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Autonomous Flight Tests of a Distributed Electric Propulsion Demonstrator Based on a Total Energy Control System

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Abstract

Novel airframe design concepts are often proposed in conjunction with the use of electric motors to propel future aircraft. Among all possibilities, we might surely mention the distributed electric propulsion (DEP) aimed at exploiting the airframe-propulsion interaction to improve aerodynamic performance. In particular, if a relatively high number of propellers are placed in front of the leading edge of the wing, the blowing may yield improvements in some aerodynamic performance indexes (lift coefficient, lift-to-drag ratio, stall speed, etc…). Notwithstanding the apparent simplicity of the concept, the nature of such aero-propulsive interaction is far from being trivial and, consequently, its mathematical modeling is challenging. To provide for a thorough understanding of the aero-propulsive interaction entailed by DEP, at Politecnico di Milano, we have been passionately working on that subject since 2020, when a scaled radio-controlled DEP demonstrator, named SwitchMaster, was designed and built to support further research. This scaled prototype is characterized by a wingspan of 2.1 m and features 6 propellers mounted on the wing leading edge. Between March and April 2022, we performed an extensive campaign with the goal of providing flight data to identify an aerodynamic model for the SwitchMaster including the blowing effect. At present, we are working to overcome these obstacles and turn the SwitchMaster into a flying platform to test DEP-related control methodologies with an improved level of accuracy. Specifically, we have implemented a fully automatic testing campaign. A new flight test campaign is in progress and has a two-fold goal: demonstrating the effectiveness of fully automated testing and providing data for additional system identification activities. In the present paper, we report the preliminary results of the experimentation.

1. Introduction

The aviation industry is undergoing a profound transformation driven by the urgent need to improve its effectiveness and costs. Within this context, Distributed Electric Propulsion (DEP) represents a promising solution among unconventional aircraft design concepts, especially when the interaction of the propeller wake and the wing is exploited in the attempt of increasing the overall aerodynamic performance.

Clear, DEP may offer unique advantages such as increased aerodynamic efficiency, enhanced control authority, and system redundancy, making it particularly suitable for short-haul and regional aviation applications.

To provide for a thorough understanding of the aero-propulsive interaction entailed by DEP, at Politecnico di Milano, we have been passionately working on that subject since 2020, the year when a DEP concept for flight training application, named AeroSwitch, was devised[5] and a scaled radio-controlled DEP demonstrator, named SwitchMaster, was designed and built to validate the AeroSwitch concept and support further research.[7] This scaled prototype, see Fig. 1, is characterized by a wingspan of 2.1 m and features 6 propellers mounted on the wing leading edge. Between March and April 2022, we performed an extensive campaign with the goal of providing flight data to identify an aerodynamic model for the SwitchMaster based on modified stability and control derivatives, adapted to capture the blowing effect.[1] The tests also showed some limitations connected with the experimental setup: particularly, the pilot reported some difficulties in achieving a precise trim and suitably perturbing the airplane to excite the dynamic response of interest for identification purposes.

A key advancement presented in this work is the full automation of the flight test campaign through the integration of an autopilot system. We expect that, through this approach, we can cope with the limitations of manual piloting observed in previous studies by ensuring precise, consistent, repeatable test conditions. In fact, in order to experience significant blowing effects at some airspeed values, one has to fly at very high angles of climb γ, up to 40 deg and

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Figure 1: The SwitchMaster demonstrator.

consequently the airplane shall consistently maintain specific angle of climb and speed. Moreover, the exitation of the aircraft modes, needed for system identification procedures, was also automated and included as an option in the autopilot program.

The present project began by upgrading the initial version of the Simulink-based simulator developed in earlier work, by including a fully non-linear flight dynamics model, and the aerodynamics rendered through the formulation developed during the first test campaign,[1] which considers the effect of blowing. Based on this improved simulator, a new autonomous test campaign was designed, with the goal of studying the blowing with the entire envelope of the SwitchMaster. The main idea is to execute doublet maneuvers to excite the longitudinal and lateral-directional airplane modes at different angles of attack and different propeller advance ratios.

