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Aircraft noise sound quality evaluation of continuous descent approaches

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ABSTRACT

Continuous Descent Approaches (CDAs) can potentially impact the quality of sounds that aircraft produce. It is known that CDAs can present potential benefits with reductions in excess of 5 dBA (A-weighted level) in peak noise level, L_{Amax}. However, it is unknown if these reductions in A-weighted level, which is known to be a poor predictor of perceived annoyance, also correspond to an improvement in the aircraft noise sound quality. Auralization is used to analyze how the sound in a CDA changes compared to a conventional approach and how sound quality and annoyance are affected. A short-range aircraft flying various conventional approaches and CDAs is simulated. The noise produced over both approaches is auralized at two representative ground locations, 30 and 25 km before touchdown, where the sounds are analyzed for changes in sound quality. The important loudness reduction is the only significant component reducing noise annoyance. Less effective masking leads to higher tonality in CDAs. Some reductions in sharpness and fluctuation strength are also observed at both locations. Changes in roughness are less clear and seem to vary with the location. The benefits of CDAs in terms of predicted annoyance are observed at both locations due to the dominant contribution of loudness in the annoyance metrics. These benefits are expected to be higher the farther away from the airport, with benefits reducing considerably with decreasing distance to touchdown. Auralizing and analyzing the sound quality, not only gives a direct impression of the sounds residents will be exposed to, but also gives additional insight regarding how the changes in the sounds will potentially relate to the perceived annoyance.

Keywords: Continuous Descent Approach; Aircraft Sound Quality; Auralization. I-INCE Classification of Subjects Numbers:13; 52; 76; 79.

1. INTRODUCTION

Global air traffic is forecasted to double within the next 20 years, as indicated in the global market forecasts of Airbus and Boeing (1), (2). A negative consequence of this growth is the increase in noise annoyance suffered by residents living in airport vicinities. To reduce the negative impact to communities and avoid the disadvantage of additional economical noise penalties, alternate noise efficient operations, such as Continuous Descent Approaches (CDAs), are being considered for implementation at various major airports (3), (4). CDA procedures avoid the need for extended periods of level flight employing a reduced engine thrust, ideally in a low drag configuration, prior to the final approach fix. The intention of a CDA is to keep the aircraft at higher altitudes for longer, thereby increasing the distance to observer and reducing noise annoyance. In addition, CDAs can also reduce the aircraft fuel burn, with the consequent overall environmental benefit (3).

Regarding community noise impact, previous studies have shown that CDAs provide potential benefits in terms of community noise with reductions of up to 5 A-weighted decibel (dBA) in peak noise level, L_{Amax} as well as in Sound Exposure Level (SEL) (5). However, it is unclear if these reductions in A-weighted level, which is a poor predictor of perceived annoyance (6), (7), also

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correspond to an improvement in the quality of the aircraft sounds that reach the residents on the ground. An improved sound quality correlates directly with lower perceived annoyance. The L_{Amax} and SEL values only indicate a part of the overall picture with regards to the audible sound an aircraft would produce while flying on a CDA procedure. They do not capture important differences in aircraft sounds such as the influence of tonal components, spectral balance and temporal changes in intensity, which have a direct influence on the perceived annoyance. A clear and comprehensive comparison can therefore only be made by comparing the sounds in terms of sound quality an aircraft produces while flying a CDA with a standard approach procedure. In order to so, the use of the technique of auralization can be applied, with synthesizing sounds being a more economical option than performing flight tests. The synthesized sounds will not only give a direct audible impression of the acoustic signature on the ground, but they can furthermore be correlated to changes in annoyance, by performing a sound quality analysis of the resulting sounds and computing the overall predicted annoyance using the computed sound quality metrics. It can then become clear what the A-weighted level changes imply in terms of annoyance and if the CDAs will actually fulfill their goal of reducing the community noise impact.

The paper is divided into five main sections. The study setup is explained in Section 2, where the reference aircraft's specifications are described in Section 2.1. The flight paths are presented in Section 2.2. Section 2.3 shortly describes the Integrated Noise Simulation and Assessment module (INSTANT), while the auralization procedure is treated in Section 3. Section 4 briefly explains the noise assessment methodology followed to perform the noise assessment in standard and sound quality. The comparison of the flight paths in the various metrics is presented in Section 5, with the conclusions of the current study provided lastly in Section 6.

2. STUDY SETUP

The reference aircraft used for the analysis is described in Section 2.1.The study missions, i.e., the reference approach and CDA flight paths modeled and analyzed in this paper can be found in Section 2.2. How the noise is predicted at the source is explained in Section 2.3.

2.1 Reference aircraft

A short-range aircraft has been selected as reference. A greater relative growth within the next 20 years in domestic traffic is expected, as compared to international flights (1), (2). Domestic flights typically have a shorter range, which leads to a higher number of movements per hour. They represent therefore a more frequent annoyance than long-range flights. Among the most common short-range aircraft, the Airbus A320, in its different versions, is an actual and future representative airplane with a large number of aircraft in operation, as well as a large total number of orders. From a European perspective, in the year 2015, the A320 accumulated over three times more movements than its biggest competitor, the Boeing B737 at Heathrow airport (3). Based on this reasoning, the approach of an A320-like aircraft can be regarded a representative scenario of a random European airport.

