Modeling and synthesis of aircraft flyover noise

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EXECUTIVE SUMMARY

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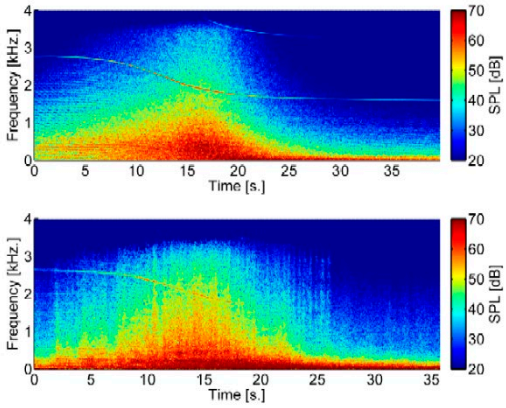

Problem area

Aircraft noise auralization has become a more common tool to assess future aircraft designs or the impact of new air routes. However, the tools that are used are rarely compared to actual measurement results. Hence, it is hard to assess which part of the auralization tool needs improvement.

Description of work

To assess the capabilities of current auralization methods, the NLR's toolchain for aircraft noise auralization is used and compared to measurements. By using prediction methods, the noise of four departing Boeing 747-400 from Schiphol's Aalsmeerbaan were auralized. By auralizing the results at the same location as one of the noise monitoring stations, the results could be directly compared at a spectral level.

Results and conclusions

Overall noise metrics such as SEL en LAmax were reproduced relatively well. Deviations could still be seen when evaluating the SPL during the actual flyover of the aircraft. However, audible

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differences were clearly noticeable when listening to both the auralization and measurement. For instance, low frequency noise and broadband fan were under predicted. The impact of uncertainty in atmospheric conditions, aircraft position and ground constitution was ruled out by analysing variations of these parameters. Hence, the source noise prediction is the likely cause of this audible difference. Furthermore, the ground interference was hypothesized to lead to a 'rasping' sound effect in the auralization results. Such an effect is absent in measurements as turbulence will induce a coherence loss between the direct and ground reflected ray.

Applicability

NLR's virtual acoustic simulator, the 'Virtual Community Noise Simulator' (VCNS) can be improved with the current knowledge. Efforts have been initiated to include the coherence loss effect. Furthermore, other research establishments now have a clear indication of the fidelity of auralization using aircraft source noise prediction methods.

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Content

Modeling and synthesis of aircraft flyover noise

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Abstract

Traditionally aircraft flyover noise is assessed by displaying contours of noise metrics. These models can be used to study noise mitigation measures but they lack the posibility to play-back the audible sound as predicted by their calculations. To that end, noise synthesis is an option that allows to experience differences due to noise abatement procedures or new aircraft designs. A noise synthesis technique for aircraft noise is demonstrated by predicting the noise at a noise monitoring location near an airport. By comparing the synthesized results to a recorded measurement, an indication on the capability of this technique has been acquired. Differences between the synthesized and measured sound remain. A large part of that difference is believed to be caused by the inherent uncertainty when using predictive empirical source noise models. It is shown that differences between departure routes can be captured, thereby illustrating the potential of this method to listen to different take-off procedures. Future improvements in source noise prediction and the inclusion of the effects of turbulence on propagation will further aid to the realism of synthesized aircraft noise.

Keywords: aircraft noise synthesis, source noise prediction, acoustic propagation, digital signal processing

1. Introduction

The amount of worldwide air traffic has been increasing over the last decades. This has an adverse effect on the noise impact of communities near airports. As such, airports face expansion limitations based on the aircraft noise received in communities. These regulations are usually imposed by legislators who are concerned to protect the communities from adverse effects. In the Netherlands restrictions are inflicted based on computed aircraft noise, in specific noise control points, which are not allowed to exceed a specific yearly dose.

Difficulties remain in the process to predict the amount of noise and the response to that noise, which are two vital operations to estimate the effect on communities. Noise prediction models can basically be categorized in long-term (multi-event) average models or short-term (single-event) models. The difference is that single-event models are specifically tailored to

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predict the system noise of the aircraft on the ground for a single flyover [1, 2]. Multi-event models, like INM [3] and other implementations of ECAC Doc.29 [4], offer predictions for a combination of multiple aircraft and trajectories flying over a community. As such they make a concession, compared to single-event models, in the amount of detail accounting for directivity, noise spectrum and propagation effects. Multi-event models are thus suited to incorporate the annual traffic around an airport and provide results upon which regulations are usually based.

Multi-event models are often used to estimate the effects of noise mitigation measures. These studies are usually executed for procedures like a location based thrust-cutback or continuous descent approach. But given the underlying modeling assumptions, the reliability of the results of such a study become questionable. Single-event models could offer this fidelity but need a lot more aircraft specific input than a multi-event model. Even if such a model is used, its results are commonly expressed as contour plots. Such results are usable to experts who can judge such a result and the underlying models. Non-experts have more difficulty examining the implications from such plots. For instance, differences inside a contour remain, i.e. two locations enclosed in a 58 L_{DEN} contour can exhibit different sound levels and characteristics for the same flyover. The actual sound of such a flyover would provide more insight and allow for a more careful balance judging the potential of noise mitigation measures. Experiencing and comparing audible results from a noise abatement procedure could act as a translation tool to indicate the effects of the effort. This could potentially aid the communication between the operators, airports and communities that are affected to display the potential of noise mitigation measures.

