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EXPERIMENTAL AND THEORETICAL ASSESSMENT OF AERODYNAMIC AND STABILITY DERIVATIVES OF A SUBSCALE AIRCRAFT

Igor Mayer Soares
Leonardo Murilo Nepomuceno
Roberto Gil Annes da Silva
Technological Institute of Aeronautics (ITA), São José dos Campos, São Paulo, Brazil
imayersoares@gmail.com
leaobravo@gmail.com
gil@ita.br

Abstract. *This work aims to determine aerodynamic and stability derivatives of a subscale aircraft, applying Vortex Lattice Method and validating them with gathering data from wind tunnel tests conducted with a 3D printed aircraft in subscale of 1/2 of the real aeromodel. First, the geometry of the aircraft was designed with the software package named AVL, that employs a vortex lattice model for the lifting surfaces, together with a slender-body model for fuselages and nacelles. The wind tunnel model was printed in ABS material. Finally, a flight simulator based on 6DoF equations were built to validate the aerodynamic model and verify the stability of aircraft.*

Keywords: *Subscale Aircraft, 3D printed, Aerodynamic Model, System Identification, Wind Tunnel Test*

1. INTRODUCTION

The subscale methodology (Monteiro (2017)), for evaluation of dynamic behavior of flight vehicles and development of new concept of aircraft, associated with the system parameters identification methodology (Jategaonkar (2015)) has grown in recent years with the aim of increased the knowledge during the conceptual project by reducing the cost of flight tests on full scale aircraft, where eighty percent of the total cost of developing a new flight vehicle is allocated(Rueda (2015)). The advent of 3D-printing has reduced prototypes manufacturing time and 4MV method has reduced the time of flight testing operations time. System parameters identification from flight tests based on 4MV method requires an aerodynamic model as trustworthy as possible to reduce errors during the cost function process of minimization (Nepomuceno (2017)).To develop this model, the aerodynamics, stability and control derivatives of a flight vehicle must be determined. This work focuses on "Model" (Third M of the 4MV method) through computational analysis and wind tunnel tests.

2. BAE HAWK AIRCRAFT

The BAE Systems Hawk (Fig. 1) is a British single-engine, jet-powered advanced trainer aircraft, and its first flight took place in Dunsfold, Surrey, in 1974. This work was based on a 3D-printed subscale (Fig. 2) of the BAE Hawk D006 aeromodel (Fig. 3), which will be used during flight tests campaign.

Figure 1. BAE Hawk T.1

Figure 2. BAE Hawk printed

Figure 3. BAE Hawk model

3. METHODOLOGY

3.1 Aerodynamic Model

The aim of aircraft system identification is to identify aerodynamic, stability and control derivatives of the flight vehicle (Jategaonkar (2015)). The aerodynamic model includes all forces and moments acting on aircraft (Lift, Drag, Side Force, Pitch, Yaw and Roll). For longitudinal and lateral-directional modes, the coefficients of forces and moments are described by Eq.1 to Eq.6.

$$C_L = C_{L_0} + C_{L_\alpha}\alpha + C_{L_q}\frac{qc}{2V} + C_{L_{i_h}} i_h \tag{1}$$

$$C_D = C_{D_0} + \frac{1}{\pi A e} C_L^2 \tag{2}$$

$$C_Y = C_{Y_\beta}\beta + C_{Y_p}\frac{pb}{2V} + C_{Y_r}\frac{rb}{2V} + C_{Y_{\delta_a}}\delta_a + C_{Y_{\delta_r}}\delta_r \tag{3}$$

$$C_M = C_{M_0} + C_{M_\alpha}\alpha + C_{M_q}\frac{qc}{2V} + C_{M_{i_h}} i_h \tag{4}$$

$$C_N = C_{N_\beta}\beta + C_{N_p}\frac{pb}{2V} + C_{N_r}\frac{rb}{2V} + C_{N_{\delta_a}}\delta_a + C_{N_{\delta_r}}\delta_r \tag{5}$$

$$C_l = C_{l_\beta}\beta + C_{l_p}\frac{pb}{2V} + C_{l_r}\frac{rb}{2V} + C_{l_{\delta_a}}\delta_a + C_{l_{\delta_r}}\delta_r \tag{6}$$

3.2 Computational Analysis

With the geometry and airfoil characteristics of wing and empennage of BAE Hawk Model, the aerodynamics, stability and control derivatives were estimated using the software Athena Vortex Lattice. The chordwise and the spanwise number of panels is shown in Tab. 1.

