

NOISE ASSESSMENT OF AIRCRAFT WITH DISTRIBUTED ELECTRIC PROPULSION USING A NEW NOISE ESTIMATION FRAMEWORK

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Future aircraft are envisioned to have significantly smaller noise footprint and emissions impact in order to satisfy the ambitious long-term aircraft noise and emissions goals set by several organisations worldwide, for example ACARE and NASA. Distributed electric propulsion (DEP) is anticipated as one of the most suitable and efficient options for powering these aircraft. DEP is the dispersion of thrust among multiple propulsors that are driven electrically rather than mechanically. This paper presents preliminary noise estimations for a civil aircraft that uses various DEP architectures (e.g. different number of electric propulsors, powered by either batteries or gas turbine engines), obtained through a new noise estimation framework that estimates noise variations arising from technological and/or operational changes with respect to a baseline scenario, where the noise levels are known. The aim of the paper is therefore twofold; investigate the possible noise benefits of DEP aircraft, whilst on the other hand demonstrate the core methodology and capabilities of our framework for estimating the noise impact of future aircraft concepts. This preliminary study indicates the framework's potential in correctly capturing trends.

Keywords: Airport noise, Novel aircraft noise prediction, Distributed electric propulsion

1. Introduction

Air traffic demand is forecast to significantly grow during the next few years [1, 2]. To compensate for the associated potential increase of aviation environmental impact [3], ambitious performance goals have been elaborated for future aircraft by several organisations worldwide. For instance, the Advisory Council for Aeronautics Research in Europe (ACARE) Flightpath 2050 [4] envisions to reduce aircraft noise by 65%, NO_x emissions by 95% and CO₂ emissions by 75% relative to the performance of year 2000 civil aircraft. NASA's 'N+3' technology goals [5] targeting the year 2035 are equally aggressive. Delivering these goals requires planning new mitigation strategies, involving technological advances, reshaped flight operations and the evolution of novel aircraft concepts, such as aircraft using distributed electric propulsion (DEP), i.e. arrays of electrically driven propulsors. Clearly, methods for predicting the mitigation strategies impact (i.e. which ones are likely to achieve the highest reduction of environmental impact around airports) are needed to support decision making.

This paper presents preliminary noise predictions for a civil aircraft using various DEP architectures, carried out using an in-house aircraft noise estimation framework. Hence, the aim of this paper is twofold; investigate the potential noise benefits of DEP aircraft, whilst on the other hand demonstrate the framework capabilities on estimating the noise impact of novel aircraft concepts. The various DEP architectures examined in this paper involve DEP systems consisting of different number of electric propulsors, powered by either a gas turbine engine (e.g. a turboshaft), in which case the aircraft uses a Turboelectric Distributed propulsion (TeDP) system, or batteries, which constitutes an All-Electric (also termed universally-electric) DEP aircraft.

2. Framework architecture

This section gives a brief description of the framework; more details available in [6, 7]. Aircraft noise mitigation strategies are operational and/or technological changes aiming at reducing noise levels at observer locations. Existing noise prediction tools typically assess the noise impact of such strategies by calculating absolute aircraft noise values, using either experimentally obtained data, typically Noise-Power-Distance (NPD) databases, or high-fidelity mathematical models. Prediction tools relying on measurements, like INM [8], are impractical in assessing the impact of future aircraft designs. Mathematical tools, such as ANOPP [9], attempt to simulate the complex aircraft noise generation and propagation mechanisms and typically require hundreds of inputs some of which are proprietary to manufacturers; which poses limitations in their accuracy, despite their fidelity level.

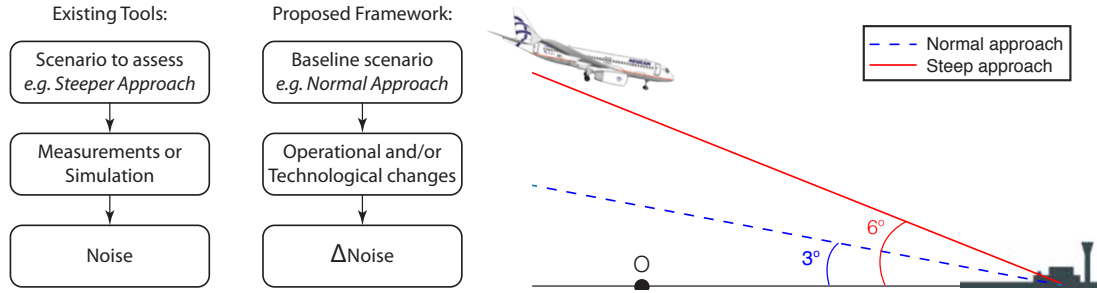


Figure 1: Left: Schematic representation of the proposed framework flow, compared to that of typical existing noise prediction tools. Right: Vertical profiles of normal and steeper descent operations.

