PROJECT OF A SIMULATOR FOR IDENTIFICATION OF LONGITUDINAL DERIVATIVES OF STABILITY AND LATERO DIRECTIONAL

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Abstract. *This work presents a simulator for analysis of the dynamic behavior of Unmanned Aerial Vehicles (UAVs). The considered system of simulation together shapes the six degrees of freedom of the aircraft with its derivatives of stability and control. The model can be simplified to represent the degrees of freedom of the longitudinal and latero-directional dynamics of the UAV, in order to simplify the project of the stabilization system and control of the vehicle. The algorithm considered here makes use of the Matlab/SIMULINK which was added the BlockSet AeroSim. This BlockSet supplies a complete set of tools the fast development of aerodynamic models of aircraft with six degrees of freedom. The simulator implements the propulsive models, of the longitudinal and latero-directional dynamics, without dynamic coupling subject to external gust influences and other external disturbances. It still allows to insert signals of entrances with ways of excitement in the desired frequencies and to verify the results for these specific entrances. The developed dynamic modeling is used to develop maneuvers of flight test aiming at the identification of the stability derivatives and control of the UAV .*

Keywords*: Unmanned Aerial Vehicles, derivatives of stability, latero directional, propulsive model.*

Nomenclature

φ = roll angle [deg]
p = roll rate [rad/s]
q = pitch rate [rad/s]
r = yaw rate [rad/s]
θ = pitch angle [deg]
ψ = yaw angle [deg]
I_x, I_y, I_z = moment of inertia about X, Y and Z body axes, [kg.m^2]
I_{xz} = product of inertia with respect to X and Z body axes, [kg.m^2]
$\bar{q}$ = dynamic pressure, [N/m^2]
C_l^{CG}, C_m^{CG}, C_n^{CG} = moment coefficients along X, Y, and Z aerodynamic axes
L_{tw}, N_{tw}, M_{tw} = moments produced by propulsion
u, v, w = components of aircraft velocity along X, Y and Z body axes, [m/s]
S = wing reference area, [m^2]
m = total aircraft mass, [kg]
x_{rpcg} , y_{rpcg} ,z_{rpcg} = distances between the aerodynamic center and the CG, [m]
F_R, F_L = forces of the right and left engine, [N]
σ = angle of inclination of the engine in relation to axe X of the body, [deg]
x_{twcg}, z_{twcg} = distance of the engine in relation to the CG, [m]
C_x, C_y, C_z = force coefficients along X, Y, and Z body axes
X_{tw}, Z_{tw} = forces produced by propulsion
C_D = drag force coefficient
C_Y = side force coefficient
C_L = lift force coefficient
C_l^{RP} = rolling moment coefficient
C_m^{RP} = pitching moment coefficient
C_n^{RP} = yawing moment coefficient
δ_e = elevator deflection, [deg]
δ_a = aileron deflection, [deg]
δ_r = rudder deflection, [deg]
β = angle of sideslip, [deg]
α = angle of attack, [deg]
V = airspeed, [m/s]
l_s = reference length for latero-directional motion, [m]
l_μ = reference length for longitudinal motion, [m]
Λ = aspect ratio of the wings
e = Oswald's span efficiency factor
i_H = horizontal stabilator deflection, [deg]

1. INTRODUCTION

In recent years, the applications of unmanned aerial vehicles (UAVs) have grown dramatically in many fields. They are moving more and more into the limelight of discussion for various military and civil applications. In particular, dangerous, dull, and dirty missions are often executed by UAVs instead of human beings in order to perform different missions ranging from reconnaissance, intelligence acquisition, to actual combat missions.

The Aeronautical Command *(CTA – Comando-Geral de Tecnologia Aeroespacial)* is to the front of the UAV project (showed in fig. 1), to be used in civil and military missions of air reconnaissance, monitoring of natural resources, electric nets and oil ducts. The studies started in the 80's, with *Acauã*. Nowadays, the project aims to using the same platform with electronics systems improved and the engine changed into one more powerful.

