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Sound Perception Study of Auralized Novel Propeller Design for Future Electrical Air Mobility Platforms

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To reduce climate impact of aviation, it is imperative to consider to introduce aircraft based on electrical engines. These electrical aircraft replace jet engines by propeller-driven propulsion systems, making the propeller the dominant noise source. A quieter and more efficient propeller blade design may generate a different noise signature, justifying a perception study to assess overall noise impact. In this study, a novel designed propeller "S2PROP" is compared with a baseline propeller "XPROP". Both blades were measured in an aeroacoustic wind-tunnel, and wind-tunnel measurements of tonal and broadband noise were used as an input to generate fly-over sound samples of an aircraft equipped with these propellers. Atmospheric absorption, the secondary ground reflection path and Doppler effect were considered in creating a synthesized flyover sound. A noise simulator with virtual reality glasses and headphones was used to simulate both a visual and audible flyover procedure for participants of the perception study. Although a noise reduction is attained at the highest sound level around 600Hz for the S2PROP, it also generates higher broadband sounds at higher frequencies, resulting in finding no significant differences in perceived loudness or annoyance in the study between the two propeller designs.

I. Introduction

The impact of aviation on climate change is evident: the propulsion of aircraft is almost exclusively based on kerosene, a fossil fuel that contributes to CO2 gasses and climate warming [1]. Although sustainable aviation fuels, based on biofuels or synthetic fuels are slowly introduced [2], another approach for climate impact reduction of aviation is to introduce aircraft based on electrical engines [3]. While the batteries are still an engineering challenge to overcome, electrically propelled aircraft have the benefit of not emitting any green-house gasses, and even for a hybrid electric/hydrogen-based aircraft equipped with a fuel cell, green-house gases are limited to only water vapor. This approach has the benefit that noise from piston or combustion engines is replaced by (quieter) electrical engine noise, with the propeller noise as dominant noise source for the vehicle, similar to current turboprop aircraft [4]. For this reason, and the opportunity of electrical engines to widen the design envelope of propellers, there are compelling arguments to develop a quieter and more efficient propeller blade than those now in use. As a different propeller

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design will also generate a different noise signature, a perception study can help to assess overall noise impact of a novel designed propeller blade.

II. Methodology

A. Propeller design

A novel design called "S2PROP" was based on a scaled baseline propeller "XPROP" used in earlier projects [5–7], and optimized for both higher efficiency and reduced noise output. Although the design of the blade itself is outside of the scope of this paper, the resulting geometry is shown in Fig. 1. Details on this design can be found in another article of this conference [8].

Acoustic measurements have been conducted at the aeroacoustic wind-tunnel (AWT) of NLR. For the test the TUD propeller test rig with rotating balance is used, which is placed on the NLR external balance such that the propeller is located at tunnel centreline at 0.5m downstream of the nozzle. Test configurations include empty tunnel, no propeller, XPROP propeller and S2PROP propeller, for Mach =0.09, Ma=0.12 and Ma=0.15 at different blade angles and advance ratios by changing the RPM.

For the acoustic measurements 10 ½" microphones, all equipped with wind screens, were placed on stakes to ensure they were at propeller height. In order to be able to measure the directivity of the propeller they were placed under axial directivity of -30 degrees to 50 degrees in increments of 10 degrees with the final microphone placed on the opposite side for validation purposes, as can be seen in Fig. 2 and Table 1.

