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Aero-Propulsive Modeling and System Identification of a Distributed Electric Propulsion Flying Model

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Abstract. This contribution illustrates a novel approach to aero-propulsive modeling and system identification for Distributed Electric Propulsion (DEP) aircraft. The placement of multiple propellers along the wing leading edge significantly alters the flow field, affecting both performance and flying qualities. A direct modeling approach based on simplified theoretical formulations is insufficient to accurately predict the complex behavior of the aircraft. Therefore, model identification is necessary to achieve some insight on the phenomenon. Based on the identified model, the aim is twofold: to generalize the modeling for aircraft design and analysis, and to develop a high-fidelity simulation tool for control law synthesis and advanced applications. The flight test campaign supporting the identification activities was carried out through fully automated flight tests using the scaled DEP demonstrator SwitchMaster, as discussed in [1].

Introduction

Distributed Electric Propulsion (DEP) represents a promising solution among unconventional aircraft design concepts, because the interaction between the propellers and the wing is exploited in the attempt of increasing the overall aerodynamic performance [2]. DEP offers several benefits in efficiency, control authority and system redundancy.

However, the aerodynamic coupling between propeller slipstreams and the airframe introduces strong nonlinearities that challenge conventional modeling techniques. To address this challenge, a dedicated research effort has been conducted at the Politecnico di Milano using the SwitchMaster demonstrator, an electrically powered, radio controlled aircraft featuring six propellers distributed along the leading edge of the wing.

Earlier studies [1, 3, 4] focused on the design, preliminary flight testing, and the development of an autonomous flight control framework based on a Total Energy Control System (TECS). Building on that foundation, the present work focuses on identifying a complete aero-propulsive model from flight data. The identification campaign was conducted using an autonomous flight test procedure designed to systematically excite the aircraft's dynamic modes under different blowing conditions. The identified model captures the impact of distributed propellers on stability and control derivatives, providing a formulation for subsequent simulation and control studies.

This paper details the applied methodology and estimation techniques, discusses DEP-specific identification challenges and shows results illustrating propeller-induced aerodynamic effects.

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Aero-Propulsive Modeling

DEP introduces a strong coupling between aerodynamic and propulsive effects due to the blowing phenomenon, where the propeller slipstream accelerates the local airflow over the wing. This increases lift but also alters drag and aerodynamic moments, leading to a complex interaction in which aerodynamic and thrust contributions cannot be easily separated. While this coupling poses modeling and control challenges, it also offers opportunities for improved performance and innovative control strategies.

The identification campaign was performed exclusively under the Collective Thrust Control (CTC) conditions, with all propellers operating at the same rotational speed and producing equal thrust. The reference model adopted for parametric identification is a non-linear formulation of conventional fixed-wing aircraft dynamics. The propeller advance ratio, $J = \frac{U}{nd}$, where U is airspeed, n the propeller rotational speed and d the diameter, quantifies the influence of propeller-induced blowing relative to aircraft airspeed.

Aerodynamic coefficients in the equations of motion follow standard constitutive relationships:

$$C_{(.)_{(.)}} = C_{(.)_0} + C_{(.)_\alpha}\,\alpha + C_{(.)_{\hat{q}}}\,\hat{q} + C_{(.)_{\delta_e}}\,\delta_e + C_{(.)_{\alpha^2}}\,\alpha^2 \qquad \text{longitudinal}$$

$$C_{(.)_{(.)}} = C_{(.)_0} + C_{(.)_\beta}\,\beta + C_{(.)_{\hat{p}}}\,\hat{p} + C_{(.)_{\hat{r}}}\,\hat{r} + C_{(.)_{\delta_a}}\,\delta_a + C_{(.)_{\delta_r}}\,\delta_r \qquad \text{lateral-directional}$$

In the previous identification campaign [4], performed manually without the support of an automatic flight testing system, stability and control derivatives were found to vary with the propeller advance ratio J. Accordingly, each derivative is expressed as:

$$C_{(.)_{(.)}}(J) = C_{(.)_{(.)}}^{unb} + \Delta C_{(.)_{(.)}}(J)$$

where $C_{(.)_{(.)}}^{unb}$ denotes the unblown value, i.e., evaluated with $J \rightarrow \infty$ and $\Delta C_{(.)_{(.)}}(J)$ the blowing-induced contribution.

System Identification

The flight test methodology, including automated excitation maneuvers and trim management through the Total Energy Control System (TECS), followed the approach outlined in [5, 6]. The identification aimed at estimating the stability and control derivatives $C_{(.)_{(.)}}(J)$, including the propeller blowing effects $\Delta C_{(.)_{(.)}}(J)$.