Table 1 – Design specifications of the reference aircraft

Parameter	Unit	Value
MTOM	kg	73414
OME	kg	42090
MLM	kg	61900
Max. Fuel	kg	19135
Max. Payload	kg	18633
Pax. Capacity	-	150
Engine Type (2x)	-	V2527-A5
SLST	kN	119941
Design Range	NM	2344
Cruise Mach	-	0.78

More precisely, the reference aircraft is an A320-200 similar aircraft, which has been designed using the Multidisciplinary Integrated Conceptual Aircraft Design and Optimization (MICADO) Environment of the Institute of Aerospace Systems (ILR), of RWTH Aachen University. The MICADO environment allows for an automated aircraft design and assessment capability, given a set of top-level requirements and specifications (8). The basic design specifications of this aircraft are presented in Table 1. In Table 1, the parameter MTOM is the Maximum Takeoff Mass, OME is the Operating Mass Empty and MLM is the Maximum Landing Mass of the designed aircraft; SLST refers to the Sea-level Static Thrust of the modeled engines. It can be seen that the aircraft is required to carry 150 passengers over a design range of 2344 Nautical Miles (NM), which is typical for such short-range aircraft. The values in Table 1 are seen to be in close agreement with an actual A320-200 aircraft (8).

2.2 Study missions

Both study approaches are regarded as precision approaches. Firstly, conventional step approaches with horizontal flight segments at two typical altitudes, 2000 and 3000 ft., are modeled (9). Next, the CDAs are simulated for two different continuous descent glide slope angles, 3 and 4 degrees, prior to the Instrument Landing System (ILS) final segment glide slope interception.

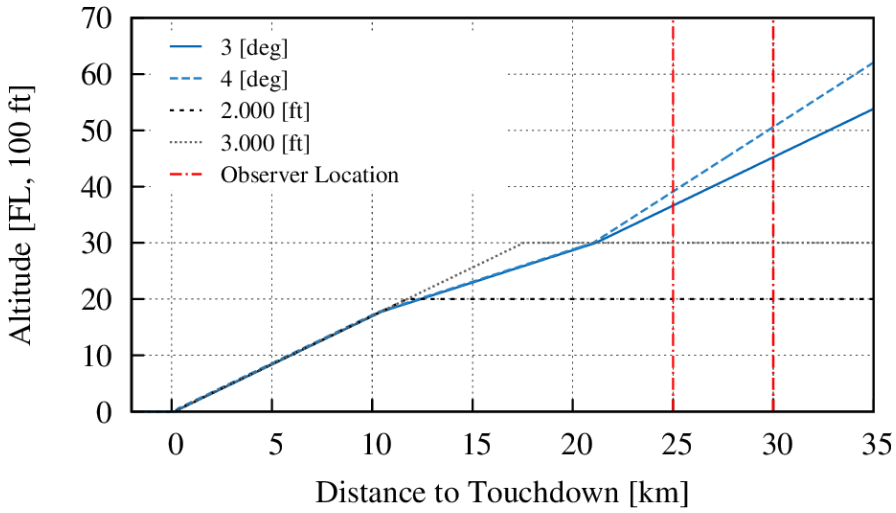

Figure 1 – Flight path comparison of the modeled approach paths

A descent is deemed to be continuous if no segment of level flight extending over a horizontal track distance longer than 2.5 NM occurs, below a flight altitude of 6000 ft. Level flight in this regard is interpreted as any segment of flight that does not have a height change of more than 50ft over a track distance of 2 NM or more (3). As can be observed in Fig. 1, below around 1500 ft (i.e. a Flight Level (FL) of 15) there is no difference between flight paths. This is due to the fact that for a precision approach, the final segment begins at the Final Approach Point (FAP), which is defined as the point on the localizer centerline (or the specified ILS azimuth) where the intermediate approach altitude intercepts the nominal glide path. This can occur at heights between 1000 ft (300m) and 3000 ft (900m) which in the case of a 3° (300ft/NM) glide path will occur at a distance between 3 NM (5.5km) and 10 NM (18.5km) from the touchdown point (9). Consequently, it can be expected that no difference in aircraft community noise annoyance will occur between approach procedures from this segment onwards. With this fact in mind, two observer locations have been selected, one located at 30 km and one at 25 km directly below the flight path. It is expected that potential benefits of CDAs would be encountered at these locations. Some relevant parameters defining the aircraft trajectory for each considered flight path at both observer locations are presented in Table 2. Here, TAS refers to the aircraft True Airspeed, ROC to Rate of Climb and C_L refers to the lift coefficient.

The flight path segment altitudes and aircraft configuration have been selected according to the standard operating procedures of the A320. Since an altitude of 2000 ft is the lowest height permitted before second flap step deflection, which is automatically followed by landing gear extension, the conventional approaches are flown in approach configuration prior to the ILS final segment glide slope interception. Approach configuration in this regard implies that the flaps have been deflected to 14 degrees, and the slats to 18deg. The CDAs are flown however in a clean configuration and low thrust

setting until the FAP. In the CDA trajectories (see Figs. 1 and 2), a segment between 3000 and 2000 ft, can be observed, where the glide slope is captured by the aircraft. To avoid a glideslope capture from above, where the pilot workload would be considerably increased, an intermediate flight segment with a 2 degree glide slope angle has been defined, allowing enough time for the aircraft to reduce the speed excess before setting the approach configuration. Figure 2 shows a graphical variation of important flight parameters, besides the altitude profile of the modeled flight paths in Figure 1. These figures include variations over the flight path of the true airspeed in knots, the ratio of engine thrust, T to Sea-level Static Thrust, SLST, and variation of the low-pressure spool speed N1 in revolutions per minute. Fig. 2 left) shows the operational parameter variations for the conventional approaches and Fig. 2 right) for the CDAs