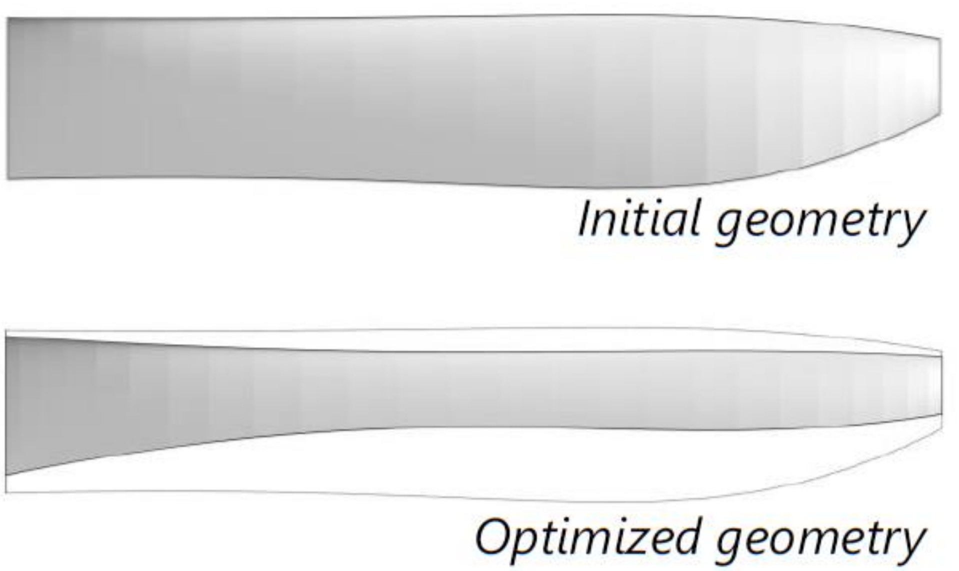

Fig. 1:. Top: the baseline design of the blade (XPROP). Bottom: the novel design of the blade (S2PROP).

B. Propeller measurements

Measurements in the wind-tunnel showed promising results for the reduction of lower frequencies in the sound spectrum for the new S2PROP design. As can be seen in Fig. 3, the tonal frequencies with the highest sound pressure level at 580 Hz or 680 Hz (for the two RPMs) is lower for the S2PROP than for the XPROP. On the other, the higher harmonic frequencies show higher spikes, but they appear at significant lower sound pressure levels. Also, the broadband sound of the S2PROP is higher than the XPROP at frequencies above 1500 Hz. A more elaborate description of the design and operating criteria of the S2PROP can be found in [8].

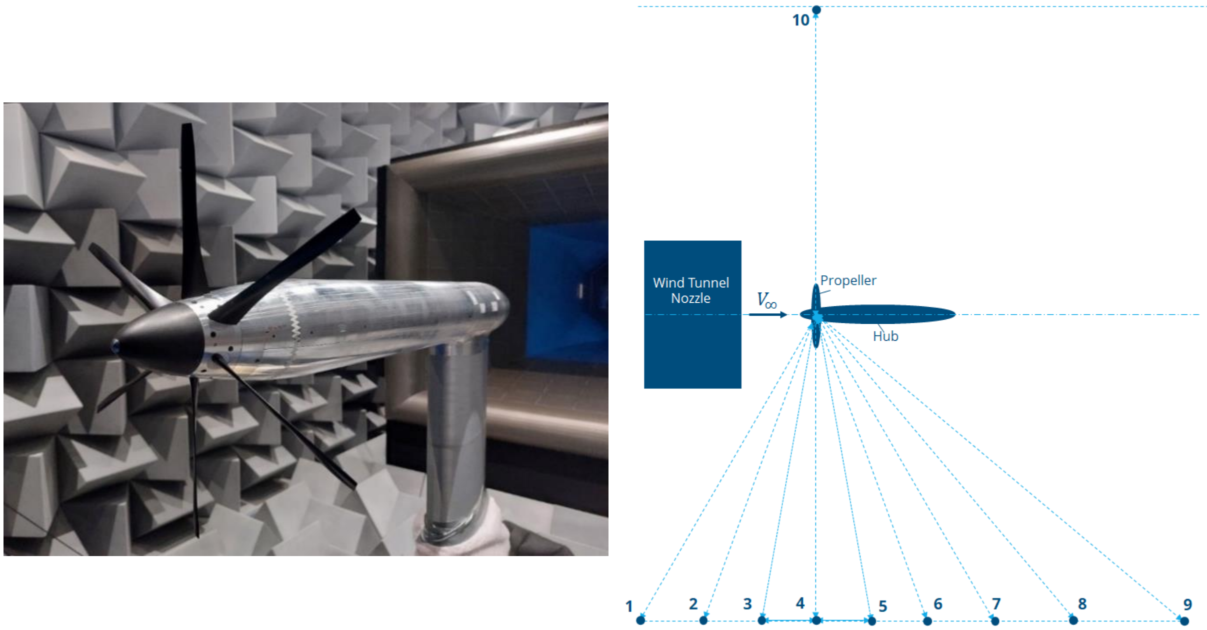

Fig. 2: Left: S2PROP in the NLR Aeroacoustic Wind-Tunnel (AWT), Right: Propeller microphone setup in NLR-AWT

