Aerodynamic and stability analysis of a VTOL flying wing UAV

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Abstract. The stability analysis of an aerial vehicle is an of great importance integral part of its design procedure. It is of even greater importance in the case of tailless aircraft, which are prone to stability issues. In the present study, the aerodynamic and stability characteristics of a Vertical Take-off and Landing (VTOL) fixed wing Unmanned Aerial Vehicle (UAV), designated as MPU RX-4, are investigated. The MPU RX-4 has a flying wing layout and is capable of performing, both conventional flight, like a regular fixed wing aerial vehicle, as well as vertical hovering, like a multicopter, adapting on different operational demands and achieving rapid field deployment. In this study, the preliminary design phase of the MPU RX-4 is presented and the aerodynamic performance, as well as, its stability and control behavior are assessed using both semi-empirical correlations, specifically modified for lightweight flying wing UAVs, and Computational Fluid Dynamics (CFD) analyses. These correlations are employed to estimate the non-dimensional aerodynamic coefficients for various flight conditions (e.g. cruise, loiter, maximum speed, etc.) of the MPU RX-4 flight envelope. Furthermore, the correlations are validated with dedicated CFD analyses in order to assure their level of accuracy. Finally, the MPU RX-4 stability and control derivatives, and the required control surfaces deflection for steady level flight are computed, in order to assess its overall aerodynamic performance and flight characteristics.

1. Introduction

The commercial use of Unmanned Aerial Systems (UAS) has seen a rapid increase in recent years. This is due to the drastic decrease of their purchase price, the use of advanced autopilot systems that allow their operation from novice operators/pilots, and their significantly smaller operational cost compared to other manned alternatives. UASs are involved in a wide range of missions, from security and border monitoring, to emergency medicine transport and/or search and rescue operations. In many cases, the Unmanned Aerial Vehicles (UAVs), that are the most critical part of a UAS, are equipped with environment perception algorithms that enable them to operate autonomously, collect the necessary data, and provide the desired feedback to the operator.

The UAVs, available in the market for commercial use, can be categorized based on their dimensions, maximum takeoff weight (MTOW), geometry as well as their way of lift generation. Regarding the latter they are classified either as multicopters or fixed-wing UAVs. Multicopter configurations are dominant...
in commercial applications, since they have the significant advantage that they can perform vertical take-off and landing (VTOL), provide access in areas that are not easily traversable, hover over locations of interest, while also offer increased portability in some cases [1]. Their main disadvantage is the high power consumption of their motors, which drastically limits the flight time and payload weight. Contrarily, fixed-wing configurations require significantly less power since the main wing is responsible for the generation of lift and have reduced aerodynamic drag. These benefits of more efficient aerodynamic design, attribute to increased payload capability, endurance and/or cruise speed. Moreover, fixed-wing aerial vehicles have an inherent gliding capability and less rotating or exposed parts, thus the risk of component damage is smaller, compared to multicopters.

The present study is performed in the framework of the Multirole Portable UAS “MPU” research project, which aims to develop a portable small UAS, capable of hybrid flight. The UAV will perform a variety of missions, including, cartography, photogrammetry, search and rescue, inspections, patrols and precision pharming. The UAV is a fixed-wing configuration but with hybrid flight capability, thus incorporating also some of the advantages of multicopters. The UAV will be a multirole platform, equipped with various cameras (RGB, Thermal, Multispectral), able to carry a small payload for emergency situations (medicine, wireless transceiver, etc.), and also able to operate in conditions of high humidity, rain and dust. Unlike other VTOL fixed wing UAVs, in the design of the MPU RX-4 special care is given to minimize the number of additional motors, used only for the VTOL phase, as well as their area exposed to freestream flow during conventional flight. During the conceptual design phase, two different flying wing configurations were investigated [2], using traditional analytical pre-sizing methods, low fidelity analyses (Vortex-Lattice Method) and semi-empirical/statistical correlations specifically modified for lightweight flying wing UAVs. The most suitable configuration was selected, both in terms of aerodynamic performance and VTOL controllability, and is further investigated and altered in the current phase of preliminary design.

