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Conceptual estimation of the noise reduction potential of electrified aircraft engines★

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Abstract – The advent of electrified propulsion systems for civil aircraft promises not only notable reductions of CO_2 and NO_x emissions, but also of perceived noise. In an attempt to estimate the noise reduction potential of fully electric aircraft engines, the current study compares the noise generated by classical turboprop and turbofan engines with noise spectra calculated for electrified engines. The calculation is based on published far-field sound pressure level spectra at different noise certification points, which are then modified to account for the absence of combustion-related noise sources. In addition to the overall sound pressure level, changes to the effective perceived noise level are also taken into account. The results clearly show that the electrification of the engine alone will not lead to the notable noise reductions that are required in order to achieve the goals for future aviation set by the European Commission. Instead, continued research is necessary to further reduce noise sources that will continue to be present in novel electrified aircraft systems, such as fan noise and airframe noise.

Keywords: Aircraft noise, Electrified aero engines, Electrification, Effective perceived noise level

1 Introduction

One of the major contributions to the overall aircraft noise is the noise generated by the engines. According to the European vision for aviation as described in the "Flightpath 2050" program, one of the main goals besides a reduction of CO_2 and NO_x emissions is to reduce the perceived noise emission of aircraft by 65% relative to the capabilities of typical new aircraft in the year 2000 [2]. The electrification of the aircraft engine is one approach to try to achieve these goals [3, 4]. First steps to overcome the associated new technology challenges are the so-called more electric aircraft [5, 6], which means that many aircraft subsystems previously being driven hydraulically, pneumatically or mechanically are operated electrically. In the future, the aim is to produce even less pollutants and noise by introducing hybrid-electric aircraft or even all electric aircraft, where the conventional thrust components will be replaced with fully electric systems as well. So far, the concept of electrified engines has been considered in a variety of preliminary sizing studies for hybrid-electric aircraft (see, e.g., [7–12]), but the related noise generation has only been addressed by very few researchers.

One detailed investigation of advanced concepts and technologies for hybrid-electric aircraft is the study by NASA together with industry partners and academia [13]. Based on simulations and empirical predictions of subcomponent noise, they incrementally compared different aircraft concepts both regarding airframe design and regarding the engine, including a concept with a hybrid-electric propulsion system. Regarding the noise emission they found only a small benefit of the hybrid-electric aircraft compared to the best previous aircraft design with a conventional propulsion system. Synodinos et al. [14] developed a method to calculate noise-power-distance curves for novel aircraft designs based on an arbitrary number of noise sources, which can include existing data sets from measurements or prediction models and even approximations for the effect of new noise reduction technologies. The method allows to calculate the noise exposure contour maps on the ground, and hence enables comparison of aircraft with conventional engines to those with future electrified engines. In a subsequent study by the same authors [15], this method was used to investigate the noise reduction capability of a novel tube-and-wing aircraft that uses distributed electric propulsion with up to 12 electric propulsors. Berton and Nark [16] analytically analyzed the takeoff noise of a single-engine

★Preliminary results of this study have been shown at the 48th German Acoustics Conference as paper number 476 [1]

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single-propeller electric general aviation aircraft using NASA tools. Their study was motivated by the ability to operate electric motors at low rotational speeds at maximum shaft power, which is not possible for reciprocating engines, and which allows for a low-noise takeoff when using a variable-pitch propeller at low shaft speeds. The review paper by Spakovszky [17] contains an interesting outlook on some aspects of the aircraft engine electrification on the resulting noise, mentioning both positive consequences as well as potential challenges that have to be taken care of. In the work of Huang et al. [18], the effect of distributed propulsion on the noise generation of an electrified aircraft was estimated. They observed high potential especially for the reduction of propeller loading noise. However, they found a very high sensitivity of the noise radiation on the location of each propeller, confirming that more research is required to properly explore the potential noise reducing effects. Thomas and Hansman [19] specifically explored the possibility of using the additional drag generated by windmilling fans driven by electric motors of hybrid-electric aircraft to enable steeper and delayed deceleration approach flight procedures, which in turn can significantly decrease community noise. Wassink et al. [20] performed a conceptual study on electric commuter aircraft that already indicates the noise reduction potential, which was mainly achieved by modifying the blade number as well as the dimension and rotational speed of the propellers of the aircraft. A very detailed review of the relevant noise emissions of electric aircraft was published by Greenwood et al. [21]. It qualitatively details the opportunities that arise due to the use of electric motors instead of combustion engines, but also of the many challenges that still have to be solved in order to enable quiet operation of such aircraft. More recently, Zaghari et al. [22] presented a study in which the coupled performance of both the electric motor and the propeller of electrified aircraft was analyzed, which was done by matching efficiency maps of the propeller and the electric machine. Among other findings they observed that quieter propeller designs increase the energy consumption, while for a given energy consumption an increase of the motor size leads to a noise decrease.

In the public perception, however, there seems to be a popular misconception regarding the noise generation by electrified engines: The common belief, that the electrification of the aircraft engine alone will already solve all problems. This opinion is potentially based on experiences with electric cars, which appear to drive almost silently at low speeds [23] when tire noise and wind noise are not yet dominating.

The aim of the current paper is to preliminary estimate the noise reduction potential by means of the electrification of engines for civil aircraft. Thereby, the focus is on regional, medium-range aircraft with designs similar to todays aircraft, but with an electrified propulsion system instead of a turboprop or turbofan engine driven by a conventional gas turbine. Thus, such an aircraft could basically look similar to the one shown in Figure 1, which depicts a general tube-and-wing configuration aircraft with four electrically driven turbofan engines. Of course, it is possible that future all electric aircraft will have a quite different design

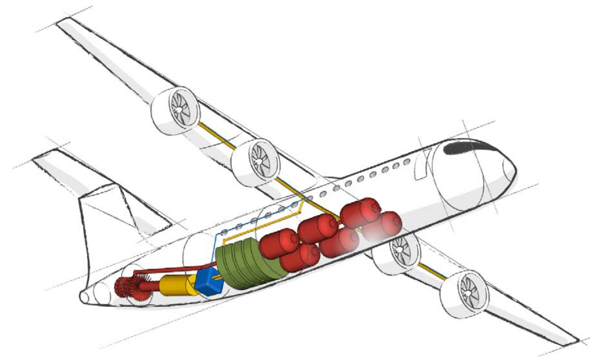

Figure 1. Schematic of a possible hybrid-electric regional aircraft [©DLR | J. Benthaus, S. Kazula].

or a different integration of the propulsion system [24], but this has not been taken into account in the current investigation.

The present paper is organized as follows: First, the procedure for aircraft noise certification measurements is briefly explained. Then, the method used for the estimation of the possible noise source reduction is explained in detail for both conventional turboprop engines as well as for turbofan engines. In turn, resulting changes in aircraft noise due to the electrification are presented, followed by a short discussion of new noise sources that could be important in future all electric aircraft engines. Finally, the study is summarized briefly.

2 Aircraft noise quantification

According to the International Civil Aviation Organization (ICAO), the noise generated by civil aircraft is measured at three distinct noise certification reference points, which are depicted in Figure 2. The first one (*approach*), located 2 km from the runway threshold where the flight altitude is 120 m, is used to measure the noise during approach. There, the engine thrust is notably reduced and the noise from the airframe (such as the high-lift devices and the landing gear) becomes a dominant contribution. The second certification point (*takeoff/ sideline*) is located at the side of the runway, 450 m from the runway axis, where the highest noise levels are measured during takeoff. At this point, the engines deliver maximum thrust. The third point (*takeoff/flyover*) is located 6.5 km from the brake release point, directly under the takeoff flight path. There, the aircraft is gaining altitude, but the thrust has already been reduced by the pilot (cut-back).

