Computed Noise Emission of an Electric Propulsion Unit of a Regional Aircraft

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Introduction

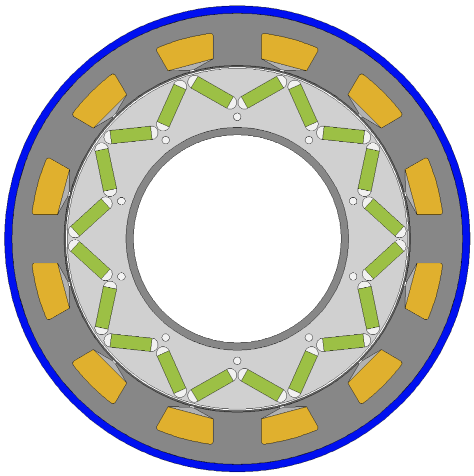
The electrification of aircraft powertrains presents a promising approach for reducing emissions, such as CO_2 and NO_x, within the aviation sector. Many concepts for fully-electric or hybrid-electric aircraft, which often utilize open rotors, face challenges with noise generation from the propulsion system. This issue is particularly pronounced in distributed electric propulsion systems that involve multiple propellers, where additional interference effects have to be considered.

High-power electric motors are central to the propulsion of such novel electrified aircraft. While numerous studies have focused on the noise produced by propellers in distributed electric propulsion systems, only a limited number have recognized the potential noise contributions from the electric machines themselves. Given the high power density and lightweight requirements of these electric motors, which tend to operate effectively at high rotational speeds, the noise they generate could be significant, particularly at medium to high frequencies.

In a previous study, the combined noise generation from electric machines and propellers in a regional aircraft equipped with varying numbers of propulsion systems in a distributed electric propulsion setup was investigated [1]. The aim of the present paper is to use the same method to assess the noise emissions from the propulsion system, but this time using an electric machine topology that is optimized with respect to efficiency and minimum overall mass. This will provide an improved understanding of the expected noise contribution of the electric machine of the electric propulsion system to the total noise.

Table 1: Top Level Aircraft Requirements (TLARs) considered in the present study.

MTOM (kg)	21,395	**wing aspect ratio**	11.37
OEM (kg)	16,375	**fuselage diameter (m)**	2.75
PAX	42	**design range (NM)**	740
max. payload (kg)	5,250	**cruise Mach number**	0.4
wing area (m^2)	64.2	**cruise altitude (ft)**	24,000
L/D **mid cruise**	16.9	C_L **mid cruise**	0.73



Machine diameter (mm)	312
Machine length (mm)	201
Airgap length (mm)	1
Continuous power (kW)	350
Maximum speed (rpm)	9200
Drive unit mass (kg)	80
Drive unit mission efficiency (%)	95.7

Figure 1: Schematic and characteristics of the final design of the electric machine: housing (blue), stator (gray), windings (orange), permanent magnets (green), rotor (light gray), shaft and stator bandage (dark gray).

Method

The regional aircraft considered in this study is based on an ATR 42 aircraft, which serves as a concept to assess the feasibility of integrating solid oxide fuel cell in the scope of the "H_2EAT" project of the German Aerospace Center [2]. Table 1 shows the according Top Level Aircraft Requirements. The aircraft is equipped with eight propulsion units. Each of these units consists of an electric motor, a gearbox with 5:1 transmission ratio and a propeller with six rotor blades.

The electric motors are radial-flux interior permanent magnet synchronous machines in inrunner configuration. At cruise condition, they deliver approximately 300 Nm of continuous shaft torque at a rotational speed of 6,805 rpm. The motor-gearbox unit was optimized using a metamodel-based optimization approach with regard to electromagnetics, thermals and rotor stress in order to achieve maximum mission profile efficiency and minimum overall mass. A schematic of the corresponding motor is depicted in Fig. 1. The propeller has a diameter of 2.5 m and can deliver 4 kN of thrust force. For the acoustic calculation, NACA 16-type airfoils were used for the rotor blades for simplicity. In this study, only the noise emissions of the electric motor and the propeller are considered, as they are expected to be the most important acoustic sources. Other sources, such as aerodynamically induced noise, which becomes important at approach, are neglected.

The method used to calculate these noise contributions is shown in Fig. 2. It consists of an analytical model to calculate the thickness and loading noise of the propeller [3, 4]

