Aircraft Design Optimization for Lowering Community Noise Exposure Based on Annoyance Metrics

Sahai, Abhishek; Snellen, Mirjam; Simons, Dick; Stumpf, E

DOI
10.2514/1.C034009

Publication date
2017

Document Version
Accepted author manuscript

Published in
Journal of Aircraft: devoted to aeronautical science and technology

Citation (APA)
Sahai, A., Snellen, M., Simons, D., & Stumpf, E. (2017). Aircraft Design Optimization for Lowering Community Noise Exposure Based on Annoyance Metrics. *Journal of Aircraft: devoted to aeronautical science and technology*, *54*(6), 3421-3432. https://doi.org/10.2514/1.C034009

Aircraft Design Optimization for Lowering Community Noise Exposure Based on Annoyance Metrics

Abhishek K. Sahai[*], Mirjam Snellen[†] and Dick G. Simons[‡]
Aircraft Noise and Climate Effects Research Group, Delft University of Technology,
Delft, 2629HS, The Netherlands

Eike Stumpf[§]
Institute of Aerospace Systems, RWTH Aachen University, Aachen, 52062, Germany

This paper focuses on the annoyance aspect of aircraft noise, which relates to the quality of the sound reaching communities, and attempting to potentially lower this annoyance by optimizing an aircraft's design. Use is made of sound quality metrics since these are known to have a high correlation with perceived aircraft noise annoyance. A representative short-range aircraft is optimized for minimal community noise impact by varying the thrust to weight ratio and wing-loading parameters. The changes in noise impact are investigated for both certification and sound quality metrics to quantify design sensitivities. The optimized aircraft is seen to have a noticeably different sound depending on the metric it was optimized for. The use of sound quality metrics is seen to provide much clearer information regarding the character of the sound reaching the residents than the conventional A-weighted level and Effective Perceived Noise Level metrics used for certification. The certification metrics prove deficient in capturing important aircraft noise characteristics such as its tonal content, which is a strong contributor to the perceived annoyance. Feedback from psychoacoustic tests is required to confirm whether the presented modified aircraft sounds, optimized for the different metrics, are indeed perceived as less annoying and more acceptable.

---

[*] Assistant Professor, Aircraft Noise and Climate Effects Research Group (ANCE), Faculty of Aerospace Engineering, TU Delft, 2629HS, Delft, The Netherlands.

[†] Associate Professor, Aircraft Noise and Climate Effects Research Group (ANCE), Faculty of Aerospace Engineering, TU Delft, 2629HS, Delft, The Netherlands.

[‡] Full Professor and Chair, Aircraft Noise and Climate Effects Research Group (ANCE), Faculty of Aerospace Engineering, TU Delft, 2629HS, Delft, The Netherlands.

[§] Professor and Head, Institute of Aerospace Systems (ILR), RWTH Aachen University, 52062, Aachen.

Nomenclature

T/W = Aircraft thrust to weight ratio

W/S = Aircraft wing-loading

S = Wing area

b = Wing span

$N1$ = Fan rotation speed (Engine low-pressure spool speed)

M = Aircraft Mach number

h = Aircraft altitude

N = Loudness

N' = Specific Loudness

z = Critical band rate

K = Tonality

S' = Sharpness

f = Frequency

B = Number of fan rotor blades

A_{fan} = Fan inlet area

$A_{j,1}$ = Primary jet area

$A_{j,2}$ = Secondary jet area

V_{app} = Aircraft approach speed

I. Introduction

The conventional approach to reducing the aircraft noise impact for residents in airport vicinities has been to attempt to minimize or reduce the loudness based A-weighted level (dBA or also L_A). All reductions in community noise impact have been traditionally presented to both policymakers and residents in dBA values. The dBA metric is however a very simple metric to approximate the human perception of hearing – it follows the 40 phon loudness level curve from the equal loudness contours developed by Stevens [1] and accounts for the fact that the human ear perceives higher frequencies as louder than lower frequencies below about 3.5 kHz. The metric however does not take into account the influence of tonal content, spectral balance and the fact that sounds having different levels will have different perceptions of loudness for different frequencies i.e. they do not all follow the frequency dependence of the 40 phon loudness level curve.

For certification purposes, use of the Effective Perceived Noise Level (EPNL) metric is made, which was developed solely for assessment of aircraft noise. The EPNL metric is an annoyance based metric which makes use of equal ‘noisiness’ curves [2] accounting for the non-linear frequency sensitivity of the human ear, adds a tonal penalty to take into account the influence of tonal content as well as a duration correction to account for the flyover exposure time of an aircraft. The EPNL metric, although complex and extensive to compute, also suffers from some limitations, particularly with regards to assessing tonal content. It incorporates a broadband frequency division, giving tones between 500-5000 Hz a higher penalty and those below 500 Hz or above 5000 Hz a lower penalty. Tones at different frequencies however produce different perceptions of annoyance and prominent tones below 500 Hz such as those from propeller or Counter Rotating Open Rotors (CROR) will furthermore be absorbed less effectively by the atmosphere. The EPNL metric also does not take into account the number of tones present in a spectrum and masking effects from low frequency noise, which can affect how tonal a sound is perceived to be.

The goal in this paper is to present a means of improving on the current noise assessment approach by taking into account the in-depth knowledge gained in the previous decades about human perception of sounds, and applying this knowledge to the aircraft design and optimization process. The aim here is to investigate the possibility of designing aircraft that may inherently sound less annoying or more acceptable to residents due to having considered annoyance, beyond that represented in certification metrics, during the aircraft design and optimization process. For this purpose, the metrics of Zwicker’s loudness [3], Aures’ tonality [4] and von Bismarck’s Sharpness [5] have been implemented to assess simulated aircraft noise spectra. The use of these sound quality metrics to assess aircraft noise annoyance is based on findings from previous research by Angerer et al. [6] and More et al. [7] that loudness and tonality, in this order, have been shown to best correlate with the actual psychoacoustic annoyance experienced by listeners in test environments, followed by roughness and sharpness. Although the roughness of aircraft noise, which measures fast loudness fluctuations of the order of 50-80 Hz [8], can be a significant annoyance contributor for propeller based aircraft, it is of less relevance for conventional turbofan engines. As such, it has been left out of the current analysis.

Sharpness is a measure of the high frequency content of a sound and has been included in the analysis to see trends in changes to high frequency aircraft noise.

In Section II the paper will firstly describe the aircraft design and noise prediction methodology, used to simulate aircraft noise and optimize designs to minimize community noise impact. A brief introduction to the sound quality metrics is then provided in Section III. In Section IV design sensitivity studies are subsequently performed, to see how varying certain overall design parameters such as the aircraft wing-loading (W/S) and thrust to weight ratio (T/W) can impact community noise levels via the impacted areas on the ground in individual metrics. The thrust to weight ratio here refers to the maximum thrust the engines produce and the Maximum Takeoff Weight (MTOW). Certification noise impact is also considered in parallel but not as an optimization target. The distinction between certification noise impact (close to the airport) and community noise impact (at larger distances from the airport) is important as the certification noise values are not always representative of the noise impact farther away from the runways, due to changes in the aircraft's flight path or atmospheric propagation effects. A comparison is then made in Section V of designs optimized for certification and sound quality metrics. The different optimized designs are lastly auralized, i.e., converted to synthesized sounds using advanced signal processing techniques developed at RWTH Aachen University [9], [10] [9-10] and the sounds are compared to a reference short-range aircraft's sound for a standard approach and departure procedure, at sample observer locations on the ground.

II. Aircraft design and noise modeling methodology

A. Aircraft design and optimization methodology

For performing the aircraft design and optimization studies, use has been made of the Multidisciplinary Integrated Conceptual Aircraft Design and Optimization (MICADO) environment [11], developed at the Institute of Aerospace Systems (ILR) of RWTH Aachen University. Using the MICADO environment, a complete conceptual aircraft design can be derived from a set of Top Level Aircraft Requirements (TLARs) with a minimum of user input, in an automated way. Fig. 1 shows MICADO's loop structure and how an aircraft is designed and optimized using its methodology. The overall MICADO environment consists of a series of modules. Each module is intended to perform a specific aircraft design or analysis task. Based on the TLARs and certain design specifications (such as number of engines, position of wing), the aircraft geometry components such as the wing, fuselage, landing gear and stabilizers are sized for a first estimate design. This is followed by an estimation of the aircraft aerodynamics, weights, block fuel and performance for a specified typical flight profile or a 'mission' of the aircraft. The process is iterated, going through all sizing and analysis modules till a convergence for key representative aircraft design parameters, such as the MTOW and Operating Weight Empty (OWE), is achieved. The fully converged aircraft design can then be assessed in detail for various evaluation criteria such as block fuel over specific 'study' missions, aircraft operating and lifecycle costs, pollutant emissions as well as noise impact. Depending on the optimization target, which in this paper is the community noise impacted area on the ground for the various metrics, the aircraft design can be optimized and its design sensitivities for selected design changes can be analyzed. The MICADO environment has been used for several aircraft design studies and its short range aircraft design used in this study, similar to the Airbus A320, has been validated against reference data provided by Airbus as part of the CERAS project* [11].

