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Auralization of novel aircraft configurations

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ABSTRACT

A joint initiative of NLR, DLR, and TU Delft has been initiated to streamline the process of generating audible impressions of novel aircraft configurations. The integrated approach adds to the value of the individual tools and allows predicting the sound of future aircraft before they actually fly. Hence, an existing process for the aircraft design and system noise prediction at DLR has been upgraded to generate the required input data for an aircraft auralization framework developed by NLR and TU Delft. This paper presents the new process and an initial application towards the fully automated auralization of novel aircraft configurations within the conceptual aircraft design phase. Such an early auralization of the new designs enables the aircraft designer to assess the success of selected low-noise measures in an intuitive way in addition to the conventional measures, e.g. noise isocontour areas. The auralization result is able to capture all the predicted noise shielding measures used in the current application and indicates that, for an approach condition, drastically reduced ground noise exposure can be achieved.

1 INTRODUCTION

Traditional noise contour programs, such as the Integrated Noise Model from the FAA, or the European equivalent ECAC.Doc.29, are used to predict and/or regulate the noise induced by aircraft operations [1]. Such tools are developed to evaluate the effect of multiple-flights flown throughout an entire year of operations on an airport. The complexity and size of such a task implies that several modeling assumptions have to be made. This limits the opportunity to model specific noise contributions and separately account for source specific propagation effects. Hence, novel aircraft configurations cannot be adequately integrated in such a model. To that end, a more sophisticated model, predicting the major noise sources individually depending on geometry and operating condition is essential. Additional output data, e.g. spectral shapes for individual components, is required in order to fully assess the noise generation by these vehicles.

The result of both a traditional noise contour program and a more advanced simulation model is usually presented using noise contours or footprints. Such noise contours only present a glimpse of the acoustic consequence on the ground. They fail to provide more insight than a mere indication of a specific noise metric. It would be ideal to assess the audible consequences of perceived noise levels on a more subjective scale. Hence, we would like to listen to the aircraft in addition to analyzing its noise footprint. This is of course especially the case if dealing with novel and non-existing technologies and vehicles.

Recent advances in auralization have enabled researchers [2-6] to transform predicted noise signatures to an audible signal at an arbitrary receiver location. This involves detailed source noise prediction and application of propagation processes, all in the time domain. Hence, auralization enables to actually listen to a flyover of an aircraft that is still in the design phase. For example, predictions were made of the audible impact of a Hybrid Wing Body type aircraft [7] and a Counter Rotating Open Rotor [8].

To get a better understanding of such effects, combined with our curiosity in the audible signature of novel aircraft, we decided to establish an automated process for the auralization of novel aircraft designs. Within this new process, the aircraft design and the source noise prediction is done by TU Braunschweig's PrADO aircraft design synthesis code [9] and DLR's PANAM code [10,11], respectively. The NLR/TUD developed auralization capability [12] is used to generate audible output for each vehicle under a selected flight operation. Hence, we focus on the auralization of novel aircraft that are still in the conceptual design phase.

In this joint NLR-DLR-TU Delft cooperation we aim to investigate and demonstrate that it is possible to automatically obtain an audible impression of radical new designs along their simulated flight path within a conceptual design process. Furthermore, such impressions can serve as a feedback to the aircraft designers if they are on the right track in reducing aircraft noise or to assess annoyance of future aircraft as early as within the conceptual design stage.

2 AIRCRAFT DESIGN AND NOISE PREDICTION TOOLS

Our current approach is to combine the NLR-DLR-TU Delft capabilities to not only predict aircraft noise, but also to realize an audible representation of novel aircraft designs. To that end, several tools were combined. Figure 2 shows the DLR interfacing between PrADO (aircraft design) and PANAM (aircraft noise prediction) tools.