2. Tools and Methods

2.1. Preliminary design modifications

During the preliminary design, extensive structural and stability analyses are performed, in the context as described by Anderson [3], and consequently minor changes are made to the layout of the aerial vehicle. The final geometry of the canards is designed, taking into consideration structural and stability limitations, as well as their aerodynamic performance. Specifically, the canard tips are used as mounting points for the main motors.

In order, for the UAV, to transition from conventional to vertical flight, the motors, and consequently the canards, must rotate 90°. To achieve that, a low weight rotation mechanism is designed [4] and installed in the stationary part of the canard (Figure 1a). This constrains the canard airfoil thickness and taper ratio since the mechanism must be accommodated on the interior of the canard. The airfoil selected is the symmetrical NACA0018. Moreover, during VTOL, the UAV operates as a tricopter, with the two main motors installed on the canards and the rear motor in the main body area. The performance of the UAV during VTOL, as well as its controllability, add an additional constrain related to the minimum distance between the two main motors, thus limiting the possible span of the canards.

Figure 1. (a) Dimensions of the MPU RX-4 canards and (b) geometry modification details.
Regarding the rear motor required for VTOL flight, it is stationary installed near the trailing edge of the “main body” region, with its thrust vector lying on the symmetry plane of the UAV. For this area is critical in the wing’s lift production, it is deemed necessary not to significantly alter the external geometry. To achieve that, the main motor and its propeller, are positioned inside the wing. The system is based on a three-point star base (Figure 1b), that does not affect the efficiency of the propulsion system. In the area covering the propeller disk, the wing’s external geometry is comprised of four semi-circular hatches (Figure 1b). Each hatch is connected to a servo actuator, that enables it to open during VTOL, allowing the rear motor to operate properly [4].

The presence of the rear motor hatches, dictates that the UAV must have a landing system that elevates the aerial vehicle a specific distance from the ground, (to enable the hatches on the pressure side to open completely). This is achieved with the addition of three vertical fins (Figure 1b). These fins serve the dual purpose of the landing system, as well as vertical empennage, improving the lateral stability of the UAV, an area in which tailless configurations have a disadvantage [5]. For the sizing of the vertical fins, aside from their performance as vertical empennage, their structural integrity as a landing system is considered, as well as their drag penalty. As a result, a NACA0018 airfoil is used, with the span of each vertical fin being 235mm, as required for the smooth operation of the rear motor hatches.

2.2. CFD methodology
For the evaluation of key aerodynamic characteristics, high fidelity Computational Fluid Dynamics (CFD) computations are performed. The Reynolds Averaged Navier-Stokes (RANS) equations are solved, and an appropriate turbulence model is used for their closure. The necessary 3D CAD of the aerial vehicle’s external layout is designed using the Autodesk Inventor 2019 software. The computational grid is generated, using the commercial BETA ANSA pre-processing software (v19.1.0). All cases are solved on the ANSYS Fluent software (Release 18.2), using a pressure-based solver. The SIMPLEx scheme is employed for the pressure-velocity coupling and a second order spatial discretization scheme for all the transport equations that are solved. The computational grid consists of both structured and unstructured regions, with emphasis given in the areas with strong pressure gradients and/or where flow separation is most likely to appear (Figure 2a). In the area above the UAV’s external surface exists a structured region, with 25 hexahedral cells in the normal to the wall direction, to accurately capture the boundary layer development. The height of the first cell (in the normal to the wall direction) is appropriately selected for a corresponding y’ well below 1, and thus lying inside the viscous sublayer, as required by the adopted one equation Low-Reynolds Spalart-Allmaras (S-A) turbulence model [6]. The S-A turbulence model has been widely used in aeronautical applications and has been proven to be an adequate turbulence model for predicting turbulent or transitional external flows with imposed external pressure gradients, such as the ones around airfoils and wings: it is capable to correctly correlate the occurring strong pressure gradients with the developed boundary layers [7]. The computational grid used for the analyses has around 12×10⁶ cells and it is the result of an extensive grid independency study, performed at cruise conditions.