Table 1. Number of panels in chord and spanwise

Surface	Airfoil	**Chordwise**	**Spanwise**
Wing	RG14-a	15	40
Horizontal Tail	NACA0012	10	10
Vertical Tail	NACA0012	10	10

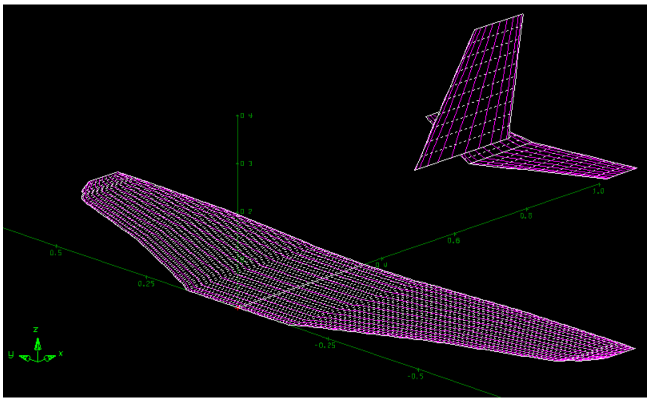

Figure 4. Model of BAe Hawk in AVL

3.3 Wind tunnel Model

The scale of the 3D printed aircraft for the model aircraft is 1/2. The printing material was ABS and total manufacturing time had been of 24 hours, which show that this advent is so quick to test new configurations compared to conventional methods (machining and rolling in composite material). After final assembly, the surface underwent to a surface finishing process to correct the imperfections from the printing process and guarantee the aerodynamic properties (Padilha (2017)).

This model aims to obtain static derivatives: $C_{L\alpha=0}$, $C_{L\alpha}$, $C_{M\alpha=0}$, $C_{M\alpha}$, $C_{D\alpha=0}$, $C_{D\alpha}$, $C_{Y\beta}$, $C_{N\beta}$, $C_{l\beta}$.

3.4 Simulator

A simulator was written in MATLAB software (Stevens and Lewis (2003)), to evaluate:

- The equilibrium conditions, based on a aeromodel cruise flight, the equilibrium conditions for longitudinal and lateral-directional modes are shown in Tab.2;

Table 2. Flight Conditions

Flight Condition	Value	Unit	
Velocity	30	m/s	
Altitude	647	m	Longitudinal
Density	1.225	kg/m^3	
Take-off Weight	3	kg	
Coordinate curve radius	200	m	Lateral-Directional

- System stability, through eigenvalues analysis (Etkin (1959));
  - Short Period: Variations in θ and α ;
  - Phugoid: Variations in θ and V;
  - Rolling: Variation in p;
  - Dutch Roll: Variations in ϕ and β;
  - Spiral: Dominant variation in ϕ.
- The dynamic response of inputs in elevator, aileron and rudder. These inputs shall simulate the inputs to be applied in flight tests.

4. RESULTS

4.1 Aerodynamic Model

The results of Vortex Lattice Method are shown in tha Tab.3.

