Simulation process for perception-based noise optimization of conventional and novel aircraft concepts

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Noise from civil air traffic affects millions of people worldwide. Aircraft noise management should be addressed by different principal elements, such as noise reduction at the source and noise abatement operational procedures. To date, usually conventional noise metrics are applied towards the acoustical optimization while noise effects are usually only indirectly accounted for. The objective of this contribution is the optimization of conventional and novel aircraft concepts with respect to their evoked aircraft noise annoyance. The optimization will be based on the perceived sound and the associated annoyance. To do so, virtual aircraft flyovers are auralized based on noise level predictions, i.e. they are artificially made audible. The auralization is accomplished by parametric sound synthesis and a 3D spatial audio technique. Short-term noise annoyance is measured through controlled listening experiments in which participants rate the level of annoyance for each auralized flyover. The aircraft design and the flight path are evaluated according to the associated annoyance. The subsequent ranking can be compared to a “conventional” ranking based on standard noise metrics. The results of such a study will help to identify parameters describing aircraft and flight path parameters that have an impact on noise annoyance. Consequently, these parameters can then be selected for further optimization to reach even lower levels of noise annoyance and not simply reduce standard noise metrics. Ultimately, the main goal of the research is optimizing the noise annoyance of (novel) aircraft along tailored flight paths. This contribution documents the status quo of the joint DLR and Empa activities, i.e., the structure of a pilot study. First results that were obtained while developing the methodology and the test cases within the pilot study are presented.

Nomenclature

L	Sound pressure level, dB rel. 20 μ Pa	<i>Subscript</i>	
f	Frequency, Hz	e	Emission
f_c	One-third octave band center frequency, Hz	AC	Aircraft
t	Time, s	i	Receiver index
p	Sound pressure, Pa	j	Sub-source index
$\mathbf{r}$	Position vector in three-dimensional space	k	Pure tone index

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Vehicle variants

V-R	“reference”	[DBE13-000]	Dissertation Bertsch (2013): PrADO reference aircraft, Ref. ³
V-R(af)	“retrofit”	[DBE13-010]	V-R with low-noise airframe measures
V-2		[DBE13-400]	Dissertation Bertsch (2013): PrADO low-noise vehicle, Ref. ³
V-2(af)	“game changer”	[DBE13-410]	V-2 with low-noise airframe measures

I. Introduction

Noise from civil air traffic affects millions of people worldwide. Continuing increases in the population, the increasing number of passengers and aircraft movements will further aggravate the problem in the future. The current solution to this problem is to optimize air traffic by minimizing the noise exposure of the affected persons. According to the “Balanced Approach” of the ICAO¹, aircraft noise management should be addressed by four principal elements: (i) noise reduction at the source, (ii) land-use planning and management, (iii) noise abatement operational procedures, and (iv) operating restrictions. The focus of the work in this paper are the two technical elements: noise measures at the source (i) and low-noise procedures (iii). For that purpose, conventional noise metrics are usually applied toward the acoustical optimization while noise effects, such as annoyance, usually remain unaccounted for. However, relationships between predictable metrics, which are needed for an numerical optimization, and the associated noise annoyance are still vague.

The objective therefore is the optimization of conventional and novel aircraft concepts with respect to their evoked aircraft noise annoyance. Noise prediction software that is used in aircraft design, such as ANOPP2² (NASA) or PANAM³ (DLR), allows the calculation of sound emission in a fine temporal and spectral resolution. Furthermore, in the past years significant scientific progress has been made in auralization. This is a technique that allows to artificially make non-existing (future) situations audible. By combining these two methodologies, the gap between the design of novel aircraft and procedures, and their acoustical perception with its effects on people could be narrowed. This approach is initiated by a research group at NASA Langley which introduced the term “perception influenced design” (PID) for this approach⁴.

The joint DLR and Empa activities are initiated with a pilot study. The setup of that study and initial results are presented in this contribution.