The noise measurements at these locations are taken by means of single microphones in one-third octave bands with center frequencies from 50 Hz to 10 kHz over the whole passing time of the aircraft in time segments with a duration of 0.5 s. From these data, the *Effective Perceived Noise Level* (EPNL), L_{EPN}, is determined according to Annex 16 of the ICAO [26]. This standard procedure takes into account the perceived "noisiness" of the sound, tonal characteristics contained in the measured sound pressure

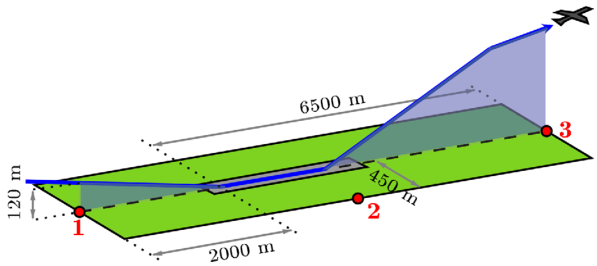

Figure 2. ICAO aircraft noise measurement points, 1: approach, 2: takeoff/sideline, 3: takeoff/flyover (adapted from [25]).

level spectrum (so-called spectral irregularities) as well as the duration of an aircraft flyover event. The EPNL is the basis for the certification of aircraft in the US according to the Federal Aviation Administration (FAA) as well as in Europe according to the European Union Aviation Safety Agency (EASA).

3 Aircraft noise data

Detailed acoustic data for modern civil aircraft is not freely available, as engine manufacturers or airlines naturally do not publish this information. Therefore, the preliminary estimation described in the present paper is based on aircraft noise data taken from the literature [27] for different engine types at the certification measurement points shown in Figure 2. This data set contains spectra of the sound pressure level obtained for the different noise sources of an aircraft with a typical engine type. It will subsequently be modified in Section 4 to simulate the effect of an electrification on the resulting noise that would be measured at the same certification points.

3.1 Noise generation by conventional turboprop engines

In a first step, data will be presented for a typical turboprop engine, as the subsequent calculations of the effect of the electrification on the resulting noise generation are simpler due to the more basic design of this engine type compared to a high-bypass turbofan engine. Figure 3 shows a schematic of a turboprop engine. Corresponding sound pressure level spectra of the major noise sources of an aircraft driven by a conventional turboprop engine are shown in Figure 4 for two of the three certification points (the approach reference point and the takeoff/flyover reference point). The spectra allow for some basic conclusions regarding the noise contribution of the different sources to the overall noise of the aircraft. It can be seen that by far the major noise source at low and medium frequencies is the propeller, which contributes both strong tonal noise as well as broadband noise. Another source that notably contributes noise at high frequencies is the compressor. During the landing phase (Fig. 4a), the combustor generates broadband noise mainly at medium frequencies. It is well below the noise generated by the propeller with the exception of a small frequency range approximately between 1.25 kHz

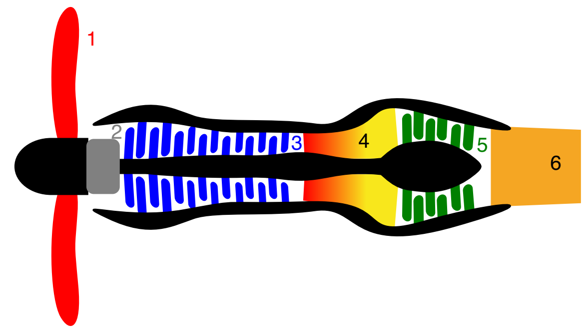

Figure 3. Schematic of the noise sources in a turboprop engine (1: propeller, 2: gear box, 3: compressor, 4: combustor, 5: turbine, 6: jet).

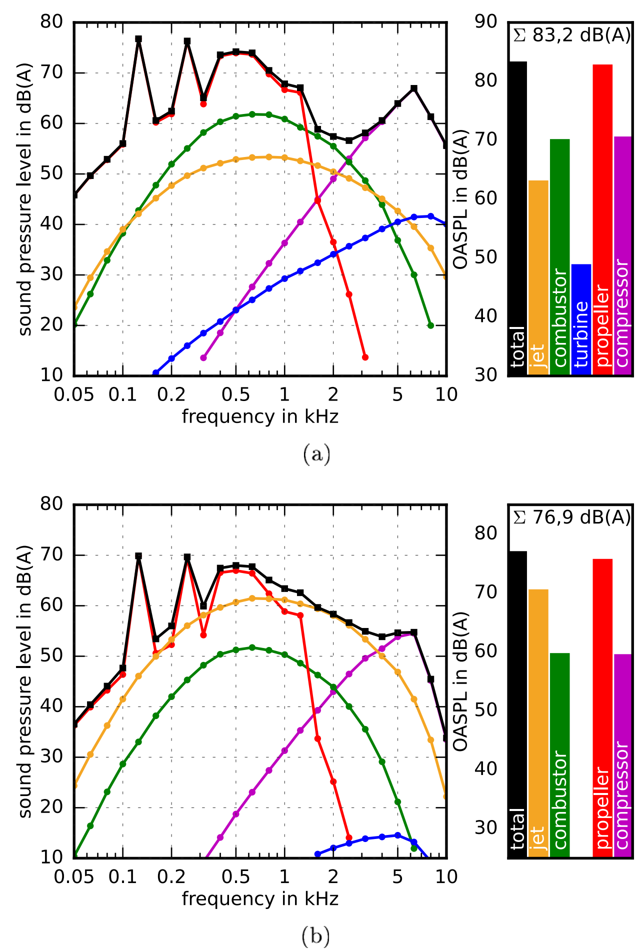

Figure 4. Sound pressure level spectra of an aircraft with conventional turboprop engine at two of the reference points from Figure 2, data taken from [27]. (a) Approach (1); (b) Takeoff/Flyover (3).

and 2.5 kHz, where it leads to a notable increase of the total noise. Noise from the jet and the turbine are basically insignificant at this certification point, while noise from the gear box is not considered in [27] at all.

However, the noise source contributions are different for the takeoff phase of the flight, as shown in Figure 4b.

Now, the jet is a dominant noise source which gets masked at low and medium frequencies by the propeller noise only, but which contributes at one-third octave bands with center frequencies from approximately 1.6 kHz to 4 kHz. The noise generated by the compressor is well below that generated by the jet, while the noise contributed by the turbine is practically insignificant.

It should be mentioned here that the current estimation does not include concepts such as Counter-Rotation Propellers, which are known to be very fuel-effective, but which also lead to many additional noise sources due to acoustic and aerodynamic interaction effects [28, 29].

3.2 Noise generation by conventional turbofan engines

The most important noise sources of a conventional turbofan engine are the jet, the fan, the combustor, the turbine and the compressor. Figure 5 schematically shows the origin of these sources, while Figure 6 depicts the typical directivity and approximate strength of those noise sources for a modern engine with a high bypass ratio.

Figure 7 shows the sound pressure level spectra measured for an aircraft driven by a conventional turbofan engine with a bypass ratio of 6:1 at the three certification points shown in Figure 2. The fan is a dominant noise source at all flight conditions especially in the range of medium to high frequencies, where it emits strong tonal components. These components are caused by flow interactions of the turbulent wake from the rotor blades with the downstream stator blades. In addition, during takeoff the fan emits the so-called "buzzsaw" noise. It is generated by forward-radiated shock waves that form at the rotor blades when their tips rotate with Mach numbers $M > 1$ [31].

