noise alone cannot reproduce the measured levels.

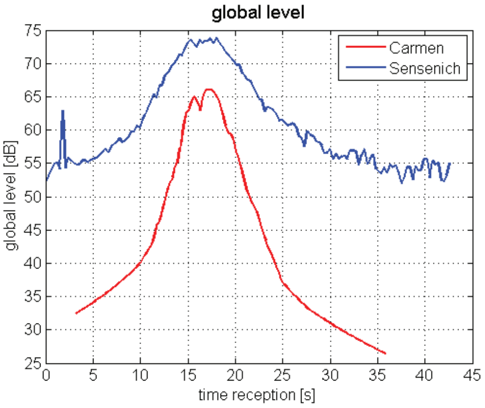

Figure 9 – Global level for overflight 2700 min^{-1}, **ANIBAL** propeller

It becomes quite impossible to gather information about the validity of the turboprop noise model from this comparison in global level. The focus is therefore put on the tones only.

As shown in Figure 4, the first frequencies of interest for this configuration are 225 Hz and 675 Hz, the tone at 450 Hz being polluted by exhaust noise. The first three tones, with their frequency evolution and levels, are given in Figures 10 and 11. The results for the frequency values as well as the levels are very satisfying. Especially the first harmonic shows a close reproduction of the measured levels. It appears that the propeller contribution is clearly higher than the exhaust contribution since the calculation reproduces nearly perfectly the level for about 15 seconds. For the second harmonic the level seems to be more or less independent from the emission angle. Exhaust and propeller noise hence present equivalent levels.

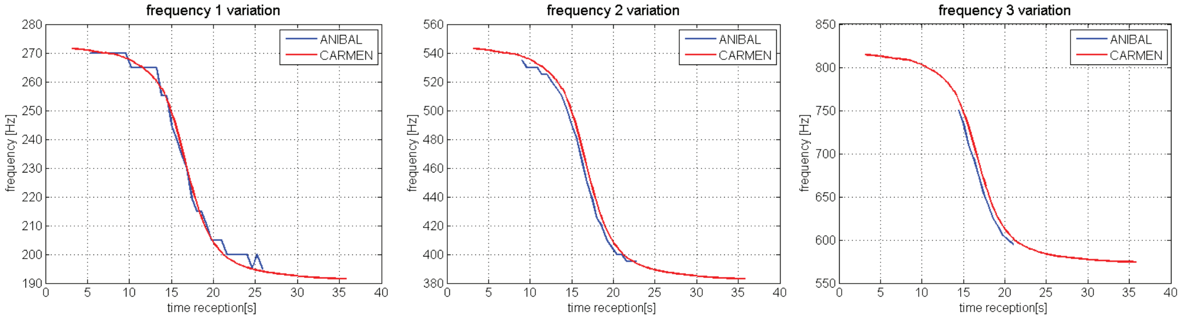

Figure 10 – Doppler shift on three first **ANIBAL** propeller tones (225 Hz, 450 Hz and 675 Hz), overflight 2700 min^{-1}

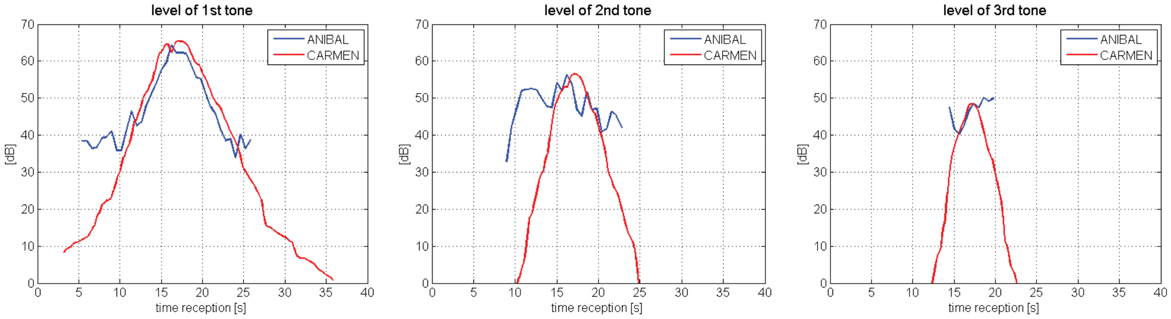

Figure 11 – Tone levels (**ANIBAL** - 225 Hz, 450 Hz and 675 Hz), overflight 2700 min^{-1}

4.3 Climb

4.3.1 Climb configuration Sensenich

The second configuration represents a climb trajectory. It is illustrated in Figure 12.