II. Research concept

II.A. General

From an acousticians point of view, incorporating aural perception in the development phase of future aircraft and flight procedures is sustainable and target-oriented, and thus promising. Driving forces behind this research are questions like, if and how aircraft designs based on this approach differ from conventionally designed aircraft. Maybe, some partial sound sources of an aircraft are permitted to produce a higher sound power due to e.g. auditory masking or because they do not increase noise effects or even reduce them. In particular, future aircraft technologies, such as active high-lift or electrification, should be evaluated and optimized according to their impact on people. Here, one important aspect is the aural perception and the effect it has on human beings.

Selected working questions in this research are:

1. Can the aural perception of an aircraft flyover be influenced by operational modifications and aircraft design alterations?
2. Do individual aircraft components affect the perceived sound differently depending on their geometry, operating condition, and the observer location?
3. Are, in contrast to conventional noise metrics, some aircraft components allowed to generate more sound power, while the overall flight event is nevertheless perceived as less or equally annoying?
4. Would the permission for some noise sources to generate more sound power enable unconventional aircraft designs?

5. Will aircraft developed with this optimization procedure look and sound differently than aircraft designed in the classical way?

In contrast to other activities that focus on the topic in a singularity manner, i.e. for a single source type, a single operating condition or a single intervention type, our aim is to investigate different types of measures together, their interaction and at a series of observer points that are relevant for aircraft noise community annoyance. To that aim, we model physical sources along a realistic flight path and thereby model the complex “orchestra” of various sound sources along the flight path. For example, when changing from the standard Low Drag Low Power (LDLP) approach to a Continuous Descent Approach (CDA), not only the flight path is changed, but also the source characteristics. This is because operational conditions determine the source emission, e.g. a steeper flight segment can cause increased flight velocity resulting in higher airframe noise. Furthermore, to reduce speed, the high-lift system has to be deployed at a greater distance to the runway already or air breaking devices have to be applied. Besides this, also novel aircraft designs and technologies along arbitrary flight trajectories (departure, fly-by and approach), at multiple relevant observer locations on the ground will be treated.

II.B. Pilot study

As a starting point of the joint research, a pilot study is conducted with the following three objectives:

1. Proof of concept of the simulation process.
2. Identification of open research questions and development needs for realistic auralizations.
3. Assessment of the annoyance reduction potential of novel aircraft concepts and procedures, i.e. including a separate as well as a combined assessment.

To treat these three objectives, a methodology is developed and exemplarily applied. To do so, an existing aircraft and procedure, as well as novel aircraft concepts and alternative procedures will be investigated. This will allow an estimation of the annoyance reduction potential and the comparison of future technologies and procedures based on the perceived sound exposure. The structure and initial results of the pilot study are presented in this contribution.

The methodology and the experimental design of the pilot study are explained in the following sections III and IV, respectively.

III. Methods

III.A. General requirements for simulation tools

From the research questions in section II some general requirements on the used simulation tools are deduced. These requirements are either related to the acoustical source, the propagation or the receiver.

1) To assess the influence of different aircraft components on the total impact, individual sources have to be represented separately. This requires a componential source model by which the relevant sources are independently described.

2) When assessing modifications to the aircraft or the procedure, it is not sufficient to just consider one selected operational condition. Instead, the various configurational settings along typical flight procedures have to be considered which demands an adequate flight simulation.

3) Possible future technologies should not be evaluated on a fixed flight path of today. Instead, the flight path should be adapted to the inherent flight performance of each vehicle to reveal the true potential of the technology. An example illustrating this is that a low-noise highlift system could increase drag, which under a prescribed velocity would require a higher thrust setting, counteracting an overall noise reduction. Thus, individual technology-matched flight procedures must be modeled.

4) When dealing with aircraft community noise, it is not sufficient to just evaluate noise emissions, i.e. limiting the focus on the source only. Noise is received in the vicinity of the ground and along the flight path, where sound propagation affects the received sound. Therefore, sound propagation to relevant observer locations has to be considered.

5) The auditory perception of new aircraft and procedures shall be considered. This can be accomplished using the technique of auralization where an aural impression is artificially generated.

