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# MODELING OF FIXED WING UAV PLATFORM USING COMPUTATIONAL TOOLS

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**Abstract.** To develop a robust and/or adaptive control system for an UAV, a good mathematical model based on aerodynamic analysis is required. The software modeling and identification results for a small unmanned aerial vehicle (UAV) are presented in this article. Stability pre-analysis and mass distribution of the model are performed based on XFLR5. The numerical values of the derivatives and aerodynamic coefficients are calculated through the AVL software using the geometric parameters of the airplane. The identified geometrical and aerodynamical parameters of the airplane are used in a mathematical model and then the model is simulated in a Matlab environment. The results of the simulated airplane model are presented and analyzed to show that the mathematical model behaves as expected. Graphical results showing the simulated airplane behavior to different input commands are presented.

**Keywords:** Modeling, XFLR5, AVL, Fixed-wing, UAV

## 1. INTRODUCTION

Unmanned aerial vehicles, known as UAVs, had its origin mainly in military applications. Despite this, its use has expanded to several areas, such as commercial, scientific, agricultural, surveillance, aerial photography, recreational, etc. Additionally, a variety of sizes and geometrical configurations of the aircraft, or the aerial platforms, are available. In general, small UAVs are designed to fly at low altitude (usually below 1000 meters) since it is very common that their mission involves, for example, a close observation of objects on the ground. This low-altitude flight contributes to situations in which the aircraft may fall from its flight. In this sense, a good modeling based on the aerodynamic geometry and aerodynamic coefficients of the aircraft is essential to obtain a robust and precise control system that reduces the chances of failure in the executed tasks.

Here, a procedure using a numerical software to identify aerodynamic coefficients and their use together with geometric parameters to build a non-linear model of an airplane is presented. Du (2011) presents a similar methodology to develop flight control system for small aircrafts with great results. Currently, there are several free and commercial computer softwares that allow the designer to develop, analyze and simulate the aircraft. Examples of these programs include: AVL, DFDC, JavaProp, JavaFoil, XFoil, Qprop, XFLR5, Datcom, Matlab/Simulink, among others.

In this work, we used the XFLR5 and AVL programs for modeling and analysis, followed by Matlab/Simulink for simulation.

### 1.1 Problem statement

The objective of this work is to obtain a mathematical model of aircraft using the softwares XFLR5, AVL and Matlab/Simulink. The methodology here presented allows the designer who does not have in-depth knowledge of aeronautical concepts to obtain a mathematical model for control system designs and to analyze the flight dynamics.

Since obtaining mathematical models direct from flight mission using instrumented aircraft is difficult, this work contributes to obtaining a good mathematical model following simple steps. Another advantage of this procedure, compared with the flight mission, is that it is not necessary for one to possess skills such as electronics (to develop and embed the electronic system to record the data log) and remote piloting (to control and operate the aircraft to be modelled).

Considering a general non-linear model of a fixed wing aircraft, written as a function of the geometric parameters, and aerodynamic derivatives, some steps using geometrical parameter measurements and numerical software programming are done in order to identify the parameters specific to the airplane in question. Once these parameters are identified, the non-linear model is then written using these numerical values. Then, the non-linear model with the

parameters specified to the desired aircraft can be simulated and its behavior can be analyzed and compared to the known general behavior of a fixed wing aircraft.

The process presented here will follow stages of specification, modeling, stability analysis and simulation.

## 2. EQUATIONS OF MOTION OF A FIXED-WING AIRCRAFT MODEL

According to Stevens and Lewis (2016), the modeling of a UAV is done by using the equations of motion for a conventional 6-DoF aircraft. The body-axes equations are described below:

### Force equations

$$\dot{U} = rV - qW - g \sin \theta + (X_A + X_T)/m \quad (1)$$

$$\dot{V} = -rU + pW + g \sin \phi \cos \theta + (Y_A + Y_T)/m \quad (2)$$

$$\dot{W} = qU - pV + g \cos \phi \cos \theta + (Z_A + Z_T)/m \quad (3)$$

### Moment equations

$$J_x \dot{p} - J_{xz}(\dot{r} + pq) + (J_z - J_y)qr = \bar{L} \quad (4)$$

$$J_y \dot{q} + (J_x - J_z)pr + J_{xz}(p^2 - r^2) = M \quad (5)$$

$$J_z \dot{r} - J_{xz}(\dot{p} + qr) + (J_y - J_x)pq = N \quad (6)$$

### Kinematic equations

$$\dot{\phi} = p + \tan \theta (q \sin \phi + r \cos \phi) \quad (7)$$

$$\dot{\theta} = q \cos \phi - r \sin \phi \quad (8)$$

$$\dot{\psi} = (q \sin \phi + r \cos \phi) / \cos \theta \quad (9)$$

### Navigation equation

$$\dot{p}^N = U c \theta c \psi + V(-c \phi s \psi + s \phi s \theta c \psi) + W(s \phi s \psi + c \phi s \theta c \psi) \quad (10)$$