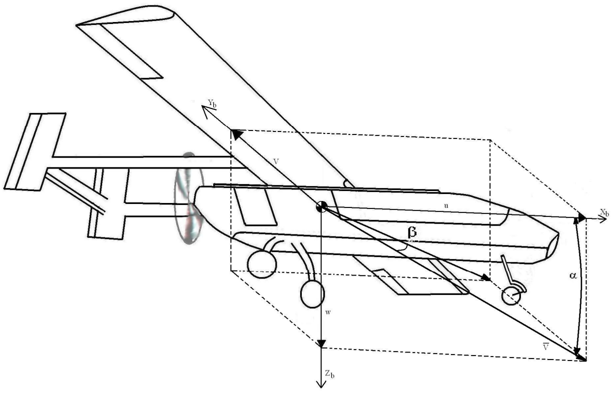

Figure 1 – UAV

The simulation plays an important role in minimizing risk prior to flight-testing. By adjusting the functions of the UAV according to the simulation results the stability of the UAV can be improved. A good simulation plays an important role in designing and fine tuning control algorithms to make them more precise, and thus to make the UAVs more reliable.

The algorithm considered here makes use of the *Matlab/SIMULINK* which was added the *BlockSet AeroSim*. The simulator of the complete nonlinear dynamic is done in the structure of blocks in the *Simulink* (fig. 2), became possible the person project the results of the aircraft control system. The software *Matlab (version 7.0)* was used in the development of the simulator, due to its increase utilization and utilities tools in this area.

The research described in this paper focuses on utilization of commands – group of entrances (velocity, elevation, derivatives of stability, etc.) and maneuvers (variation on the surfaces of control: aileron, elevator and rudder) - and discussing the effects of the airplane's behavior based on the commands used. The simulation results will be compared with experimental data, and the results applied to the design of the control algorithms.

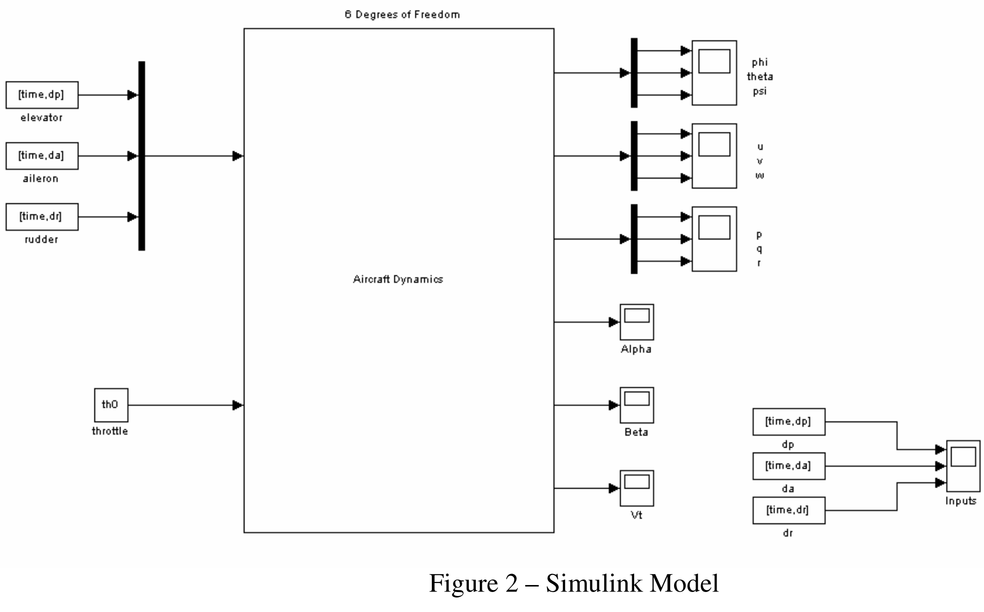

Figure 2 – Simulink Model

2. AIRCRAFT DYNAMIC

2.1. The aircraft equation of motion of six degrees of freedom

According to Jategaonkar (2001), using nonlinear coupled on airplane equation with six degrees of freedom and considering a symmetrical airplane with constant mass and propeller engine, the equations of motion can be expressed as follows.