The UAV is designed and expected to operate at altitudes less than 400ft, in compliance with regulations concerning UAV flights in Greece, and for that reason the analyses are performed with air properties for this altitude, with data taken from the U.S. Standard Atmosphere. Regarding the turbulence parameters, the eddy viscosity ratio and the turbulence intensity values were set equal to 0.2 and 1% respectively, which are considered as typical flight conditions [8]. A wide range of angles of attack is examined to ensure that all possible flight conditions are investigated, including stalling conditions.

Additionally, the influence of the main motor’s propeller, on the overall UAV performance is examined. The effect that the propeller has on the flow, is modeled with the addition of source terms in the momentum equations of the RANS, using User Defined Functions. The momentum source terms (with units N/m³) are implemented on a separate subdomain of the control volume, which corresponds to the volume of the propeller disk (Figure 2b) and are quadratic polynomial functions of the velocity.
components of the computational cells, in the x, y and z direction (Equation 1). This simplified approach is based on the work of Salpingidou et al. [9], where a surrogate model is used to model the thrust force. This procedure has been previously implemented and validated on a Medium Altitude Long Endurance (MALE) UAV by Panagiotou et al. [7]. More specifically, at different flight velocities (corresponding to different propeller rotational speed) the required pressure difference $\Delta p_{prop}$ across the disk, of area $A_{prop}$ and thickness $l$, is calculated so the produced thrust $T_{req}$ equals the total drag of the UAV. The coefficients $c_0$, $c_1$ and $c_2$ remain constant throughout the subdomain, while the velocity component in the $i$ direction $u_i$ is calculated in each computational cell. An iterative procedure is performed, where on each iteration, the required thrust and thus, the polynomial coefficients, are calculated based on the drag value of the previous iteration. Finally, convergence of the drag value is achieved, with the divergence between the last two iterations being about 0.15%.

$$\frac{T_{req}}{A_{prop} \cdot l} = \frac{\Delta p_{prop}}{l} = c_0 + c_1 \cdot u_i + c_2 \cdot u_i^2$$

(1)

Figure 2. (a) The computational mesh on the surface of the MPU RX-4 and (b) the propeller disk subdomains used for modelling the propeller.

2.3. Control surface sizing and stability study

The stability characteristics of an aerial vehicle heavily depend on the design of each part of the overall design (e.g. main wing, fuselage, engine etc.), but more importantly on the empenage. In the case of tailless aerial vehicles, the absence of vertical and horizontal stabilizers creates an important issue thus, making an accurate stability analysis of paramount importance to evaluate the flight behavior and controllability of the aerial vehicle.

The analysis can be broken down into the inherent response of the aerial vehicle to external disruptions of its equilibrium position, and its behavior when a control surface is deflected. In general, the two necessary conditions for a successful mission are the ability to achieve equilibrium flight and the capability to perform maneuvers for a wide range of flight velocities and altitudes. In order to achieve these conditions, the aerial vehicle must be equipped with aerodynamic and propulsive controls surfaces such as elevators, ailerons, rudders etc. [10]. Elevators are responsible for the longitudinal control, while rudders and ailerons are used for directional and lateral control, respectively. The control surfaces produce a restoring moment which allows the aerial vehicle to return in its equilibrium position. The fundamental parameters that determine the longitudinal stability are presented (Equation 2), with the condition for stable flight of the pitching moment coefficient at the center of gravity $C_{m_{cg}}$ being zero.

$$C_{m_{cg}} = C_{m_0} + C_{m_\alpha} \alpha + C_{m_{\delta e}} \delta e = 0$$

(2)

