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NOISE CONTROL FOR A BETTER ENVIRONMENT

Aircraft Engine Positioning Psychoacoustic Optimization within Conceptual Aircraft Design

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ABSTRACT

Several engine over-the-wing (EoW) aircraft are designed to fulfil the same Top Level Aircraft Requirements of a reference aircraft by means of a successive engine position variation. The noise reaching the airport surrounding area is evaluated according to EPNL, loudness, and tonality in a coupled study where the aircraft performance and its relation to noise is analyzed together. The aircraft performance decrease, due to this unconventional configuration, is qualitatively justified since the noise annoyance is reduced thanks to wing noise shielding. A very important tonal reduction is observed. The parameter sensitivity analysis leads to two main results: First, the engines should be placed towards the wing leading edge to enhance the fan discharge noise shielding, and secondly, as near as possible to the fuselage for the purpose of utilizing the larger wing area available to improve shielding. These results should be validated with fan noise models developed for accurately predicting fan noise in the near field.

Keywords: Engine over the wing, Sound Quality, Aircraft Noise, Psychoacoustics.
I-INCE Classification of Subject Number: 13

1. INTRODUCTION

Since the first public reactions against jet aircraft noise in the 60s great progress has been made. New technologies, such as chevron nozzles, and the increasing bypass ratio of modern engines have effectively reduced aircraft noise. Nevertheless, air traffic is increasing steadily, cities are growing bigger and the public concern against noise is increasing [1,2]. The design of inherent sound optimized aircraft, beyond the reduction of engine noise or the use of components or technologies specially developed to tackle down a determined noise source, is needed to meet the challenges that aviation will face within the next decades. In this context, the ILR Noise Simulation and Assessment Module (INSTANT) has been developed to account for individual noise sources taking the aircraft geometry and operating conditions provided by an existing conceptual aircraft design framework (MICADO) into account. Consequently, an overall design process with integrated noise optimization capabilities, in terms of conventional noise metrics and also in Sound Quality metrics, can be performed [3,4].

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Among the reasons that might lead an aircraft designer to select an over-the-wing or fuselage mounted engine configuration, stands out the increased noise shielding. Noise shielding consists of placing a physical barrier between the engines and the ground by means of the aircraft wings, fuselage and/or tailplane, which can effectively block and deflect the sound rays mainly emitted by the fan. These unconventional engine positions increase the ground clearance. Higher bypass ratios are easily realizable, improving fuel burn and reducing emissions [5]. Also, the landing gear integration in the wing is simplified with the advantage that long, and thus heavier, landing gears can be avoided. This engine position not only provides adequate ground clearance against nacelle strike but also improves safety in the unlikely event of a wheels-up landing or water ditching. Furthermore, the likelihood of foreign object ingestion damage is significantly reduced [6]. In addition, under-the-wing mounted engines might require thrust gates in the flap system. Gaps of any kind, such as in the B787, reduce lift, increase drag and enhance interaction noise. The flaps cannot be deployed to higher angles without encountering the high dynamic pressures and temperatures of the exhaust gases of the engine. If thrust gates are not provided, the jet wake interferes with the deployed flaps system as for example in the A350 XWB family. Potential vibrations, thermal impact and interaction drag have to be adequately analyzed [7].

The focus of the paper is to assess how different over the wing engine positions influence the noise on the ground. Several variants of a short range over-the-wing engine aircraft are designed by changing the engine position within the wing span, chord and vertical location. In this sense, the aircraft is treated as a complete systems and the interconnection between aircraft performance and noise can be investigated. Since the noise certification points, defined in the ICAO Annex 16 Volume 1[8], are very close to the runway, the study is extended to the airport surrounding area, where relative improvements can be more precisely observed over bigger areas. Also, these results provide more information of how noise affects the communities living in the most conflictive zones, which are not located right next to the airport runways. The study is not just limited to the conventional metrics but it is extended to the Sound Quality metrics, since they can reflect with a higher precision the real annoyance caused by aircraft noise [9,10].

The paper is divided in five sections. The ILR Noise Simulation and Assessment Module (INSTANT) is presented in Section 2. In Section 3, the reference aircraft and the consequently resulting family of aircraft is introduced. The results are discussed in Section 4 according to conventional and Sound Quality (SQ) metrics. Finally, a conclusion is given in Section 5.

2. ILR NOISE SIMULATION MODULE

The source noise models implemented in INSTANT are based on methods developed and incorporated in NASA's Aircraft Noise Prediction Program (ANOPP), which includes the model of Krejsa et al. [11] for fan noise, and Stone et al. [12] for jet noise, which includes the effects of chevrons nozzles. The airframe noise is calculated using the methods developed by Dobrzynski et al. at the German Aerospace Center (DLR). The airframe noise is approximated as a combination of clean wing, trailing edge devices, leading edge devices, spoilers and landing gear noise contributions[13–17]. The source noise models are semi-empirical in nature and can accurately reproduce the sensitivity of parameters according to given operating conditions. The generic noise prediction capability they offer can be applied to any conventional aircraft and engine, flying over any simulated flight path [4]. The numerous inputs required by the source noise models to predict the noise from the engine fan, jet and airframe are simulated in time steps of 0.5 seconds over the flight path. The thermodynamic inputs required for the engine noise calculation are obtained from detailed engine decks provided by the gas turbine analysis and modeling software Gasturb13[18]. 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 engine sea level static thrust. 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 are left out of the prediction and subsequent analysis due to their relatively low contribution to the overall aircraft noise [3,4,10,13]. The application of noise shielding is of outstanding importance for the correct evaluation of installation effects produced by different aircraft configurations, e.g. over-the-wing or tail mounted engines. Currently, there are different noise shielding prediction algorithms available. For an assessment tool, at aircraft conceptual design, computational time and accuracy is of highest importance so that it can be effectively used in an iterative way inside of a design loop. Based on a tradeoff between accuracy and calculation time, two different methods, both developed by Lieber et al. at NASA and used in ANOPP, have been implemented in the ILR design environment accounting for the relative position between engine-wing. A barrier shielding method is used to model the noise shielding achieved positioning the engine over the wing [19,20]. The method explained in detail in [21] has been selected to model the engine-wing/flap noise reflection. This method accounts for conventional under-the-wing engine aircraft and predicts the noise increase at ground observer positions that results when the discharge fan noise reflects off of the wing surface[3]. Although, the use of a discrete fan noise source position developed to model the far field noise could lead to inaccurate results when used in the near field for noise shielding.