Table 1: Microphone locations in regards to the propeller axis

Micnr.	x[mm]	y[mm]	z[mm]
1	1154.7	-2000	0.0
2	-727.9	-2000	0.0
3	-352.7	-2000	0.0
4	0.0	-2000	0.0
5	352.7	-2000	0.0
6	727.9	-2000	0.0
7	1154.7	-2000	0.0
8	1678.2	-2000	0.0
9	2383.5	-2000	0.0
10	0.0	+2000	0.0

C. Auralization for drone flyover

To evaluate the sound of the new propeller in a human subject study, the sound of the propeller should be made audible in a setting that mimics the way the propeller is used: installed on an air vehicle and performing a realistic operation. For this study, a flyover of a Pipistrel Velis electric aircraft is simulated using the equivalent sound of a scaled XPROP propeller and a scaled S2PROP propeller. Wind-tunnel measurements of tonal and broadband noise were used as an input to generate fly-over sound samples of an aircraft equipped with these propellers. The measurements were corrected for the emission angle change due to the wind-tunnel shear layer, the sound attenuation within the wind-tunnel and the background noise of the wind-tunnel itself [9]. The corresponding power spectral densities of the microphone recordings are subsequently scaled to simulate a fly-over of a real-sized propeller as used on the Pipistrel. Subsequently, hemispheres are created to describe the source noise, both in terms of tonal noise and broadband noise [9]. Synthetization of tonal noise consists of the selection of a discrete amount of tones derived from the corrected microphone recordings. For the synthetization of broadband noise, an overlap-add procedure of each processing block

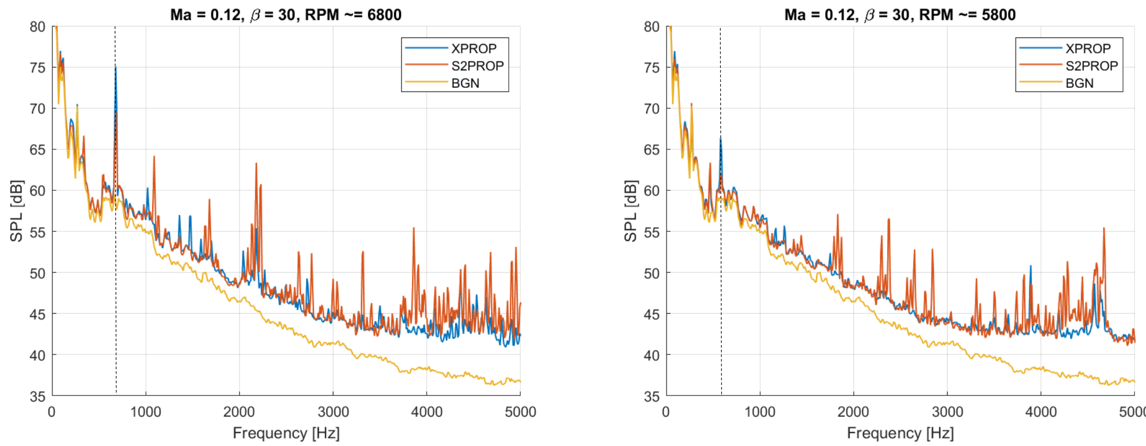

Fig. 3. Results from measurements in acoustic wind-tunnel for two different operating conditions. 6800 RPM on the left and 5800 RPM on the right. The measured background noise of the wind-tunnel is also displayed as BGN. The dashed vertical line is the first blade passing frequency.

