Design of UAM Concept Vehicles with Distributed Electric Propulsion Systems

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Abstract Noise is the main challenge regarding the public acceptance of Urban Air Mobility (UAM). In an ongoing research project at the German Aerospace Center, two different UAM vehicle concepts were developed, including the design of the vehicles and that of the electric powertrain. For both vehicles, an identical mission as well as identical Top Level Aircraft Requirements were defined. The main difference between the vehicles is the propulsion strategy: One vehicle is powered by open rotors and the other by ducted fans. The current paper presents results from the design of the vehicles and their distributed propulsion systems, including propeller and fan design as well as detailed information on the architecture of the electric powertrain.

Introduction

Urban Air Mobility vehicles are gaining increasing attention, as they provide an interesting concept for passenger transportation especially in densely populated areas. However, their primary disadvantage is the generation of noise by the distributed propulsion systems, which is estimated to be the main challenge with respect to public acceptance [1, 2].

The aim of the current study is the detailed design of two example UAM vehicles with different propulsion systems – open rotors or ducted fans – which will be compared with

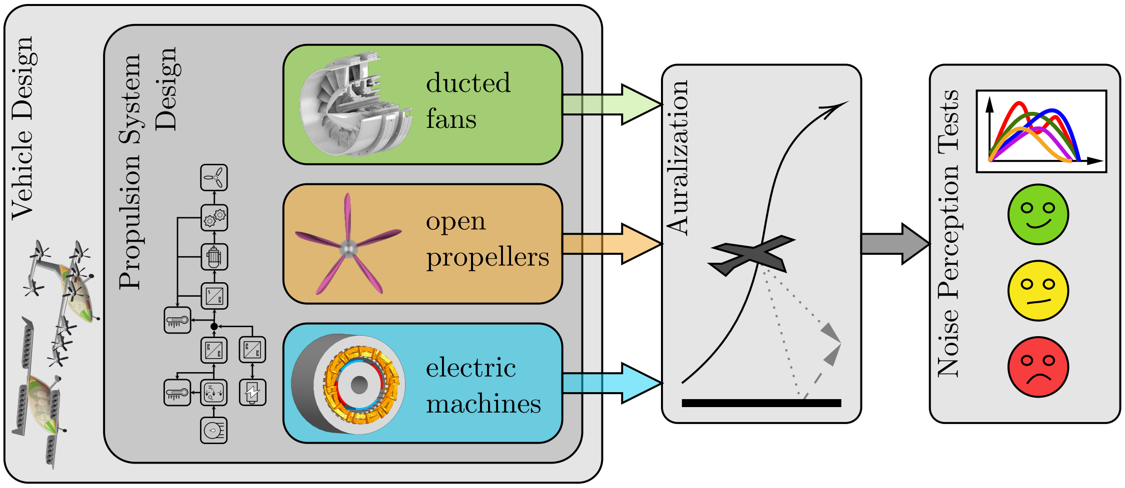


Figure 1: Methodology used in the study (the current contribution is focused on the left block).

respect to their noise generation and human perception in a subsequent step of the research project (see Fig. 1). To this end, several measurements on a set of open rotors, on single ducted fans and on a representative electric motor will be combined to represent different distributed electric propulsion systems. Then, synthetic flyover noise data will be generated based on these measurements. Finally, the resulting recordings will be used in psychoacoustic tests to determine subjective response and annoyance. The present paper gives an overview of the first step of the study, the design of the two vehicles with their respective propulsion systems, with more details given in [3].

Method

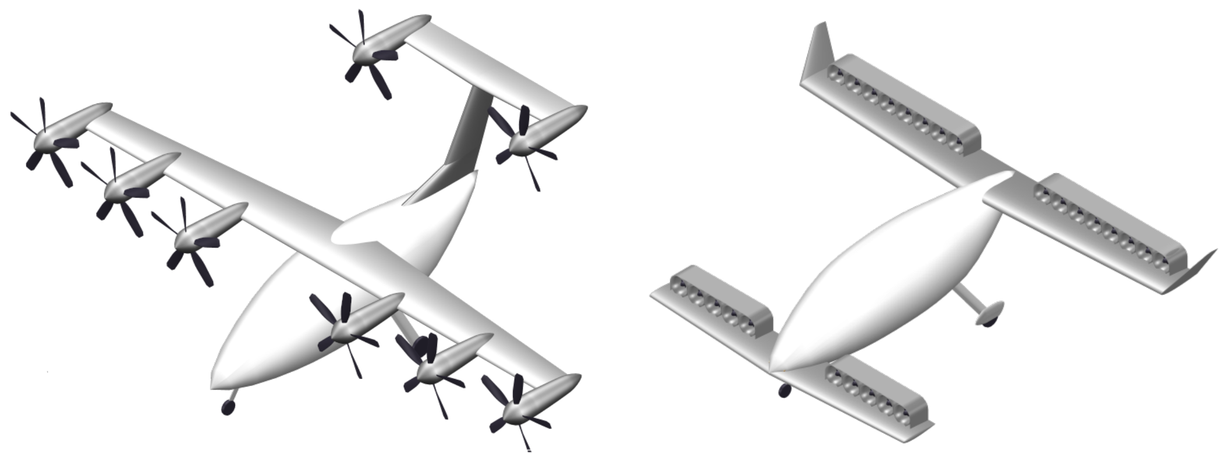
In order to enable a better comparison of the noise generated by the two vehicles, identical Top Level Aircraft Requirements (TLARs) were used for both. These are (1) a range of 100 km plus reserve, (2) a cruise flight speed of 200 km/h, (3) a payload of 450 kg (one pilot and four passengers) and (4) an entry into service of 2030 – 2035. Based on these TLARs and under consideration of additional requirements like initial inputs for the powertrain sizing and the sizing of wing and cabin, concepts for one vehicle driven by tiltable open rotors (labeled "Tilt Rotor") and another one driven by tiltable ducted fans ("Tilt Duct") were developed in an iterative multidisciplinary workflow. Additional information on this method can be found in [4].