3. CONCEPTUAL AIRCRAFT DESIGN

The purpose of this section is to present the aircraft developed for the study. First, the reference aircraft is introduced. Then, key performance parameters of the family of aircraft derived from the reference aircraft are compared.

3.1. Reference Aircraft

The ILR-02T as a derivative of the A320-200 with a T-Tail configuration and under-the-wing engines has been developed for this paper. The same procedure has been followed as for the design of the CSR-01[22]. Some of the most important Top Level Aircraft Requirements (TLARs) used for the ILR-02T are presented in Table 1. The design process of such an aircraft is out of the scope of this paper. More information can be found in [23,24].

3.2. Engine Position Variation Results

The calculation method implemented in MICADO to estimate the overall performance variation of an over-the-wing engine aircraft will be in the near future presented in detail in Pereda´s Doctoral Thesis with title “Conceptual Design of Sound Optimized Aircraft”. In this paper, just the resulting aircraft are presented. The engine reference point, which is located at the fan inlet, is iteratively changed. The engine chord position x/c is varied for x/c = {0.3, 0.55, 0.8}, where c is the local wing chord. Simultaneously, the span position is varied for

$y/b^{\#} = \{0.2, 0.25, 0.3\}$ and $z/D_{out} = \{0.5, 0.9\}$, where $b^{\#}$ is the wing semispan and D_{out} is the engine exhaust diameter. Every possible combination is done and eighteen aircraft are finally created.

Table 1: Key Aircraft Characteristics of ILR-02T

Parameter	Symbol	Unit	ILR-02T
Design Range	R	NM	2,350
Design Passenger Capacity	-	PAX	150
Design Payload	PL	kg	15,300
Cruise Mach Number	M_{Cr}	-	0.78
Wing-Loading	W/S	kg/m^2	625.62
Thrust-to-Weight Ratio	T/W	-	0.344
Maximum Take-Off Weight	MTOW	kg	77,245
Operating Weight Empty	OWE	kg	42,189
Wing Weight	W_W	kg	9,632
Landing Gear Weight	W_{LG}	kg	2,210
Engine Type	-	-	2 x V2527-A5
Sea-Level Static Thrust	SLST	kN	130.41
Block Fuel @ design mission	BF_{DM}	kg	16,290
Block Fuel @ study mission	BF_{SM}	kg	5,903

As depicted in Figure 1, when the engine is positioned over the wing the Operational Weight Empty (OWE) is increased up to a 3,04%, mainly due to a heavier wing, as shown in Figure 2 A. The reason is that the wing torsional rigidity GJ is negatively influenced when the engine is placed over the wing, backwards of the elastic axis, and towards the wing tip, despite the positive bending moment relief. This position can also cause complex wing flutter characteristics. These two reasons require the wing structure to be reinforced with a consequent weight increase. However, when the engines are placed under the wing, the ground clearance has to be guaranteed with longer and thus heavier landing gears. Figure 2 B shows how the landing gear mass is reduced for over-the-wing aircraft.