As depicted in Fig. 1, the proposed framework estimates the noise impact of mitigation strategies starting from a baseline scenario for which noise levels are known. For instance, rather than directly calculating or measuring the noise impact of a steeper descent approach (see sketch in Fig. 1), the framework estimates the noise level change relative to the conventional descent. Noise estimation is performed computationally, bypassing dependance on noise measurements; whereas the fact that only noise changes are sought reduces computational complexity and the need for confidential inputs. This enable fast assessment of the noise impact of mitigation strategies and novel concepts.

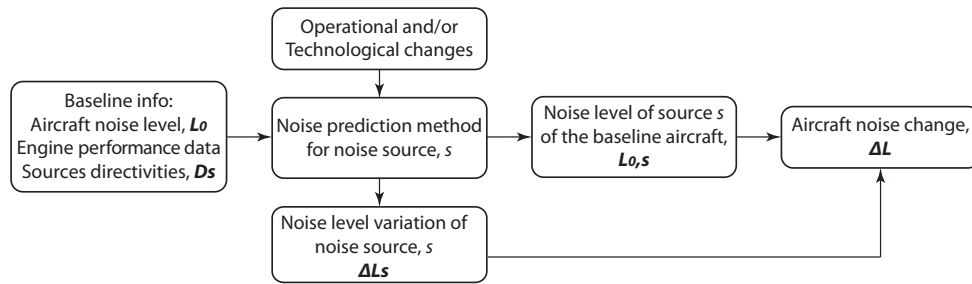


Figure 2: The proposed framework flowchart.

Figure 2 shows the framework flowchart. Operational and/or technological changes induce noise level variation ΔL_s on individual aircraft noise source, s , (e.g. jet, fan, etc.). ΔL_s is estimated with noise prediction methods for individual sources, such as Heidmann's [10] for fan noise. For instance, based on Lighthill's analogy [18], the jet noise variation with gross thrust F_G is expressed as

$$\Delta L w_j = 10 \log \frac{N'}{N} + 10 \log \frac{F'_G}{F_G} + 60 \log \frac{V'_j}{V_j}, \quad (1)$$

where the values corresponding to the condition after the thrust change are denoted with an accent. In Eq. (1), N is the number of engines or propulsors and V_j is the jet effective velocity (i.e.

includes airspeed V_0 influence) corresponding to thrust F_G . Variables like V_j that are included in the various expressions yielding ΔL_s can normally be estimated through public engine and performance data available in manufacturers websites and/or the EASA type certificates [16]. The framework is independent of specific prediction methods and can use any potential new model for existing or new noise sources. Also, the framework treats the aircraft as a lumped noise source, consisting of the desired noise sources, typically the dominant ones (e.g. fan, jet and airframe for modern turbofan aircraft [15]). Variations ΔL_s are combined with the noise levels $L_{0,s}$ of each source s of the baseline aircraft to yield the noise level variation of the whole aircraft

$$\Delta L = 10 \log \left[1 + \frac{\sum_{s=1}^N \left[10^{L_{0,s}/10} (10^{\Delta L_s/10} - 1) D_s \right]}{10^{(L_0/10)}} \right]. \quad (2)$$

Baseline aircraft noise levels L_0 are freely available in the ANP database [12]. Also, the procedure for obtaining the levels $L_{0,s}$ of the baseline aircraft individual noise sources is described in [7].

3. Distributed Electric Propulsion aircraft

The proposed noise framework estimates noise variation due to technological/operational changes. This section presents an overview of the procedure followed to estimate changes involved in the presented DEP study, namely: a) propulsors design and performance changes (see Table 1), and b) thrust requirements changes, due to the fact that aircraft weight varies among the various DEP configurations examined. Accurate estimation of these changes is beyond the scope of the present paper, since these changes are normally known inputs to the proposed framework.

