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A Procedure for Developing a Flight Mechanics Model of a Fixed-Wing Drone with Unusual Configuration using Empirical Methods

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Abstract

There is an inherent dilemma in designing new aircraft featuring innovative configurations: on one hand, simplified methods based on statistical data may produce unreliable results due to the unique nature of the configuration being analyzed; on the other hand, more sophisticated methodologies, such as those based on computational fluid dynamics (CFD), incur a computational cost that does not align well with the requirements of preliminary design and optimization applications. Among all aircraft with unconventional configurations, special mention goes to fixed-wing drones with vertical take-off and landing capabilities, devised for improved endurance performance than quad- or multi-copter unmanned aerial vehicles (UAV). Fixed-wing drones often feature unique designs, such as tandem wings, box wings, or three-surface configurations, specifically engineered to accommodate multiple rotors required for both horizontal and vertical flight. Modeling these aircraft is actually challenging due to the complex aerodynamic interactions between the lifting surfaces, fuselage, and gondolas. This work supports this task by proposing a procedure to model the aerodynamics of a fixed-wing UAV with an innovative configuration. The process is based on multiple Datcom analyses, conducted in sequence, with the outputs appropriately combined to create an overall model of the aircraft. The procedure is validated against flight data of a UAV with an innovative three-surface configuration.

1. Introduction

The aviation industry is rapidly evolving, driven by the demand for innovative and efficient aircraft configurations. Among these, unconventional designs for fixed-wing drones, devised to support Vertical Take-Off and Landing (VTOL), are gaining significant interest due to their performance and operational flexibility. However, generating a suitbale mathematical model of these configurations is challenging due to the complex interactions between the lifting surfaces, fuselage, and gondolas. This fact crucially highlights that the preliminary design phase of such aircraft remains a challenge, necessitating reliable and efficient predictive models. In fact, CFD methodologies, potentially capable of providing a suitable modeling of unusual configurations, are usually employed in the later design stages, when the configuration is largely finalized, leaving little opportunity for wide-space optimization of the aircraft. Empirical and semi-empirical aerodynamic methods, such as those implemented in the Digital Datcom,[3, 10] have been widely used for conventional aircraft; however, being based on historical data, they are not well-suited for modeling flying machines in unusual configurations.

This research aims to fill this gap by extending the capabilities of Digital Datcom to accommodate unconventional aircraft configurations. The proposed semi-empirical methodology is validated through an analysis using the Dragonfly DS-1, displayed in Fig. 1, a fully electric VTOL fixed-wing drone featuring a Three-Surface Aircraft configuration.

This UAV, developed by Overspace Aviation,[5] serves as a case study to assess the applicability and accuracy of the extended Digital Datcom approach. This method aims to provide a more effective tool for the early-stage model assessment of innovative UAV designs and for facilitating performance improvements and design refinements to optimize existing drone operational efficiency.

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Figure 1: Dragonfly DS-1 VTOL. Image courtesy of[5]

The estimated lift-curve and drag polar will be compared with flight data, showing that the proposed procedure provides a good approximation of the lift curve. However, the drag is not adequately rendered and this deserves additional investigations.

2. Methodology

The aerodynamic characterization of the Dragonfly DS-1, given its three-surface configuration, presents unique challenges that cannot be directly addressed using traditional models such as USAF Digital Datcom. These methods, originally developed for conventional aircraft, rely on predefined empirical correlations that are not inherently applicable to configurations with multiple lifting surfaces. While Digital Datcom provides an efficient framework for computing aerodynamic coefficients and stability derivatives, its default structure assumes a single main wing and a conventional horizontal tailplane (or canard). As a result, it lacks the built-in capability to account for aerodynamic interactions between multiple lifting surfaces, a fundamental aspect in three-surface aircraft. To overcome this limitation, this research develops an extended modeling approach that integrates Digital Datcom within a structured sequential analysis framework. Rather than treating the aircraft as conventional or attempting to approximate the entire configuration with an equivalent wing, the methodology decomposes the aerodynamic contributions of each lifting surface and systematically reconstructs the complete flight mechanics model. Unlike high-fidelity CFD simulations, which resolve the full aerodynamic field and account for surface-to-surface interactions explicitly, Digital Datcom requires modifications to approximate the aerodynamic behavior of non-standard geometries.