	Vortex Lattice Method								
	$\alpha = 0$	α	β	p	q	r	δ_{i_h}	δ_a	δ_r
C_L	0.320	4.636	-	-	8.886	-	0.012	-	-
C_D	0.033	-	-	-	-	-	-	-	
C_Y	-	-	-0.279	0.008	-	0.235	-	2.94×10^{-4}	2×10^{-4}
C_M	-0.157	-0.873	-	-	-8.648	-	-0.026	-	-
C_N	-	-	0.094	-0.011	-	-0.092	-	2.17×10^{-4}	8.3×10^{-5}
C_l	-	-	-0.030	-0.390	-	0.062	-	3.506×10^{-3}	1.9×10^{-5}

Table 3. VLM Analysis

4.2 Wind tunnel Model

To reach the same Reynolds number table 4 shows the respective velocities for sea level air density ($1.225 kg/m^3$). The lowest speed at which the wind tunnel was able to obtain reliable results for longitudinal mode was 16.5 m/s and for the lateral-direction was 20 m/s.

Thus, the test plan comprised speeds from 16.5 m/s to 45m/s. Unfortunately, it was not possible to reach stall speed for lateral-directional mode

Velocity	Flight Tests (m/s)	Wind Tunnel Tests (m/s)	Reynolds Number
Stall	11	16.5	200000
Cruise	16	24	245000
Max	30	45	545000

Table 4. Velocities to reach the same Reynolds Number

Figures 5 to 10 shows results of wind tunnel tests. Table 5 shows coefficients identified by tests.

