STABILITY AND CONTROL OF AN UNMANNED AERIAL VEHICLE FOR AERIAL PHOTOGRAPHY USING ANALYTICAL AND NUMERICAL METHODS

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Abstract. *This current work aims at analyzing the stability and control of a short range unmanned aerial vehicle (UAV) with an imaging system. The vortex lattice method and the lifting line theory will be applied in order to estimate aerodynamic characteristics of the airplane. Data in trimmed flight will be obtained by means of simulations using the vortex lattice method; and the dynamic model of the airplane will be built based on results from these simulations.*

Keywords: *stability, control, UAV*

1. NOMENCLATURE

C_l	rolling moment coefficient	ϕ	airplane bank angle
C_m	pitching moment coefficient	θ	pitch angle
C_n	yawing moment coefficient	ω	undamped natural frequency
V	velocity	ζ	damping ratio
x_{CG}	longtudinal position of CG	**Subscripts**	
Greek Symbols		a	aileron
Δ	increment of a parameter	e	elevator
α	angle of attack	r	rudder
β	angle of sideslip	**Superscripts**	
δ	control surface deflection angle	.	time derivative

2. INTRODUCTION

UAV's (Unmanned Aerial Vehicles) are unmanned aircrafts controlled at a distance or by autonomous control systems. Such aircrafts have several applications: they can be used to carry conventional payloads; as different sensors; to work as aerial target or to carry lethal loads, in this case they are used for military purposes. The market and field of activity of UAV's have been increasing lately, once unmanned aircrafts manage to perform different tasks at lower costs, with more safety and, in many cases, more effectiveness. It is estimated that the world market of UAV's may reach $13,6 billion in 2014.

The concept of unmanned aerial vehicles appeared between 1914 and 1918 in the military environment due to the advent of aircrafts that carried lethal loads and worked as remote bombs. Over the years they were used for different functions, including civil applications such as agriculture, meteorology, reconnaissance, surveillance and imaging (Austin, 2010).

UAV's for aerial photography are already used. Generally, such aircrafts use the combination of high-resolution cameras with video cameras in order to provide images and videos of areas of interest.

The guarantee of enough aerodynamic stability is essential in a project of an aircraft with an imaging system. This situation is required, so that casual disturbances related to the course of the aircraft, such as turbulence or wind gusts, do not bring about deviations that are prejudicial to data acquisition.

This current work aims at developing a study of aerodynamic stability and control of a short range UAV with gyrostabilized imaging system. In order to carry out the work, numeric simulations will be executed by means of the vortex lattice method and the lifting line theory to estimate aerodynamic characteristics of the aircraft.

3. METHODOLOGY

The selection of the wing airfoil took into account requirements of range and endurance of the airplane. The airfoil should have a high C_L/C_D ratio, minimizing the power required and extending the range and autonomy of the airplane, in addition the airfoil must have low pitching moment, reducing the size of horizontal tail and total drag of the aircraft. In order to choose the wing airfoil three typical airfoils for low speed were analyzed: Clark-Y, Eppler 374 and Eppler 423 (Fig. 1).

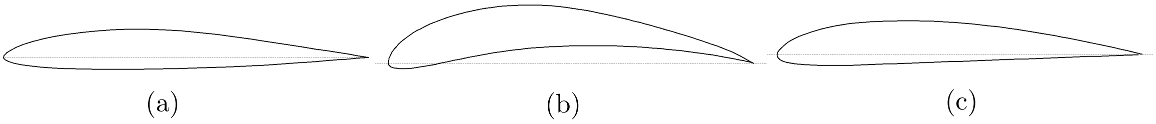
(a) (b) (c)

Figure 1. (a) Eppler 374; (b) Eppler 423; (c) Clark-Y.

The position of the CG is then chosen so that it meets the required stability. Rosa (2006) suggests that the static margin should be between 5 and 20%. However, is desirable that the CG is positioned in the same position of the wing aerodynamic center (approximately quarter-chord). Because of the ease in molding, therefore, the pitching moment of the wing at that point is constant.

The GC was placed in the wing quarter-chord resulting in a static margin of 24%. The value is slightly above the recommended, however the aircraft must have enough stability to capture images with quality. Additionally, smaller airplanes tend to suffer more with turbulence, requiring more stability.

The initial sizing of the tail was made according to the tail volume coefficient (Raymer, 1992). The principle of this methodology is the consideration that the primary function of the tail is to counter the moment produced by the wing, and thus the tail size is closely related to the wing size.