Models that can synthesize calculations (convert a calculation into an audible result) are rare but gaining ground in different places in the scientific community. Differences between the methods exist, for instance [5] is focussed on the re-synthesis of measured aircraft sound whereas [6–8] focuses on the synthesis from system noise predicitions. A lucid examples of this new technology is the synthesis of sound from a Hybrid Wing Body by NASA [9]. Using such predictive models has the benefit of experiencing aircraft flyovers that are still in the conceptual or preliminary design stage.

At the NLR, work to this end started in 2007 by the creation of a Virtual Community Noise Simulator (VCNS) in a collaborative effort with NASA. The simulator is a sister of the NASA Community Noise Test Environment (CNoTE [6]). The simulator immerses a test person in a virtual environment where an aircraft flyover can be experienced both visually and audibly.

Following [8], where first attempts in the noise synthesis were made by the NLR, a comparison of the synthesis method to typical real life data is desired. Other authors have compared to measurements as well, especially the aircraft noise synthesis team at NASA looked at synthesis including temporal variations [10–13], although comparisons to full flyover synthesized results remain rare. The only one that is known to the authors is by [14] where a small comparison effort to measurements was made. However, their noise prediction is of a propietary source and therefore it is not clear what the ability of a synthesis technique based on an empirical predictive method is. As such it is necessary to see how the predictions hold up compared to measurements. To that end, the current study will synthesize measured flyovers at a noise monitoring location and quantify the merits and quality of the current method. From that, further indications on future research and on the limitations of the method will follow.

2. Flight mechanics and Source noise

The current study researches the abilities of the synthesis technique by comparing it to measurements. To that end four flyover recordings from departures at Schiphol airport are used from a nearby noise monitoring terminal together with the trajectories of the aircraft. Analysis of the flight mechanics and the source prediction models is necessary to obtain a sound source prediction from the aircraft which is the basis of any predictive synthesis technique.

2.1. Flight mechanics

The four departing aircraft studied here are Boeing 747-400's equipped with CF6-80C2 engines. The method explained in this article is generic and could be expanded to different aircraft or trajectories as well. The ground track of the flights used in this study is qualitatively shown by figure 1.

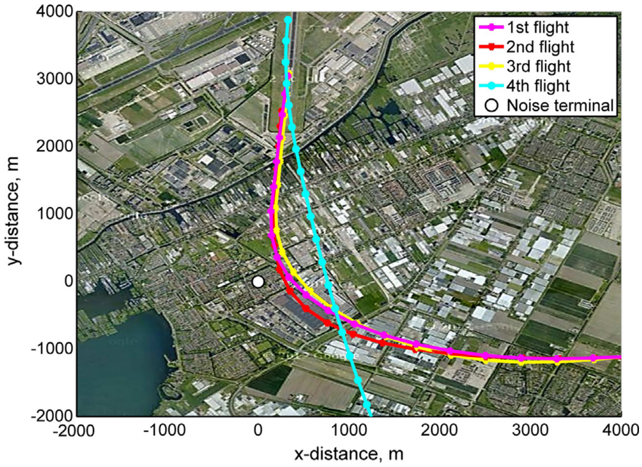

Figure 1: The ground track of the flight trajectories and the noise monitoring terminal in a nearby community.

Figure 1 shows three departures that fly more or less the same trajectory whereas one flight deviates. This is the difference between the two departure routes used for this runway. The minimum distance between the noise monitoring location and the fourth flight is larger than the others, which will be shown to have a clear effect on the sound levels.

The radar supplies a reading every 4 seconds on which the aircraft is assumed to be in equilibrium. Consequently, the effects of aircraft accelerations are excluded from the analysis. Furthermore, the ground speed is assumed to equal the airspeed corrected for a 3 m/s headwind component that was the average for the measurement day. Solving for equilibrium conditions, and using a B747-400 lift-drag polar whilst assuming maximum take-off weight conditions, allows us to calculate the required thrust, drag and lift. The required thrust was a full power condition for that part of the trajectory under study here, which is in line with the take-off condition. With the thrust setting the calculation of the engine state was initiated. The engine state is necessary to provide engine flow conditions to the source noise prediction modules. To calculate the engine state the same method as reported in [8] was used. The engine data used was constructed from publicly available data and data available within the NLR GSP model [15].

2.2. Source noise

Aircraft noise is generaly subdivided in two categories: engine noise and airframe noise. The engine is the primary source of interest during take-off, during landings the noise of the airframe has become equally important. Empirical models have been used to calculate the source noise levels because they need a limited amount of input and offer a reasonable accuracy for a low computational time. They also provide generic capabilities that potentially allows to evaluate different aircraft.

Engine noise has been split into three sub-sources, jet mixing noise, fan noise and core noise. Jet broadband noise has been modeled using the model developed by Stone [16]. The model estimates the mixing noise as a function of the exit velocity, pressure and temperature of the engine outflow. Three distinctive areas have been modeled due to different outflow regions where mixing occurs. Although jet noise is a distributed source, it is assumed that it can be represented as a point source since the distance to the observer is large for flyover conditions.