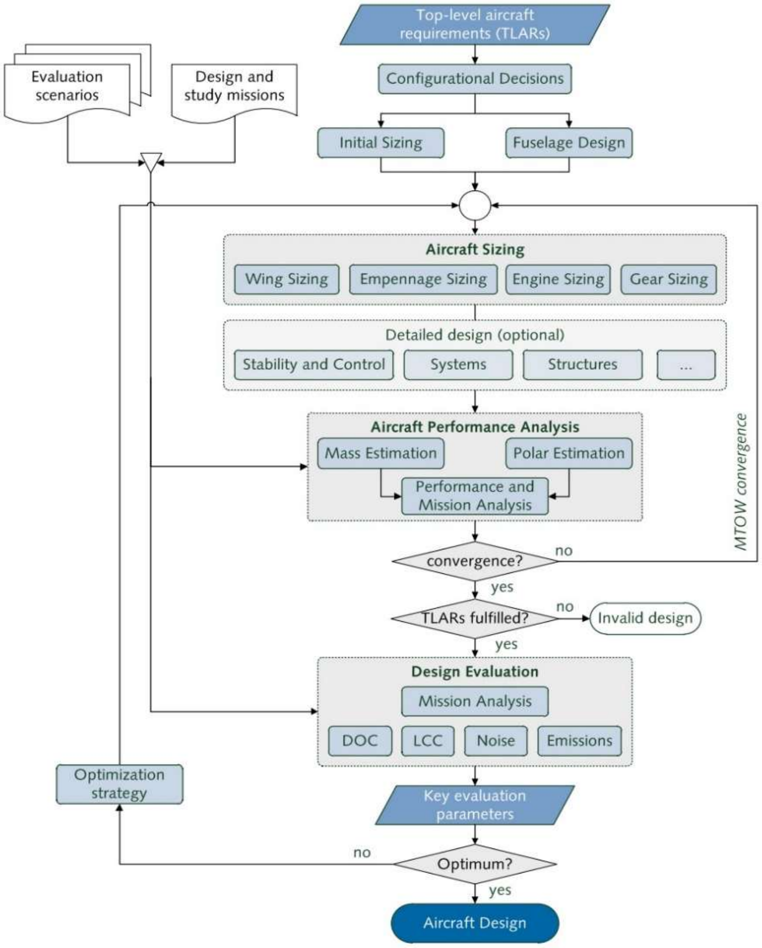

Fig. 1 Aircraft design and optimization methodology using the MICADO environment

---

* https://ceras.ilr.rwth-aachen.de/

B. Aircraft noise modeling and assessment methodology

The simulation and assessment of aircraft noise has been performed using the Integrated Noise Simulation and Assessment module (INSTANT)[*] [12-13], which was developed at the Institute of Aerospace Systems (ILR) of RWTH Aachen University to model and assess the noise produced by commercial aircraft for aircraft design and flight procedure analyses. The software has been used for several applications such as aircraft noise analysis of current aircraft designs, community noise impact analysis of both standard and noise abatement flight procedures [14] as well as Virtual Reality (VR) applications such as auralization and 3D visualization of aircraft noise in airport vicinities [9-10].

As is necessary for applications relating to aircraft design and optimization, the use of high-fidelity computational methods is ruled out due to their excessive computational costs. For the studies presented in this paper in Sections IV and V, several design variants of an aircraft are iteratively designed and optimized, with up to a hundred designs being assessed for their noise impact. As such, the use of semi-empirical and analytical source noise calculation methods is necessary at the expense of accuracy [15]. The most well-known publically available source noise models are those incorporated in NASA's Aircraft Noise Prediction Program (ANOPP) [16] and INSTANT also makes use of these models to predict the noise at the source. Fig. 2 shows the noise simulation and assessment methodology followed by INSTANT, which is briefly described below.

The noise impact on the ground is estimated starting with an aircraft and engine design. The aircraft design is performed using the MICADO environment and the engine performance cycle is modeled using the gas turbine design software Gasturb [17]. The cycle parameters used as inputs for the source noise models such as stage temperatures, pressures and mass flows are exported from Gasturb as so-called 'decks', which are files containing each parameter's value as a function of fan or low-pressure spool speed $N1$, aircraft Mach number M and altitude h. The engine geometry parameters needed for noise calculation such as the number of fan blades, stator vanes, stage areas and diameters are obtained from an empirical database as functions of the engine maximum Sea Level Static Thrust (SLST). The airframe geometry parameters such as the flap and wing area, landing gear geometry etc. are obtained directly from the MICADO environment.

---

[*] Formerly called ILR's Noise Simulation and Assessment module

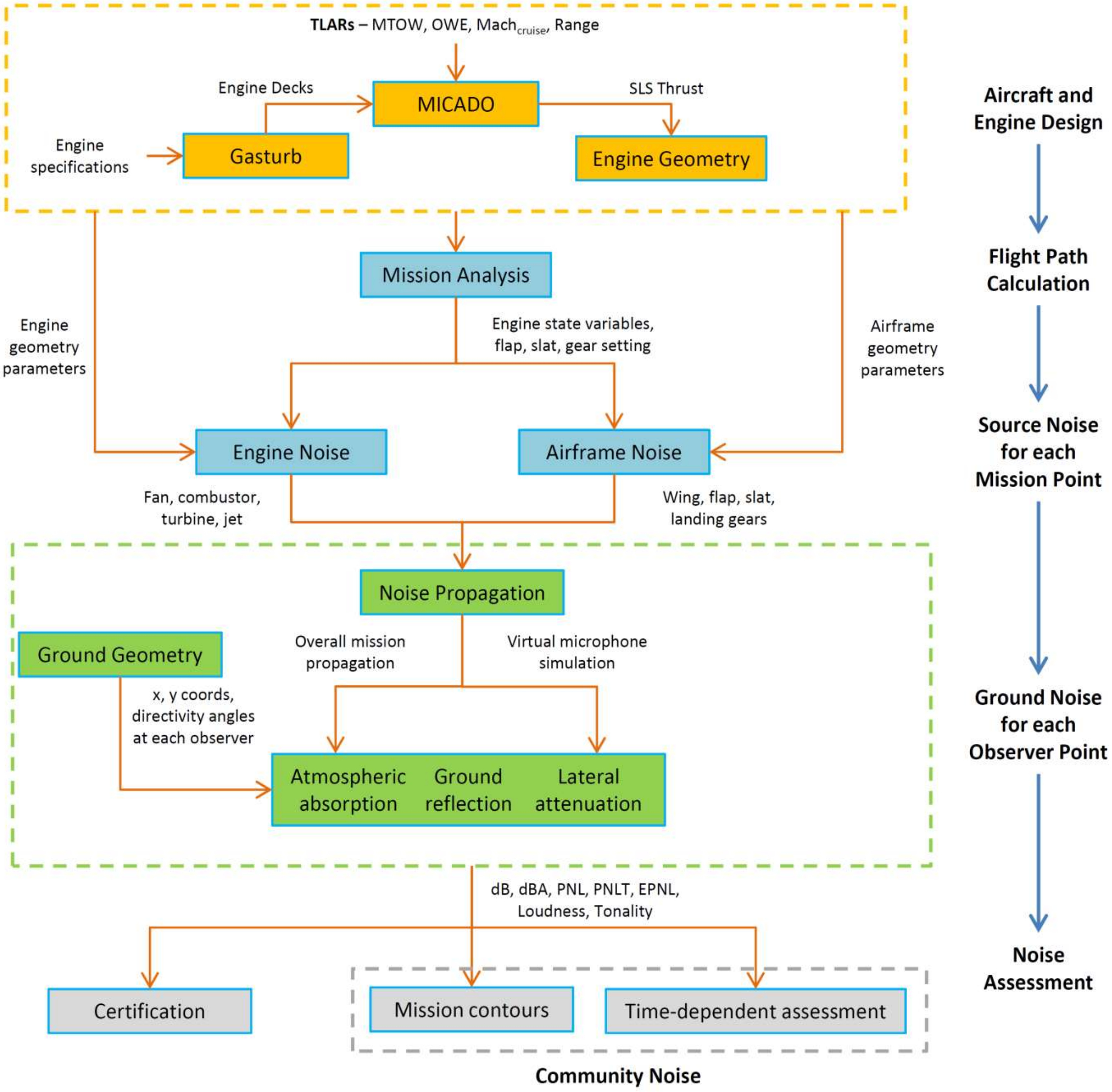

Fig. 2 Noise modeling and assessment methodology using INSTANT

The next step in the noise simulation process is the generation of flight paths. These are generated using the mission analysis module of the MICADO environment for selected flight procedures, and provide all the operational and thermodynamic inputs required for airframe and engine noise calculation. The noise is then simulated at the source for time-steps of 0.5 seconds for both the engine and airframe noise sources. The engine component source noise models of Heidmann for fan noise [18], Emmerling for combustor noise [19], Matta for turbine noise [20] and Stone for jet noise [21] are used to calculate the engine noise for each time-step of the flight path. The model of Fink [22] is used to calculate the noise due to the individual airframe geometry components such as wing trailing edge, flap, slat and landing gear. The focus of the analysis presented in the subsequent sections is kept on the most dominant aircraft noise components namely jet noise, fan noise and airframe noise. Combustor and turbine noise are therefore not considered in the design and optimization analysis in Sections IV and V. Combination or buzzsaw tones from the fan are also excluded from the analysis as they occur only during the initial takeoff phase for high thrust settings and not during later departure phases or during approach. It is recognized however that buzzsaw tones can be an important source of annoyance during the takeoff phase and subsequent studies focusing on the annoyance optimization of buzzsaw noise, in combination with the other engine noise components, have been planned at TU Delft.

Since the ANOPP based models were developed intending to predict far-field noise, the overall aircraft (i.e. engine plus airframe) is hereby regarded as a point source in order to perform the propagation steps that follow source noise calculation. The aircraft source noise is propagated to the ground after applying the propagation and absorption effects of spherical (geometric) spreading, atmospheric absorption according to ISO 9613-1:1993 [23], ground reflection according to Chien-Soroka theory [24], applying Delany and Bazley's ground impedance model [25] and lateral attenuation [26]. For the purposes of this study, a straight line propagation path has been assumed, with no wind or temperature gradients between the aircraft and the observer. The inclusion of atmospheric turbulence, which would not affect the optimization results severely, yet can make the auralized sounds presented in Section V more realistic, has also been left out of the current analysis. Depending on the user specified ground geometry, the noise assessment can be performed for a single point on the ground for time-dependent noise prediction i.e. simulation of virtual microphones on the ground; for an array of points for certification analysis of aircraft designs for noise according to the ICAO Annex 16 methodology [27]; or for a full grid of points for 'mission level' assessment in the form of noise contours, displaying maximum noise impact values at each ground point in various certification and alternate metrics. INSTANT has been verified against publically available NASA ANOPP reports [28-29] as well as with flyover measurement data in [13]. Its sensitivity to several source noise inputs has been presented by the authors in [12].

III. Use of sound quality metrics to approximate annoyance

The sound quality (SQ) metrics have been developed for sound perception in general, not just for the sound of an aircraft. These metrics are based in the field of psychoacoustics and have been widely applied to the *sound engineering* of products from well-established industries such as automotive and industrial design engineering. Due to their high correlation with perceived annoyance, the SQ metrics have been used in this paper for approximating the perceived annoyance due to aircraft noise. For this purpose, the noise assessment capability of INSTANT has been extended to assess the predicted aircraft noise spectra in terms of their sound quality. The methodology with which the SQ metrics are implemented to assess simulated aircraft noise spectra is relatively new in the aerospace community and has been described in [13-14] by the authors. The SQ metrics used in this study are briefly described in the following subsections.