$$\dot{p}^E = U c \theta s \psi + V(c \phi c \psi + s \phi s \theta s \psi) + W(-s \phi c \psi + c \phi s \theta s \psi) \quad (11)$$

$$\dot{p}^D = -U s \theta + V s \phi c \theta + W c \phi c \theta \quad (12)$$

For a better analysis of the aerodynamic behavior of the aircraft we use the stability and wind axes systems. In particular, the aerodynamic forces are easily manipulated in the wind axes system, which is given in terms of the angle of attack ( $\alpha$ ) and the angle of sideslip ( $\beta$ ). Thus, the force equations in the wind axes, as introduced in Jung and Tsiotras (2007) are:

$$m \dot{V}_T = T \cos(\alpha + \alpha_T) \cos \beta - D + m g_1 \quad (14)$$

$$m \dot{\beta} V_T = -T \cos(\alpha + \alpha_T) \sin \beta - C_w + m g_2 - m V_T r_s \quad (15)$$

$$m \dot{\alpha} V_T \cos \beta = -T \sin(\alpha + \alpha_T) - L + m g_3 + m V_T (q_s \cos \beta - \sin \beta) \quad (16)$$

Where  $V_T$  is the total air speed,  $q_s$  and  $r_s$  are the pitch and yaw rates projected on the wind axes,  $m$  is the mass of the aircraft and  $g_1$  and  $g_2$  are the gravitational acceleration projections on the wind axes system. The aerodynamic forces are lift ( $L$ ), drag ( $D$ ) and crosswind force ( $C_w$ ) while  $T$  is the thrust force exerted on the aircraft.

### 3. PARAMETERS IDENTIFICATION

The development of this modeling methodology begins by obtaining the geometric measurements of the real model aircraft. In our case we used the Piper J-3 Cub 1/6 scale. Fig. 1 illustrates the model used.



Figure 1. Piper J-3 Cub 1/6 scale aircraft

It is also necessary to obtain measurements of aircraft masses, i.e., the mass of each component installed in the aircraft, such as wings, horizontal stabilizer, vertical stabilizer, fuselage, engine, servos, electronic board and battery. The geometric measurements are used to obtain the 3D drawing and the masses are used to carry out the stability analysis in the modeling software.

#### 3.1 Software XFLR5

The XFLR5 software is an analysis tool for airfoils, wings and planes operating at low Reynolds numbers (XFLR5, 2015). Sequentially, we implemented the following steps in the modeling process with the XFLR5: 1 – Construction of the 3D drawing and distribution of the masses, 2 – Analysis of airfoils, 3 – Analysis of the complete aircraft, 4 – Stability analysis.

Fig. 2 illustrates some parameters obtained.

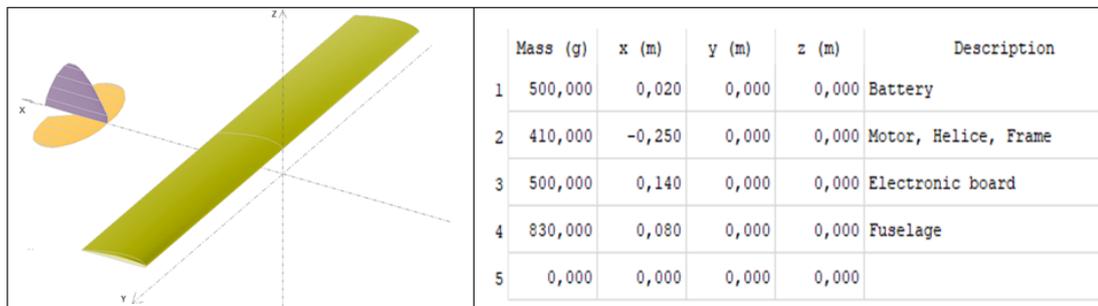


Figure 2. 3D drawing and Mass distribution of the Piper J-3 Cub aircraft in the XFLR5

We used the XFLR5 to evaluate the dynamic stability and temporal response of the aircraft, as well as to obtain the ideal mass distribution for later use with the AVL software.