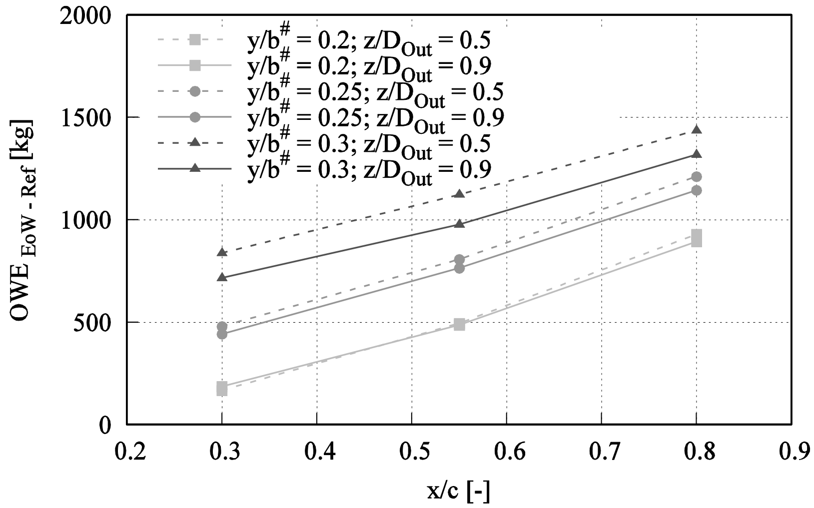

Figure 1: OWE Comparison of EoW to Reference Aircraft

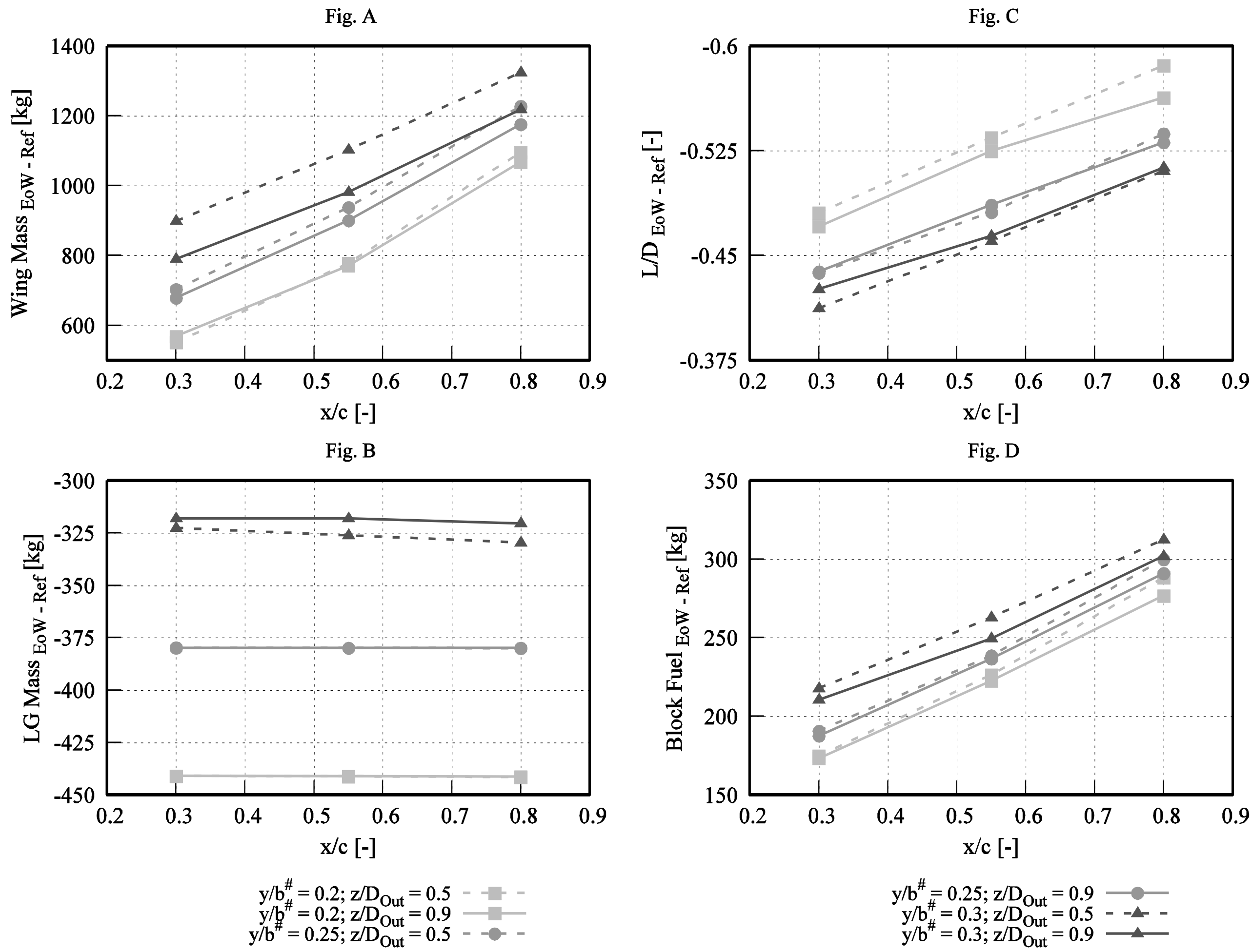

Figure 2: Comparison of different parameters of EoW to Reference Aircraft

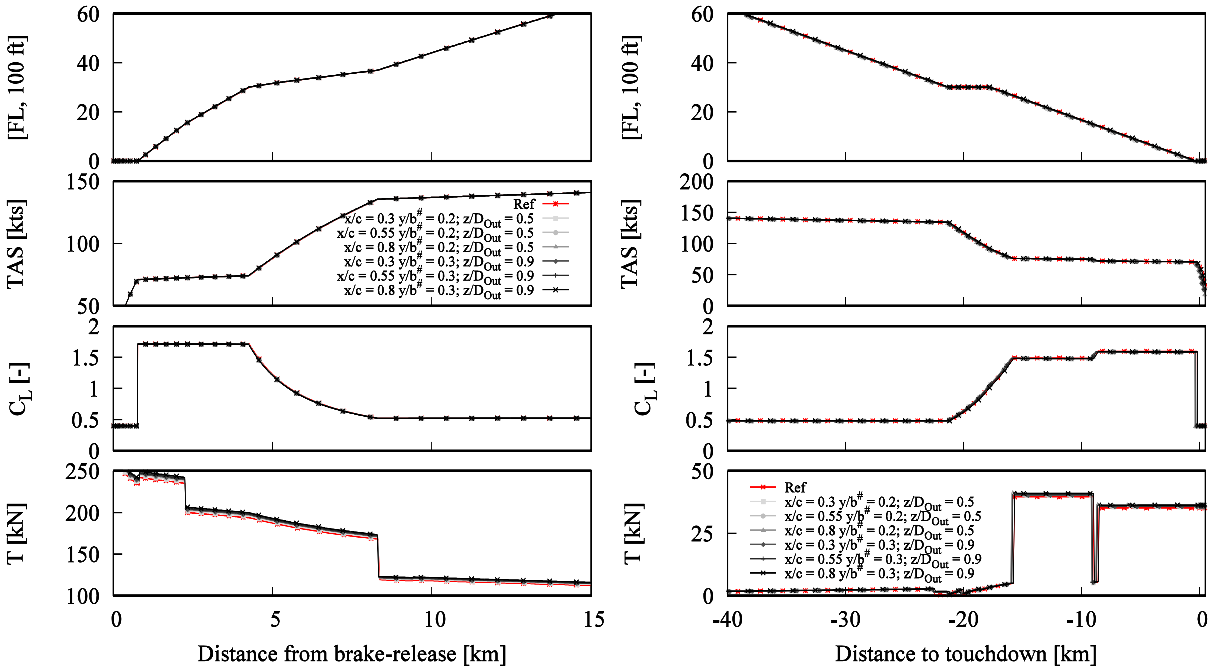

Figure 3: Departure (left) and Approach (right) Flight Paths

Placing the engine over the wing is aerodynamically unfavorable since the airflow is disturbed on the upper wing side, where the most lift is generated. Figure 2 C shows how the lift to drag ratio is modified. When the engines are placed close to the fuselage and towards the wing trailing edge the aerodynamic disturbance reaches its maximum. On the other hand, placing the engines towards the wing tip and to the front causes the most favorable results. According to the dashed lines, the further away the engine is from the wing surface, the smaller the reduction in lift to drag ratio. The combination of the aircraft mass increase and the worsened aerodynamical properties lead to an increase of the fuel consumption. In Figure 2 D, the block fuel for a study mission with a range of 800NM and the design payload is plotted. The difference in performance among aircraft configurations leads to almost unnoticeable modification of the approach and departure flight paths. Figure 3 describes the departure (left) and approach (right) flight paths in terms of aircraft altitude (FL), true air speed (TAS), coefficient of lift (C_L) and thrust (T). The only noticeable difference is observed when the reference aircraft thrust is compared to any EoW aircraft, which slightly increases when placing the engine over the wing. Figure 4 shows both designs.

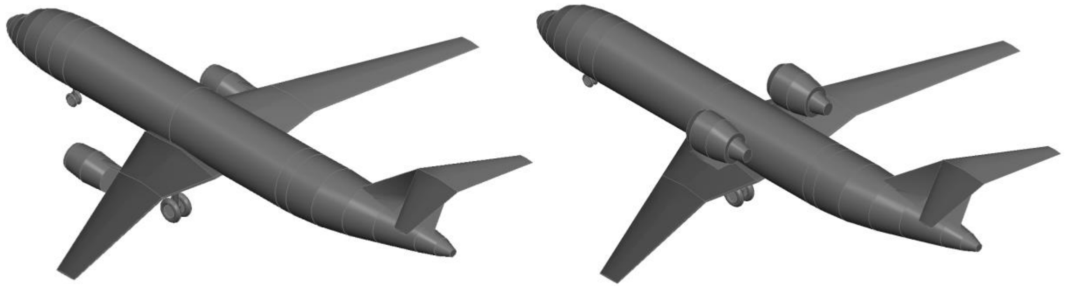

Figure 4: Reference (left) and EoW ($x/c=0.3$; $y/b^{\#} = 0.2$; $z/D_{out}=0.5$) Aircraft

4. NOISE ANALYSIS

The overall noise signature of advanced turbofan engines with highly loaded, wide chord fan blades is dominated by fan discharge noise [11]. Modern, high pressure cores and high bypass ratios extract significant energy from the core air flow, which tends to reduce primary jet noise. This contrasts with older technology engines, such as the engines used in this paper, where jet noise is still prominent and fan inlet noise is