In particular, the method used in this study addresses the absence of direct three-surface modeling capabilities by performing independent aerodynamic analyses of the individual lifting components and integrating their contributions through a structured data-processing methodology. This ensures that the aerodynamic coefficients obtained remain physically consistent with the three-surface layout while preserving the advantages of rapid computation characteristic of semi-empirical methods.

The following sections detail the implementation of this methodology, including the specific steps used to model the vehicle aerodynamics and the validation process employed to assess the accuracy of the adapted approach.

2.1 Sequential Analysis Framework

The development of a structured flight mechanics modeling approach for the Dragonfly DS-1 requires a precise definition of its geometry, mass properties, and flight conditions.

Given the limitations of Digital Datcom in handling three-surface configurations, a sequential analysis framework is implemented using the Matlab-based interface, called `RunDatcom`, originally developed in[8] and extended in.[9]

`RunDatcom` is composed of six dedicated scripts, each responsible for different aspects of the aircraft configuration. Once the main script is executed, these modules work together to generate the overall flight mechanics model.

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A key element of this framework is the type of analysis field, which allows for the selection of one of 16 predefined analysis configurations, determining which aircraft components are included in the aerodynamic evaluation. This sequential methodology ensures that the contributions of each lifting surface are properly accounted for, while maintaining the computational efficiency of semi-empirical modeling.

2.2 Definition of Aircraft Geometry and Flight Conditions

To develop an accurate flight mechanics model, it is essential to establish well-defined flight reference parameters that were selected to be representative of the cruise phase of the Dragonfly DS-1.

Moreover, the UAV geometry is extracted from a high-fidelity CAD model, allowing for a precise description of the aircraft.

3. Procedure for Generating the Aircraft Model

The aerodynamic modeling of the Dragonfly DS-1 in Digital Datcom follows a sequential approach, where multiple analyses are performed to systematically evaluate the aircraft aerodynamic coefficients, stability derivatives, and control effectiveness. Due to the inherent limitations of Datcom, certain structural elements, such as the engine nacelles, ground support arms, and complex tail structures, are not explicitly modeled. Instead, simplified representations are used to ensure compatibility with the software computational framework while preserving the fundamental aerodynamic characteristics of the aircraft.

- Analysis 1 defines the fuselage, front wing, and rear wing, treating the rear wing as the horizontal tail to align with Datcom computational structure. This analysis also includes the implementation of ailerons on the front wing to assess their aerodynamic influence on roll control.

- Analysis 2 introduces an alternative configuration where the ailerons are moved to the rear wing. Due to Datcom limitations, a canardbased approach is used, treating the front wing as a canard and the rear wing as the primary lifting surface. This adaptation ensures that the aerodynamic contribution of rear-wing ailerons is correctly computed.

- Analysis 3 represents a critical step in defining the stability and control derivatives of the Dragonfly DS-1. The simulation is performed in two sequential phases. In the first phase, the aircraft is modeled as a body-wing-tail configuration, where the front and rear wings are treated as the main wing and tail, respectively. In the second phase, the results from the first phase are incorporated into a refined simulation using external aerodynamic data via the EXP section of Digital Datcom. This approach ensures that stability derivatives and control effectiveness are computed using an aerodynamically consistent representation of the three-surface configuration. To align with Datcom computational constraints, a fictitious wing is introduced in the second phase. This geometrically equivalent structure allows Datcom to correctly interpret the rear wing as the primary lifting surface, ensuring that the aerodynamic forces and stability derivatives are accurately modeled. Additionally, this second phase includes the horizontal tail, vertical tail, ventral fin, and elevator, which are incorporated to provide a complete assessment of the aircraft aerodynamic stability characteristics.