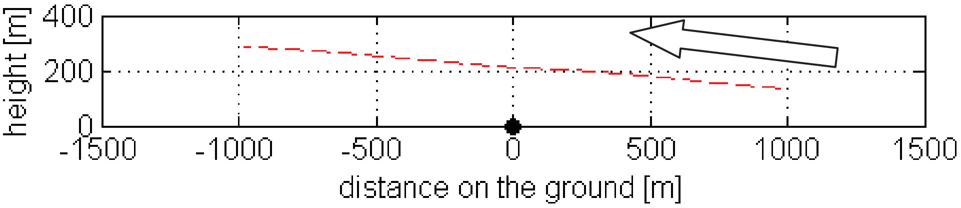

Figure 12 – Aircraft climb trajectory (**Sensenich**) and microphone position (black dot)

The measured global levels (Figure 13) show once again the drop above the microphone. The calculation doesn’t catch it, but otherwise follows the measurement. The frequency variations of the tones (Figure 14) give very satisfying results. Again the first harmonic gives the illusion of being less accurate than the three others, but this is due to the 5 Hz sampling frequency and the axis discretization.

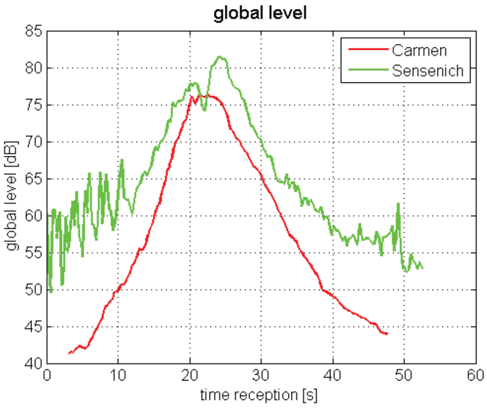

Figure 13 – Global level for climb configuration, **Sensenich** propeller

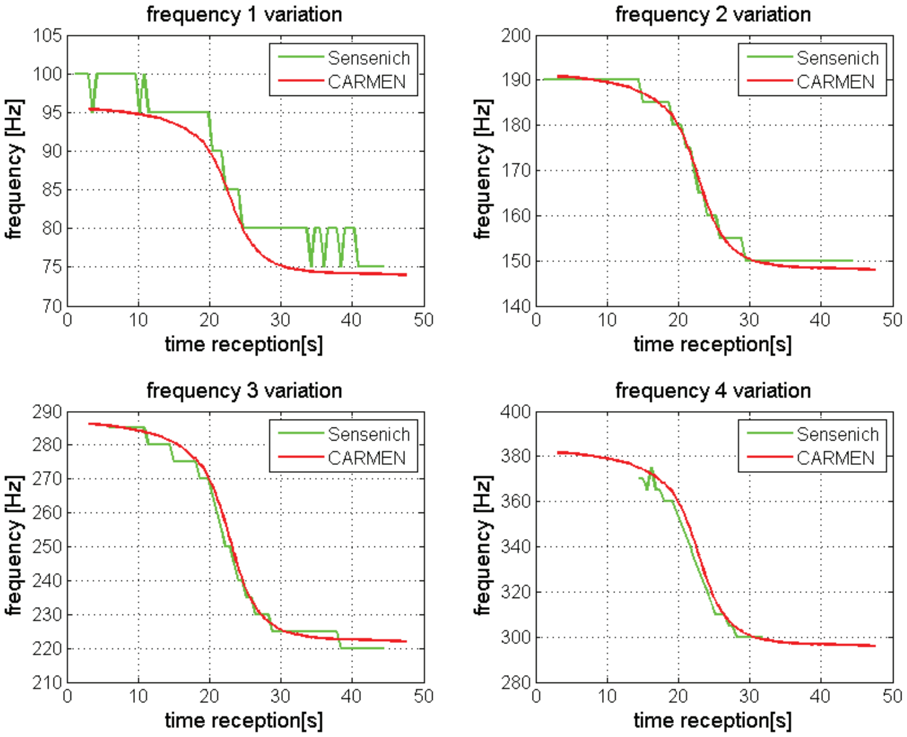

Figure 14 – Doppler shift on first four **Sensenich** propeller tones (90 Hz, 180 Hz, 270 Hz and 360 Hz), climb configuration

The levels in Figure 15 are very close to measurement. The first harmonic shows, again, the drop in measurement, which explains the global level tendencies. This drop is not simulated, but the levels are otherwise very close to measurement for more than thirty seconds. That means that on the first harmonic the main contribution lies in the propeller, even outside of the propeller plane.