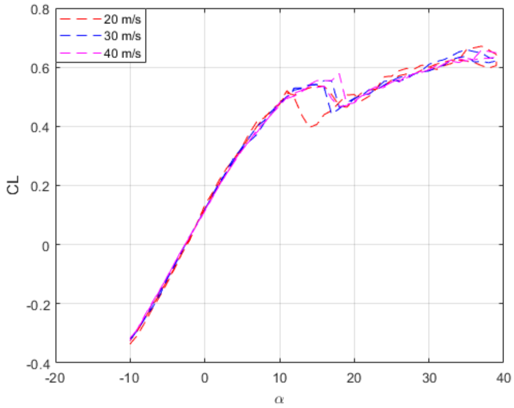

Figure 5. $C_{L\alpha}$

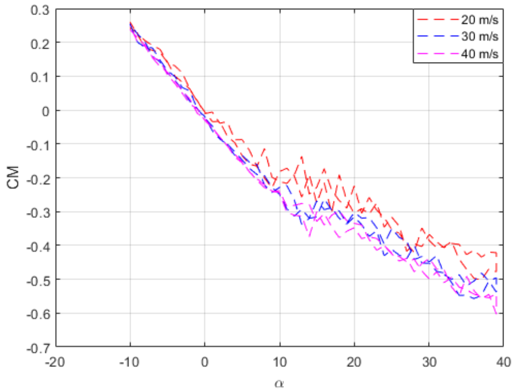

Figure 6. $C_{M\alpha}$

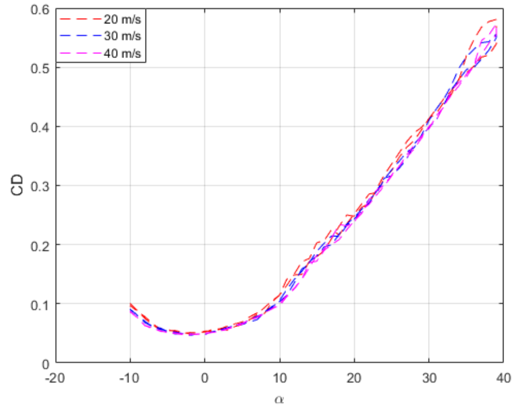

Figure 7. $C_{D\alpha}$

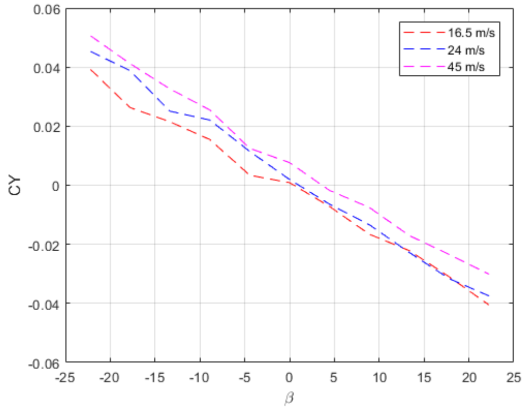

Figure 8. $C_{Y\beta}$

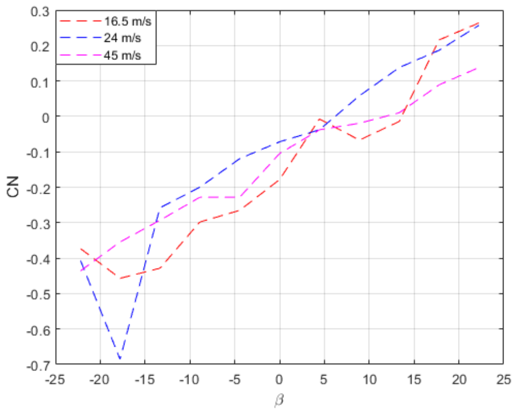

Figure 9. $C_{N\beta}$

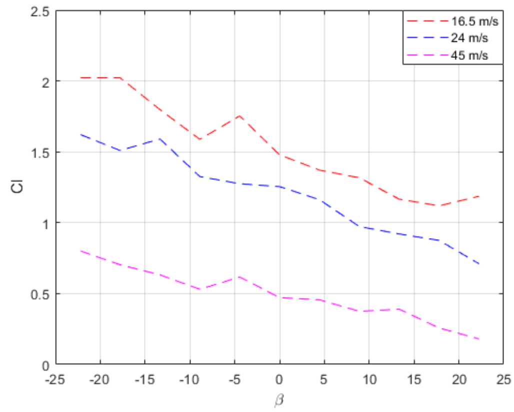

Figure 10. $C_{l\beta}$

Velocity (m/s)	20	30	40	Mean
$C_{L\alpha}$	3.94	3.82	3.82	3.86
$C_{M\alpha}$	-1.27	-1.88	-1.55	-1.56
$C_{D\alpha=0}$	0.052	0.048	0.05	0.05
Velocity (m/s)	16.5	24	45	
$C_{Y\beta}$	-0.2	-0.22	-0.36	-0.26
$C_{N\beta}$	0.06	0.047	0.053	0.053
$C_{l\beta}$	-0.56	-0.48	-0.49	-0.051

Table 5. Static Derivatives

4.3 Aerodynamic model

Figures 11 and 12 shows the equilibrium flight path for both modes. This result compare VLM and Wind Tunnel coefficients. It is possible to see that for static coefficients the prediction of VLM and the values obtained by wind tunnel test are closer.

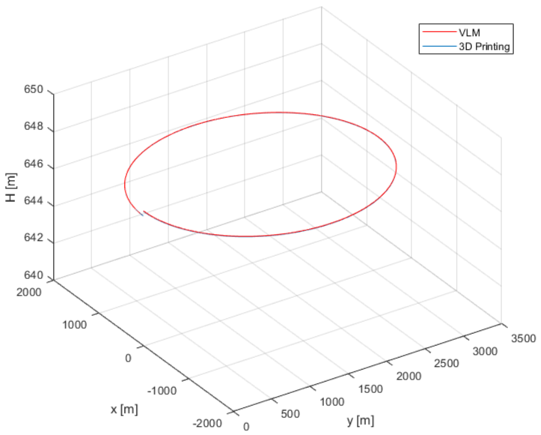

Figure 11. Lateral-Directional Path

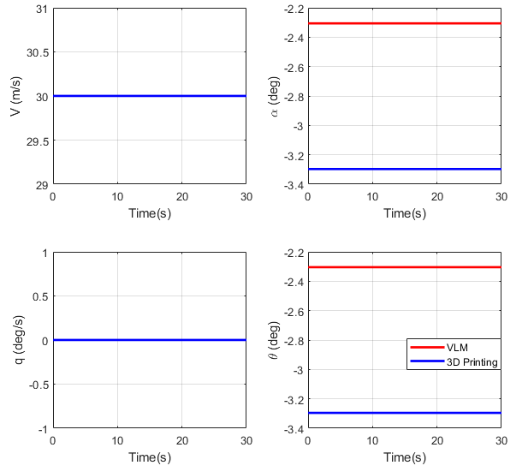

Figure 12. Longitudinal States

For a doublet input in the elevator the dynamic behavior is n show in Fig. 13.