- Analysis 4 evaluates the horizontal tail separately, accounting for the modified flow conditions caused by the forward lifting surfaces. Since Datcom does not explicitly compute downwash effects in tandem-wing configurations, a correction factor is applied to adjust the tail effective angle of attack. This correction is derived from the results obtained in Analysis 3, ensuring that the aerodynamic forces and stability derivatives reflect real operating conditions.

- Analysis 5 considers the isolated vertical stabilizer to analyze its effect on yaw stability and control derivatives. This configuration removes all other aerodynamic components, allowing for a precise evaluation of the vertical tail aerodynamic forces and moments.

- The final analysis focuses on evaluating the aerodynamic influence of the ventral fin in isolation. To correctly model this contribution, all other aerodynamic components are removed, and only the fuselage and ventral fin are retained.

The flight mechanics model of the Dragonfly DS- 1 is constructed by integrating stability and control derivatives extracted from sequential analyses previously described.

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Lift, drag, and pitching moment coefficients are obtained from the second phase of Analysis 3. Elevator deflection effects on lift, drag, and pitching moment are also evaluated in the second phase of Analysis 3. This step ensures accurate modeling of the aircraft longitudinal control response.

On the other hand, dynamic stability derivatives are primarily extracted from the first phase of Analysis 3, Analysis 4, Analysis 5 and Analysis 6. Roll and yaw control derivatives from aileron deflections are assessed in Analyses 1 and 2, which examine their effectiveness on the front and rear wings, respectively. By systematically combining these contributions, the flight mechanics model effectively captures the aerodynamic behavior of the analyzed drone while maintaining computational efficiency. Since Digital Datcom does not inherently account for all aerodynamic contributions, additional empirical corrections are introduced to refine the model. One of the most significant adjustments involves compensating for the absence of engine nacelle modeling. To account for this, a correction factor is introduced, based on classical aerodynamic estimations,[7] ensuring that the final model better represents the aerodynamic behavior of the Dragonfly DS-1.

4. Comparative Analysis of Experimental and Semi-Empirical Data

To validate the flight mechanics model of the Dragonfly DS-1 from an aerodynamic point of view, a comparative analysis is conducted between the aerodynamic data obtained from experimental flight tests and the semiempirical methodology. This evaluation aims to assess the reliability of the developed model and identify potential discrepancies among different approaches.

Experimental flight data, obtained from multiple test campaigns, represent real-world aerodynamic performance and are processed by selecting stable flight conditions through a structured data filtering methodology described in.[2]

4.1 Derivation of polar from flight data in steady horizontal flight.

From flight data log of the Ardupilot software,[1,4] the velocity components in the north–east–down (NED) reference fram $\boldsymbol{V}^{\mathcal{N}}$ are readily avalaible along with the Cardan angles ϕ, θ, and ψ, namely roll, pitch, and heading.

The component of the velocity in the body frame $\boldsymbol{V}^{\mathcal{B}}$ can then be computed as

$$\boldsymbol{V}^{\mathcal{B}} = \boldsymbol{R}^T \boldsymbol{V}^{\mathcal{N}} \tag{1}$$

with

$$\mathbf{R} = \begin{bmatrix} \cos\psi\cos\theta & \cos\psi\sin\theta\sin\phi - \sin\psi\cos\phi & \cos\psi\sin\theta\cos\phi + \sin\psi\sin\phi \\ \sin\psi\cos\theta & \sin\psi\sin\theta\sin\phi + \cos\psi\cos\phi & \sin\psi\sin\theta\cos\phi + \cos\psi\sin\phi \\ -\sin\theta & \cos\theta\sin\phi & \cos\theta\cos\phi \end{bmatrix}, \tag{2}$$

The components of the velocity can also be corrected for wind speed, if this indication is available, according to the treatment of.[2]

Cleary, from vector $\boldsymbol{V}^{\mathcal{B}}$ the longitudinal U, lateral V, and vertical W components are readily available.