Table 1: Estimated performance data for the electric propulsors used in this study and A320 data.

Aircraft type	A320	DEP Aircraft					
Number of propulsors	2	2	4	6	8	10	12
Fan diameter (m)	1.61	2.0	1.4	1.0	0.73	0.5	0.38
Rated thrust (kN)	117	106	55	37	28	22	18
Airflow (kg/s)	355	458	233	155	118.5	95	76.5
Fan speed (rpm)	5650	4386	6142	8602	12047	16872	23630

Distributed propulsion (DP) is the spanwise dispersion of propulsive thrust among multiple propulsors (e.g. small turbofans, hybrid fuel cell-gas turbine engine [22], electric propulsors), aiming at improving aerodynamics, noise and emissions performance [19]. DP benefits are analysed in [20]. DEP systems use electric propulsors consisting of a fan driven by an electric motor. In a Turbo-Electric (TeDP) aircraft, the propulsors array forming the DEP system is powered by one or more turboshaft engines, while All-Electric DEP aircraft are envisaged to use exclusively electric power sources, such as batteries. Figure 3 shows the propulsion system component chains of the examined DEP aircraft.

This study investigates the noise impact of both TeDP and All-Electric DEP aircraft as well as the impact of varying the number (and hence dimensions) of the electric propulsors, as specified in Table 1, which also lists the geometry and performance data corresponding to the various propulsor sizes. Propulsors upper size limit is constrained to 2 m by the baseline A320 height. Remaining data in Table 1 are based on the efan propulsor [22] and engine performance trends in references [16, 21]. Range and passenger capacity of the DEP aircraft are set to 900 nm and 150 passengers respectively.

The procedure for estimating aircraft thrust requirements variation with number of propulsors and power source is briefly discussed next. Thrust and power requirements are established by the aircraft weight, which is the sum of the Operating Empty Weight (OEW) and weights of passengers, propulsors, power supply system and fuel/ batteries. OEW and passengers weight remain fixed for

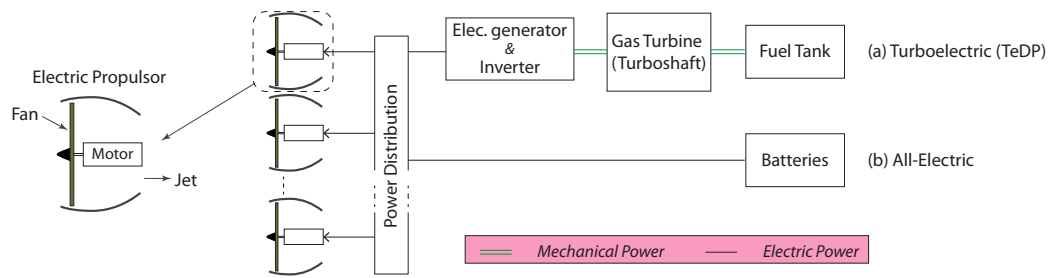


Figure 3: Component chain schematic of the DEP aircraft examined in this paper.

all DEP aircraft configurations. The All-Electric and TeDP versions of the DEP aircraft use identical electric propulsors, whose weight is estimated based on empirical formulas for the motor [13] and the fan [14], whereas nacelle and lining weights are estimated based on the propulsor surface area. An important outcome is that although the weight of a single propulsor increases with fan diameter, the total weight of the propulsors array decreases with number of propulsors (see left plot in Fig. 5). This indicates that in terms of weight, it is beneficiary to seek the maximum possible number of propulsors.

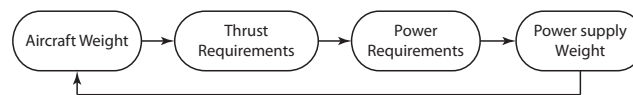


Figure 4: Loop describing the relationship between aircraft weight and power supply weight.