Figure 1. Flow diagram of the simulation process for perception-based noise optimization of conventional and novel aircraft concepts including the used tools. (Details see text.)

6) In contrast to previous work, e.g. Ref.⁵, where conventional noise metrics were used, here the response of people should be considered. For this, experimental listening tests with subsequent statistical analysis can be performed.

7) Optimizations should be performed through simulation of new technologies and procedures. Therefore, a parametric description (as opposed to purely empirical) of the aircraft noise emissions (operation and geometry of aircraft and engine), a parametric sound synthesis and a parametric sound propagation simulation are essential.

III.B. Overview of the simulation and optimization process

Figure 1 shows a flow diagram of the simulation and optimization process. The process principally reflects a tool chain consisting of four modules that are based on different disciplines and require different expertise. At DLR, aircraft and procedures are designed, and the corresponding sound emissions along the flight path are estimated. The existing aircraft design process with integrated noise prediction capabilities as introduced in Refs.^{3,5} allows to tailor low-noise flight procedures to the specific aircraft design under consideration⁶, and is applied within this study.

At Empa, these simulated flyovers are auralized at virtual observer locations, and the designs are assessed according to their aural perception. In an iterative procedure, the employed models and designs are adapted and improved. The following sections describe the four simulation modules and the used tools.

III.C. Aircraft design

The aircraft designs are established with the tool PrADO (Preliminary Aircraft Design and Optimization). The underlying design process is explained in Ref.³. On the basis of the chosen Top Level Aircraft Requirements (TLAR), starting values for the design calculation are determined and entered into the simulation process. Subsequently, the required aircraft design stages are iteratively executed until convergence of the design parameters is achieved, e.g. aircraft masses and fuel consumption. For each stage different methods are available, e.g. statistical approaches or analytical methods. At convergence, a physically meaningful aircraft design is obtained that fulfills the chosen TLAR. PrADO finally yields all required input data for a noise emission level prediction with PANAM (Parametric Aircraft Noise Analysis Module).

III.D. Emission level prediction

For the prediction of the sound emission of the aircraft, the software PANAM developed by DLR is used. PANAM was specifically developed for noise predictions from a PrADO aircraft design, i.e. using PrADO

Figure 2. Simulation principle of PANAM with flight trajectory discretization and the componential source model. Note that in the presented simulation process, the mentioned sound propagation effects are applied in the auralization.

Figure 3. Flow diagram of the auralization process to synthesize aircraft flyovers.

results as input data. Thereby, the aircraft is acoustically modeled as a point source moving along a 3D trajectory in discrete time steps. The major noise sources of the aircraft are described by semi-empirical, parametric sub-sources. These sub-sources are parametric with respect to geometry, as well as the instantaneous operating condition of the aircraft. The variation of the ranking of individual sub-sources along an approach or departure are thereby reproduced. For broadband sub-sources, directional emission levels in 1/3 octave bands are obtained. Fan tones build an exception, as they are calculated at discrete frequencies with the corresponding sound power. An additional ray-tracing tool, SHADOW⁷, is used to predict structural shielding effects of engine noise. These shielding effects are used by PANAM to reduce the emission levels accordingly. The simulation principle of PANAM is depicted in Figure 2. For the subsequent simulation of a flight at a virtual observer location on the ground, the sound emission data in direction of the virtual observer is saved for discrete flight times. The flight trajectory is discretized in time steps δt_e of 0.5 s. This emission data is used as input in the auralization module.

III.E. Auralization of flyovers

Using the technique of auralization, aircraft flyovers at virtual observer locations near the ground are artificially made audible, including the generation of a spatial impression. The principle of auralization according to Vorländer⁸ is the separate representation of sound generation, propagation, and reproduction. As illustrated in Figure 3, the auralization process is structured into the three modules emission synthesis, propagation filtering, and 3D reproduction. The audible sounds are thereby completely artificially created by digital audio synthesis techniques.

