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CONTROL DERIVATIVE ESTIMATION OF NONCONVENTIONAL UAV DESIGN

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Abstract: *The fast-moving technologies have enabled many new applications of Unmanned Aerial Vehicles for military and commercial purposes. This technology improvement has opened an incredible number of new opportunities for UAVs to be used for a variety of societal challenges. Despite the considerable investments and operational success, the nonconventional UAV design has not been well documented in the literature. In this paper, the nonconventional X-tail design will be evaluated. Control derivative estimation has been done by different methods.*

Keywords: *UAV, CFD, derivative, flight control.*

1. INTRODUCTION

During the last decade, Unmanned Aerial Vehicle (UAV) technology has seen a shift from military use to civil and commercial applications [1-6]. This shift has opened an incredible number of new opportunities for UAVs to be used for a variety of societal challenges. Different platforms [7-9] are used for different aspects of an event [10], such as surveying, search and rescue, crop analysis, environmental monitoring, infrastructure assessment, etc. The main advantage of fixed-wing UAVs is greater efficiency, longer endurance, and better performance. The greater range and endurance offered by fixed-wing designs lead to complexities in flight planning and approval, operator training, and licensing requirements, especially in use cases where a larger area needs to be covered (beyond visual line-of-sight operations). The main disadvantage of the fixed-wing UAVs is the need for a runway. This disadvantage can be reduced by implementing a parachute and airbag that will require less space for landing and launch from a catapult [11] or powered launcher. Despite some of the mentioned disadvantages, fixed-wing UAVs have been widely implemented for military applications. In the last 10 years, the number of nonconventional UAVs has increased significantly. Despite the considerable investments and operational success of Unmanned Aerial Systems, the nonconventional UAV design has not been well documented in the literature. The well-known aerodynamic principles that are given in the literature [12-14] apply to UAV design. The main drawback is that the literature mentioned is primarily based on higher Reynolds numbers [15] that usually do not apply to UAVs. UAVs primarily operate at low Reynolds numbers and aerodynamic characteristics of airfoils at low Reynolds numbers are given in [16]. In the last few years combining vertical take-off and landing characteristics with fast-forward flight capabilities of fixed-wing UAVs is very popular [2-4, 7, 8]. By implementing vertical take-off and landing the UAVs can be easily operated in urban spaces.

In this paper, the nonconventional X-tail UAV design is analyzed and different methods have estimated control derivative. This UAV's tail configuration is very popular for the HERO family of loitering munitions [17]. According to the information in [17] the HERO series of high-precision loitering munition systems brings a unique design that enables maximum maneuverability with pinpoint strike accuracy and mission abort and reengage capability. This tail configuration has been used for the conceptual tail design of the loitering munition system Osica given in Figure 1. Osica is a fully autonomous UAS designed for attack missions. It is high-precision loitering munitions equipped with anti-tank warheads capable of destroying armored vehicles. UAVs' technical characteristics are given in Table 1. Osica is a project of the Military Technical Institute under development. The loitering munition systems [18] have reached high interest in the last few years.

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Figure 1. UAV Osica in the take-off phase

Table 1. Technical characteristics

MTOW [kg]	8
Operative speed [km/h]	100
Operative altitude [m]	500
Endurance [min]	≥30
Link Range [km]	20
Engine	Electric BLDC
Take-off	Pneumatic launcher
Warhead weight [kg]	1.5

2. X-TAIL DESIGN

The well-known tail configuration as is conventional, T-tail, H-tail, V-tail, and inverted V have been documented in the literature [19] and the basic design steps are:

- Select tail configuration.
- Select tail location.
- Select tail volume coefficient.
- Calculate the tail moment arm.
- Calculate the tail planform area.
- Select tail geometry.
- Select the tail airfoil section.
- Determine tail lift curve slope.
- Calculate the aerodynamic moment coefficient.
- Calculate the tail desired lift coefficient.
- Calculated tail angle of attack at cruise.
- Estimate downwash angle at the tail.
- Calculate tail incidence angle.
- Calculated necessary tail angle of attack at different UAV speeds.
- Estimate UAV stability characteristics.
- Optimize the tail configuration if necessary.

To estimate aerodynamic coefficients and stability characteristics different tools are available. The most popular tools for airfoil analysis at low Reynolds numbers are probably XFOIL [20] and XFLR5 [21]. Additional data about airfoil characteristics can be found in [22]. For the tail, selecting a symmetric airfoil with the minimum profile drag coefficient is usual. Analysis of symmetric NACA airfoil characteristics has been done by XFLR5 software. Tail airfoils characteristic at cruise speed have been estimated and are given in Figures 2 and 3. According to the presented data in Figures 2 and 3 and the calculated tail incidence angle of attack at different airspeeds, it is possible to find adequate airfoils. For the preliminary X-tail design, the initial airfoil that is analyzed in this paper is the NACA 0012.

