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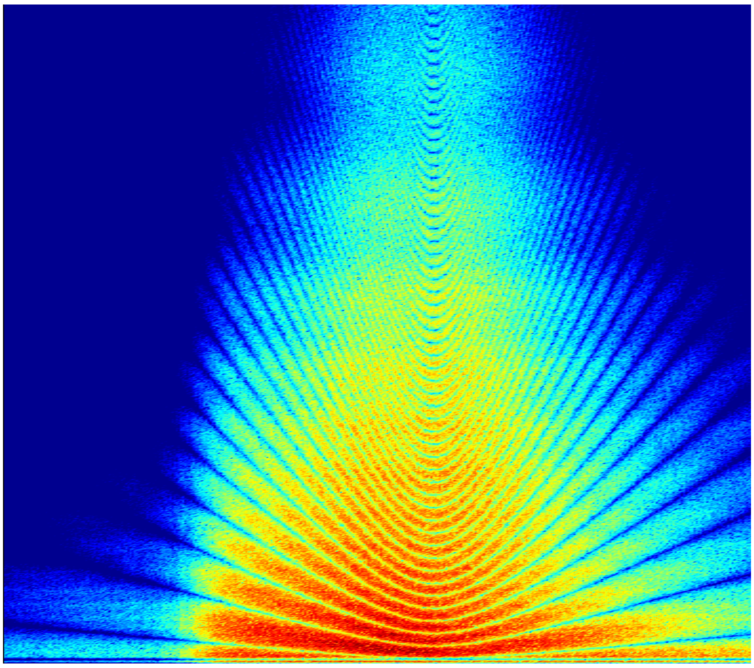
Executive summary

Aircraft Noise Simulation for a Virtual Reality Environment



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Author(s)
M. Arntzen
T.A. van Veen
H.G. Visser
D.G. Simons

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Knowledge area(s)
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Noise Prediction (aircraft)
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Noise Synthesis
Virtual Community Noise Simulator

Problem area
Noise prediction tools are commonly used by engineers to make a prediction for a yearly dose metric. Aircraft noise annoyance predictions based on these traditional tools lack fidelity when modelling a single aircraft flyover. For objective psychoacoustic annoyance evaluation of new procedures, different aircraft types or changing atmospheric conditions, a new modelling approach is necessary.

Description of work
A research effort has been initiated to develop a toolchain that links each of the components that are relevant to calculate and simulate aircraft noise as it is heard on the ground. This allows the use of synthesized sound in a virtual reality simulator and enhances follow-up annoyance investigations. The functioning of the toolchain components and integration is described in this paper.

Results and conclusions
For this paper, the generic toolchain has processed the parameters of a Boeing 747-400 of which exercise the results are presented. Audible results are illustrated by spectrograms to show the difference between sound levels under different atmospheric conditions. It

This report is based on a presentation held at the 17th AIAA/CEAS Aeroacoustics Conference, Portland OR, 5-8 June 2011.

is noticed that the atmospheric effects can be large on the the noise characteristics that are audible on the ground. Noise levels can be damped severely by a changing humidity and temperature. Including the prevailing wind conditions, from a balloon sounding in the Netherlands, will lead to the aircraft being submersed in a silent shadow zone before it is audible. The toolchain will be further developed to include tonal noise and to reduce the computational time. The results presented here are already a strong indication that, for a single aircraft flyover, the atmospheric effects can have a profound influence.

Applicability

As a result it is now possible to predict the noise levels and characteristics of future procedures that are not flown yet around airports. Not only can the results be made audible but they can also be integrated in a virtual environment. This further strengthens the capability to execute objective psychoacoustic testing of, amongst others, noise mitigation measures.

Nationaal Lucht- en Ruimtevaartlaboratorium, National Aerospace Laboratory NLR

Anthony Fokkerweg 2, 1059 CM Amsterdam,
P.O. Box 90502, 1006 BM Amsterdam, The Netherlands
Telephone +31 20 511 31 13, Fax +31 20 511 32 10, Web site: www.nlr.nl

Nationaal Lucht- en Ruimtevaartlaboratorium

National Aerospace Laboratory NLR

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Aircraft Noise Simulation for a Virtual Reality Environment

M. Arntzen, T.A. van Veen, H.G. Visser[1] and D.G. Simons[1]

[1] TU Delft

This report is based on a presentation held at the 17th AIAA/CEAS Aeroacoustics Conference, Portland OR, 5-8 June 2011.

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Contents

Aircraft Noise Simulation for a Virtual Reality Environment

M. Arntzen* and T.A. van Veen.†
National Aerospace Laboratory NLR, Amsterdam, Netherlands

H.G. Visser‡ and D.G. Simons.§
Delft University of Technolog, Delft, Netherlands

Aircraft noise annoyance predictions based on traditional tools lack fidelity when modelling a single aircraft flyover. For evaluating annoyance of new procedures, different aircraft types or changing atmospheric conditions, a new modelling approach is necessary. A research effort has been initiated to develop a toolchain that links each of the relevant components. This allows the use of synthesized sound in a virtual reality simulator and enhances follow-up annoyance investigations. The toolchain components and current capabilities are presented in this paper. Audible results are illustrated by spectrograms to show the difference between different atmospheric conditions. Through the development of the toolchain, it becomes possible to demonstrate audible results of changing aircraft procedures, type and atmosphere in a virtual reality environment. This opens new ways to investigate how people value aircraft noise in different atmospheres in combination with smart planning of aircraft procedures.