Fan noise comprises both broadband and tonal components. The tonal components are caused by fan rotor-stator interaction and, dependent on the power setting, shocks emmanating on the fan rotor. The latter noise is popularly known as Buzz-Saw noise. Heidmann developed a model [17] to predict fan noise which was updated [18] to yield better results. In the analysis of the update, it was noted that the Buzz-Saw noise was severly overpredicted. Therefore, changes were made to counteract these overpredictions by using measurments from a CFM56 engine. Differences were however still observed when a CF6-80C2 engine was modeled. Consequently, the fan tonal noise predictions, as made by the updated Heidmann model, have been corrected by inspecting the published measurements [18].

Engine nacelles are usually treated with acoustic lining material to suppress noise in the inlet as well as the (bypass) exhaust. In the previously mentioned update of the Heidmann model, this deficiency in the prediction capability was noticed as well. Consequently, an empirical method to estimate liner effects was constructed based on measurements [19]. This method has been used to calculate the effects of liners.

Core noise consists of compressor noise, combustion noise and turbine noise. Compressor noise was included as well based on calculations with the Heidmann model. This did not contribute significantly to the overall level. Combustion noise is modeled using the method described in [20] and was found to contribute only at specific angles. Given the results of CF6-80C2 turbine noise predictions [19], it was decided not to include turbine noise in the current modeling. Its effect is expected to be of the same magnitude as the compressor and therefore relatively unimportant.

Airframe noise is modeled using the method described by Fink [21]. The method calculates the broadband noise stemming from the individual components that generate noise, i.e. gears, slats, flaps, wings. Although it is a relative old method, and some parts are being replaced in new system noise prediction tools [1], it is still used for this study. This is based upon the notion that the underlying aircraft data set that Fink used included a B747. Consequently it is assumed that the results should be modeled relatively well for the case studied here.

The source noise prediction models give results for static engines. To model flight effects, corrections for Doppler shift and convective amplification have to be applied. These effects are included in some of the prediction models whereas in others they are not taken into account. In general, all the flight effects have been ignored at the source noise prediction stage. Formulas to calculate the convective amplification as found in [22] were used for mono-, di- or quadrupole sources. Doppler shift will be treated in the section 3.

3. Propagation and Synthesis

Propagation is usually treated seperately from source noise production in aircraft noise synthesis. This modularity allows for easy accomodation in the VCNS and to retain flexibility if a different source prediction needs to be adopted.

3.1. Calculation of propagation

The propagation characteristics are calculated using a compact source assumption, i.e. all sound emanates from the aircraft center of gravity. This allows to apply propagation effects on the resulting sum of the individual source noise components. In [23], the underlying phase relations are retained by taking the individual distance between the components into account before summing the individual contributions. As indicated in [9], acoustic ”beating” can occur due to differences in Doppler shift between the engines. It is a barely noticeable effect and occurs only for tonal noise components. This is however not reported to occur in real life (as far as the authors know) and therefore judged to be a theoretical result that can be ignored. As such, the compact source approximation is applied resulting in an incoherent addition of the sound level of the other 3 engines. Consequently, the compact source approximation allows us to calculate the propagation effects with respect to the center of gravity location only.

Three individual propagation effects are calculated for the current application. The first effect is the application of spreading losses calculated by the spherical spreading law. This result is valid for a homogeneous atmosphere where straight acoustic ray paths occur. The occurance of curved-ray paths and its effect on noise synthesis, was demonstrated recently [23]. These curved paths occured for two conditions, namely shallow propagation angles and particular atmospheric wind conditions. This module was not used for the current application due to the fact that both conditions were not met during the measurements.

The second effect is atmospheric absorption. The atmosphere dissipates sound energy due to ”classical” and relaxational effects. The classical effects refers to classical physics, i.e. viscosity, heat generation and diffusion. Relaxational processes cause air molecules to temporarily store some of the sound energy by means of vibration and rotation of an air molecule. This energy is radiated at a small time lag causing interference thereby attenuating the amplitude of the acoustic wave. Absorption effects are modeled using the ANSI/ISO standard [24]. The average weather conditions (T= 10 $^\circ C$, p=999.6 hPa, RH=96%) of the measurement day were taken to calculate the atmospheric absorption. During the flyovers there was no rain despite the high (daily average) relative humidity.

A third effect is due to ground reflected sound waves. At elevated microphone positions sound of the direct and ground reflected ray interfere, which is distincitvely present in the sound of a flyover. Depending on the ground constitution, sound waves are attenuated or phase shifted differently for different frequencies. The two ray path contributions are added according to,

$$p = A\frac{e^{ikr_1}}{r_1} + QA\frac{e^{ikr_2}}{r_2} \qquad (1)$$

where A is the amplitude, k the wave number, r the range of the direct (r_1) or ground reflected (r_2) ray and Q is the wave reflection coefficient which accounts for the aforementioned attenuation and phase shift. In this study, the reflection coefficient is calculated for plane-waves, which depends on the ground impedance characteristics and incidence angle of the sound wave. The ground impedance is calculated with the model described by Delaney & Bazley [25]. Its ease of use has made this a popular model because one parameter, the effective flow resistivity, allows us calculate the resistance and reactance of the ground. The noise monitoring terminal is located on a grass field, i.e. modeled by an effective flow resistivity of 250 Rayls, at 10 meters height to minimize the effect of ground reflection. Equation 1 inherently assumes that ground interference always occurs. This is only the case if both sound waves are coherent. It is well known that turbulence decreases the coherence of a signal [26]. This effect will be noticeable in the measurement signal but is not included in the synthesis as the synthesis uses equation 1 to calculate the effect of the ground plane.