A. Zwicker's stationary loudness

Loudness is the subjective perception of the magnitude of a sound and is widely regarded as the most important sound characteristic affecting the perceived annoyance due to aircraft noise [30-31]. For simple pure tones, the loudness can be estimated using equal loudness contour curves, which were created by matching the subjective loudness of a sound with a reference 1 kHz pure tone at a given level. The main aim of using the equal loudness curves is to account for the non-linear frequency sensitivity of the ear, whereby higher frequencies are perceived as louder than frequencies below about 3.5 kHz. The dBA metric uses the 40-phon[*] loudness level curve, as mentioned earlier, to calculate the A-weighting and approximate the human hearing response. The EPNL metric uses similar equal noisiness curves to estimate the perceived noisiness or annoyance of aircraft sounds as its basis [32]. Complex sounds such as those from an aircraft and its engine consist of both broadband and multiple tonal components. For such sounds, additional effects such as the masking of high frequency noise components from lower frequency noise are important in determining the overall perceived loudness. Applied to aircraft noise, this implies that any engine tone has the potential to either completely or partially mask other tones and harmonics that lie at higher frequencies than its own frequency. Broadband noise from the jet and airframe, which peaks at low frequencies and extends over large parts of the spectrum, is very effective in masking the higher frequency tones originating from the fan. This concept of spectral masking plays an important role in understanding the changes in predicted annoyance for different design variations presented in Section IV.

Zwicker's loudness calculation method estimates these spectral masking effects besides using the knowledge on equal loudness curves, thereby providing a potential improvement over the currently used metrics by incorporating more

---

[*] Loudness is expressed in sone on a linear scale and on a logarithmic scale, the loudness is expressed in the loudness level with unit phon.

detailed knowledge on the perception of sounds. For this paper's research work, Zwicker's method as described in ISO532-B and DIN 45631 [33] has been used to calculate the loudness of aircraft noise spectra on the ground. The aircraft sound has been regarded as stationary over the 0.5 second intervals modeled using INSTANT, neglecting any transient effects occurring for shorter durations. The loudness values as obtained using INSTANT have been successfully validated against publically available references such as [34] and [35] for several 1/3 octave band spectra, as shown by the authors in [13].

B. Aures' tonality

The tonal content of aircraft noise is a major contributor towards the perceived annoyance and is, after loudness, the second most important aspect with regards to the perceived annoyance due to aircraft noise [6-7]. With the importance of the tonal content in mind, it is therefore essential that the annoyance due to tonal components can be estimated in the most comprehensive and accurate way. As mentioned earlier, the EPNL metric attempts to capture the impact of tonal content of aircraft noise by applying a tonal penalty to the Perceived Noise Level (PNL) values depending on the protrusion level and frequency of the strongest tonal component. The drawbacks of this metric however are that the penalties have the same value for frequencies over a very broadband range of 500 to 5000 Hz, that masking of tones by broadband noise as well as other tones is not considered, and that the influence of the total number of tones present in a sound is also neglected. The dBA metric does not consider tonal content in any form at all. From the annoyance studies carried out by Angerer et al. [6] and More et al. [7], it was found that the annoyance due to aircraft tonal noise can be found with a reasonably high correlation using the tonality metric developed by Aures [4]. The method developed by Aures for quantifying the tonality of noise has been outlined in [4] and quantifies the influence of tonal prominence, frequency, bandwidth and loudness relative to overall spectral loudness, to determine the perceived tonality of a sound. It also considers masking effects on each tone from other tones present in the spectrum and from the broadband noise surrounding each tone, to determine whether a tone is aurally relevant for tonal perception. Validation of the tonality values computed using INSTANT for predicted spectra with tonality values for synthesized audio computed by the Sound Quality Analyzer software has been presented by the authors in [10] and [13], for a 777-300 comparable Long-Range (LR) aircraft and an A320-200 comparable Short-Range (SR) aircraft.

C. Von Bismarck's sharpness

Although sharpness was found to be the fourth relevant sound quality attribute after loudness, tonality and roughness, with regards to the experienced annoyance due to aircraft noise by both [6] and [7], it is still a useful metric in understanding annoyance effects due to changes in spectral content. A sound is perceived to be 'sharper' when it has more high frequency content than low frequency content. The sharpness metric can thus show when high frequency noise such as from the fan is starting to gain prevalence over low frequency jet and airframe noise in the aircraft noise spectra. It has been implemented in INSTANT based on the method of von Bismarck, which makes use of a sharpness weighting function that weighs all spectral content at or above 2700 Hz increasingly more heavily. The sharpness values as obtained using INSTANT have also been validated against publically available references [34] and [35] for 1/3 octave band spectra, as presented in [13].

IV. Design parameter sensitivity analysis

In order to analyze how modifying aircraft designs can alter the aircraft noise and annoyance impact on the ground, two overall aircraft design parameters – the aircraft wing-loading, *W/S*, and the thrust to weight ratio, *T/W,* have been varied from their reference values for a representative Short-Range (SR) aircraft. Changes to these parameters scale the entire aircraft and have both a direct and indirect influence on the noise impact on the ground. The aircraft wing-loading directly affects the wing plus high-lift device areas and spans, which directly alters the airframe noise produced by the aircraft. Alongside this, the wing-loading also affects the flight path of the aircraft as a larger wing can aid in a steeper initial departure and final approach. The thrust to weight ratio scales the entire engine and has a very strong effect on the noise produced by the whole engine as well as by its individual components. This is due to the fact that the engine geometry parameters such as the fan diameter (d_{fan}), number of rotor blades (B) and stator vanes (V) as well as the primary and secondary jet areas ($A_{j,1}$, $A_{j,2}$) among others are all scaled with the maximum producible sea level static thrust, SLST. The change in geometry is also coupled with a change in the thermodynamics of the engine, which is adjusted for each design iteration by scaling the engine decks using the MICADO environment. As with the *W/S* changes, a higher *T*/*W* can also alter the flight path by allowing a steeper and faster climb out during departure, which affects noise impact on the ground for residents living both close to and farther away from the airport.

The analyzed SR aircraft is comparable to an Airbus A320-200, powered with an IAE V2527-A5 engine model, which is a typical power plant used for this aircraft. Previous studies have shown that relative design changes from reference values for a short-range aircraft are also representative for the changes for long-range aircraft. The SR aircraft results can therefore be regarded as generally applicable [12]. The noise impact on the ground is analyzed in this paper in terms of both certification and sound quality metrics. The focus is placed on community noise impact, and the impacted area on the ground is calculated based on the number of grid points lying within certain specified sound level contours for standard takeoff and approach procedures. This is illustrated in Fig. 3 with the maximum value noise contours in the dBA and EPNL metrics, for a standard takeoff procedure of the SR aircraft.

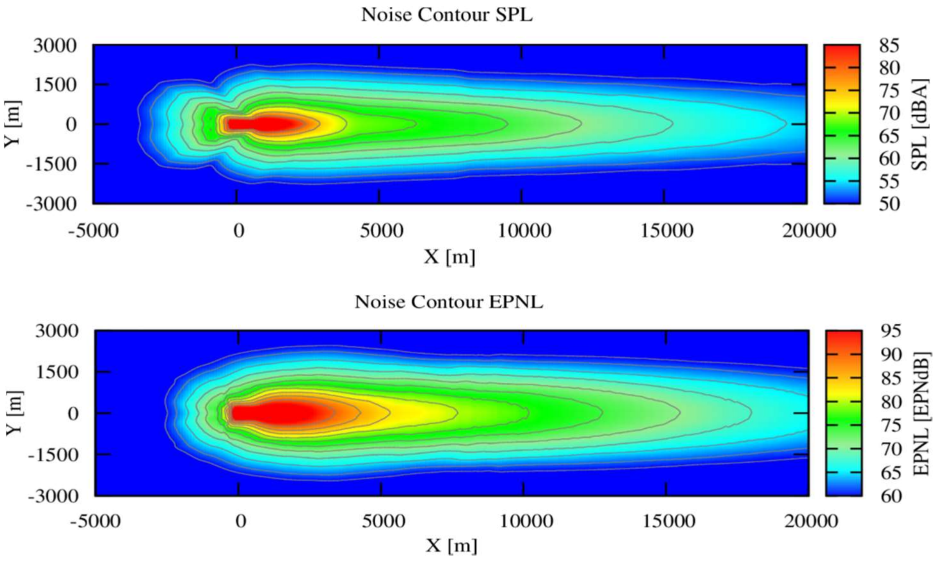

Fig. 3 Takeoff community noise contours for the SR aircraft in dBA and EPNL metrics

Changes in community noise impact are investigated by choosing both a low noise impact value (denoted as threshold 1) and a high noise impact value (denoted as threshold 2) for each noise metric by computing the impacted area at two chosen threshold values. This is done due to the fact that modifying an aircraft's design can alter the flight path of the aircraft, which can result both in changes in the noise impact for residents living close to the airport, as well as in the noise impact farther away from the airport due to differing spherical spreading and atmospheric absorption effects. The representative values for each metric analyzed in this paper are summarized in Table 1. The dBA and EPNL metrics as well as their low and high threshold values are more common and familiar; for the sound quality metrics, the threshold values for each metric have been chosen specifically for the SR aircraft, based on typical high and low metric values that were observed for its community noise impact. The loudness level had similar maximum and minimum levels in phon as the EPNL metric in EPNdB, the tonality of the SR aircraft was on the whole low and only exceeded 0.1 t.u. during the approach phase, and the sharpness thresholds were also chosen based on high and low sharpness values observed for the SR aircraft. Different threshold values may be required to be chosen for different aircraft, as a long range aircraft for instance will be louder and more tonal due to the likely use of a larger fan. The goal therefore is to minimize the community noise impact of the specific aircraft being studied.

Table 1 Low noise impact (threshold 1) and high noise impact (threshold 2) values for each metric

Metric	*Threshold 1*	*Threshold 2*
A-weighted level [dBA]	55	75
EPNL [EPNdB]	65	85
Loudness level [phon]	65	85
Tonality [t.u.]	0.075	0.1
Sharpness [acum]	0.75	1.0

The aircraft noise simulation on the ground has been performed for observer points over a grid of 30 km x 20 km for departure paths and 40 km x 20 km for approach paths, with a ground point resolution of 100 m x 100 m. Since the goal of the parametric variations was not to deviate too strongly from the reference SR design, each design variant aims a convergence for the same MTOW and OWE values, as well as the same TLARs as the reference SR aircraft. Tables 2 and 3 show, for the SR aircraft's departure and approach phases respectively, the community noise impacted areas in km^2 for the mentioned metrics. The impacted areas have been calculated based on the maximum noise impact values occurring at each ground grid observer location, and thus represent the affected area within which the maximum noise impact value for each metric is equal to or higher than the specified threshold value. For community noise exposure optimization purposes, this approach ensures that the noise exposure can be reduced by design changes for the largest possible number of affected residents. The values of the impacted areas for the various metrics will be discussed in the following subsections.