The onboard software was developed to allow the aircraft to autonomously execute all planned missions and automatically perform the required maneuvers for the identification. During such maneuvers, the elevator, rudder and aileron deflections as well and engine power were kept frozen to trimmed values, to enable open-loop identification. In this way, possible interference from feedback control during data acquisition was prevented.

After completing the entire test campaign, the collected flight data were processed and fed into an automated parametric identification workflow. Most of the analysis steps have been automated, resulting in a flexible and scalable code suite capable of efficiently handling large volumes of test data.

The preliminary results from this experiment show that autonomous flight enabled an extensive test campaign, during which the required conditions for speed and vertical velocity were consistently achieved prior to initiating the perturbations used for system identification.

2. Framework for autonomous flight testing

2.1 Challenges in modeling and testing DEP-induced blowing

As witnessed in many literature contributions,[2,4] DEP introduces a strong coupling between propulsion and aerodynamics due to the so-called blowing effect. In this effect, the airflow over the wing is locally accelerated by the propeller slipstream, which increases the dynamic pressure and enhances lift generation, but also modifies drag and aerodynamic moment. This interaction creates a complex scenario where the aerodynamic and propulsive forces are not easily separable, but it also offers opportunities for innovative control strategies.

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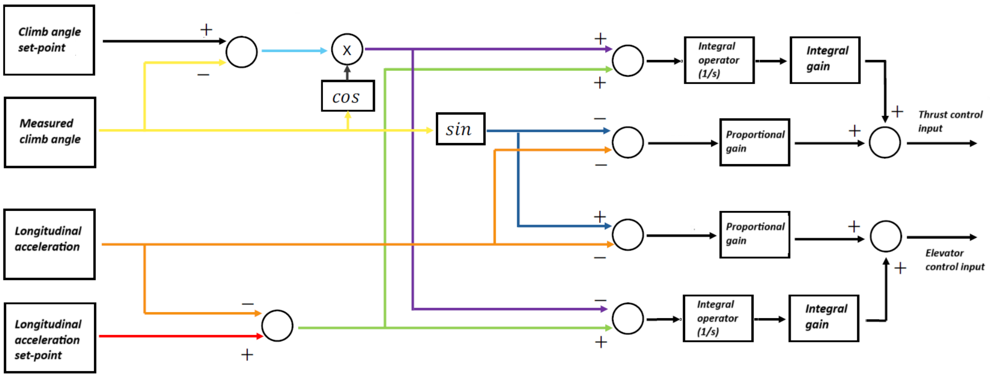

Figure 2: Caption

As also noted in a previous paper,[1] a key parameter for quantifying the blowing is the propeller advance ratio, denoted as J and computed as $J = \frac{U}{nd}$, where U is the aircraft airspeed, d is the propeller diameter and n is the rotational speed of the propeller expressed in revolutions per second. The advance ratio J quantifies the extent to which the air is accelerated by the propeller relative to the aircraft speed, reflecting how significantly the propeller influences the aerodynamic performance of the airplane.

To study the impact of blowing, in this experimentation, only collective thrust control (CTC) was considered: all motors operate at the same speed, producing identical thrust.

On the other side, individual thrust control (ITC), where each motor can be controlled independently, allowing asymmetrical thrust and blowing, although feasible using the SwithMaste, is not part of the present work.

As already mentioned in the introduction, to model the blowing impact on the aerodynamic performance, one has to test multiple condition with different advance ratio and reasonably similar angle of attack. This entails that the aircraft should cover during the flight campaign a wide range of climb angles γ (up to 40 deg) for different flight speeds. For this reason, the straightfoward altitude and speed hold, on which total energy control is based, cannot be employed without modification.

2.2 Autopilot based on Total Energy Control System

To enable fully autonomous execution of the flight test campaign, an autopilot system was developed with the primary objective of maintaining a specified airspeed and angle of climb. The control architecture adopted for this purpose is based on the Total Energy Control System (TECS),[3] a control method that regulates the exchange between kinetic and potential energy through a synergic use of throttle and elevator inputs.