Kinematics equations:

$$\dot{\varphi} = p + (q*\sin\varphi + r*\cos\varphi)/\tan\theta \quad (1)$$

$$\dot{\theta} = q*\cos\varphi - r*\sin\varphi \quad (2)$$

$$\dot{\psi} = (q*\sin\varphi + r*\cos\varphi)/\cos\theta \quad (3)$$

The coefficients φ, θ e ψ are the Euler's angles. They express the relative orientation between two coordinate systems. They are rotated three times successively, in a determined order, to do the first coordinate system to coincide with second.

Moment equations:

$$\dot{p} = [1/(I_x*I_z - I_{xz}^2)]*[(I_x - I_y + I_z)*I_{xz}*p*q - (I_{xz}^2 + I_z^2 - I_y*I_z)*q*r + \bar{q}*S*l_s*(I_z*C_l^{CG} + I_{xz}*C_n^{CG}) + I_z*L_{tw} + I_{xz}*N_{tw}] \quad (4)$$

$$\dot{q} = [1/I_y]*[\bar{q}*S*l_\mu*C_m^{CG} + M_{tw} - I_{xz}(p^2 - r^2) + (I_z - I_x)*p*r] \quad (5)$$

$$\dot{r} = [1/(I_x*I_z - I_{xz}^2)]*[(I_{xz}^2 - I_x*I_y + I_x^2)*p*q - (I_x - I_y + I_z)*I_{xz}*q*r + \bar{q}*S*l_s*(I_x*C_n^{CG} + I_{xz}*C_l^{CG}) + I_{xz}*L_{tw} + I_x*N_{tw}] \quad (6)$$

The coefficients p, q and r are the components of the angular velocity along X, Y, and Z body axes respectively.

Forces equations:

$$\dot{u} = r*v - q*w + g*\sin\theta + \bar{q}*S*C_x/m + X_{tw}/m \quad (7)$$

$$\dot{v} = p*w - r*u + g*\cos\theta*\sin\varphi + \bar{q}*S*C_y/m \quad (8)$$

$$\dot{w} = q*u - p*v + g*\cos\theta*\cos\varphi + \bar{q}*S*C_z/m + Z_{tw}/m \quad (9)$$

Where the coefficients of longitudinal force (C_x), the lateral force (C_Y), the vertical force (C_z), the rolling moment (C_l^{CG}), the pitching moment (C_m^{CG}) and the yawing moment (C_n^{CG}) are in relation to the body axe and are functions of the aerodynamic derivatives and control. The engine exerts two forces and three moments: X_{tw} in the longitudinal axe and Z_{tw} in the vertical axe, and L_{tw} around axe X, M_{tw} around axe Y and N_{tw} around axe Z.

Normally the coefficients are expressed in relation to the reference center, thus have that to convert them from point of gravity of the body (CG) to aerodynamic control point. For this, the rotation of the body axe for the stability axe it is enough. Thus:

$$C_x = -C_D*\cos\alpha + C_L*\sin\alpha$$

$$C_z = -C_D*\sin\alpha - C_L*\cos\alpha$$

$$C_l^{CG} = C_l^{RP} - C_Y*(z_{rpcg}/l_S) + C_Z*(y_{rpcg}/l_S)$$

$$C_m^{CG} = C_m^{RP} + C_X*(z_{rpcg}/l\mu) - C_Z*(x_{rpcg}/l_\mu)$$

$C_n^{CG} = C_n^{RP} - C_X*(y_{rpcg}/l_S) + C_Y*(x_{rpcg}/l_S)$

$X_{tw} = (F_L + F_R) * \cos\sigma$

$Z_{tw} = -(F_L + F_R) * \sin\sigma$

$L_{tw} = (F_L - F_R) * y_{twcg} * \sin\sigma$

$M_{tw} = X_{prop} * z_{twcg} - Z_{prop} * x_{twcg} = (F_L + F_R) * \cos\sigma * z_{twcg} - (-(F_L + F_R) * \sin\sigma * x_{twcg})$