Table 2 SR aircraft community noise impacted area for a standard takeoff flight path

Metric	*Community noise impact threshold*	*Impacted area* **[km^2]**
A-weighted level	55 dBA threshold	50.4
	75 dBA threshold	2.3
EPNL	65 EPNdB threshold	79.6
	85 EPNdB threshold	6.5
Loudness level	65 phon threshold	84.9
	85 phon threshold	4.6
Tonality	0.075 t.u. threshold	1.9
	0.10 t.u. threshold	0
Sharpness	0.75 acum threshold	51.1
	1.0 acum threshold	17.3

Table 3 SR aircraft community noise impacted area for a standard approach flight path

Metric	*Community noise impact threshold*	*Impacted area* [km^2]
A-weighted level	55 dBA threshold	67.2
	75 dBA threshold	2.8
EPNL	65 EPNdB threshold	93.8
	85 EPNdB threshold	6.8
Loudness level	65 phon threshold	102.2
	85 phon threshold	7.8
Tonality	0.075 t.u. threshold	172.5
	0.10 t.u. threshold	127.8
Sharpness	0.75 acum threshold	94.8
	1.0 acum threshold	27.3

A. Wing-loading (*W*/*S*) variation

Figure 4 shows the results for the *W/S* variation from the reference value of 629 kg/m^2 for the SR aircraft and the effect of the variation on the community noise impact in terms of sound quality metrics. The curves show the *percentage changes* in the impacted areas from the reference values shown in Tables 2 and 3 for the low impact (threshold 1) and high impact (threshold 2) values for each metric. As several changes can be seen to take place, changes in the loudness, tonality and sharpness impact are explained individually.

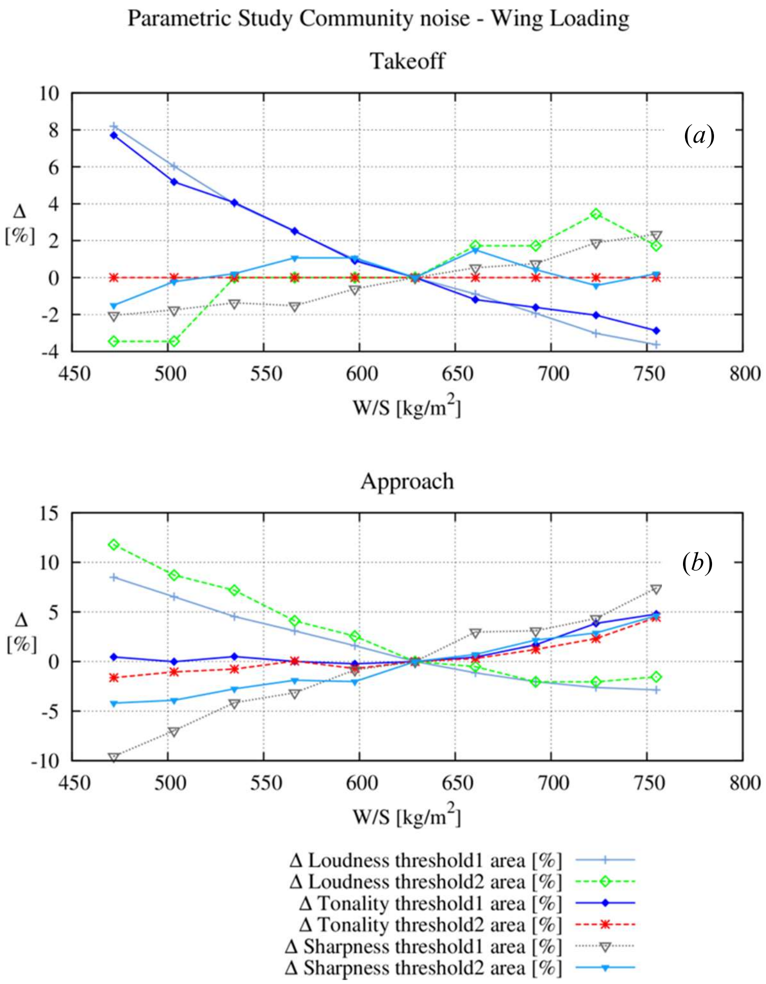

Fig. 4 *W*/*S* variation results for community noise impact for (a) takeoff and (b) approach flight phases in SQ metrics

i. Changes in loudness impacted areas:

For the takeoff phase (Fig. 4 (a)), looking at the loudness impacted areas, it can be observed that the *W/S* variation produces opposite trends for the 65 phon threshold 1 and 85 phon threshold 2 impacted areas. For a lower wing-loading, the threshold 1 loudness impacted area is seen to increase with decreasing *W*/*S*, whereas the threshold 2 loudness impacted area is seen to slightly decrease. Knowing that aircraft noise is dominated by engine noise during takeoff and that the higher noise impact values generally occur closer to the runways while the lower impact values occur farther away from the runways, this observation is linked to how the wing size affects the flight path of the aircraft during departure. In order to elucidate how a lower *W/S* value can increase the threshold 1 loudness impacted area but decrease the threshold 2 loudness impacted area during takeoff, Fig. 5 shows three departure flight paths of SR aircraft design variants having *W*/*S* values of 471.8 kg/m^2 (a larger wing size), 629.1 kg/m^2 (the reference value) and 754.9 kg/m^2 (a smaller wing size). Fig. 5 (a) shows that during the initial takeoff phase, when the thrust setting is maximum (*N1* = 100%), the larger wing for the low *W/S* value of 471.8 kg/m^2 makes the SR variant require a shorter ground roll to take off, which results in the aircraft flying at higher altitudes initially compared to the reference SR aircraft. This results in the smaller threshold 2 loudness impacted area for the lower *W*/*S* values.

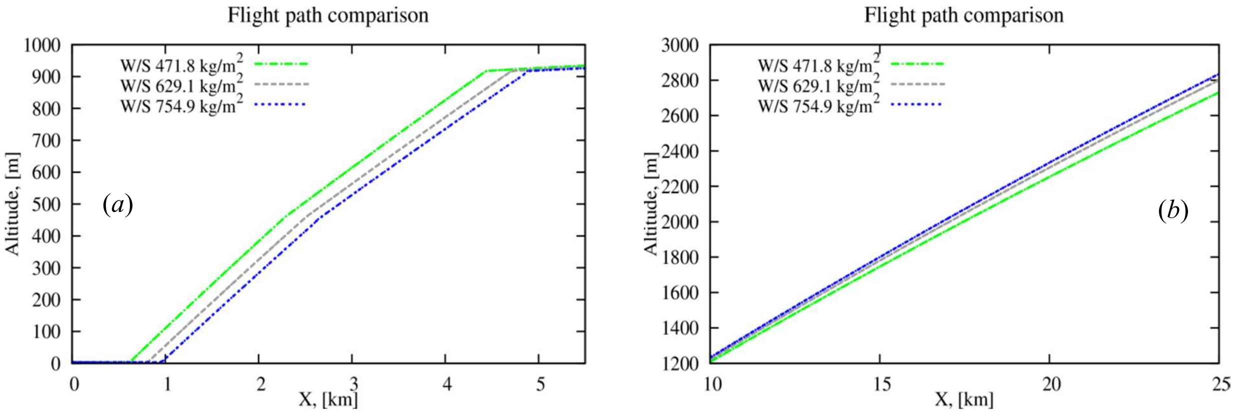

Fig. 5 Flight path comparison for low and high *W*/*S* values – (a) initial departure and (b) later departure phase

Over the whole procedure however, Fig. 5 (b) shows that at larger distances from the point of brake release on the runway (taken as the origin, X = 0), the larger wing for the low *W*/*S* value results in the aircraft flying at slightly lower altitudes in the later departure phase. As modeled in MICADO, for a standard takeoff procedure, the engine thrust is reduced to a cutback setting from X = 10 km (in the range of *N1* = 90%), from which point onwards the differences in flight altitude start becoming noticeable for the three wing-loading variants. As the aircraft has less thrust available from X = 10 km onwards, yet is slightly heavier due to the larger wing, the aircraft begins to fly at a lower altitude for low wing-loading values. This results in the increased threshold 1 loudness impacted area for low *W*/*S* values during takeoff.

For the approach phase, shown in Fig. 4 (b), the airframe noise is generally of comparable intensity to engine noise and this is also the seen for the SR aircraft's noise modeled using INSTANT (98 EPNdB for engine noise and 96 EPNdB for airframe noise at the approach certification point). The changes in noise impact on the ground during approach can therefore be both due to changes in the approach flight path, as for the departure phase, as well as due to changes in the airframe noise produced by the scaled wing and high lift devices. It can be observed in Fig. 4 (b) that both of the loudness threshold areas decrease with a higher wing-loading and the corresponding smaller wing size. For the *W*/*S* studies carried out for the SR aircraft, the aircraft was redesigned for the smaller wing size and ultimately produced lower airframe noise. The reduction in airframe noise due to the smaller wing size therefore outweighed the increase due to a higher approach speed for the high *W*/*S* redesigned aircraft. As modeled in the MICADO environment, a slightly smaller wing of the SR aircraft also results in smaller high-lift devices, as the climb and approach requirements are still met comfortably with the available thrust. A smaller SR wing therefore does not require larger high-lift device areas, which would otherwise partly increase the airframe noise. As is seen in Section V, the smaller wing SR aircraft indeed has a higher approach speed during landing, as would be expected.

ii. Changes in tonality impacted areas:

An interesting observation in the *W*/*S* variation and its effect on the sound quality metrics in Fig. 4 is that a change in wing-loading can also alter the tonality of aircraft noise, albeit the changes are slight. Airframe noise, as currently modeled in INSTANT, is purely broadband and tones due to fuel vents or other cavities in the airframe structure are currently not modeled. A change in the tonality of aircraft noise due to airframe noise variation is in this case due to how airframe noise affects the prominence of fan tones, and how effectively it can mask the fan tones, besides possible changes to the flight path. For the takeoff phase, it can be noted in Table 2 that the tonality impact of the SR aircraft is quite low due to the broadband jet noise dominating the fan tonal noise at maximum and close to maximum engine thrust settings (0.06 t.u. at the flyover certification point, compared to 0.1 t.u. at the approach point). As such, changes to the airframe noise intensity will not be sufficient to significantly affect the fan tones' prominence in the overall aircraft noise spectra. The tonality changes for the takeoff phase in Fig. 4 (a) are mainly due to changes in the aircraft's flight path, shown previously in Fig. 5. The low tonality threshold 1 area increases for low *W*/*S* values since the aircraft, because of its larger wing size, then flies closer to the ground farther away from the runway and the fan tones undergo lower atmospheric absorption. For the fundamental fan tone occurring at 2600 Hz for the thrust cutback setting, the observed difference in altitude of approximately 100 m results in atmospheric absorption being reduced by 2 dB. The opposite effect is analogously seen for high *W*/*S* values. The high tonality threshold 2 area during takeoff remains unaffected for any *W*/*S* variation, as the SR tonality during takeoff never exceeds the higher threshold 2 value of 0.1 t.u. The low tonal content of the SR aircraft during takeoff can also be observed in the respective takeoff spectrograms, presented in Section V-B.

