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Model-based synthesis of aircraft noise to quantify human perception of sound quality and annoyance

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Abstract

This paper presents a method to synthesize aircraft noise as perceived on the ground. The developed method gives designers the opportunity to make a quick and economic evaluation concerning sound quality of different design alternatives or improvements on existing aircraft. By presenting several synthesized sounds to a jury, it is possible to evaluate the quality of different aircraft sounds and to construct a sound that can serve as a target for future aircraft designs. The combination of using a sound synthesis method that can perform changes to a recorded aircraft sound together with executing jury tests allows to quantify the human perception of aircraft noise.

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1. Introduction

This research makes use of aircraft noise fragments recorded within the framework of the European FP6-STReP project SEFA (Sound Engineering for Aircraft) [1]. The SEFA-project involves members of the Airbus consortium as well as institutes and universities from the following countries: Germany, France, England, Sweden, Italy, Belgium, Portugal and Hungary. The purpose of this EC project is to analyse aircraft noise and determine the parameters that correlate best with noise annoyance. Once these are known, new measures of sound quality for aircraft noise will be developed and used to define optimal noise signatures which will then be evaluated using psychometric testing. New tools such as virtual aircraft and listeners will be developed, enabling a new type of simulations for the investigation of measures to reduce aircraft noise. A preceding part of the SEFA project focussed on the identification of relevant physical parameters (vs. engineering and operating concerns) which impact the noise perceived at the ‘‘virtual resident’’ location. For this purpose, a sound simulation approach was developed capable of synthesizing aircraft noise at resident, i.e. audible virtual aircraft sound tracks, vs. aircraft design parameters (flight path, engine RPM, engine/airframe single sources, ground effect, propagation effects, etc.). These sound tracks will also be used in the identification process of the most relevant design criteria for aircraft/engine and noise/annoyance perception [2,3]. The work described in this paper aims at the same targets, but focusses on sound as perceived on the ground.

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Although new technologies did bring considerable sound reductions in the past, the continuously growing demand for smooth transport possibilities caused an increase of transport noise during the last 40 years [4]. Concerning aircraft noise, take-off and landing are the operating conditions that cause most of the noise and annoyance. Noise map information and self-report of noise exposure are consistently associated under these conditions; noise and annoyance are increasing simultaneously over the last decades [5]. Moreover, the awareness of aircraft noise by citizens seems to increase during the last years and this causes the annoyance to rise further. Research indicates for instance that, although both the calculated number of people exposed to high average sound levels and the measured number of flight-related events at the measuring locations around Brussels airport decreased, the citizens around Brussels did report significantly more annoyance due to aviation in the period 2001–2004 [6].

In contrast to the situation 40 years ago, nowadays a lot of noise sources in modern aircraft are of similar loudness. Fan, turbine, compressor, jet noise and aerodynamic noise due to airflows around the body of the aircraft can all be dominant depending on the mode of operation [7,8]. To achieve a noise reduction noticeable by humans on the ground, several of these sources have to be reduced simultaneously. The fact that technological breakthroughs are needed in several different areas at the same time limits future achievable noise reductions of passenger aircraft. To reduce the annoyance caused by aircraft noise, noise control engineering solutions can no longer focus only on lowering the total produced sound levels, they should also focus on the improvement of the quality of the perceived noise. For realizing this, it is important to be able to simulate the effect of each noise source on the total sound quality.

The human hearing is a very complex mechanism that is not as adequately understood in the present state-of-the-art as needed for accurate predictions of perceived sound quality under various circumstances. Noise metrics are useful for the determination of specific aspects of sound quality [9,10], but real hearing sensations remain essential for qualifying the global sound quality. In certain fields, sound quality is already incorporated in the noise standards, e.g. in fan noise for office applications. At present sound quality is not yet incorporated in the aircraft noise standards in Europe, but numerous guidelines and standards apply, e.g. day/night weightings in an attempt to include experienced annoyance in future noise regulations.

Sound design is a well-established methodology in the fields of, e.g. speech and music synthesis [11–15], but the techniques were not yet applied for aircraft exterior noise. Until recently, there was no efficient manner for designers to critically examine an aircraft design with respect to its sound quality since no synthesis method of sufficient quality exists for aircraft noise. An additional shortcoming of the existing sound evaluation techniques is that a lot of technical knowledge is needed to interpret metrics and figures in order to draw proper conclusions concerning even the basic properties and features of the sounds.

The final objective of the research is to examine the influence of several sound sources on the quality of the total sound produced by modern aircraft as perceived on the ground. A synthesis method should facilitate the evaluation of several changes to existing aircraft or new designs in a quick and affordable way by performing a virtual simulation. Hence, the first objective of this research is the development of a sound quality equivalent aircraft sound synthesis method.

2. Aircraft sound spectra

This section first clarifies the method that was applied for the calculation of the time–frequency spectra shown in this paper. Afterwards it analyses the spectral content of recorded aircraft noise fragments of different aircraft, representative for the fleet of passenger aircraft in the year 2005. The actual method to synthesize aircraft sounds starts from these recorded fragments and is explained in Section 3.

2.1. Calculation of the time–frequency spectra

The spectra of the time-varying aircraft noise recordings are calculated by executing consecutive Hanning windowed DFT's on fragments of the recorded noise [16]. Table 1gives an overview of the applied parameters and Eq. (1) defines the N-point symmetric Hanning window. More complex algorithms for handling time-dependant spectral representations of non-stationary signals, such as, e.g. the FTT after Terhardt [17,18], were not considered further since this simple method already resulted in syntheses of sufficient quality

Table 1
Parameters for the calculation of the time–frequency spectra

Noise recording		DFT	
Length	T_{Tot} (s)	Frequency resolution	3 (Hz)
Sample frequency	44.1 (kHz)	Window length	3^{-1} (s)
		Number of windows	300
		Time resolution	$T_{\mathrm{Tot}}/300$ [s]
		Overlap	35%–60% (depends on T_{Tot})

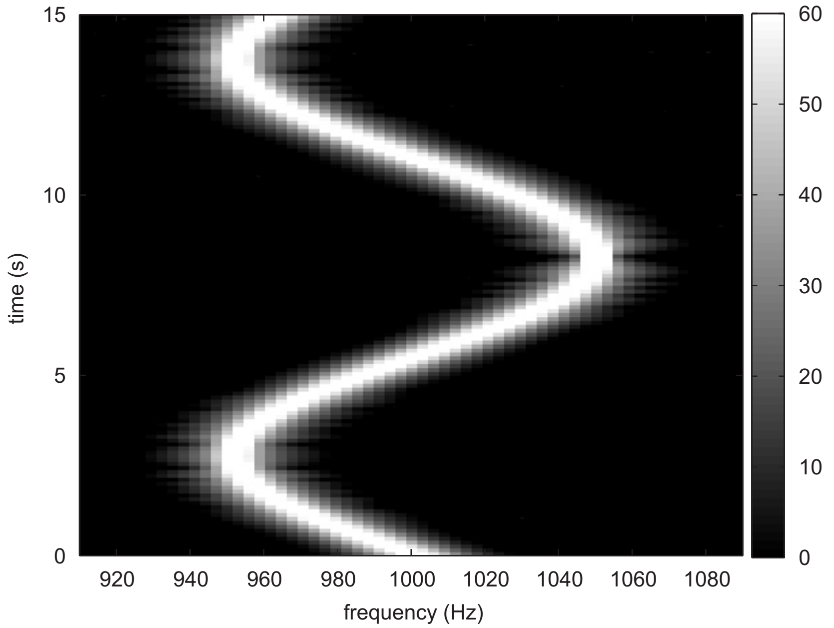

Fig. 1. Time–frequency spectrum of a tone; $f = 1000 + 50\cos(2\pi 0.1t)$ Hz, sound pressure level dB (re. 2×10^{-5} Pa).

(see Section 4). Fig. 1 shows the result for a tone with frequency $f = 1000 + 50\cos(2\pi 0.1t)$ Hz. The use of a Hanning window adds distortion to the sound fragment being analysed in the form of amplitude modulation. This results in sidebands in the spectrum of the signal, as can be seen in Fig. 2 which shows the time–frequency spectrum of a white noise signal in the third-octave band around $f_c = 1000$ Hz ($f_L = 891$ Hz, $f_H = 1120$ Hz). However, this did not prevent the achievement of a sound quality equivalent sound synthesis method (see Section 4.2) and hence, this simple method is suitable here.

$$w(i) = 0.5\left(1 - \cos\left(\frac{2\pi i}{N-1}\right)\right), \quad \text{where } 0 \leqslant i \leqslant N-1. \tag{1}$$

2.2. Main features in aircraft noise spectra

Different types of passenger aircraft have been studied, mainly aircraft with jet engines but also some smaller propeller driven aircraft. Both take-off and approach events are captured and the noise recordings are made according to annex 16 of the International Civil Aviation Organization (ICAO) convention. The sample frequency used to record the sounds is 44.1 kHz, the microphone positions and heights (1.2 m above ground level) are taken according to the standards, [7,19]. However, no information about the trajectory of flight is known for the different sound fragments.