An airplane model is built for simulations performed by the vortex lattice method and the lifting line theory (Fig. 2). The lift and drag coefficients as a function of angle of attack are extracted out of these simulations executed on XFLR5 software.

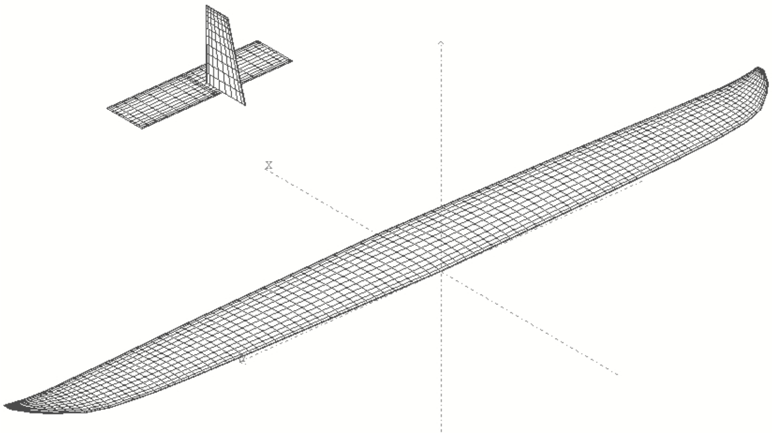

Figure 2. Airplane model.

Main stability characteristics, such as stability derivatives and static margin, are extracted from AVL software via simulation using vortex lattice method. For the resolution of the dynamic model of the aircraft, Eq. (1) and Eq. (2) (Bryan, 1911) were applied. The dynamic equations are solved using a MATLAB code proposed by Ly (1997) with modifications which uses the geometric characteristics of the aircraft and the stability derivatives to construct the dynamic model.

$$\begin{bmatrix} \Delta\dot{V} \\ \Delta\dot{\alpha} \\ \Delta\dot{q} \\ \Delta\dot{\theta} \end{bmatrix} = F_1 \begin{bmatrix} \Delta V \\ \Delta\alpha \\ \Delta q \\ \Delta\theta \end{bmatrix} + G_1 \begin{bmatrix} \delta_e \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} \Delta\dot{\beta} \\ \Delta\dot{p} \\ \Delta\dot{r} \\ \Delta\dot{\phi} \end{bmatrix} = F_2 \begin{bmatrix} \Delta\beta \\ \Delta p \\ \Delta r \\ \Delta\phi \end{bmatrix} + G_2 \begin{bmatrix} \delta_a \\ \delta_r \end{bmatrix} \tag{2}$$

The matrices F_n and G_n in equations above contain parameters of the trimmed flight condition.

4. RESULTS

The software XFLR5 was used to calculate the position of the neutral point using the vortex lattice method. Curves of C_m versus α were plotted for the C_m calculated in relation to different points of the aircraft. The location where $dC_m/d\alpha$ is zero marks the position of the neutral point (Fig. 3). The position found for the neutral point were x = 0.147 m, or 58.5% of the mean aerodynamic chord.

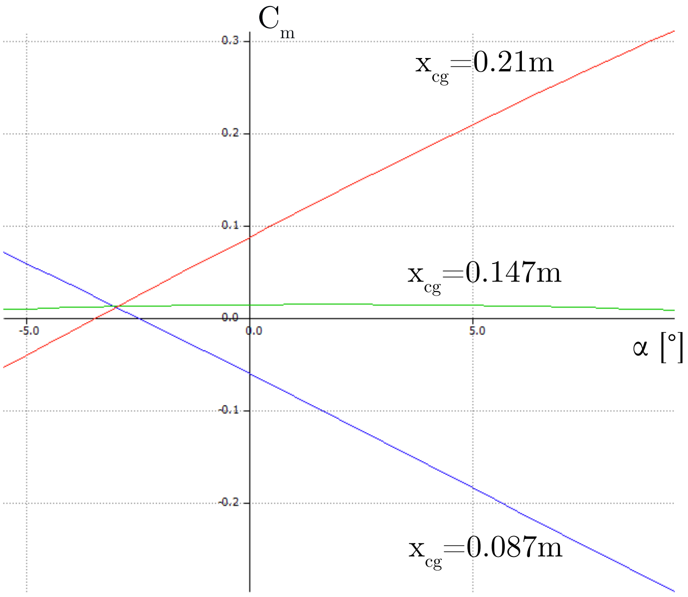

Figure 3. C_m versus α.