The classical TECS, developed under the assumptions of small angles, works well for level flight or climb with low path angles γ. However, first testing and preliminary simulations revealed that in the desired test envelope the aircraft reaches relatively steep angles of climb, which violate the usual assumptions (i.e., $\sin\gamma \approx \gamma$ and $\cos\gamma \approx 1$. To address this limitation, a revised TECS implementation was derived and tested in simulation. The updated formulation incorporates the full trigonometric relationships, allowing for accurate computation of energy rates even at larger values of γ. The scheme of such improved TECS control is displayed in Fig. 2

Once validated in the Simulink environment, the updated TECS scheme was ported to the onboard flight controller firmware. Adjustments were made to ensure numerical stability and proper integration within the control architecture. The result is an autopilot system capable of managing a wide range of flight conditions while maintaining accurate tracking of the desired airspeed and climb angle setpoints.

2.3 Integration of the control system within the control platform and software-in-the-loop simulation

In order to make it possible to perform a full automatic campaign aimed at system identification purposes, it is necessary to integrate the new control system features into PX4.[6] The autopilot can be used for reaching trim conditions while following a proper trajectory, executing the required maneuvers, controlling each motor independently and carrying out automatic safety checks. The PX4 Flight Stack is composed of many modules.

Following a standard Software Engineering procedure, we started defining the goals of the *system-to-be* and the *domain assumptions*, which led to the definitions of the *system requirements*. The main goal is trimming the airplane at any feasible combination of J and α, holding TAS and γ setpoints while following a GPS flight plan. Afterwards, the airplane has to execute safely and autonomously all the doublet maneuvers for parametric identification. As a result of the Requirement Analysis, many other functionalities have been progressively developed to allow the airplane to follow setpoints in terms of speed and climb angles, to glide, to check the trim conditions, to execute maneuvers for system identification, to perform safety checks. In order to implement the above functionalities, three major PX4 modules were modified: "Position Control", "TECS" and "Control Allocator".

A total number of 11 flight modes were also implemented to support the testing. Among all, we can mention 4 modes: standard flight, glide, climb and sink modes. In the standard flight mode, TECS receives a linear trajectory composed of altitude setpoints from Position Control, and computes $\dot{h}_{sp}$. In the glide mode, on the other side, the throttle setpoint is set to zero and the Potential Energy Rate is ignored. This leads to the fact that only speed setpoint is followed through a suitable elevator action. Climb and Sink modes are very similar, activated when exists an altitude rate setpoint positive or negative, respectively, coming from Position Control. In this mode, when the distance to the altitude setpoint goes below a margin, the nominal $\dot{h}_{sp}$ is reduced gradually, until it reaches zero, effectively stabilizing the aircraft near the altitude setpoint.

To test and validate the modified PX4 software before flight, a simulation Software-In-the-Loop (SIL) environment was set up. This was achieved using Gazebo simulator, which was already integrated in the system as a default simulator. To monitor and communicate with the control system, the ground station software QGround- Control was used, connected to PX4 through a MAVLink/UDP stack. The ground station allows configuring system parameters at runtime, setup actuators, changing flight mode, performing auto-tuning and creating and loading a new GPS flight plan for autonomous flight. This simulation environment made it possible to test software updates safely and in a quite realistic way, before the actual flight test campaign. Hence, the system parameters were properly configured, the TECS gains set, the Attitude Controller auto-tuned and the needed flight plans were tested, for each speed and γ angles scheduling.

3. Flight testing campaign

The flight test campaign was planned and executed from February to June 2025, trying to improve the performance obtained in the previous manual-piloted campaign.

The test flights were designed based on simulations using Simulink and validated through Software-In-the-Loop (SIL) simulations in Gazebo. Simulink was used to predict trim conditions over a wide range of airspeeds (from 13 m/s to 20 m/s) and climb angles (from -15Â° to 40Â°, including a glide mode), with the goal of testing multiple advance ratio J for similar angle of attack.

To perform steep climbs and low-speed flight, conditions critical for reaching low values of J, the autopilot was upgraded with a modified TECS that removed the small-angle assumption. This new controller was first validated in simulation and then successfully implemented on the real flight controller. Each mission consisted of a sequence of climb and descent segments, with test maneuvers (i.e. doublets excitations) triggered only when the aircraft reached specific tolerances on airspeed and angle of climb with the respect to the setpoints. Additional safety logic ensured the automatic interruption of any maneuver that risked violating attitude or control limits. Data were logged directly from the PX4 flight controller, which integrates a suite of sensors including accelerometers, gyroscopes, GPS and a Pitot probe. This allowed for high-resolution data acquisition throughout all phases of the flight. The result is an autonomous framework for systematic flight testing, enabling reliable and repeatable system identification.