The power supply systems weight is then assessed; it depends on the aircraft peak power requirements and establishes the aircraft weight; which in turn determines the power requirements, creating a loop as depicted in Fig. 4. Hence, assessing the power supply weight requires several iterations of calculations, until results converge. Concerning the TeDP aircraft, it is sensible to assume that the turboshaft weight is not sensitive to relatively small output power variations, due to the inability to fine-scale all its parts. This conclusion is also extracted from observing the turboshaft engine specification database [21]. Therefore, the selection of turboshaft type is assumed unrelated to the number of propulsors. A turboshaft engine is selected according to the TeDP aircraft power requirements that are estimated at 23 MW. Based on the specific fuel consumption (1.019×10^{-5} kg/Ns) of the chosen turboshaft, fuel requirements for the 900 nm mission are estimated at 9 t, including 3 t safety reserve.

A key challenge associated with All-Electric aircraft is reducing batteries weight, i.e. increase their specific energy density, ϵ . This study assumes $\epsilon = 1500 \text{ Wh/kg}$, which is expected to be achieved by year 2035 due to battery technology developments [3]. As previously implied, batteries weight as function of propulsors number is estimated using a loop process until the values converge. The power requirements starting value for the loop process is assumed to be the TeDP value, i.e. 23 MW.

The right plot of Fig. 5 shows the estimated weight of the various DEP aircraft, at takeoff and approach. While the TeDP aircraft is lighter in approach due to the fuel consumed throughout the flight, weight remains unchanged for the batteries-powered All-Electric aircraft. Figure 6 shows the resulting aircraft thrust requirements (calculated using the SAE-AIR1845A procedure [17]) that are more demanding for the heavier All-Electric aircraft than both the TeDP and A320.

4. Noise Estimations

DEP aircraft noise sources are the power generator, electric propulsors and airframe. This section discusses noise sources contribution and presents noise estimations for the 900 nm, 150 Pax mission.

The noise contribution of the power generator is assumed negligible independently of power system type: in the All-Electric aircraft, this is due to the low noise features of battery systems; whereas

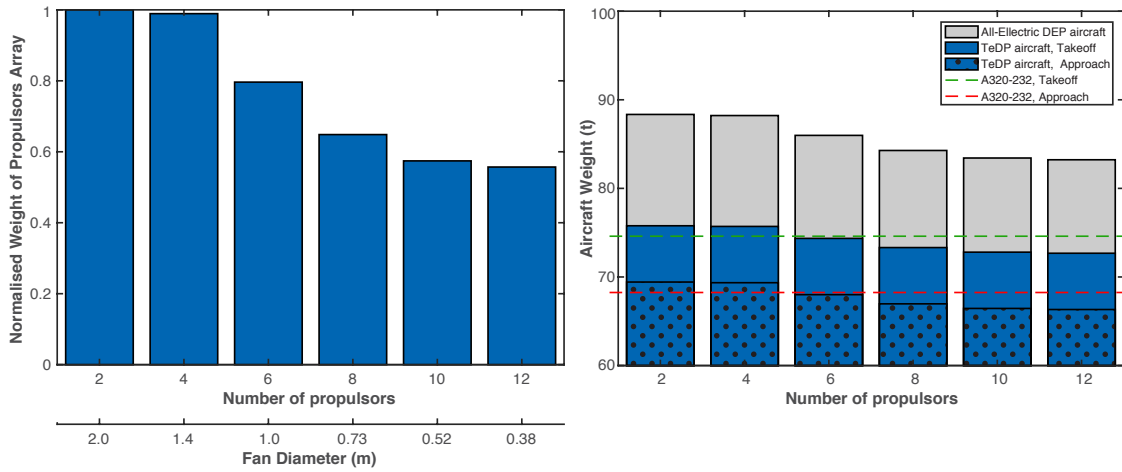


Figure 5: Left: Variation of total weight of propulsors with number of propulsors. Right: Weight of the different DEP aircraft variations at takeoff and approach