at least as high as fan discharge noise [25]. In Figure 5 the noise reaching the ground, separated in jet, fan and airframe, is plotted for two fixed observer positions at departure (left) and approach (right), and compared between the reference aircraft and an over-the-wing engine aircraft. It can be noticed a large area between the filled grey and black curve representing the fan noise ground reduction within the flyover due to wing noise shielding. Jet noise cannot be shielded because it is a distributed source downstream of the engine [12]. With fan discharge noise dominating modern turbofan engine noise, together with jet noise becoming less prominent, wing noise shielding is supposed to become even more effective than for engines of previous generations [26].

In this paper the noise is analyzed according to the noise reaching the ground area around the airport for the reference and every EoW aircraft configuration. An example of this area around the airport can be found in Figure 6, where the maximum noise value calculated during the flight procedure is plotted on the ground. The area subject to a maximum value exceeding a certain threshold is computed, and compared to the reference aircraft. In Figure 6, a contour outlines the area subject to a maximum value of 65EPNdB, which is selected since it represents the frontier between mid to high noise annoyance. The size of both areas is compared in Figure 7. It can be noticed that the total area over 65 EPNdB can be reduced from 99.2 km^2 down to 84.44 km^2 (area reduction of 15%) when the engines are placed over the wing. As shown by the dashed lines, the closer the engine to the wing, the smaller is the area over 65 EPNdB. The improved wing noise shielding outweighs the performance decrease, when compared to higher vertical engine positions (Compare Figure 1 and Figure 7). Also, if the engines are brought close to the leading edge the noise is reduced, due to the bigger wing area available for shielding. The engine span position does not seem to play a crucial role when the engine is placed close to the leading edge. If the engine is moved backwards, the closer the engine to the fuselage, the more effective is the noise shielding, and thus the noise reduction.