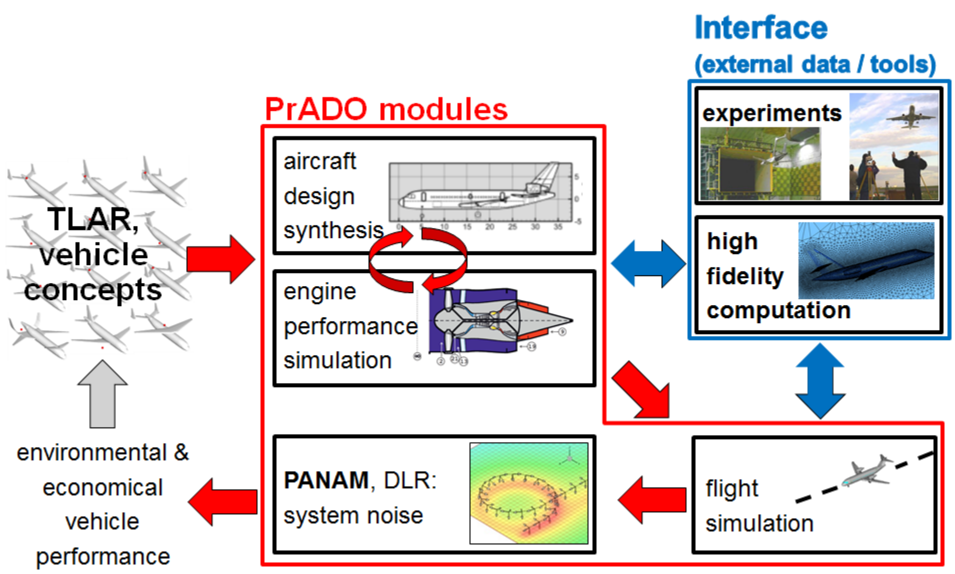

Figure 1: Aircraft design synthesis process with integrated noise prediction capabilities; see Ref. [11]

The aircraft design synthesis code PrADO represents the main framework of the overall simulation process, as depicted in Figure 1. The flight simulation and the system noise prediction are implemented as simulation modules into the PrADO framework [10]. The PrADO code is comprised of a multitude of such modules that each are assigned to a specific task or discipline in the process of conceptual aircraft design, e.g. another dedicated module is specifically assigned to the structural sizing of the wing. The resulting output of certain PrADO modules can furthermore be replaced by data from measurements or external high-fidelity tools, as depicted in Fig. 1. See ref. [13] for an example of the implementation of external input data from measurements into the simulation process. Based on given Top Level Aircraft Requirements and a predefined base vehicle, all relevant disciplines and interdependencies of this vehicle can be simulated and their outcome can be assessed. All design modules are operated consecutively and in an iterative order where each module is based on the accumulated output of the previous modules. The subsequent modules will again generate input data for other additional modules. This iterative process will continue and is repeated until specific preselected design parameters have reached convergence. For example, the required fuel weight and the maximum take-off weight of the vehicle have to converge to fixed values after some iterations of the overall process. If the preselected design parameters reach convergence, a valid and final aircraft design has been identified that can be operated along the given design mission.

This final vehicle is then simulated along a predefined approach and departure flight in order to assess the aircraft system noise. This special module of PrADO models the vehicle along these procedures, generates, and finally collects all the required input data for the system noise analysis. The simulation module for the system noise prediction is the DLR code PANAM. PANAM is a scientific tool, i.e. featuring a componential noise source break-down based on parametric noise source model for each major noise contribution. For instance, noise shielding effects can be incorporated by using a DLR Ray-Tracing tool, i.e. SHADOW [14]. More information about PANAM can be found in refs. [10, 11,13].

Auralization as a technique to transform predictions into an audible waveform is not new. However, the application of these techniques to aircraft noise prediction is a novelty. This holds especially true for an application within the conceptual aircraft design process. Thereby, the designer of novel aircraft configurations can already listen to his or her designs as early as possible within the design process. The framework created for this capability is called PASTA, i.e. Prediction of Aircraft Source, Trajectory and Auralization. Although not explicitly dubbed 'PASTA', the models in ref. [12] form part of this auralization framework which is also described briefly in the next section..

The novelty of the current study is that through efficient interfacing we are able to evaluate an audible impression of a novel aircraft configuration. This allows a direct feedback loop to aircraft designers and to evaluate aircraft that do not fly today. The resulting toolchain is shown in figure 2.

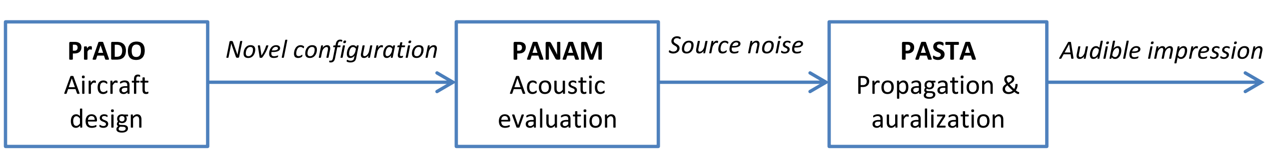

Figure 2: The interdependency and intermediate result of each tool.