in the time domain is used, whereby the power spectral density of these processing blocks are based on the corrected microphone recordings. An estimated level flyover track was used together with the position of the observer to determine the relative distance and speed between the source sound and the observer. Atmospheric absorption, the secondary ground reflection path and Doppler effect were considered in creating a synthesized flyover sound. No additional reflections (e.g. on the facade of a nearby building) were assumed. The resulting output for flyover event of 500ft for both the XPROP and the S2PROP is presented in Fig, 4. The peak sound level of both events already showed some indications that the expected reduction of noise as seen in Fig.3 could not be recognized after applying the full chain of auralization on the measured data from the wind-tunnel. This is probably due to a combination of A-weighting and the contributions of higher recorded values for the S2PROP in the higher frequencies. But as sound characteristics of both propellers can still be different, the preparation for the perception study was continued. The NLR Virtual Community Noise Simulator (VCNS) [10] allowed to add binaural sound reception based on the location of the aircraft, the position of the observer, and the attitude of the head of the observer.

III. Study set-up and execution

D. Study set-up

A sound perception study was performed to evaluate and compare the noise impact of the new S2PROP propeller compared to the baseline XPROP propeller. For this purpose, NLR VCNS was used to create a controlled environment for the perception of these sounds. This simulator consists of a computer, a virtual reality headset and some headphones, and runs an instance of the VCNS software. The simulator was configured to simulate both a visual and audible flyover procedure within two pre-recorded environments: a rural environment, but with a highway in the distance at 500m, and an urban environment with housing and a local road. Both environments were recorded respectively close by, or in a small city in the Netherlands. The recordings were done using a 360 degrees video recorder and a first-order ambisonics audio recorder. Only the rural environment was used for comparison of the sounds of the two propellers, as it was more quiet than the urban environment. A separate sound level meter was used to record the actual environmental sound level and was used later to calibrate the environmental sound in the simulator. A Pipistrel Virus SW aircraft was used as visual model for representing the aircraft equipped with both the XPROP and S2PROP propellers. Although the propeller blades were not specifically designed for this selected aircraft, it would allow the participants of the study to evaluate the propeller sounds in comparison with other air vehicles. Flyovers at a speed of 44 meters per second and at 500 feet and 1000 feet were simulated, as these relatively low heights would make the expected sound sufficiently loud to evaluate the sound characteristics by the participants of the study. The participant in the study is equipped with virtual reality glasses as visual and will act as observer for the flyover events. But to prevent the observer to follow the aircraft in an uncomfortable straight flyover, the flight tracks have lateral offset to the observer similar to the altitude, making the viewing angle 45 degrees at most. As reference, and to keep the simulation interesting for the participants, also some other (pre-recorded) flyover events were added:

