Preliminary design of an electromechanical actuator for eVTOL aircrafts in an urban air mobility context

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Abstract. Urban areas face issues like traffic congestion, noise, and pollution. In this context Urban Air Mobility (UAM) offers a solution by utilizing the urban airspace for transportation, in particular, the exploiting of Electric Vertical Take-Off and Landing (eVTOL) vehicles is promising in terms of noise and environmental pollution, despite challenges like safety issues and financial constraints. To overcome these issues, Prognostic and Health Management (PHM) plays a vital role in ensuring safety and reliability. The proposed case study focuses on a compact Electro-Mechanical Actuator (cEMA) for flap control surface. A preliminary design is proposed with the aim of reducing dimensions and weight while maintaining performance and reliability. This work represents one of the first steps in the creation of a digital twin for the design, sizing, and application of PHM logics.

Introduction

The issue of overcrowding in cities and the resulting environmental and noise pollution, has spurred the search for alternative mobility solutions. One potential solution is Urban Air Mobility (UAM), which aims to establish a safe, and sustainable air transportation system within cities [1]. UAM should be exploited for various purposes, including passenger transport, package delivery, and emergency services [2]. It is part of the broader concept of Advanced Air Mobility (AAM) [3], which encompasses emerging aviation markets. UAM primarily utilizes electrically powered Vertical Take-Off and Landing (VTOL) aircrafts. The development of all-electric aircraft with compact Electro-Mechanical Actuators (cEMAs) has been driven by the need to reduce environmental pollution in cities [4]. However, progress in UAM has been hindered by a few fatal accidents, noise restrictions, and financial challenges [5]. In this context, safety, airworthiness, propulsion efficiency, and performance are crucial aspects in UAM research [6]. A way to improve the safety and the reliability of these systems is the application of Prognostic and Health Management (PHM) techniques. About that the development of High-fidelity (HF) model allows the study of performance variations and the identification of potential defects to obtain the definition of a Digital Twin (DT) to be used as a virtual test bench of the real system.

Requirements of the cEMA

The first step in the cEMA design and sizing is the definition of the control surface chosen as case study and then the related specific requirements. Despite variations in configuration [7], eVTOL aircrafts share similar actuation systems. The case study chosen is the flap actuator responsible for the thrust vectoring in a tiltrotor aircraft.

Performance requirements. The steady-state performance requirements involve accuracy, resolution, and hysteresis. The first one must be achievable under all operating conditions including actuator faults that do not result in the complete system failure. In the present work, a minimal accuracy equal to 0.3° is considered [8]. The resolution is due to the sensors system and must be smaller than the required accuracy to properly control the surface. The hysteresis represents the difference between the input command required for the two different directions moving of the surface to achieve the same angle movement. At a first approximation this requirement can be negligible and calculated after the overall EMA sizing. The dynamic performance requirements address the analysis of the actuator response to commands and disturbances in both time and frequency domains, and it aims at studying the stability, the tracking, the impedance, and the damping characteristics of the system. These requirements are mostly linked to the definition of the control algorithm and parameters. Another technical requirements regard the maximum load the servo actuator must bear: it depends on factors such as overall inertia, maximum external load, and friction losses. Finally, the maximum and effective strokes as well as the rated speed of the actuator need to be determined. For this application a minimum stroke of 90° is needed, in addition a minimum-security margin of about 20% in both directions is considered and the total operational actuator stroke shall be from -20° to 110°. The rated speed is defined for assuring that the actuator, without external load and with the power supply at the minimum guaranteed level, reaches its maximum stroke within a specified time. For this application a minimum speed has been set to 360°/s [9,10].

Safety and reliability requirements. To define safety and reliability requirements, it is essential to determine the expected operational lifespan of the system. During this time the system should ensure the requirements without the need for structural component replacement. The flap actuator system reliability is commonly associated with the failure rate, which represents the frequency of failure occurring within a specific period of time. The loss of control, due to a single failure or combination of failures, shall be less than $1x10^{-6}$ per flight hour [11,12].

Proposed architecture design

To meet the demanding requirements of UAM EMAs in terms of compactness, simplex solutions often fall short of airworthiness standards. Previous literature has presented various fault-tolerant architectures based on redundancy for EMAs [13]. The conventional EMA architecture for flight control actuators is typically composed of an electric motor, power electronics and control electronics (including sensors), mechanical transmission (with gearboxes, reducers or ball screws), and fail-safe devices (e.g., clutches, brakes) [14].