The toolchain presented in figure 2 is now fully automated and includes all interfacing necessary to create and predict the audible signature of future aircraft concepts.

3 AURALIZATION

The current section describes some of the auralization aspects in some more detail based on ref. [12] since auralization within the context of aircraft design is a relative novel application.
The source noise prediction tool (PANAM) provides a one-third octave emission broadband spectrum towards an arbitrary observer for each time step of the simulated flight. Additionally, there are discrete tones emanating from the fan, compressor and/or other tonal sources. The tonal sources can easily be auralized by sine waves, i.e. additive synthesis. However, for broadband sources this is inconvenient. To synthesize a broadband spectrum, use is made of white noise shaped according to the spectral shape predicted by the source noise calculation. Since the resulting spectrum is still in the frequency domain, an Inverse Fourier transform (IFFT) is used to obtain the pressure-time waveform. To include changes in the underlying directivity pattern of an aircraft during a flyover, causing audible artifacts if not treated, an Overlap-Add technique is used to stitch the output of the IFFT together. The result is a source spectrum in the time domain that can be used to be propagated to the ground.

During propagation there are three effects that account for the propagation phenomena. The first is atmospheric absorption. Due to viscous effects and molecular relaxation the acoustic waves are attenuated by the medium during propagation. Especially the latter depends on humidity and temperature and accounts for the majority of absorption. In essence, atmospheric absorption reduces the high frequency content as found at the source whereas low frequency content is less affected. Furthermore, atmospheric absorption is proportional to the traveled distance of the acoustic wave and can be converted into a Finite Impulse Response (FIR) filter that is applied to the source signal.
To account for the spreading of sound, an attenuation is applied to the signal that is inverse proportional to the distance between the source and receiver, i.e. spherical spreading law. As such, a straight path between source and receiver is implied. Curved path calculations are also possible. By atmospheric refraction, acoustic rays that are shielded from ground-based observers (by smart aircraft designs) might still reach the ground. Such calculations can be taken into account [15] although this is not yet done.

As a consequence of aircraft (or observer) movement, a Doppler shift is perceived by the observer. Application of Doppler shift, in the time domain, is achieved by a Variable Delay Line (VDL). A VDL delays the waveform by a variable amount, effectively compressing and stretching the waveform. Besides Doppler shift, the ground interference effect is also integrated by the VDL. A ground reflected wave hits the observer ear at a slightly delayed time, with respect to the direct wave, thereby resulting into a characteristic interference pattern. A soft ground and/or turbulence induced coherence loss can also be integrated [16].

The resulting waveform at the observer is thus comparable to an artificial microphone recording. A future step could be to introduce the resulting recording in a virtual acoustic simulator thereby simulating the flyover in a virtual reality scene and incorporating listener audio effects.

4 APPLICATION

The new overall simulation and auralization process is ultimately applied to single-aisle, medium-range transport aircraft. This aircraft type has been selected due to its predicted market share of over 70% by 2030. By that time, the majority of all flight operations at larger airports will be represented by such vehicles and thus have a dominating presence and impact on airport noise [17, 18].

For the selected reference vehicle, fan noise has been identified as a dominating contribution to the overall noise impact. This is especially the case along the approach procedure [10]. As a consequence, new vehicle variations of the base design focus on a reduction of this important noise source [10]. A dedicated design study revealed several promising concepts towards structural shielding without significant economical drawbacks. The investigated vehicle variants can be grouped into four categories according to the most dominant shielding device, i.e. main wing, empennage, fuselage / wing, and wing / empennage [10]. For this auralization process the most promising vehicle design was selected. Hence, besides the reference aircraft "V-r" the overall process is applied to a high-wing design with engines mounted above the fuselage/wing junction as shown in Figure 3, i.e. referred to as "V-2".