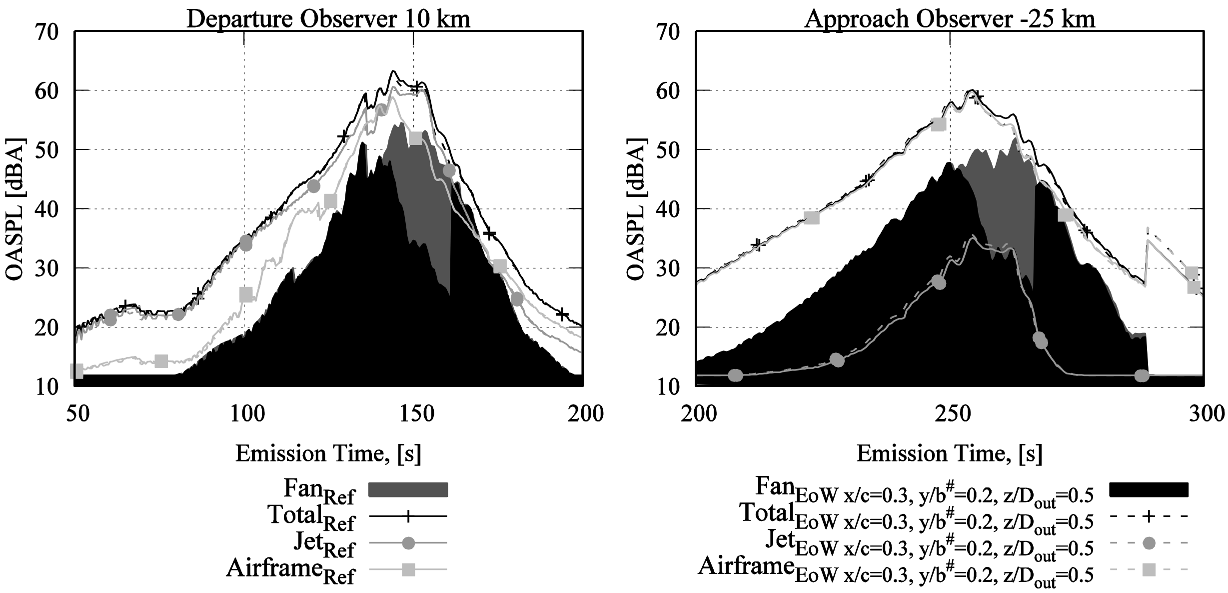

Figure 5: Noise for a ground observer at 10 km after brake release (left) and 25 km to touchdown (right)

It can be observed in Figure 8 that the noise is more effectively reduced during approach than at departure. This is due to the logarithmic nature of noise addition. If a dominant source is reduced, in this case the fan noise is shielded; other former not dominant sources can become dominant. During departure the jet noise dominates due to the high thrust required. The fan noise is comparable to the airframe noise and lies below the jet noise as shown in Figure 5 left. Therefore shielding the fan noise is not as effective as during the approach (see Figure 5 right), where the thrust is low, and so is the jet noise. The fan noise reduction is captured by the use of conventional metrics such as EPNdB. Despite this, the expected reductions are not enough to justify a real implementation. The study is therefore extended to the Sound Quality metrics in order to better comprehend the real noise annoyance of the different aircraft.

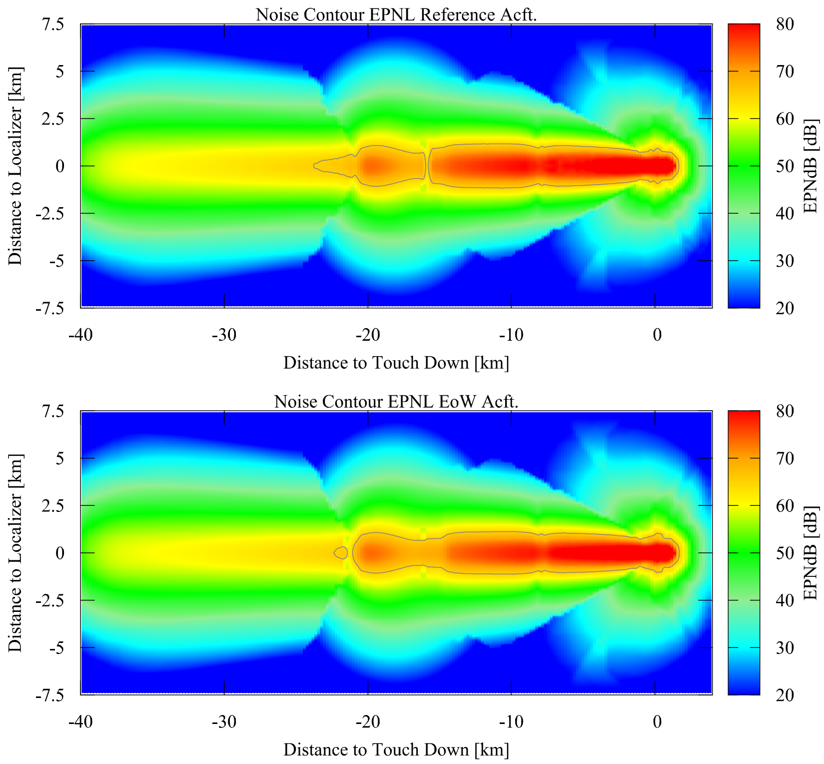

Figure 6: Approach EPNL Noise Contour for the Reference (top) and an EoW (x/c=0.3; $y/b^{\#}$ = 0.2; z/D_{out}=0.5) (bottom) aircraft

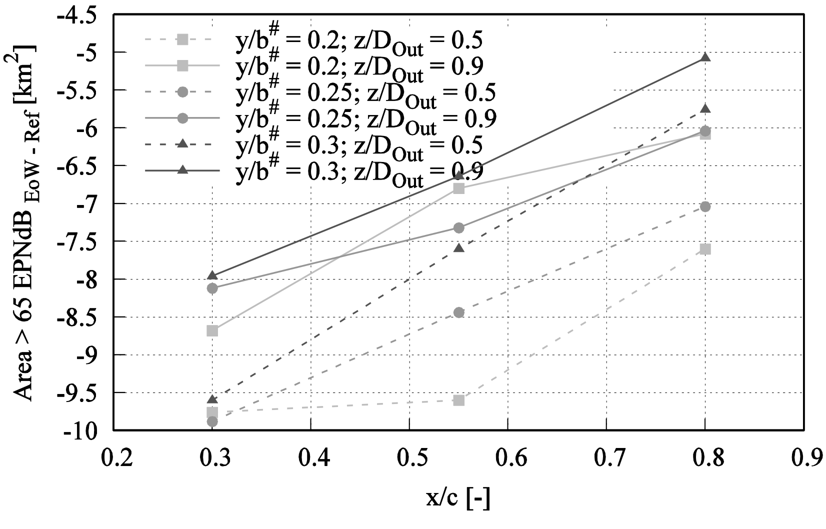

Figure 7: Total Ground Area Difference over 65 EPNdB for EoW to Reference Aircraft