For the second, third and fourth harmonic the calculation follows very nicely the calculation for about 15 seconds, and the exhaust noise becomes predominant again before and after the maximum directivity of the propeller.

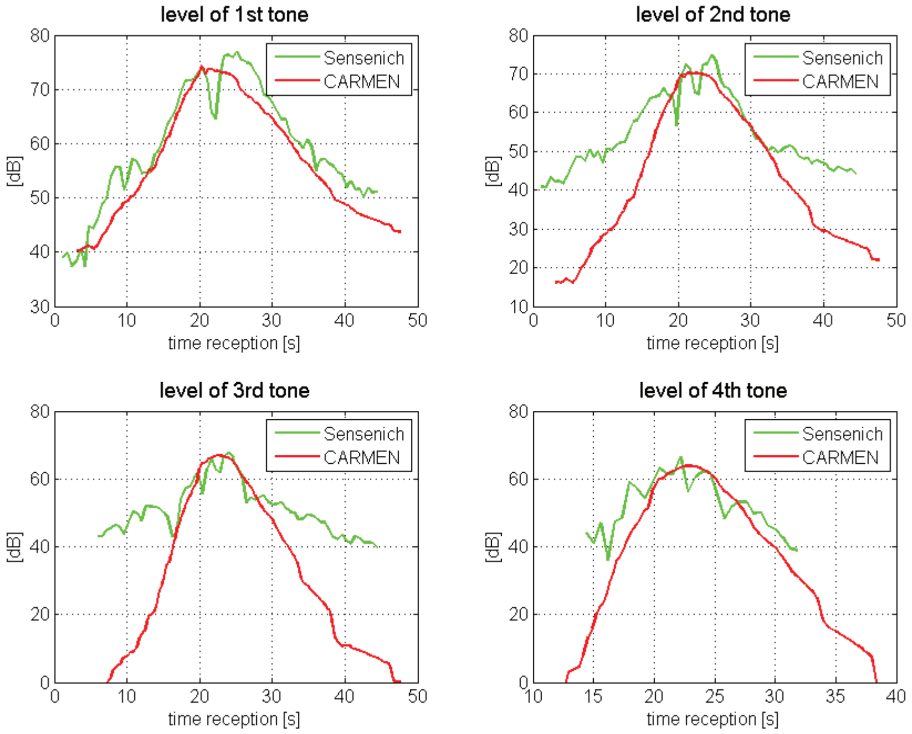

Figure 15 – Tone levels (**Sensenich** - 90 Hz, 180 Hz, 270 Hz and 360 Hz), climb configuration

4.3.2 Climb configuration ANIBAL

As is shown in Figure 16, the aircraft is slightly higher in this configuration than for the Sensenich climb.

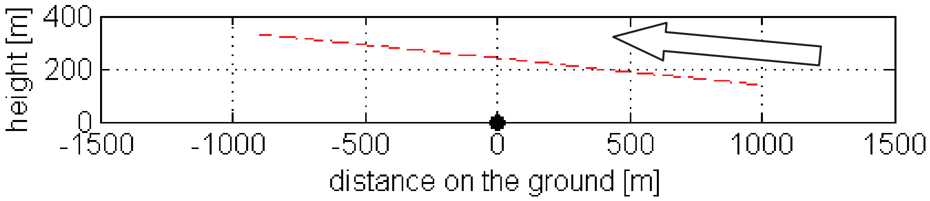

Figure 16 – Aircraft climb trajectory (**ANIBAL**) and microphone position (black dot)

The noise reduction of the ANIBAL propeller leads again to a predominance of exhaust noise which is not caught by the CARMEN calculation (Figure 17).