The derivative $dC_m/d\alpha$ = -1.497, then the UAV is statically stable. This value of $dC_m/d\alpha$ is typical for aircrafts with high stability, like cargo and transport airplanes (Raymer, 1992).

The derivatives used in the MATLAB program were obtained via the software AVL, considering the speed of 15 m / s with full load of 5 kg in straight level flight. These conditions result in an angle of attack of α = 0.51°, a C_L of 0.3437 and a C_D of 0.015. The moments of inertia of the aircraft were calculated using a three-dimensional model designed in Solidworks software.

The solution of the equations leads in the poles shown in Fig. 4. in which the poles with negative real part are convergent and poles with positive real part are divergent poles.

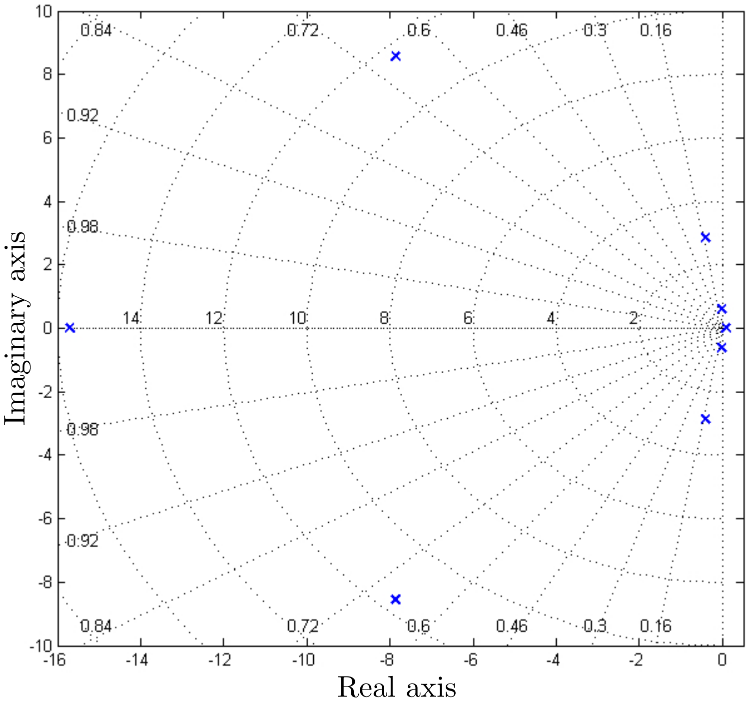

Figure 4. Airplane model.

The poles represented in Fig. 4 show that only the spiral mode has a positive real part, which means that this is the only mode that diverges. However, it will be shown that the divergence of the spiral mode is very slow, taking several seconds to be noted, and that corrections can easily be made.

Figure 5 shows the dynamic behavior of the aircraft in response to elevator and rudder pulse inputs, respectively.