In general, the fan continues to be the most challenging noise source regarding an efficient noise reduction [32]. Typical fan noise reduction measures include absorbing liners [33, 34], concepts like swept and/or leaned stator blades [35] or active noise control [36]. When comparing Figure 7a with Figures 7b and 7c, it can be observed that noise generated by the airframe strongly contributes to the total noise during the landing phase of the aircraft with reduced engine thrust. It basically consists of low-frequency noise from the high lift devices (flaps and slats) and the landing gear. Especially the latter may contain strong tonal components due to vortex shedding [37], perceived as particularly annoying. The remaining noise sources, the combustor, the turbine and the jet, are less relevant regarding the total aircraft noise. The noise generated by the combustor principally contributes at medium frequencies, especially during takeoff. This is visible in Figures 7b and 7c. The turbine generates noise at medium up to high frequencies, which is mostly due to the aerodynamic noise generated by the interaction of the turbulent wakes from an upstream rotor or stator with the downstream stator or rotor. Turbine noise becomes even dominant at high frequencies during approach (see Fig. 7a). Typical methods for the reduction of this rotor-stator interaction noise consist of swept or leant blades, increasing the distance between rotor and stator and by choosing suitable values of relative numbers of rotor and stator blades to minimize tonal noise. Jet noise, which was the major noise source in early aircraft engine designs (and continues to be so in military low-bypass ratio engines), has been strongly reduced through years of research [38]. This culminated in modern turbofan designs with high bypass ratios, where the velocity of the core jet has been notably reduced and the bypass flow provides additional shielding of the core jet noise. In Figure 7, the mid-frequency jet noise is basically the contribution with the least strength at all measurement locations.

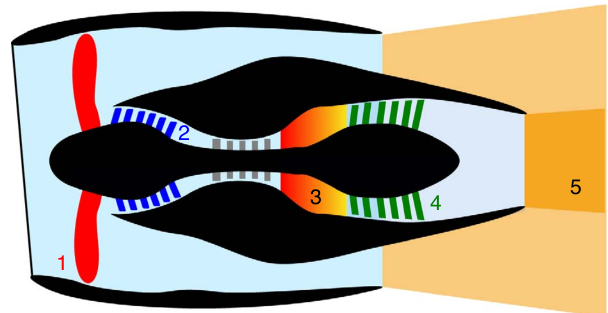

Figure 5. Schematic of the noise sources in a high-bypass ratio turbofan engine (1: fan, 2: compressor, 3: combustor, 4: turbine, 5: jet).

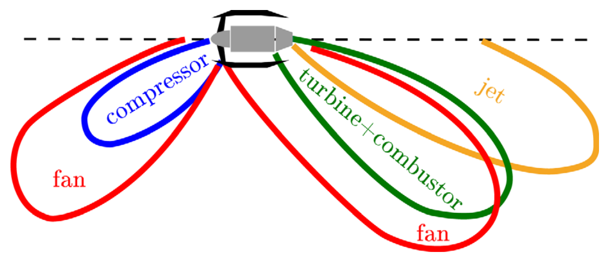

Figure 6. Qualitative assessment of the directivity of high-bypass ratio turbofan engine noise sources [30].

3.3 Turbofan engine data extrapolation towards higher bypass ratios

Modern turbofan engines have even higher bypass ratios, so it is reasonable to attempt an estimation of the noise reduction potential for those engine types as well. Again, as far-field noise data for modern high bypass ratio turbofan engines is not available, another approach has been chosen instead: The sound pressure levels given for the aircraft with turbofan engines with bypass ratio 6:1 were extrapolated to a higher bypass ratio of 10:1. It is thereby assumed that this increase in bypass ratio will mainly affect the noise generated by the fan. In the present preliminary estimation this effect was considered by increasing the fan diameter and decreasing the rotational speed based on data from two existing turbofan engines, which are given in Table 1. One has a bypass ratio of 6.4:1 and the other of 9.6:1. They are taken as representative for turbofan engines with bypass ratios of 6:1 and 10:1, respectively.

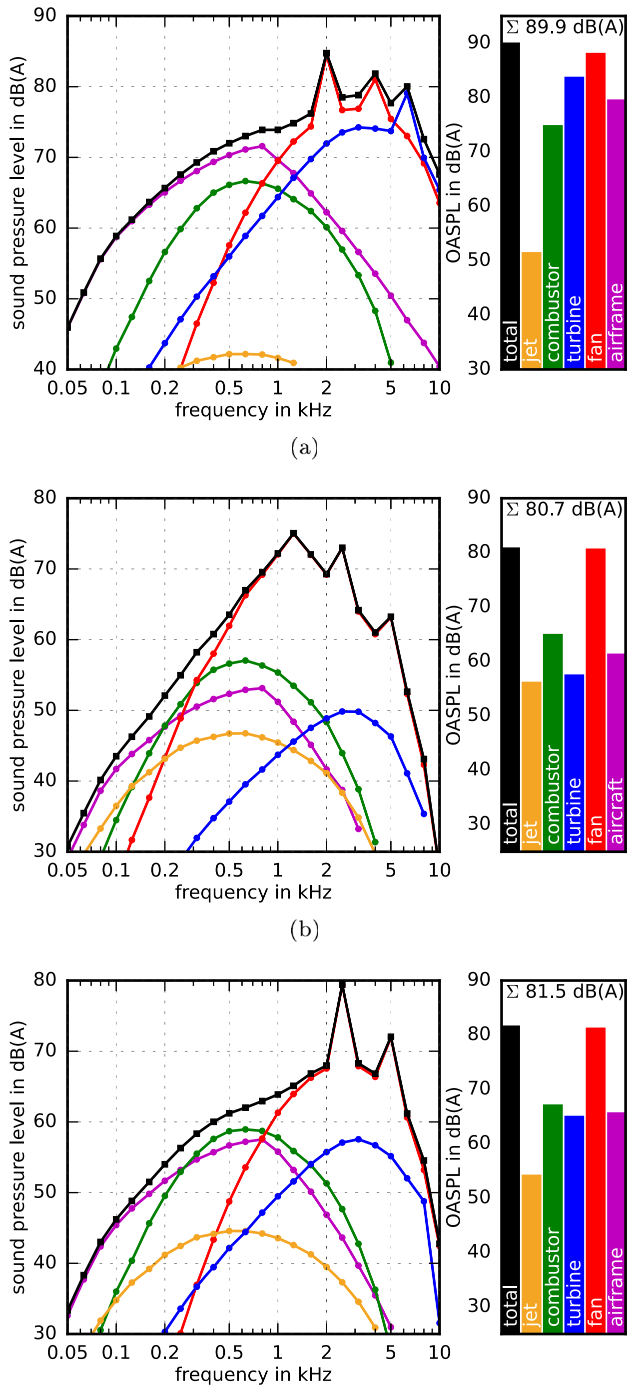

Figure 7. Sound pressure level spectra of an aircraft with conventional turbofan engine with a bypass ratio of 6:1 at the three certification points from Figure 2, data taken from [27]. (a) Approach (1); (b) Takeoff/Sideline (2); (c) Takeoff/Flyover (3).

In general, a decrease in rotational speed will have two acoustic effects: First, it will lead to a decrease in broadband noise from the fan. If it is assumed that most of the fan noise is generated by the outmost part of the blade and the tip and under consideration of the increase in fan diameter, the decrease in rotational speed from 3300 min^{-1}

Table 1. Data from two modern turbofan engines with different bypass ratio.