#### 3.2 AVL- Athena Vortex Lattice

AVL is a program for the aerodynamic and flight-dynamic analysis of rigid aircraft of arbitrary configuration. To perform the analysis of an aircraft and to obtain the aerodynamic coefficients of the mathematical model, we need to provide two types of input files to AVL software: .mass and .avl, which describe the mass distribution and geometry of the aircraft model. After executing AVL, using the inputs corresponding to the desired flight condition, angle of attack and speed, the Longitudinal and Latero-directional Aerodynamic Derivatives & Control were obtained.

### 4. SIMULATION OF THE NONLINEAR MODEL

To evaluate the behavior of the aircraft and model's verification, specific maneuvers were performed to excite the longitudinal and latero-directional movements. The dynamics of an airplane's motion are excited by applying inputs to

its control surfaces, such as pulse, step, multistep or harmonic inputs (Jategaonkar, 2006). The evaluation was done to each dynamic mode of the airplane, the longitudinal and the latero-directional modes.

To verify the behavior of the built model, starting from a straight level flight we applied a pulse in the elevator, as presented in Fig.3. The resulting variation in the angle of attack (AoA) is presented in Fig. 4. This behavior corresponds to the expected AoA behavior of a fixed wing aircraft when its longitudinal mode is excited. Figs. 5 and 6 shows the velocity and altitude aircraft behavior, respectively, corresponding to the longitudinal mode behavior. It can be noted that, just after the pulse is applied to the elevator, the altitude begins to increase and reaches its maximum at the same time as the velocity reaches its minimum value, as it is expected.

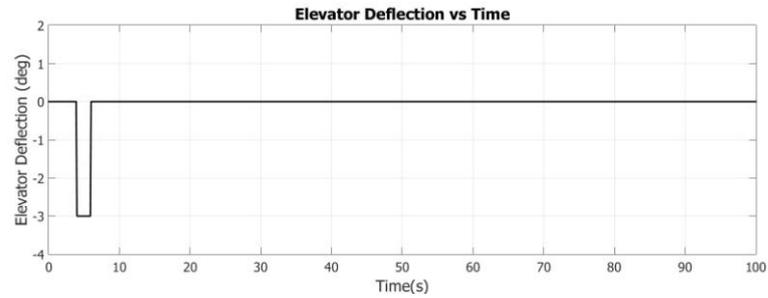


Figure 3. Elevator Pulse input (deg)

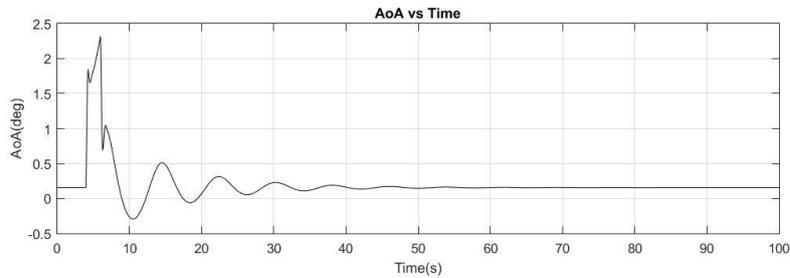


Figure 4. Angle of attack (AoA) variation - Elevator Pulse input

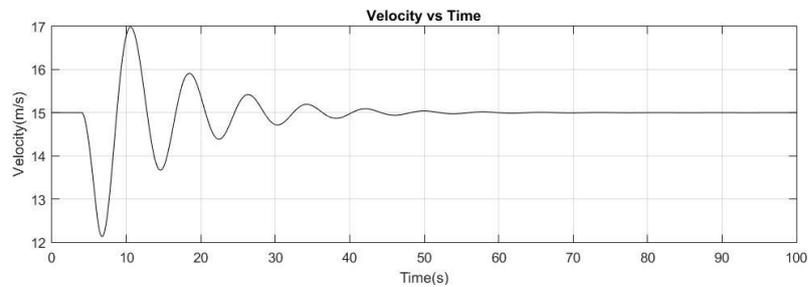


Figure 5. True Velocity variation - Elevator Pulse input

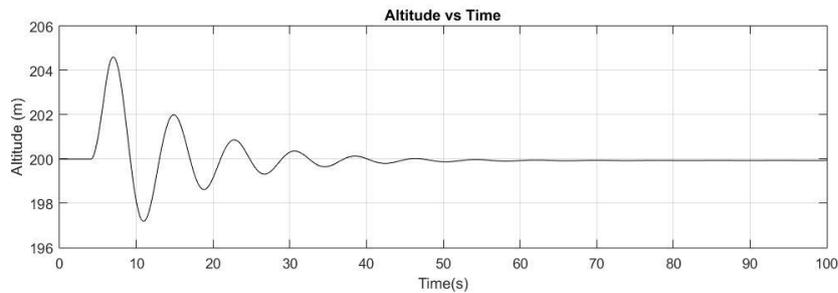


Figure 6. Altitude variation - Elevator Pulse input

Aiming the analysis of lateral-directional behavior, the aircraft was subjected to Dutch-roll and spiral maneuvers. The Dutch Roll maneuver provides maximum information on frequency and damping of the oscillatory movement, as

shown in Jategaonkar (2006), being easily excited with Doublet type inputs at the rudder control. In order to excite the spiral mode, a pulse input was applied on rudder control surface, as presented in Fig. 7.

