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Design, Implementation and Testing of a Distributed Electric Propulsion Demonstrator

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Abstract

This paper introduces the demonstrator for the AeroSwitch concept, which combines an electric or hybrid-electric Distributed Electric Propulsion (DEP) airframe with a set of control logics allowing the in-flight simulation of either a single-engine or a twin-engine aircraft, in both normal and failure conditions. This aims at a drastic simplification and cost reduction of pilot training, with the use of a single platform to provide both single-engine and multi-engine training. A scaled flying model, christened the SwitchMaster, was developed and thoroughly tested on ground and in flight providing insight into DEP aeropropulsive effects, demonstrating the AeroSwitch concept effectiveness, and deploying a fitting testbed to develop not only the AeroSwitch dedicated control laws, but also further applications in Propulsion-Controlled Aircraft (PCA) technology.

1 Introduction

In 2020, a Politecnico di Milano team was awarded the 1st place in the annual AIAA Graduate Student Aircraft Design Competition with a Distributed Electric Propulsion (DEP) design aimed at a radical change in pilot training. The competition called for the design of a “General Aviation Trainer Aircraft Family” with high commonality in components and systems, to address the problem of providing economical flight training for both single-engine and multi-engine operations. Seeking a radical solution, the team devised the AeroSwitch concept, which allows considering a single aircraft platform instead of a family including a single-engine and a twin-engine, to fulfill both roles in flight training. Indeed, this design solution is capable of simulating “in flight” the aeromechanical behavior of either a single-engine, with its inherent non-symmetric behavior requiring significant pedal compensation, or a twin-engine, accommodating All-Engine Operative (AEO) as well as One-Engine Inoperative (OEI) conditions.

The AeroSwitch concept was the subject of an international patent [1] and was embodied in a scaled demonstrator, the SwitchMaster, a fitting testbed to develop not only the control laws that inspired the AeroSwitch concept, but also further innovative applications in the field of Propulsion-Controlled Aircraft (PCA) technology, such as trajectory steering, attitude control and stability, high-lift augmentation.

2 The AeroSwitch concept

2.1 Motivation

Pure-electric and hybrid-electric propulsion systems have received a great deal of attention in recent years in aviation [2–4]. The main drivers are environmental sustainability and overall flexibility, with potential enhancement of performance, reliability and safety. From an environmental point of view, the null (pure-electric) or reduced (hybrid-electric) chemical emissions promise variously graded benefits for air quality. Also, lower aircraft noise levels may be achieved [5].

In addition, a system of multiple electrically-driven propellers may be conceived in ways that allow for a higher freedom in configuration design. When the installed thrust is split onto a large number of EMs distributed along the leading edge of lifting surfaces, this is known as DEP [6]. The reduced dimensions and weights of EMs compared to traditional ICEs may be exploited to compensate in part the weight increase associated with batteries and other components of innovative propulsion systems, while achieving more performance-optimized design solutions or PCA applications.

In the AeroSwitch concept, an electric or hybrid-electric DEP airframe is considered to provide a sufficient degree of redundancy in the thrust effectors. This can be exploited by driving them individually, to achieve the desired capability of in-flight simulating a single-engine airplane, a twin-engine airplane in normal conditions (AEO), or a twin-engine airplane in critical-engine-out conditions (OEI).

2.2 Single- and multi-engine effects

In single-engine propeller-driven airplanes, the propeller induces a lateral-directional imbalance that the pilot quickly learns to counteract with appropriate inputs on the flight controls, according to the different flight phases (as effects depend on propeller RPM). From a physical point of view, it is possible to distinguish the contributions to this imbalance as the spiraling slipstream, the tilted thrust action line (the so-called "P-factor"), the applied torque and the gyroscopic precession. The main overall result is the generation of a yawing moment that may be very intense at high power rating, impacting on flight characteristics and handling qualities. Typically, designers arrange airframe shape details in order to compensate this effect in cruising regimes, while in low- or high-power regimes pilots must actively counteract this tendency to yaw. Thus, this is a crucial element of the pilots training and therefore providing the means to experience it in the AeroSwitch framework is an essential requirement.