Engine	Bypass	Fan	
	Ratio	Diameter	rpm
Trent 800 [39]	6.4:1	2.8 m	3300 min^{-1}
Trent XWB [40]	9.6:1	3.0 m	2700 min^{-1}

to 2700 min^{-1} can be converted into a decrease in tip speed to roughly 88% of its former value. For a typical dipole-like aeroacoustic noise source it is known that the sound power scales with U^6 when the chord is small compared to the acoustic wavelength[1], with U being the tip speed. Thus, the decrease in rotational speed of the fan by 12% leads to a broadband noise decrease of 3.4 dB across the whole spectrum. Second, a reduction of the rotational speed will also affect the tonal noise generated by the fan. For simplicity, it is assumed that the frequency of the tones will change, but that their magnitude will remain the same (apart from the 3.4 dB decrease detailed above). Now, narrowband spectra are not available for the engines considered in the current analysis as the data are given in one-third octave bands. For those, the lower frequency limit is 0.89 ($2^{-1/6}$) times the band center frequency, and hence a decrease of tone frequency with a factor of 0.88 would shift only those tones that are located in the lower half of the current frequency band. Tones located in the other half of the frequency band, with frequencies above the center frequency, would simply shift into the lower half of the same band. However, for simplicity, all tonal components were shifted to the next lower one-third octave band for the turbofan engine with a bypass ratio of 10:1.

The results of this procedure are shown in Figure 8, again for the three noise certification points from Figure 2. Compared to the spectra shown in Figure 7 it can be observed that the broadband noise generated by the fan is reduced over the whole range of frequencies, while the tones appear in the next lower one-third octave frequency band. All other noise sources are the same as for the turbofan with bypass ratio of 6:1. Due to the decrease in fan broadband noise, the total noise of the turbofan engine with a bypass ratio of 10:1 decreases from 89.9 dB(A) at the approach certification point to 88.0 dB(A) compared to the engine with the 6:1 bypass ratio. At takeoff, the noise decreases from 80.7 dB(A) to 77.8 dB(A) at the sideline certification point and from 81.5 dB(A) to 78.6 dB(A) at the flyover certification point.

4 Method

In this section, the data presented in Section 3 will be modified to account for the effect of an electrification

[1] For non-compact blades, a dependence on U^5 would have to be considered. However, considering the large number of 22 blades (as in the Trent XWB engine [40]) the blade chord length is smaller than the acoustic wavelength in the frequency range where fan noise is dominant, and hence the acoustic compactness assumption is appropriate.

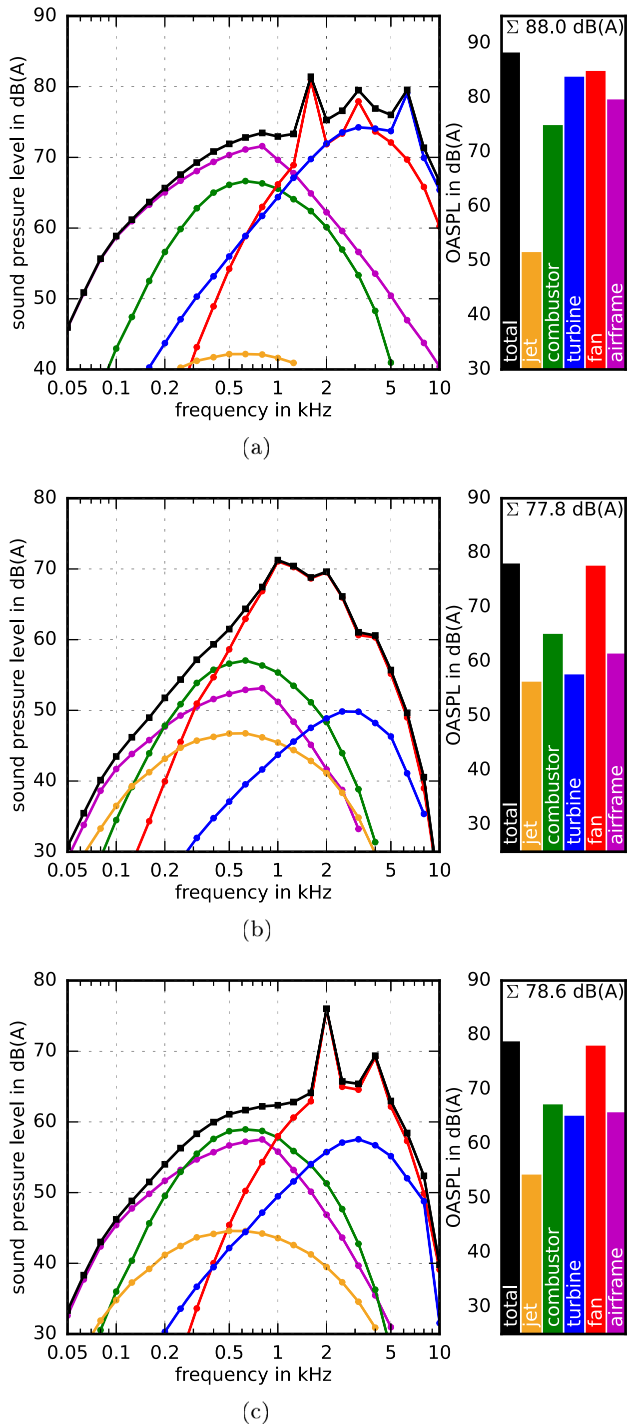

Figure 8. Sound pressure level spectra of an aircraft with conventional turbofan engine with a bypass ratio of 10:1 at the three certification points from Figure 2, based on an extrapolation of data taken from [27]. (a) Approach (1); (b) Takeoff/Sideline (2); (c) Takeoff/Flyover (3).

of the engines on the resulting noise generation. The general procedure is outlined in Figure 9. In a first step, noise sources that belong to components highly likely to no longer be present in electrified engines, such as the combustor, the turbine and the jet, will simply be omitted, while other noise sources, such as the propeller and the fan, will be modified according to their anticipated future utilization.

Among the noise sources that will not be present anymore in future electrified aircraft engines are the core jet of current turboprop and turbofan engines, for example. However, since the jet is responsible for a part of the thrust generated by the engine, this loss in thrust needs to be compensated. In theory, several scenarios are possible to make up for this loss. One solution, which is a likely option to be applied to future, electrically driven aircraft, is the use of distributed propulsion systems. The total thrust will then be provided by a larger number of rather small engines. This will provide possibilities for a further noise reduction due to the smaller tip speeds, but may also lead to a number of new noise sources due to the acoustic interaction from the single propellers or fans. Another scenario is the increase of the propeller or fan diameter. However, modern turbofan engines already have very high bypass ratios in the order of 10:1 and above, leading to fan diameters of about 3 m [40]. Without drastic changes to the aircraft design it is unlikely that a further increase in diameter is possible for underwing configurations due to the need for clearance between the engine and the ground. A third scenario is simply an increase in propeller or fan speed. It could be argued that engines currently operate at the maximum rotational speed already, and a further increase is practically not possible because the propeller or fan would then constantly operate at supersonic conditions. However, for the current preliminary estimation of the resulting noise this scenario is most suitable, since the increase in rotational speed will have the highest impact on the noise generation. Any impact of this increase on the propeller or fan performance, however, is not taken into account. The resulting modified sound pressure level spectra at the three certification points will then be converted into an overall sound pressure level and compared to that of the original engine.

In a second step, the resulting data will be used to calculate the difference in EPNL that can be obtained as a result of the electrification. This is of utmost significance, as this is the value used for aircraft certification purposes. In order to calculate the L_{EPN} difference, several assumptions had to be made: First, it was assumed that the trajectory remains the same, meaning that an aircraft with electrified engine will follow the same flightpath as a current aircraft of the same size. Second, it was assumed that the flight duration and velocity will also be the same and, third, that the mass of the aircraft will also not change. In addition, differences in noise directivity of the single sources were neglected, as this information is not available. Whether these premises are realistic remains to be found out when the first regional aircraft with electrified engines are in use, but within the scope of the current preliminary noise prediction and the resulting level of accuracy they are clearly justified.