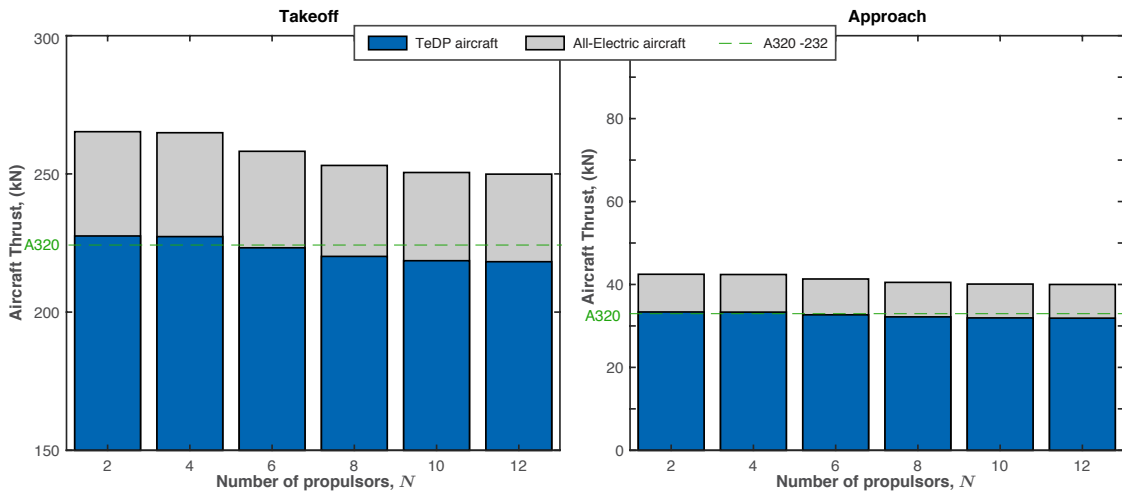


Figure 6: Estimated takeoff and approach thrust requirements of the different DEP aircraft variations.

turboshaft engines in TeDP aircraft are designed to produce minimum thrust and hence it is assumed that their exhaust velocity is low and generates negligible noise impact, compared to the propulsors.

Electric propulsors components i.e. the fan, jet and motor, as depicted in Fig. 3, constitute noise sources of the aircraft. The noise contribution from the motor is assumed small compared to the jet and fan noise. DEP aircraft concepts where propulsors are partially buried in the airframe for exploiting Boundary Layer Ingestion (BLI) benefits [20] feature an additional noise source originating from the fan interaction with the non-uniform inlet flow [23]; these cases are not discussed in this paper.

Airframe noise variation between the DEP and baseline aircraft arise just from operational changes (i.e. different flap settings, different landing gears state), since both feature the airframe of the conventional A320. Ultimately, noise variation between the baseline and the various DEP aircraft is performed based on the noise variation of the fan, jet and airframe.

The specific inputs supplied to the framework for producing the noise estimations presented next are: a) Noise and engine performance information from the ANP database [12], b) ANOPP directivity data [9], c) NASA experimental averages in [15] and d) the semi-empirical methods of Heidmann [10] for fan noise, Fink [11] for airframe noise and the Lighthill's acoustic analogy [18] for jet noise.

Figure 7 illustrates the sound power level (PWL) differences between the baseline A320 and the DEP aircraft variations at takeoff and approach, for fixed flight profiles (i.e. fixed trajectories and

airspeed). The possibility of noise-optimising the takeoff trajectory of each aircraft variation is not examined. At takeoff, where propulsion noise dominates, PWL is reduced for both TeDP and All-Electric aircraft, despite the increased takeoff thrust requirements of the latter (see Fig. 6). This is because total airflow traversing the propulsors is larger than the airflow passing through the A320 turbofans (see Table 1). For instance, while the 4 propulsors DEP total airflow is $4 \times 233 = 932$ kg/s, it is 710 kg/s for the A320. Thus, for the same thrust the examined DEP aircraft are associated with lower jet velocities than the A320 and hence are quieter, as implied by Eq. (1).

At approach, where airframe noise dominates, the TeDP variations are slightly quieter than the A320, due to the reduced propulsors' noise and because TeDP with more than 4 propulsors are lighter than the A320 (see Fig. 5). The significantly heavier All-Electric variations are noisier than the A320 because, considering current technology, it is assumed that they require larger flap deflection angles for fulfilling the approach flight profile; airframe noise increases with flaps deflection angle [11]. While the fact that airframe noise dominates at approach constitutes this increase important. Possible future technologies for reducing All-Electric aircraft approach noise are enhanced lift-to-drag ratio to eliminate further flap deflections, and/or batteries with larger specific energy density to reduce aircraft weight. Figure 7 includes the estimated noise impact of these technologies. Further noise reductions can be achieved by designing quieter airframes (DEP aircraft in this study use the A320 airframe).