$N_{tw} = (F_L - F_R) * y_{twcg} * \cos\sigma$

2.2. Aerodynamic model

The aerodynamic stability and control derivatives, which establish the aerodynamic characteristics of the aircraft, are linked to the dynamic model, through the following aerodynamic model:

$$C_D = C_{D0} + (1/\pi*e*\Lambda)*C_L^2 \quad (10)$$

$$C_Y = C_{y0} + C_{Y\beta}*\beta + C_{Yp}*(p*l_s/2*V_t) + C_{Yr}*(r*l_s/2*V_t) + C_{Y\delta a}*\delta_a + C_{Y\delta r}*\delta_r \quad (11)$$

$$C_L = C_{L0} + C_{L\alpha}*\alpha + C_{L\dot{\alpha}}*(\dot{\alpha}*l_\mu/2*V_t) + C_{Lq}*(q*l_\mu/2*V_t) + C_{L\delta e}*\delta_e + C_{LiH}*i_H + (C_{L0Cs} + C_{L\alpha Cs}*\alpha)*C_S \quad (12)$$

$$C_l^{RP} = C_{l0} + C_{l\beta}*\beta + C_{lp}*(p*l_s/2*V_t) + C_{lr}*(r*l_s/2*V_t) + C_{l\delta a}*\delta_a + C_{l\delta r}*\delta_r \quad (13)$$

$$C_m^{RP} = C_{m0} + C_{m\alpha}*\alpha + C_{mq}*(q*l_\mu/2*V_t) + C_{m\dot{\alpha}}*(\dot{\alpha}*l_\mu/2*V_t) + C_{m\delta e}*\delta_e + C_{miH}*i_H + (C_{m0Cs} + C_{m\alpha Cs}*\alpha)*C_S \quad (14)$$

$$C_n^{RP} = C_{n0} + C_{n\beta}*\beta + C_{n\dot{\beta}}*(\dot{\beta}*l_s/2*V_t) + C_{np}*(p*l_s/2*V_t) + C_{nr}*(r*l_s/2*V_t) + C_{n\delta a}*\delta_a + C_{n\delta r}*\delta_r \quad (15)$$

In the most of cases the aerodynamic coefficients are expressed in the aerodynamic body axe. In this case is necessary to apply a transformation for the body axes. The adimensional aerodynamic coefficients depend on: the angle of attack and the angle of sideslip; the Mach's number, and in certain cases, the Reynolds's number; the components of angular speed; and the position of the surfaces of control of the aircraft.

The coefficient C_s incorporates the derivates by engine in the model.

2.3. Propulsive Model

According to Paglione (1993), being thrust a specific function of velocity, by altitude, as well as engine throttle (th), a good approximation of propulsive model is:

$F = Fmax * th * (V/Vi)^{nv} * (\rho(h)/\rho i)^{n\rho}$

th = engine throttle, [%];
Vi = initial speed, [m/s];
ρi = atmosphere density, [kg/m^3].

where: $0{,}75 \le n\rho \le 0{,}85$ – $h \le 11000$ m
$n\rho = 1$ – $h > 11000$ m

nv =
- -1 alternative engines plus propeller
- 0 turbojet or subsonic jet
- +1 supersonic jet

3. SIMULATION RESULTS AND DISCUSSION

The simulation of dynamic of UAV is made considering the initials data, the stability derivatives and control. The table 1 shows the property of the airplane. The table 2 shows initial data to simulate.