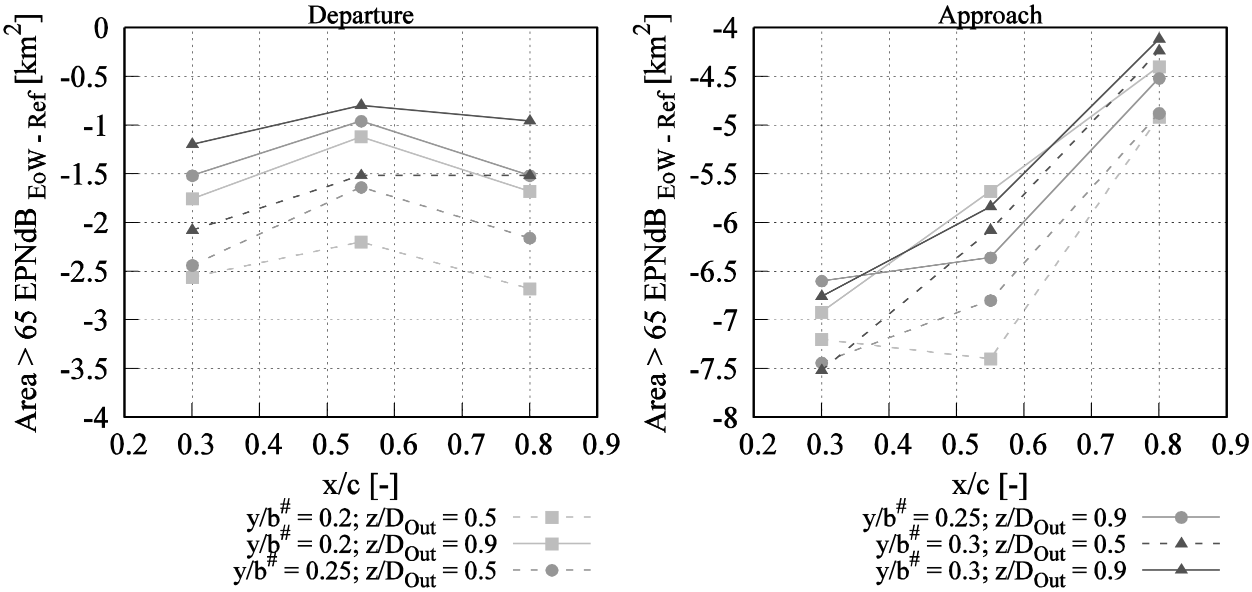

Figure 8: Departure (left) and Approach (right) Ground Area Difference over 65 EPNdB

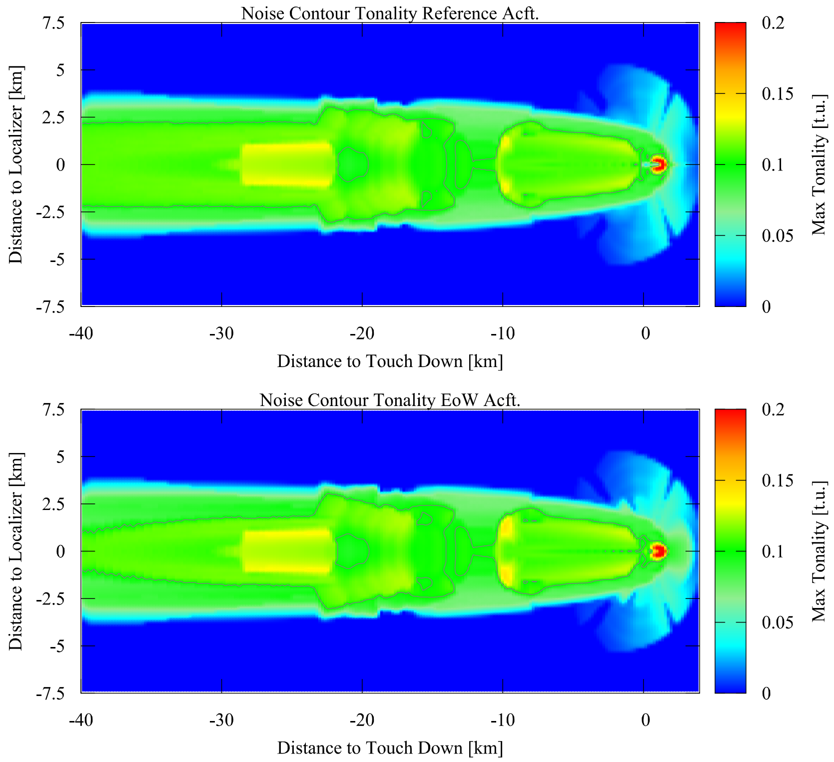

Figure 9: Approach Tonality Noise Contour for the Reference (top) and EoW (x/c=0.3; $y/b^{\#}$ = 0.2; z/D_{out}=0.5) (bottom) Aircraft

Loudness, which is considered the major contributor to noise annoyance, is defined as the subjective perception of the magnitude of a sound and corresponds to the sound's overall intensity. The total area according to the Zwicker´s loudness ground points that exceeded a maximum of 65 Phon have been compared in Figure 10 left, leading to a maximum area reduction from 158.48 km^2 to 153.56 km^2

(area reduction of 3%). Another sound quality index is the tonality K, which is a measure of the perceived strength of unmasked tonal energy present within a complex sound. Tonality represents the second largest contributor to aircraft noise annoyance [4,9,27]. Especially the jet, but also airframe noise, can effectively mask tones due to its broadband nature. The principal sources of tonal noise are the fan and the landing gear. The landing gear remains retracted or extended at the same flight path positions independent of the engine location, and thus does not contribute to any relative increase or decrease of tonality. Other known sources of tonal noise, such as cavity noise, require a precise defined geometry, which is not available at conceptual aircraft design phase and hence is not included in the noise calculation method. Therefore, when the fan is shielded the principal source of tones is neutralized leading to a very important tonality reduction as shown in Figure 10 right. This reduction is much more significant during the approach since the jet noise is low, and thus cannot mask any tones unlike during departure. A total area over 0.1 t.u of 167.36 km^2 is calculated for the reference aircraft, which can be reduced down to 126.04 km^2. This means an area reduction of about a 25%. These results should be validated with fan noise models developed for accurately predicting fan noise in the near field instead of point source models.