Figure 3 shows an example of the airplane trajectory during a simulated test, including the execution of multiple pitch doublets for identification purposes, performed at different flight path angles. In the figure, the red and blue markers indicate the beginning and the end of a doublet maneuver for system identification. Clearly, the maneuver for system identification are also performed during climb phases, according to the desired J and speed.

4. System Identification

The aircraft system identification process aimed to accurately model both the longitudinal and lateral-directional dynamics using flight test data. The primary objective was to derive the stability and control derivatives needed to enhance simulation models and optimize the aircraft control systems. This identification process was conducted in two key stages: initially using the equation-error method, followed by the output-error method, with the equation-error results serving as initial estimates for the latter. The entire process is formally described in a previous publication.[1]

For the longitudinal dynamics, elevator doublet maneuvers were primarily employed, as they are designed to excite the short-period mode of the aircraft. The identification process began with the equation-error method, where the stability and control derivatives were estimated using a regression-based approach. Specifically, linear regression,

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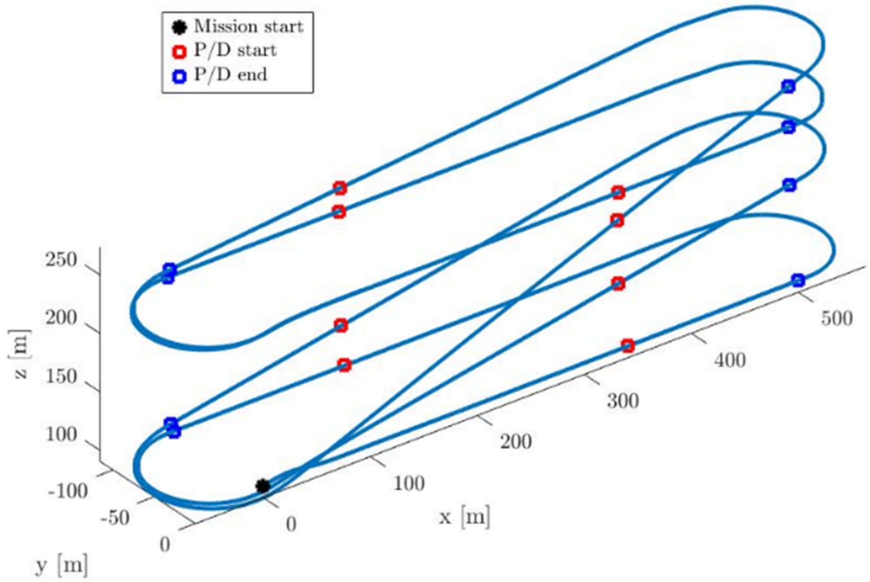

Figure 3: Example of the airplane trajectory in a simulated test campaing.

based on the ordinary least-squares principle, was applied. In this method, the stability and control derivatives were estimated by minimizing the sum of squared differences between the modeled and measured aerodynamic forces and moments. The result of this regression served as the initial guess for the output-error method. The output-error method involved simulating the aircraft response to the maneuver and comparing the simulated outputs with the measured data. This method is based on a maximum likelihood approach, where the stability and control derivatives are determined by minimizing the sum of the weighted squared differences between the measured aircraft outputs and those generated by the model. The objective is to find the set of stability and control derivatives that best reproduce the measured response of the aircraft. During the optimization process, the time histories of key outputs, such as U, α, q, θ, and h, were used to retrieve the stability and control derivatives. These outputs provided the necessary data for comparison with the simulated results, which guided optimization. To further improve the accuracy of the identification, refinements were made by normalizing the initial estimates and the states to be optimized, improving the numerical conditioning of the optimization process, enabling the algorithm to converge more effectively.

A total of 110 elevator doublet tests were conducted to identify the longitudinal stability and control derivatives. The tests covered a speed range from 12 to 20 m/s and climb angles between -20 and 40 deg. As a result, the advance ratio varied between 0.25 and 0.65, while the angle of attack ranged from 1 to 12 deg.