The behavior of the aircraft model to this input is presented in Fig. 8 and corresponds to the expected behavior of a fixed wing airplane in spiral mode. Fig. 9 shows the rapid damping on Sideslip angle variation resulting from the pulse in the rudder, but the aircraft doesn't return to stable region.

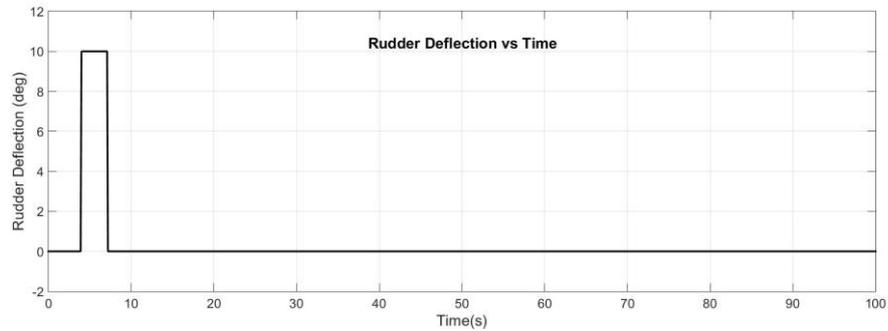


Figure 7. Rudder pulse input

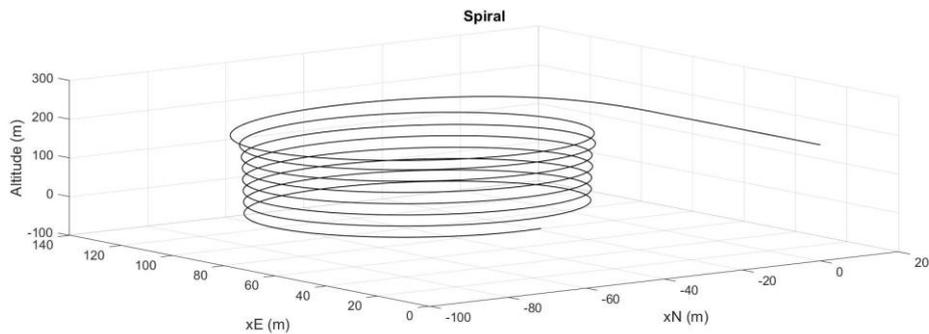


Figure 8. Aircraft spiral mode behavior, resulting from the rudder pulse input

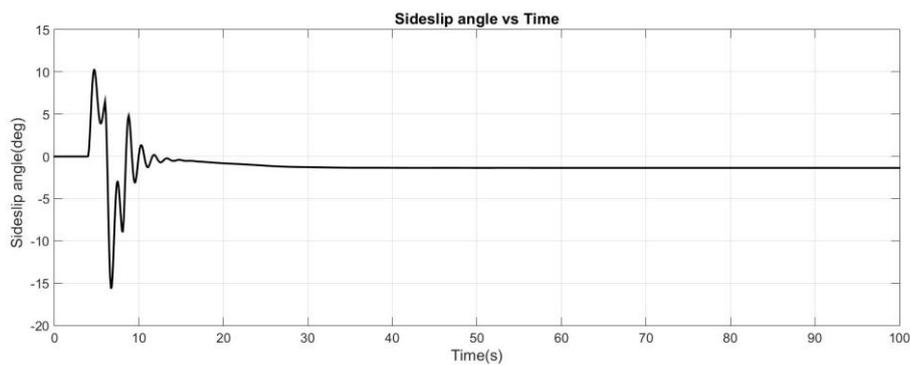


Figure 9. Sideslip angle ( $\beta$ ) variation – Rudder pulse input

Fig. 10 shows the Doublet input on the rudder control surface and Fig. 11a and Fig. 11b presents the Yaw angle variation ( $\psi$ ) and Roll angle ( $\phi$ ) as a result of Dutch-roll movement as described on Cook (2013). The aircraft shows this coupled latero-directional movement until thirteen seconds, and later it tends to a spiral mode.