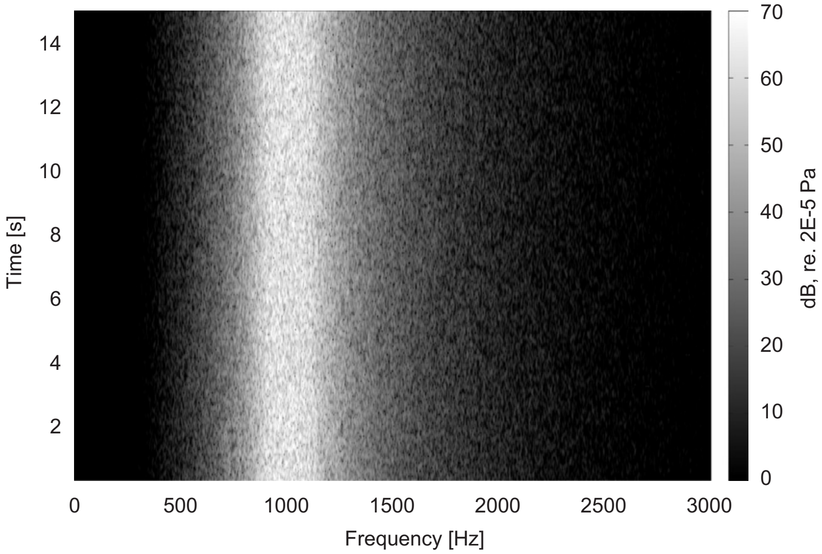

Fig. 2. Time–frequency spectrum of a white noise signal in the third octave band with $f_{\text{centre}} = 1000\,\text{Hz}$.

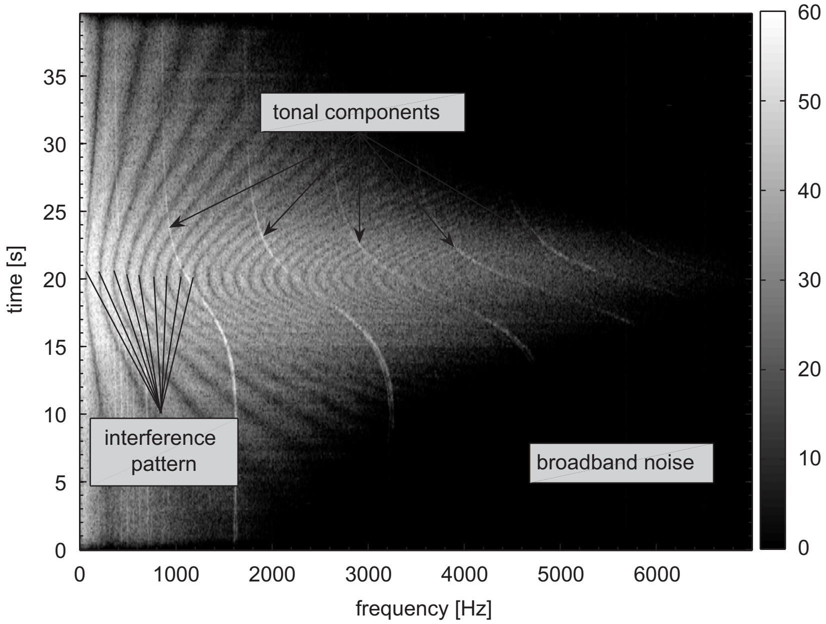

Fig. 3. Time–frequency spectrum of aircraft noise measured during take-off, sound pressure level dB (re. 2×10^{-5} Pa).

Fig. 3 shows a typical time–frequency spectrum of aircraft noise, measured during take-off. This spectrum shows the evolution of the distribution of energy across frequency. Note that only the most relevant part of the frequency axis is shown for the sake of clarity. The figure reveals three major components in ground-perceived aircraft noise: some tonal components, broadband noise and an interference pattern. Although the latter is not really a noise source but rather the result of interference between direct and reflected noise, it is treated nevertheless as a different 'component' in the synthesis method. The aircraft passes the microphone at around second twenty here, corresponding with the bending points in the interference valleys and the tonal components.

Tonal components are mainly caused by several noise sources in the engine such as the turbine, the compressor and the fan. Moreover, they can arise from flows over cavities and over non-aerodynamic components of the aircraft (e.g. flows over the cavity where the landing gear is stored during flight and flows around the flaps on the wings). Fig. 4 shows an example of a recorded noise with two closely spaced tonal components, one from the left engine and one from the right engine. Some large wide-body aircraft develop a specific kind of tonal components. During high load conditions of the engine, i.e. primarily at take-off, shock waves develop at the front of the fan blades when conditions of supersonic tip speeds occur. Each pressure wave has the shape of a saw tooth and the produced tonal components with a very characteristic noise are therefore called buzz-saw components [7]. 'Buzz-saw' is an effect that develops because the produced pressure waves impinge on the engine inlet, resulting in a clear directivity of the produced sound towards the front of the aircraft. Fig. 5 shows how this phenomenon is visible in a time–frequency spectrum of recorded noise originating from a large aircraft during take-off. A discrete tone at the rotational speed of the axis and several of its harmonics arise in the spectrum. Besides the buzz-saw components, also 2 conventional tonal components and an interference pattern are clearly visible in Fig. 5. The fact that the frequency spacing between the buzz-saw components (approximately 100 Hz in Fig. 5) is sometimes rather small requires a slightly different synthesis strategy as compared to the synthesis of the conventional tonal components, see Section 3. Because of the pronounced directivity of this noise, these components are only audible when the aircraft approaches the (ground) observer. As soon as the aircraft passes the observer, the components are no longer perceived and disappear in the time–frequency spectrum. The impact of buzz-saw components on sound quality is clearly distinctive from the impact of conventional tonal components. Literature already revealed that buzz-saw is very annoying for passengers inside the aircraft [7]; this research shows that also people on the ground experience very much annoyance due to the occurrence of this phenomenon, see Section 4.

Broadband noise arises a.o. from the combustion chamber during the combustion process, from the turbulence in the jet of the engines and from air flow around the body of the aircraft. On both the tonal and the broadband components an interference pattern is visible caused by reflections on the ground. The time and frequency dependence of the interference pattern can be explained by the reflection characteristics of the ground, the trajectory of the aircraft and the position of the microphone. An interference pattern is clearly

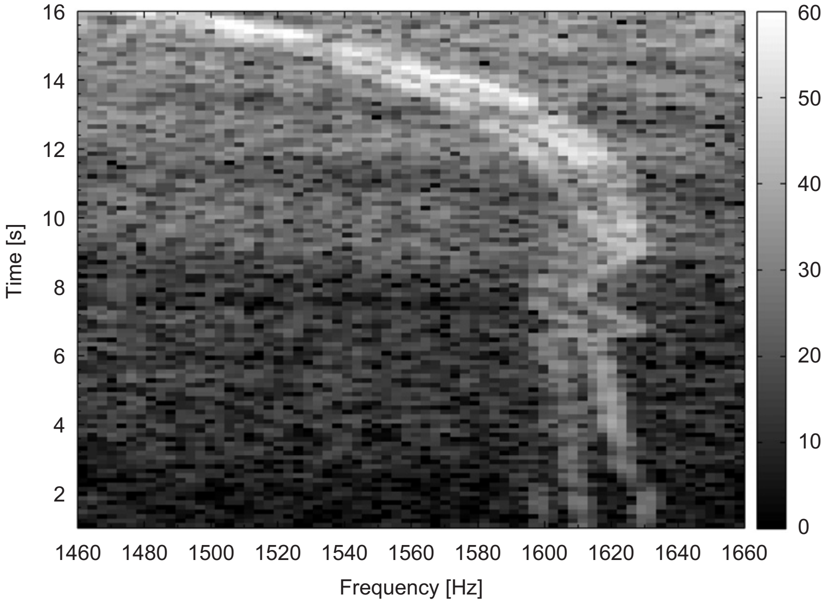

Fig. 4. Recorded time–frequency spectrum that exhibits two tonal components with closely related frequencies, sound pressure level dB (re. 2×10^{-5} Pa).

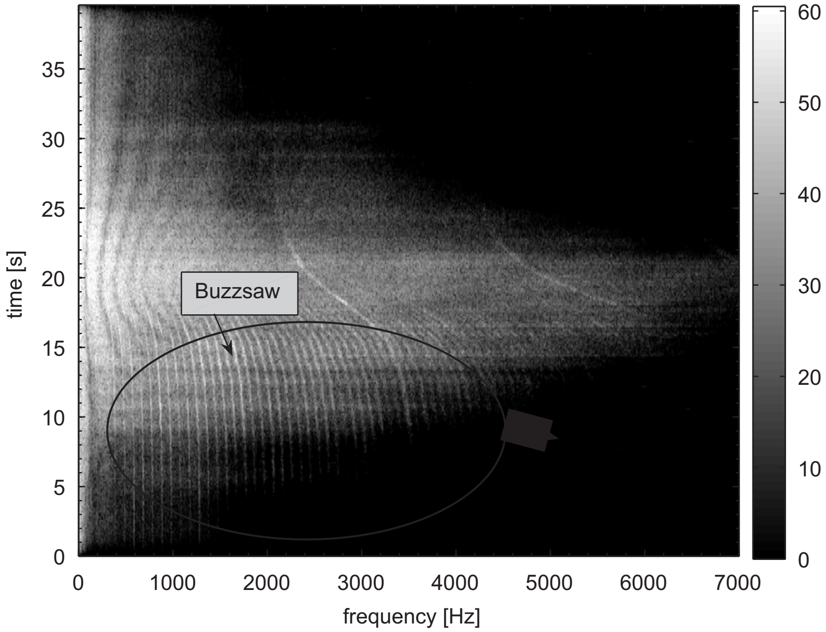

Fig. 5. Time–frequency spectrum exhibiting the buzzsaw effect, recorded during take-off, sound pressure level dB (re. 2×10^{-5} Pa).

visible in Fig. 3 for frequencies below 3000 Hz. The destructive interference valleys indicated in Fig. 3 are curved because the position of the aircraft with respect to the microphone changes with time.