In a next step, three different powertrain topologies were designed for the two vehicles (see, for example, [5]), consisting of a battery-only concept, a fuel cell-only concept and a hybrid system using both fuel cells and batteries. This method is based on the actual power requirements over the course of a whole mission, and it considers important details like the thermal management system and necessary balance of plant components for the fuel cell system that are neglected in the initial vehicle design process.

Finally, corresponding propulsors were designed for each vehicle. The propeller design was derived from an inverse propeller design method based on classical Blade Element Momentum Theory (BEMT) [6] as well as detailed Computational Fluid Dynamics (CFD) analysis. The model will later be analyzed with respect to its noise generation in an aeroa-

Table 1: Comparison of the performance of the two vehicles.

Parameter	Tilt Rotor Vehicle	Tilt Duct Vehicle
MTOM, kg	2,334	2,927
Disks and diameter	8 × 1.85 m	26 × 0.46 m
Disk loading, N m^{-2}	1,065	6,645
Hover power, kW	896	1,259
Cruise lift-to-drag ratio	12	10
Cruise power, kW	105	156



(a) Tilt Rotor

(b) Tilt Duct

Figure 2: Visualizations of the two UAM vehicles.

coustic wind tunnel [7] in order to generate data for the planned auralization and subsequent psychoacoustic analysis. These experiments comprise the interaction of multiple propellers, thus including aerodynamic and acoustic interaction effects. Likewise, different ducted fans were designed that can be examined in an acoustic fan test stand [8] and hence deliver data to be used for psychoacoustic studies of the Tilt Duct vehicle. For both vehicles, an example electric motor was selected, which will be examined with respect to its noise generation and performance in a motor test bench, aiming to include potential effects of the electric machine to the psychoacoustic analysis.

Results

A comparison of the main performance parameters of both vehicles is given in Table 1, while Fig. 2 shows corresponding visualizations. It can be seen that the higher number of propulsors for the Tilt Duct vehicle leads to a higher mass and higher power requirements compared to the Tilt Rotor vehicle.

Figure 3 shows a schematic of an example electric powertrain, consisting of two power sources (battery and fuel cell) with corresponding converters, an inverter, electric machine and a gearbox. Two thermal management systems (TMS), one for the fuel cell system (FCS) and one for the electric drive train (EDT) consisting of the electric machine, its inverter and the gearbox, are also included and were designed and sized for the two vehicles.

The propeller that was designed for the Tilt Rotor vehicle is a variable pitch propeller,

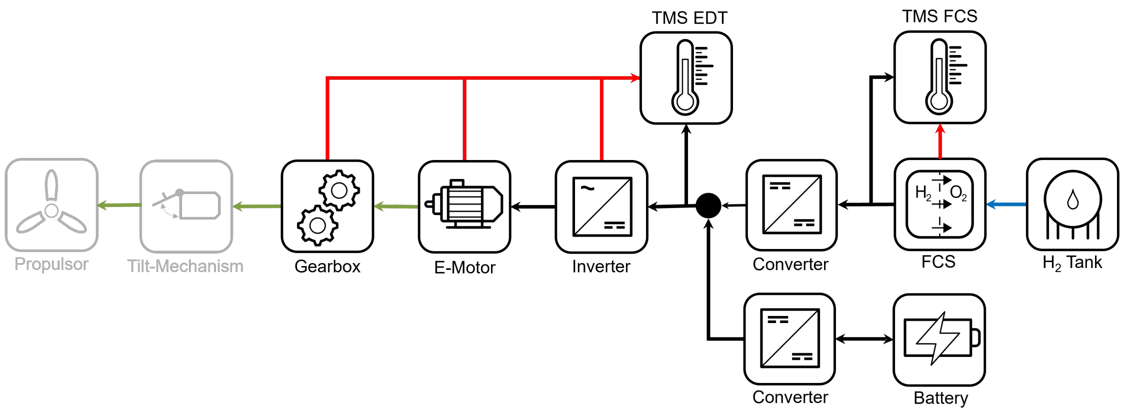


Figure 3: Schematic of an example powertrain driven by a fuel cell system and a battery (TMS: thermal management system, FCS: fuel cell system, EDT: electric drive train).