In a first step, the sound emissions of each sub-source at a reference distance are synthesized based on the emission data obtained from PANAM. State-of-the-art methods for aircraft noise synthesis^{9,10} are used to synthesize the emission sounds. The sounds of broadband, noise-like sources (e.g. airframe and jet) are generated using subtractive synthesis where noise signals are processed by digital, time-variant filters to spectrally shape them. Tonal components are generated using additive synthesis by single oscillators. Each digital oscillator is individually steered by a time-variant frequency and amplitude control function.

Figure 4. Photograph of the listening room of the listening test facility AuraLab at Empa, Switzerland.

In a second step, the effects of sound propagation from the source to the receiver are simulated separately for each sound source. Relevant propagation effects include the Doppler frequency shift, geometrical spreading, air attenuation and the ground effect. They are implemented by applying digital filters to the emission signals. Because the propagation conditions change during the flyover, time-variant filters are applied. The sum over the signal contributions of all sub-sources at the receiver point correspond to a sound pressure signal, p , in Pascals, represented by a monophonic digital audio signal.

In a third step, this signal is fed to a multichannel audio reproduction system. This allows the creation of a spatial impression of a flyover. For that, the time-variant angles of sound incidence at the observer are needed. Using this directional information, the monophonic signal is distributed to a 3D loudspeaker array to create a perceivable sound field. The calculation of the speaker feeds is denoted as reproduction rendering. It is realized by a frequency-dependent amplitude panning technique. Each channel of the reproduction system has to be calibrated using a sound level meter at the listening zone.

For the auralization, mainly tools that have been recently developed at Empa for other environmental noise sources are used^{11–14}.

III.F. Listening tests and noise annoyance

The best studied non-auditory effects of aircraft noise on the population are sleep disturbances and long-term noise annoyance¹⁵. This work only considers the latter, which, per definition, is determined in field studies where people rate their noise annoyance integrally over longer periods. We use the basic assumption that long-term noise annoyance is related to short-term noise annoyance from single flight events. Only this assumption allows the evaluation of different noise scenarios in the laboratory.

With experimental listening tests, different sound scenarios are quantitatively compared. A typical test procedure is structured into five parts: Introduction, orientation, training examples, actual listening test, and questionnaire. During the listening test, participants rate acoustical stimuli according to their acute, individually experienced annoyance. The experiments are conducted in the listening test facility AuraLab at Empa. This laboratory features superior acoustical conditions with respect to room acoustics, building acoustics, and electroacoustics. Figure 4 shows a photograph of the listening room with the position of the participant (chair), the semi-spherical loudspeaker array and a screen (not used in this study).

The participants independently and individually rate acoustical stimuli. The posed questions and the rating procedure are oriented at standardized questionnaires for socio-acoustic surveys according to Ref.¹⁶. The collected ratings of 15–30 participants are statistically analyzed. This allows the comparison between scenarios (e.g. aircraft design or flight procedure) and finally an assessment of their annoyance reduction potential.

Figure 5. Illustration of the test cases of the pilot study consisting of combinations of different aircraft and landing procedures.

IV. Pilot study

To meet the objectives given in section II, a pilot study is conducted with the aim to develop the methodology of the simulation process (Figure 1) and apply it exemplarily.

IV.A. Overview

The pilot study focuses on approaches of large civil aircraft. Test cases covering three different aircraft with different flight procedures are considered, as illustrated in Figure 5. Their generated noise will be auralized at several observer points on the ground distributed along the flight path. These virtual flyovers will serve as stimuli for a listening test where the short-term annoyance will be assessed by participants.

The study includes an existing aircraft as well as possible future designs. Besides the present standard landing procedure, also possible future procedures are considered. This will allow to exemplarily compare the potential of different noise control measures, namely the potentials of

- the aircraft by retrofitting or novel design (with today's standard flight procedure),
- the flight procedure tailored to the specific aircraft,
- the combination of aircraft and procedure.

