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Objective quantification of perceived differences between measured and synthesized aircraft sounds

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ABSTRACT

This paper presents an approach with which perceived audible differences in aircraft sounds can be quantified and presented in an objective manner. The objective quantification of the subjectively heard audible differences is intended to serve two primary goals. It can firstly enable developers of auralization technology to make the auralized sounds more realistic by identifying in which aspects the synthesized sounds differ from their real-life counterparts and to what extent. The quantification can secondly provide an improved and more detailed means of distinguishing between aircraft sounds in general, beyond the conventional metrics of A-weighted Sound Pressure level (dBA) or Effective Perceived Noise Level (EPNL) used currently to assess aircraft noise. In this study sound quality metrics are used to quantify the differences in aircraft sounds. These metrics are widely used in other industries such as the automotive sector. Audio files of a reference aircraft, made over identical flight paths at a noise monitoring station in the vicinity of Schiphol airport, are compared in terms of both conventional and sound quality metrics for four measured and four auralized audio files. It is observed from the comparison that differences that may appear small in the conventional metrics can be significant in terms of the sound quality metrics. Significant differences in measured and synthesized sounds are observed for the aircraft considered in this study with regards to the tonal content and fluctuations in amplitude that occur over time. The conventional metrics are seen to capture the overall loudness aspect of aircraft sounds, but give no clear information regarding which spectral or temporal characteristics cause the sounds to be perceived as audibly different.

1. Introduction

Aircraft noise is a very complex noise source, containing both broadband and tonal frequency components which span a wide range of frequencies. Additionally, aircraft noise can contain strong and rapid fluctuations in amplitude over time, which further add to its complexity. The noise produced by aircraft has traditionally been expressed in a specific overall value such as the maximum A-weighted Sound Pressure level (dBA), Sound Exposure Level (SEL) and also the Effective Perceived Noise Level (EPNL). Any differences in the noise two aircraft produce have therefore till now been expressed in these commonly used metrics by the aerospace community. These metrics quantify differences in overall noise impact. However, they do not indicate in which way the sounds differ from each other and which spectral or temporal characteristics are the cause of the overall difference. Further deficiencies become apparent when two aircraft have very similar noise impact values when expressed in A-weighted Sound Pressure levels and EPNL values, yet their sounds are noticeably different when heard by observers. Previous studies such as those by Hellman and Zwicker [1] and Scharf and Hellman [2] have shown that traditional metrics such as dBA and others that use it as a basis, do not suffice in clearly distinguishing between sound signatures and studies by Angerer et al. [3] have shown that they also do not correspond well to the actual perceived annoyance caused by aircraft noise, something which is an overall goal of any aircraft noise metric. Similar deficiencies have been identified to some extent for the EPNL metric, particularly when trying to capture differences in tonal content of aircraft noise, as shown by More et al. in [4] and by Sahai and Stumpf in [5] and [6]. These conventional metrics can therefore lack in capturing important differences in aircraft sounds, such as the prominence of tonal noise in relation to broadband noise, fluctuations in amplitude over time or the ratio of high to low frequency noise for instance. The ability to objectively capture differences between aircraft sounds is of fundamental importance for reducing the adverse effects due to aircraft noise experienced by residents. Any noise reductions achieved solely by focusing on

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metrics that do not fully capture the individual aspects of aircraft noise may not result in a reduction of the actual annoyance experienced by residents.

The current paper aims to build on the work of Arntzen et al. [7], where a comparison of measured and synthesized aircraft noise of the same aircraft was presented and the differences in noise impact were expressed in conventional dBA and SEL metrics. It was observed that although the differences in $L_{A\,\max}$ values were 0–3 dBA and in SEL values 0–4 dBA, the measured and synthesized sounds were audibly quite clearly different. Some of the audible differences observed were that the synthesized tones were too prominent, the low frequency noise had been underpredicted and that there was significantly more turbulence in the recordings due to the presence of wind-gusts. These differences were not captured by the A-weighted metrics and the results highlighted the need to express differences in aircraft sounds in an improved, objective manner. Another study, focused on the auralized sounds of future Counter Rotating Open Rotor (CROR) engines by Rizzi et al. [8], has also shown that audible changes in the quality of the sounds due to improved blade designs are not always clearly expressed in terms of EPNL values. By starting with a focus on comparison of synthetic and measured aircraft sounds, various factors can be investigated which play an important role in distinguishing between aircraft sound signatures in general. The objective distinction of aircraft sound signatures and their individual characteristics serves the second, more overall goal of designing aircraft for optimal sound, whereby aircraft designs can be optimized to meet required, more acceptable target sound signatures. This approach is intended to shift the focus from ‘low-noise’ aircraft design, which is the current practice, towards low-annoyance or ‘perception-influenced’ aircraft design. This is an approach which focuses on influencing aircraft designs towards achieving a more favorable human response to aircraft noise, as presented by Rizzi in [9] and by Diez et al. in [10] and [11].