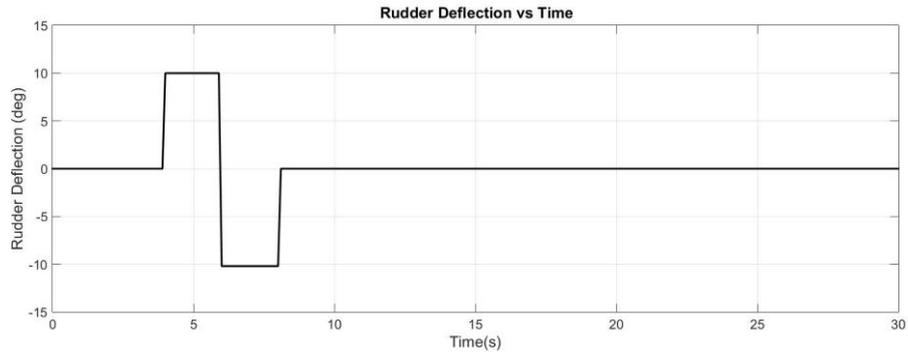


Figure 10. Rudder Doublet input

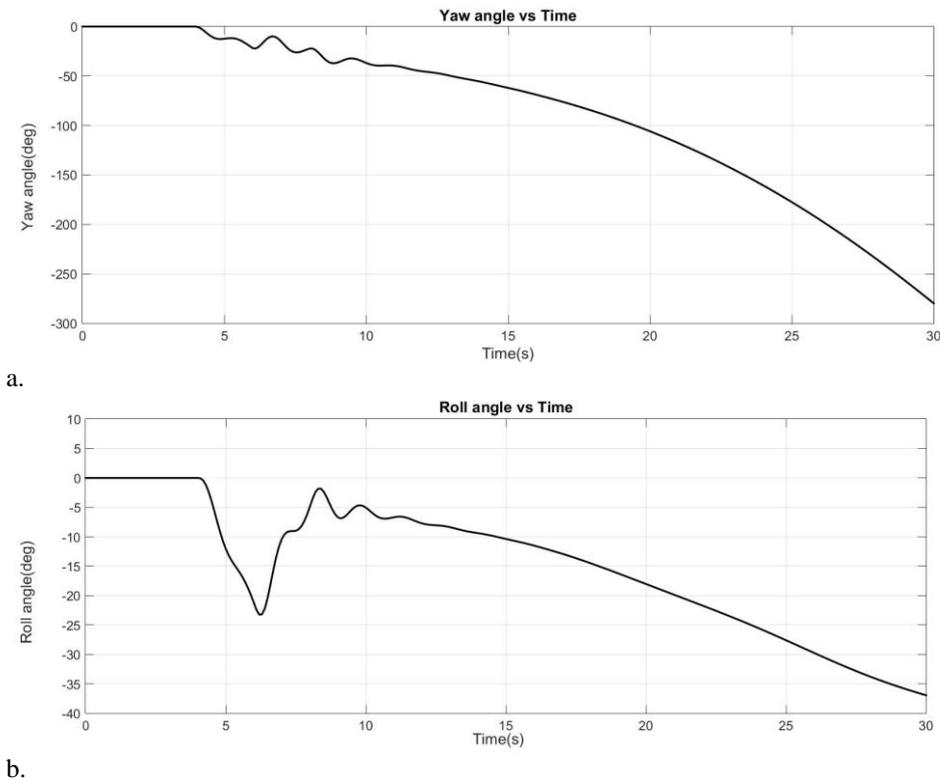


Figure 11. Aircraft Dutch-roll mode behavior, resulting from the rudder doublet input. (a) Yaw angle behavior. (b) Roll angle behavior.

## 5. CONCLUSION

This work introduces a valuable development for the mathematical modeling and previous identification of small aircrafts. It consists in a simple and low cost process, with results consistent with the expected behavior of a fixed wing airplane for the dynamic longitudinal and latero-directional modes. The 3D modeling of the aircraft Piper J-3 Cub 1/6 scale by the XFLR5 software allowed the acquisition of the mass distribution, position of the neutral point in relation to the CG and previous stability analysis without experimental setups, which, in general, is more time consuming. The computational tool AVL allowed the simplified acquisition of the longitudinal and latero-directional stability derivatives and the inertia matrix, essential data for mathematical modeling of the aircraft. A flight mission to record a flight data log is in progress and will allow the comparison between the behavior of the model obtained with the procedure presented here and the behavior of the actual Piper J-3 Cub 1/6.

## 6. ACKNOWLEDGEMENTS

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## 8. RESPONSIBILITY NOTICE

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