Finally, the angle of attack α is computed as

$$\alpha = \arctan\left(\frac{W}{U}\right). \tag{3}$$

The longitudinal and normal aerodynamic forces in the body axes are easily computed as

$$F_x = ma_x - T \tag{4}$$

$$F_z = ma_z \tag{5}$$

being m is the mass of the aircraft, a_x, a_y, a_z the accelerations in the body frame; and T the thrust, which can be estimated from manufacturer's data,[6] as reported in.[2]

The non-dimensional longitudinal and normal aerodynamic force coefficients are computed as

$$C_X = \frac{F_x}{\frac{1}{2}\rho U^2 S} \tag{6}$$

$$C_Z = \frac{F_Z}{\frac{1}{2}\rho U^2 S}, \tag{7}$$

being U the velocity vector absolute value, ρ the air density and S the reference wing area.

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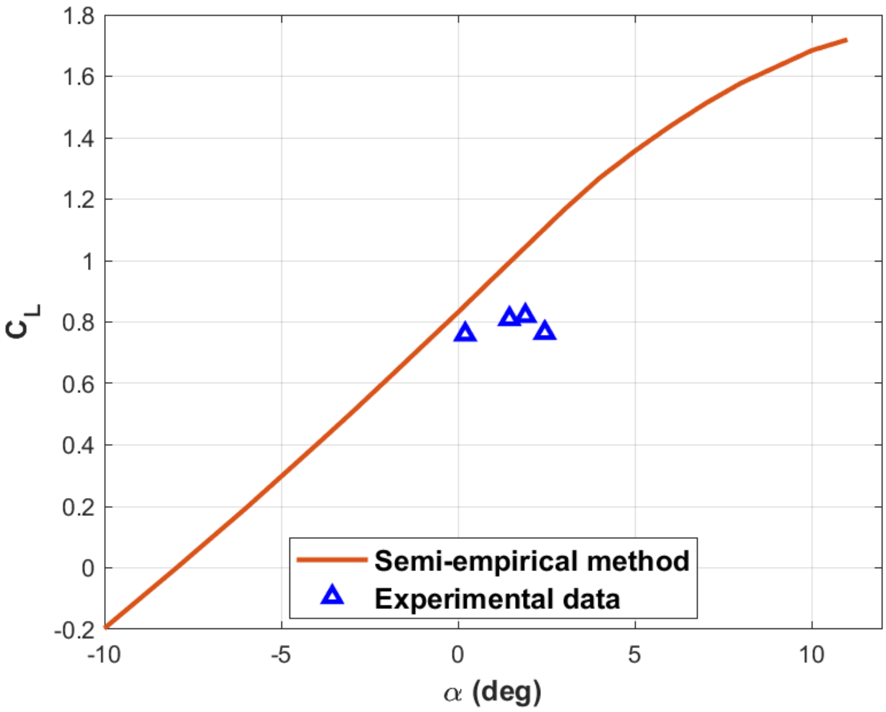

Figure 2: Lift curve comparison. Solid line: estimation from semi-empirical method; triangle markers: experimental data from flight testing.

From (6), lift and drag coefficients are readily computed, through the standard relatioships as

$$C_L = -C_Z \cos\alpha + C_X \sin\alpha \tag{8}$$

$$C_D = -C_X \cos\alpha - C_Z \sin\alpha \tag{9}$$

From the estimation of lift and drag coefficients, and angle of attack, (see Eq. (3) and (8), one can readily obtain the lift curve and drag polar, which can be compared with the predictions of the presented semi-empirical methodology.

4.2 Comparison between experimental data and estimation of the semi-empirical method

The comparison is conducted by analyzing both lift curve and the drag polar.

Figure 2 represents the comparison in terms of the lift curve. The semi-empirical method overestimates the lift coefficient by approximately 15%. Given the simplification adopted in the modeling methodology, this result is still satisfactory from preliminary investigation, even if it requires further analyses to reduce the estimation error.

Dealing with the polar drag displayed in Fig. 3, the results highlight a systematic offset, with the semiempirical model predicting lower drag coefficients compared to experimental data. The observed discrepancies indicate that the semi-empirical method underestimates aerodynamic drag due to simplifications in the modeling process, particularly the omission of elements such as support structures.