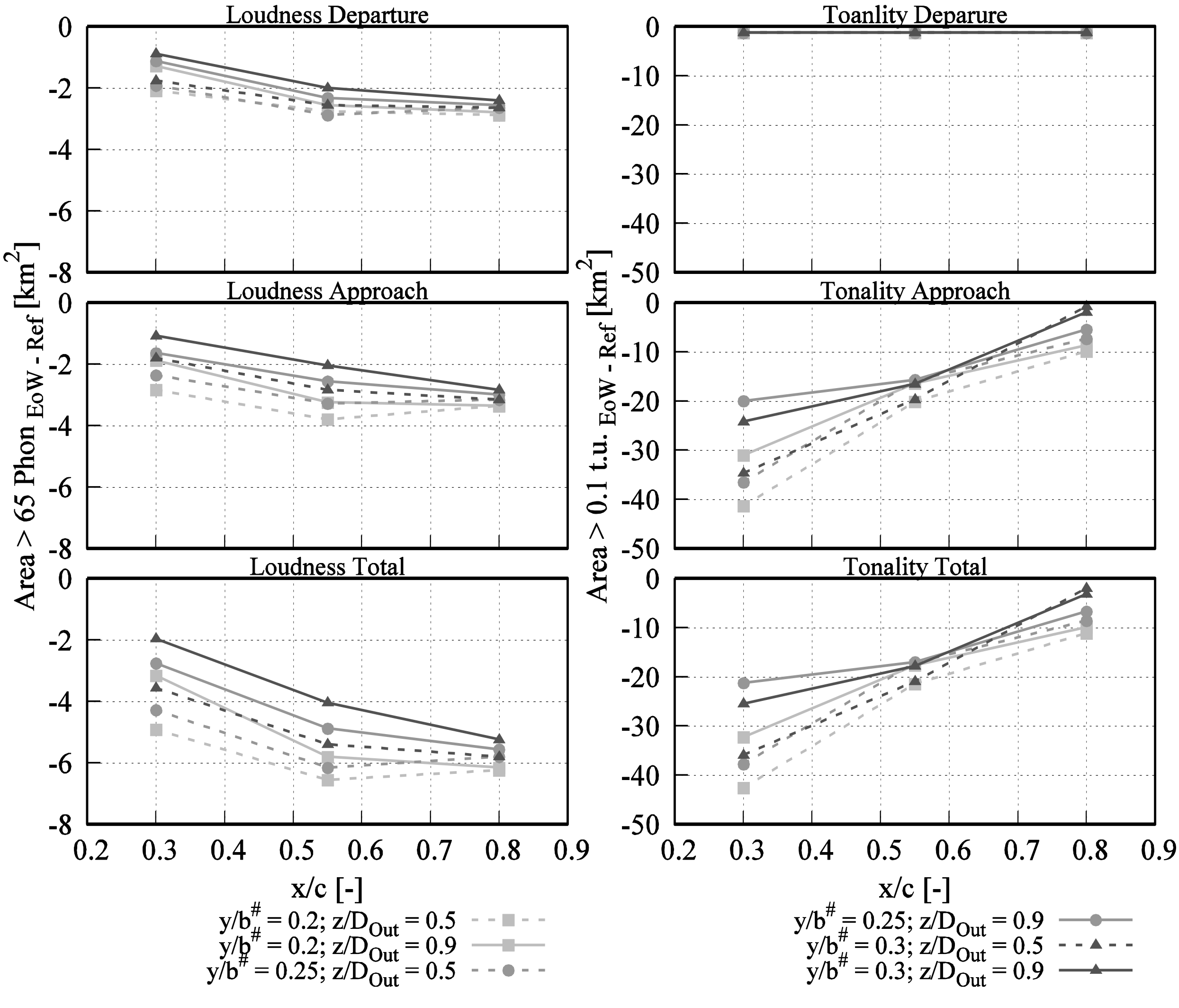

Figure 10: Loudness (left) and Tonality (right) Ground Area Difference for EoW to Reference Aircraft

5. CONCLUSION

Positioning the engines over the wing is an effective measure to reduce noise on the ground. The aircraft performance decrease produced by this unconventional configuration is compensated with an important noise annoyance reduction obtained via wing noise shielding. Since the detail level at conceptual aircraft design is not high enough to define a precise optimum engine position and accurately estimate the noise reduction for a general future aircraft, two main results can be drawn from the parameter sensitivity analysis: First, the engines should be placed towards the wing leading edge to enhance the fan discharge noise shielding, and secondly, as near as possible to the fuselage for the purpose of utilizing the larger wing area available to improve shielding. However, these results should be treated carefully, since the use of a discrete fan noise source position, developed to model the far field noise, could lead to inaccurate results when used in the near field for noise shielding. In the same way, tonality is expected to be strongly reduced, especially in modern high- or ultrahigh bypass ratio engines. Other engine positions such as a fuselage or tail integration will be studied in the near future and compared to an over-the-wing engine installation.

This study is limited to the aircraft noise and performance. To allow a real integration in the actual air transportation system, the economic viability of this design must also be analyzed.