As for multi-engine airplane operations, while normal (AEO) circumstances normally imply fully symmetric flight conditions and hence do not require pilot compensation to achieve coordinated flight, critical-engine-out (OEI) circumstances clearly demand major control actions by the pilot, in a safety-critical situation. In fact, in a conventional twin-engine airplane, the thrust units are placed on the wings, with a significant moment arm with respect to the aircraft's center of gravity. When an engine fails, the remaining engine induces a relatively minor rolling moment imbalance and a substantial yawing tendency. As a consequence, another essential requirement in the AeroSwitch framework is the capability to reproduce OEI conditions and their impact on flight characteristics and handling qualities, ruling out any consequence on flight safety.

2.3 Development

In the AeroSwitch concept, an even number of EMs are placed symmetrically with respect to the longitudinal axis, such that propellers on the left and right sides spin in the opposite direction, as this allows perfectly symmetric flight in multi-engine mode. Single-Engine (SE) and Multi-Engine (ME) flight conditions are achieved by setting the corresponding modes in a dedicated Flight Control System (FCS). To provide realistic single-engine and multi-engine flight conditions and forestall potentially dangerous events in case of motor failures, a specific system logic and redundancy of the electric motors management has been developed in the AeroSwitch FCS, as outlined in Figure 1. This refers to the specific implementation on a six-propeller aircraft, as the Trybrid (Figure 2), designed for the AIAA Graduate Student Aircraft Design Competition (other implementations are possible, say with 8 or more thrust units). It features two distinct Energy and Propulsion Management Systems (EPMS). The EPMSs are responsible for feeding the EMs, regulating their throttle level individually, and for the entire power and energy management, charge/discharge of batteries and power generation system (i.e. an ICE or a fuel-cell system, if present in hybrid-electric fashion) management.

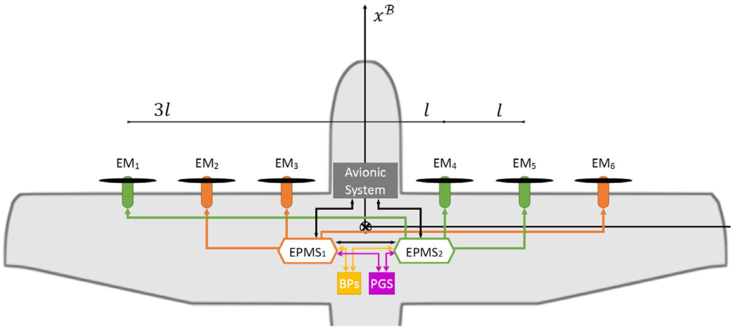

Figure 1: The AeroSwitch system on the Trybrid.

Figure 2: Trybrid general configuration.

Each EPMS controls half of the EMs, chosen so that their equivalent moment vanishes when driven at the same rating. Even in case of failure of one EPMS, 50% of the installed power is still available and capable of granting symmetric flight. Each EPMS embeds a small (Micro Electro-Mechanical Systems (MEMS) inertial unit, used to estimate aircraft attitude and aerodynamic angles, aiming at controlling the sideslip and bank angle according to the flight mode (Figure 3). The EPMSs are also responsible for failure identification and management, based on their interconnection with avionic and propulsive subsystems, as illustrated in Figure 4.

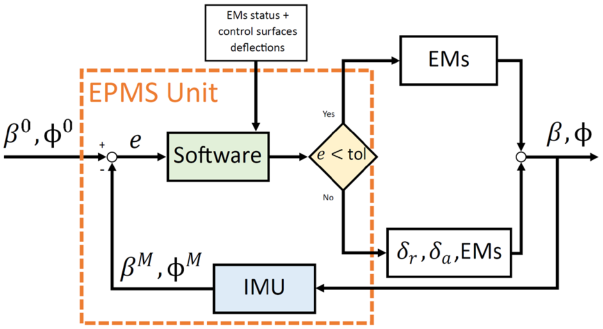

Figure 3: EPMS unit feedback loop.