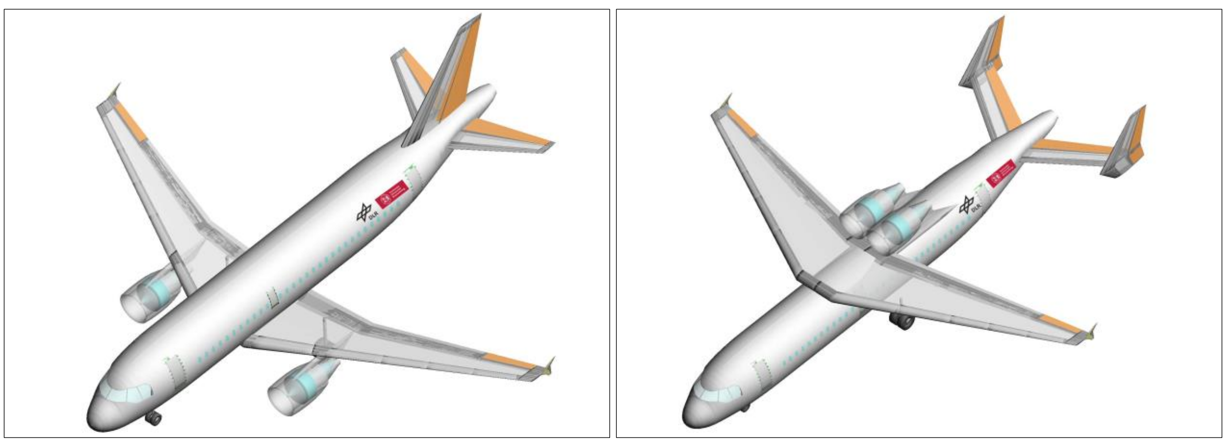

Figure 3: The reference vehicle V-r (left) and shielded concept version V-2 (right)

To quickly assess the shielding effect of both vehicles, the noise emission on a hemisphere has been simulated with the Ray-tracing tool SHADOW as depicted in Figure 4. The system noise emission of both vehicles for one similar flight condition is predicted on a hemisphere, i.e. for a flight speed of 130 m/s and clean configuration (high-lift system and gear retracted). The selected operating condition is somewhat typical for a departing vehicle and demonstrates the significant amount of engine shielding due to the selected engine location above the wing-fuselage-junction. Emission noise level reduction in excess of 10 dB can be achieved for certain emission angles.

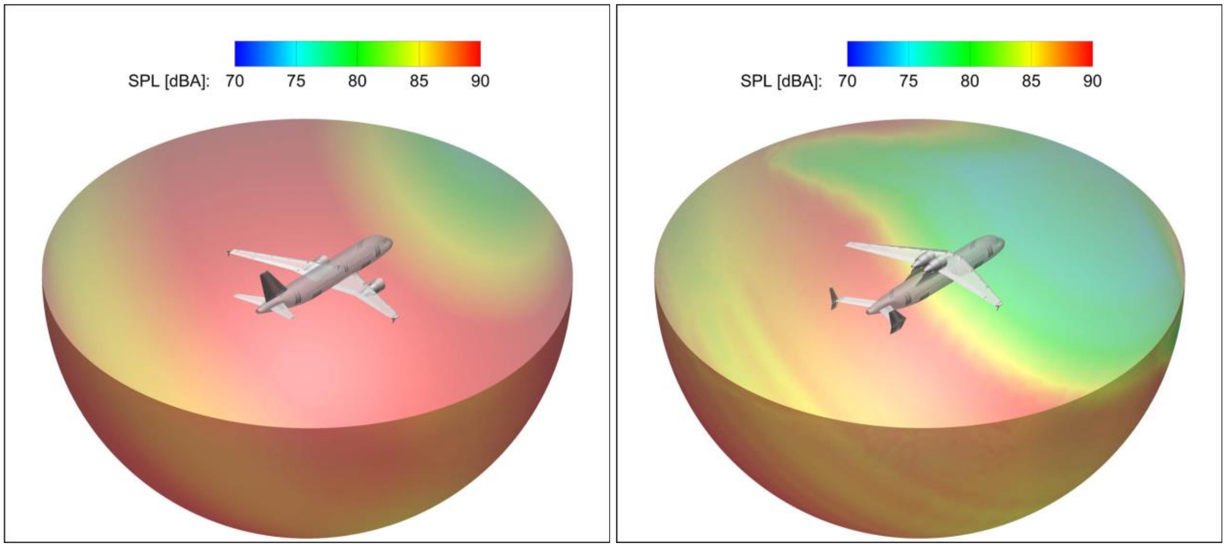

Figure 4: The effect of shielding is demonstrated here by calculating the noise level on a semi-hemisphere around the reference V-r (left) and shielded vehicle V-2 (right).