Table 2 – Distinguishing parameters for the modeled approach paths

	Altitude[m]		TAS[m/s]		Thrust[kN]		ROC[m/s]		Config.[-]		C_L[-]	
Observer[km]	25	30	25	30	25	30	25	30	25	30	25	30
CDA 3°	1129	1393	135	137	26.1	25.6	-1397	-1414	Clean	Clean	0.481	0.482
CDA 4°	1199	1554	136	138	25.9	25.3	-1867	-1899	Clean	Clean	0.481	0.482
Ref. 2000ft	609.6	609.6	90	90	64.79	64.85	0	0	Appr.	Appr.	1.038	1.039
Ref. 3000ft	914.4	914.4	91	91	64.77	64.80	0	0	Appr.	Appr.	1.039	1.040

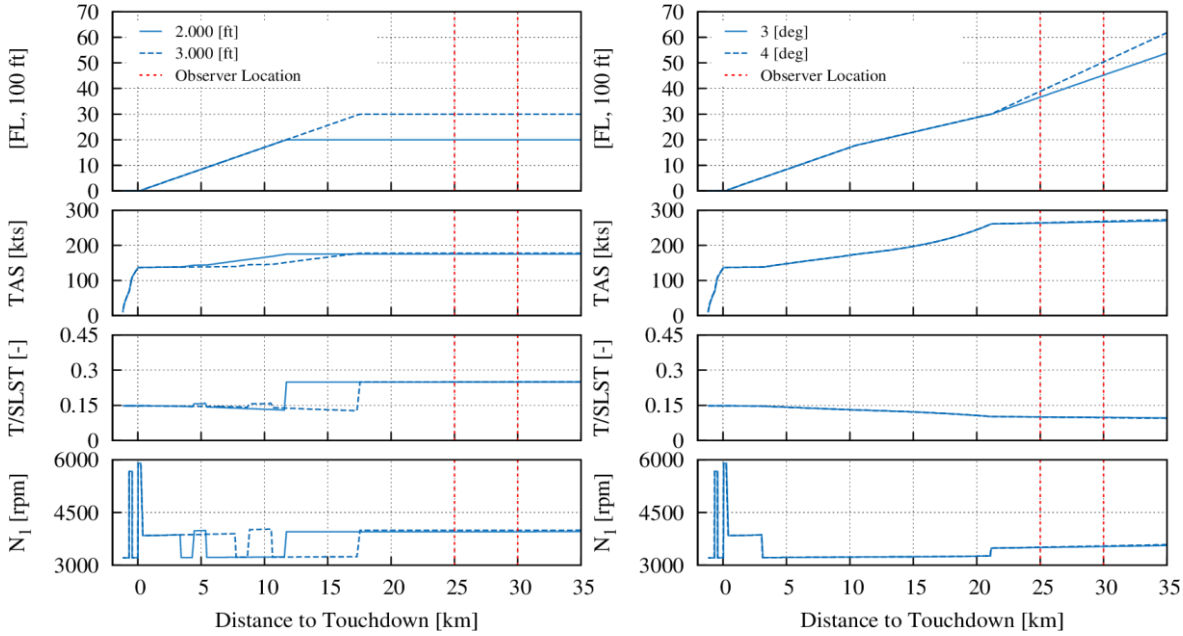

Figure 2 – Relevant parameter variation for conventional and CDA´s approaches

2.3 Noise modeling

The Integrated Noise Simulation and Assessment module (INSTANT) has been used to model the aircraft noise at source. INSTANT was developed at the ILR of RWTH Aachen University and is used jointly by TU Delft and RWTH Aachen. The source noise models implemented in INSTANT are based on methods incorporated in NASA's Aircraft Noise Prediction Program (ANOPP), which includes the model of Heidmann (10) for engine fan and compressor noise, Stone (11) for jet noise and Fink (12) for airframe noise. The numerous inputs required by the source noise models to predict the noise from the engine fan, jet and aircraft airframe are also simulated over the modeled flight paths i.e. over all the study missions presented in Figs. 1-2. The thermodynamic inputs required for engine component noise calculation are obtained from detailed engine decks made using the gas turbine analysis and modeling software Gasturb (13), for the V2527-A5 engine model. The engine geometry inputs used for noise calculation are obtained from an empirical engine geometry model, which scales parameters such as the number of fan blades, vanes, stage areas etc. based on the SLST of the engine. The airframe geometry inputs such as the flap and wing area, landing gear geometry etc. are obtained from the

MICADO environment. Combustor and turbine noise from the engine are left out of the prediction and subsequent analysis, due to their relatively low contribution to the overall aircraft noise. The predicted noise results from INSTANT have been verified with publically available references (14), (15) and validated with measured data as presented in Sahai et al. (16), (17). The source noise models used in this study are semi-empirical in nature and although they do not provide an exact match to measured data in terms of the predicted spectra and directivities, they are still regarded as state of the art aircraft noise prediction models. The generic noise prediction capability they offer can be applied to any conventional aircraft and engine, flying over any simulated flight procedure. The noise predicted at the source using INSTANT can be propagated to either individual or grids of ground points for assessment in various metrics, to simulate virtual microphones measuring aircraft flyovers or to create noise contours in various metrics in airport vicinities. For the purposes of the current study however, the source noise predicted using INSTANT is propagated by means of several digital filters and gains implemented in the auralization software developed at the TU Delft, to produce the sound signatures at the previously mentioned representative observer locations.