The propeller tone levels are well below the exhaust tone levels, and therefore harder to extract. Thus only the first harmonic is shown in Figure 18. While the frequency evolution is clearly shifted, the tone levels follow the measured levels very closely when near the propeller plane, that is to say around the time 25 seconds, where the aircraft is above the microphone.

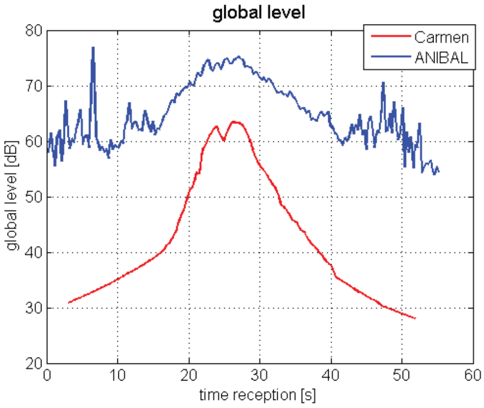

Figure 17 – Global level for climb configuration, **ANIBAL** propeller

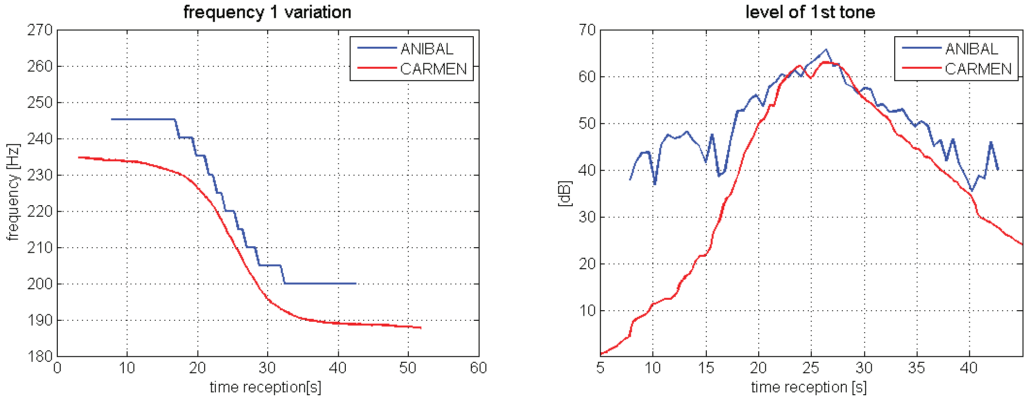

Figure 18 – First **ANIBAL** propeller tone (225 Hz), climb configuration

5. CONCLUSIONS

The assessment of the propeller noise model in CARMEN was studied by comparison to the measurements performed during the ANIBAL campaign. The small commercial aircraft on which first the reference Sensenich, and then the ANIBAL propeller were mounted is dominated by propeller tones only in the propeller plane, and by exhaust noise tone outside of this directivity, unfortunately for our case.

In the time windows, however, where propeller noise is maximum, the CARMEN calculation reproduces very well the measurements, as much for the tone frequencies as their levels. The Sensenich propeller, which produces tonal noise very close, in level, to the exhaust tones, is very well modeled by calculation. The same goes for the first harmonic of the ANIBAL propeller measurements where the exhaust noise doesn't coincide in frequency, and CARMEN therefore follows closely the measured levels.

The comparison of the propeller noise to measurement data leads to the conclusion that for a realistic prediction of small aircraft noise, the simulation of exhaust noise and propeller noise are necessary, the latter being very well done by CARMEN.

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REFERENCES

1. H. Gounet, « Model for predicting 1/3 octave band spectrum of a turboprop: propeller noise », RT 1/19967 DCPS/DSNA, September 2012
2. I. LeGriffon, « Turboprop and core noise in CARMEN », RT 12/20838 DCPS/DSNA, November 2014
3. B. Magliozzi, « V/STOL Rotary Propulsion Systems Noise Prediction and Reduction », Report FAA-RD-76-49, August 1976
4. P. Garderein, J.M. Bousquet, « ONERA propeller aerodynamic activities in Brite-Euram program APIAN-GEMINI », Workshop on European Research on Aerodynamic Engine, Braunschweig, September 2000
5. T. Lefebvre, S. Canard-Caruana, C. Le Tallec, « DTP ANIBAL – Rapport de synthèse final », RT 6/08726 DPRS, September 2009