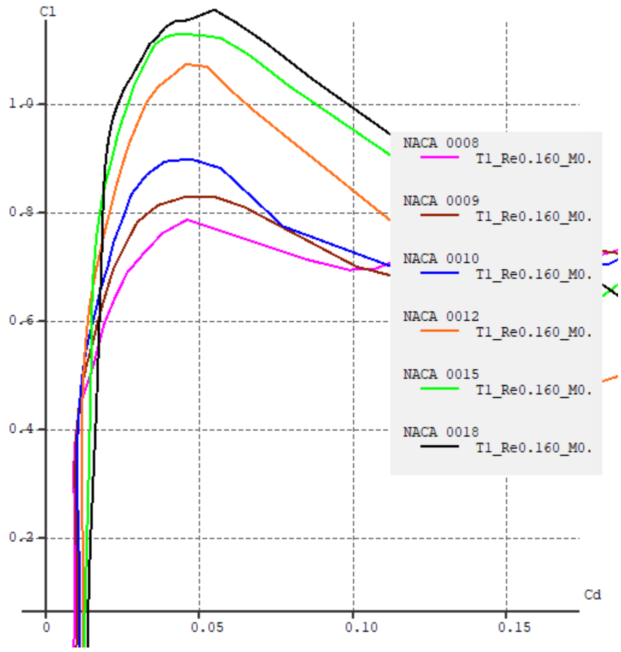

Figure 2. Airfoils polar

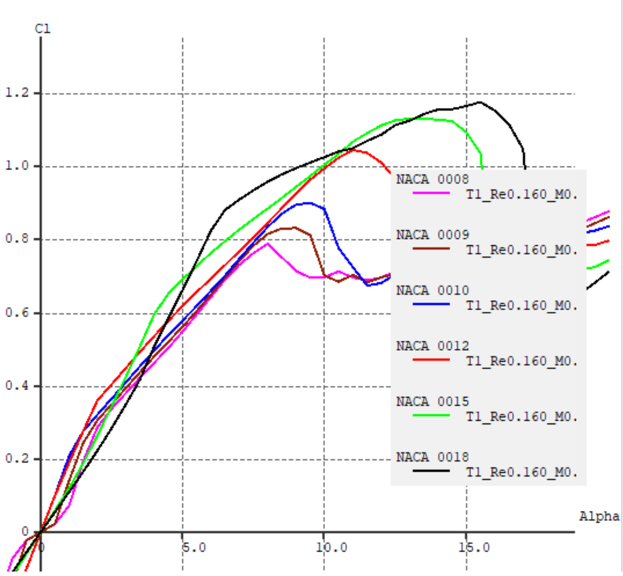

Figure 3. Airfoils coefficient of lift vs angle of attack

The procedure to define the X-tail area is defined in a few steps. First, the conventional empennage's vertical and horizontal tail areas are defined by a well-known tail volume coefficients method that can be found in textbooks [12]. In the next step, the data from [23, 24] have been used to estimate the equivalent X-tail area with the defined angle between the X-tail and the horizontal of 45 degrees.

3. CONTROL DERIVATIVE ESTIMATION

Equations for estimating stability and control derivatives are well known. These derivatives can be estimated by using empirical methods such are DATCOM [25] and ESDU [26], commonly available textbooks [11, 12, 27, 28], NACA reports, wind-tunnel testing [29-31], computational fluid dynamics (CFD) [32-33], estimated from flight data or combination of just mention methods. Each of these approaches has some advantages and some disadvantages concerning cost, time consumption, range of applicability, and computational time. In this paper, the control derivative has been estimated by empirical methods given in [34], by vortex lattice method (VSPAERO) implemented in Open Vehicle Sketch Pad (OpenVSP) [35], and by CFD analysis [36]. OpenVSP is an open-source parametric aircraft geometry tool originally developed by NASA. VSPAERO is a useful tool for aerodynamic and flight dynamic analysis that consist of the vortex lattice and panel method. Additional useful information about stability derivative estimation can be found in [37]. To speed up the calculating process the aircraft or UAV geometry must be simplified. Simplified preliminary UAV geometry for vortex lattice analysis is given in Figure 4 and detailed information about UAV geometry and aerodynamic data can be found in [38].

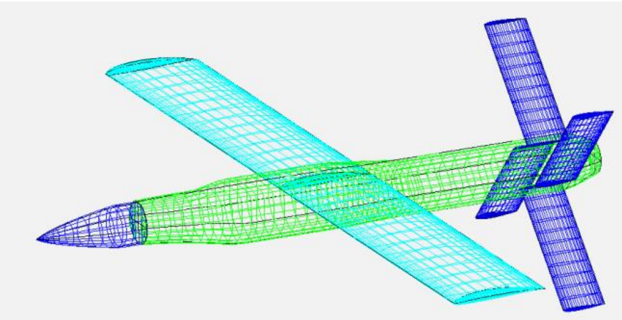

Figure 4. Simplified UAV geometry

It is important to mention that numerical methods OpenVSP and Ansys Fluent have been used indirectly to estimate the UAV control derivatives. First, it was calculated aerodynamic moment coefficient about the main axis at zero angle of attack, zero angle of sideslip, and zero deflection of the control surfaces. In the next steps, the aerodynamic moment coefficient was calculated at zero angle of attack, zero angle of sideslip, and deflection of control surfaces as it is given in Figure 5.