I. Introduction

As a result of the continuing growth in air traffic demand and the rising level of urbanization around many airports, airports across the globe are increasingly confronted with the need to deal with the impact of noise on the quality of life in the surrounding residential communities. This is due to the fact that, at a short distance, aircraft noise is one of the loudest sound sources in today's public environment. Although prominently audible, it is hard to comprehend the impact of aircraft noise because of the complex interaction of sound production, propagation and perception. Since aircraft are able to generate a high sound emission, minimizing the noise level at specific locations around the airport is a frequently used strategy to minimize the impact of aircraft annoyance on the public. Tools have been developed to predict these noise level footprints based on measured aircraft noise. The measured aircraft noise at a specific power and distance are represented in so called Noise-Power-Distance-tables (NPD). These tables are the backbone of a wide range of aircraft noise models in current use, like the Integrated Noise Model[1] (INM).

Measurement results are condensed into the NPD-table metrics that describe the noise level, like for instance Sound Exposure Level (SEL). It is a well-known fact that different people react differently to noise and that only the SEL, or an equivalent metric like $L_{A,max}$, is not a good basis to asses annoyance. Human annoyance is based on a sophisticated biological process that constitutes of the ear, detection, brain perception and emotional association. Each of these processes is different for each person, which offers an explanation why different people are annoyed differently by the same sound. For instance, aircraft noise frequently includes a broad-band component and a tonal component. People can judge tonal components to be more annoying than the broad-band component, which is not reflected in a SEL or $L_{A,max}$ value. This all contributes to the complex nature of aircraft noise annoyance. Therefore, reducing aircraft noise annoyance by minimizing the noise contour area of a choosen metric is only a part of the solution. To obtain a more complete representation of annoyance, one should be able to predict the audible aircraft noise and determine the impact of the aircraft sound on people.

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* PhD candidate at NLR, Environment and Policy support, Anthony Fokkerweg 2, Amsterdam.
† Senior Research Scientist at NLR, Environment and Policy support, Anthony Fokkerweg 2, Amsterdam.
‡ Associate Professor at TU Delft, Air Transport & Operations, Kluyverweg 1, Delft, Associate Fellow AIAA.
§ Full Professor at TU Delft, Air Transport & Operations, Kluyverweg 1, Delft.

Traditional aircraft noise annoyance methods use results based on NPD-tables. A method based on such an NPD-table is short of the possibility to predict the aircraft noise spectrum, temporal behaviour and directional characteristics. With a dose-response relationship, determined from an enquiry[2], the corresponding annoyance of a person is calculated. At the Dutch National Aerospace Laboratory (NLR) research is initiated to obtain a more comprehensive picture on aircraft noise annoyance to enhance future aircraft operations. To this end, the NLR obtained a Virtual Community Noise Simulator (VCNS) from NASA and collaborates with NASA to expand the annoyance research capabilities. The simulator utilizes a helmet mounted visor to submerse an observer into a virtual reality environment. A headphone is placed on the observer ears to present binaural flyover noise to the observer. Since a recognizable visual environment and audio signals are presented in the VCNS, the psychological impact of aircraft noise can be investigated. Together with airports and operators, new procedures can be fully evaluated on their impact on people that live nearby airports. Currently, the VCNS is used in combination with radar tracks and flyover noise measurements. Although this offers a high simulation fidelity, the operator is restricted to this specific case, including the conditions of the atmosphere during the measurements.

To predict how the sound of future aircraft procedures is received by an observer in a variety of conditions, an extensive set of measurements is required. Not only is this an expensive process, the atmospheric conditions during the measurements remain of vital importance. Improvements are necessary that allow to simulate and control such an experiment. A new method is therefore developed that is able to permit the operator to control the simulation parameters like aircraft type, trajectory and atmosphere. Since a variety of parameters are researched, a short computation time is one of the key requirements in the model development. Studying this broad range of relevant parameters allows us to design new silent procedures in accurate reproducible conditions and in a short amount of time. The traditional method and the new method are illustrated in Figure 1.