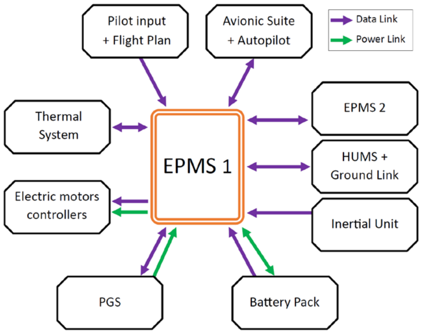

Figure 4: EPMS unit connections.

2.4 In-flight simulation modes

The EPMSs are coded so as to simulate SE or ME by actuating EMs on an individual basis. For example, driving one of the outboard motors with a lower power rating than the others when increasing or reducing power from cruise setting will reproduce the typical SE situation. Clearly, when flying in SE mode, appropriate provisions are in order, to insure that system failures (such as EPMS malfunction or thrust unit failure – be it due to the EM, the propeller, or bird strike) do not affect the safety of flight, especially in view of pilot training for SE rating. Therefore, dedicated control laws for failure modes are included in the FCS to deal with emergency situations in SE mode. Due to dependence not only on thrust and airspeed, but also on propeller geometry, fuselage and tail geometry, attitude, center of gravity location, etc., a general *a priori* prediction of the lateral-directional imbalance is unfeasible. Therefore, an investigation of typical sideslip angles for a General Aviation aircraft was carried out by numerical simulation and by flight testing a CZAW PS-28, obtaining excellent agreement and a convenient estimation to be used in the setup of the FCS.

The ME mode configuration works in a much simpler fashion, as there is no need to simulate non-symmetric unwanted propulsive effects. In this case also, dedicated control laws for failure modes are included in the FCS to deal with emergency situations in ME mode. Details on the specifications of SE and ME normal and emergency control logics will be discussed in a future work.

3 The SwitchMaster demonstrator

3.1 Design and implementation

For the scaled demonstrator, an off-the-shelf approach was pursued by selecting the Legacy Aviation Turbo BushMaster 84”, a high-wing, single-engine, wood-made RC flying model with a wing span of 2.13 m and a maximum take-off mass of 4.5 kg (Figure 5). This model matches the general configuration of the Trybrid and provides several convenient features such as a simple airframe construction, conferring easiness to modify and repair; availability of spare parts; roomy space inside the fuselage, to host the AeroSwitch electronic devices; generous control surface authority, which mitigates some of the hazards that may be encountered when flight testing an innovative configuration.

Figure 5: The Turbo BushMaster 84” CAD representation.

Figure 6: The SwitchMaster during flight tests.

The model was modified by removing the ICE and propeller placed on the nose and adding the six thrust units on the leading edge of the wing (Figure 6). The selected EM was the Dualsky XM2838EA-14 V3, coupled to a Graupner Elektro 10×5” propeller and controlled by a Zubax Myxa A2 Electronic Speed Controller (ESC), capable of delivering 15.5N of static thrust at full power, with a 22.4 A supply. The ESCs are placed behind the motors, inside the wing structure. For the energy and power source, a 4S LiPo battery pack consisting of 4 lithium-polymer cells in series configuration, for a total of 14.8 V nominal voltage, was selected. The sizing comprises two of these packs in parallel, with a total capacity of 8000 mAh and maximum current of 240 A. This guarantees proper performance at peak power and a flight time estimated to be around 10 minutes with normal throttle usage.

The Holybro Pixhawk 4 control system [7] was selected for the SwitchMaster avionics. This is an integrated Flight Test Instrumentation (FTI) unit equipped with a suite of embedded sensors: accelerometers, gyroscopes, magnetometer, GNSS sensor and Pitot-static port. The system is capable of supporting manual flight control, assisted flight control, or automatic flight control. In addition, the EPMS unit was designed and implemented at DAER, providing a simpler realization, with the pilot directly selecting the working mode and injecting the failures. This component, dubbed Multi-Motor Management Unit (M3U), was considered enough to demonstrate the AeroSwitch functionality on a scaled demonstrator. Figure 7 illustrates the SwitchMaster avionic arrangement.