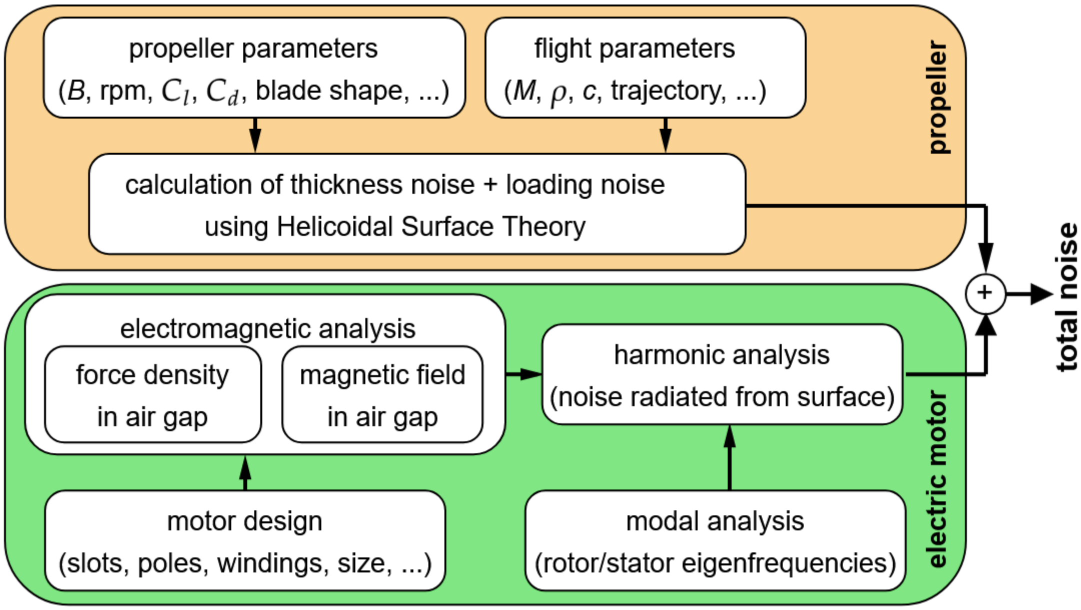


Figure 2: Methodology applied in the current study (adapted from [1]).

and a multiphysics finite element method to obtain the sound radiation of the stator surface of the electric machine which is caused by electromagnetic forces in the air gap between rotor and stator. Both calculations are performed for the cruise operating point, where the conditions of air at an altitude of 24,000 ft during cruise are employed ($c = 310.9\,\mathrm{m/s}$ and $\rho = 0.57\,\mathrm{kg/m^3}$).

Propeller Noise Calculation: In order to calculate the sound power level of the propeller, the sound pressure is evaluated using the Helicoidal Surface Theory at multiple locations on a sphere with 5 m diameter surrounding the propeller. Each of these sound pressure time signals is calculated for a duration of 1 s, which equals 23 revolutions of the rotor. A block-wise Fast Fourier Transform (FFT) analysis is employed using Hanning windows with 4,096 samples, resulting in a frequency resolution of 4.88 Hz.

Electric Motor Noise Calculation: In a first step, the electromagnetic forces due to the magnetic flux field in the air gap are calculated. These forces acting on the stator teeth are combined with the results from a modal analysis of the stator to obtain the resulting vibrational field of the structure. The corresponding surface velocities are then used as an excitation boundary condition for a spherical acoustic region around the motor. Finally, the resulting sound pressure levels are evaluated inside that sphere to obtain the sound power level.

Results

In Figure 3, sound power level results for the propeller and motor are presented, which were derived using the method explained in Figure 2. The propeller and motor contribute to distinct frequency ranges within the spectrum. The lower frequencies, below 500 Hz, are predominantly associated with the propeller, while the motor's influence is noted for frequencies above 500 Hz. The propeller's contributions are primarily defined by blade passing

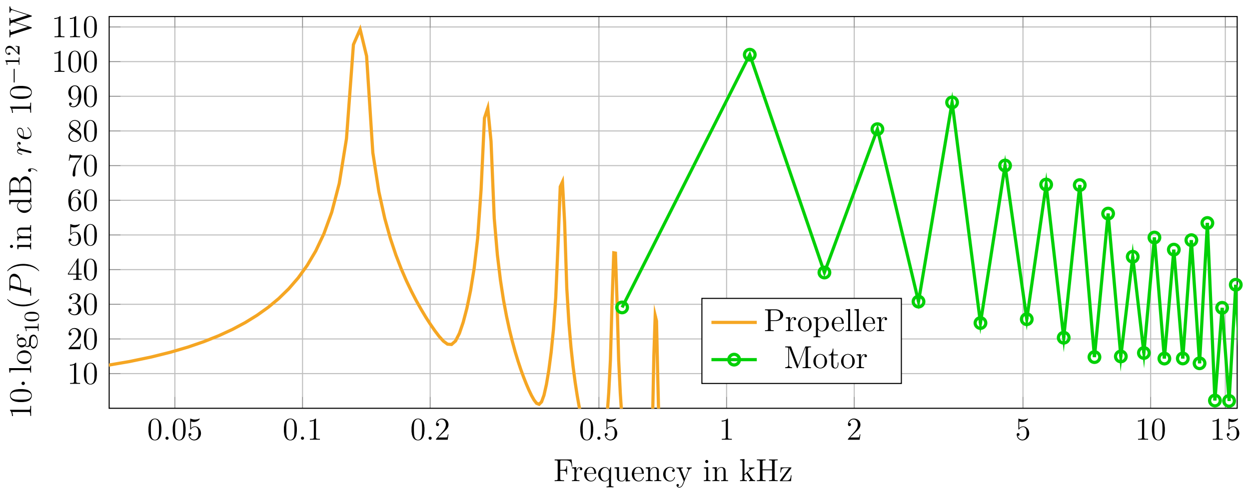


Figure 3: Sound power level of propeller and motor at cruise condition.

frequencies (BPFs), with the first order having a sound power level of 109.3 dB and being 20 dB higher than the second blade passing frequency. The most significant effect from the electric machine is observed at 1.1 kHz, with a sound power level of 102 dB. A notable sound power level is only observed for the even multiples of the electric frequency. The second highest peak has the same level as the second blade passing frequency. The overall sound power level of motor and propeller combined amounts to 110.2 dB.

Summary and Conclusion

This paper presents a method to compute the noise emissions of a propeller and an electric machine of an electric propulsion unit. The analysis of the sound power level spectrum shows, that the blade passing frequencies of the propeller contribute to the low frequency range. Above 500 Hz only the noise radiated by the motor is relevant. This highlights the importance of including the electric machine in the calculation of the noise emission of the propulsion unit.

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