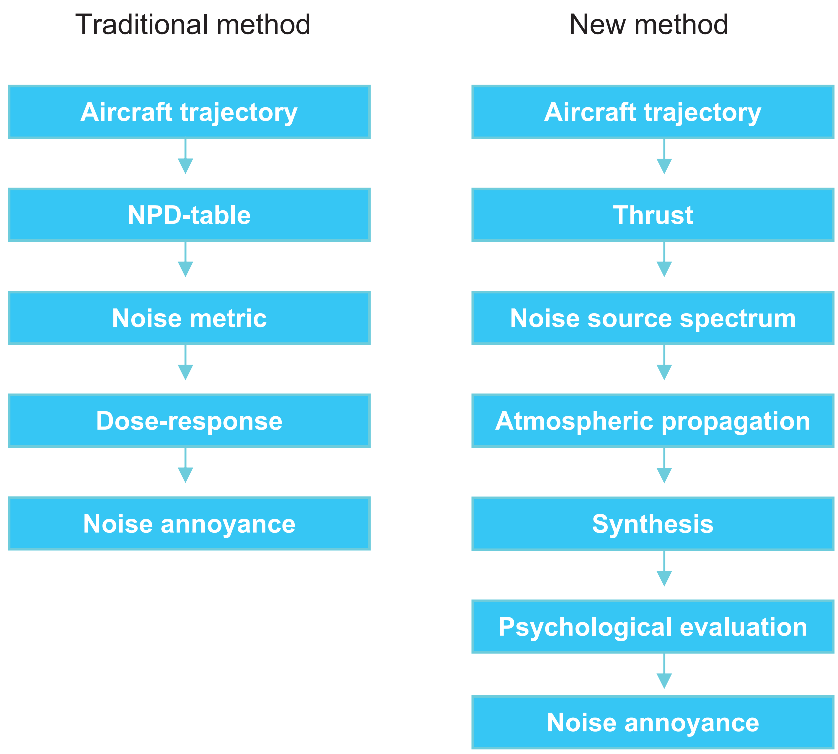

Figure 1 The traditional method and the new method to asses the annoyance of aircraft flyover noise

To construct the new method, and allow psychological investigations in aircraft noise, a computational toolchain is developed to make the results audible and visible in the simulator. Other investigators researched aircraft sound synthesis[3,4] but did not address a specific toolchain as proposed in the new method and focussed on specific parts. For instance in Ref. 3, the synthesis is based on measured data but the aircraft trajectory calculations are not treated. Whereas in Ref. 4, the measured data are re-synthesized and it is shown that the synthesized results can not be differentiated from the original measurements. However, the effect of a different procedure or atmosphere is not mentioned. Therefore this new method allows to investigate noise annoyance on a level that has not been demonstrated yet, to the best of the author's knowledge. Especially the option to control the atmospheric conditions in detail and present the audible effects have not been found in literature. In this paper, the modelling approach and some preliminary results are shown to illustrate the potential of the new method.

II. Methodology

In order to control every parameter relevant to aircraft noise annoyance, the aircraft sound must be made audible, i.e. synthesized, with the new method. Therefore tools are developed or implemented that are able to predict the individual parts in Figure 1. The tools are based on Matlab and are highlighted from hereon.

A. Flight mechanics

To predict an aircraft trajectory, rather than using a radar track, the flight mechanics are modelled. This constitutes to a trajectory and thrust prediction. The trajectory prediction is based on a point mass model of the flight mechanics rather than an elaborate model that includes control surface deflection. A point mass model neglects some of the fast transient aircraft dynamics. However, it is thought that the impact of these dynamics on sound is small. A point mass model reduces the elaborate equations of motion into six ordinary differential equations (ODE's). The use of ODE's allow the use of a simple Runge-Kutta (fifth-order) numerical integration scheme. To fly a trajectory, the user specifies way-points on the ground that he would like the aircraft to follow at a specified pressure altitude and calibrated airspeed. A Proportial Integral Differential controller is used to control the variables that correspond to pilot input. This ensures that the desired trajectory is flown by the aircraft and allows to model a variety of standard departures or approaches.

In the process of solving the ODE's, the thrust must be predicted at the corresponding operating conditions. A simple but effective approach is used by modelling the different components of the engine by their characteristic parameters (compression ratio, efficiency,etcetera), see for instance Ref. 5. This gives a fair indication on the design point thrust of a jet engine. When the engine is operated at a different condition than the design point, these parameters change. The so-called off-design calculations require an elaborate approach to recalculate the parameters corresponding to the off-design condition. To circumvent this problem, the parameter trends for off-design conditions are extracted by using the GSP-software developed at NLR[6]. This completes the input for the engine model to predict the thrust along the trajectory for the majority of engine operating conditions. Output of this model is the actual thrust, fuel flow and typical thermodynamic parameters of the engine. These parameters are directly available in the simulation. The thrust is needed to solve the ODE's whereas the other parameters are necessary for the source sound prediction models.

B. Source Sound

Aircraft sound is emmitted at a broad spectrum of frequencies and is generated by two major factors, the airframe and the engine. In order to model arbitrary aircraft, a generic method to predict aircraft source sound is necessary. Whereas research models are able to give good results, they are frequently tuned to specific conditions. Therefore an engineering method is desired that is able to represent a variety of aircraft. Models that meet this criterium are usually based on empirical observations. Three empirical models exist that predict the relevant sources of civil aircraft: the Stone model[7], the Heidmann model[8] and the Fink[10] model. In this paper we demonstrate the results of the toolchain on the broad-band noise component of a Boeing 747-400.