3. AURALIZATION

Using the predicted spectral and directional information at the source obtained using INSTANT, the source noise is then synthesized for the conventional approaches and CDAs. Due to their very different character, different techniques are followed for the synthesis of broadband noise from the jet and airframe and tonal noise from the fan. For auralizing the tonal noise from the fan, an additive synthesis technique (18), (19), (20) has been used, which employs the use of Eqs. 1 and 2 to create the time-history of the tonal signal over the entire flight path.

$$s_i(t) = A_i cos(\phi_i(t) + \phi_0) \tag{1}$$

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

Each tone's signal is constructed using this method as a cosine wave with amplitude A_i, instantaneous phase ϕ_i and initial phase ϕ_0, which is set as a random phase offset in order to give the synthesized sound a more realistic and less coherent character. The instantaneous phase ϕ_i is calculated from the instantaneous frequency f_i of each tone, using Eq. 2. By constructing each individual tone using this technique, the overall tonal signal can be generated by adding together all the individual tonal signals. During the approach phase, the dominant tonal noise source is the fan, which can be quite clearly audible and prominent due to the jet noise being of low intensity for an approach flight idle engine setting. The tonal noise from the fan during approach primarily originates from rotor-stator blade interaction and these rotor-stator interaction tones from the fan have therefore been auralized in the current study. The fan rotor-stator interaction tones and their harmonics occur at the Blade Passage Frequency (BPF) and at its integer multiples. The individual magnitude of each interaction tone and the frequency at which it occurs are obtained from the model of Heidmann implemented in INSTANT.

For broadband noise synthesis, an Overlap-Add technique is used, which uses white noise as a basis to generate synthetic aircraft broadband noise. The models of Stone for jet noise and Fink for airframe noise produce source noise spectral information as 1/3-octave spectra. The first step in the broadband synthesis process is to convert the 1/3-octave source noise spectrum for jet and airframe noise in the direction of the observer to a narrowband noise spectrum. This is done for each 'mission point' or flight point modeled along the flight path, which for the current study is in time-steps of 0.5 seconds. White noise is then generated in the frequency domain and subsequently convolved with the narrowband source noise spectra. The frequency domain results are transformed to the time domain via an Inverse Fast Fourier Transform (IFFT), to get the broadband signal time history. As the aircraft flies past the observer point, the directivity angle between the aircraft and the observer point changes continuously, which results in the source noise in the direction of the observer also changing continuously. In addition, the noise reaching the observer can change due to changes in the aircraft's thrust setting, high-lift device setting and gear extension during the approach procedures. Both these factors can result in audible artifacts in the synthesized sound as the aircraft flies past an observer point. In order to avoid these artifacts from occurring, the convolution of the white noise and narrowband spectra is performed after combining the signals with an overlap and windowing them using a Hanning window.

The above two steps provide the combined tonal and broadband noise signal at the source. In order

to simulate the noise impact at the observer points on the ground, propagation and flight effects are subsequently applied to the source noise signals as several gains and digital filters. The propagation effects of spherical spreading, atmospheric absorption according to ISO-9613-1:1993 (21) and ground reflection according to Chien-Soroka theory (22) using Delany and Bazley's (23) ground impedance model are applied to propagate the source noise signal to the signal on the ground. To account for the moving source effect, the Doppler shift is applied to the signal via a Variable Delay Line (VDL), using the time-varying time-delay between the emission time at the source and the reception time at the observer point (24). The VDL performs a spline interpolation between the samples to avoid any resulting aliasing effects, if the time-delay results in a delayed emission time that lies in between two reception time values.

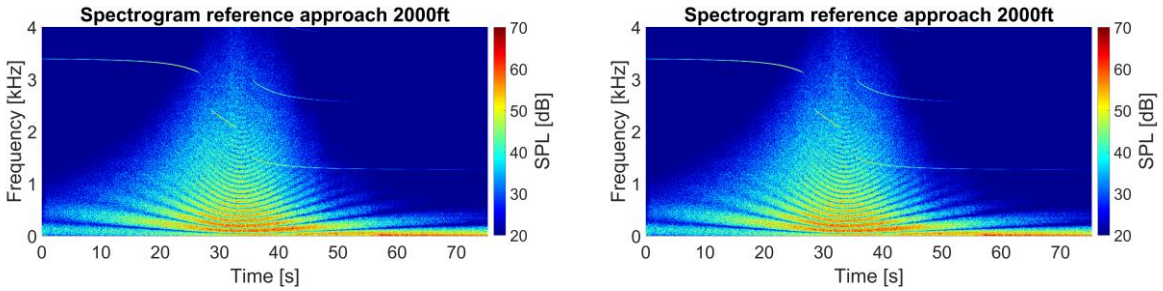

Figure 3 – Reference approach at 2000ft for respectively 25 and 30 km from touchdown