3. Synthesis method

Fig. 6 shows an overview of the developed synthesis method for aircraft noise as perceived on the ground. The method starts with the calculation of a time–frequency spectrum for each of the captured sounds, see Section 2.1. No additional information about the aircraft or the trajectory of flight is available, the synthesis is based on the recorded sound fragment only.

To reach a realistic aircraft sound synthesis with equivalent perceived sound quality compared to the measured sound, it was found necessary to reconstruct all tonal components, broadband noise and the interference pattern up to about 10 kHz. Although humans can hear noise up to approximately 20 kHz, the 10 kHz threshold appeared to be sufficient due to several masking effects that occur and the fact that there is almost no energy left in the sound above 10 kHz. This section explains how each component has been synthesized.

3.1. Tonal components

To obtain a correct synthesis of a tonal component, both its frequency (Section 3.1.1) and amplitude (Section 3.1.2) have to be reconstructed correctly in function of time. Special care must be taken in case the frequency of the tonal component is modulated over more than 10 Hz (Section 3.1.3). The final synthesis of each tonal component is done as a sine with time varying amplitude and frequency [16].

3.1.1. Time–frequency behaviour

As can be seen in Figs. 3 and 5, all tonal components exhibit a curved shape in the time–frequency spectrum. This curved shape is introduced by the Doppler effect. In the Doppler formula, Eq. (2), f_o is the frequency in Hz measured at the position of the observer, f_b is the broadcasted frequency in Hz, c is the speed of sound in the propagation medium in m s^{-1} and c_{so} is the speed of the source in the direction of the observer in m s^{-1}. In the developed synthesis method, the value of c is always chosen to be the value of the speed of sound in air

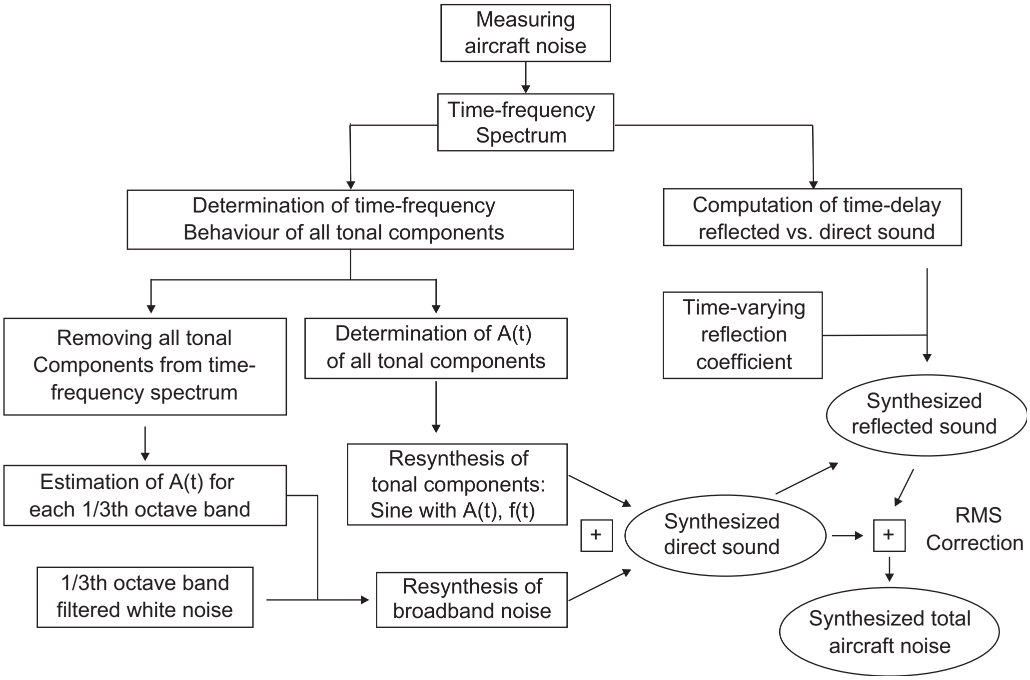

Fig. 6. Overview of the developed synthesis method.

at 20 °C, i.e., $c = 343\,\mathrm{m\,s^{-1}}$:

$$f_o = f_b \frac{c}{c - c_{\mathrm{so}}}. \tag{2}$$

Eq. (2) cannot be used directly to calculate the Doppler shift in the proposed synthesis. No information about the trajectory of flight is available and hence the speed c_{so} of the aircraft towards the observer (i.e. the microphone here) is not known in practice. In the implementation used here, the user describes the frequency vs. time behaviour of a single tonal component by indicating some points of the component in the time–frequency spectrum. The time–frequency behaviour of this tonal component is derived from the indicated points by performing a low-pass interpolation. The obtained curve is then corrected at each discrete time step by searching for higher amplitudes at spectral lines in the neighbourhood of the original curve in the time–frequency spectrum. In case higher amplitudes are found, the frequency is corrected (the frequency of the spectral line with the highest amplitude is retained). The speed of the aircraft towards the observer in function of time, $c_{\mathrm{so}}(t)$, is derived from this corrected curve by using the Doppler formula of Eq. (2). After marking the behaviour of this first tonal component in the time–frequency spectrum, the user marks one additional point for each additional visible tonal component in the spectrum and together with the inferred speed of the aircraft towards the observer the frequency vs. time behaviour of all other tonal components are calculated. Tonal components that are not visible in the time–frequency spectrum are not considered because it is assumed that those components do not contain enough energy to be perceived by a human observer. This assumption did not lead to any audible inaccuracies in the synthetic sounds.

3.1.2. *Amplitude in function of time*

Once the frequency vs. time behaviour of each visible tonal component is known, the amplitude of each tonal component in function of time can be estimated. The information available in the time–frequency spectrum (Section 2.1) is not sufficient for the amplitude estimation of the tonal components due to a too low time resolution in this spectrum. Fig. 7 summarizes the procedure for the estimation of the tonal amplitude in function of time, starting from the recorded time signal of the noise. The discrete short time Fourier transform (DSTFT) is used for a first estimate of the tonal amplitudes; afterwards a correction is performed.

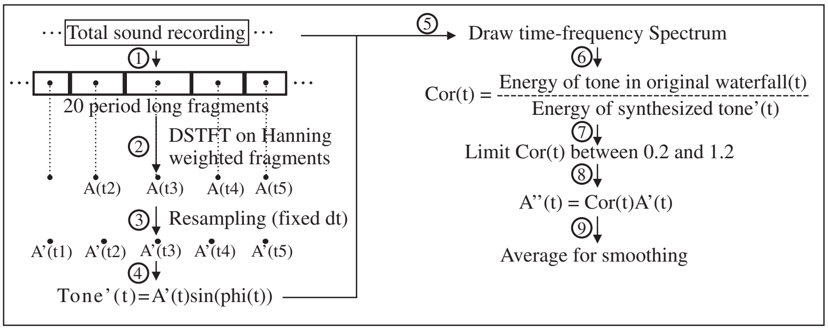

Fig. 7. Determination of the amplitude of a tonal component in function of time.