Both the difference in total overall A-weighted sound pressure level as well as the difference in EPNL will be presented in Section 5.1. While the first is a purely physical measure of the noise generation by the respective aircraft, the latter includes the psychoacoustic effects of noisiness

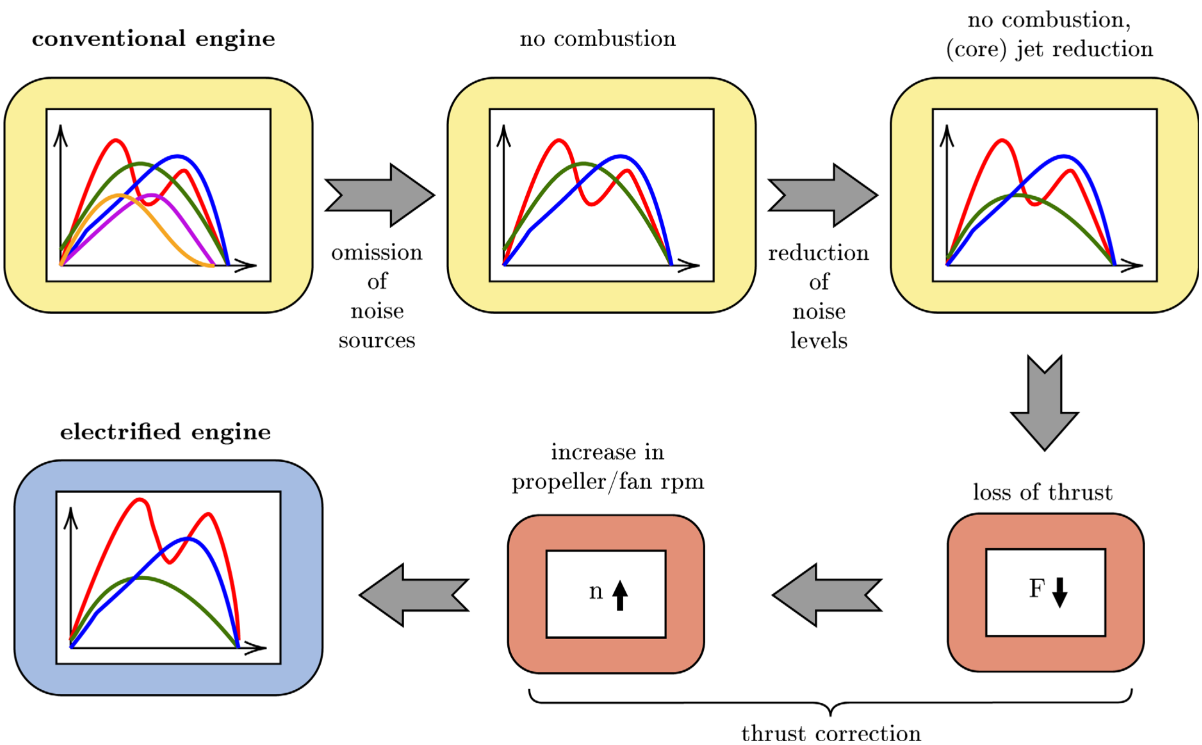

Figure 9. Procedure used to estimate the noise sources of electrified aircraft engines as described in Sections 4.1 and 4.2.

and tonality as well, thus leading to a better understanding of the potential acceptability of future aircraft with electrified engines.

4.1 Effect of electrification on turboprop noise

As future electrified turboprop engines do not burn a mixture of fuel and pressurized air inside a combustion chamber, the noise generated by the compressor, the combustor and the turbine can be completely omitted. More important, electrified turboprop engines also will have no jet from the exhaust, and hence this noise source can be omitted as well. In civil turboprop engines, however, the jet is responsible for approximately 10% of the total thrust [30], which needs to be compensated in the case of an electrified engine. Considering (a) that according to affinity laws the thrust force F is proportional to the volume flow and hence to the pressure inside the turboprop for incompressible conditions, and that (b) the pressure depends on the square of the rotational speed n yields the simple relation

$$\frac{F_1}{F_2} = \left(\frac{n_1}{n_2}\right)^2, \tag{1}$$

where the index 1 characterizes the thrust force and rotational speed of the original engine and 2 those of the engine with increased rotational speed to account for the losses due to the omission of the jet. Thus, it can be calculated that the propeller rotational speed will have to be increased by approximately 5% to account for the loss in thrust force.

Regarding the noise generated by the propeller, the approach used here is identical to that used for the calculation of fan noise generated by a turbofan with a higher bypass ratio of 10:1 in Section 3.3. Again, two effects are considered: First, the increase in rotational speed will lead to an increase in broadband noise assuming a typical dipole-like scaling of the noise with the sixth power of the speed at the outermost part of the blade. Thus, the increase of the rotational speed of the propeller by 5% leads to a broadband noise increase of 1.3 dB. As the frequency of the tonal components is also increased by just 5%, a shift into the next higher one-third octave band has not been included for the turboprop engine. Therefore, the sole effect of the higher rotational speed on the noise generated by the propeller is the increase of the broadband part.

4.2 Effect of electrification on turbofan noise

The approach regarding the estimation of the noise generation by an electrified turbofan engine is somewhat more complicated, but basically similar to that described for the turboprop engine in the previous section. First, all noise sources that will not be present in an electrified turbofan engine are simply omitted, which concerns the combustor and the turbine. In a turbofan engine, the jet actually consists of two components, the inner, hot core jet and the colder bypass flow. Here, it is assumed that the core jet is not removed completely, but that its velocity is reduced to the same value as that of the bypass flow. Matching the corresponding acoustic data shown in Figure 7, values of 461 m/s and 265 m/s are given in [27] for the velocity of the core jet and the bypass flow of a turbofan engine with a bypass ratio of 6:1, respectively. Now it is assumed that the noise generated by the jet scales with the sixth power of the velocity U, which is true for coaxial jets [41].[2] Thus, the velocity reduction of the core jet leads to a notable broadband jet noise decrease of approximately 14 dB. In a second step, the required increase of the fan rotational speed, which is needed to account for the loss of thrust as explained above, is estimated and its acoustic effect on the far-field noise is predicted. To this end, the thrust ratio

$$\Phi = m\frac{F_{\mathrm{c}}}{F_{\mathrm{b}}} = \frac{U_{\mathrm{c}} - U_0}{U_b - U_0} \tag{2}$$

was calculated. In Equation (2), m is the bypass ratio, F_{c} and U_{c} are the thrust force and velocity of the core jet, respectively, while F_{b} and U_{b} are the thrust force and velocity of the bypass flow. U_0 is the aircraft velocity during takeoff, which was taken to be 80 m/s (155 kts). Based on these values it can be estimated that the core jet accounts for roughly 25% of the total thrust for an aircraft with a bypass ratio of $m = 6$. Using Equation (1) it can now be estimated that the rotational speed of the fan has to be increased by 12% in order to account for the loss of thrust of 25% for the electrified turbofan engine with a bypass ratio of 6:1.

Now, again assuming a scaling of the broadband fan noise with the sixth power of the blade tip velocity, this increase in rotational speed of the fan leads to a broadband noise increase of 3 dB. In addition, since the upper frequency limit of a one-third octave band is 1.122 ($2^{1/6}$) times the band center frequency, a shift of the tones in the next higher one-third octave band was taken into account. This is partly due to the fact that in the current study, the change in L_{EPN} due to the electrification of the engine will also be calculated. As the broadband noise starts to decrease at higher frequencies, distinct tones in this range are stronger promoted compared to the broadband noise. Thus, they lead to higher penalties due to tone correction. Additional propagation effects such as frequency-dependent air absorption were not taken into account.