Table 1 – Specifications of the airplane

Weight	1177,2 [N]
Wingspan	5,02 [m]
Wing reference area	3,55 [m^2]
Ix, Iy e Iz - Moment of inertia	132,54; 52,99 e 85,93 [kgf.m^2]
Ixz - Cross product of inertia	0,05 [kgf.m^2]

Table 2 – Initial data

Airspeed	41.67 [m/s]
Initial altitude	500 [m]
Initial conditions	p0 = 0 [rad/s] q0 = 0 [rad/s] r0 = 0 [rad/s] u0 = 32.9926 [m/s] v0 = 0 [m/s] w0 = 0.6974 [m/s] phi0 = 0 [rad] theta0 = 0.0211 [rad] psi0 = 1.3090 [rad]

The Simulink allows to inside analyzing the behavior of dynamic systems from the construction of its mathematical models. It is done with/considering blocks diagrams constructed by the interactive environment of the Simulink and executed for the numerical engine of the MATLAB. In this way, all interconnected blocks represent the interactions in an aircraft.

In the figure 3 we can see how the Eq. (1), (2) and (3) are represented in the Simulink.

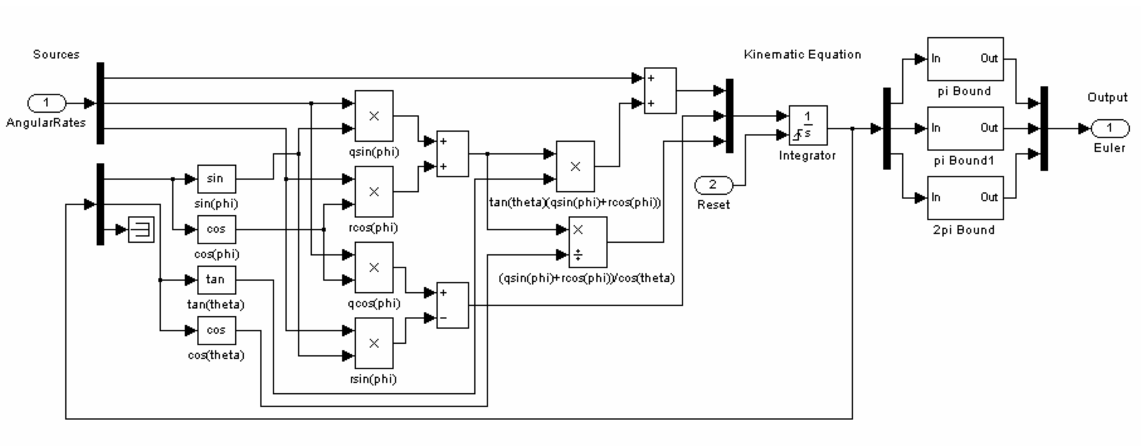

Figure 3 – Kinematic equation

In the figure 4 show how the Eq. (4), (5) and (6) are represented in the Simulink.