An important observation is the small PWL differences between the DEP aircraft variations of the same power source type (TeDP or All-Electric) but different number of propulsors. The maximum takeoff PWL difference, observed between the 2 and 10 propulsors cases is 0.5 dB for the TeDP and 0.9 dB for the All-Electric aircraft. During approach, it is around 0.8 dB for both DEP aircraft types.

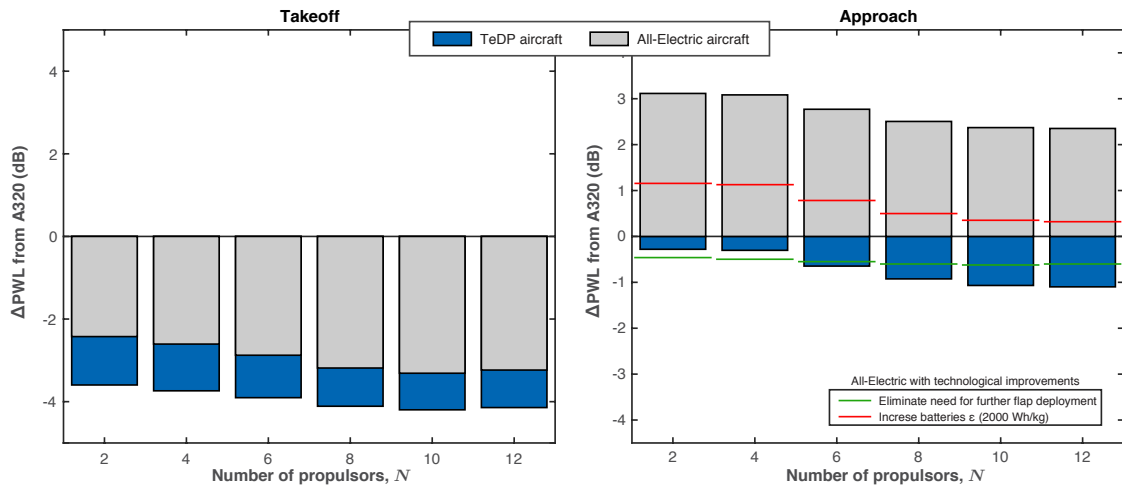


Figure 7: Estimated PWL difference between the A320 and the DEP aircraft for fixed takeoff and approach thrust.

A substantial feature of the proposed framework is that it allows computational construction of NPD curves [7]. NPD curves, that are the main input for producing noise exposure contour maps around airports, normally derive from aircraft flyover noise measurements and hence are available only for existing aircraft. Computationally derived NPD curves enable assessing the potential benefit of novel aircraft designs in terms of noise exposure reduction around airports. Figure 8 demonstrates this capability by showing computed takeoff NPD curves for the 6 propulsors DEP aircraft and the corresponding 90 dB SEL noise contours, as produced by RANE airport noise model [24]. The contour areas indicate that DEP aircraft are quieter than the A320; the heavier (due to batteries weight) All-Electric is noisier than the TeDP, since it needs more thrust for realising the fixed takeoff trajectory, leading in increased propulsors' noise. Figure 9 depicts the variation of all-electric aircraft PWL with number of propulsors along with the noise benefits of making the aircraft lighter by increasing the batteries specific energy density. Minimum noise value occurs at $N = 10$ and $\epsilon = 1800$ Wh/kg.