In order to provide some excerpt from the results, Fig. 4 and 5 present a comparison between flight test data (cyan circles/lines) and simulation results for an elevator doublet maneuver, after system identification. The first plot refer to a gliding condition while the second one to a climb

In both the examples, the first-guess model, i.e. the one identified with the equation-error method (red lines), shows a qualitative good agreement with the flight data but exhibits undesired oscillatory behavior in both airspeed and attitude, which may indicate an incorrect estimation of the damping in pitch derivative. In contrast, model identified with the output-error (yellow lines) produces smooth responses that closely match the measured data. These findings highlight the promising potential of the ongoing SwitchMaster model identification effort.

5. Conclusion

Accurately modeling the aerodynamic effects of DEP systems remains a complex challenge, both in the context of conceptual design and advanced applications.

In this context, performing flight tests, aimed at system identification, with a DEP demonstrator becomes a valuable strategy for characterizing and interpreting the aerodynamic influence of propeller-induced airflow over the wing. To support this goal, the SwitchMaster demonstrator has been used across several flight test campaigns in recent years, initially relying on conventional ground-based remote piloting. Yet, extracting a reliable aeromechanical model from these flight data proved challenging due to limitations inherent in manually executing the required Flight Test Techniques (FTTs).

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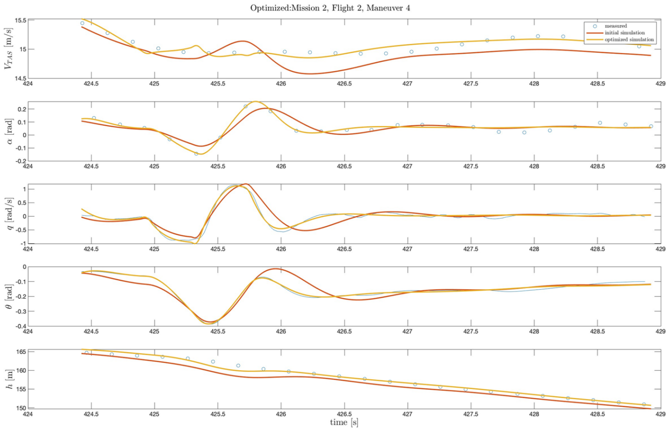

Figure 4: Agreement between time histories of the measured flight data (cyan circles/lines) and outputs of the model identified with the equation-error (red lines) and with output-error (yellow lines) for an elevator doublet in gliding condition.

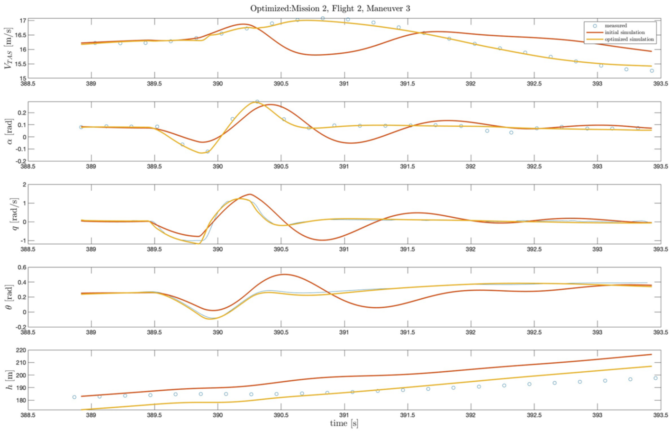

Figure 5: Agreement between time histories of the measured flight data (cyan circles/lines) and outputs of the model identified with the equation-error (red lines) and with output-error (yellow lines) for an elevator doublet climb condition.

To address this, a fully autonomous flight testing framework was developed and implemented. This system enabled more precise control of trim conditions and maneuver execution, significantly expanding the range of flight conditions that could be explored and analyzed.

As a result, this approach serves as a powerful enabler for refining analytical models of DEP aerodynamics using system identification methods. This lays the groundwork for future research focused on multiple topics connect to flight mechanics and control.

Notably, it also opens the door to propulsion-based flight control strategies, potentially offering redundancy or even alternatives to traditional aerodynamic control surfaces.

6. Acknowledgments

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