The paper is divided into five main sections. The aircraft noise measurement and auralization methodology as explained in [7] is briefly recapitulated in Section 2. The sound assessment methodology, which is done via a combination of an Audio Assessment Module (AAM) currently being developed for automated aircraft noise audio assessment and the PULSE Reflex software of Bruel and Kjaer, is explained in Section 3. Section 3.1 explains the steps used for the implementation of the sound quality metrics of stationary loudness and sharpness in the AAM, as well as a brief background on the tonality, roughness and fluctuation strength metrics as used in PULSE Reflex. The comparison of the aircraft noise assessment in conventional and sound quality metrics is performed in Section 4 and the conclusions of the current work are presented in Section 5.

2. Noise measurement and synthesis approach

The reference aircraft used for making the comparison of measured and synthesized (i.e. auralized) aircraft noise is the Boeing 747–400 equipped with four CF6-80C2 engines. The comparison has been made for four takeoff flight paths of the 747–400, with the noise measured at a noise monitoring location near Schiphol airport Amsterdam, situated 3.8 km in front and 400 m to the right of the runway in the aircraft takeoff direction. The noise measurement has been performed using the Noise Monitoring System (NOMOS),[1] which continuously measures noise from aircraft at 31 ground locations spread over the extended vicinity of Schiphol airport. Each monitoring station, including the station selected for the comparison in this study, makes use of type 1 sound meters manufactured by Bruel and Kjaer, having a measurement accuracy of 0.7–0.9 dBA. The measurement system is coupled with radar to get information on the type of aircraft and satisfies ISO 20906 requirements for monitoring aircraft sound in airport vicinities [12]. The selected noise monitoring station was located on a grassy field, with the microphone placed on a pole at a height of 10 m in order to minimize the effect of ground reflections and absorption from the ground surface [13]. The measured audio data was provided by Schiphol airport for the initial analysis of Arntzen et al. in [7] and is considered highly accurate and reliable data, also used to make policymaking decisions and for community outreach for noise affected communities. The noise has been both measured and auralized at the same monitoring location. As can be seen in the measured audio spectrograms in Figs. 1–4 shown at the end of this section, relatively strong wind-gusts were present during the day of the measurements, which are observed as vertical spikes in the measured spectrograms. The microphone has a small wind cap but the equipment does not include a wind speed meter, which would aid in the quantification of the local wind and the resulting wind-induced turbulence. The wind cap was in this case not sufficient to shield the microphone from the strong wind-gusts and a larger wind shield would be required to minimize the effects of the gusts in the future. The first three flight paths, Flight Path (FP) 1 to 3, follow a similar trajectory with the aircraft flying closer to the monitoring station than during FP 4, where it flew further away from the monitoring station in a lateral direction. The intensities of both measured and synthesized aircraft noise are therefore higher for FP 1–3 than for FP 4, due to the shorter distance between the aircraft and observer for the first three flight paths.

The aircraft noise synthesis firstly requires the simulation of aircraft noise at the source. For this purpose, the inputs required by the fan, jet and airframe source noise prediction models were simulated over the measured flight paths. The source noise models used for the synthesis are based on NASA’s Aircraft Noise Prediction Program (ANOPP), which includes the model of Heidmann [14] for fan and compressor noise, Stone [15] for jet noise and Fink [16] for airframe noise. For calculating the engine noise, which is the dominant noise source during takeoff, the engine state over the flight path was simulated using the NLR and TU Delft Gas-turbine Simulation Program (GSP) software [17], by creating a representative CF6-80C2 engine model. All the thermodynamic inputs required for the engine noise calculation were then extracted from GSP for the thrust required for the given aircraft takeoff weight, lift produced and drag experienced during the takeoff phase using relevant lift-drag polars. Since combustor and turbine noise are not dominant during takeoff, their simulations were left out of the prediction and subsequent analysis. The source noise models used in this study are semi-empirical in nature and although they do not provide a hundred percent match to measured data in terms of the spectra and directivities, particularly for the more modern aircraft of today, they are still regarded as state of the art prediction models. Their generic noise prediction capability can be applied to any conventional aircraft and engine, and their computational efficiency also makes their use highly desirable. Some audible differences between the synthesis and measurements are therefore expected. The goal here is to quantify them in an improved way to the conventionally used metrics.

Using the predicted spectral and directional information at the source, the source noise is then synthesized. Due to their very different nature, different approaches are followed for the synthesis of broadband noise and tonal noise. For auralizing tonal noise, an *additive synthesis* technique has been used, such as that used by Allen et al. in [18] and by Sahai et al. in [19] and [20], which is shown through Eqs. (1) and (2).

$$s_i(t) = A_i \cos\big(\varphi_i(t) + \varphi_0\big) \tag{1}$$

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[1] NOMOS live noise monitoring available at http://noiselab.casper.aero/ams/#page=home, accessed on 24-05-2017.