The Stone model provides an estimation of the jet mixing noise and engine shock noise. However, the engine shock noise is not dominant in this case and not treated explicitly. The Stone model describes three mixing noise sources: the large scale, transitional scale and small scale mixing noise. Mixing noise exists due to the velocity difference of exhaust gasses and the surrounding air. The large scale mixing noise occurs behind the engine where the by-pass and core massflow collide and start to mix. Transitional scale noise is produced due to the velocity difference between the core and bypass airflow. Small scale mixing noise is caused by the velocity difference of the bypass duct and the ambient air flow. Stone fitted the data to the engine flow and operating conditions with aeroacoustic relationships in mind. With the help of the thrust output parameters at every time step of the aircraft trajectory simulation, the theoretical jet noise spectrum is calculated.

Heidmann made a model to predict the fan noise and modelled three components: the fan tones, buzz-saw and broad-band noise. The fan tones are generally caused by unsteady loading on the rotor and stator vanes of the fan. These fan tones are an integer multiple of the Blade Passage Frequency (BPF). Buzz-Saw is a complex noise source that is generated by the shocks that form on a fan when reaching a helical tip Mach number larger or equal 1. In a perfect environment, the shock noise frequency is a multiple of the BPF. However, small imperfections and aeroelastic loading cause that the shock noise is not a multiple of the BPF. The shocks coalesce together into a single noise system that is repeatedly radiated for every rotation of the fan. Buzz-Saw is therefore seperated by the shaft frequency rather than the BPF. Heidmann does not predict this frequency dependency and smears out the buzz-saw energetic contribution over the 1/3rd-octave bands. This eliminates the underlying physical phenomenon and makes it hard to synthesize this effect from the Heidmann model prediction. Investigation into the tone representation for the tone synthesis are not yet finished. Therefore the tone noise is not yet included at this point in the simulations. Although the vital improvements to the Heidmann model, as suggested in Ref. 9, are incorporated.

Airframe noise is modelled using the Fink model. This simple model gives an estimation of the broad-band noise of different airframe components. The contributions of each component are added to give the total estimate of the airframe. Fink allows to model the aerodynamic surfaces and gears. In our case, the Boeing 747-400 flyover, a clean configuration was used. The only relevant contributions to the broad-band noise are then formed by the turbulent flow leaving the wing and horizontal tail surfaces. Fink used a Boeing 747-100 to assess the empirical relationships, therefore this simple prediction method is suited for our simulation case.

C. Propagation and atmosphere

It is well known that the atmosphere has a significant impact on the propagation of aircraft noise. Not only is the atmospheric absorption crucial, wind specifically transports the sound waves and has a direct effect on travel time. Several techniques (e.g. in order of increasing fidelity: Ray-Tracing, Parabolic Equation (PE) solver, Normal Modes Method, Fast Field Program (FFP)) exist that are able to take these effects into account. Whereas an FFP and a Normal Mode program solve the Helmholtz equation, PE-methods and ray-tracing use approximations of the wave equation to solve the propagation problem.

A high fidelity FFP tool from the ESDU[11] is explored in this research. The added benefit compared to ray-tracing, is the inherent capability to calculate diffraction without the need to offer fidelity. The downside is the large computational cost invoked by the FFP for a large range and a high-frequency. Both are apparent in aircraft flyover noise and therefore excessive computational effort for the simulation in this paper was made in the order of days on a desktop computer. For now we want to capture the computational fidelity but new ray-tracing developments are started to reduce this computational burden by imposing computational requirements on the toolchain.

Input to the propagation tools described above, is an atmospheric representation including wind, temperature and humidity. Several investigators use logarithmic profiles for the simulation of wind speed in their propagation problems. These profiles can be obtained relatively easily with a so called roughness height where the wind speed is assumed to be zero. The roughness height is implemented as a parameter that is characteristic for the distribution of typical objects on the ground like concrete, grass, vegetation and even buildings. However, these kind of functions lack the ability to inherently model complex behaviour like temperature inversions and change in wind direction as a function of altitude. Based on similarity theory, Businger-Dyer relations and Pasquill classes, an indication on a mean logarithmic profile can be found in Ref. 12. Nonetheless, temperature inversions or altitude dependent change of wind direction can not be modelled using the above relationships. Moreover, these kind of profiles are generally limited to meteorological layers[13] close to the ground. For more accurate descriptions, the governing equations (with turbulence closure) must be solved numerically. Since actual weather prediction is out of the scope of this research, this interesting path was not further examined. To include realistic atmospheric information, data from balloon soundings[*] were used. With the developed toolchain, we were able to use these realistic data which are measured in a variety of places. In this paper, we used an atmospheric scenario as acquired on the 4th of February of 2011 at the Bilt in the Netherlands. On this day there was a strong southwestern wind, as depicted in Figure 2, that caused serious trouble for landing and departing aircraft at Schiphol airport in the Netherlands.