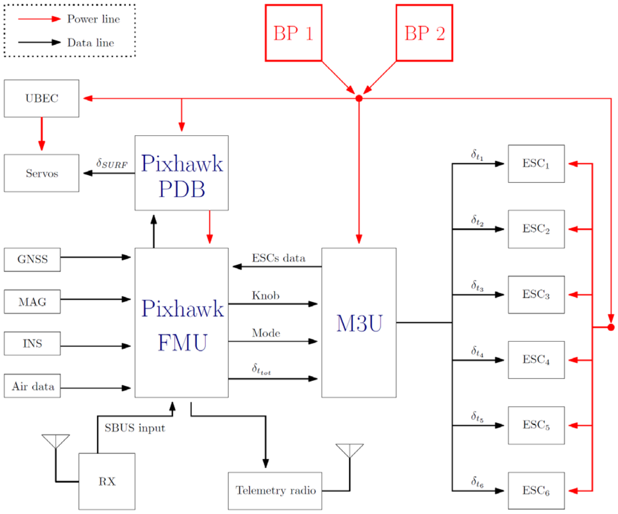

Figure 7: Schematic of the SwitchMaster avionics.

Due to the DEP configuration, structural modifications of the wing were necessary, to accommodate the motor supports and the panels for embedding the ESCs. Both components have been designed, 3D-printed, and statically tested after mounting. A dummy spinner in the nose was built, to host the Pitot probe. Finally, the overall mass resulted to be 4.95 kg, with structural items totaling 2.39 kg. The control system contributes with 0.37 kg, whereas propulsive elements amount to 1.64 kg, plus wiring. Weight and balance were checked, with the center of gravity placed close to the position suggested by the original model's manufacturer. Due to the increased aircraft mass, the wing loading rose to 93.3 N/m^2, which is higher than the typical value for the category (80 N/m^2 for high performance RC models).

The final configuration was deemed fit to support the demonstration of the key elements of the AeroSwitch concept:

- AEO ME flight mode, in which the aircraft shall demonstrate normal flight behavior.
- OEI ME flight mode, employed for ME pilot training.
- Normal SE flight mode, employed for SE pilot training.

- One Electric Motor Inoperative (OEMI) conditions in SE flight mode, i.e. failure simulation, to insure that safety is always guaranteed also for a SE-rated pilot.

3.2 Wind tunnel testing

Prior to flight testing, a thorough investigation of the aerodynamics of the chosen DEP configuration was carried out, involving a bench tests, wind tunnel thrust unit characterization (Figure 8), and full DEP wing experimentation (Figure 9).

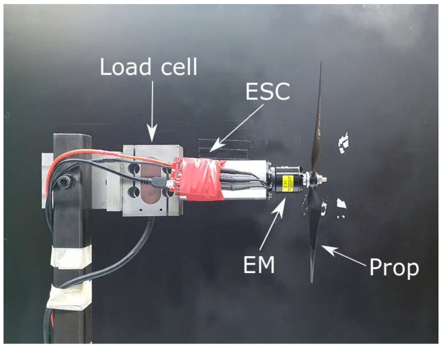

Figure 8: Thrust unit setup for wind tunnel tests.

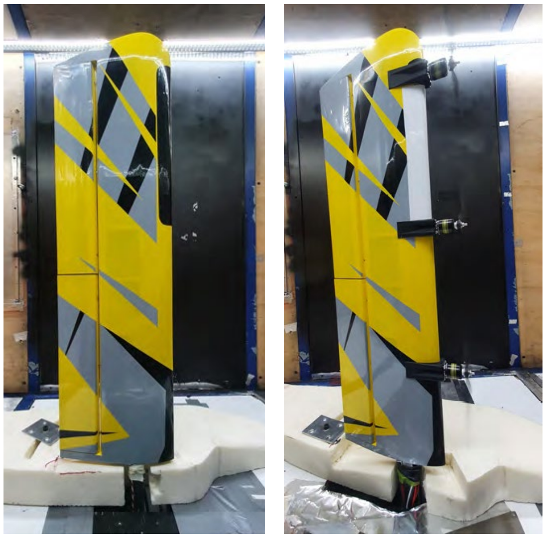

Figure 9: Original (left) and fully-equipped SwitchMaster wing (right) setup for wind tunnel tests.