Both vehicles are now simulated along a typical approach and departure procedure in order to generate the required input data for the auralization. Flight altitude, true air speed (TAS), and thrust are depicted in Figure 5 for both vehicles along the departure and approach procedures, respectively. Furthermore, the selected observer locations for the auralization are included in the figures.

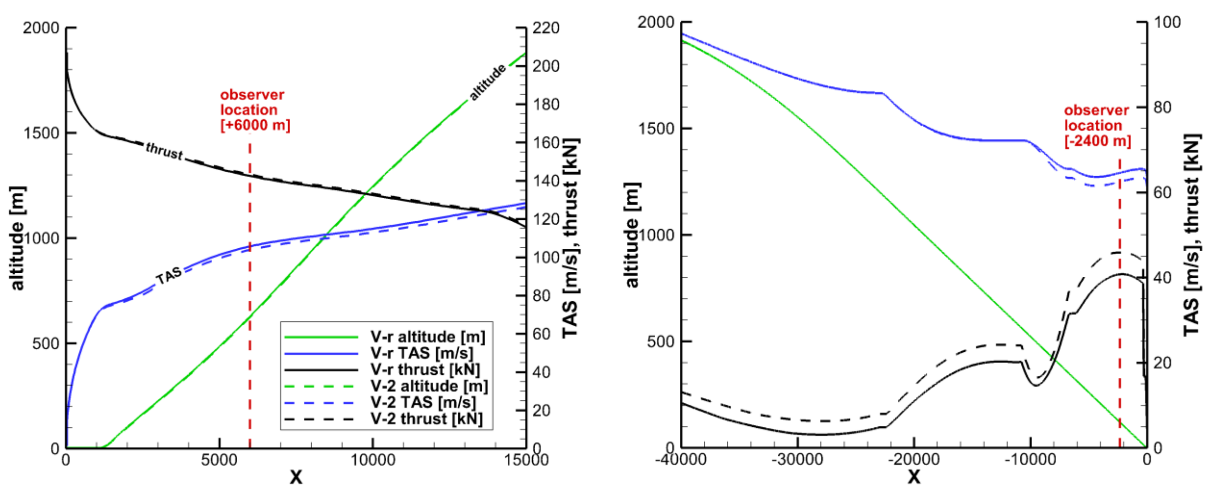

Figure 5: Departure (left) and approach (right) flight trajectories for the two vehicles under consideration. The two preselected observer locations for the auralization are indicated, i.e. "Flyover" and "Approach" as specified in ICAO ANNEX 16, Volume 1.

The auralization is performed at preselected grid points to demonstrate the integrated capabilities of our toolchain. The selected grid/observer location are also indicated in Figure 5. Both observer locations along departure and approach correspond with the certification points "Flyover" and "Approach" as specified in ICAO ANNEX 16, Volume 1. Hence, the shortest distance of the aircraft to the observer for the approach condition is much smaller than for the departure condition.

The auralizations were executed for both vehicles and resulted in the simulation of two waveforms that can be listened too. Unfortunately, it is impossible to include audio files in a paper. These initial results are accessible on the TU Delft website of the Aircraft Noise & Climate Effects (ANCE) group (http://www.lr.tudelft.nl/ance). Spectrograms are included in this paper to obtain a visual impression of the audible content of the auralized results.