In a first step, the total sound recording is split into fragments with a length of 20 periods of the tonal component. The fragments will be of different length, expressed in seconds, since the frequency of the tone to be estimated varies with time. The value 20 is chosen based on experience, the maximal frequency shift of the tonal components will be less than 1 Hz over these 20 periods for all sounds considered. In a second step, the amplitude of the tonal component at time t_n is calculated as the modulus of the DSTFT calculated on the 20 period long Hanning windowed time fragment around t_n. Eq. (3) formulates the STFT of $x(t)$ in the continuous domain [20]. In this equation, $x(t)$ is the time signal and $w(t)$ is a weighting function. The STFT can be interpreted as a "sliding window continuous time Fourier transform (CTFT)". The idea is to isolate the signal in the vicinity of time τ, then perform a CTFT analysis in order to estimate the 'local' frequency content at time τ. Eq. (4) gives the formulation of the DSTFT of $x(n)$, when frames with a constant length are considered. In this equation, m is the frame index, S is the number of samples advanced between frames and $w(i)$ is a weighting function. Since the frequency of the tonal component varies here, the fragments have no constant length in time which means a DSTFT with frames of different length is used here. Eq. (5) gives the expression for the DSTFT as it was used here. In this equation, x is the measured sound signal and h is the chosen weighting function, i.e. a Hanning weighting, Eq. (1). Eq. (6) indicates the number of data points in each 20 period fragment, with $f_s = 44.1\,\text{kHz}$ the sample frequency of the signal and $\lceil(x)$ denoting the smallest integer value larger than x. The choice of the window used in the DSTFT determines the trade-off between time vs. frequency resolution. The use of wider windows will give better frequency resolution but worse time resolution and vice versa. Here, no overlap is used between the fragments, the amplitude is estimated once every 20 periods. The signal is resampled in step 3 in order to achieve amplitude values at equidistant moments in time. In the next step, a tone is synthesized with the estimated amplitudes and frequency in function of time.

$$\mathrm{STFT}\{x(t)\} = X(\tau,\omega) = \int_{-\infty}^{\infty} x(t)w(t-\tau)\exp(-\mathrm{j}\omega t)\,\mathrm{d}t, \tag{3}$$

$$\mathrm{DSTFT}\{x(n)\} = X[m,k] = \sum_{i=0}^{N-1} x[i+mS]w(i)\exp(-\mathrm{j}2\pi k N^{-1} i), \tag{4}$$

$$X[m,k] = \sum_{i=0}^{N(m)-1} x\left[i + \sum_{p=1}^{m-1} N(p)\right] h(i)\exp(-\mathrm{j}2\pi k (N(m))^{-1} i), \tag{5}$$

$$N(m) = \left\lceil \left(\frac{1}{f(m)}20f_s\right)\right. . \tag{6}$$

These energy-based amplitude calculations give only an indication, not an entirely correct value of the amplitude in function of time for the following reasons: (I) they are function of the frequency resolution, (II) they are DSTFT based while the signal is not stationary, (III) they are erroneous if neighbouring broadband frequencies are playing a non-negligible role in the energy calculations. Therefore, an additional time dependant correction factor is introduced. The value of the correction factor is achieved by division of the energy of the tone in the original recording through the energy of the tone synthesized in step 4, based on the information in their time–frequency spectra (steps 5,6). The width of the tones along the frequency axis varies in time and plays obviously an important role in the energy calculations. The width is considered to be proportional with the slope of the tonal component in the time–frequency spectrum, with a minimum width of 10 spectral lines. Based on experience, the correction factor is limited between 0.2 and 1.2 in a next step. The corrected amplitude of the tone is then found as the product of the amplitude before correction and the limited correction factor (step 8). Since the resulting time signal is too nervous an additional averaging was performed (step 9).

3.1.3. Frequency modulation

Analysis of the measured sounds revealed that the frequency of the tonal components is often not stationary, on top of the doppler-frequency shift. The reason for this can be diverse, e.g. small RPM variations in only one engine. When 2 tonal components (often originating from different engines as previously shown in Fig. 4) have nearly the same frequency, they can interfere in the spectrum. A detailed study of the physical reasons of the frequency modulation or the slight variation in frequency between tones originating from different engines goes beyond the scope of this research, but a solution for a high-quality sound synthesis is provided. When the frequency of a tonal component is modulated over a frequency interval larger than 10 Hz, an additional operation is executed on the time–frequency behaviour derived in Section 3.1.1 to simulate this effect. Different techniques, like e.g. adding sine signals of various frequencies have been tried, but finally adding white noise (filtered with a low-pass filter up to maximal 100 Hz) to $f(t)$ came out as the best solution for an adequate synthesis. The amplitude of the added noise determines the amplitude of the frequency modulation effect and this can be adapted for each individual component to achieve the best results.

3.1.4. Buzz-saw components

Buzz-saw components are synthesized in a very similar way compared to the above discussed ‘conventional’ tonal components. Because of the small spacing between the buzz-saw components however, the amplitude estimation of a buzz-saw component can be wrongly influenced by some of its neighbouring components. The higher frequency resolution needed for the estimation of the amplitude can only be achieved with longer fragments. This is why 100 (not 20) periods of the buzz-saw component are used for the amplitude estimation; the amplitude of the buzz-saw components is only estimated once every 100 periods. Further extension of the fragments is not advisable since the noise is not stationary. Buzz-saw noise is very tonal and it has been observed that it is not critical to determine fluctuations in the amplitude of the sound pressure of these components with a rate higher than once every 100 periods [16].

3.2. Broadband noise

The part of the spectrum which does not belong to tonal components is considered to be broadband noise. In Fig. 3 for example, the tonal components are visible as light, curved lines in the spectrum; the rest of the spectrum is broadband noise. Broadband noise is synthesized in third-octave bands in analogy with the human hearing system. As such, only the amplitude in function of time has to be known for each frequency band, see Fig. 6.

The amplitude of the broadband noise in each third-octave band in function of time is determined based only on the energy information in the time–frequency spectrum at that time, Eq. (7). The average energy in band i at time t, $E_{\text{average}}(i,t)$, is calculated as the sum of the energy on all spectral lines in band i not covered by a tonal component at time t, scaled with the ratio of the total number of spectral lines in the band, i.e. $N_1(i)$, and the number of spectral lines in the band not covered by a tonal component at time t, i.e. $N_2(i,t)$. The energy of the tonal components is omitted in the calculation of the average broadband energy in the octave band since it is impossible to discriminate between the contribution of the tonal component and the broadband noise component. The synthesis of the broadband noise is accomplished by filtering white noise with the correct band pass filters and shaping the amplitude of the signal in function of time. Butterworth filters are used to perform the filtering because of the smooth characteristics of these filters and the flat magnitude response in the pass band [16]. Finally, all third-octave band syntheses are summed together to obtain the total sound synthesis of the broadband noise.

$$E_{\text{average}}(i,t) = \frac{N_1(i)}{N_2(i,t)} \sum_{k=1}^{N_2(i,t)} E\ (\text{spectral line } k,\ \text{time } t). \tag{7}$$

3.3. Interference pattern

Smith showed that the interference pattern in aircraft sounds is caused by reflections on the ground [21]. Formula (8) and (9) give the frequencies in Hz at which constructive, respectively, destructive interference occurs. In both formula, c is the speed of sound in the propagation medium in $\mathrm{m\,s^{-1}}$ and Δl is the path length difference between the direct and the reflected sound in m. In the developed synthesis method, the value of c is treated as a constant, equal to the value of the speed of sound in air at 20 °C, i.e. $c = 343\,\mathrm{m\,s^{-1}}$.

$$f_{\text{con},j} = j\frac{c}{\Delta l} \quad \text{with } j = 1,2,3,\dots\ , \tag{8}$$

$$f_{\text{des},k} = \left(\frac{1}{2}+k\right)\frac{c}{\Delta l} \quad \text{with } k = 0,1,2,3,\dots\ . \tag{9}$$

Figs. 3 and 5 show both the time and frequency dependence of the interference pattern. To be able to resynthesize the interference pattern, the time delay of the reflected sound with respect to the direct sound in function of time has to be known, see Fig. 6. In addition, information about the reflection characteristics of the reflecting ground is needed.

The required time delay between the direct and the indirect sound is inferred from the time vs. frequency behaviour of one interference valley in the time–frequency spectrum, since no information about the trajectory of flight is available in this research. In the implementation used here, the user marks the behaviour of one destructive interference valley by marking some points of that valley. A polynomial is fitted through the indicated points and this polynomial is used for further synthesis. Order 15 was chosen since this resulted in the best visual agreement between the polynomial and the interference valley in the spectrum. Since sound quality equivalent syntheses were achieved (see Section 4.2), there was no need to change the order in the end. The ground curve of the interference pattern ($k = 0$ in formula (9)) is inferred from this polynomial, with the knowledge that the microphone is positioned 1.2 m above ground level and the fact that all aircraft pass almost right above the microphones. This means $f_{\text{des},0} \approx (\frac{1}{2}+0)\frac{343}{2.4} = 71.5\,\text{Hz}$ at flyover because the path length difference Δl is about 2.4 m at flyover (twice the height of the microphone). Formula 9 provides an easy way to calculate the path length difference in function of time when the frequency of a destructive interference valley in function of time is known. The time delay between the ground reflected sound and the direct sound is calculated by simple division of the time dependent path length difference through the speed of sound in the propagation medium.

Figs. 3 and 5 show that the interference pattern is no longer visible at higher frequencies due to the absorption characteristics of the air and the ground. It became clear throughout the research that the frequency dependence of the interference pattern is not that critical to reach high synthesis quality. The time dependence of the interference pattern on the other hand is more critical and can certainly not be neglected. The time dependence is caused by the reflection coefficient dependency on the angle of wave incidence. Since the aircraft is moving with respect to the microphone, the angle of incidence is constantly changing resulting in a time dependant reflection coefficient. To integrate in the sound synthesis the frequency dependence of the reflection characteristics of the ground, a transition region is identified by the user. Below this transition zone the interference is clearly visible and above it the interference is no longer observable. The frequency variation of the reflection coefficient of the ground is modeled by the two simple weighting functions, shown in Fig. 8. More complex models for the synthesis of the frequency dependence of the reflection characteristics of the ground are not necessary to reach a sufficient quality of the synthesized sound, see Section 4.