The latter activity involved a spare wing of the Turbo BushMaster, together with three extra thrust units, thus allowing to test the exact DEP wing system in Politecnico di Milano’s “G. De Ponte” wind tunnel, which provides a 3 m × 1.5 m × 1 m test section and is powered by 6 fans totaling 100 kW installed power. The maximum achievable airspeed is about 50 m/s, which is far enough to cover the entire flight envelope of the SwitchMaster. This activity included testing of the original wing of the baseline Turbo BushMaster wing and the fully-equipped DEP wing of the SwitchMaster at several angle-of-attack and angle-of-sideslip values, both in clean and flapped configurations. For the DEP wing, conditions at various throttle settings, with all motors operating, as well as with various instances of one-motor-inoperative conditions were investigated. The experimental campaign involved over 2,000 test points and delivered dozens of lift curves and polar curves for each combination of operating parameters. Among the main results, a direct comparison of aerodynamic forces experienced in the two variants of the wing allow a detailed estimation of the effects of the DEP aeropropulsive interaction.

Figures 10 and 11 show examples of such results. Generally, lift data were found to be accurately matching numerical predictions. Figure 10 contrasts the lift effect of fully flapping the baseline wing (yellow) against the clean configuration (blue). As seen, a 13% increase in maximum lift coefficient from 0.84 to 1.08 is accompanied by a decrease in the critical angle of attack value from 13 deg to 10 deg.

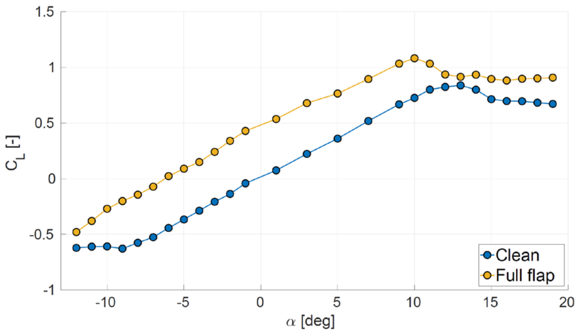

Figure 10: Lift curves of baseline wing at 15 m/s, in clean and flapped configurations.

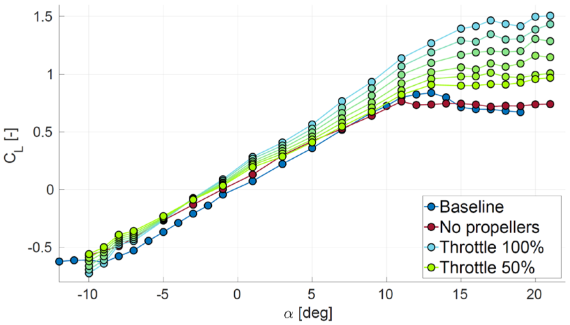

Figure 11: Lift curves for the DEP wing at 15 m/s in clean configuration.

Figure 11 illustrates the lift curves of the baseline wing (blue), the DEP wing without propellers (to ascertain the effect of the nacelles installed on the wing leading edge; red), and the DEP wing with all thrust units operating at 50% throttle (green) and 100% throttle (cyan). Among the main findings, it is observed the important effect upon the maximum lift coefficient, which – at full power – is increased by 80% with respect to the baseline, reaching 1.51. In addition, maximum lift is achieved at angle of attack of 21 deg, thus demonstrating the remarkable effectiveness of DEP as a high-lift device.

The experimental studies carried out showed that large differences may occur between the real behavior of the aeropropulsive interaction of the blown wing and prediction based on numerical simulation, especially when it comes to drag. Indeed, the local shape and surface finish of the wing and, especially, its movables with their large grooves greatly impact on lift and drag generation, hindering the effectiveness of drag numerical predictions, at least in this specific application.

The results from the wind tunnel testing, in addition to their interest *per se* in the investigation of blown-wing effects, were employed in the model implemented in a piloted flight simulator, to gain preliminary experience and familiarize with the aircraft's flight characteristics and handling qualities before deploying the SwitchMaster flight test campaign.