To meet the condition $C_{m_{cg}} = 0$ (trim condition) a deflection of the elevator is necessary, namely $\delta_{trim}$, as shown in Equation 3, with the trim angle of attack, $\alpha_{trim}$ being influenced also by the change of the aerial vehicle’s lift coefficient due to elevator deflection. In both equations, the zero angle of attack pitching moment coefficient ($C_{m_0}$), the pitching moment due to angle of attack derivative ($C_{m_\alpha}$)
and the pitching moment due to elevon deflection derivative \( (C_{m\delta e}) \) are used. Similar analyses are made for lateral and directional stability.

\[
\delta_{\text{trim}} = -\frac{C_{m\alpha} + C_{m\alpha a_{\text{trim}}}}{C_{m\delta e}}
\]

(3)

To perform the stability analyses, it is necessary to calculate several parameters of the aerial vehicle. The unconventional layout of the MPU RX-4 requires extra attention to the assumptions and simplifications usually done in traditional methods for stability evaluation. More specifically, the lack of empennage requires the position of the elevators on the main wing. This is achieved with the use of elevon control surfaces (Figure 3a), that perform both as ailerons and elevators, thus eliminating the excess weight that would be required for servo actuators and control surface hinges. Their deflection angle range is divided between the two control surface functions (40% for elevator, 60% for aileron), and can operate simultaneously.

![Figure 3](image.png)

**Figure 3.** (a) Representation of the elevon control surface (b) Trimming diagram of the MPU RX-4.

The methodology for the stability analysis followed is based on the work of Roskam [11], with dedicated modifications for lightweight tailless UAVs. Roskam provides robust equations that incorporate the influence of each individual component of the aerial vehicle (wing, fuselage, horizontal tail, control surfaces, etc.) to its overall performance, with high accuracy. In the case of the MPU RX-4 several adjustments of the equations are required, to take into account its unconventional layout. Specifically, the outer section of the main wing, from the control surface inner position to the wingtip, is regarded as the horizontal stabilizer [12]. Moreover, the influence of the triple-fin landing system is examined thoroughly, as it contributes significantly to the UAV’s directional stability. It is modeled as a combination of twin vertical stabilizers in the rear of the aerial vehicle and a conventional single one in the front. The desired result of the analysis is to provide the information necessary for the calculation of the trim condition (Figure 3b). Furthermore, the total behavior of the UAV is estimated, for its stability and control derivatives are computed. These derivatives are used to correlate the change in the forces and moments acting on the vehicle, with key aerodynamic and flight characteristics. Indicatively their influence on lift force, pitching and yawing moments is shown (Equations 4-6).

\[
L = \frac{1}{2} \rho V^2 S \left( C_{l\alpha} \alpha + C_{l\delta} \frac{\bar{\alpha}}{2V} q + C_{l\delta e} \delta_e \right)
\]

(4)

\[
m = \frac{1}{2} \rho V^2 S \bar{\alpha} \left( C_{m\alpha} \alpha + C_{m\delta} \frac{\bar{\alpha}}{2V} q + C_{m\delta e} \delta_e \right)
\]

(5)

\[
l = \frac{1}{2} \rho V^2 S b \left( C_{l\alpha} \beta + C_{l\beta} \frac{b}{2V} p + C_{l\epsilon} \frac{b}{2V} r + C_{l\delta e} \delta_e \right)
\]

(6)

In these equations, \( \rho \) refers to the air density, while \( V, S, b \) and \( \bar{\alpha} \) are the UAV’s flight velocity, reference area, wingspan and mean aerodynamic chord, respectively. Additionally, the \( C_{ij} \) derivatives refer to the
change of lift ($L$), pitching moment ($m$) and yawing moment ($l$) ($i$ index), as a result of a change in the angle of attack ($\alpha$), sideslip angle ($\beta$), pitch rate ($q$), yaw rate ($r$) and elevator deflection ($\delta_e$) ($j$ index).

The calculated values of the stability and control derivatives for the MPU RX-4 are then compared against available data from literature, and other tailless UAV configurations. Additionally, several CFD computations are conducted for a range of control surface deflection and sideslip angles, thus definitively validating the computed derivatives.