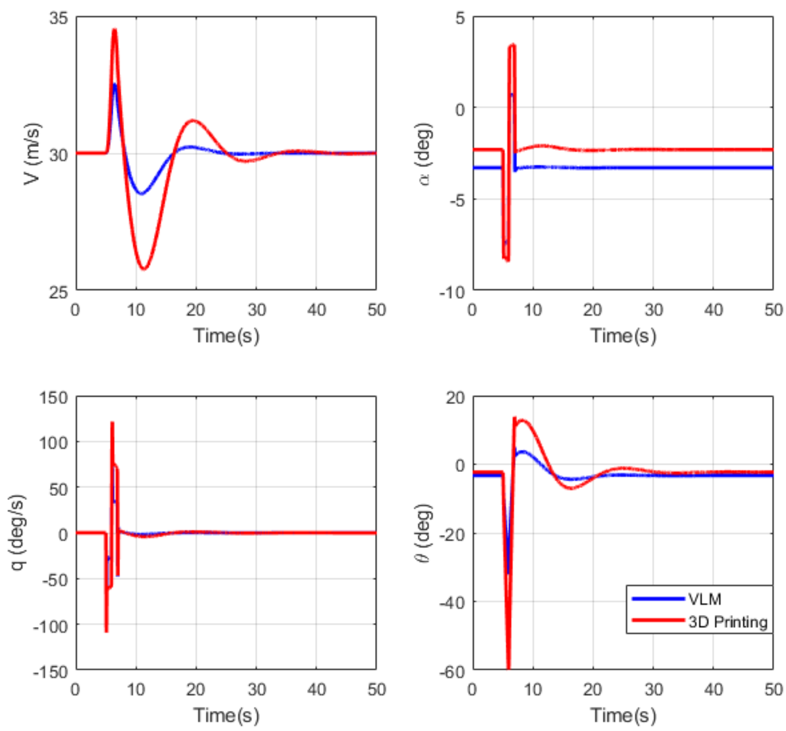

Figure 13. Behavior of longitudinal states at an elevator input - Surface: Elevator; Type: Doublet; Duration: 2 seconds; Amplitude: 3 degrees

4.4 VLM and Wind Tunnel Tests comparsion

Table 6 compare results obtained by VLM model and Wind Tunnel Tests.

Coefficients	VLM	Wind Tunnel	Difference (%)
$C_{L\alpha}$	4.636	3.86	-17
$C_{M\alpha}$	-0.873	-1.56	80
$C_{D\alpha=0}$	0.033	0.05	52
$C_{Y\beta}$	-0.279	-0.26	-7
$C_{N\beta}$	0.094	0.053	-44
$C_{l\beta}$	-0.030	-0.51	70

Table 6. Static Derivatives

4.5 Conclusion

This paper presents the first part of the development of a study that aims to identify aircraft dynamics at high angles of attack, where nonlinearities of aerodynamic coefficients are observed, and to obtain a reliable mathematical model that reproduces aircraft behavior throughout the process. , using low-cost tools, either computational (mid-fidelity software) or manufacturing (3D printing).

The fidelity of wind tunnel data can be observed in the results. The scrolling data (Fig. 10) showed great deviation for different speeds, behavior to be investigated with new campaigns; however, the slope of the curve was approximate.

Comparing the data from the VLM and wind tunnel analysis, it is possible to observe the contribution of the fuselage in:

- Reducing of lift;
- Increasing of drag;
- Reducing directional stability (By general, fuselage has a negative contribution for this mode (Etkin (1959));

Despite the large percentage difference between some derivatives, the simulated VLM model can reproduce responses very close to the wind tunnel data. A CFD model will be developed to identify the effects of fuselage interference on lifting surfaces and validate the VLM results.

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