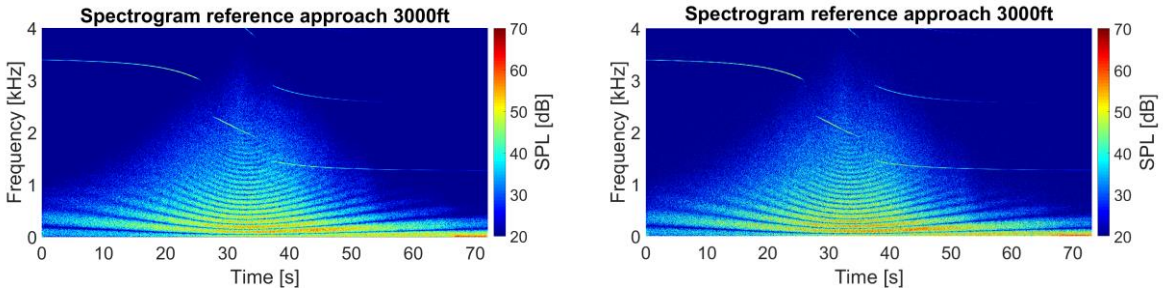

Figure 4 – Reference approach at 3000ft for respectively, left to right, 25 and 30 km from touchdown

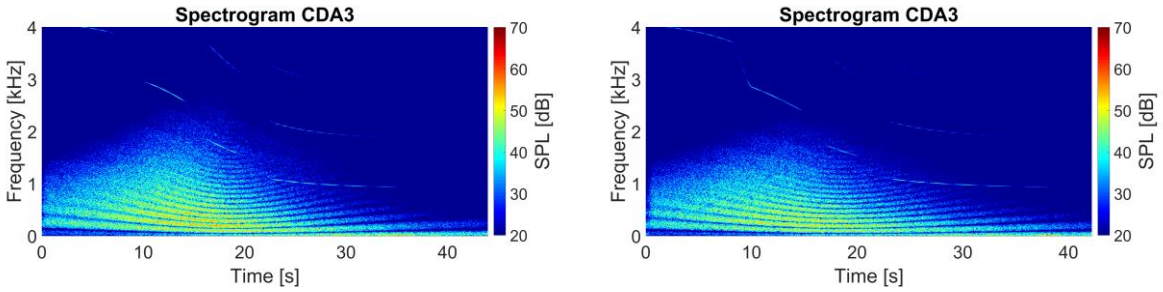

Figure 5 – 3 degree CDA approach for respectively, left to right, 25 and 30 km from touchdown

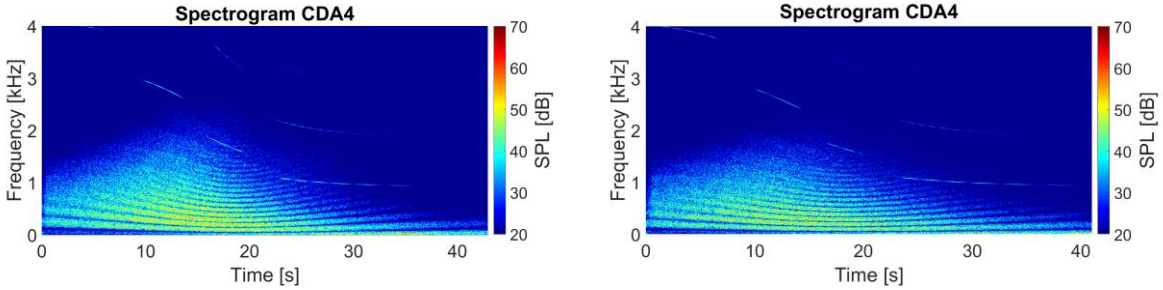

Figure 6 – 4 degree CDA approach for respectively, left to right, 25 and 30 km from touchdown

The spectrograms of the reference approaches with horizontal segment altitudes at 2000 ft and 3000 ft, as well as the spectrograms of the CDA flight paths with 3 and 4 deg glide slope angles are presented in Fig. 3 to 6.

4. NOISE ASSESSMENT METHODOLOGY

This section briefly describes the methodology with which the noise assessment in terms of standard and SQ metrics is carried out for the comparison of reference approach procedures and CDAs. It is known from previous studies that the A-weighting based metrics poorly capture differences in aircraft noise (25), (26), and also correlate poorly with perceived annoyance due to aircraft noise (6), (7), (27). The studies performed by Angerer (6) as well as More (7) made use of sound quality (SQ) metrics to quantify the influence of individual aircraft noise characteristics on the perceived psychoacoustic annoyance. This perceived psychoacoustic annoyance was predicted by combining the sound quality metrics in overall annoyance metrics and the results were compared with listening test results using test audiences. The use of the SQ metrics was regarded as the most suitable approach since it focused on elementary perceptual features of sound for modeling how annoying a sound is perceived to be. The use of SQ metrics is therefore also made in the current study to analyze how the sounds produced by CDAs differ from reference approach procedures and how they may correlate with changes in the residents' perceived annoyance. The assessment will attempt to therefore go beyond the current practice of presenting noise impact changes in L_{Amax} and SEL metrics and present changes in the aircraft sounds reaching observers in terms of changes in their sound quality.