The identification process involved two main steps: first, solving the Equation-Error Method (EEM) for each selected maneuver, and second, applying the Output-Error Method (OEM) [7]. The EEM provided initial parameter estimates by minimizing the squared differences between modeled and measured aerodynamic coefficients, using a least-squares solution. These estimates served as initial guesses for the OEM, which refined the parameters by minimizing, through an optimization problem, a cost function quantifying the difference between measured and model-predicted outputs, such as airspeed, angular rates and attitude angles. The cost function, expressed as a weighted sum of squared output errors over the maneuver duration, provides a quantitative measure of model fidelity. In the OEM, initial conditions were also treated as optimization variables to account for small state uncertainties, and parameters were normalized by their initial estimates to improve numerical conditioning. The optimization, performed via the *fmincon* algorithm, included physical bounds to avoid unrealistic solutions and local minima.

Compared to the EEM, the OEM provided higher fidelity and dynamic consistency, as illustrated in Fig. 1, which reports a representative elevator doublet maneuver. The simulated responses using OEM parameters showed a markedly improved match with measured data. Fig. 2 further shows that OEM-based simulations closely match the measured motion states and aerodynamic coefficients.

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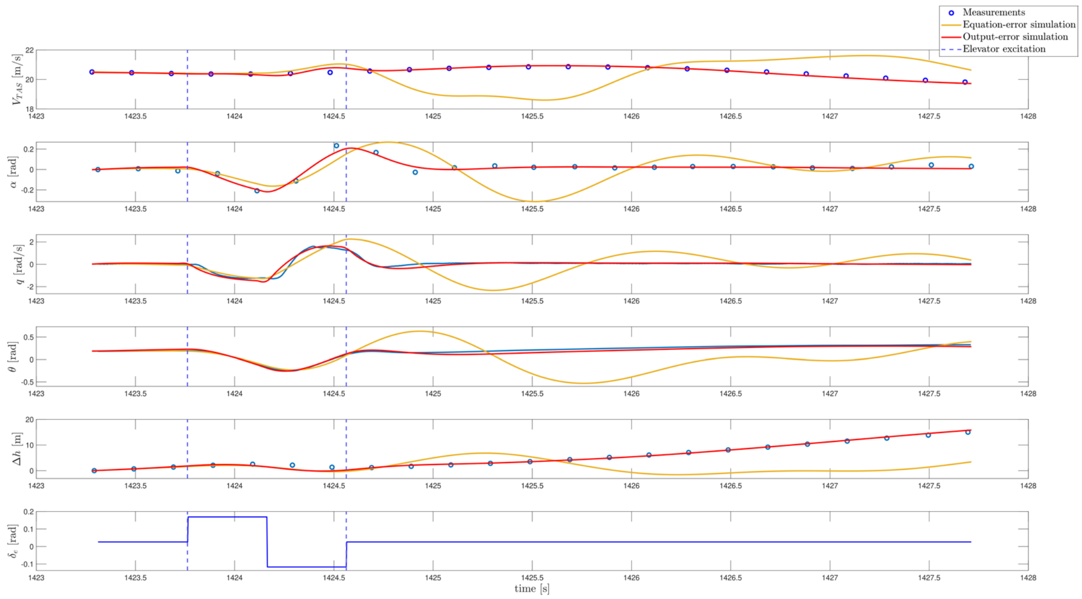

Figure 1: Longitudinal output time histories from measured data, simulated with Equation Error and Output-Error results.

Results

The identified aerodynamic derivatives were analyzed to evaluate the impact of propeller blowing on the aircraft's longitudinal and lateral-directional dynamics. Stability and control derivatives were identified for each stabilized maneuver, defined by its trim advance ratio J_{TRIM} and angle of attack α_{TRIM}. The resulting derivatives were plotted as functions of J and grouped into clusters based on α_{TRIM}, facilitating the interpretation of their trends across different flight conditions.