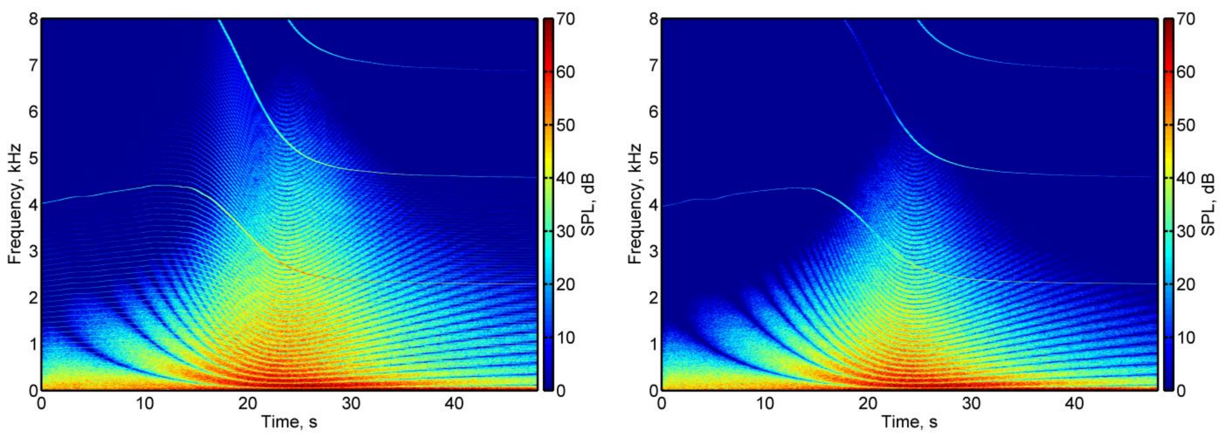

Figure 6: Spectrograms of the auralized waveform for the departure condition. The reference vehicle V-r is shown on the left, the shielded vehicle V-2 on the right.

Figure 6 shows the difference between the V-r and V-2 vehicle for the departure condition. There are clear differences, predominantly in the absence of Buzz-Saw tones for the V-2 vehicle. These tones have effectively been shielded by the structure. The fan rotor-stator tones and the fan broadband contribution were attenuated as well. This broadband noise reduction can be noticed around 25 seconds for the V-2 vehicle as, for instance, broadband noise above the second harmonic of the blade passage frequency is missing. However, the sound level is dominated by sound in the frequency range below 2000 Hz. In this departure case this can, besides others, be linked to jet noise. Such a low frequency contribution is relatively hard to shield. As a consequence, when listening to both results the clear difference is the absence of tones. Besides departure, the approach was simulated and its resulting spectrograms are shown in figure 7.

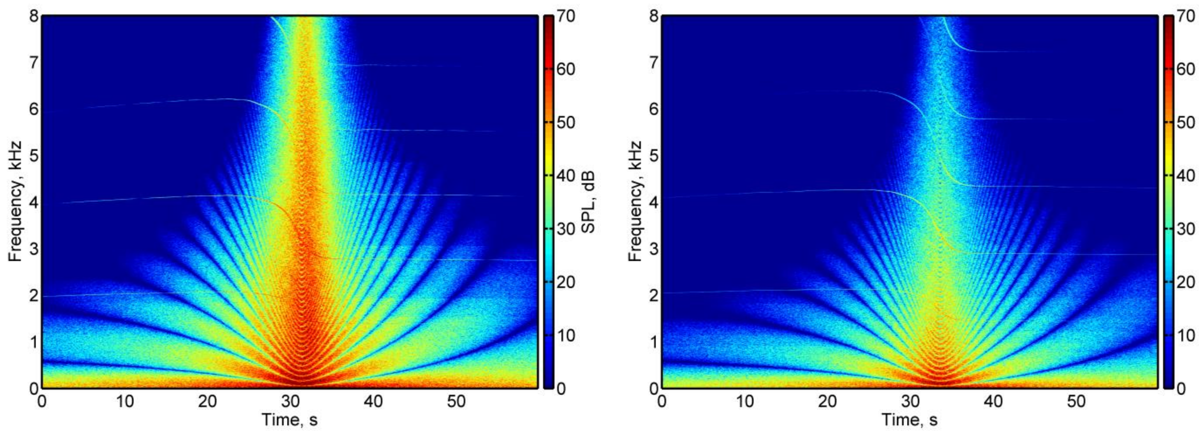

Figure 7: Spectrograms of the auralized waveform for the approach condition. The reference vehicle V-r is shown on the left, the shielded vehicle V-2 on the right.

Figure 7 shows the difference for the approach condition. Since for this aircraft the engine noise in approach is not dominated by jet noise but by fan noise, the difference due to shielding is relatively large. The spectrograms show that the V-2 vehicle is clearly more silent than the V-r vehicle. Both tonal and broadband content has been attenuated heavily by the structural shielding of fan noise by the aircraft. Besides listening to the aircraft, we can look at the overall sound characteristics during the flyover. Figure 8 shows the time variation of the A-weighted Sound Pressure Level (SPL).