3. Results and discussion

At the end of preliminary design, the UAV has several changes compared to the conceptual configuration. In Figure 4, the geometric characteristics of the MPU RX-4 are presented. The basic dimensions differ slightly from the conceptual design phase, with the most notable changes being the increase in height of the UAV due to the addition of the triple-fin landing system, and the sizing of the canard span.

![Figure 4](image1.png)

**Figure 4.** The MPU RX-4 at the end of the preliminary design phase.

From the CFD analyses, the lift and drag coefficients of the UAV are computed. In Figure 6a, where the lift coefficient is plotted as a function of the angle of attack (AoA), the linear evolution of the $C_L$ is disrupted at $12^\circ$ AoA with a sudden drop and then increases again until stall, at $18^\circ$. The same decrease in lift with an associate increase in drag, is also evident in the UAV’s drag polar (Figure 6b). Even though this is not the typical behavior of a conventional UAV, it can be attributed to the use of canards. More specifically, the total lift of the aerial vehicles is the sum of the lift produced by the main wing, and the canards. The latter are entering into their stalling region at $12^\circ$ AoA (Figure 5) and thus the lift component associated with them decreases dramatically. Since the lift contribution of the main wing is significantly larger, due to the airfoils used, as well as the reference area, the total lift increases in higher angles of attack, while the canards remain stalled. Finally, the aerial vehicle enters in stall at around $18^\circ$.

![Figure 5](image2.png)

**Figure 5.** Relative pressure contour on the UAV surface at $12^\circ$ AoA, with detail of canard stalling.
In Figures 6c and 6d the rolling and yawing moments are presented respectively, as a function of the sideslip angle $\beta$. From these and Figure 3b, it can be concluded that the UAV is statically stable in all principal axes, because the pitching, rolling and yawing moment stability derivatives (gradients of the figures) are $C_{m\alpha} < 0$, $C_{l\beta} < 0$ and $C_{n\beta} > 0$.

**Figure 6.** (a) Lift versus angle of attack, (b) drag polar, (c) rolling and (d) yawing moments versus sideslip angle of the MPU RX-4.

In Table 1, certain stability derivatives of the MPU RX-4, calculated at cruise conditions (velocity 65km/h and sea level flight), are presented. Its values are compared against those of two UAV with similar configurations (Figure 7), namely the small lightweight Zagi flying wing and the tactical blended-wing-body (BWB) DELAER RX-3 UAV [12]. As it is expected, the three UAVs have stability derivatives of the same order of magnitude, since their geometry and size are comparable, thus validating the methodology presented earlier, that is followed for their computation.

**Figure 7.** (a) The Zagi flying wing UAV and (b) the DELAER RX-3 BWB UAV [12].
Table 1. Comparison of selected stability derivatives of the MPU RX-4, Zagi and DELAER UAVs.

| Derivative (rad⁻¹) | MPU RX-4 | Zagi | DELAER RX-3 |
|---------------------|-----------|------|-------------|
| $C_{L_e}$           | 4.49      | 3.50 | 5.91        |
| $C_{m_e}$           | -0.38     | -0.57| -0.70       |
| $C_{m_{se}}$        | -0.28     | -0.32| -0.57       |
| $C_{y_{p}}$         | -0.196    | -0.074| -0.51      |
| $C_{l_{p}}$         | -0.088    | -0.028| -0.11      |

4. Conclusions

The present work focuses on the aerodynamic and stability characteristics of the MPU RX-4, a flying wing UAV with VTOL capabilities. During the preliminary design phase, several optimizing alterations are made to the external geometry and the sizing of key parts is finalized (i.e. canards, triple-fin landing system). Additionally, a detailed stability analysis is performed, using semi-empirical correlations, modified for lightweight flying wing UAVs. The results are complemented by extensive CFD computations, that validate the aforementioned analytical methodology and estimate the UAV’s aerodynamic performance. The necessary trim angle of the elevon control face is calculated, for stable flight during cruise. Finally, the stability and control derivatives of the UAV are estimated and compared against those of similar tailless UAVs.

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