3.3 Flight testing

The SwitchMaster underwent a thourough flight test campaign aimed at demonstrating the functionality and potential of the AeroSwitch concept, in view of full-scale applications. Safety was the main driver throughout the whole activity, carrying out preliminary validation of flight test techniques, followed by progressive expansion of the investigated flight envelope totaling 35 flight test missions. Topics were tested in order of priority and hazard profile. The campaign included:

- Familiarization flights
- AeroSwitch concept validation flights, including SE and ME normal and failure modes
- Performance and flying qualities characterization flights
- PCA initial investigation flights, where non-symmetric thrust was applied to enhance directional control and provide automatic turn coordination.

The data recorded by the FTI were live streamed through a telemetry link to a PC serving as ground control station. This was extremely useful during the trials, allowing looking-up of timestamps, altitude, airspeed, heading and attitude. This provided valuable references for flight test cards and guiding the pilot on ground. A total of 49 parameters were acquired in flight, with an original sampling rate ranging between 4 and 300 Hz, downsampled to 10 Hz for convenience. These included air data, GPS data, inertial data, actuator levels, command and other ancillary parameters, including an event counter.

SE mode and ME mode tests were carried out in level, climbing and descending straight flight, as well as in turning flight, at multiple trim speeds between 10 and 16 m/s. Simulating the single-engine behavior in SE mode involved a number of trials in which the thrust asymmetry was progressively moved from the innermost to the outermost thrust units. Multiple thrust settings were tested, leading to angle of sideslip (β) values ranging between 2 and 8 deg and bank angle (Φ) values between 1 and 20 deg, when no coordination was applied. These values match well with the measured sideslip behavior of single-engine light aircraft, as demonstrated by the above-mentioned CZAW PS-28 flight test campaign. As an example, Figure 12 shows the time histories of multiple flight parameters during a SE mode constant speed trial without rudder compensation.

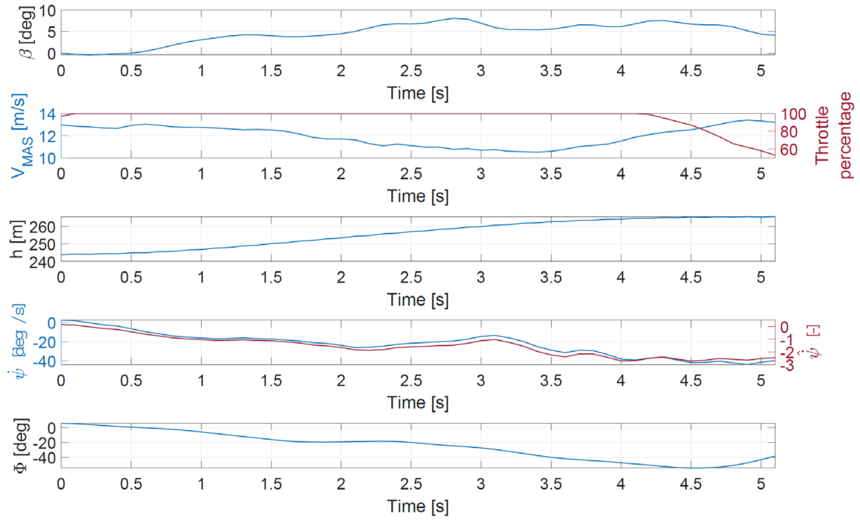

Figure 12: SwitchMaster time histories in SE mode in a straight flight at almost constant airspeed.