The variation of the angle of incidence over time due to the movement of the aircraft, together with the angle dependence of the reflection coefficient of the ground is considered as a time dependency of the reflection coefficient of the ground. On the low-frequency part of the sound, an interference pattern is modeled by using

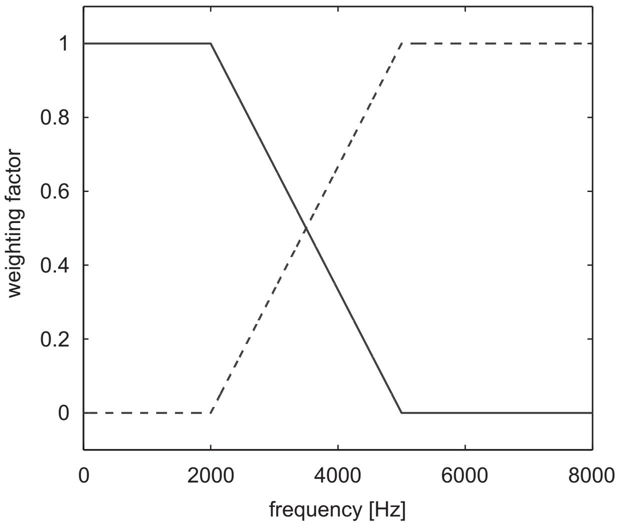

Fig. 8. Weighting factors for the interference pattern synthesis. ——— Weighting for the interference part - - - - weighting for the no interference part.

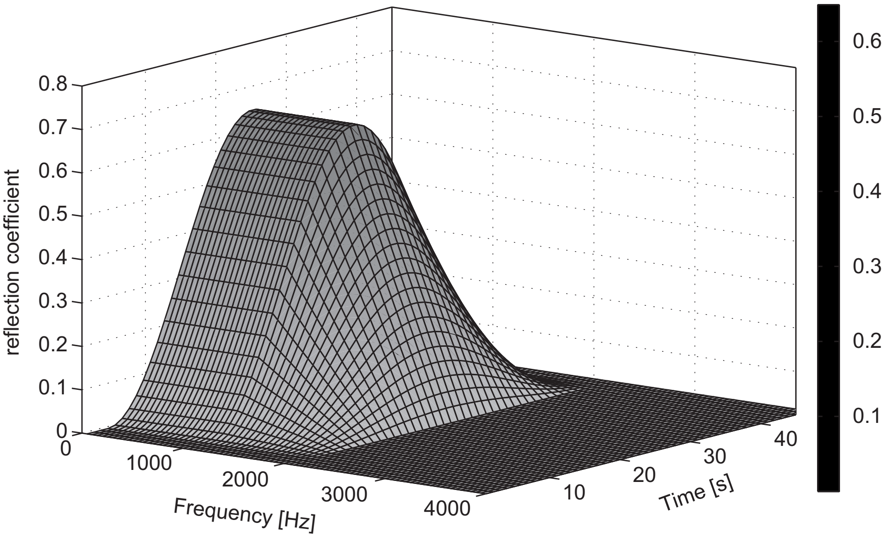

Fig. 9. Assumed behaviour of the reflection coefficient (both time (varying reflection angle because of movement of the aircraft) and frequency dependent).

this time dependent reflection coefficient and the time dependent time delay derived earlier. The proposed synthesis method avoids the measurement of the reflection coefficient and assumes this time dependency to be Hanning (Eq. (1)) shaped. The reflection coefficient used in the developed synthesis method has a shape as shown in Fig. 9, which shows both the time and frequency dependence of the reflection coefficient. Besides Hanning curves, some other curves like, e.g. Hamming, Blackman, … were briefly tested but this did not result in better syntheses. Since sufficient synthesis quality was achieved with the proposed synthesis method (see Section 4.2), the Hanning shape was retained.

To synthesize the interference pattern on the low-frequency part of the sound, both a direct and a reflected signal must be synthesized. Note that, multiple reflections together with reflections on other obstacles besides the ground have not been considered in this synthesis. The syntheses of the broadband noise and the tonal components are weighted with the solid line of Fig. 8. It is assumed that direct and reflected sound are of equal amplitude before the reflection. The reflected sound is obtained by applying a proper time delay and amplitude weighting to the direct sound. Afterwards, both these sounds are summed together and finally, the root mean square (rms) of the amplitude of this summed signal is made equal to the rms of the amplitude of the measured signal to reach the final low-frequent sound synthesis, see Fig. 6. This amplitude correction is needed since part of the sound is absorbed in the reflection. The high-frequent part of the sound is also synthesized and added to the low-frequent part in order to achieve the final sound synthesis.

4. Validation

The validation chapter contains 2 sections, i.e. a pretest section and a main experimental section. The pretest described in Section 4.1 identifies the main manipulators in the sound quality of aircraft sounds. The main validation test, described in Section 4.2, proves the performance and validity of the developed synthesis method to create aircraft sound syntheses that are from a sound quality perspective equivalent with real measured aircraft sound.

4.1. Pretest: sound quality of aircraft sounds

An initial jury test was performed to identify the most annoying components in aircraft noise. Later on, the development of the synthesis method (Section 3) was based on these findings. This test makes no use of the developed synthesis method yet, only real measured sounds are used. In the future, more detailed studies towards sound quality of aircraft sounds can be performed by using the outlined aircraft sound synthesis method evaluated in the main test (Section 4.2).

4.1.1. Acoustical material

During the execution of the SEFA project [1], researchers measured the noise of 87 events of 45 different types of passenger aircraft. The measurements took place in Germany during 3 successive days in August 2004. The recordings include the noise of 50 take-offs, 34 approaches and 3 fly-overs. All fragments are recorded according to annex 16 of the International Civil Aviation Organization convention. Out of these recordings, a team of 8 international experts selected a group of 15 sounds of aircraft during approach and 17 sounds of aircraft during take off. The 32 sounds originate from 23 different type of aircraft. All these recorded sounds were converted to sounds with an equivalent loudness of 89.5 EPNdB to emphasize the quality of the sounds rather than the loudness. Within the SEFA project [1], there exist strict agreements not to mention the types of the aircraft and hence all sounds are numbered in this text and only some general features of the aircraft can be given, see Tables 2 and 3for the sounds used in the discussion of both tests. The sounds had a duration in between 40 and 70 s.

4.1.2. Subjects

The jury consisted of 12 male and 9 female listeners between 16 and 55 years old, all with normal hearing (self-reported, not tested). The average age of the group was 27.6 years.

4.1.3. Experimental design

All 21 members of the jury performed the test independently and could listen to all sounds as much as desired to formulate an opinion. Because of the long duration of the test, the sounds were presented to the jury by the use of a two-speaker system [27,28]. The test was performed in an office environment with background levels below 40 dB (re. $2E^{-5}$ Pa). Both speakers have a measured frequency response which is flat up to ±4 dB in between 60 Hz and 20 kHz. The amplifier has a total harmonic distortion of 0.8% (40 Hz–20 kHz, both channels driven 100 W per channel (8 Ω)). After the judgment of the sounds of approaching aircraft, the test was paused for half an hour before continuing with the take-off sounds. Both parts of the test took about 45 min to complete and the playback device was controlled by the experimenter.

Table 2
Rough description of the spectra of the sounds (approach) used in the pretests

Aircraft (AP)	8	11	12	13	22	23
Size	Large	Large	≈ Largest	Medium	Small	Small
Engine	Jet	Jet	Jet	Propeller	Jet	Jet
Tonal components (frequency without doppler)	(loud) ≈ 1000 Hz ≈ 1300 Hz ≈ 2000 Hz – (quiet) ≈ 3000 Hz ≈ 5000 Hz ≈ 6000 Hz	(quiet) ≈ 2000 Hz ≈ 4000 Hz	(loud) ≈ 2000 Hz ≈ 4000 Hz ≈ 6000 Hz – (quiet) ≈ 7000 Hz – Frequency modulation >100 Hz	(loud) ≈ 50 Hz ≈ 100 Hz ≈ 150 Hz ≈ 200 Hz ≈ 250 Hz ≈ 1000 Hz – (quiet) ≈ 5000 Hz	(quiet) ≈ 500 Hz ≈ 1000 Hz ≈ 2000 Hz	(quiet) ≈ 2500 Hz ≈ 5000 Hz
Broadband noise >40 dB	Up to ≈ 7000 Hz	Up to ≈ 7000 Hz	Up to ≈ 10,000 Hz	Up to ≈ 7000 Hz	Up to ≈ 10,000 Hz	Up to ≈ 10,000 Hz
Broadband noise >0 dB	Up to ≈ 10,000 Hz	Up to ≈ 10,000 Hz	Up to ≈ 15,000 Hz	Up to ≈ 10,000 Hz	Up to ≈ 15,000 Hz	Up to ≈ 15,000 Hz
Interference pattern	Very clear up to ≈ 3500 Hz	Very clear up to ≈ 2000 Hz	No strong interference pattern	Clear up to ≈ 3000 Hz	Clear up to ≈ 2000 Hz	Clear up to ≈ 3000 Hz

Table 3
Rough description of the spectra of the sounds (take-off) used in the pretests