[*] http://weather.uwyo.edu/upperair/sounding.html

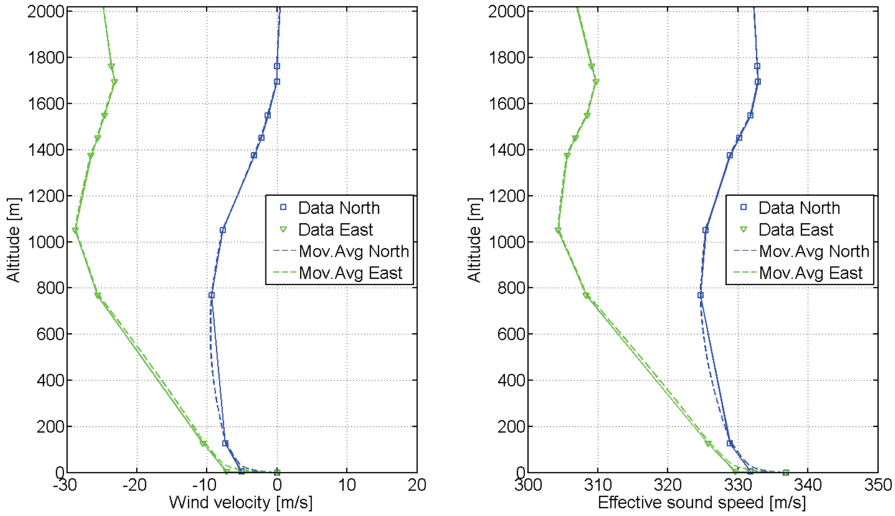

Figure 2 Wind profile as used in the current simulation

We see that the North- and East-bound component of the wind are negative, which implies a South-Western wind. The data-points are taken at discrete heights, to get a continuous profile, the results are linearly interpolated (based on the available data points) at every meter altitude and a moving average of 5 meters is applied. This leads to a smooth continuous profile as is shown by the striped line results. Since the wind is rather strong, a shadow zone will emerge where the sound waves from the aircraft are well damped. These shadow zones are predicted by ray-tracing as zones in which no sound penetrates. However, it is well known that this is not true due to diffraction of sound, turbulence and the existence of ground waves. Therefore noise of a flying aircraft, reaching an observer after being emerged in a shadow zone, can not be accurately predicted by ray-tracing if not corrected for these effects. This is another reason why we have used a FFP for these calculations. All of the above mentioned propagation models neglect the effect of viscosity on sound waves. The viscosity damps the waves and can be corrected when taking the atmospheric absorption into account. A standard model for absorption, as used for the simulations, is described in Ref. 14 and depends on the relative humidity and temperature.

D. Sound synthesis

Using the propagation method, the sound spectra at the observer position due to the aircraft flyover are obtained. These results must be auralized using a synthesis method. The broad-band component of the spectra are defined in 1/3rd octave bands. An overview of the sound synthesis method, as coded in Matlab Simulink, is given in Figure 3.

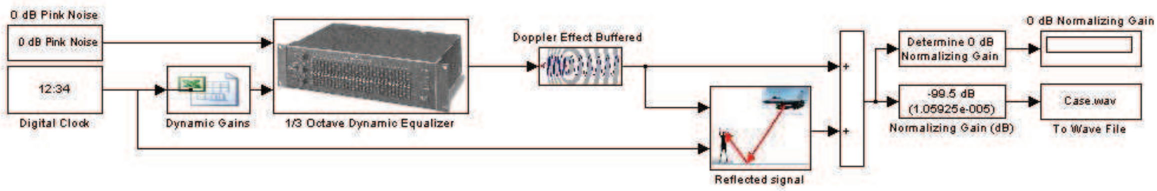

Figure 3 Sound synthesis algorithm

For each 1/3rd octave band, a pink noise source is combined with a relative gain corresponding to the calculated broad-band noise results. As a result of the flyover and atmosphere, the gains of the bands change in time. A dynamic equalizer is developed in Matlab to apply the specific momentary gains to the pink noise source. The result is an audible representation of the flyover.

An aircraft is a moving source and therefore a Doppler shift must be applied to the frequencies arriving at the observer. A time delay is applied to the output of the equalizer to simulate the Doppler effect[15]. This mimics the Doppler shift due to the fact that specific parts of the wave reach the observer at a different time, thereby effectively changing the frequency at the observer.

To simulate the ground reflection effect, a reflected wave is added to the results of the dynamic equalizer. A hard ground, or perfect reflector, is assumed. This implies that the amplitude of the reflected waves equals the direct wave so there is a small phase shift. The phase shift is due to the difference in path length of the incident and reflected sound wave. Rather than using a 1/3rd octave band representation, it is vital that the ground reflection is applied to the continuous spectrum. Audible results where the effect of the ground reflection is implemented in an 1/3rd octave band representation for modification of the dynamic gains are poor.