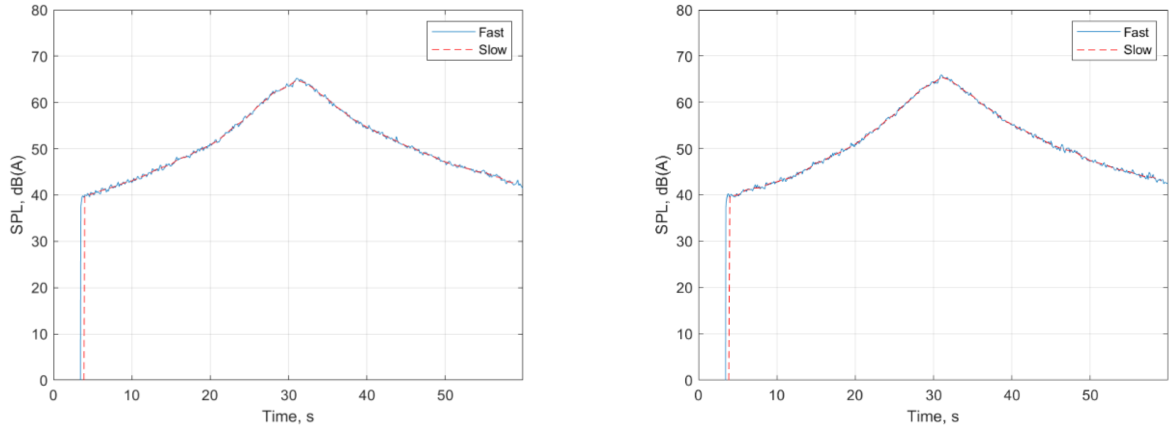

Fig. 4. A-weighted Sound Pressure Level of auralized signal of 500ft flyover of the simulated Pipistrel with XPROP blade (left) and S2PROP blade (right). "Fast" is the $1/8^{th}$ second measured averaged, while "Slow" is the one second measured averaged value.

a (15kg) drone, an EC135 helicopter, a Pipistrel Velis electric, and a Boeing 737 with their corresponding visual models.
The following procedure was followed for the participants of the study:

1. Participants filled in an informed consent form and a demographics questionnaire and,
2. participants put on the Virtual Reality Glasses and the headphones. They received a handheld controller, to answer the questions and to indicate to proceed to the next event,
3. before the start of the actual experiment, participants were presented with two practice trials to get used to the virtual environment and the controller used to answer the questions,
4. participants experienced the 15 measured events and answered them at the end of the event,
5. participants finished the experiment, took off the simulator and were thanked for their cooperation.

The consent form indicated the purpose of the study, privacy regulations, the ability to voluntarily stop the experiment if the participant wants to, and was similar to previous study according to European privacy and ethics regulations. It also asked if the participant had any epileptic condition (due to the use of Virtual Reality Glasses) and if he or her had any hearing condition. Any participants that answered yes here were disqualified from participating. The demographic questionnaire asked about age, gender, education, living location, and whether they were working in aerospace.
After each flyover, participants were asked how loud and how annoying the flyover was perceived. This method is called the "regular method" in this article for the event evaluation. One additional method, the "toggling method", was also tested where the sound during the flyover toggled between two states. The idea behind this method was to experience a closer comparison between the two sounds. This method was only done for the 500ft and 1000ft flyovers of the XPROP vs S2PROP flyovers. One state had the XPROP sound, while the other state had the S2PROP sound. The interval time for the toggling was 5 seconds. Except for the sound, also the colour of the visual Pipistrel model was toggled between an orange and green colour, and a text appeared on the screen with the displayed colour[*]. This method allowed a direct comparison of two events that sound closely similar. Participants had to indicate which state of the event (green or orange) was louder or more annoying. As these were two events in total, the colours were swapped for the two propeller sounds to prevent that the presented colour had a bias towards the sound perception.
All events were randomly presented for each participant to prevent bias based on order of events, with the exception of the fixed first two example events. Also, half the participants first evaluated the toggling events and then the regular events, and the other half evaluated the regular events first, and the toggling events at the end.
The duration of the experiment in the simulation was 15 minutes, and including instruction and filling the consent work and questionnaire around 20 minutes in total. Because this time was short, participants volunteered to participate and did not get a reward for their time spent doing the experiment.

E. Study execution

[*] Except for an additional marker for which state was displayed, it also helped in case participants had colour blindness, a condition that was not asked from, nor tested for, the participants.

A total number of 21 participants were invited and were gathered from the NLR and from acquaintances of two of the authors. Most of the tests were executed at NLR premises in Amsterdam and Marknesse, The Netherlands, but as the system is fully portable, some tests were conducted by the authors at home locations (all in the Netherlands). The age of the participants was between 19 and 58 with an average age of 35.5. From the participants 62% were male and 38% female. Most of the participant were highly educated, as almost half (48%) of participants finished a university bachelor or master degree and 10% finished a PhD. 19% of participants finished an applied university (HBO) degree and 19% a secondary vocational education (MBO). 5% of participants obtained only a high school diploma. Most people, 76%, had affinity with aerospace, not unexpected as most participants were from NLR.