IV.B. Description of the test cases

Generally, all simulated test cases are physically possible and technically feasible. This concerns the aircraft design and operation as well as the flight procedures. The top level aircraft requirements (TLAR) of all vehicles are identical. Each aircraft approaches a fixed touch-down point on the same straight flight path. However, height, speed profiles, thrust setting, and configurational setting may vary for each vehicle.

The test cases are built up around a reference case which corresponds to an known, existing case. The reference case consists of a reference aircraft (V-R) with a reference landing procedure. The reference aircraft is similar to a current commercial aircraft of the type Airbus A319. The reference landing procedure is similar to current standard landing procedures as established at major airports. The reference case is initially simulated and auralized by the described methodology and used for verification and model adaptations. An earlier, detailed comparison of available experimental data and simulated noise levels can be found in Ref.³ for the V-R.

On that basis, additionally two potential, future, low-noise aircraft designs are investigated. First, V-R(af) corresponds to a retrofitted version of the V-R baseline with possible future noise measures. The selected low-noise measures as applied to V-R(af) are the following:

Figure 6. Illustrations of the studied reference aircraft V-R / retrofitted version V-R(af) and the “game changer” V-2(af).

- landing gear mesh fairing: landing gear noise -3 dB,
- porous edges: flap noise -5 dB,
- and slat droop nose design: slat noise -6 dB.

Underlying basic assumption is that the installation of the low-noise modifications do not negatively impact aerodynamics or weight. No low-noise technology is assumed for the engine noise sources. Second, V-2(af) is based on an available low-noise aircraft from Ref.³ and also retrofitted with low-noise measures as listed above for the V-R(af) (see Figure 6). Its specifications are taken from Ref.³, where the baseline version is denoted as V-2. Only the acoustic shielding of the V-2 architecture will reduce the fan noise contribution. The V-2(af) is understood as a “game changer”. Both low-noise aircraft are forced to perform the standard, reference procedure.

In addition to the different aircraft designs, alternative aircraft-specific landing procedures are used for all three aircraft. Each vehicle design is simulated along the reference flight procedure and along its individual low-noise flight procedure (see Figure 7). This results in a total of six virtual approaches (see Figure 5). The two technical principal elements of the “Balanced Approach” of the ICAO¹, i.e. measures at the source and the procedure, are thus considered.

V. First results

This section describes first results that were gathered while developing the methodology and the test cases within the pilot study.

V.A. Data interface between emission prediction and auralization

The interface between the simulation module emission level prediction (section III.D) and the auralization module (section III.E) has to be defined. Apart from a common reference distance (in this work 1 m), particular attention has to be put on kinematic and convective source effects that are relevant for fast moving sound sources, which are responsible for the Doppler frequency shift, Doppler amplification and convective amplification. The Doppler frequency shift should not be included in the emission data, as this effect is implicitly modeled during the propagation filtering in the auralization. In contrast, the mentioned amplifications are included in the emission data already, as convective amplification is source-specific.

The emission data consist of acoustical and positional data sets. Spectral emission levels for broadband source components are described by sound pressure levels, $L_{e,i,j}(t_e, f_c)$, at a reference distance of 1 m. These levels are provided separately for each observer i and each broadband sub-source j . They are calculated in 31 one-third octave bands for center frequencies, f_c , from 20 Hz to 20 kHz. The emission time, t_e , is resolved in

Figure 7. Three landing procedures of the pilot study described by their height and speed profiles, and the setting of the flaps, as a function of the horizontal distance to the touchdown point. The black curves show the reference landing procedure and the colored curves two tailored procedures. The gray lines indicate the chosen observer locations (see section V.F).

0.5 s steps. Four broadband components jet, airframe, fan, and fan buzzsaw noise are considered ($j = 1 - 4$). Narrowband components are represented by discrete pure tones described by the vector $\langle f_k(t), L_{e,i,k}(t_e) \rangle$, consisting of tone frequencies, f_k , and their corresponding levels, $L_{e,i,k}$. Five fan harmonics are considered ($k = 1 - 5$). This set of acoustical data is used as input for the emission synthesis of the auralization process (see Figure 3).