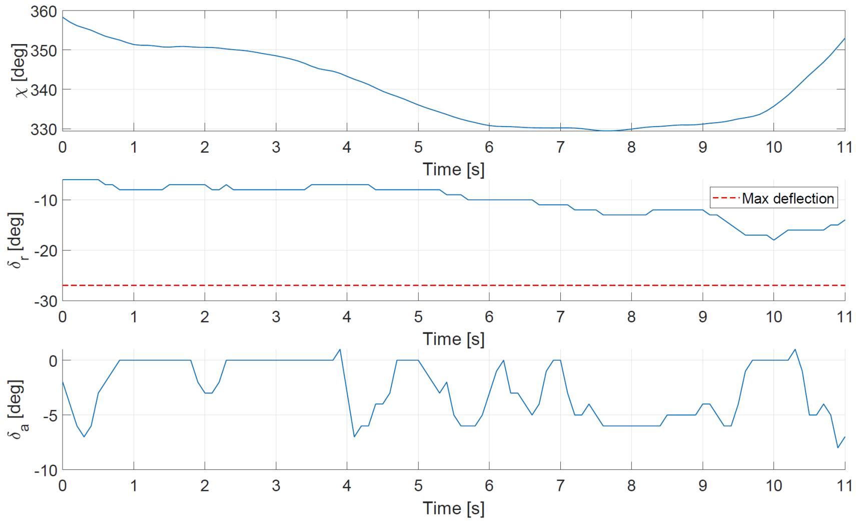

Figure 13: Time histories in ME mode OEI conditions (EM$_1$ out).

In normal ME mode, symmetric thrust distribution led to uneventful symmetric flight. A thorough experimentation of the effects of switching off one EM at a time, led to OEI ME mode conditions that can be representative of the expected OEI condition in a twin-engine airplane. Shutting down the motors EM_3, EM_2, and EM_1 (see Figure 1) leads to the demonstration that straight flight is achievable with rudder deflection of up to 10 to 12 to 15 deg, aileron deflection of up to 2 to 4 to 6 deg, and a corresponding bank angle of 10 to 12 to 20 deg, respectively. Figure 13 shows the effect of applied rudder (δ_r) and aileron (δ_a) controls on track angle χ in the case of switching off EM_1, which imposes the most penalizing effect. Switching off two EMs inhibited straight flight even at full rudder deflection, *i.e.* 27 deg.

As an example of PCA applications, Figure 14 illustrates the case of a 180 deg flat turn carried out with thrust asymmetry, with the complete suppression of lateral control. Multiple tests showed a gentle and predictable behavior of the aircraft, which effectively completed the maneuvers while the pilot was almost a motionless spectator. Also, testing turn coordination through thrust asymmetry in place of the rudder to correct the sideslip induced in a turn led to promising results.

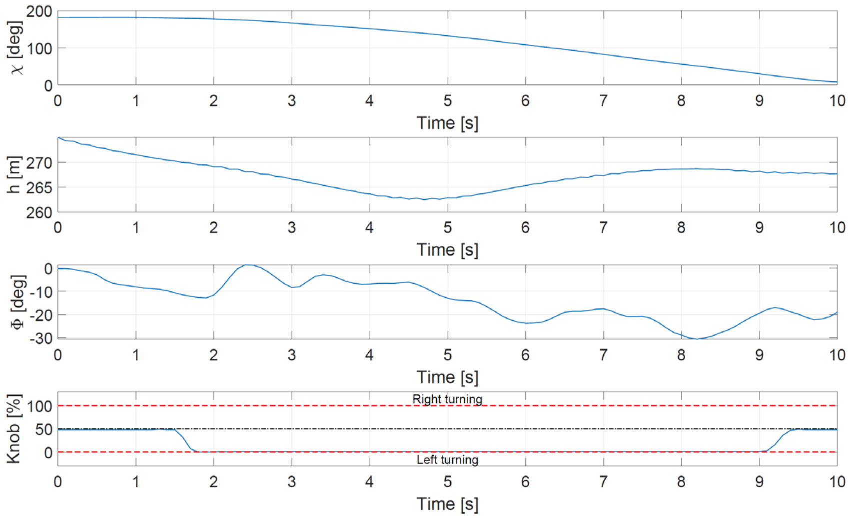

Figure 14: Time histories of a thrust-controlled flat turn.

Further flight test activities, currently ongoing, are related to model identification. A vast array of maneuvers are considered, both general/aerobatic such as tonneaux, pull-ups and push-overs, Schneider turns, loops, and dedicated flight test techniques, such as pitch, roll, and yaw pulses, doublets and 3-2-1-1.