For the electrification of the turbofan engine with a higher bypass ratio of 10:1 (Fig. 8), the same approach was used. As no velocities for the core jet and the bypass flow are available, the same velocity ratio was assumed as for the engine with a bypass ratio of 6:1 (it should be noted here that this simplification is not critical, as the noise contribution from the jet to the total noise is practically insignificant). Due to the higher bypass ratio, however, the core jet provides only 17% of the total thrust (compared to 25% for the engine with $m = 6$). Hence the rotational speed only needs to be increased by 8% to make up for the loss in thrust, which leads to a broadband fan noise increase of 2 dB. In addition, as the frequency of the fan tones also increases by just 8% instead of 12%, it was assumed that the tones are not shifted into the next higher one-third octave band. Thus, the electrification of a turbofan engine with a higher bypass ratio will have a much smaller negative effect on the fan noise and, subsequently, on the total aircraft noise.

[2] As a side note, for a free jet, velocity dependence according to U^8 would be expected [42].

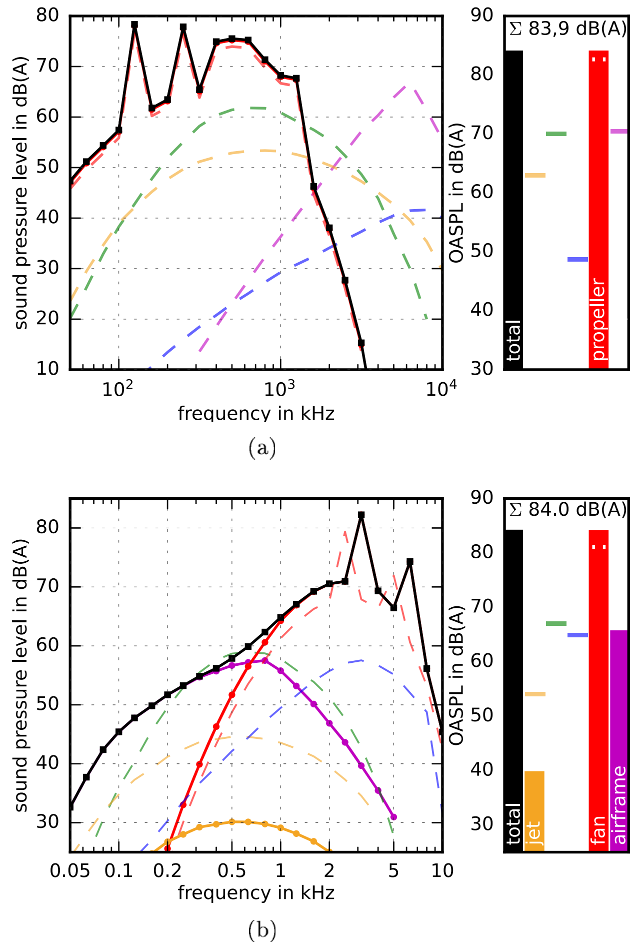

Figure 10. Estimated sound pressure level spectra of an aircraft with electric engines, based on data taken from [27] (solid lines: spectra for the electrified engine, dashed lines: spectra for the conventional engine for comparison). (a) Turboprop at the approach reference point; (b) Turbofan with $m = 6$ at the takeoff/flyover reference point.

5 Results

5.1 Noise reduction due to electrification

For each engine type (turboprop and turbofan) and each certification point for which data are available in [27], the sound pressure level spectra that would be obtained after electrification have been estimated following the procedure described in Sections 4.1 and 4.2. The results are detailed exemplarily in Figure 10a for the noise measured at the approach certification point for an aircraft with turboprop engines (see Fig. 4a for comparison) and in Figure 10b for the noise measured at the takeoff/flyover certification point for an aircraft with turbofan engines with a bypass ratio of 6:1 (see Fig. 7c for comparison). The diagrams contain the spectra of the conventional components (including the jet, the combustor, the turbine and

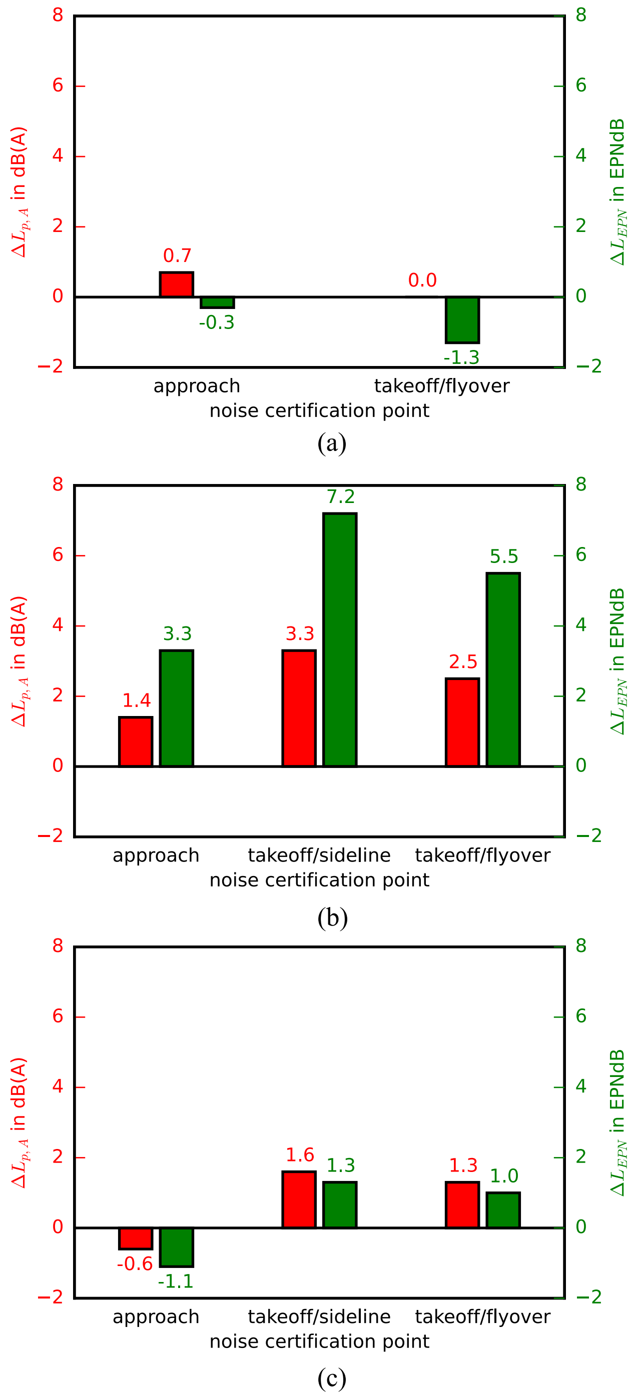

Figure 11. Overview of the estimated difference in noise generation due to electrification of the propulsion system, red: difference in total A-weighted sound pressure level, green: difference in effective perceived noise level under the assumptions specified in Section 5.1 (positive values indicate a noise increase, negative values a noise reduction). (a) Turboprop; (b) Turbofan with $m = 6$; (c) Turbofan with $m = 10$.

the compressor) and the spectra of the components of the electrified engine, while the change in overall A-weighted sound pressure level for each noise source is also indicated.