The positional data includes the aircraft position vector $\mathbf{r}_{AC}(t_e)$ as a function of the emission time, t_e , as used for the acoustical data. Additionally, the observer locations $\mathbf{r}_{R,i}$ are needed. From this set of positional data the propagation geometry from source to receiver is determined and used as input to the propagation filtering (see Figure 3). Furthermore, from the positional data the angles-of-incidence of the incoming sound at the observer are determined. Together with a chosen virtual observer orientation, this directional information steers the spatialization of the sound, i.e. the 3D reproduction rendering (see Figure 3).

V.B. Quality of positional data

As part of the auralization process, from the positional data of the aircraft, $\mathbf{r}_{AC}(t_e)$, the traveling time of the sound wave from the source to the observer is calculated. As the distance between aircraft and observer changes over time, the traveling time changes over time as well. At the observer, this manifests itself as a variable time delay of the source sound, i.e. the propagation delay. This delay causes the well-known Doppler effect. In the propagation filtering, the Doppler frequency shift is implicitly simulated by implementing the variable propagation delay. This implementation is close to the underlying physical mechanisms but sets requirements on the quality of the positional data of the aircraft.

It was found that even small discontinuities in the positional or operational data can lead to disturbing audible artifacts in the auralized flyovers. Such discontinuities were mainly observed in the context of recorded cockpit data (FDR), when used as input data for the noise prediction for validation. The audible artifacts mainly appeared with tonal components, e.g. from the fan, that were unnaturally modulated in frequency. The reason for that is that a slight step in the positional data provokes a step in the propagation delay. A sudden change in the delay leads to a sudden signal compression or expansion, resulting in sudden frequency shifts. The relative frequency shift is equal to the Doppler factor, defined as the derivative of the emission time, t_e , with respect to the observer time. Above 500 Hz and at 4 Hz modulation frequency, the just-noticeable frequency modulation of human hearing is as low as 0.7 % of the tone frequency¹⁸. Thus, the relative change to the Doppler factor introduced by aircraft position discontinuities should be kept smaller

than 0.7 %. Calculations revealed that for a source approaching a receiver with a speed of Mach 0.35, the positional error should be kept below 1.5 m to fulfill this requirement. A preliminary listening test with a 1 kHz pure tone as a source signal revealed that for the same situation and the chosen time resolution of 0.5 s even a positional error of 1 m creates an audible artifact.

A solution to this is to smooth the input data over time. This can be achieved by various algorithms (e.g. filtering, local regression or smoothing spline) that should be chosen depending on the data quality. It is beneficial to perform this operation already prior to the flight simulation. Firstly, this is closer to physics. And secondly, also other parameters of the emission data will behave more smoothly.

V.C. Transitions between configurations and operational conditions

Artifacts are also experienced when assembling the simulated flight path by individual and separate flight segments without implementing a smooth transition between segments. Abrupt changes in the aircraft configuration were found to create unrealistic changes in the perceived loudness and spectral shape. This was observed in the context of the extension of high-lift devices and the deployment of the landing gear. This can be avoided by choosing observer locations that are not in the vicinity of changes to the aircraft configuration. However, when comparing different procedures at several relevant exposure points, as in this study, the inclusion of transitions between operational conditions in the stimuli can hardly be avoided.

The reason for the unrealistic aural impression was that the initial modeling in PANAM was too coarse for an auralization. In reality, changes to the aircraft configuration do not happen suddenly, but gradually change over several seconds, and therewith the involved sound emissions changes continuously. For example, the deployment of the landing gears takes several seconds. Consideration of the transition times thus has an impact on the auralization while conventional immission metrics such as isocontour areas of sound pressure level are usually not affected.