3.4 Model identification

A first attempt to produce a flight simulator for the SwitchMaster was carried out using the Xplane software. Although this is known to be a realistic tool for many fixed-wing aircraft, it delivered mixed results in the case of the SwitchMaster, most likely due to difficulty of accurately capturing the aeropropulsive interaction induced by the DEP. Indeed, while longitudinal behavior appeared reasonably well conveyed by the model, simulated lateral-directional dynamics were quite far from matching flight data from dedicated tests, such as Dutch Roll excitation. Tweaking the model geometry to better match the data was tried, without solving the problem. Therefore, a new approach was deployed by modelling the aircraft within the Simulink software, while using Xplane only for visualization.

This activity is currently ongoing and initial results appear quite promising. Figure 15 shows the comparison between the measured and estimated values of the coefficients of sideforce, rolling moment, and yawing moment for a bank-to-bank rolling maneuver. The estimation was carried out by identifying the model with an output-error approach using two different sets of variables, one including the square of the angle of sideslip, and the other without it. As apparent, both estimations are fairly close to the flight data, with a slightly better approximation in the case of the identification including β^2.

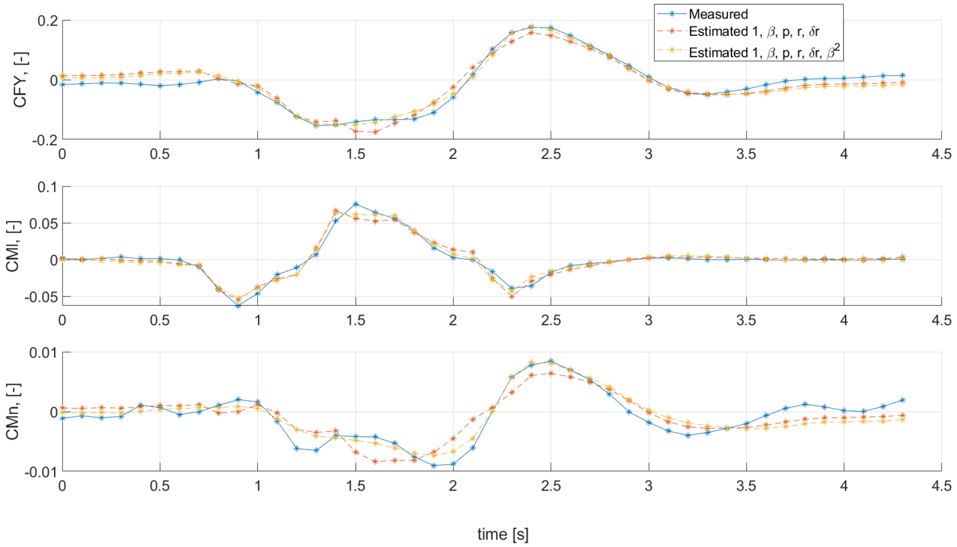

Figure 15: Measured (blue) and estimated (red, yellow) values of lateral-directional force and moment coefficients for a rolling maneuver.

4 Conclusion

The presented work took inspiration from the AeroSwitch concept for a DEP aircraft capable of effectively simulating the behavior of a single-engine propeller-driven airplane, as well as that of a multi-engine one in AEO and OEI conditions. The SwitchMaster demonstrator, obtained by a major modification of a commercial remotely-piloted model aircraft, provided a complete preliminary validation of this concept, successfully emulating the desired behavior in all relevant flying modes. The original control unit that was designed and implemented to enforce such modes was able to successfully work throughout the full ground and flight test campaign, as well as the rest of the propulsive and airframe components that were integrated in the model aircraft. The flight test results showed compliance to the stringent requirements related to single-engine and multi-engine OEI in-flight simulation. In addition, further tests to investigate advanced applications of DEP configurations confirm the feasibility of PCA concepts. Current activities include the identification of the numerical model of the SwitchMaster, involving further flight testing, aimed at producing a tool capable to accurately reproduce the peculiar dynamic behavior of the aircraft that results from the DEP aeropropulsive interaction. This shall be a fundamental asset for pilot training, investigation of aeropropulsive effects and their modelling through offline and piloted flight simulations, as well as future research efforts in control automation and performance optimization.

Acknowledgements

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