3.2. Synthesis

The source noise prediction results in several discrete tones and a broadband component. The fan rotor-stator tones are predicted to be at an integer multiple of the Blade Passage Frequency (BPF). The tonal Buzz-Saw noise is predicted by the Heidmann model on a $1/3^{rd}$ octave band spectrum. Therefore a translation has to be made from the continuous spectrum to the discrete frequencies at which the tones should occur. These tones are known to be harmonics of a fundamental frequency equal to $RPM/60$. By examining the number of discrete tones in the specific $1/3^{rd}$ octave bands, the amplitude of the individual tones can be calculated if a distribution is assumed, e.g. even. Each tone is synthesized by its instantaneous phase, which is integrated to obtain the entire tone history. The most current and conclusive overview on aircraft tonal synthesis is presented in [11] where tones are synthesized according to,

$$s_i(t) = A_i \cdot cos\,(\phi_i + \phi_0) \tag{2}$$

$$\phi_i = 2\pi \int_{-\infty}^{t} f_i\,(\tau) d\tau \tag{3}$$

where i indexes individual tones, A is the amplitude, ϕ_0 is a random phase offset for each particular tone and ϕ is the phase constructed from the instantaneous frequency f_i. This allows to integrate varying frequencies due to changing engine states. By constructing individual tones using this method a simple summation suffices to generate the total tonal component. This technique is in general referred to as an additive synthesis technique.

For broadband noise a different technique based on white noise is used. There are two options, the first is to propagate the noise in the frequency domain to the ground where the resulting sound can be auralized using a time varying $1/3^{rd}$ octave band equalizer [8]. A more elegant approach is to synthesize the broadband noise at the source and propagate it in the time domain to the listener position [6, 23]. This also allows time domain source predictions to be taken into account by the same propagation methodology. The latter broadband synthesis technique is used and briefly described from hereon and displayed in figure 2.

The input from the source prediction is provided as a $1/3^{rd}$ octave band spectrum which has to be converted to a narrow band spectrum. Depending on the size of the Inverse (Fast) Fourier Transform (IFFT), the amplitude results from the $1/3^{rd}$ octave band spectrum are subdivided into narrow band bins. The IFFT size used in this study is 8192. Such a relatively large size is necessary to get enough resolution at the low frequency bins which would otherwise lead to an incorrect representation of the low frequency noise in the synthesized sound.

White noise is created in the frequency domain as a vector containing random (normally distributed) real and imaginary parts. The next step is to convolve an amount of samples (called a block) with a narrow band spectrum. Using the IFFT, the results are transformed to the time domain. During a flyover, the narrow band spectrum will change due to the varying observation

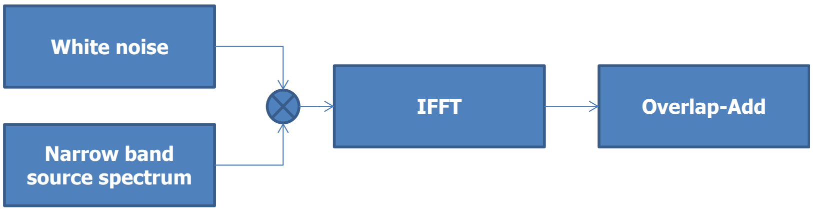

Figure 2: The procedure applied in the synthesis of broadband noise.

angle or engine state. This effectively means that the filter kernel, i.e. the convolution in the frequency domain, is changing as a function of time. This manifestst as audible artifacts due to different filter output, especially if the filter kernel changes rapidly when the aircraft is in the direct overhead position. To circumvent these artifacts, the signal is stitched together using an Overlap-Add (OLA) technique. The OLA technique is comparable to an inverse application of the short time Fourier transform. Intermediate steps, each with a different filter kernel, are made within a block of samples. The output of each intermediate step overlaps due to the small increment in position within the block. These overlapping results are windowed (Hanning) and added together. Due to this procedure the output of the entire signal is continuous in time and reflects the appropriate change due to changing observation angle or engine state. Once the broadband noise is synthesized, the tonal noise is added which gives the total source noise in the time domain at the source position. Next, the results have to be propagated to the ground including Doppler shift. For this, one more step of digital signal processing is needed.

3.3. Applying propagation

From propagation calculations the losses that need to be applied are accumulated. To propagate the sound from the source to the receiver, several digital signal processing steps are needed. This procedure is captured in figure 3.

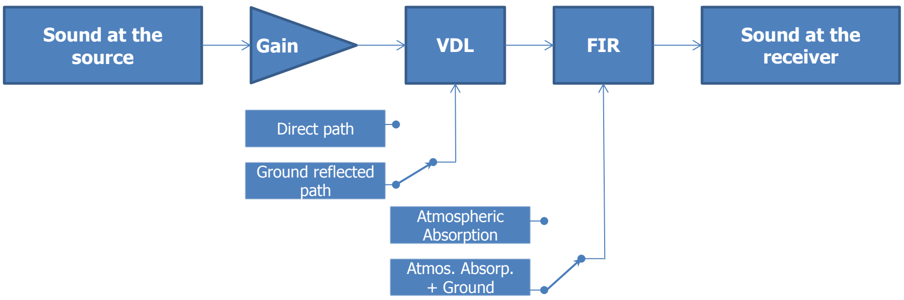

Figure 3: The procedure applied for the propagation of synthesized sound to the receiver.