Consequently, smooth transitions between operational conditions were introduced to the simulation process. Typical transition durations were estimated and applied to the data describing the aircraft configuration and the operating conditions. This modified flight data was used as input in PANAM to predict the sound emissions. This type of intervention requires appropriate emission models for the sub-sources and is an example of the previously mentioned importance of parametric models with respect to geometry and configuration. In PANAM, the prediction of airframe noise from the landing gear involves the extended length of the gear as input parameter. This allows to simulate the deployment of the landing gear by continuously changing this parameter up to the actual fully extended length over a predefined duration. In PANAM, the settings of flaps and slats are described by their deflection angles. This allows to continuously change these angles during a transition. With this approach, smooth and realistic auralizations also including transitions between configurations and operational conditions are created.

V.D. Cavity tones

Comparisons of narrowband spectra from synthesized sounds of the reference aircraft A319 with corresponding audio recordings (Ref.¹⁷) revealed that in contrast to the matching fan harmonics, additional tonal components occur in the recorded sounds that are missing in the synthesis. Most of the tones could be attributed to wing cavity tones that are generated by airflow at the fuel overpressure vents in the wings. This is a well-known phenomenon, e.g. see Ref.¹⁹ for a detailed overview. To counteract it, DLR has developed vortex generators that can be mounted to the wings as a retrofit. Such aerodynamically generated tonal sounds are not explicitly covered by current emission models of PANAM and were thus not included in an initial simulation.

Recordings of several aircraft of the A320 family (without vortex generators) showed that the wing cavity tones are relevant for the hearing impression, in particular at observer locations far from the runway. Recorded sound files that demonstrate the effect of the vortex generators are available for download from the Lufthansa website^a. Thus, an auralization of the reference aircraft V-R (technology status 2017) for these observers will also include cavity tones.

As a first approximation, the sound generation mechanism of a cavity tone can be modeled by a Helmholtz resonator upon flow excitation at its neck. Therewith, the sound power is maximal close to the resonator's resonance frequency. This narrow resonance peak is perceived as a tone. The resonance frequency is mainly determined by the resonator's geometry, particularly the volume of the air cavity and the neck. In contrast

^a<https://www.lufthansagroup.com/en/responsibility/climate-and-environmental-responsibility/active-noise-abatement.html>

to the frequency, the sound power strongly depends on the flow velocity, theoretically by the tenth power according to Tang²⁰. Based on that, the emission of a cavity tone is modeled here by a constant frequency value and an emission level function depending on the vehicle speed.

For the reference aircraft V-R, two wing cavity tones are considered. Their frequencies are estimated from field measurements of aircraft from the A320 family. The corresponding emission level functions are developed from data of a recent semi-empirical aircraft noise emission model²¹ by Empa. This data complements the emission data from PANAM.

V.E. Propagation effects

Due to the large propagation distances and the spectral content of the sources, air attenuation is an important propagation effect for aircraft noise calculation as well as for its auralization. This highly frequency dependent effect is due to the absorption of sound in the atmosphere and depends on the local air pressure, air temperature and humidity. It often suffices to consider a homogenous atmosphere for aircraft noise level predictions. However, first listening experiments suggest that for auralization a stratified atmosphere should be considered. To account for that, instead of a constant air absorption coefficient, a time-variable effective sound absorption coefficient is used in the model that is determined by integration along the propagation path. For that purpose, temperature, humidity and atmospheric pressure height profiles are used.

It was further found that the inclusion of the ground effect and amplitude fluctuations due to atmospheric turbulence²² both serve to increase realism and plausibility of auralized flyovers. Ground effect, defined as the spectral pattern induced by interference of direct and ground reflected sound, is simulated here by an additional signal path that interferes with the direct sound signal. The interaction of the reflected sound wave with the ground is modeled depending on the geometry and ground properties, i.e. its airflow resistivity. Sound propagation through a turbulent atmosphere results in amplitude and phase fluctuations. Stochastic amplitude fluctuations are modeled here as a function of frequency and propagation distance. The effect gets stronger with increasing frequency and with increasing sound propagation distance²³. Thus, its spectral characteristics and its strength change during a flyover. Measurements suggest that the magnitude of the amplitude fluctuations is limited²³. This saturation effect is also taken into account in our model by limiting the standard deviation of the level fluctuations to 3 dB.