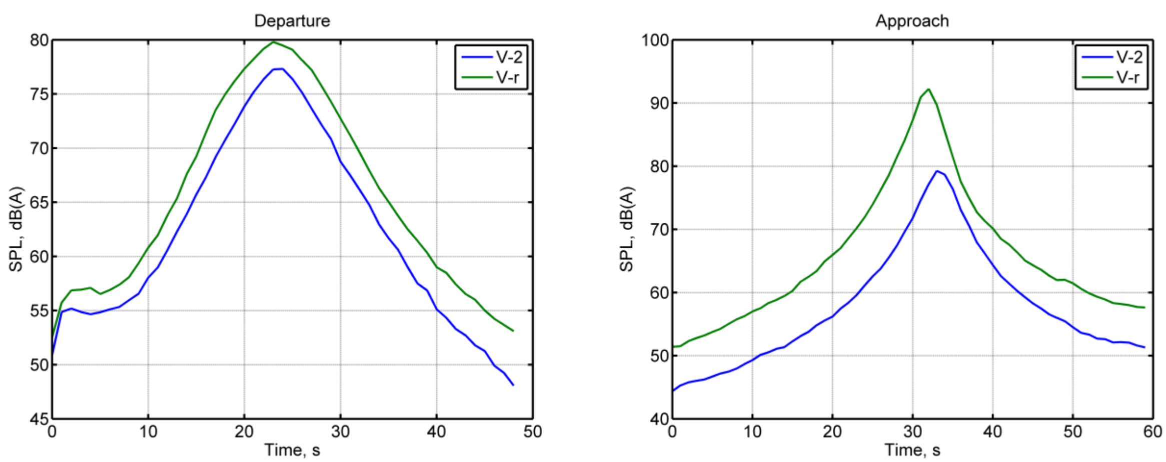

Figure 8: The SPL for both vehicles in case of departure (left) and approach (right) procedures.

The results depicted in figure 6 show that the difference for the approach condition is relatively large. More than 10 dB(A) of the peak level was shielded by the novel configuration resulting in a much lower noise exposure on the ground. The integrated noise metrics associated with this time level history, are tabulated in table 1.

Table 1: Noise metrics from the auralized results

Procedure	Vehicle	LAmax, dB(A)	SEL, dB(A)
Departure	V-r	79.8	89.0
Departure	V-2	77.3	85.6
Approach	V-r	92.3	97.0
Approach	V-2	79.3	85.3

One of the other differences between the V-2 and V-r vehicle, which is only noticeable upon close inspection, is a slightly different Doppler shift due to the change in vehicle velocity (see figure 5). This effect is very small. For instance, the audible impact of the different Doppler shift of the tones is negligible.

The result of this study shows that it is possible to generate an audible impression of radically novel aircraft designs before such aircraft do fly. Comparing the reference vehicle to a novel configuration allows assessing the audible impact for varying procedural conditions.

5 CONCLUSIONS

A newly established cooperation between NLR, DLR, and the TU Delft is presented. The overall goal of the activity is the prediction and auralization of novel aircraft configurations along their individual and tailored flight trajectories. The new auralization process is comprised of several simulation tools in order to perform the required tasks, i.e. aircraft and engine design, flight simulation, aircraft system noise prediction, and ultimately the auralization of the results. The first three tasks are executed with an existing tool chain by DLR and TU Braunschweig, whereas the latter is a NLR and TU Delft development. The individual tools and skills of the different organizations are combined for the first time in order to enable an auralization capability as early as within the conceptual design of novel low-noise aircraft.

The new overall auralization process is scheduled to run fully automated for any new aircraft concepts generated with the existing DLR and TU Braunschweig tool chain. Thereby, the required input data for not only the aircraft system noise prediction but moreover for the new auralization part have to be generated within the subsequent simulation tools within the overall process. According to the specific and individual flight performance of each aircraft design variant, a typical approach and departure procedure can be simulated. Along these simulated flights, the system noise is predicted and all required input data for the auralization are generated. The existing DLR and TU Braunschweig process has been upgraded and enhanced accordingly.

The given application example features two vehicles from a previous DLR study [10]. The process yields an audible representation of the reference and the new low-noise concept. The aircraft designer now has the option to listen to both vehicles and finally to fully assess the modified noise generation and moreover the actual annoyance of the low-noise vehicle compared to the reference. According to the initial results shown here, and made accessible on the TU Delft website (http://www.lr.tudelft.nl/ance), the success of the low-noise measure can be assessed in an intuitive way in combination to the conventional measures, e.g. noise metrics as provided in Table 1 or noise emission directivities as shown in figure 4. As expected, the audible results confirm the reduction in perceived sound on the ground.