III. Results and discussion

In this paper, a few results are presented that give a short impression of the toolchain's capabilities. Three cases are presented with a straight flyover. For the three cases, the altitude (1000 m) and calibrated airspeed (120 m/s) are fixed, the B747-400 is in a clean configuration. An overview of the main parameters are shown in Table 1.

Table 1 The three test-cases for the straight flyover

Case	Propagation method	Relative Humidity [%]	Temperature [deg C]
1	Spherical spreading	75	15
2	Spherical spreading	10	10
3	Fast Field Programm	75	15

In case 1 and 2, a spherical spreading loss is taken into account. This omits the influence of the windfield on sound propagation, however the wind influence on the flight mechanics is taken into account. The aircraft is flying on a heading of 50 degrees, straight into the wind. A typical result, for case 1, is illustrated in Figure 4.

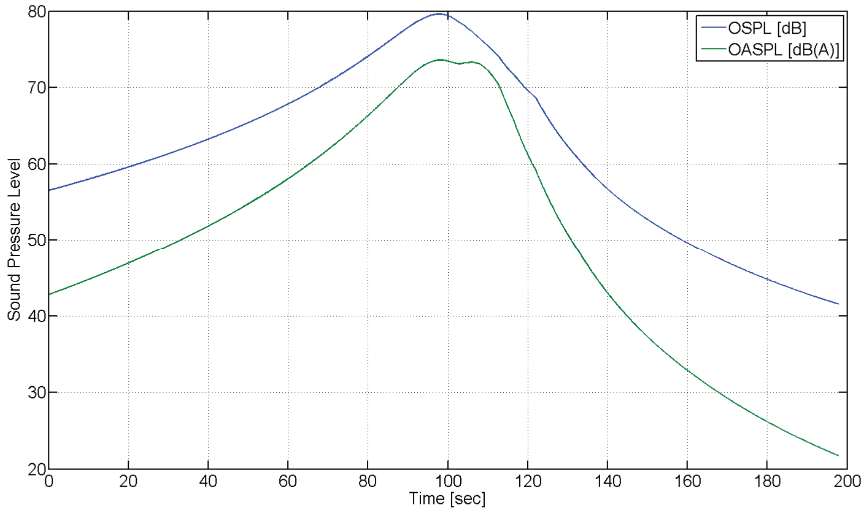

Figure 4 Broad band noise result for case 1

Figure 4 shows the calculated overall sound levels of the broad band noise, both unweighted and A-weighted, at the observer. For this case, the fan tone and buzz-saw noise output from the Heidmann model is suppressed. The aircraft is straight overhead at 104 seconds after the start of the simulation. The effect of A-weighting is large, this means that there is a relative large presence of low frequency noise. This effect becomes larger when the aircraft is flying away from the observer, since both lines in Figure 4 diverge. Additionally, a distinctive kink is present in the OASPL result around 102 seconds due to the different directivity patterns of the noise sources. The different directivity patterns are illustrated in Figures 5-7, which are a representation of the noise sources on a sphere with a radius of 1 meter. For these figures, the engine is operating at 100% N1 and the aircraft is flying straight over the observer, e.g. the azimuthal angle is 90 deg.

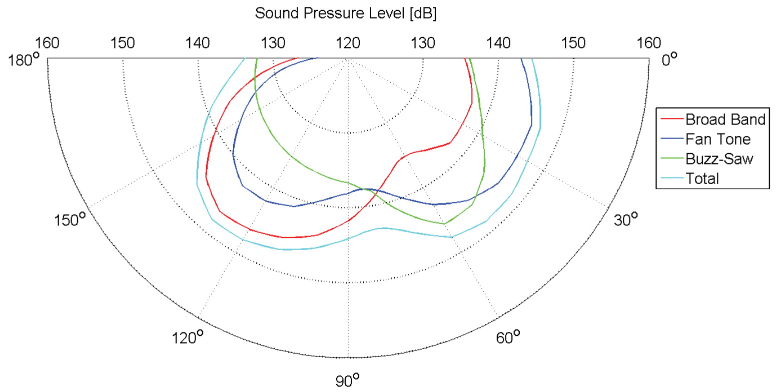

Figure 5 Fan noise prediction of the simulated engine in static-sea-level conditions

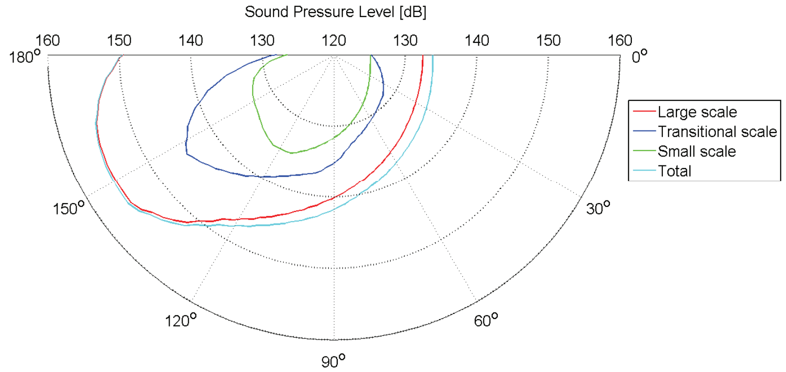

Figure 6 Mixing noise (broad-band) prediction of the simulated engine in static-sea-level conditions