During the approach phase, the tonality of aircraft sounds is much higher due to the aircraft flying at flight idle thrust setting (30-40% *N1*). For such low thrust settings, the jet noise is of much lower intensity and fan noise is therefore the dominant engine noise component. This is reflected in Table 3, where both threshold 1 and threshold 2 tonality impacted areas are significantly higher than during takeoff. Fig. 4 (b) shows that a higher *W*/*S* value can increase both the low and high tonality impacted areas by slight amounts. This is attributed to the fact that the smaller wing for high *W*/*S* values produces lower airframe noise (wing size reduction again outweighing approach speed increase in the current study), and a reduction in airframe noise makes the fan tones gain a greater tonal prominence relative to the overall aircraft noise spectra. A reduction in tonality impacted area of 5% is however relatively low and a higher reduction in tonality would be needed to significantly alter the tonal perception due to a change in wing-loading. Whether such a change in tonality is perceptible or not depends on the tonal frequencies and levels, as well as on the levels and composition of other noise components present in the spectra. Further research may be needed to quantify when a change in a particular SQ metric starts becoming noticeable to a listener.

iii. Changes in sharpness impacted areas:

As mentioned earlier, sharpness of aircraft noise is a factor that doesn't severely affect the perception of annoyance but it nonetheless indicates if design changes have resulted in an increase or decrease of high frequency noise. It can be seen in Fig. 4 that both threshold 1 and threshold 2 sharpness impacted areas decrease for decreasing *W*/*S* values. This indicates that the ratio of high to low frequency noise in the spectra has decreased, or equivalently, the low frequency noise content has increased. As explained earlier, low *W*/*S* values correspond to a larger wing size, which in turn produces more low frequency airframe noise, peaking at frequencies lower than 2700 Hz.

iv. Changes in dBA and EPNL impacted areas:

To compare the changes presented for *W*/*S* variations in sound quality metrics with changes in the dBA and EPNL certification metrics, Fig. 6 shows the corresponding changes in community noise impact for the SR aircraft in terms of the certification metrics. When comparing with the changes in sound quality metrics, for the most part, the variation in the community noise impact in terms of the dBA metric for the SR aircraft is aligned with the loudness variations. The changes in the dBA threshold 2 impacted area during takeoff are however twice as large as the changes in the loudness threshold 2 area observed in Fig. 4 (a). It can also be seen that the EPNL metric is seen to follow very similar trends to the loudness metric shown in Fig. 4. This is the case during the approach phase, with the EPNL metric following the same trends and undergoing similar changes in the impacted areas as the loudness metric. The only exception is seen to be the threshold 2 EPNL impacted area during takeoff for low *W*/*S* values, which is seen to follow the same trend as the threshold 1 EPNL area, compared with a very slight opposite trend for the loudness impacted areas seen in Fig. 4.

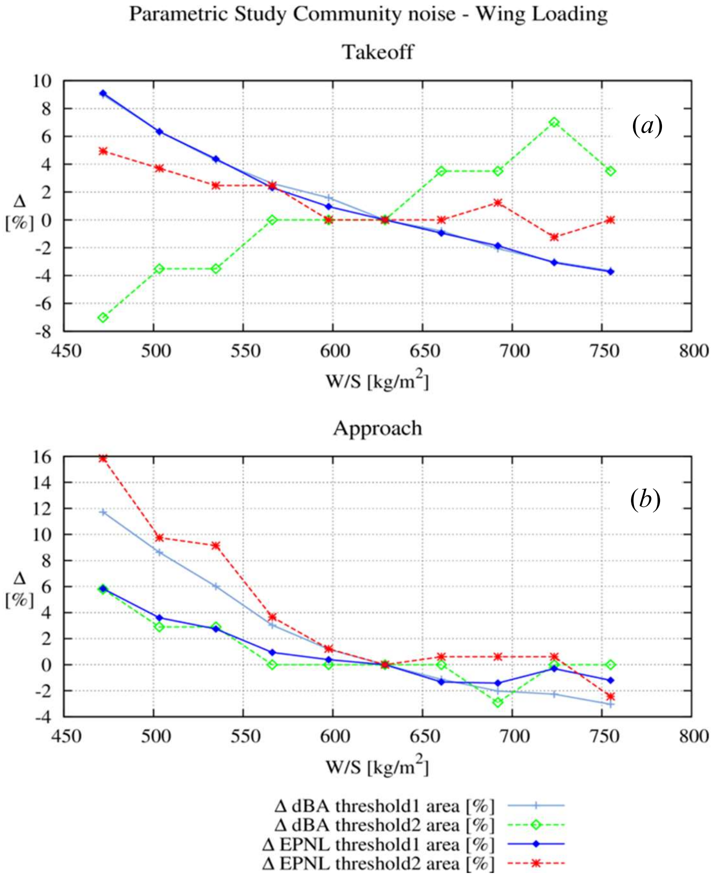

Fig. 6 *W*/*S* variation results for community noise impact for (a) takeoff and (b) approach flight phases in dBA and EPNL metrics

B. Thrust to weight ratio (*T*/*W*) variation

Fig. 7 shows the variation of the SR aircraft *T*/*W* around its reference value of 0.311, and its corresponding effect on community noise impact in sound quality metrics. It can be noticed that the changes in terms of the SQ metrics for a variation of the thrust to weight ratio are much larger than what was observed for the *W*/*S* variation in Figs. 4 and 6.

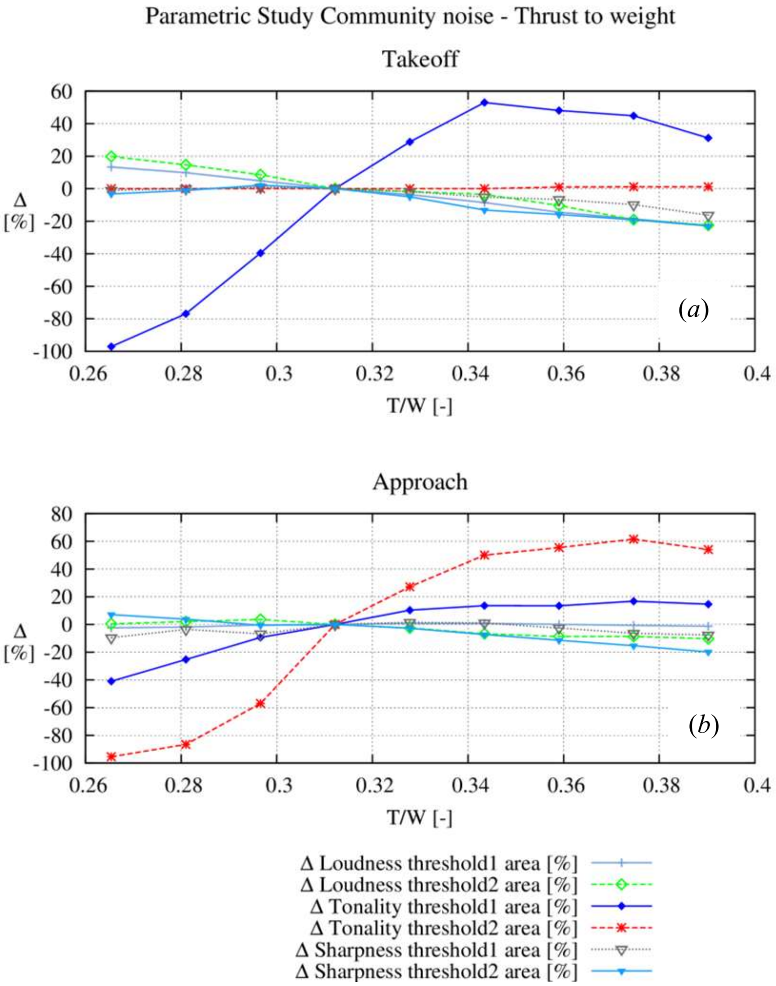

Fig. 7 *T*/*W* variation results for community noise impact for (a) takeoff and (b) approach flight phases in SQ metrics

Looking at the loudness impact on the community during takeoff, it can be observed that both loudness impacted areas are decreased for higher *T*/*W* values and increased for lower *T*/*W* values. This implies that a larger engine, for a higher *T*/*W* value, will be quieter whereas a smaller scaled engine will be (relatively) louder. It can be seen in Fig. 7 (a) that the loudness impacted areas during takeoff can be reduced quite significantly by up to 20% if the *T*/*W* value is increased to 0.395. As for the *W*/*S* variation, a factor that adds to the loudness reduction during takeoff for a *T*/*W* variation is its effect on the flight path. A higher available thrust for comparable aircraft weight and drag allows a steeper climb out of the aircraft. This effect additionally results in a reduced community noise impact due to an increased separation between the aircraft and the ground. The changes in loudness impact for *T*/*W* variation during the approach phase are seen to be lower than during the takeoff phase. For the approach phase, a decrease in the threshold 2 loudness impacted area of up to 10% can be observed for high *T*/*W* values and a slight increase of up to 5% can be observed for low *T*/*W* values.

The most notable observation in the T/W variation for the SR aircraft is the strong change in tonality impact for both the takeoff and approach phases. For the takeoff phase, it can be seen that the threshold 1 tonality impacted area can be reduced to negligible amounts by scaling down the T/W value to 0.265. For the approach phase, the threshold 1 tonality impacted area can be reduced by up to 40% and the threshold 2 tonality impacted area can be reduced to negligible amounts. This implies that the higher tonality during approach is harder to decrease than the lower tonality during takeoff by means of engine scaling. The fact that a larger engine is on the whole quieter but more tonal is seen in general for modern turbofan engines used in the aerospace industry today. A very high bypass ratio engine such as a General Electric (GE) -90 is relatively quieter due to its much lower jet velocities but also has much higher fan tonal noise due to its much larger fan. The fan noise for such large engines can be as strong as jet noise even during takeoff, which is in contrast to what is observed for smaller engines [36].