IV.Results

The individual flyover events of aircraft with either the XPROP or the S2PROP, the regular method, were analysed. Results from a two way repeated measures ANOVA showed no overall effect of propeller type on annoyance (F(1, 20) = 1.74, p = .202, η^2 = .080) and on loudness (F(1, 20) = 0.02, p = .898, η^2 = .001). For the toggling method, similar results were found when directly asked if the aircraft with the S2PROP or XPROP were more annoying. One-sample t test showed the answers did not significantly differ from the (middle) answer '5' on the 11-point Likert scale, ranging from 0 as 'S2PROP is more annoying' to 10 as 'XPROP is more annoying' at 500ft and vice versa at 1000ft. This result was both found at 500ft (t(19) = 1.67, p = .110) and 1000ft (t(19) = 0.00, p = 1.00). Due to an outlier, one participant was removed from this analysis.

An effect was found on flyover altitude (500ft at 65dB(A) vs. 1000ft at 60dB(A)) on annoyance (F(1, 20) = 5.29, p = .032, η^2 = .209) and loudness (F(1, 20) = 6.52, p = .019, η^2 = .246). Here, the flyover at 500ft (65dB(A)) (M = 5.05, SD = 2.01) was significantly more annoying than the flyover at 1000ft (60dB(A)) (M = 4.29, SD = 1.79) (t(20) = -2.61, p = .017). This effect was only found for the aircraft with the baseline XPROP propeller and not for the aircraft with the S2PROP propeller (t(20) = -1.39, p = .180).

The opposite effect was found for perceived loudness, where the flyover at 500ft (65dB(A)) of the aircraft with the S2PROP propeller was considered significantly louder (M = 5.14, SD = 2.33) than the flyover at 1000ft (60dB(A)) (M = 4.43, SD = 2.18) (t(20) = 2.15, p = .044). This effect was not found for the aircraft with the baseline XPROP propeller (t(20) = 1.81, p = .086).

Lastly, when compared to the original recorded sound of the Pipistrel (M = 3.67, SD = 2.08) for the 500ft flyover at 65 dB(A), a one way repeated measures ANOVA shows that both the S2PROP sound events (M = 4.71, SD = 2.24) and the XPROP sound events (M = 5.05, SD = 2.01) were significantly more annoying (F(1, 28) = 8.81, p = .003, η^2 = .306) than the recorded Pipistrel adjusted for 500ft flyover altitude.

V.Conclusion and discussion

In this perception study, the annoyance of two different propeller designs was evaluated in a human perception study. To evaluate the sound of the new propeller in a human subject study, the sound of the propeller was made audible in a setting that mimics the way the propeller is used: installed on an air vehicle and performing a realistic operation. For this purpose, auralizations were made using wind-tunnel test measurement data for two different propeller configurations: a baseline blade "XPROP" and a novel design called "S2PROP". The propeller of a Pipistrel Velis electric aircraft was replaced by the XPROP and S2PROP and presented to participants in a Virtual Reality setting with a visual model of a Pipistrel Velis. Results showed, however, no difference in annoyance and perceived loudness towards both the XPROP and S2PROP. This result was both expected and unexpected: expected as the analysis of the auralized signal also showed limited to no reduction in peak sound level noise (Fig.4); unexpected as wind-tunnel measurements showed a significant reduction of sound pressure level for the highest tonal frequency around 600Hz of the S2PROP compared to the XPROP (Fig.3). Presumably, both the human ear's insensitivity for lower frequencies (often translated into an A-weighted scaling) and the higher sound pressures at other frequencies of the S2PROP have contributed to limited to no differences in perceived loudness or annoyance. Conversely, both the S2PROP and XPROP configurations were more annoying than the original flyover of the Pipistrel. However, it should be considered that the S2PROP and XPROP were designed for different conditions and thrust settings than the propeller of the Pipistrel aircraft. This reported higher annoyance could also be an indication of the limitation of the applied auralization: only (dominant) propeller noise was auralized and not (less dominant) airframe noise. Also, other influences or differences between recording and auralization could contribute in differences, e.g. turbulence effects that were not applied in the auralization, or additional environmental sound co-recorded during the recording of the Pipistrel aircraft. As the Pipistrel recordings were normalized to either 60 dB(A) or 65 dB(A) LA_{max}, equivalent to the S2PROP auralized sound levels, these additional environmental recordings may be considered more pleasant compared to the cleaner auralized sounds. Incorporating the Pipistrel propeller design as additional propeller blade in a future study could help to understand the differences in sound perception between auralized sounds and recorded Pipistrel sounds.