The source signal represents the total aircraft noise and is processed by a gain, a Variable Delay Line (VDL) and a Finite Impulse Response (FIR) filter. Depending on the path, i.e. direct or ground reflected, different input for the VDL and FIR filter is used. The propagation spreading loss, calculated by the spherical spreading law, is implemented as a gain equal for all frequencies.

Before the filter can be applied, the frequency change due to the Doppler shift needs to be applied to correct for the moving source effect. This is accomplished using a VDL. It is well known [27] that a change in the time basis of a signal will alter its frequency. Using the travel time of the acoustic wave, which will change as the aircraft is flying over, the time basis of the signal can be mapped [6]. Consequently, an interpolation operation is required since the delay may result in a non-integer sample at the receiver time base. In the current application a spline interpolation is used being superior to linear interpolation which is hampered by aliasing effects if the source noise is not properly sampled. The resulting interpolation routine thus maps the original signal according to a variable time delay which is why this step is commonly refered to as a VDL.

Given the fact that atmospheric absorption is frequency dependent, absorption is implemented as a filter. To get an appropriate filter, an IFFT of the desired transfer function is all that is required to get FIR filter coefficients. These simple filters can be relatively short (128 taps) and still provide good results whilst the filter taps can be interpolated upon without the filter becoming unstable.

As a result of the above operations, the sound of the direct ray is synthesized. Differences between the direct and ground reflected ray emanate to a modification by the reflection factor Q in equation 1 and a difference in travel time. The same steps as for the direct ray are thus executed although the reflection factor is transformed into an additional FIR-filter as well. This filter is convolved with the atmospheric absorption filter and applied to the source noise after the application of the time delay.

4. Results and Discussion

In this work the focus is on a comparison of synthesized and measured sound of four flyovers. The recordings at the noise monitoring terminal are low-pass filtered (cut-off at 3500 Hz) and resampled (at 8000 Hz) to minimize data storage since a lot of airtraffic is monitored. To get the same representation a similar procedure is applied to the synthesized sound, i.e. the synthesized sound is downsampled from 44.1 kHz to 8000 Hz and a similar low-pass filter is applied. Sound metrics like $L_{A_{max}}$ and SEL are however calculated for the entire spectrum for both the recording and synthesized sound.

4.1. Results

Probably the best way to represent audible sound on paper is by use of a spectrogram where the frequency content is plotted as a function of time. Figures 4 through 7 show the resulting spectrograms for all 4 flights.

The audible results are made available with this paper and can be listened through the Aplied Acoustics website. These files are mixed combinations of the synthesis and measurement for each flyover. They alternate every two seconds between the synthesized and measured recording. As such, an impression of the differences between the synthesis and measurements can be obtained.

Flights 1 through 3 are closest to the noise monitoring location at approximately 10 seconds, whereas for flight 4 this is at approximately 8 seconds.

A few differences appear visible in all spectrograms. The first is that there is always more low frequency content in the measurements than there is in the synthesis. Secondly, the first

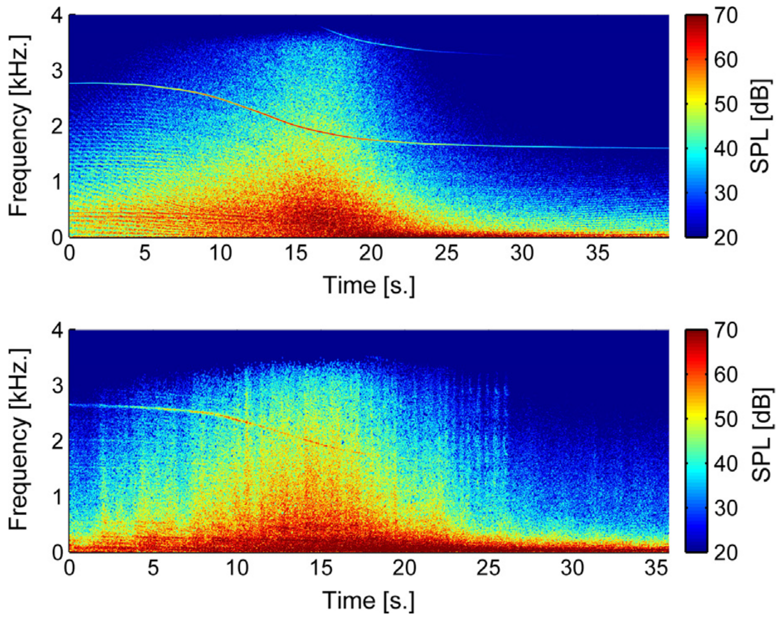

Figure 4: The spectrogram of the synthesized (top) and measured (bottom) flyover for the 1st trajectory.