To improve the predictive accuracy of the semiempirical model, future refinements should introduce empirical correction factors to account for unmodeled aerodynamic effects. Additionally, calibrating the equivalent wing definition could enhance the model reliability. The ultimate goal is to refine the semi-empirical methodology, ensuring consistency with both numerical simulations and real-world aerodynamic performance.

5. Conclusion

This study presents a structured methodology for modeling the aerodynamics of a three-surface UAV using a semi-empirical approach. By adapting the USAF Digital Datcom within a sequential analysis framework, the method enables efficient estimation of stability and control derivatives, thereby extending the applicability of empirical tools to unconventional configurations.

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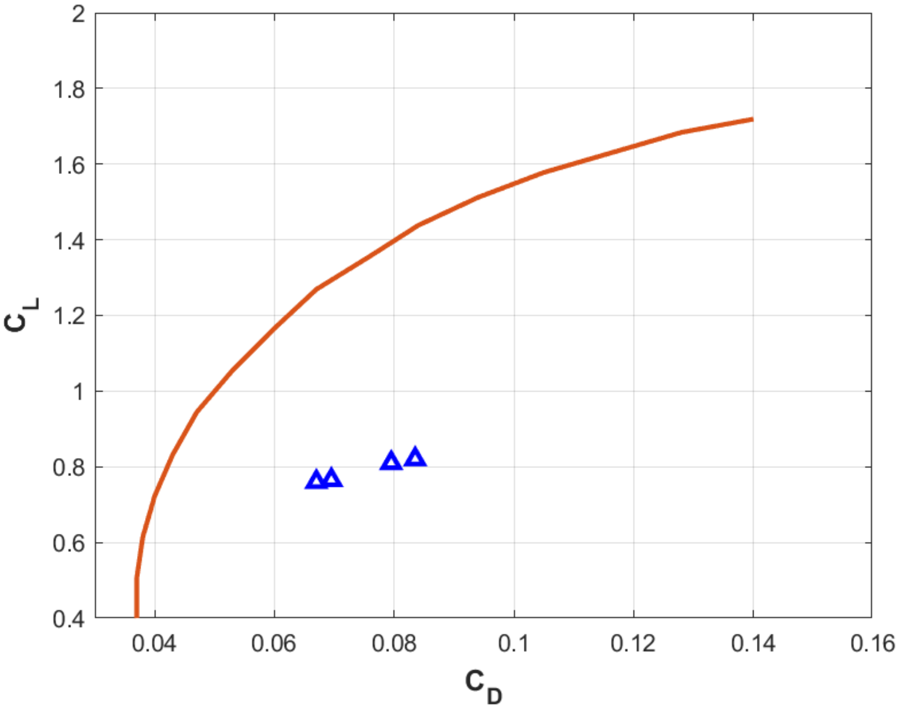

Figure 3: Polar comparison. Solid line: estimation from semi-empirical method; triangle markers: experimental data from flight testing.

From the outcomes of the present work, we can derive the following conclusions.

- Comparative validation against experimental flight data showed a consistent underprediction of drag, likely due to structural contributions and other unmodeled effects.
- The same comparison in terms of lift coefficients suggests that the semi-empirical methodology is associated with slightly higher lift prediction. This error is consistent with the empirical nature of the employed estimation process and is considered adequate in the preliminary design phases.
- These discrepancies suggest that while the methodology effectively captures overall aerodynamic trends, it lacks the accuracy needed for high-fidelity performance evaluations.
- These findings underscore both the potential and the limitations of semi-empirical methods for unconventional aircraft. While the approach is well-suited for preliminary design due to its computational efficiency, further refinements are necessary.

Future work should focus on introducing empirical corrections for unmodeled aerodynamic contributions, refining the process, and expanding the validation dataset with high-fidelity simulations and experimental data. By systematically addressing these challenges, this methodology can evolve into a more reliable tool for the aerodynamic characterization of non-standard VTOL configurations.

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