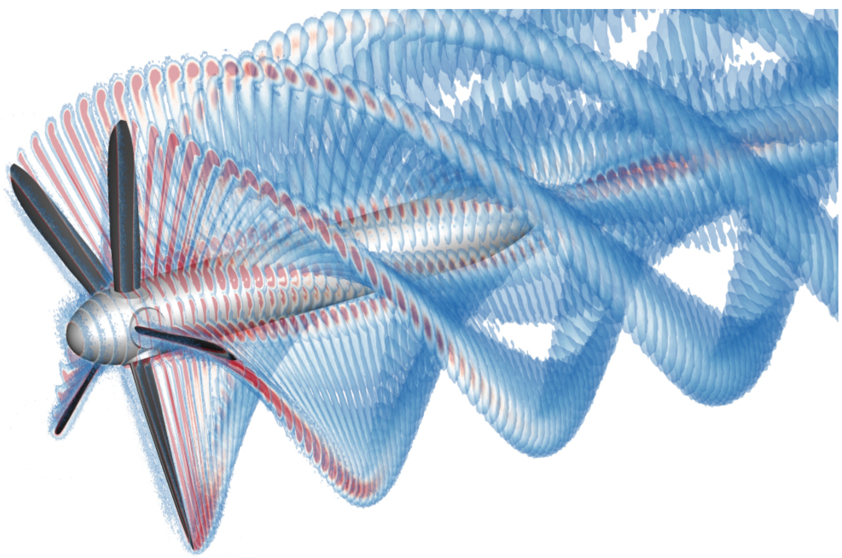
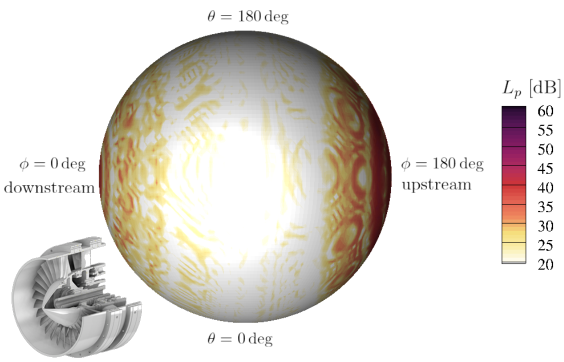


Figure 4: RANS simulation result of the isolated tilt-rotor propeller at cruise.

which enables high efficiency in both operating modes targeted, hover and cruise. It has five blades and a diameter of 1.85 m. The design tip Mach numbers are 0.30 in cruise flight and 0.52 in hover. The performance of the rotor was analyzed using a Reynolds-Averaged Navier Stokes (RANS) simulation utilizing the DLR TAU-Code [9]. Figure 4 shows an example result of a single rotor at cruise conditions.

For the Tilt Duct vehicle, three different fan designs were developed, with the aim to create variations in the acoustic signature in order to enable significantly different flyover noise signals for the planned psychoacoustic studies [10]. One is a reference fan with 18 rotor blades and 21 stator blades, while another is a fan designed for a reduced generation of tonal noise (31 rotor blades, 21 stator blades) and a third one designed for a low broadband noise generation (31 rotor blades, 10 stator blades). As an example result, the noise directivities of the low-tone fan and the low-broadband noise fan are shown in Fig. 5.

An initial analysis was also performed for the electric motor to be used for the Tilt Rotor vehicle. It consists of a general comparison of the noise contribution from two different



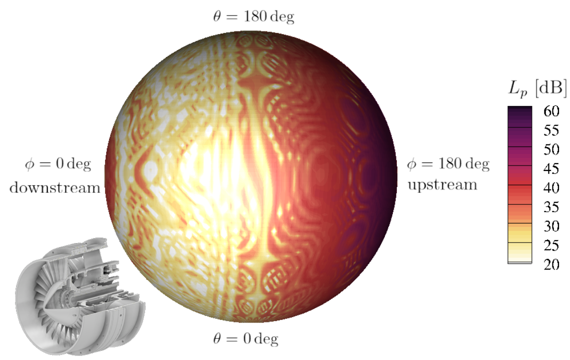


Figure 5: Tonal noise directivities plotted on a hemisphere of radius 100 m for the low-tone fan with 31 rotor blades and 21 stator blades (left) and the low-broadband noise fan with 31 rotor blades and 10 stator blades (right).

motor versions via numerical simulation: One is a direct drive version of the motor, which is directly connected with the propeller and hence spins with the propeller rotational speed, and the second is a motor version coupled with an additional gearbox [11]. It was found that the geared version, which rotates much faster, may lead to an additional tonal noise contribution at high frequencies, which could affect psychoacoustic metrics such as sharpness.

Summary

The present paper gives an overview of the design process for two UAM vehicles driven by different types of distributed electric propulsion systems. One systems consists of eight tiltable open rotors and the other of 26 tiltable ducted fans. More details on the design process can be found in [3]. Based on acoustic measurements on propellers and ducted fans in dedicated acoustic facilities at a later stage of the project, these concept vehicles will be used for an auralization of flyovers and subsequent psychoacoustic analyses.

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