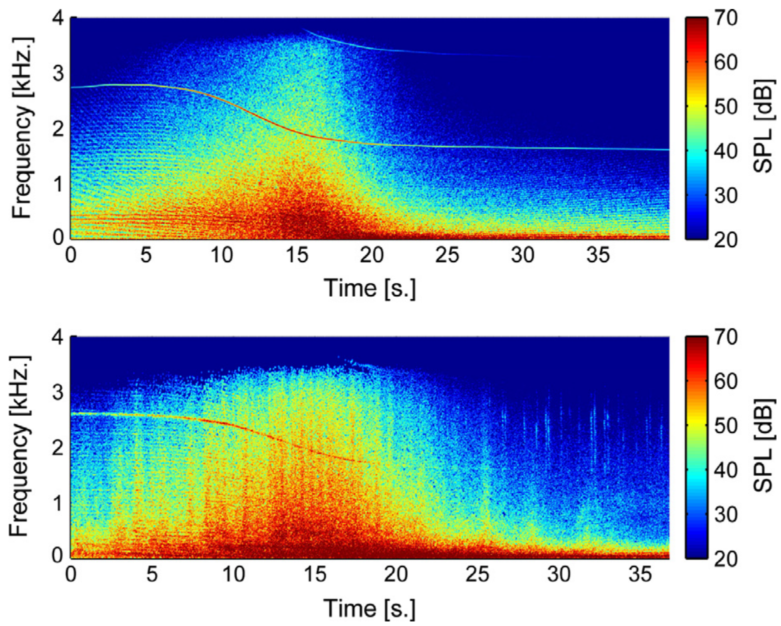

Figure 5: The spectrogram of the synthesized (top) and measured (bottom) flyover for the 2nd trajectory.

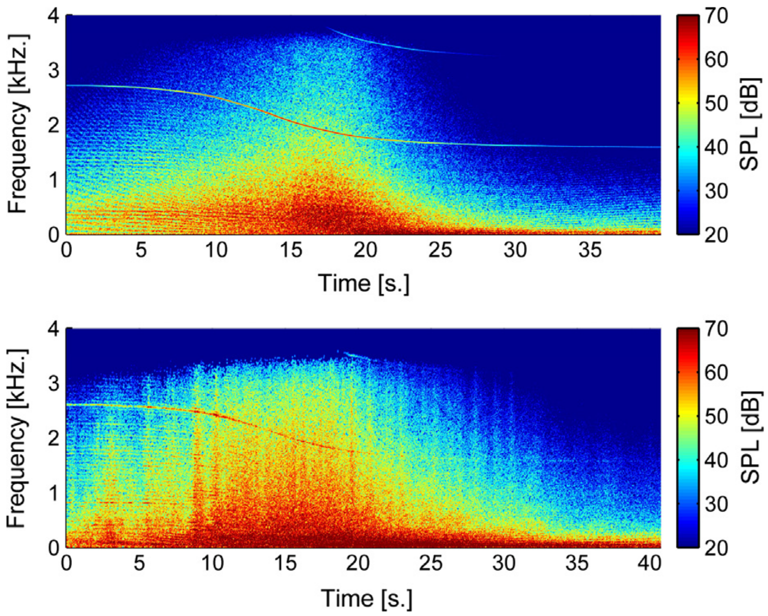

Figure 6: The spectrogram of the synthesized (top) and measured (bottom) flyover for the 3rd trajectory.

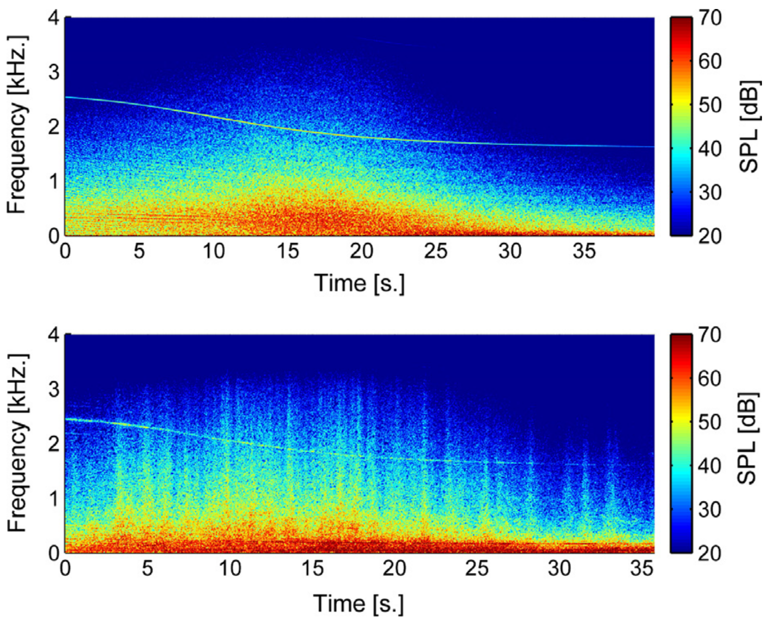

Figure 7: The spectrogram of the synthesized (top) and measured (bottom) flyover for the 4th trajectory.

BPF tone amplitude seems to be overpredicted compared to the measurement, especially if the aircraft is retreating. The second BPF tone is lost in the anti-aliasing filter, given the cut-off frequency of 3500 Hz of the low-pass filter. This is a limitation due to the used measured data in the noise monitoring terminal. In general, the frequency at which the Doppler shifted BPF tones are synthesized and measured coincide to good approximation. Thirdly, the synthesized ground interference effect is more pronounced compared to the measurements. In the measurement data it only occurs for low frequencies if the aircraft is nearby. A final observation is the presence of short temporal variations in the sound levels of the measements, which can be identified as vertical stripes (thus more or less frequency independent) in the spectrogram. This effect is not found in the synthesis although short temporal variations can be included, at the source, by the techniques employed by [11, 12]. Since no explicit input or other means to describe these variations at the source are known for this particular (engine) source they were not included. No temporal variations due to the atmospheric propagation effects are captured by the current synthesis methodology.