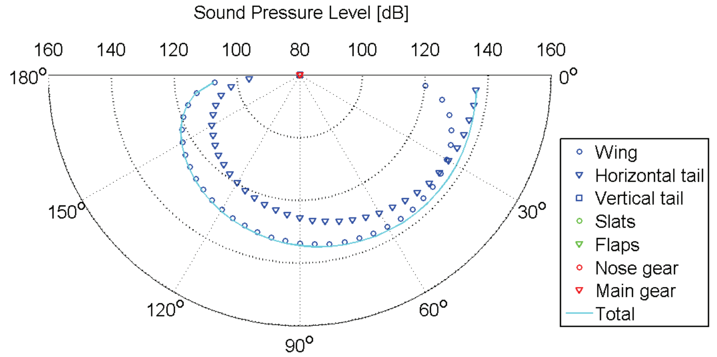

Figure 7 Airframe noise (broad-band) prediction as used in the simulation

The SPL's of the different sources, as illustrated in Figures 5-7, are defined on a sphere, whereas the results in Figure 4 are at the observer. The atmosphere damps high frequency waves more efficient than their low frequency counterparts. Due to atmospheric absorption, the directivity pattern (and corresponding peaks) in the SPL at the source does not necessarily match with the resulting spectrum at the observer. To illustrate the end result of the sound synthesis, spectrograms of the different cases are presented next.

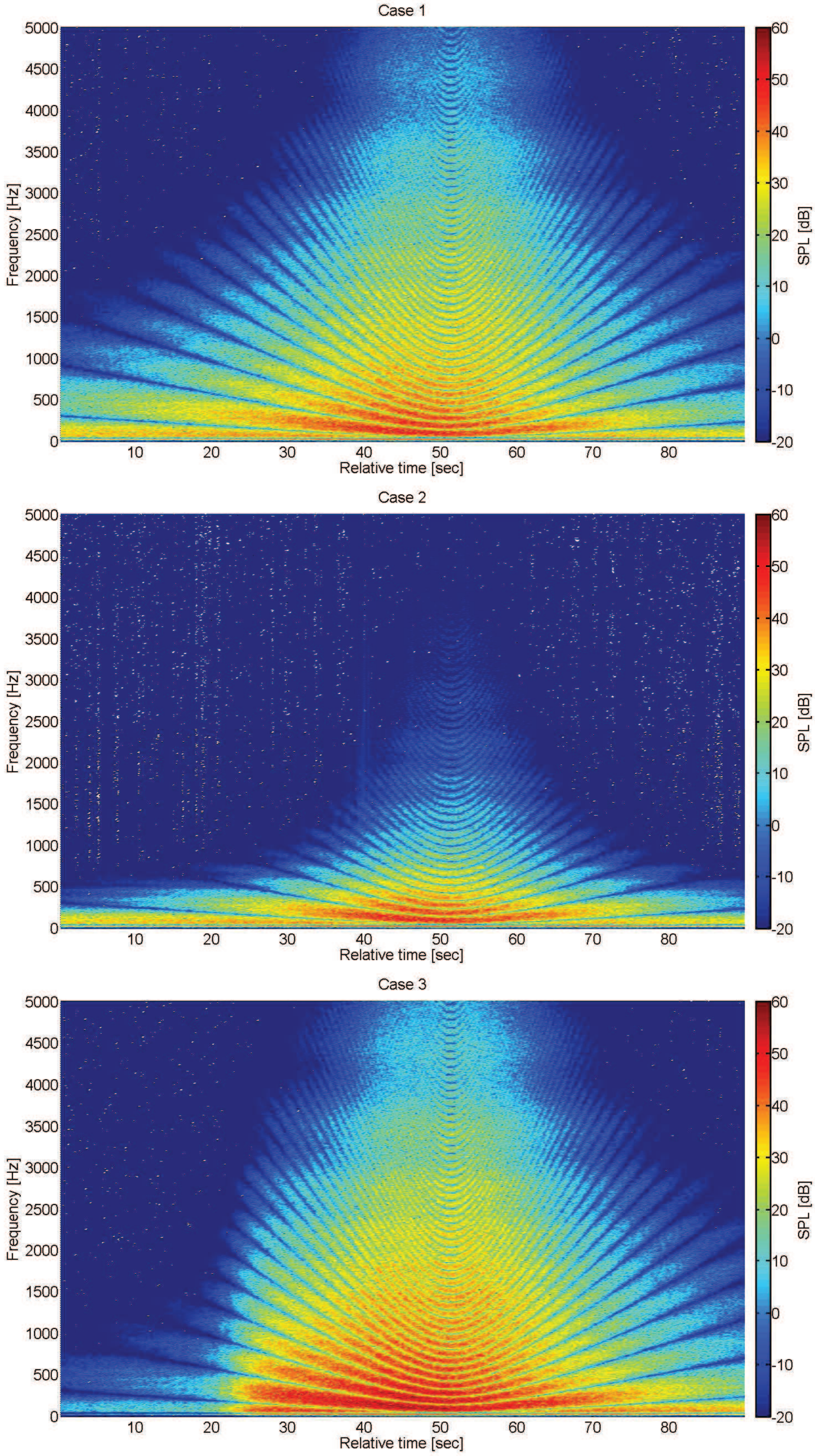

Figure 8 Spectrograms, with a resolution of Δf = 5 Hz and Δt=0.25 seconds, of the synthesized signal for the three cases of Table 1