Aircraft (TO)	8	11	12	13	22	23
Size	Large	Large	≈ Largest	Medium	Small	Small
Engine	Jet	Jet	Jet	Propeller	Jet	Jet
Tonal components (frequency without doppler)	(loud) ≈ 2800 Hz	(Very loud) ≈ 2600 Hz ≈ 5200 Hz	(loud) ≈ 2000 Hz ≈ 4000 Hz – (quiet) ≈ 6000 Hz	(Very loud) ≈ 50 Hz ≈ 100 Hz ≈ 150 Hz – (loud) ≈ 1800 Hz	(quiet) ≈ 500 Hz ≈ 1050 Hz ≈ 2100 Hz ≈ 3200 Hz ≈ 4200 Hz ≈ 5500 Hz	(quiet) ≈ 3400 Hz
Buzz-saw	Loud	Loud	Loud	No	Quiet	No
Broadband noise >40 dB	Up to ≈ 4000 Hz	Up to ≈ 6000 Hz	Up to ≈ 8000 Hz	Up to ≈ 3000 Hz	Up to ≈ 5000 Hz	Up to ≈ 4500 Hz
Broadband noise >0 dB	Up to≈ 5500 Hz	Up to ≈ 10,000 Hz	Up to ≈ 15,000 Hz	Up to ≈ 7000 Hz	Up to ≈ 10,000 Hz	Up to ≈ 6000 Hz
Interference pattern	Very clear up to ≈ 2000 Hz	Clear up to ≈ 1000 Hz	Very clear up to ≈ 2000 Hz	Very clear up to ≈ 1000 Hz	Clear up to ≈ 5000 Hz	Very clear up to ≈ 6500 Hz

4.1.4. Scaling

In this test, all 32 sounds were compared with a reference sound, one for take-off (0TO) and one for approach (0AP). The characteristics of both reference sounds are shown in Table 4. The reference sounds were

Table 4
Rough description of the spectra of the reference sounds used in the pretests

	Size	Engine	Tonal components	Broadband >40 dB	Broadband >0 dB	Interference pattern
Reference approach	Large	Jet	(loud) ≈ 2200 Hz ≈ 4400 Hz	≈ 7000 Hz	≈ 8000 Hz	Clear up to ≈ 2000 Hz
Reference take-off	Large	Jet	–	≈ 3500 Hz	≈ 4500 Hz	Very clear up to ≈ 3000 Hz

Table 5
Comparison of the sounds of 15 aircraft during approach with a reference sound (0AP), by 21 test persons

Sound (AP)	4	5	8	9	11	12	13	15	16	17	18	19	20	22	23
Person 1	−1	−1	0	1	0	−3	−2	2	1	−2	0	−2	0	3	1
Person 2	−3	0	−2	2	−3	1	−2	3	−1	−3	1	1	−2	3	2
Person 3	−1	0	1	0	1	−2	−1	2	−2	0	−2	1	−1	0	2
Person 4	2	−1	1	1	2	1	−1	2	3	−2	3	2	0	−3	−3
Person 5	−2	1	1	2	−1	−2	0	0	2	−3	0	−2	−1	0	1
Person 6	0	0	1	1	0	−1	−1	2	−1	0	0	−1	−1	1	2
Person 7	−1	−2	−1	0	−1	1	−1	0	−2	−2	0	−1	−2	−3	−2
Person 8	−3	2	0	−2	0	−3	−1	3	−1	−2	−2	−1	1	2	2
Person 9	2	−1	3	0	−1	−3	−2	2	1	−2	2	1	0	2	−2
Person 10	−1	0	2	0	2	−2	−1	2	1	−1	0	−1	−1	1	0
Person 11	−2	−1	0	−2	1	−1	−2	1	0	−1	2	1	2	2	1
Person 12	1	−2	0	0	−1	−3	1	2	−2	0	−2	−1	1	2	1
Person 13	−1	0	0	0	2	−2	−2	2	2	−3	−1	−2	2	−2	−1
Person 14	2	0	3	3	1	1	−2	3	−1	−2	−1	−2	2	−1	−1
Person 15	−2	0	−1	1	1	0	0	−1	0	−2	0	1	0	2	3
Person 16	0	0	1	0	2	−2	−2	1	−1	−1	1	−1	0	1	2
Person 17	−2	−2	−1	1	1	0	1	3	1	−2	0	−2	2	2	2
Person 18	−1	0	1	1	−1	2	−1	1	−1	2	1	0	−1	3	3
Person 19	0	−1	−1	1	0	0	−1	0	0	−1	0	−1	−2	2	1
Person 20	1	0	−1	0	0	0	2	0	1	0	0	1	0	−1	−2
Person 21	0	0	1	1	2	−2	−1	1	1	−1	1	−1	−1	0	0

The range of the scale was $[-3, 3]$, -3 denoting 'much less pleasant' and $+3$ denoting 'much more pleasant' compared to the reference sound.

always repeated for each comparison, without the ability to skip listening to the reference sounds. Each member of the jury had to give a score in between -3 and 3 (integer numbers) for each comparison. The score -3 means that the sound quality of the test sound is much worse compared to the sound quality of the reference sound, 0 means they have the same sound quality and $+3$ means the sound quality of the test sound is clearly superior to the sound quality of the reference signal. The reference sounds were selected from the set of SEFA sounds by the group of experts described above. The aim was to select neutral sounds.

4.1.5. Description of the data

Tables 5 and 6 give an overview of the answers given by the jury. The 2 tables give the results of the comparison of 15, respectively 17, sounds with the according reference sound.

4.1.6. Discussion

Subject bias, i.e. the fact that some subjects tend to use different parts of scales, occurs often when simple scales like the one here are used. Some people score more severe than others, others are more generous. To overcome this problem, the judgments from each particular subject are first made to have a mean of 0 and a

Table 6
Comparison of the sounds of 17 aircraft during take-off with a reference sound (0TO), by 21 test persons

Sound (TO)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	21	22	23
Person 1	2	−2	2	−1	1	−1	2	−2	2	−2	−2	0	−2	−2	2	0	0
Person 2	−1	−2	2	−2	1	−1	−3	−2	1	1	2	−1	1	−2	−1	2	3
Person 3	−2	−2	0	−1	−1	−2	0	−2	−3	−1	−1	−2	−3	−2	0	0	1
Person 4	3	−3	−2	−2	1	−2	2	−3	3	3	0	3	−1	−3	3	−2	1
Person 5	1	−3	1	−2	−1	0	1	−2	−3	−1	0	−1	0	−2	−1	0	2
Person 6	−2	−1	1	1	−3	−3	−1	−1	−2	−2	−1	1	−1	−3	0	2	1
Person 7	1	−1	−2	−3	0	−2	−2	−3	−3	−2	−2	−3	−3	−1	−2	−2	−2
Person 8	−1	−3	1	−3	1	−3	2	−3	1	−2	−3	−2	−1	−2	−2	3	1
Person 9	0	−2	2	−2	0	−2	2	−2	−1	0	−3	0	−1	−2	−3	2	2
Person 10	−1	−2	0	−1	−1	−1	0	−2	−2	−1	−3	−2	−3	−3	−1	−1	−1
Person 11	−1	−2	−1	−1	−1	−1	−2	−2	1	−1	−3	0	−1	−2	1	1	0
Person 12	0	−1	0	0	−1	0	0	2	−2	1	−1	1	2	2	−2	−1	0
Person 13	0	−2	1	1	−1	−1	2	−1	−2	2	1	0	0	−1	0	1	−1
Person 14	0	−2	0	−3	−2	0	−1	−2	−2	−1	−3	−1	−1	−3	−2	−1	2
Person 15	−2	1	0	0	2	0	0	0	−1	−2	−1	1	−1	1	0	1	1
Person 16	−1	−3	0	−2	−1	−2	1	−3	−2	−1	−3	−3	−2	−2	0	0	−1
Person 17	0	−1	0	−1	0	0	0	−2	−3	1	−2	−1	−1	−2	1	−1	2
Person 18	−2	−3	−1	0	−1	−2	−2	0	1	−1	−2	−2	−1	−3	0	1	−1
Person 19	1	−1	0	1	−3	−1	1	−2	−1	1	−1	−2	−1	−2	−2	−1	−1
Person 20	−1	0	−2	1	−1	0	−1	−1	−1	0	−2	0	0	−1	−3	0	−2
Person 21	−1	−2	0	−2	−1	−2	−1	−1	−2	−1	−2	−2	−2	−3	−1	−2	−1

The range of the scale was [−3, 3], −3 denoting 'much less pleasant' and +3 denoting 'much more pleasant' compared to the reference sound.