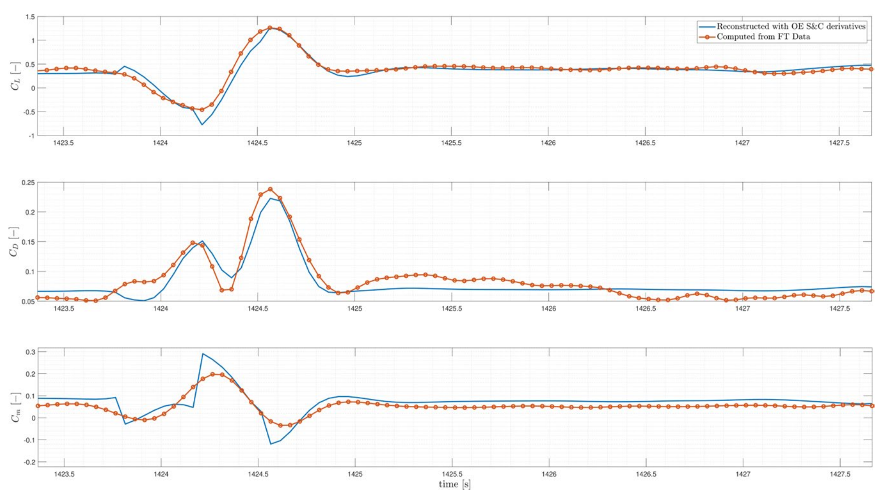

Figure 2: Comparison of longitudinal aerodynamic coefficient time histories, computed from the identified model (blue) and the flight data (red).

Several derivatives showed a clear exponential dependence on J: C_{L_0}, C_{m_0}, $C_{m_{\hat{q}}}$ and $C_{m_{\delta_e}}$ for the longitudinal dynamics, and C_{S_β}, C_{l_β}, C_{n_β} and $C_{l_{\delta_a}}$ for the lateral-directional dynamics.

The remaining terms exhibited only random fluctuations around a mean value, indicating negligible sensitivity to the blowing effect. Derivatives exhibiting a dependence on J were fitted using exponential functions $C(J) = C_\infty + p_1 e^{-p_2 J}$, or, in some cases, the sum of two exponential terms, where C_∞ denotes the asymptotic unblown value ($J \rightarrow \infty$).

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As shown in Fig. 3, the lift coefficient increases with the blowing effect, thus at low J. In the unblown condition, data scattering led to adopting the mean value as representative. Improved accuracy is expected from refining the glide test procedure to ensure that the autopilot maintains properly trimmed flight conditions even without engine thrust. Variations in pitching moment derivatives mainly result from increased dynamic pressure at low J and from slipstream-tail interactions causing additional downwash.

In the lateral-directional dynamics, the derivatives linked to sideslip (C_{S_β}, C_{l_β}, C_{n_β}) show an exponential dependence on J due to propeller slipstream effects on the fuselage and vertical tail. Among the control derivatives, $C_{l_{\delta_a}}$ is the most affected, as the slipstream enhances ailerons effectiveness and roll control at low J.

Overall, the identified exponential trends confirm the strong aero-propulsive coupling introduced by DEP and offer a quantitative foundation for modeling and control analysis.

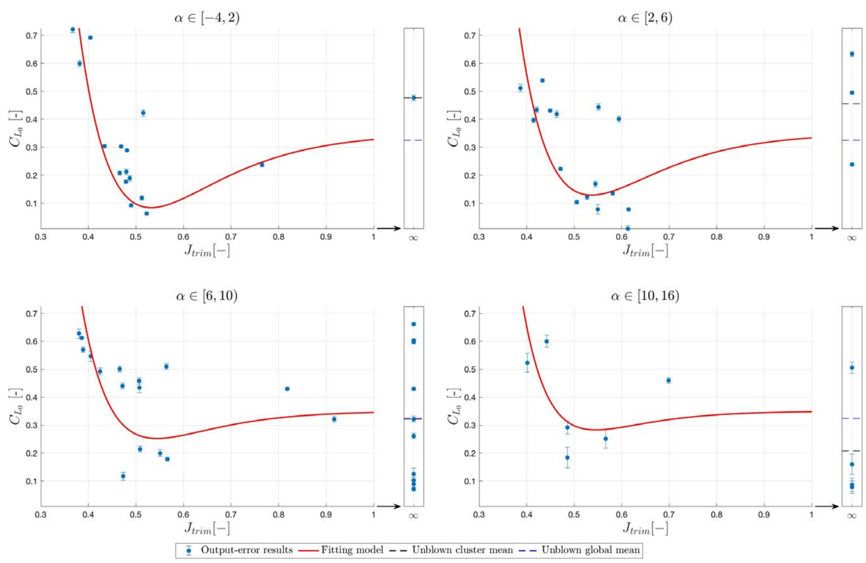

Figure 3: Trends of C_{L_0} with respect to J_{trim} divided into α_{trim} clusters.

Semi-Local Model Identification

The aerodynamic model obtained by fitting the clustered stability and control derivatives from the Output-Error identification was defined as the parametric global model, representing a generalized formulation compared to the local models, which are specifically optimized for each maneuver.