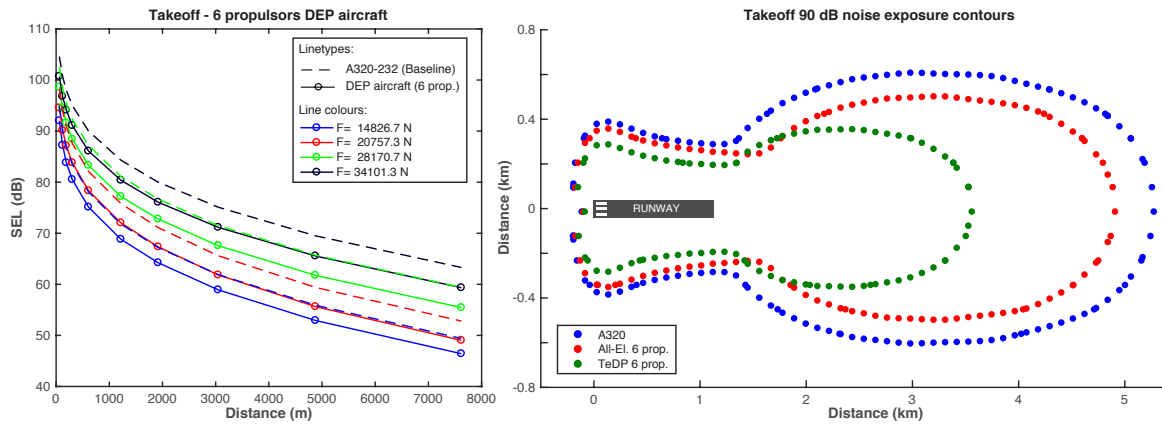


Figure 8: Estimated takeoff NPD curves for 6 prop. DEP aircraft and associated 90 dB SEL contours.

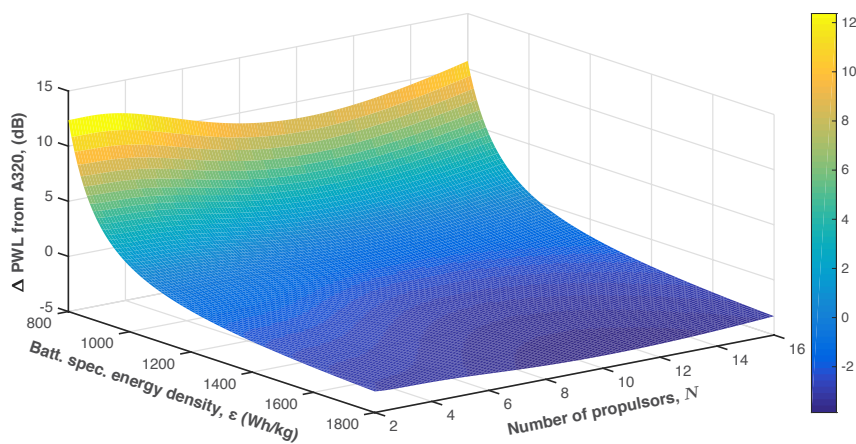


Figure 9: All-electric aircraft PWL against number of propulsors and batteries specific ener. density.

5. Conclusions

Preliminary noise estimations were made and discussed for TeDP and All-Electric DEP concept aircraft consisting of different number of electric propulsors mounted on the A320 airframe. Results suggest potential noise gains of DEP aircraft, especially at takeoff. Future technologies (quieter airframe, lighter batteries, etc.) may allow similar gains at approach. This study's estimations were based on the A320 takeoff and landing profiles; further noise gains may be feasible through operational improvements. Also, thrust requirements were calculated based on current technology levels; propulsive efficiency improvements (e.g. BLI, advanced fans) may lead to further noise reductions.

Capabilities of the framework used to perform the noise estimations were also demonstrated; its integration with other airport noise tools was displayed by providing noise inputs to RANE for producing noise exposure contour maps for a 6 propulsors DEP aircraft. Clearly, performing noise impact studies for novel aircraft while bypassing the need of measurements and/or confidential data is a substantial advantage of the framework, since it facilitates airport planning and decision-making. Its applicability extends to novel operations as well; the framework is currently being used to investigate the optimum, in terms of noise, takeoff and approach angles of existing civil aircraft. Some points not discussed in this paper but elaborated on in [7] and in future publication are listed below:

- Propulsors' size influence on aircraft drag is ignored due to their small drag contribution.
- The minimum thrust provided by each propulsor satisfies the safety-induced thrust requirements according to airworthiness regulations. Also, a statistical study was performed to determine the acceptable number of propulsors failing within the DEP array.

- Framework validation performed through comparison of estimated NPD curves for existing aircraft with published ones showed an error within ± 1.5 dB.
- The framework accuracy mainly depends on the adaptation level of noise prediction methods to new technologies and/or the development of new ones.
- Error embodied in the baseline noise levels does not prevent the framework ability to correctly render trends, since it estimates noise changes.

Future work includes estimating the noise impact of further electric aircraft designs, featuring different propulsors types and configurations, incorporating other effects, such as frequency variation with propulsors size, the effects related to the electric motor and BLI.

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