Next to the spectrograms the Overall A-weigthed Sound Pressure Levels (OASPL) are calculated and shown in figure 8.

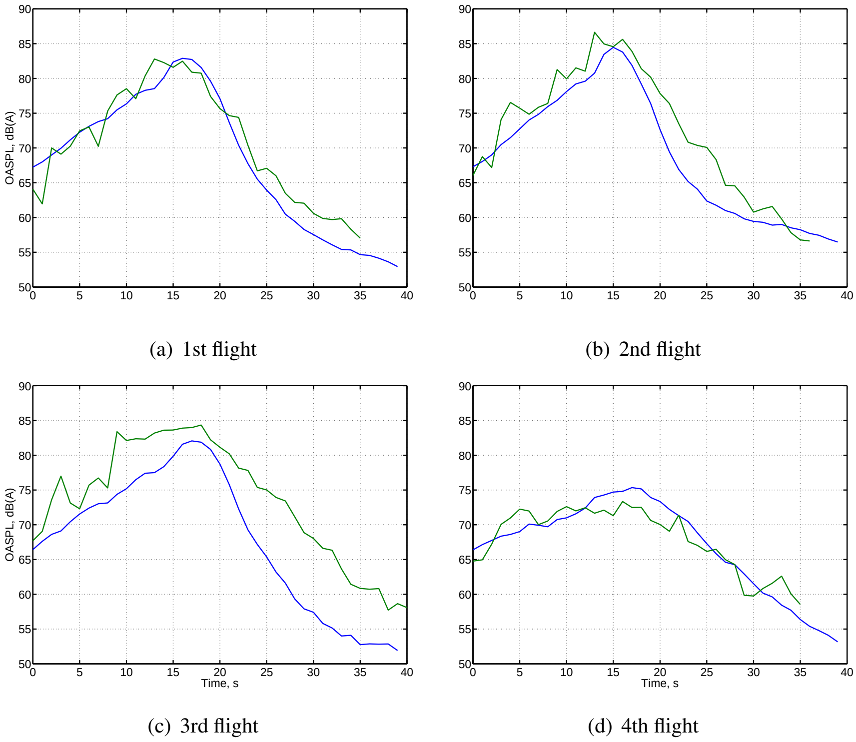

Figure 8: Differences in the sound levels between the synthesized (blue) and measured (green) data.

From this figure it can be observed that the sound levels of the first flight are well captured by the synthesis techniques. The agreement deteriorates for the second and the third flight. Especially when the maximum level has passed it seems that the lines are diverging slightly. The overall sound metrics are reported in table 1.

Table 1: Sound metrics of the flyovers, all metrics in dB(A)

Flight	Synth. $L_{A_{max}}$	Meas. $L_{A_{max}}$	Synth. SEL	Meas. SEL
1	82.9	82.8	91.2	91.3
2	84.7	86.5	92.5	94.2
3	82.1	84.3	90.6	94.5
4	75.3	72.9	86.0	85.2

4.2. Discussion

Differences between measurments and synthesis are likely to occur given the use of empirical source noise prediction methods. For instance, in [28] similar methods are used and compared to the measured certification values. They reported simliar deviations for take-off and sideline angles. ANOPP differences with respect to measurements are published as well [29]. Similar results can be found for the PANAM empirical noise prediction model [2]. Consequently, the differences in sound metrics reported here are in line with what the authors consider the state-of-art in empirical source noise prediction. Uncertainty in source noise prediction will influence the outcome of a synthesis effort.

In all the synthesized spectrograms it seems that the low frequency sound, i.e. frequencies up to 500 Hz, is underpredicted. This can be attributed, to some extent, to low frequency backgroud noise that is not represented in the synthesis. Given the effect of A-weighting the differences do not manifests themselves severly in the accumulated noise metrics. This is a reason why empirical prediction tools can calculate similar (A-weighted) noise metrics while differences do appear. A similar effect occurs in EPNL calculations were sound below 50 Hz is not included in the accumulated noise metric. Since such metrics are used to validate and verify empirical noise models, it is nearly impossible to assess the validity of such predictions at low frequency based on the most common noise metrics.

Differences in the broadband component from 500 Hz up until the 1st BPF are in general increasing with increasing frequency. On first sight the differences seem small, especially for the 1st flight. For the 3rd flight the differences are relatively large. A closer look to figure 6 shows that the measurement contains more broadband sound around the 1st BPF. It becomes even more different once the spectrum above the 1st BPF is considered. The synthesis contains sound of approximately 40 dB whereas the measurement contains easily 10 dB more. Broadband noise around the BPF is, especially for the considered take-off conditions, the spectral domain of fan noise generated noise.

Tonal noise forms another audible difference between synthesis and measurement. In general the Buzz-Saw noise is overpredicted except for the third flyover. The authors are not sure what causes this difference and think that two feasible explanations exist. The first is that a slightly different power setting between the flyovers is not captured (or not well enough) by the current methodology. A second explanation might be that due to acoustic lining the actual Buzz-Saw noise is attenuated more efficiently as predicted by the empirical method. In the future, a more detailed analysis regarding this subject could be executed but this is right know outside the scope of the current study.