V.F. Observer locations

To create stimuli for the listening test, appropriate observer locations have to be selected. They should be representative for community noise annoyance as experienced around major existing airports, i.e. spatially distributed observers. For the pilot study, the virtual observers are located directly under the flight path. Their height is set to 1.2 m above ground. This corresponds to the standard ear level of a seated person. This was chosen because in the listening test, participants will be sitting on a chair and their aural impression should correspond to that.

During an approach, the aircraft configuration (e.g. setting of flaps) changes over time, which distinctively affects the sound emission and thus the reception on the ground. Configuration changes are modeled as a function of the aircraft type and the procedure. To cover the influence of the configuration, together with the resulting flight trajectory (height and speed profiles), multiple virtual observer points are required per single flight. This is in contrast to the single official “approach reference noise measurement point” used for the aircraft noise certification as specified by ICAO²⁴. The observer points orient themselves at today’s aircraft noise exposure. To represent relevant exposure situations, the observers should cover the extreme configurations (clean and all set) as well as at least one intermediate condition. Therefore, at least three observer points are required to cover one procedure.

By considering the three procedures according to section IV.B, it was found that only three fixed observer locations with respect to the touchdown point do not suffice to adequately represent these procedures. It was therefore decided to use four observer points in the pilot study. They are located at 25, 15, 8 and 4 km before touchdown. To relate them to the flight trajectory, these locations are indicated in Figure 7 by vertical gray lines.

With the six test cases described in section IV.B, this results in a total of 24 different flyovers to simulate, corresponding to 24 stimuli for the listening test. From experience, this is a reasonable number of stimuli for a listening test on environmental noise.

Figure 8. Exemplary spectrograms of synthesized flyover sounds from different aircraft, procedures and observer points. The distances observer-touchdown are indicated in the captions. Time 0 s is the instant when the flyover is perceived directly from above.

V.G. Spectrograms

With the described methodology, the 24 flyovers could be successfully simulated and plausibly rendered audible, which was verified by recent pretests. As intermediate data in the simulation chain, a sound pressure signal for each flyover is synthesized during the auralization. From these signals any classical noise metric and psychoacoustic parameter can be calculated. This also includes spectro-temporal analysis with fine spectral and temporal resolutions.

Figure 8 exemplarily shows spectrograms of synthesized sound pressure signals. The spectrograms were created using the short-time Fourier transform and represent power spectral densities with logarithmic amplitude and frequency axes. The four panels cover different aircraft, procedures and observer points. In the displayed data, different emission and propagation phenomena can be observed. This involves the presence of a broadband noise basis; distinct frequency components that vary over time and that are related to fan harmonics and wing cavity tones; a quasi-symmetrical level-time dependence due to geometrical spreading; the typical trough-shaped pattern of the ground effect; vertical bands from turbulence-induced amplitude fluctuations; and dropping tone frequencies due to the Doppler frequency shift. For both shown aircraft, the levels close to touchdown (lower panels) are larger than at the far location (upper panels). The levels of the “game changer” V-2(af) (right panels) are smaller than that of the reference aircraft V-R (left panels). In contrast to V-2(af), the aircraft V-R shows discrete tones. The two tones above 1 kHz are the first and second fan harmonic. They are particularly more prominent close to touchdown (lower panel). In contrast, far from touchdown (upper panel) two cavity tones between 500 Hz and 1 kHz are apparent. Whether such differences are perceivable and whether they influence the short-term noise annoyance can only be disclosed by a listening test.

VI. Conclusion

The presented methodology allows the auralization of flyovers from novel aircraft designs on arbitrary flight trajectories in the laboratory. First results from an ongoing pilot study demonstrate the feasibility of the approach. They also show that for realistic auralizations, special attention must be given to certain aspects that are irrelevant for the prediction of classical noise metric. These aspects for example regard the quality of positional data, transitions between configurations, the ground effect or the influence of atmospheric turbulence on sound propagation. Using this methodology, the annoyance reduction potential of some novel

aircraft concepts and procedures will be investigated in upcoming experimental listening tests.

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