6. REFERENCES

1. Airbus S.A.S.: 'Global Market Forecast: Growing Horizons 2017/2036', 2017.
2. Anonymous: 'Heathrow Environmental Noise Directive Noise Action Plan 2013-2018: The action plan – Revised draft submitted in January 2014', 2014; available at https://www.heathrow.com/file_source/HeathrowNoise/Static/Noise_Action_Plan.pdf.
3. M. Y. Pereda Albarrán, F. Schueltke, and E. Stumpf: 'Sound Quality Assessments of Over-the-Wing Engine Configurations Applied to Continuous Descent Approaches', *AIAA Aviation, 25–29 June 2018, Hyatt Regency Atlanta, Atlanta, Georgia,* 2018.
4. M.Y. Pereda Albarrán, A. K. Sahai, and E. Stumpf: 'Aircraft noise sound quality evaluation of continuous descent approaches', *Internoise 2017 Hong Kong,* 2017.
5. Peter Jeschke: 'Luftfahrtantriebe I und II', Aachen, 2012.
6. D. P. Raymer: 'Aircraft Design: A Conceptional Approach: AIAA Education Series', 2nd edn; 1992, Washington, DC, American Institute of Aeronautics and Astronautics.
7. D. Reckzeh: 'Multifunctional Wing Moveables: Design of the A350XWB and the Way to Future Concepts', *29st Congress of the International Council of the Aeronautical Sciences,* 2014.
8. International Civil Aviation Organization ICAO: 'Environmental Protection: Volume I, Aircraft Noise'; 2014, Montréal, Quebec, International Civil Aviation Organization.
9. S. R. More: 'Aircraft noise metrics and characteristics: PARTNER Project 24 Report COE-2011-004', PhD Thesis, Purdue University, 2011.
10. A. K. Sahai: 'Consideration of Aircraft Noise Annoyance during Conceptual Aircraft Design', Dissertation, Aachen, RWTH-Aachen, 2016.
11. E. A. Krejsa and J. R. Stone: 'Enhanced Fan Noise Modeling for Turbofan Engines'; 2014, Cleveland, OH United States.

12. J. R. Stone, E. A. Krejsa, and B. J. Clark: ‘Jet Noise Modeling for Coannular Nozzles Including the Effects of Chevrons’, 2003; available at https://ntrs.nasa.gov/search.jsp?R=20030093553.
13. L. Bertsch: ‘Noise Prediction Noise Prediction within Conceptual Aircraft Design’, Deutsches Zentrum für Luft- und Raumfahrt e.V., Braunschweig, Germany, 2013.
14. W. Dobrzynski, L. Chow, P. Guion, and D. Shiells: ‘A European Study on Landing Gear Airframe Noise Sources’. 6th Aeroacoustics Conference and Exhibit, Lahaina,HI,U.S.A, 12 June 2000 - 14 June 2000. American Institute of Aeronautics and Astronautics, 1–11.
15. W. Dobrzynski, L. Chow, P. Guion, and D. Shiells: ‘Research into Landing Gear Airframe Noise Reduction’. 8th AIAA/CEAS Aeroacoustics Conference & Exhibit, Breckenridge, Colorado, 17 June 2002 - 19 June 2002. American Institute of Aeronautics and Astronautics.
16. W. Dobrzynski: ‘Konfigurationen 2020 : Abschlussbericht 01. Januar 2006 - 30. Juni 2006 zum Vorhaben "Konfigurative Lärmkriterien" ; Laufzeit des Vorhabens: 01. August 2003 - 30. Juni 2007’.
17. W. Dobrzynski, L. C. Chow, M. Smith, A. Boillot, O. Dereure, and N. Molin: ‘Experimental Assessment of Low Noise Landing Gear Component Design’, *International Journal of Aeroacoustics*, 2010, **9**(6), 763–786, doi: 10.1260/1475-472X.9.6.763.
18. J. Kurzke: ‘How to Create a Performance Model of a Gas Turbine From a Limited Amount of Information’. ASME Turbo Expo 2005: Power for Land, Sea, and Air, Reno, Nevada, USA, June 6–9, 2005. ASME International Gas Turbine Institute, 145–153.
19. L. Lieber and R. Golub: ‘Small Engine Technology (SET) - Task 13 ANOPP Noise Prediction for Small Engines: Jet Noise Prediction Module, Wing Shielding Module, and System Studies Results’; 2000, Phoenix, AZ United States.
20. F.H.V. Dewitte: ‘Aircraft Noise Shielding Assessment: The creation of a software tool to a predict aircraft noise shielding’, Master Thesis, Delft University of Technology, The Netherlands, 2016.
21. L. Lieber, D. Brown, and R. A. Golub: ‘Small Engine Technology (SET) Task 23 ANOPP Noise Prediction for Small Engines, Wing Reflection Code’; 2000, Phoenix, AZ United States.
22. CeRAS: ‘Central Reference Aircraft data System’, 2014; available at http://ceras.ilr.rwth-aachen.de.
23. K. Risse, E. Anton, T. Lammering, K. Franz, and R. Hoernschemeyer: ‘An Integrated Environment for Preliminary Aircraft Design and Optimization’. AIAA SciTech, Honolulu, Hawaii. American Institute of Aeronautics and Astronautics.
24. K. Risse: ‘Preliminary Overall Aircraft Design with Hybrid Laminar Flow Control: Vorentwurf von Flugzeugen mit hybrider laminarer Strömungskontrolle’, PhD thesis, RWTH Aachen University, 2016.
25. H. E. Bloomer: ‘Investigation of wing shielding effects on CTOL engine noise’, 1979; available at https://ntrs.nasa.gov/search.jsp?R=19790044957.
26. J. J. Berton: ‘Noise Reduction Potential of Large, Over-the-Wing Mounted, Advanced Turbofan Engines’, 2000; available at https://ntrs.nasa.gov/search.jsp?R=20000057037.
27. J. Angerer, R. Erickson, and D. McCurdy: ‘Development of an annoyance model based upon elementary auditory sensations for forsteady-state aircraft interior noise containing tonal components’, *NASA Technical Memorandum 104147*, 1991.