Looking at the sharpness impact, it can be seen in Fig. 7 that both sharpness impacted areas decrease for higher T/W values, for both takeoff and approach phases. This is rooted in the fact that the number of fan blades for a larger scaled engine decreases according to the empirical database used in INSTANT (see Table 4 for some of the values used for the different designs). This shifts the fan tones to lower frequencies, thereby reducing the sharpness of the aircraft noise reaching the ground. The lower blade number for larger scaled engines is also one of the reasons why the tonality increases for high T/W values, as the frequency weighting in Aures' tonality calculation method gives a higher tonality perception to lower frequencies, with maximum tonality perceived in the range of 500-1000 Hz.

V. Design optimization possibilities

This section combines the analysis performed in the previous section and explores the possibility of low annoyance aircraft design i.e. the possibility of designing aircraft that may be perceived as less annoying due to having considered the sound quality of aircraft noise as an optimization target. It is understood that an optimization for a single sound quality metric may not necessarily yield a lower annoyance design and feedback from listening tests will be needed to confirm whether any reduction in annoyance by lowering an individual SQ metric has indeed been achieved. The use of combined annoyance models, such as those proposed by Fastl [8] and More [7], which combine the effects of individual SQ metrics into an overall metric, may also be more apt in capturing overall annoyance. The goal in this paper is to however analyze the design sensitivities for each individual metric first, before an overall annoyance model can be applied. It is considered important to firstly quantify individual sensitivities for each metric, which may otherwise be masked if only an overall annoyance metric is used. Both Fastl and More's models are furthermore dominated by loudness and the effect of tonality or another SQ metric may for instance not be noticed, unless focused on individually. The application of overall annoyance models as design optimization targets, as well as comparisons with feedback from listening tests, are considered important next steps to the current low annoyance aircraft design research. The metrics that are used as targets for analyzing optimization possibilities in this paper are the EPNL metric, loudness metric and tonality metric. The MICADO environment has again been used to perform the optimizations of the SR aircraft for community noise impact, in terms of each target metric. Section V-A shows a comparison of the optimized designs in terms of their noise impact in the various metrics. Alongside this, the effect on aircraft performance of each optimized design variant when compared to the reference SR aircraft's performance is also presented. Section V-B then shows how the metric reductions presented for the optimized designs correspond to the actual sound produced on the ground. This is shown via spectrograms of auralized audio for each optimized design, at sample locations on the ground for a standard approach and a standard departure flight path.

A. Comparison of optimized aircraft designs

The optimizations of the SR aircraft have been made by varying the T/W and W/S values simultaneously, over a range of ±25% from their reference values. This has been done for the same target MTOW and OWE as the reference SR aircraft and for the same TLARs. The TLARs have not been enforced as design constraints to allow the optimizer of the MICADO environment to have more design options available while searching for an optimum. The optimization target here is the cumulative (sum of takeoff plus approach) threshold 2 community impacted area for each target metric, with the aim of reducing the higher community noise impact values. To keep track of the potentially adverse effects on aircraft performance of optimizing aircraft for minimal noise impact, changes in the aircraft MTOW, OWE and block fuel are presented, as well as the requirements for the Takeoff Field Length (TOFL), time to climb from 1500 ft to the Initial Cruise Altitude (ICA), approach speed V_{app} and Landing Distance (LDN). The values of these parameters for the reference SR aircraft are: TOFL = 2200 m, time to climb to ICA = 25 min, V_{app} = 138 knots and LDN = 1850 m.

Table 4 shows the relevant aircraft design and performance parameters for the reference SR aircraft design, the minimal EPNL impact SR design, the minimal loudness impact SR design and the minimal tonality impact SR design.

The cumulative community noise impact in terms of the A-weighted level, EPNL, loudness and tonality metrics is presented and the noise impact is also shown at the certification points. Furthermore, some engine and airframe geometry parameters are also shown for each design variant, which serve as inputs to the INSTANT source noise models and aid in explaining some of the resulting noise impact changes on the ground.

Table 4 Comparison of reference SR aircraft with minimal EPNL, minimal loudness and minimal tonality optimized designs

Parameter Name	*Reference SR*	*Minimal EPNL*	*Minimal Loudness*	*Minimal Tonality*
Engine geometry parameters				
Fan inlet area, A_{fan} [m^2]	2.058	2.585	2.58	1.895
Fan rotor blades, B [-]	31	29	29	43
Primary jet area, $A_{jet,1}$ [m^2]	0.201	0.285	0.285	0.172
Secondary jet area, $A_{jet,2}$ [m^2]	1.01	1.26	1.26	0.92
Airframe geometry parameters				
Wing area, S [m^2]	117.68	112.37	117.17	131.35
Wing span, b [m]	33.39	32.64	33.32	35.24
Aircraft design and performance parameters				
Wing-loading, W/S [kg/m^2]	629	689	659	556
Thrust-to-Weight ratio, T/W [-]	0.312	0.400	0.400	0.275
Max SLST [kN]	113.34	151.87	151.46	98.36
MTOW [kg]	74014	77428	77221	73046
OWE [kg]	40166	42047	42133	39731
Block fuel [kg]	13910	15235	15017	13548
TOFL [m]	1962.05	1553.56	1487.92	2273.4
Time to climb to ICA [min]	15.89	9.73	9.74	22.25
Approach speed, V_{app} [kts]	138.05	144.0	140.88	130.48
LDN [m]	1517.45	1591.87	1552.46	1425.88
Cumulative certification noise impact				
Cumulative SPL [dBA]	245.86	241.57	239.89	245.94
Cumulative EPNL [EPNdB]	275.51	270.0	270.19	274.64
Cumulative loudness [sone]	148.87	132.85	134.21	148.69
Cumulative tonality [t.u.]	0.246	0.290	0.290	0.153
Cumulative community noise impact				
75 dBA SPL area [km^2]	5.04	3.72	3.88	4.88
85 EPNdB EPNL area [km^2]	13.04	7.12	7.24	13.08
85 phon loudness area [km^2]	12.44	9.64	9.56	13.64
0.1 t.u. tonality area [km^2]	127.84	111.84	112.72	12.44

i. Effect on noise impact:

It can be observed in Table 4 that the optimizer of the MICADO environment attempted to minimize the noise impact in the EPNL and loudness metrics by selecting as large an engine as possible, by increasing the T/W to the maximum allowed value of 0.4. This increased the engine's fan inlet area and secondary jet areas by around 25% as well as the primary jet area by 40%. Furthermore, the optimizer also selected a slightly smaller wing than the reference design, in order to choose a design variant that minimizes the higher 85 EPNdB and 85 phon loudness values on the ground. The trends for the EPNL and loudness metrics were seen to be similar for the SR aircraft in Section IV as well. A W/S value of 689 kg/m^2 was found as an optimum for the minimal EPNL design and a W/S value of 659 kg/m^2 for the minimal loudness design. It can be seen that the minimal EPNL design produces a cumulative reduction in the 85 EPNdB impacted area of 45% and a 5.5 EPNdB cumulative reduction at the certification points.

The minimal loudness design reduces the cumulative 85 phon area by 23.2%, which is slightly higher than the loudness reduction of 22.5% produced by the minimal EPNL design (the two optimized designs being so similar to each other). It can be noted that the minimal loudness design does not produce the highest loudness reduction at the certification points - 12 sone compared to the 13.5 sone reduction shown by the minimal EPNL design, which indicates the importance of looking at community noise impact separately to certification noise impact. Both the minimal EPNL and minimal loudness designs produce reductions in community noise impact in the other metrics as well, with a reduction in the cumulative 75 dBA impacted area of 26.2% and 23% respectively, and a reduction in the cumulative 0.1 t.u. impacted area of 12.5% and 11.8% respectively. Both designs show an increased tonality at the certification points however, the tonality increasing due to the slightly lower fan rotor blade number and the lower $N1$ of the larger scaled engine, which shifts the fan tones to lower frequencies.

The minimal tonality design is seen to be considerably different compared to the minimal EPNL and minimal loudness designs. The MICADO optimizer selected a smaller engine via a T/W value of 0.275 and a larger wing via a W/S value of 556 kg/m^2 to minimize the cumulative 0.1 t.u. tonality impact on the ground. The smaller engine has an approximately 8-9% smaller fan inlet and secondary jet area, and a 14% smaller primary jet area. It can also be observed that the number of fan rotor blades for the smaller scaled engine is higher, with 12 additional rotor blades. With the different design, the noise impact of the minimal tonality design is also noticeably different compared to the other optimized designs. It can be seen in Table 4 that the minimal tonality design affects the noise impact in the certification metrics in a very minor way. In terms of sound quality, it increases the loudness impacted area by approximately 10% but significantly reduces the cumulative 0.1 t.u. tonality impacted area by 90.3%. This reduction does not imply that the tonality has been completely removed but rather that the tonal content in terms of its unmasked prominence has been reduced significantly to levels below 0.1 t.u. Such a reduction in the tonal content was not captured by any of the other metrics including the EPNL metric, for which the tonal content of the SR aircraft wasn't high enough to acquire the higher tonal penalties.