A refinement step followed, reapplying the Output-Error identification while constraining selected high-confidence parameters to the corresponding values from the global model within the equations of motion. In particular, C_{L_0} and C_{m_0} were fixed for the longitudinal dynamics, and C_{S_β} and $C_{l_{\delta_a}}$ for the lateral-directional dynamics, based on a trial-and-error tuning. The rest of the identification process remained unchanged, with derivatives estimated for each maneuver and fitted using exponential or mean-value models, depending on their sensitivity to J. The resulting formulation has been defined as semi-local model, since combines global constraints on selected derivatives with local estimation of the remaining ones. As shown in Fig. 4, it provides a more interpretable trend of the derivatives with respect to propeller advance ratio, compared to both the local and global models, confirming the enhanced predictive capability of this hybrid identification approach.

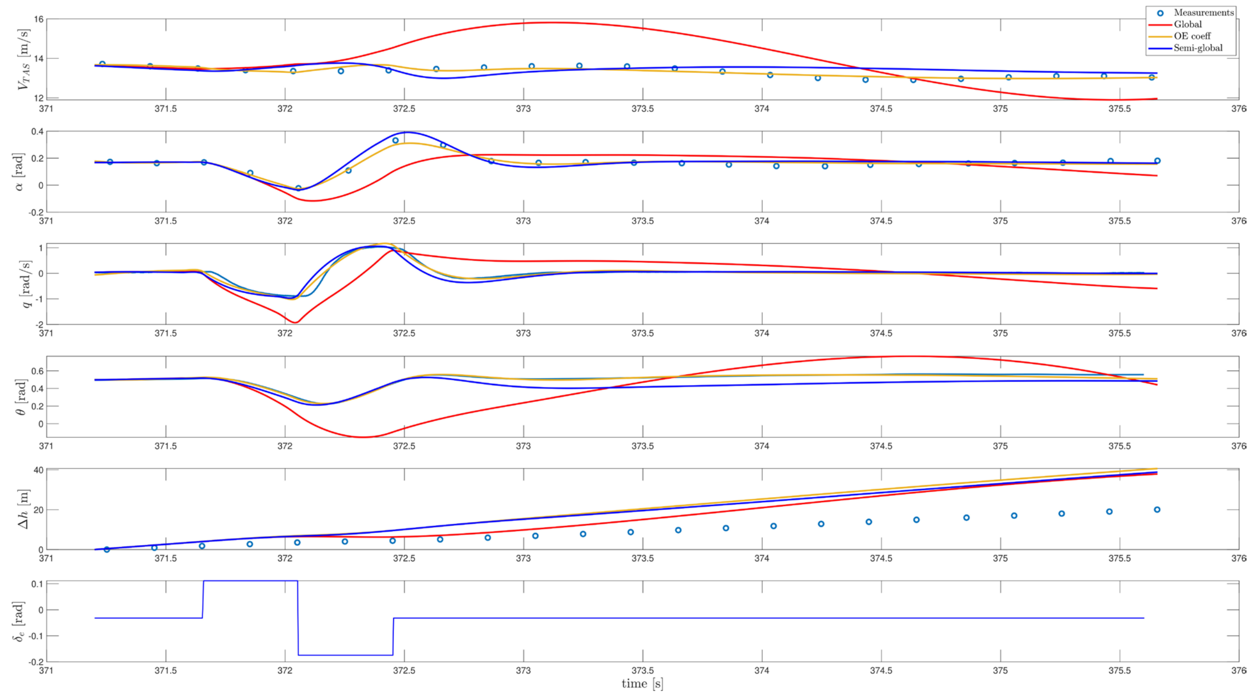

Figure 4: Longitudinal output time histories from measured data, simulated with Output-Error results and with global and semi-global fitted models.

Conclusions and Future Developments

This study presented an aero-propulsive identification methodology for a Distributed Electric Propulsion aircraft, integrating Equation-Error and Output-Error techniques within an autonomous flight testing framework. Applied to the SwitchMaster demonstrator, the approach successfully captured the non-linear aero-propulsive coupling introduced by the propeller slipstream and its impact on stability and control derivatives, leading to the development of both global and semi-global models. The semi-global formulation, incorporating selected global constraints, showed improved consistency and predictive accuracy, confirming its suitability for control-oriented applications.

Future work will extend the identification process by combining all maneuvers within similar α_{TRIM} ranges into a single optimization, where J-dependent derivatives are constrained to follow exponential laws. Successful convergence would validate the exponential dependence on the advance ratio and reinforce the robustness of the proposed aero-propulsive model.

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