For the electrified turboprop engine, the omission of the jet, combustor, turbine and compressor mainly lead to differences at high frequencies that are not dominated by the noise generated at the propeller. The slight increase of the propeller rotational speed leads to the aforementioned overall increase of the broadband noise. Due to the fact that the propeller dominates the total noise of a turboprop engine and despite the omission of the other noise sources, this leads to an overall increase of the total noise from 83.2 dB(A) to 83.9 dB(A) at this measurement point.

For the turbofan with a bypass ratio of 6:1, the omission of several classic noise sources (turbine and compressor) and the reduction of jet noise have a notable impact on the resulting shape of the sound pressure level spectrum. For the fan the increase in rotational speed leads to a broadband noise increase of 3 dB and to a shift of the tones into the next higher one-third octave band. Since the fan is the major noise source in this configuration, this has a strong impact on the total noise. Thus, in total, the electrification would lead to an increase of the total overall A-weighted sound pressure level from 81.5 dB(A) in Figure 7c to 84.0 dB(A) at the takeoff/flyover measurement location.

From the resulting spectra of the electrified engines (not shown here for all engine types and measurement locations for brevity), the differences in the total overall A-weighted sound pressure level $L_{p,A}$ due to the electrification were obtained directly. In addition, the resulting differences in L_{EPN} were calculated as described in Section 4. Figure 11 shows the resulting differences in $L_{p,A}$ and L_{EPN}. For the aircraft with turboprop engines, the differences are relatively small, as shown in Figure 11a. At the approach certification measurement point, $L_{p,A}$ increases by 0.7 dB(A), while L_{EPN} slightly decreases by 0.3 EPNdB. At the takeoff/flyover certification point, the A-weighted sound pressure level does not change due to the electrification, but the EPNL decreases by 1.3 EPNdB. Especially the decrease in EPNL, although small, is encouraging, showing that the electrification process in itself can already lead to a small reduction in aircraft noise. For the aircraft with turbofans with a bypass ratio of 6:1, Figure 11b shows that the electrification leads to a notable increase of both the total A-weighted sound pressure level as well as the EPNL at all three certification points. The strongest increase can be seen at the approach certification point, where the electrification leads to an increase of $L_{p,A}$ of 3.3 dB(A) and of L_{EPN} of 7.2 EPNdB. This is mainly due to the large increase of the fan rotational speed that is necessary to counter the loss in thrust force due to the removal of the core jet. For the aircraft driven by turbofans with a higher bypass ratio of 10:1 the results are more promising: Figure 11c shows that the noise still increases during takeoff, by 1.6 dB(A) and 1.3 dB(A) at the sideline and the flyover certification point, respectively, regarding the total A-weighted sound pressure level and by 1.3 EPNdB and 1.0 EPNdB regarding the EPNL at the same certification points. However, at the approach certification point the current estimation predicts a slight reduction of the total A-weighted sound pressure level of 0.6 dB(A) and of the EPNL of 1.1 EPNdB.

Overall, maybe contrary to popular belief, the results of the current estimation indicate that the electrification of the engines alone will not lead to the required noise reduction of 65% for aircraft in the year 2050 (which most likely relates to the noise exposure for residents on the ground [43]). However, the results do show a positive trend for aircraft with modern, high bypass ratio turbofans during approach as well as for aircraft with turboprops, which motivates research for further noise reduction approaches.

5.2 Comparisons to other studies

In an attempt to put the results of the current study into perspective, they are compared to those from other research studies. However, it should be noted that this comparison is not comprehensive, as basic assumptions and strategies differ between different investigations.

In the detailed NASA report from Bradley and Droney [13], the noise of a hybrid-electric tube-and-wing aircraft concept is compared to that of a fuel-powered truss-braced wing aircraft concept. For both designs, the EPNL at the ICAO certification points was predicted based on airframe design, flight profiles, engine type and engine power conditions. For the approach measurement point, the EPNL of the hybrid-electric aircraft was 0.3 EPNdB below that of the fuel-powered aircraft. At the flyover measurement position, an EPNL reduction of 1.5 EPNdB was predicted. At the sideline certification point, the hybrid-electric aircraft generated an EPNL that exceeded that of the fuel-powered aircraft by 0.3 EPNdB. The fact that the noise reductions and increases predicted in [13] are of similarly small magnitude as those obtained in the current study for the turbofan with the higher bypass ratio of 10:1 reveals that the method used in the current study does at least not lead to a significant overprediction of the noise reduction potential. The remaining differences are due to the fact that the two NASA concepts are not identical, meaning that the fuel-powered truss-braced wing aircraft has a different airframe than the hybrid-electric aircraft, whereas in the current study the airframe (and its subsequent noise generation) were intentionally kept constant.

In the study by Synodinos et al. [15], the conventional engines of a tube-and-wing aircraft that is based on the Airbus A320 were replaced with 2 to 12 electric propulsion systems. Thereby, two different strategies were investigated, one being a turbo-electric propulsion system and the second a battery-powered all-electric propulsion system. The comparison of the generated noise, which was calculated using the method detailed in [14], is based on the assumption that takeoff and approach trajectories remain the same. For the electrified engines, the noise contribution from power generator and electric motor were neglected, and hence the sole electric aircraft noise sources were assumed to be the fan, the airframe and the jet. Thus, the difference in noise compared to the conventional reference aircraft came from the variations of the number and characteristics of the propulsors. It was found that the aircraft version with the turbo-electric propulsion system leads to notable decreases of the sound power level during takeoff, ranging from approximately 3.3 dB with two propulsors up to 4 dB with eight propulsors. This is mainly attributed to the reduction of jet noise. Due to the large weight of the batteries, the sound power level reductions are 1 dB to 1.5 dB lower for the battery-powered propulsion system than for the turbo-electric propulsion system. At approach, the noise generated by the aircraft with turbo-electric propulsion system is 1 dB to 2 dB below that of the reference aircraft, with the highest noise reduction achieved for the version with 12 propulsors. The noise generated by the battery-powered electric aircraft exceeds the noise from the reference aircraft by 1 dB up to more than 2 dB. This is due to the fact that in the calculation an increase in flap angle was implemented to balance the increased total weight of the aircraft. The reduction in sound power level for most cases subsequently lead to notably smaller noise contour areas for both architectures. It can be stated that compared to the findings by Synodinos et al., especially for the case where the engines from the baseline aircraft are replaced by just two electrified engines, the results of the current study are not exactly equal, but they show at least the same order of magnitude. At takeoff, the current method predicts no change for the turboprop and a slight increase in the overall sound pressure level for the turbofans, while a clear decrease of about 3.3 dB for the turbo-electric propulsion system with two propulsors and still about 2.2 dB for the battery-powered system is estimated in [15]. These differences are mainly due to the fact that in the current study the most important reason for the total noise increase is the increase in fan noise due to the simplified U^6-scaling approach. The approach from Synodinos et al. employs a probably more realistic empirical fan noise prediction [44], in which the tonal peak sound pressure level scales with a smaller exponent of the rotor tip Mach number. In addition, in the present study any differences in engine weight and dimension were not taken into account, while it can be noted that the assumption of unchanged flight trajectories was made in both studies.

In the work of Wassink et al. [20], two different concepts for the propulsion system of an electrified 19-seater aircraft were investigated. One is a parallel-hybrid electric propulsion system and the other a serial-hybrid electric propulsion system. The study is based on a Do228NG reference aircraft. Notable noise reductions were obtained for both designs. For the parallel-hybrid electric propulsion system, a reduction of the total sound pressure level of 8.6 dB(A) was achieved compared to the reference aircraft. However, this was mainly due to an optimized propeller design with a higher blade number and an increased propeller diameter. For the serial-hybrid electric propulsion system an even higher reduction of the total sound pressure level of 10 dB(A) was predicted. Compared to the baseline aircraft, which has two propulsors, the design with the serial-hybrid electric propulsion system featured four propellers that have a slightly increased diameter and less blades than those of the reference aircraft. Thus, the potential noise reductions are much larger than the ones predicted in the current study, as the size and number of the propulsors were intentionally kept constant in the present preliminary study.