A difference was found in a perceived loudness and for annoyance for both propeller combined at different flyover altitudes, which is not surprising as sound levels were 65 dB(A) for 500ft and 60 dB(A) for 1000ft. Interestingly, the flyover of the Pipistrel with the XPROP was significantly more annoying but not louder at the lower 500ft altitude. On the other hand, the reverse was true for the S2PROP, where the propeller was perceived as significantly louder but not more annoying at 500ft altitude versus the 1000ft altitude flyover. This result could indicate that the sound level of the S2PROP has less of an effect on annoyance than on the baseline XPROP configuration, and it does show that the change in sound character of the two propeller blades has an effect on reported perception.

In this study, over 70% of participants worked in aviation. This affinity with aerospace could have an effect on the perception, as this could lower general annoyance. In the field of social sciences, a diverse sample is important for the reliability of the results, which should be addressed in future research with a more diverse and larger sample size. Nonetheless, this study shows that low-noise propeller design should not be based on reduction of source amplitude alone, but on the resulting noise annoyance of the emissions. By including participant testing in the design of novel propeller, noise annoyance becomes a part of the whole design process of propellers and will create a more solution-driven process for noise reduction than solely focussing on wind-tunnel test results.

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References

1. Lee DS, Fahey DW, Skowron A, Allen MR, Burkhardt U, Chen Q, et al. The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. Atmos Environ. 2021 Jan 1;244:117834.

2. European Environment Agency, European Union Aviation Safety Agency. European aviation environmental report 2022. Publications Office of the European Union; 2023.

3. Greenwood E, Brentner K, Rau R, Gan ZF. Challenges and opportunities for low noise electric aircraft. Int J Aeroacoustics. 2022 Jun 1;21:1–67.

4. Geyer TF, Enghardt L. Conceptual estimation of the noise reduction potential of electrified aircraft engines★. Acta Acust [Internet]. 2023;7. Available from: https://doi.org/10.1051/aacus/2023009

5. Li Q, Öztürk K, Sinnige T, Ragni D, Eitelberg G, Veldhuis L, et al. Design and Experimental Validation of Swirl-Recovery Vanes for Propeller Propulsion Systems. AIAA J. 2018 Dec 1;56(12):4719–29.

6. Arnhem N v., Vos R, Veldhuis LL. Aerodynamic Loads on an Aft-Mounted Propeller Induced by the Wing Wake. In: AIAA Scitech 2019 Forum [Internet]. American Institute of Aeronautics and Astronautics; 2019 [cited 2023 Dec 7]. (AIAA SciTech Forum). Available from: https://doi.org/10.2514/6.2019-1093

7. Stokkermans TCA, Veldhuis LLM. Propeller Performance at Large Angle of Attack Applicable to Compound Helicopters. AIAA J. 2021 Jun;59(6):2183–99.

8. Margalida G, della Corte B, Sinnige T, Knepper K, Soemarwoto B, Nahuis R. Low fidelity multidisciplinary methodology for efficient and quiet propeller design: Numerical investigation and experimental validation. In Rome, Italy; 2024.

9. Rizzi SA, Stephens DB, Berton JJ, Van Zante DE, Wojno JP, Goerig TW. Auralization of Flyover Noise from Open-Rotor Engines Using Model-Scale Test Data. J Aircr. 2016 Jan 1;53(1):117–28.

10. Aalmoes R, den Boer M, Veerbeek H. Virtual Reality Aircraft Noise Simulation for Community Engagement. In: INTER-NOISE and NOISE-CON Congress and Conference Proceedings. Chicago, IL: Institute of Noise Control Engineering; 2018. p. 1559–66.