It can be seen that the noise impact of the SR aircraft is different depending on the metric it has been optimized for. The loudness metric attempts to lower the overall intensity of the noise reaching the ground and the tonality metric reduces quite significantly the impact of the tonal content, with a slight increase in loudness impact. A tradeoff will likely have to be made to determine if the slight increase in loudness is worth undergoing to achieve the larger reduction in tonality and a possible reduction in perceived annoyance. The use of an overall annoyance metric, such as that of More et al. that considers the combined effects of loudness and tonality, would also be useful for future studies. For the SR aircraft, the EPNL metric does not capture the tonal content well and ultimately minimizes the overall spectral energy of the noise signatures, similar to the loudness metric. The noise impact expressed in the dBA metric also fails to capture any change in the tonal content. The consideration of the noise impact in terms of the sound quality of aircraft noise is therefore seen to provide clearer information regarding the character of the sound reaching the ground than what is seen by looking at the certification metrics.

ii. Effect on aircraft performance:

For aircraft design purposes, it is important to also consider the effect on aircraft performance that any optimization for minimal noise impact may produce, such that it may realistically be implemented by aircraft designers and by the aerospace industry. As noise or annoyance are never the primary target of an aircraft design optimization, certain losses in performance can be expected at early stages when considering noise as an optimization target, which one can attempt to minimize with refined subsequent analysis. It can be observed in Table 4 that in order to minimize the community noise impact in the EPNL metric, the SR aircraft becomes heavier, due primarily to the choice of the larger engine. The MTOW value is seen to increase by 3414 kg and the OWE sees an increase of 1881 kg, along with an increase in the block fuel of 1325 kg. This indicates that an optimization for minimal EPNL impact for the community, performed without consideration of fuel burn, would adversely affect the SR aircraft performance. It can be mentioned here that an increase in the engine size by 23%, as selected by the optimizer for the minimal EPNL design, is purely to explore the optimization limits. A smaller increase in engine size may be a more pragmatic approach, if such an optimization is desired to be pursued realistically, and the consideration of fuel burn during the design optimization would also reduce this adverse effect for an EPNL optimization. The minimal EPNL SR design, despite its heavier weight, still fulfills the TOFL, time to climb as well as LDN requirements. The smaller wing for the design however results in an increase in the approach speed to 144 knots, which is over the required approach speed of 138 knots for the reference SR aircraft. A similar effect on performance is seen for the minimal loudness design, with takeoff performance improved due to the larger engine but overall increase in aircraft weight and fuel consumed observed.

Looking at the minimal tonality design, it can be seen that minimizing the tonal impact for the community does not result in an increase in the MTOW and OWE values or also in the block fuel consumed, at a conceptual or preliminary design level. This is primarily due to the smaller engine being lighter than the reference engine, which compensates for the increase in aircraft weight from the larger wing size. With regards to the SR design requirements, because of the smaller engine of the minimal tonality design, it narrowly fails to meet the required TOFL of 2200 m, requiring 2273 m to takeoff. The climb performance of the minimal tonality design is also poorer than the reference SR design, but nonetheless still meets the specified SR requirement. As can be expected, the larger wing allows the minimal tonality design variant to have a lower approach speed and a smaller landing distance to come to a halt after touchdown, thereby meeting the V_{app} and LDN requirements comfortably.

It can be observed that the adverse effects on aircraft performance are indeed present for the sound quality optimized aircraft designs. These effects, at least at a conceptual design level, do not however appear to be so extreme such that they may prove the parallel consideration of aircraft noise annoyance during design, via the SQ metrics, impractical.

B. Correlation of optimized designs with sound

Any reduction in an aircraft noise metric's numeric value should ideally result in a less annoying and more acceptable sound that reaches the residents from the aircraft. In order to see how the changes in the metrics correspond to the actual sound reaching residents at sample locations, auralized sounds of the optimized SR aircraft design variants were created and compared with the auralized sounds of the reference SR aircraft. Fig. 8 shows the spectrograms for a standard approach at a ground location of (X,Y) = (-25 km, 0 km) for the reference SR design in Fig. 8 (a), for the minimal tonality design in Fig. 8 (b), for the minimal EPNL design in Fig. 8 (c) and for the minimal loudness design in Fig. 8 (d).

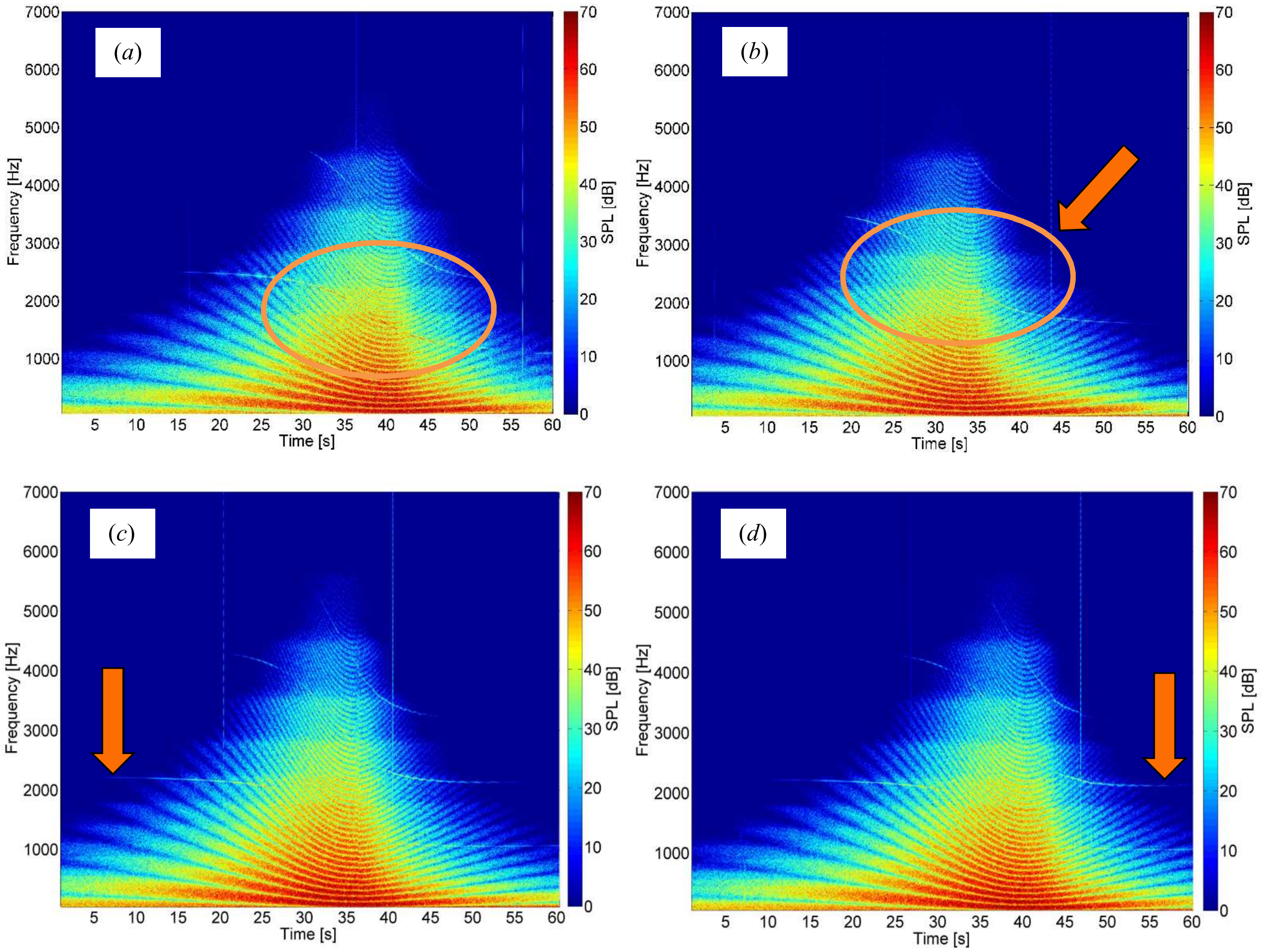

Figure 8 Spectrograms of auralized audio at (X,Y) = (-25 km, 0 km) for a standard approach procedure: (a) Ref. SR design, (b) Min. tonality design, (c) Min. EPNL design and (d) Min. loudness design.

The comparison of Fig. 8 (a) and Fig. 8 (b) shows that, overall, the reference and minimal tonality SR designs have spectrograms that deviate hardly at all in terms of the broadband content, but differ quite noticeably in terms of tonal content. The circled areas of the spectrograms in Fig. 8 (a) and Fig. 8 (b) show that the fundamental fan tone for the minimal tonality design has a considerably reduced maximum intensity, i.e. it has been lowered by more than 10 dB compared to the reference SR aircraft. It can also be observed that the fundamental fan tone, at the specified location, has been shifted to a higher frequency for the minimal tonality design from 1800 Hz to 2500 Hz, due to the higher B and higher $N1$ for the smaller scaled engine. Furthermore, the reference SR spectrogram has three noticeable tones with two having a significant intensity for large durations of the procedure whereas the minimal tonality design has only two tones noticeable. The difference in broadband content for both designs is minimal, but the overall sound which is produced, due to the lower tonality, gains an audibly perceivable different character. As mentioned in Section I, the tonal content is a significant contributor to the perceived annoyance due to aircraft noise, and the minimal tonality SR design presents one approach of minimizing this tonal impact. More certainty as to whether a clear reduction in annoyance based on the altered sound has indeed been achieved will require feedback from psychoacoustic surveys with test audiences, which was beyond the current scope and is planned for future studies. The use of an overall annoyance model that considers tonality alongside loudness would also be a logical next step, as mentioned earlier.

Figures 8 (c) and 8 (d) show the sounds produced at the same ground location if the minimal EPNL and minimal loudness designs are flown on the standard approach procedure. It can be seen that both design variants produce very similar sounds at the observer location. The broadband content is slightly increased for both designs compared to the reference SR aircraft, due mainly to the minimal EPNL and minimal loudness design variants being slightly lower in altitude at the location of (X,Y) = (-25 km, 0 km). This slight change in broadband content is however almost indistinguishable while listening to the audio files. It can also be noticed in the spectrograms of Figs. 8 (c) and 8 (d) that the fan tones for the minimal EPNL and minimal loudness designs occur at slightly lower frequencies than for the reference SR aircraft. This is due to the lower *N1* required during the approach procedure by the much larger engine, and, as mentioned earlier, due to a slightly lower blade number of the larger scaled engine (cf. Table 4). As lower frequencies are absorbed less effectively by the atmosphere and also due to the aircraft flying at slightly lower altitudes, the fan tones are audible over longer durations of the approach procedure than for the reference SR design (indicated by the arrows in Figs. 8 (c) and 8 (d)).

Figure 9 shows the differences in the sounds produced by the reference SR aircraft and the minimal loudness design for a standard departure at a ground location of (X,Y) = (12.5 km, 0 km). At this ground location, the minimal loudness design shows a clearly reduced overall spectral energy compared to the reference SR design. This is firstly due to the larger engine being quieter and secondly, as the minimal loudness aircraft has more available thrust for its larger scaled engine, it also flies at a higher altitude at this location. The fan tone that is slightly noticeable in Fig. 9 (a) has also been absorbed completely in the minimal loudness design's departure spectrogram in Fig. 9 (b). Although the fan tones along with the other source noise components are reduced for the minimal loudness design, this is primarily due to the fan tones being absorbed more effectively by the atmosphere due to the increased altitude of the minimal loudness design during takeoff. Fig. 9 shows that the loudness metric captures the overall spectral energy of aircraft noise quite well and its reduction indicates that the sound reaching the ground will on the whole be quieter.