The new auralization activities promise significant advantages for future assessment of low-noise aircraft concepts. It has been demonstrated, that the aircraft designer can get a direct feedback on the audible characteristics of new vehicles such as the V-2 still within the process of conceptual design. The audible results can directly be evaluated in order to identify further required low-noise measures in order to achieve the overall goal, i.e. the design of new aircraft with significantly reduced community annoyance.

REFERENCES

1 Integrated Noise Model (INM) Version 7.0 Technical Manual, FAA-AEE-08-01, January 2008.

2 S.A. Rizzi, B.M. Sullivan, "Synthesis of virtual environments for aircraft community noise impact studies", In 11th AIAA/CEAS Aeroacoustics conference, Monterey, CA, AIAA2005-2983.

3 M. Arntzen, D.G. Simons, "Modeling and synthesis of aircraft flyover noise", Applied Acoustics, 48, October 2014, pp. 99-106.

4 D. Berckmans, K. Janssens, P. Sas, W. Desmet, H. v.d. Auweraer, A new method for aircraft noise synthesis*, International conf. on noise and vibration 2006,* pp. 4257-4270.

5 A. Sahai, E. Anton, E. Stumpf, F. Wefers, M.Vorlaender, Interdisciplinary auralization of take-off and landing procedures for subjective assessment in virtual reality environments, 18th AIAA/CEAS Aeroacoustics conf., AIAA-2012-2077.

6 F. Rietdijk, K. Heutschi, C. Zellmann, Determining an empirical emission model for the auralization of jet aircraft, EuroNoise 2015.

7 S.A. Rizzi, A.R. Aumann, L.V. Lopes and C.L. Burley, "Auralization of hybrid wing body aircraft flyover noise from system noise predictions", AIAA Journal of Aircraft, 51(6), pp. 1914-1926, 2014.

8 S.A. Rizzi, D.B. Stephens, J.J. Burton, D.E. v. Zante, J.P. Wojno, T.W. Goerig, Auralization of Flyover Noise from Open Rotor Engines Using Model Scale Test Data, 20th AIAA Aeroacoustics conference, 16-20 June 2014, Atlanta (GA).

9 W. Heinze: Ein Beitrag zur quantitativen Analyse der technischen und wirtschaftlichen Auslegungsgrenzen verschiedener Flugzeugkonzepte für den Transport großer Nutzlasten, ZLR-Forschungsbericht 94-01, ISBN 3-928628-14-3

10 L. Bertsch, "Noise Prediction within Conceptual Aircraft Design," Braunschweig, 2013.

11 L. Bertsch, W. Heinze, M. Lummer, and J. Delfs, "Application of an Aircraft Design-To-Noise Simulation Process," *Am. Inst. Aeronaut. Astronaut.*, pp. 1–15, 2014.

12 M. Arntzen, "Aircraft noise calculation and synthesis in a non-standard atmosphere", Phd-thesis, TU Delft, 2014.

13 Pott-Pollenske, M, Wild, J.W., Bertsch, L., Aerodynamic and Acoustic Design of Silent Leading Edge Device. In: *20th AIAA/CEAS Aeroacoustics conference 2014*, DOI: 10.2514/6.2014-2076, Atlanta, USA.

14 M. Lummer: Maggi-Rubinowicz Diffraction Correction for Ray-Tracing Calculations of Engine Noise Shielding, 14th AIAA/CEAS Aeroacoustics Conference 2008, paper AIAA-2008-3050

15 M. Arntzen, S.A. Rizzi, H.G. Visser and D.G. Simons, "Framework for simulating aircraft flyover noise through nonstandard atmospheres", AIAA Journal of Aircraft, 51(3), 2014, pp. 956-966.

16 M. Arntzen, D.G. Simons, "Ground reflection with turbulence induced coherence loss in flyover auralization", International Journal of Aeroacoustics, 13(5-6), 2014, pp. 447-460.

17 Airbus Company: Airbus Market Forecast 2011-2030, online PDF version (accessed 09 Jan 2013)

18 Boeing Company: Boeing Current Market Outlook 2011-2030, online version (accessed 12 Jan 2012)