5.3 Potential new noise sources

So far, the current estimation is based only on the removal of existing noise sources, which is due to the fact that no reliable experimental or numerical data exist on novel electrified propulsion systems for regional aircraft. However, it can be expected that several components of the electrified power train may contribute notably to the overall aircraft noise (as, e.g., mentioned in [17]). This includes the electric motor, power electronics (frequency converters, rectifiers and inverters) and gearboxes.

Current research on electric motors to be used in aviation focuses on motors with rather large dimensions, with a large number of pole pairs and high rotational speeds (see, e.g., [45–47]). This means that the electric motor can be expected to contribute tonal noise especially at medium to high frequencies [48].

Huff et al. [45] used both a vibration analysis with a subsequent prediction of tones radiated from the motor casing as well as a simple empirical motor noise prediction model to estimate the noise of two different electric motor designs for future electrically powered aircraft. The resulting spectra were compared to measured fan noise data. It was found that in most cases the motor noise will not contribute to the total noise, but it was estimated that the noise contributed by the electric motor could potentially increase the total noise at flyover conditions. This, of course, will depend on the exact motor installation, which will affect motor noise directivity and possible shielding effects.

To obtain at least a rough first estimate for the noise generated by electric motors, data from the literature will be analyzed. In reference [49], A-weighted total sound power levels are given for drip-proof electric motors with 750–4000 kW, which may serve as a first estimate for motors to be used in electrified power trains for small regional aircraft. Thus, this approach is similar to the one used by Huff et al. [45]. The data are plotted as a function of the motor rotational speed for values between 250 rpm and 1800 rpm in Figure 12. Depending on whether it is intended to drive the propulsor directly or coupled with an additional gear box, it is likely that the rotational speed of electric motors suitable for electrified aircraft is notably higher. To account for such increase, the data from [49] were simply extrapolated linearly to higher rotational speeds. This may be a simplification, but it allows for a first rough estimation. It is visible from Figure 12 that the sound power level can easily reach values of 130 dB(A) at high rotational speeds in the order of 10,000 rpm. If a distance of 120 m (which corresponds to the shortest distance of a reference measurement location from the aircraft trajectory, while it also belongs to the flight phase during which the motor noise is likely to affect the total engine noise [45]) and a monopole-like directivity are assumed, this would lead to an overall sound pressure level of 77 dB(A) at the approach certification point only due to the electric motor.

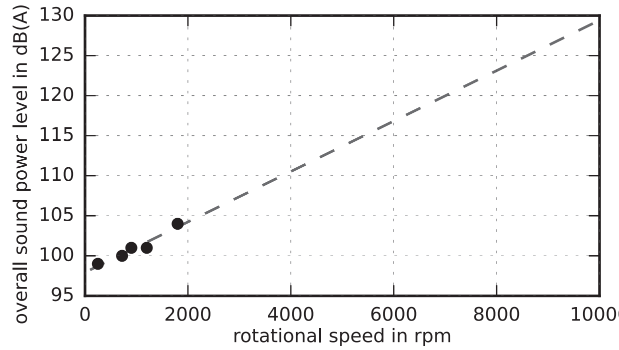

Figure 12. Approximate overall A-weighted sound power level of drip-proof electric motors with 750–4000 kW (markers: data taken from [49], dashed line: linear extrapolation).

A comparison with the overall sound pressure levels at this point (shown in Fig. 4a for turboprop engines and in Figs. 7a and 8a for turbofan engines) reveals that the additional noise contribution from the electric motor would indeed not increase the total noise significantly. However, as mentioned before, a more realistic estimation would require the knowledge of the spectral shape and the directivity of the motor noise as well as the number of motors in a distributed propulsion scenario. In addition, the current estimate is based on data from industrial machinery where typical aircraft constraints, such as power to weight ratio, are not relevant.

Regarding the influence of power electronics it is known, for example, that the switching frequency of the inverter can affect the noise from the electric motor [50]. However, at the current stage it is unclear if this is of relevance for electric aircraft propulsion.

In addition to the electric motor, which is most likely the strongest of the new noise sources in future electrified aircraft engines, noise may also be contributed by gearboxes. Typically, gearbox noise is composed of a strong tone at the gearmesh frequency (the product of the number of teeth and the gear rotational speed) plus lower amplitude peaks at slightly lower and higher frequencies. Detailed measurements performed by Oswald et al. [51] on several designs of spur gears and helical gears showed maximum unweighted sound power levels in the order of 95 dB in this frequency range. Thus, it is not likely that the noise from the gearbox exceeds the noise from the electric motor and, following the above argumentation, the noise from the propeller or the fan.

6 Summary and conclusion

The need for quieter and more sustainable aircraft continues to motivate research towards the electrification of engines for regional aircraft. As a means to obtain a preliminary understanding of the noise reduction potential of such aircraft compared to current aircraft driven by turboprop or turbofan engines, the present study gives an estimation of noise source contributions for such electrified engines based on available data of conventional engines from the literature. The results indicate that the electrification of the engines alone will not result in the postulated noise reduction required for future aircraft. In some cases, such as aircraft with turbofan engines with a bypass ratio of 6:1, the electrification may even lead to an increase in the far-field noise. This is due to the chosen strategy to balance the loss in thrust due to the omitted core jet with an increase in fan rotational speed. In other cases, such as aircraft with turboprop engines or aircraft with turbofan engines with a higher bypass ratio of 10:1 during approach, the electrification can lead to a small, but notable reduction of the total A-weighted sound pressure level and, even more important for aircraft certification, of the effective perceived noise level.

The accuracy of the present approximation is of rather lower order, which is due to several reasons: First, the results depend on the available data. For example, as no detailed data is published for very high bypass ratio turbofan engines, only an approximate extrapolation of data for a turbofan with a bypass ratio of 6:1 to one with a bypass ratio of 10:1 was possible. Second, many assumptions have been made that remain to be confirmed or falsified when aircraft with corresponding electrified engines are available, including the assumption of an unchanged trajectory, speed, duration of the flyover event and total aircraft mass.

Additional noise sources that may be present in electrically driven aircraft, like the interaction between multiple propellers for distributed propulsion systems or other interaction noise sources, will pose further challenges regarding noise reduction. In addition, psychoacoustic effects caused by variations of the rotational speed of the single rotors will have to be investigated. At the same time, of course, the emergence of novel propulsion systems also offers chances for noise reduction, such as an increased shielding of the propulsors by the aircraft body [52] or the use of boundary layer ingestion to increase efficiency [53]. This signifies that research on noise-reduction technology will remain important for novel aircraft with electrified propulsion systems.

The current preliminary estimation needs further evaluation. Since the technology is still emerging, experimental data from electrified propulsion systems for regional aircraft will most likely not be available for some time. Therefore, detailed experimental data on the components of electrified aircraft engines, such as the electric motor, the power electronics and possibly a gearbox, are needed. In the meantime, however, advanced noise prediction tools like PropNoise [54] could be used to provide more reliable engine noise data. The final goal would be to include novel, electrified engine concepts into existing aircraft noise prediction tools like PANAM [55]. This would enable the evaluation of electrified aircraft noise along specified flight trajectories and could be used, for example, to predict the noise pollution close to airports or in densely populated urban areas.

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Conflict of interest

The authors declare no conflict of interest.

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