Table 7
Tukey grouping of the 15 sounds of approaching aircraft

Aircraft	15	**22**	**23**	9	**11**	**8**	18	16	20	5	4	19	**13**	**12**	17
Group A	A	A	A	A	A	A	A								
Group B		B	B	B	B	B	B	B	B	B	B	B			
Group C					C	C	C	C	C	C	C	C	C	C	
Group D								D	D	D	D	D	D	D	D

Sounds within the same group have means that are not significantly different.

standard deviation of 1. A one-way ANOVA analysis proves that the differences in the rescaled scores between the different aircraft sounds are much larger compared to the differences in the scores of the same aircraft sound between the 21 different jury members. A Levene's test was first performed to check the homogeneity of variances in the data, which is an assumption for the ANOVA-test. For the approaching sounds, this test was not able to prove this homogeneity and hence, a Welch-ANOVA instead of an ANOVA analysis was performed for these sounds. Remark however that the results did not differ from the results of the normal ANOVA test. The F-value for the null-hypothesis that no difference exists between the scores of the different aircraft sounds, is 6.58 for the approach sounds and 6.25 for the take-off sounds. In both cases, the p-value for the null-hypothesis is smaller than 0.0001, which means this hypothesis can be rejected and a significant difference between the scores of the different aircraft exists. Afterwards, a Tukey test was performed to divide the data in groups with significant different means. Tables 7 and 8 show the results of this Tukey grouping, the sounds that are reused in the second pretest are indicated in bold. Sounds within the same group have mean scores that are not significantly different. Figs. 10 and 11 show the final results of this jury test, with the ranking of the sounds. The more positive the score, the better the quality of the sound and vice versa. The discussion and formulation of the conclusions in this paragraph is based on the 12 sounds of 6 aircraft used in the main validation test. A description of some general features is given in Tables 2 and 3.

Table 8
Tukey grouping of the 17 sounds of aircraft during take-off

Aircraft	**23**	3	**22**	7	1	10	5	21	**12**	4	**13**	6	9	**8**	**11**	2	14
Group A	A	A	A	A	A	A	A	A	A	A							
Group B		B	B	B	B	B	B	B	B	B	B	B					
Group C			C	C	C	C	C	C	C	C	C	C	C				
Group D					D	D	D	D	D	D	D	D	D	D	D		
Group E						E	E	E	E	E	E	E	E	E	E	E	
Group F							F	F	F	F	F	F	F	F	F	F	F

Sounds within the same group have means that are not significantly different.

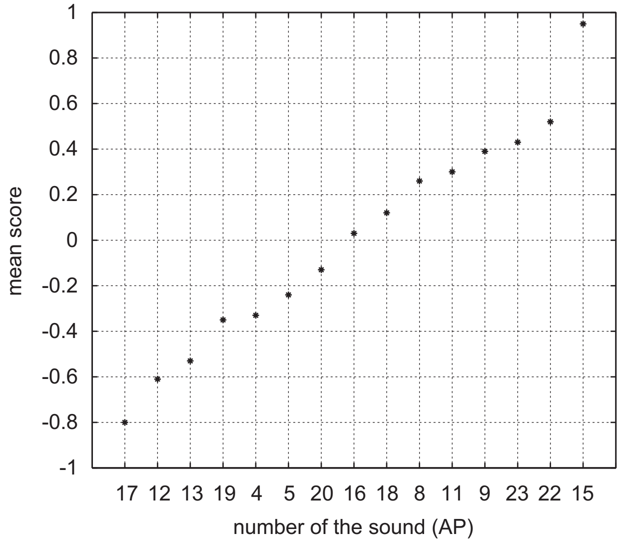

Fig. 10. Mean score of 15 sounds of approaching aircraft by 21 test persons on a scale [−3, 3]. −3 denotes ‘a much worse quality compared to the reference sound’, +3 denotes ‘a much better quality compared to the reference sound’.

In case of an approaching aircraft, both the loudness and the frequency of the tonal components have a clear influence on the results of the jury test. Sounds 12AP and 13AP contain a lot of loud tonal components and have a bad quality according to the jury. Sounds 22AP and 23AP do not contain loud tonal components and their sound quality is rated significantly higher. The tonal components of sound 12AP are smeared out over a large frequency region in the visual representation of the time–frequency spectrum and a short talk after the test revealed that a lot of the jury members perceive this sound as ‘dirty’. Nor the appearance of broadband noise, nor the results of the characteristics of the interference pattern can explain the results of the jury test which means those features do not have a dominant influence on the perceived sound quality. The sound quality of aircraft during approach is mainly determined by the presence or absence of tonal components. The jury perceives loud tonal components above 4000 Hz as extremely annoying.

This jury test further reveals that the sound quality of aircraft noise during take-off is primarily dominated by the presence or absence of loud buzz-saw components. Sounds 23 and 22 have a significantly higher sound quality compared to sounds 8 and 11, according to the jury (see Table 8). Sounds 8TO, 11TO and 12TO contain loud buzz-saw components and have a bad quality according to the jury. The louder these components, the more annoyance is experienced. The buzz-saw components in sound 22TO are not loud and this explains the rather good perceived quality of this sound, see Fig. 11. Sound 23TO does not contain buzz-saw and this sound has a very good quality according to the jury. The presence of conventional tonal components is perceived as a secondary source of annoyance only. Sound 13TO contains 3 very loud, rough tonal components and is therefore considered to have a bad quality. Sound 23TO only contains one, the least

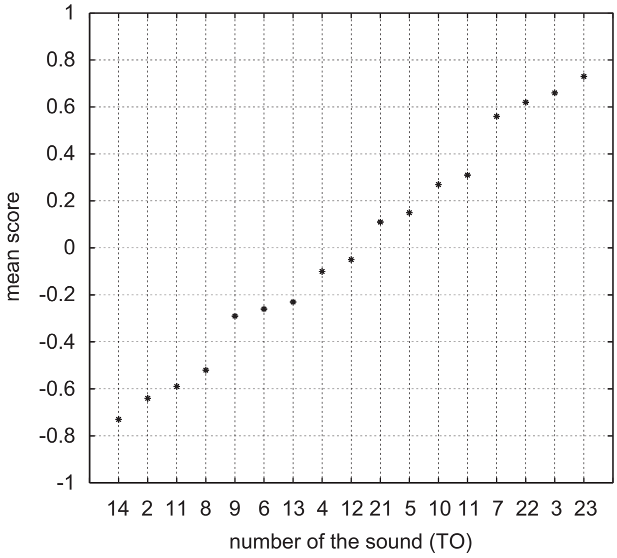

Fig. 11. Mean score of 17 sounds aircraft during take-off by 21 test persons on a scale $[-3, 3]$. -3 denotes 'a much worse quality compared to the reference sound', $+3$ denotes 'a much better quality compared to the reference sound'.

of all take-off sounds, tonal component around 3400 Hz and the quality of this sound is high. Tonal components with frequencies above 4000 Hz are extremely annoying and the louder the tonal components the more annoyance they cause, especially when they lie in a frequency region with low broadband noise levels. Sound 11TO contains a very loud and annoying tonal component around 5200 Hz on top of the annoying buzz-saw components. This explains the very bad quality of this sound according to the jury. The shape and the visibility of the interference pattern in the time–frequency spectra seem to have no clear effect on the perceived sound quality.

Tonal components in propeller noise have a worse quality compared to tonal components in jet noise, according to the jury. From a short talk after the test, it appeared that not the frequency, but rather the roughness, of the tonal components causes the bad quality of these sounds.

The jury judges that frequency modulation in the tonal components gives a bad quality to the sound. From an informal talk after the test, it appeared that the jury describes these sounds as 'dirty'. Further jury testing will have to reveal more detail about the sound quality of aircraft noise. The influence of sharpness, roughness, frequency and loudness of tonal components can be studied with the use of the presented synthesis method (Sections 3 and 4.2). Note that not only changes to the aircraft itself can be studied. Also changes in absorption characteristics of the ground around the runway, etc. can be analysed with the developed synthesis method.

After performing the jury test, both references appeared to be chosen well, i.e. neutral, since the amount of sounds that were perceived to have a worse sound quality compared to the reference signal is almost equal to the amount of sounds that was rated a better sound quality in both cases. Many people reported that the sounds (40–70 s long) were too long to compare and that the transient behaviour of the sounds makes comparison difficult.

4.2. *Main validation test*

For this test, recorded aircraft sounds were split in their components. Based on these components synthesized aircraft sounds were constructed. Differences between the synthesized and the original measured sounds as heard by a jury of listeners are investigated in order to prove the performance and validity of the developed synthesis method to create aircraft sound syntheses that are from a sound quality perspective equivalent with real measured aircraft sound.

4.2.1. Acoustical material

Out of the aforementioned measurement set of SEFA sounds, the team of 8 experts selected 12 fragments suitable for the validation of an aircraft noise synthesis method. The fragments are representative for the diversity in the fleet of passenger aircraft in the year 2005. The sounds originate from 6 different aircraft and include one recording from an approach and one from a take-off for all 6 aircraft. The sounds are selected such that all representative aircraft noise characteristics are captured in at least one of the fragments. One of the selected aircraft is propeller driven, all others have a jet engine. The time–frequency spectra of the sounds are briefly discussed in Tables 2 and 3.

4.2.2. Subjects

The jury of 21 persons used in the pretest was expanded with 2 persons: one male subject of 52 years old and one female subject of 24 years old. The average age raised to 28.6 years.

4.2.3. Experimental design

Since memory for acoustic details (e.g. tone pitch) fades in less than 10–15 s [23–25], the sounds are divided into fragments of 5 s. Fragments with a maximum sound pressure level below 20 dB (re. $2E^{-5}$ Pa) are not considered. The 71 fragments that were retained for the for the validation of the developed synthesis method were presented to the jury in a random order, though all jury members received the fragments in the same order. All members of the jury performed the test independently and could listen to the sounds as much as desired to form a final conclusion. The playback device was controlled by the experimenter. The professional dynamic closed headphones [26,27] used in this test have a flat frequency response function ranging from 5 Hz to 30 kHz and a total harmonic distortion less than 0.25% @100 dB SPL @1 kHz according to the manufacturer. The jury tests are performed in an office environment with background levels below 40 dB (re. $2E^{-5}$ Pa).