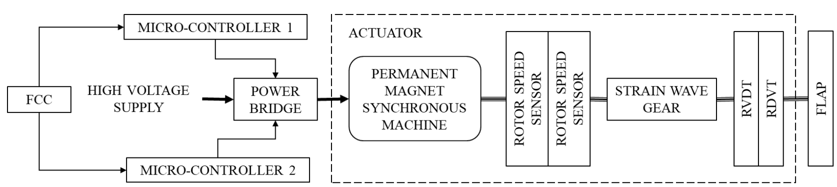

Figure 2. Proposed architecture.

In the case study, a compact rotary-output actuator architecture is chosen to fulfill the size and weight requirements for UAM applications. This architecture comprises a six-phase permanent magnet synchronous machine, fault-tolerant control electronics, a strain wave gear, and several sensors (Fig. 2).

Electric motor. In the aerospace industry, various types of electric motors have been considered for converting electrical energy into mechanical energy. The selection process involves evaluating factors such as losses, cooling, weight, volume, and other distinctive features, advantages, and disadvantages [11]. For aviation purposes, the chosen electric motor must exhibit thermal robustness and high efficiency to minimize power losses and associated cooling requirements. Four types of electric motors are considered: Permanent Magnet Synchronous Machine (PMSM), Electrically excited Synchronous Machine (ESM), Switched Reluctance Machine (SRM), and Induction Machine (IM). Among these options, the PMSM is identified as the most suitable for the present application. It offers higher efficiency and power density, lower heat production and is capable of sensor-less control, while it presents drawback as the relatively higher cost of magnets and its total loss of operation in case of one phase loss.

Mechanical transmission. Certain criteria must be considered, including a compact structure, high efficiency, and characteristics such as high loading capabilities, low kinematic error, and minimal backlash. The reducer plays a critical role in ensuring system reliability [17]. Among the available options, the strain wave gear (SWG), stands out as the preferred choice due to its superior performance in terms of compactness and reliability, keeping a good efficiency [15].

Sensors. To perform position control loop a Rotary Variable Differential Transformer (RVDT) will be exploited. For the speed loop, a rotational sensor is required and positioned on the high-speed shaft of the gearbox to enhance measurement accuracy.

Control electronics. The Electronic Control Unit (ECU) typically manages the position and speed control loops, while the current control is handled by the Motor Drive Electronics (MDE). To achieve the reliability requirements, a fault-tolerant architecture with two control channels is implemented. The architecture utilizes a dual-control/single-drive setup, and each control channel communicates with the Flight Control Computer (FCC) via separate lines.

Preliminary Fault Tree Analysis

The Preliminary System Safety Assessment (PSSA) is a top-down process that assigns reliability and safety requirements from systems to components. In Fig. 3 a preliminary example of a qualitative FTA for this specific case study is proposed [11,16,17].

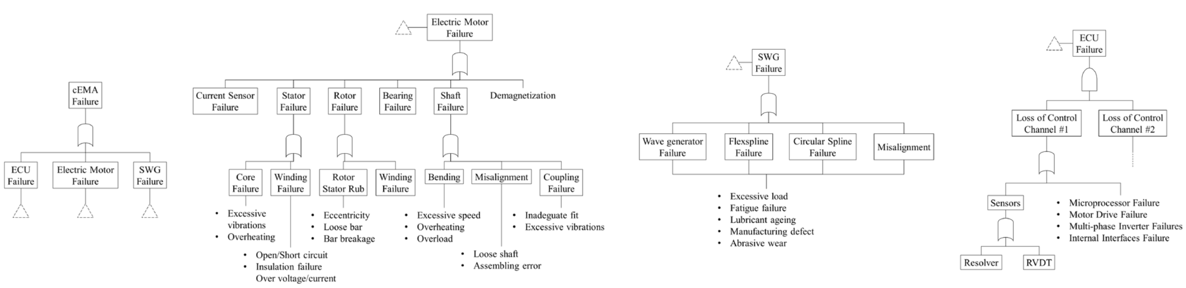

Figure 3. Preliminary FTA of an EMA for eVTOL flap surface in an UAM context.

Conclusion

UAM offers a solution to novelty urban transport challenges and eVTOL vehicles show promise in reducing noise and environmental pollution. The presented case study focuses on a cEMA for flap surface. A preliminary design sizing approach is proposed to reduce dimensions and weight while maintaining performance and efficiency. This work represents a first step in the development of a digital twin, enabling design, sizing, and application of PHM for the cEMA.

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