A combination of two software has been used to assess the auralized audio files in the various metrics: the noise assessment is partly performed using an Audio Assessment Module (AAM) being developed at the ANCE group of TU Delft and partly with the PULSE Reflex software of Bruel and Kjaer. The AAM is intended to serve as an automated aircraft audio assessment tool, which could be integrated in an aircraft design and auralization chain to optimize aircraft for optimal sound quality and minimal annoyance. The AAM can currently assess any audio file in terms of its A-weighted Overall Sound Pressure Level (OASPL), SEL and Effective Perceived Noise Level (EPNL) in conventionally used aircraft noise assessment metrics, and in the SQ metrics of stationary and time-varying loudness and sharpness. The EPNL metric is calculated according to the procedure outlined by the Federal Aviation Administration (FAA) of the United States (28), stationary and time-varying loudness have been implemented according to the method of Zwicker (29), (30) and sharpness has been implemented according to the method of von Bismarck (31). The remaining SQ metrics of roughness and fluctuation strength according to the methods of Zwicker (32) and tonality using Terhardt's method (33) have been applied using the PULSE Reflex software. It is intended in the future to fully extend the capabilities of the AAM to cover these remaining metrics as well.

5. NOISE ASSESSMENT

A combination of the AAM and the PULSE Reflex software was thus used to compare the measured and synthesized audio files for each of the modeled and auralized flight paths, at both the selected observer locations. This comparison has been split into the metric values for the conventional L_{Amax}, SEL and EPNL metrics in Section 5.1 and in the SQ metrics in Section 5.2.

5.1 Assessment in standard metrics

A homogenous atmospheric propagation model has been used for the auralizations made in this study, which does not account for the effect of turbulence due to wind or background noise, and which could modify to a certain extent the results at the observer position (17). The only effects that can lead to changes in the aircraft sounds produced at the observer locations are those occasioned by either a change in the flight path which can increase or decrease the distance to the observer, or by a modification in the noise at source, such as for example an increase or decrease of thrust setting or airspeed.

As already mentioned, the major effect pursued by CDAs is the increase of distance to the observer. The inverse square law dictates that the reduction in sound pressure level attributable to spherical spreading is equal to 6 dB for each doubling of distance (34). The inverse square law effects can be well appreciated in Tables 3 and 4 which respectively show the results in conventional metrics at 25 and 30 km from touchdown for each modeled approach procedure. By comparing the results of the 4 degree glide slope CDA to the reference approach at 2000 ft at 25 km, a L_{Amax} reduction of 6.78 dBA is captured. When the altitudes of the two approaches are compared, as can be seen in Table 2, the 4 degree CDA altitude is almost double the altitude of the 2000 ft reference approach.

For the reference approaches, the higher thrust required for the horizontal segment causes the engine noise, particularly from the fan, to be the dominant aircraft noise source. Continuous descent

approaches are flown at higher speeds (see Table 2) and the dominant aircraft noise component due to the higher approach speeds and low thrust setting for CDAs is airframe noise, which scales with the fifth power of the local airspeed for wing and slat noise and with the sixth power for compact bodies such as the landing gear and flaps (12). The reductions in the engine noise due to the low thrust setting are therefore offset to some extent by the higher airframe noise produced by the CDAs. This tradeoff between engine and airframe noise sources however leads to further noise reduction the farther away the observer is located. The most favorable case, CDA 4 degree compared to the 2000 ft reference approach at 30 km, indicates reductions of 9.24 dBA in L_{Amax}, as can be seen in Table 3.

Table 3 – Conventional metrics results at 25 km from touchdown

Conventional Metric results at 25km	Ref. 2000ft	Ref. 3000ft	CDA 3 deg	CDA 4 deg
L_{Amax} [dBA]	71.86	65.99	65.83	65.08
SEL [dBA]	82.28	77.88	76.05	75.28
EPNL [EPNdB]	86.16	81.97	78.09	77.30

Table 4 – Conventional metrics results at 30 km from touchdown

Conventional Metrics Results at 30km	Ref. 2000 ft	Ref. 3000 ft	CDA 3 deg	CDA 4 deg
L_{Amax} [dBA]	71.21	65.77	63.53	61.97
SEL [dBA]	82.21	77.92	74.08	72.77
EPNL [EPNdB]	85.94	82.08	77.33	75.60

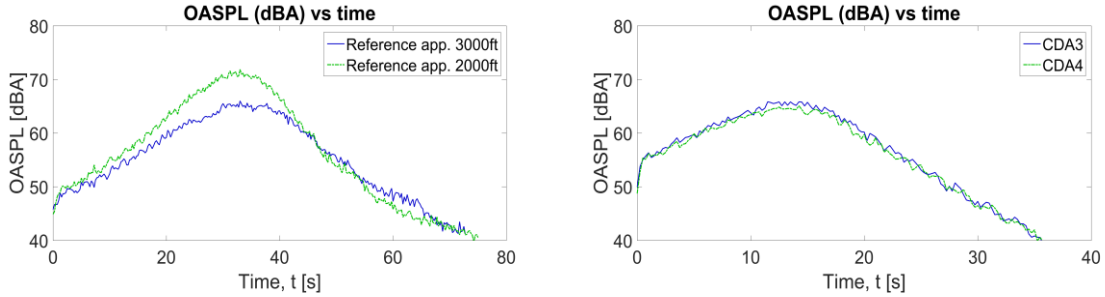

Figure 7 – Flight path comparison in terms of the OASPL (dBA) metric at 25 km from Touchdown