4.2.4. Scaling

The jury was asked to compare the 71 synthesized fragments of 5 s with the corresponding section in the measured sound. Each listener had to give his appreciation with one of the following answers: totally different (TD), different (D), slightly different (SD) or similar (S). The instruction was to use the score S only in the case that absolutely no difference could be perceived between the signals, the score TD is appropriate in all cases with obvious differences between the signals. The responses were assessed with paper and pencil.

4.2.5. Description of the data

Table 9summarizes the results of the jury test for the 12 selected sounds. In total, the jury of 23 persons answered 3 times TD (totally different), 102 times D (different), 503 times SD (slightly different) and 1025 times S (similar).

4.2.6. Discussion

Over 93% of the time the jury rated the correspondence between the synthesized fragment and its measured counterpart as S or SD, see Table 9. The jury detects the most differences for the fragments lasting from second 10 to 15, respectively, second 15 to 20 of the recordings. The aircraft passes the microphone during this period, and hence is closest to the microphone. The amplitude of the sound pressure is high and some tonal components that are not audible during the other periods become audible in this period. As expected, the syntheses are more difficult for these periods as the scores in Table 9 confirm for these fragments.

Remark that the jury detected more differences for sounds 3 and 4 (the only sounds originating from propeller driven aircraft) compared to the other sounds. This indicates the very rough, low-frequency propeller noise needs further research in order to achieve sound quality equivalent syntheses for this kind of aircraft noise. Beside roughness, another reason why propeller noise might not be as adequately synthesized as jet engine sound is the fact that the very-low-frequency tonal components are often embedded in the interference pattern in the time–frequency spectrum, so that both amplitude and frequency determination are harder to accomplish for these components. For those very-low-frequency components it is possible that a sound quality equivalent sound synthesis cannot be reached without additional measurements.

Table 9
Answers (#) of the jury of 23 persons for the 12 selected sounds (71 fragments)

(#)		Sound												Total	Total (%)
		1	2	3	4	5	6	7	8	9	10	11	12	All	All
0–5s	S	14	13	17	18	16	15	17	19	22	21	18	11	201	72.83
	SD	9	9	6	5	6	7	6	4	1	2	5	12	72	26.09
	D	0	1	0	0	1	1	0	0	0	0	0	0	3	0.36
	TD	0	0	0	0	0	0	0	0	0	0	0	0	0	0.00
5–10s	S	8	10	9	13	17	12	15	13	19	14	16	15	161	58.33
	SD	14	11	10	10	6	10	8	9	4	9	7	8	106	38.41
	D	1	2	4	0	0	1	0	1	0	0	0	0	9	3.26
	TD	0	0	0	0	0	0	0	0	0	0	0	0	0	0.00
10–15s	S	10	5	3	5	12	14	9	9	14	9	13	13	116	42.03
	SD	12	13	10	8	7	8	12	12	8	8	10	7	115	41.67
	D	1	5	10	10	4	1	2	2	1	6	0	3	45	16.30
	TD	0	0	0	0	0	0	0	0	0	0	0	0	0	0.00
15–20s	S	14	15	1	15	13	13	8	11	17	8	17	16	148	53.62
	SD	6	8	11	6	9	10	11	8	5	10	5	7	96	34.78
	D	3	0	9	2	0	0	4	4	1	5	1	0	29	10.51
	TD	0	0	2	0	1	0	0	0	0	0	0	0	3	1.09
20–25s	S	13	14	20	17	20	13	8	15	18	18	19	20	195	70.65
	SD	7	8	3	6	3	7	12	7	4	5	3	3	68	24.64
	D	3	1	0	0	0	3	3	1	1	0	1	0	13	4.71
	TD	0	0	0	0	0	0	0	0	0	0	0	0	0	0.00
	S	16	–	20	21	18	19	18	17	12	22	21	20	204	80.63
25–30s	SD	6	–	3	1	5	4	5	6	10	1	2	3	46	18.18
	D	1	–	0	1	0	0	0	0	1	0	0	0	3	1.86
	TD	0	–	0	0	0	0	0	0	0	0	0	0	0	0.00
Total S		75	57	70	89	96	86	75	84	102	92	104	95	**1025**	**62.77**
Total SD		54	49	43	36	36	46	54	46	32	35	32	40	**503**	**30.80**
Total D		9	9	**23**	**13**	5	6	9	8	4	11	2	9	**102**	**6.25**
Total TD		0	0	**2**	0	1	0	0	0	0	0	0	0	**3**	**0.18**

All sounds used in this first evaluation test were only synthesized up to 7079 Hz, the upper limit of the third-octave band with centre frequency 6300 Hz. The reason for this is that all noise fragments used for initial development of the synthesis method exhibited no significant amount of energy above 7000 Hz. However 5 out of the 12 sounds that are used in this first validation test (sounds 1, 2, 7, 8 and 10) did contain one or more 5 s fragments with a significant amount of energy between 7000 and 10,000 Hz. Sound syntheses up to 11,220 Hz may improve the results even further, without changing the basics of the synthesis method. Up to date, no additional jury test was yet performed though and hence this assumption must be checked in a future test.

This validation test proves that the developed synthesis method is adequate for all jet engine aircraft in the fleet of passenger aircraft anno 2005. The very specific buzz-saw noise is adequately synthesized by the developed method and the validations show that the use of complex frequency-dependent ground reflection coefficients is not necessary; the method explained in Section 3 seems adequate. For the adequate synthesis of propeller noise, additional research is needed.

5. Example of an application of the synthesis method

In the framework of effective noise reduction, the importance of research into more efficient aerodynamic designs of certain aircraft components is often emphasized. Airflows around non-aerodynamic components like for example the undercarriage lead to a type of broadband noise that people experience as unpleasant [29].

Aircraft manufacturers put a lot of effort in trying to make, e.g. a less noisy design for the undercarriage. A simulation of existing aircraft with less noisy undercarriage was made with the presented aircraft noise synthesis method. By means of jury testing, it was proven that for some aircraft a reduction of the broadband noise produced by the undercarriage with some dB leads to an increase of the experienced annoyance! The reason for this is that at present, this broadband noise masks certain high-frequency tonal components with even worse quality. A decrease of the broadband noise therefore has a negative influence on the experienced annoyance as long as the more annoying tonal components cannot be reduced. Current research should therefore not focus on reducing this broadband noise without first addressing the necessary progress in other areas. Without an adequate synthesis method for aircraft noise, it would be impossible to draw conclusions like this one in a fast and economic way. Aircraft manufacturers can now evaluate the influence of progress in different areas on the quality of the sound produced by the aircraft and hence, all available resources can be applied more efficiently.

6. Conclusions

A batch of measured aircraft sounds has been evaluated by a jury, as explained in paragraph 4.1. The quality of the sound from an approaching aircraft is mainly determined by the presence or absence of tonal components. Both the loudness and the frequency of the tonal components have a clear influence on the quality of the sound. The louder the tonal components, the more annoyance they cause, especially when the tonal component is not embedded in loud broadband noise. Tonal components with frequencies above 4000 Hz are extremely annoying. The upper frequency up to where meaningful broadband noise is present does not have a direct influence on the sound quality. This limit has only a secondary influence since it can (partially) mask annoying tonal components. Tonal components that are frequency modulated over more than 10 Hz are perceived as dirty and a bad quality is allocated to them.

The sound quality of aircraft noise during take-off is primarily determined by the presence or absence of loud buzz-saw components. The louder the components, the more annoyance is experienced. The presence of conventional tonal components is a secondary source of annoyance only, and the same findings as mentioned for an approaching aircraft are valid.

For both aircraft during take-off and during approach, the characteristics of the interference pattern in the time–frequency spectra have no clear effect on the perceived sound quality.

Based on the performed validation test outlined in Section 4.2, the conclusion can be drawn that the developed synthesis method is adequate for all jet engine aircraft in the fleet of passenger aircraft anno 2005. The presented synthesis method is not able to achieve adequate syntheses for propeller noise yet; additional research is needed to achieve this goal. The very specific buzz-saw noise is adequately synthesized and the validations show that the use of complex frequency-dependant ground reflection coefficients is not necessary. The presented method seems adequate and more efficient. The developed sound synthesis method allows to evaluate the influence of different noise sources on the perceived quality of aircraft noise. From the results of jury tests, the engineer can carry out specific changes to an existing aircraft, based on the a-priory knowledge of the effect of these changes on the quality of the produced noise. In this way, an economic method is developed to evaluate a lot of possible design alternatives and a target sound for future aircraft design can be developed. The new aircraft sounds will not necessarily be more quiet as compared to aircraft sound nowadays, but the quality of the sound will/should improve.

Although the synthesis method has been developed for aircraft noise, it should be possible to extend the method also to other forms of transportation noise and even to industrial noise sources.

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