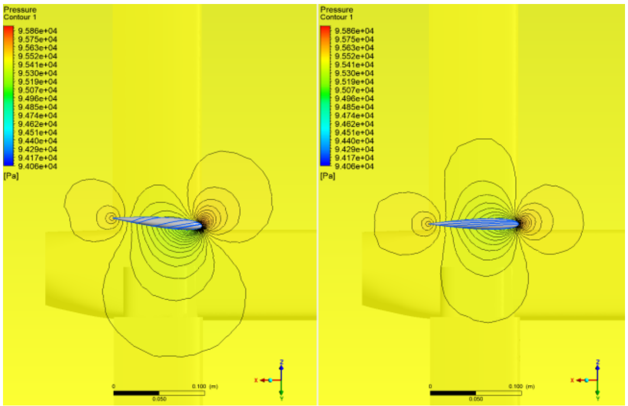

Figure 5. Control surface deflection

The control derivative about each axis has been estimated as the difference of moment coefficients divided by control angle deflection. CFD analysis was performed with unstructured tetrahedral mesh around the UAV. The resolution of a surface mesh is given in Figure 6. It was done in commercial ANSYS Fluent software by the finite volume methods. The Reynolds average Navier Stokes system of equations was solved for compressible flow using a pressure-based solver. The mesh used for this case have 8.6 million cells.

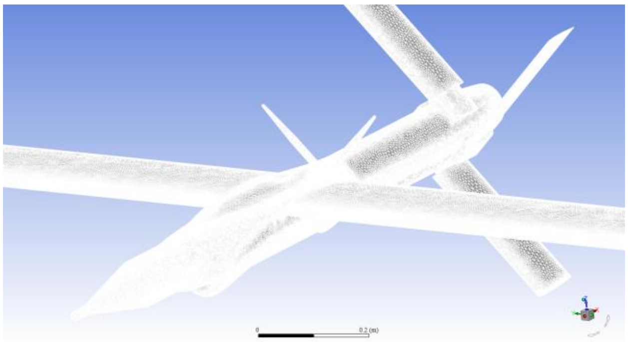

Figure 6. The resolution of a surface mesh on UAV

The Spalart-Allmars (S-A) turbulent model has been used with the second order approximation. The working fluid has been defined as ideal gas (air). The velocity inlet boundary conditions have been used for defining the velocity and direction of the free stream. The computations have been done until the convergence criteria have been achieved.

4. RESULTS AND DISCUSSION

According to the methods discussed above, in Table 2 the results for the UAV control derivative are presented. Those results have been calculated for standard atmospheric conditions at an altitude of 500 m.

Table 2. Calculated control derivatives

	Empirical methods [34]	**OpenVSP**	**Fluent**
$C_{m_{\delta_E}}$ [1/rad]	-1.841	-1.836	-2.172
$C_{n\delta_R}$ [1/rad]	-0.229	-0.212	-0.250
$C_{l\delta_a}$ [1/rad]	0.102	0.0829	0.0960

As it is shown in Table 2, the estimation of the pitching moment coefficient with elevator deflection angle deviates up to 15.5%. The empirical methods in general can be used for values of incidence and control deflection for which there is no separation of flow over the airfoil or control. Within these limitations, an accuracy of 15-20% is an acceptable value for preliminary design. Variation of the yawing moment coefficient with rudder deflection angle is up to 15.2%.

Variation of the rolling moment coefficient with the aileron deflection angle between Fluent and OpenVSP numerical methods is up to 13.6% and is acceptable for preliminary design. To estimate the rolling moment coefficient empirically slight coarse approximations have been used in the first iteration. It overestimates the rolling moment coefficient by almost 25%. This method is primarily developed for classical ailerons on the wings. To get a better estimation, a more precious approach has been used.

In the second iteration, the variation between empirical methods and Fluent was just 6.25%. In this case, the empirical methods overestimated numerical value but the difference in result is excellent.

5. CONCLUSION

Different methods have been used to estimate the control UAV derivatives of nonconventional X-tail UAV configurations.

Different methods have reached a good agreement. The results in this paper suggested that for nonconventional tail configuration, the numerical methods should probably give the best results for control derivative estimation.

To define the best method for estimating control derivative wind tunnel tests should be done or system identification based on flight test data.

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