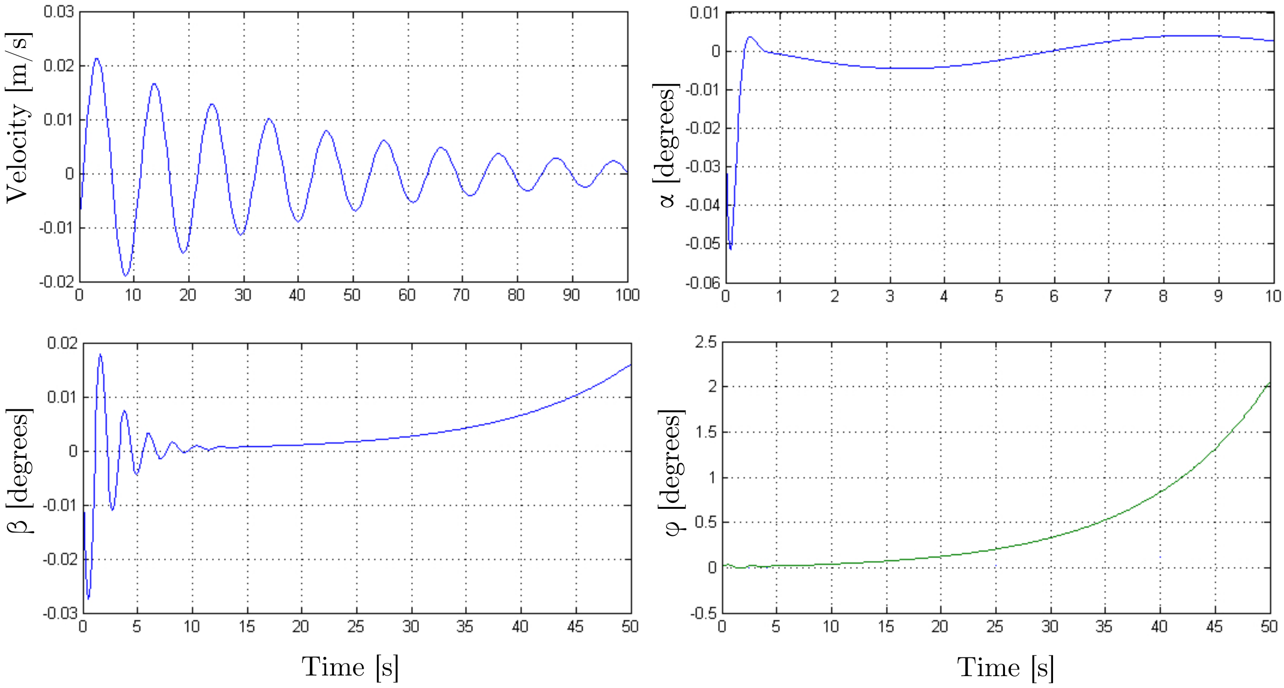

Figure 5. Airplane model.

Based on Fig. 5, it is noticeable that the low damping of the fugoid mode. The damping of this mode is directly related to the aircraft's drag in the equilibrium condition. As this value is usually low, it tends to have small damping. The longitudinal response of the aircraft shows that the motion is dominated by short period mode during the first few seconds. However, this mode is highly damped and its effects become negligible after 1s.

Regardig lateral-directiona it can be seen that the response of the aircraft is dominated by the dutch roll mode in the first few seconds, though, as the spiral mode develops, it diverges. Despite the divergence of motion, one can see that after 50 s the roll angle has a value lower than two degrees, which ensures that it is possible to make corrections in order to avoid the divergence of motion. Furthermore, MIL-F-8785C considers acceptable slow divergences in spiral mode.

Simulations results shows that the derivatives $dC_m/d\alpha$ and $dC_l/d\beta$ are both negative, also the derivative $dC_n/d\beta$ is positive ensuring static stability according to Perkins and Hage (1949). The solutions of the dynamic equations lead to five rigid body vibration modes for the airplane of which the modes fugoid, short period and dutch roll are compared with the military specification MIL-F-8785C as shown in Tab. 1.

Table 1. Comparison of the vibration modes with the specification MIL-F-8785C.

Vibration mode		MIL-F-8785C	Present work UAV
Short period	natural frequency	$\omega \geq$ 1,8 rad/s	12,51 rad/s
	damping ratio	0,3 < ζ <2,0	0,692
Dutch roll	natural frequency	$\omega \geq$ 0,4 rad/s	9,67 rad/s
	damping ratio	$\zeta \geq$ 0,08	0,141
Fugoid	damping ratio	$\zeta \geq$ 0,04	0,0667

The vibration modes of the UAV are in conformity with the specification.

5. CONCLUSION

The airfoils Eppler 423, Eppler 374 and Clark-Y were compared. Clark-Y had the best performance and meets the objective of this project from the point of view of both stability and control and aerodynamics. During the work, numerical simulations were performed using the XFOIL software to predict the behavior of airfoils used in the aircraft and the results were compared to experimental data in literature. The wing and the tail were analyzed using the vortex lattice method and the lifting line theory.

The tails has shown satisfactory performance in all simulations, being able to stabilize the aircraft and are in conformity with the specification.

Regarding stability, the stabilizing surfaces were scaled, and the aircraft's stability was statically and dynamically analyzed. In static analysis, the static margin and the $dC_m/d\alpha$ derivative confirmed the static stability of the aircraft.

With regards to dynamic stability, the vibration modes are presented according to MIL-F-8785C. The spiral mode diverged slowly, allowing interventions in motion, thus the divergence will not bring about restraints to the aircraft's performance. Analyses show that the aircraft may have good dynamic behavior and can be controlled manually.

6. REFERENCES

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