The three spectrograms each show characteristics that are typical for the defined cases. Case 1, which represents standard values for the atmospheric absorption and spreading losses, shows that the method is viable for the broad-band sound. The ground effect is clearly visible whereas the Doppler shift effect is barely noticeable. It is best illustrated in Figure 9, where case 1 is enlarged and the Doppler shift can be observed in the ground interference pattern.

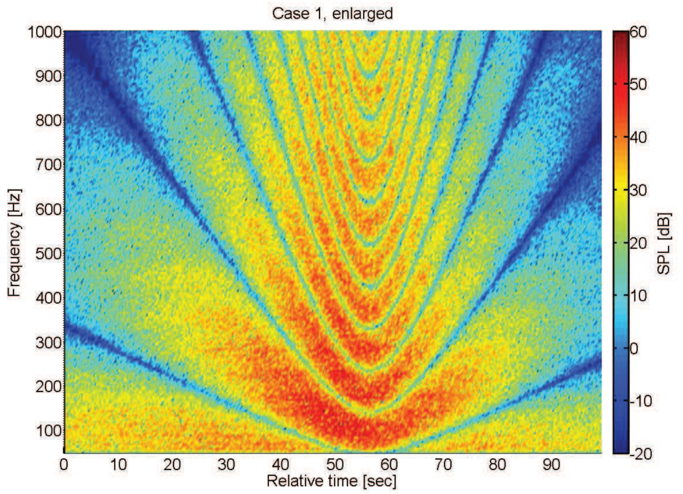

Figure 9 Enlarged spectrogram of case 1 to illustrate the Doppler shift

A Doppler shift would be clearly visible in the spectrogram if tonal noise would have been modeled and distinctive lines included. Since the signal is clean, e.g. not disturbed by turbulence, and the ground is a perfect reflector, the ground reflection is found in the complete spectrogram range.

The second spectrogram of Figure 8, shows the result of the changed atmospheric absorption. As expected, higher frequency sound is damped more efficient. This specific combination of relative humidity and temperature, ensures that even at low frequencies sound is damped. Although these conditions seem extreme, when an aircraft flies above the clouds, humidity and temperature can rapidly drop.

In the third spectrogram, a threshold (around 22 seconds) is visible in the Figure. This is the previously mentioned shadow zone. Due to the upward bending of the sound waves, no sound is heard if the aircraft is flying far away. As it comes closer, the low frequency sounds start to become audible before the high frequency sounds. When the aircraft emerges from the shadow zone, the sound intensity is a bit higher than case 1. The intensity is also slightly higher after the aircraft has passed over. Increased intensities indicate that the sound waves are focussed towards the observer due to the wind.

From the graphs it is clear that a variety of variables can be modified and the effects can be synthesized. More traditional flyover representations, like the Overall SPL (OSPL) and A-weighted version OASPL, are as well calculated as shown in Figure 4. Using generic empirical tools, it is now possible to establish differences between flyover noise by modifying the aircraft procedure or atmospheric effects. One of the downsides of the toolchain is the large computational effort that is invoked by the FFP. A ray-tracing code can run at a fraction of the computational effort and, with help of corrections based on FFP results, include aspects like diffraction and turbulence. This seems a more rewarding approach for future research. Another shortcoming is the lack of the tonal component modelling. Some ideas are established, but still need to be coded for inclusion in the toolchain. The same holds for the Buzz-Saw noise. With these three issues tackled, a high fidelity toolchain exists that models an arbitrary trajectory through an arbitrary atmosphere and makes the end result available as an audible result.

IV. Conclusion

In order to represent aircraft annoyance, for psychological evaluation, a toolchain is developed. This is, for instance, necessary to obtain a clear view whether there is room for future aircraft operations based on weather-adaptive procedures. The toolchain presented in this paper is capable of modelling different parts of the aircraft flyover and individual sound sources. Investigation into which part of aircraft noise annoys people the most become possible since the results are audible. This will lead to new insight for combining a densily populated area and aircraft operations. Before we can do these kind of experiments, the results should be verified more closely with real-life situations. A test-campaign or comparison with existing sound recordings will be executed in the future. Improvements are scheduled for the modeling of the propagation and the synthesis of the tones. However, these preliminary results are promising and demonstrate the importance of the correct modelling of atmospheric effects and the integral approach of the toolchain.

Acknowledgments

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