Another prominent audible difference is the 1st BPF tone which is, unlike the measurement, dominantly audible in the synthesized result. The tone is also very clean, i.e. not dilluted by disturbances in amplitude or phase. In [11] tonal fluctuations at the source were added to synthesis methods but these fluctuations were masked once the tonal noise was added to the broadband.

Therefore it is thought that disturbances along the propagation path, for instance turbulence, are causing the difference between synthesis and measurement which is especially noticeable in the tones. From literature [30] it is known that turbulent spectral broadening can occur, of which the effect is to distribute sound energy to other frequencies. A method to calculate these effects, together with some measured results, can be found in [31]. For future research it is desired to quantify such effects and its application in noise synthesis in more detail.

Variations in the sound level, i.e. the vertical lines visible in the spectrograms, are thought to be a propagation effect as well. It is not yet clear what the basis of this phenomena is although it is suspected to be related to wind-gusts and/or turbulence [30]. From the spectrograms it appears that this effect is frequency independent and more or less a time-varying gain. As such, it is suspected that this effect is most likely caused by gusts rather than turbulence since turbulence has a frequency dependent behaviour [26, 27, 31]. This effect is clearly not included in the synthesis and was also not found using the mean wind effect [23]. Future studies in this particular area, i.e. how to apply theoretical results, seem necessary.

Another prominent difference can be distinguished in the ground intereference effect. In the synthesized sounds the ground interference, albeit for a grass surface, appears even at high frequencies whereas this is not the case for the measured sound. This causes a "rasping" sound in the synthesized results. The absence of this effect in the measurement is contributed to turbulence as the coherence between the direct and ground reflected ray is affected. Theoretical calculations to this end can be found in [26] and were used in synthesis before [14]. However, the technique employed in [14] is tedious since its effect was included by modifying the source noise prediction to compensate for this effect. How to include these effects using a VDL is yet unknown since, for real time requirements, long filter/convolution kernels are not desired. It is clear to the authors that coherence loss due to turbulence will improve the modeling of this audible effect.

To examine the influence of the uncertainty related to some of the input parameters used in the synthesis, small variations to parameters relating propagation effects like absorption, trajectory (spherical spreading) and ground have been applied. This allows to check if these variations can explain the observed differences and is quantified by the differences in both the $L_{A_{max}}$ and SEL sound metrics. The ground surface was varied by varying the effective flow resistivity and thereby the surface impedance. The effective flow resistivity was changed from 250 Rayls to both 125 and 300 Rayls, a typical range for grass surfaces [32], to assess the audible differences. Deviations were in the order of ±0.4 dB(A) for all flights, audible differences were not noticed. Relative drastic changes to different surfaces, i.e. a concrete or snow surface, do lead to audible differences. Given the fact that the noise monitoring location is on a grass field, such large changes are deemed unreasonable.

A similar procedure was executed for atmospheric absorption. Changes in absorption were simulated by changing temperature (8-13 $°C$) and relative humidity (85%-100%). These values are within reasonable bounds reported for the average atmospheric conditions of that day. It proved that this did not influence the sound as much that it can explain the differences, i.e. audible differences are not noticeable. This is quantified by deviations on the order of ±0.1 dB(A) for the first three flights and, due to the larger relative distance to the noise monitoring location, ±0.35 dB(A) for the fourth.

To assess the uncertainty of the measured ground track of the aircraft, deviations of ±50 meter were applied to the y-coordinate of the ground track. This leads to a different transmission loss due to spreading thereby resulting in a deviation of ±0.2 dB(A) for all flights and did not noticeably affect the audible results. If the altitude of the aircraft is assumed to have a similar uncertainty, i.e. ±50 meter, this would result in larger deviations for the first three flights ±0.5

dB(A) than for the fourth flight ±0.2 dB(A). This is attributed due to the relative close distance at which the first three flights pass the noise monitoring location. A deviation of 50 meters ground track and altitude was arbitrarily chosen and may be considered as large, especially for the altitude.

Overall, this rough quantification of uncertainty leads to a maximum deviation of about ±1 dB(A) for all flights and are extremely hard to denote as audible difference. Therefore it is thought that the main reason for the reported audible and visible spectral deviations is not due to inadequate modeling of atmospheric absorption, ground impedance or trajectory deviations but due to source noise prediction.

5. Conclusion

Audible differences remain between synthesized and the measured results. With the current state-of-art empirical source noise prediction tools, it is possible to approximate the audible noise in a noise monitoring terminal for a departure. Consequently, the current combination of source noise prediction and synthesis allows us to model different departure routes and, due to the empirical nature of the source models, different aircraft types. If an exact reproduction is required, like in [5], it might be best to use a technique based on measurements. The predictive nature of such a measurement based methodology is however questionable.

The differences between the fourth flight and the first flight, i.e. the difference between two departure routes, is adequately simulated by the current synthesis technique. Hence, with the help of an aircraft noise synthesis technique it is possible to evaluate (gross) differences between different departure routes. The effect of new departure routes could thus not only be studied by looking to changes in noise contours but be listened to as well.

Improvements in the propagation of synthesized aircraft noise can be made by including effects of turbulence, both on the effect of ground reflection as well as possible modulation of the sound level. This will improve the sound quality of the results although more promising improvements should be expected through refined source noise prediction.

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