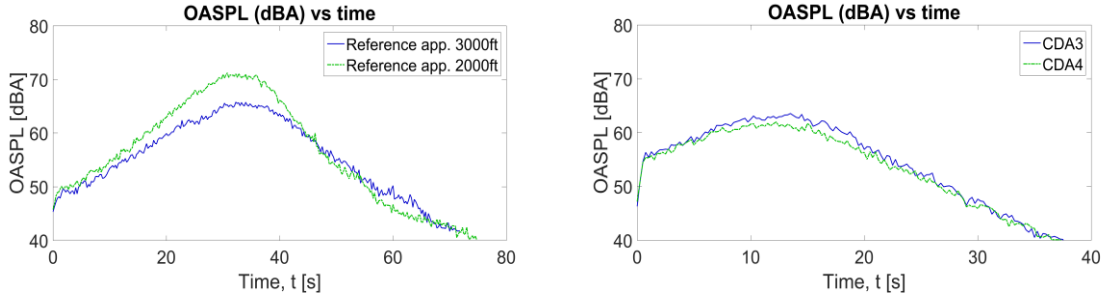

Figure 8 – Flight path comparison in terms of the OASPL (dBA) metric at 30 km from Touchdown

When continuous descend approaches are compared with each other, a direct relation between glide slope angle increase and noise reduction can also be observed for each conventional metric. Even for small resultant altitude differences between CDAs, 70 m at 25 km, flying a steeper approach shows a small reduction of 0.75 dBA. This reduction in dBA is however difficult to audibly perceive while listening to the audio files. The differences between the CDAs however increase the farther away the observer location is, resulting in more favorable noise reductions.

Another important aspect is how the sound changes for the same flight path with decreasing distance to touchdown. As expected, the reference approaches due to their horizontal segment present small noise increases between both observation points. Drag increase and the consequent thrust augmentation are responsible for this effect, since the distance to observer in this case does not change. A higher noise increase during the approach is calculated for CDAs. Since the speed, thrust setting and configuration remain practically constant for both observer locations, the only factor that can lead to higher noise is the rapidly decreasing distance to observer at 25 km compared to 30 km (cf. Fig 1).

The LAmax metric results observed in the current study are coherent with values observed in literature for comparable flight paths, which indicate reductions in excess of 5 dBA in peak noise level LAmax (5), (35). When comparing the values obtained in the other conventional metrics of SEL and EPNL at the same observation location for the different approaches, the LAmax seems to slightly under-predict the noise reduction. As an example, the already shown maximum expected LAmax reduction of 9.24 dBA when the 4 degree CDA is compared to the 2000 ft reference approach at 30 km, results in a reduction of -10.34 EPNdB in terms of the EPNL metric. A possible explanation for this difference can be found in Figs. 7 and 8. These figures show the OASPL vs time history to illustrate the dBA vs. time variation. When the OASPL (dBA) variation is compared between CDAs and reference approaches, a relatively higher peak can be observed for reference approaches. The duration exposure for the reference approaches is also significantly longer, whilst the aircraft flies by over the observer locations much faster for the CDAs, explaining why the relative benefit for CDAs in terms of SEL and EPNL are higher, when the duration is taken into account.

There are however several additional aspects of the aircraft sounds that are not captured by these metrics. It was mentioned earlier that there is a tradeoff between the engine noise and airframe noise components for the approach procedures, which varies the overall aircraft noise intensity, influence of tonal content and spectral balance, all factors that correlate directly with perceived annoyance. Additionally, fast and slow noise changes over time due to varying thrust settings and different rates of descent also affect the temporal perception and its correlation with perceived annoyance. The conventional metrics do not capture several of these aircraft noise characteristics, which are known contributors to perceived annoyance, and also do not indicate what the cause is behind the changes in the observed L_{Amax}, SEL or EPNL values. The analysis is therefore extended to the SQ metrics, which focus on individual sound characteristics and can indicate more clearly how these sounds differ from each other

5.2 Assessment in sound quality metrics

Tables 5 and 6 present the calculated values for different sound quality metrics for each approach procedure at both observation points.

Loudness is defined as the subjective perception of the magnitude of a sound and corresponds to the sound's overall intensity. Both stationary loudness and time-varying loudness are computed using the AAM. The loudness values that were exceeded for 5% of the time-history, N5, have been compared, primarily because these values correspond best to the perceived annoyance by listeners and the 5% excess values are also commonly used in the field of sound engineering and psychoacoustics (32). In accordance with the results shown for the conventional metrics, when the different approach procedures are compared in terms of loudness, a higher noise reduction can be observed. The distance increase occasioned by CDAs is a very effective method to reduce loudness, regardless of any other change affecting the noise at source. In the most favorable case, again 4 deg CDA compared to the 2000 ft reference approach at 30 km, an expected stationary loudness N5 reduction of 55.2% is calculated. The results are very similar for the time varying loudness N5 with an expected reduction of 53.7%. It is important to remember that the SQ metrics are all linear and differences can be presented as relative differences. Absolute differences in these metrics may not carry the same meaning as they do for the conventional metrics, due to their novelty as applied to aircraft noise assessment.