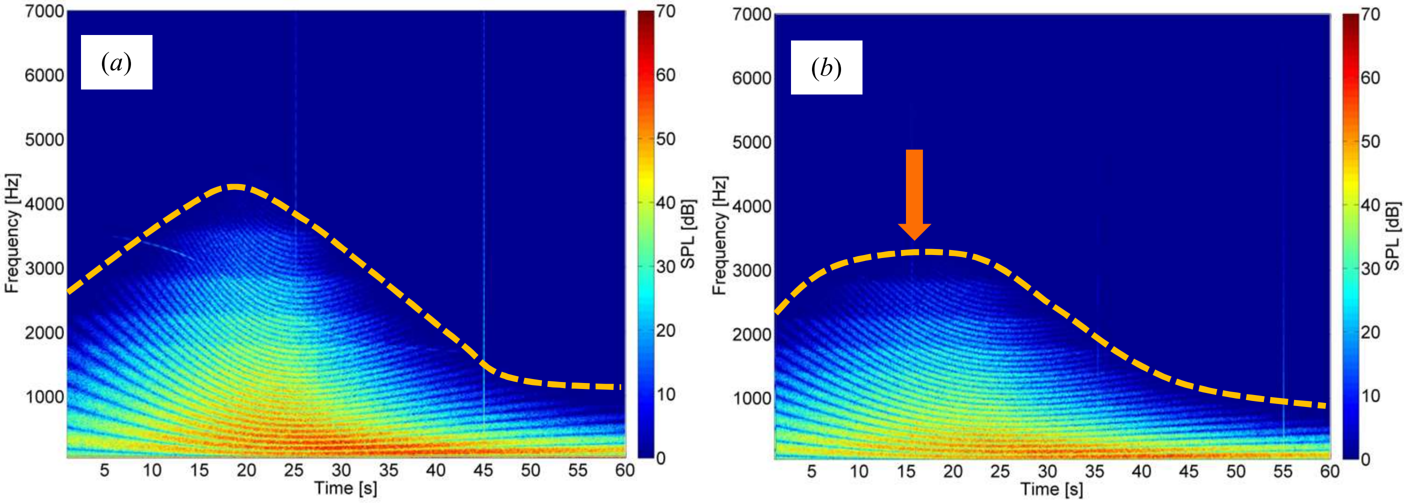

Figure 9 Spectrograms of synthetic audio created at (X,Y) = (12.5 km, 0 km) for a standard departure procedure – (a) Ref. SR design (b) Min. loudness design.

VI. Conclusion

It can be concluded in this paper that the dBA and EPNL certification metrics currently used in the aerospace industry do not fully capture important attributes of the aircraft's sound, which are known contributors to the perception of annoyance. The tonal content is seen to be particularly poorly captured by the certification metrics. Considering the annoyance in terms of the sound quality of aircraft noise can provide additional and clearer information about the character of the sound, which is not fully captured by the certification metrics. The loudness metric provides information on the overall spectral energy of aircraft sounds and shows similar trends to the EPNL metric for the considered short range aircraft. The tonality metric provides information focusing solely on the tonal content, offering a potential improvement over the certification metrics. Initial optimizations for the various metrics in this paper show that the same reference aircraft can have a noticeably different sound depending on the metric it was optimized for. The analysis indicates that by focusing on the right metrics, the sounds of an aircraft could be modified towards potentially less annoying and more acceptable sounds, by modifying the design in a focused way. For this purpose, the use of a combined annoyance model that combines the effects of the individual metrics, and performing listening tests to confirm whether the sounds are indeed perceived as less annoying, are seen as critical next steps. The adverse effects of such designs optimized for sound quality on the aircraft performance also need to be analyzed in more detail in the future. The approach of incorporating sound quality considerations in the aircraft design process nonetheless provides a new means of approximating the perceived aircraft noise impact experienced by the community and reducing this perceived noise impact by modifying the aircraft's design.

References

[1] S. S. Stevens, "The measurement of loudness," *Journal of the Acoustical Society of America,* vol. 27, pp. 815-829, 1955.

[2] K. D. Kryter, "Concepts of perceived noisiness, their implementation and application," *Journal of the Acoustical Society of America,* vol. 43, no. 2, pp. 344-361, 1967.

[3] E. Zwicker, "On the dependence of unbiased annoyance on loudness," in *International Conference on Noise Control Engineering; Newport Beach, CA, USA*, 1989.

[4] W. Aures, "Procedure for calculating the sensory euphony of arbitrary sound signals," *Acustica,* vol. 59, pp. 130-141, 1985.

[5] G. von Bismarck, "Sharpness as an attribute of the timbre of sounds," *Acustica,* vol. 30, pp. 159-172, 1974.

[6] J. R. Angerer, R. A. Erickson and D. A. McCurdy, "Development of an annoyance model based upon elementary auditory sensations for steady-state aircraft interior noise containing tonal components," NASA TM-104147, 1991.

[7] S. More, "Aircraft noise metrics and characteristics," PhD thesis Purdue University, 2010.

[8] E. Zwicker and H. Fastl, Psychoacoustics -Facts and models, Berlin, Heidelberg, New York: Springer Verlag, 1990.

[9] A. K. Sahai, E. Anton and E. Stumpf, "An interdisciplinary apporach for a virtual air-traffic system simulation for subjective assessment in VR environments," in *28th International Congress of the Aeronautical Sciences (ICAS)*, Brisbane, Australia, 2012.

[10] A. K. Sahai, F. Wefers, S. Pick, E. Stumpf, M. Vorländer and T. Kuhlen, "Interactive simulation of aircraft noise in aural and visual virtual environments," *Applied Acoustics,* vol. 101, pp. 24-38, 2016.

[11] K. Risse, K. Schäfer, F. Schültke and E. Stumpf, "Central Reference Aircraft data System (CERAS) for research community," *CEAS Aeronautical Journal,* vol. 7, no. 1, pp. 121-133, 2016.

[12] A. K. Sahai and E. Stumpf, "Incorporating and minimizing aircraft noise annoyance during conceptual aircraft design," in *20th AIAA/CEAS Aeroacoustics Conference - Part of AVIATION forum*, Atlanta, GA, USA, 2014.

[13] A. K. Sahai, "Consideration of Aircraft Noise Annoyance during Conceptual Aircraft Design," PhD Dissertation, RWTH Aachen University, Aachen, 2016.

[14] A. K. Sahai and E. Stumpf, "A comparative analysis of the subjective assessment of standard and noise abatement flight procedures," in *NoiseCon 2013 - Proceedings of NoiseCon and InterNoise 2013, INCE*, Denver, CO, USA, 2013.

[15] L. Bertsch, D. Simons and M. Snellen, "Aircraft Noise: The major sources, modeling capabilities and reduction possibilities," DLR internal report, DLR-IB 224-2015 A110, 29S, Goettingen, 2015.

[16] W. E. Zorumski, "Aircraft noise prediction program theoretical manual," NASA TM 83199, 1982.

[17] J. Kurzke, "Gasturb 11 Users Manual - A program to calculate design and off-design performance of gas turbines," GasTurb GmbH, Institute of Jet Propulsion and Turbomachinery of RWTH Aachen University, 2007.

[18] M. F. Heidmann, "Interim prediction method for fan and compressor source noise," NASA TM-X-71763, 1979.

[19] J. J. Emmerling, S. B. Kazin and R. K. Matta, "Core engine noise control program, Vol III: Supplement 1 - Prediction methods," FAA-RD-74-125, III-1, 1976.

[20] R. K. Matta, G. T. Sandusky and V. L. Doyle, "GE core engine noise investiation - Low emission engines," FAA-RD-77-4, 1977.

[21] J. R. Stone, "An improved prediction method for the noise generated in flight by circular jets," NASA TM 81470, 1980.

[22] M. R. Fink, "Airframe noise prediction method," FAA-RD-77-29, 1977.

[23] International Organization for Standardization (ISO), "Acoustics - Attenuation of sound during propagation outdoors - Part 1: Calculation of absorption of sound by the atmosphere," ISO-9613-1:1993(E), 1993.

[24] C. F. Chien and W. W. Soroka, "Sound propagation along an impedance plane," *Journal of Sound and Vibration,* vol. 43, no. 1, pp. 9-20, 1975.

[25] M. E. Delany and E. N. Bazley, "Acoustical properties of fibrous absorbent materials," *Applied Acoustics,* vol. 3, no. 2, pp. 105-116, 1970.

[26] Society of Automotive Engineers (SAE), "Prediction method for lateral attenuation of airplane noise during takeoff and landing," SAE AIR-1751, Warrendale, Pennsylvania, USA, 1981.

[27] ICAO, "Annex 16 to the Convention on International Civil Aviation: Environmental Protection Volume 1 - Aircraft Noise," ICAO, Montreal, 2011.

[28] K. B. Kontos, B. A. Janardan and P. R. Gliebe, "Improved NASA ANOPP noise prediction computer code for advanced subsonic propulsion system. Volume I: ANOPP evaluation and fan noise model improvement," NASA CR-195480, 1996.

[29] C. Y. Kapper, "Validation of Aircraft Noise Prediction Program," NASA CR-159047, 1979.

[30] B. Berglund, U. Berglund and T. Lindvall, "Scaling loudness, annoyance and noisiness of aircraft noise," *Journal of the Aoustical Society of America,* vol. 57, no. 4, pp. 930-934, 1975.

[31] H. Fastl, "Trading numer of operations versus loudness of aircraft," in *Internoise 90*, 1990.

[32] M. J. Smith, Aircraft Noise, Cambridge: Cambridge University Press, 2004.

[33] E. Zwicker and B. Scharf, "A model of loudness summation," *Psychological Review,* vol. 72, pp. 3-26, 1965.

[34] S. Kerber, "Loudness - Calculation according to DIN 45631," Institute of Human Machine Interaction, TU Munich, [Online]. Available: http://www.mmk.ei.tum.de/~kes/LoudnessMeter/index.html. [Accessed 05 09 2014].

[35] T. Cox, "Sharpness and booming," University of Salford Manchester, [Online]. Available: http://www.salford.ac.uk/computing-science-engineering/research/acoustics/psychoacoustics/sound-quality-making-products-sound-better/sound-quality-testing/sharpness-booming. [Accessed 27 03 2015].

[36] Aerodynamics and design group, "Noise," Stanford University , [Online]. Available: http://adg.stanford.edu/aa241/noise/noise.html. [Accessed 26 03 2015].