Tonality is a measure of the perceived strength of unmasked tonal energy present within a complex sound and it represents the second largest contributor to perceived aircraft noise annoyance (6), (7).Tonality K is calculated via the value exceeded for 5% of the time-history, K5 as well as via the tonality value exceeded for 50% of the time-history, K50, which is used by some standard psychoacoustics software and gives a measure of the average tonality over the entire time-history. Jet noise, because of its broadband nature and the fact that it peaks at low frequencies, is an effective way of masking tones. Airframe noise, due to the same reason, can also be an efficient masker of higher frequency aircraft noise, if it has a sufficiently high intensity to mask the tonal intensity (16). For all

the considered approach procedures, the tonality is observed to be reasonably strong and this strong tonal energy present in the aircraft noise spectra can also be seen in the spectrograms and heard in the auralizations. As the jet noise is low during approach, the fan tones become prominent in the resulting engine noise. The airframe noise, although higher for the CDAs, is still not of a strong enough intensity to effectively mask the fan tones. As a result, clearly audible tones can be heard in all the approaches (cf. Figs. 4.1-4.4) and the CDAs are unable to alter the tonal impact at either of the observer locations. The CDAs are in fact seen to increase the tonality at the 30 km observer location due to the reduced jet noise and the ineffective masking from airframe noise.

Table 5 – Sound Quality metrics results at 25 km from touchdown

SQ Metric at 25 km	Ref. 2000 ft	Ref. 3000 ft	CDA 3 deg	CDA 4 deg
Stationary N_5 [sone]	26.06	18.09	15.87	15.04
Time-varying N_5 [sone]	27.22	18.75	16.56	15.52
K_5 [-]	0.235	0.269	0.237	0.253
K_{50} [-]	0.081	0.09	0.079	0.085
R_5 [asper]	1.74	1.66	1.67	1.76
FS_5 [vacil]	1.41	1.49	1.39	1.34
S_5 [acum]	1.498	1.535	1.237	1.203

Table 6 – Sound Quality metrics results at 30 km from touchdown

SQ Metric at 30 km	Ref. 2000 ft	Ref. 3000 ft	CDA 3 deg	CDA 4 deg
Stationary N_5 [sone]	25.9	17.9	13.25	11.6
Time-varying N_5 [sone]	27.1	18.84	13.95	12.54
K_5 [-]	0.252	0.248	0.262	0.264
K_{50} [-]	0.081	0.093	0.102	0.089
R_5 [asper]	1.716	1.74	1.704	1.695
FS_5 [vacil]	1.47	1.51	1.36	1.26
S_5 [acum]	1.506	1.535	1.237	1.217

The roughness metric R quantifies the subjective perception of fast amplitude modulation of a sound, of the order of 50-90 Hz, whereas fluctuation strength FS measures the subjective perception of slow amplitude modulation of the order of 1-16 Hz. Since there are no fast changing noise components during approach, such as buzzsaw noise produced during take-off, the roughness values are relatively low and remain more or less unchanged for every study case considered. No clear changes in roughness are therefore observed from flying CDAs. Typical sources for fluctuation strength with regards to aircraft noise are wind, background noise or any other additional slow varying noise source. As mentioned earlier, the modeled atmosphere is homogenous, which implies there is no effect of wind and there are also no slow fluctuating noise sources modeled. As such, no large fluctuation strength changes would be expected in the current study. Slight reductions in FS5 of up to 16% can however be observed in Tables 5 and 6 for the CDA procedures, with the reductions being higher for the higher glide slop angle CDA. This occurs due to higher approach speeds of the CDAs, which lead to smaller slow fluctuations in intensity being registered over the time of the aircraft flyover.

The final SQ metric used to quantify the differences between the different observation points and approach procedures is the sharpness metric, which can potentially capture the differences in the high and low frequency content of the sounds. Tables 5 and 6 shows the results in the sharpness value exceeded for 5% of the time-history, as for the other SQ metrics. It can be observed that the calculated sharpness values are almost identical at both observation points. The sharpness variation can be justified under the determinate properties of each particular flight path. Continuous descent

approaches, due to the higher airspeed and the resulting higher airframe noise, which peaks at lower frequencies than the 2700 Hz frequency threshold for sharp sounds, produce less high frequency content and thus a reduced sharpness. Although the sharpness values for both CADs are lower, since sharpness is not the biggest contributor to the perceived annoyance, it is unclear if a positive effect due to lower sharpness can actually be perceived. Dedicated listening tests for psychoacoustic feedback would be required for this purpose. The sharpness metric nonetheless shows that the CDAs will have a less sharp sound, attributed to the increased airframe noise. This information could not be obtained by simply looking at the conventional metrics, which only captured differences in overall intensity.

6. CONCLUSION

The analysis presented in this paper provides a clearer picture of how the CDA sounds would be perceived compared to the reference approach sounds, and how they may potentially impact the annoyance for affected residents. In this paper it is emphasized how important it is to look beyond the conventional metrics, used today to assess aircraft noise, as an effective way to objectively distinguish between aircraft sound and their individual characteristics.

Remarkable noise reductions were observed at CDAs when conventional metrics were used (L_{Amax}, SEL, EPNL). Further reductions were observed when the duration exposure was taken into account. The use of SQ metrics led to precise information on the cause behind the overall noise changes observed in the conventional metric, confirming also the benefits of CDAs in terms of sound quality metrics. The important loudness reduction is the only significant component reducing noise annoyance. Increasing the distance between aircraft and observer is a very effective method to reduce loudness. For both approach procedures, tonality is observed to be reasonably strong. The tonality increase captured in CDAs due to the lack of effective masking can also be relevant for the perceived annoyance. No clear changes in roughness are predicted. Slight reductions in fluctuation strength and sharpness can however be observed for CDAs.

The benefits of CDAs in terms of predicted annoyance are observed at both observer locations. This benefit is reduced with reducing distance to touchdown. This study supports the application of CDAs as an effective way of reducing aircraft noise annoyance to residents in the vicinity of airports.

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