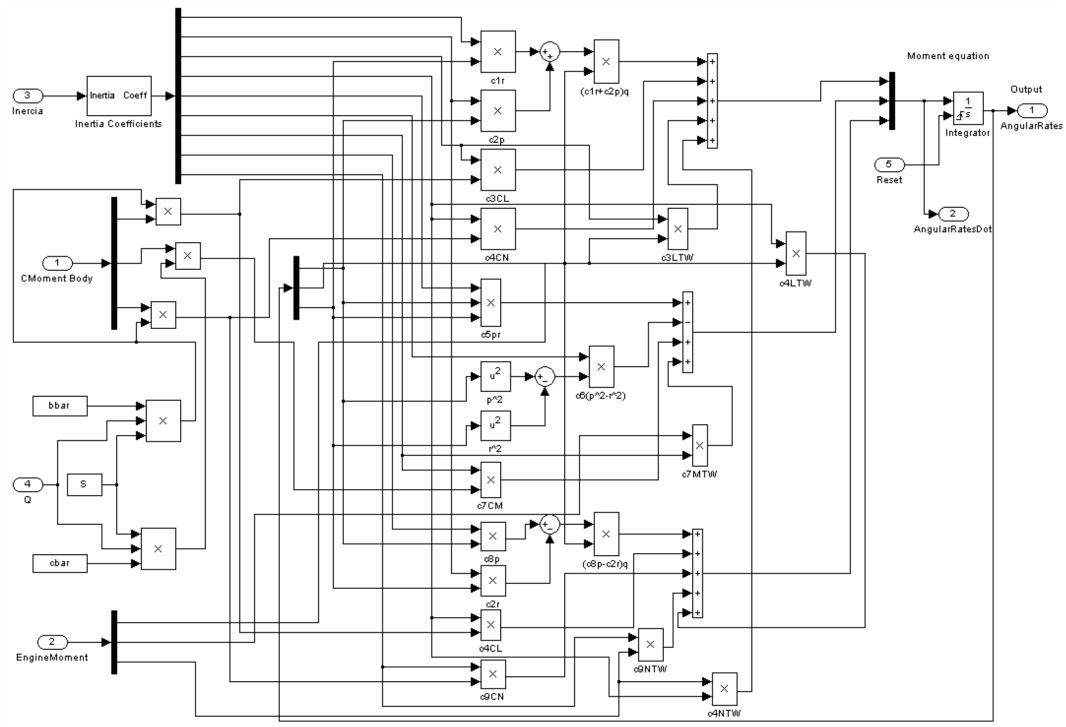

Figure 4 – Moment equation

In the figure 5 we can see how the Eq. (7), (8) and (9) are represented in the Simulink.

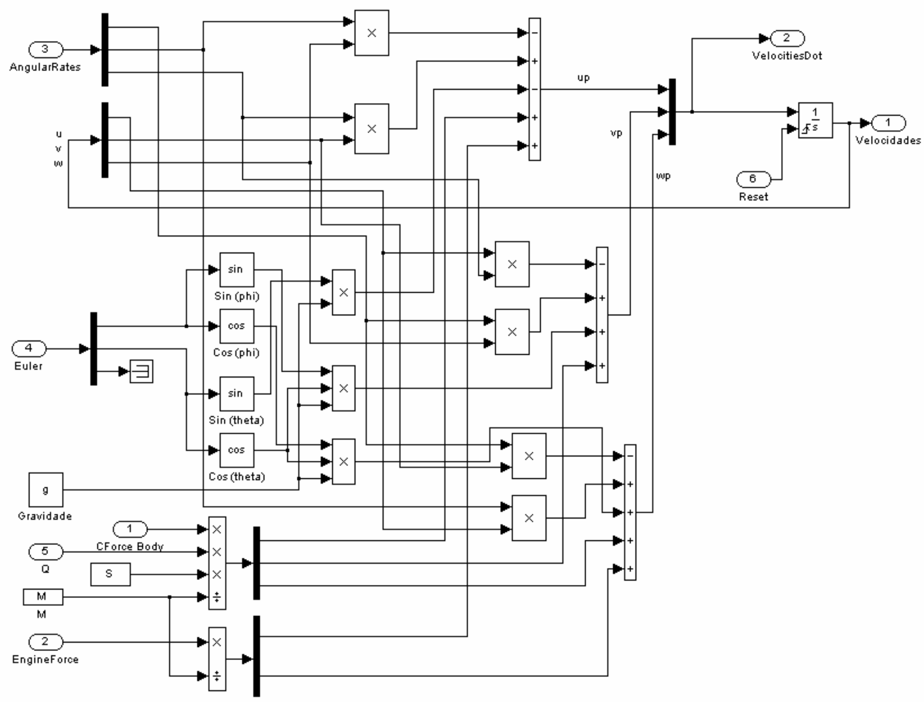

Figure 5 – Forces equation

In the figure 6 we can see the representation in the Simulink of aerodynamics coefficients, Eq. (10) to (15), where each block is one equation.

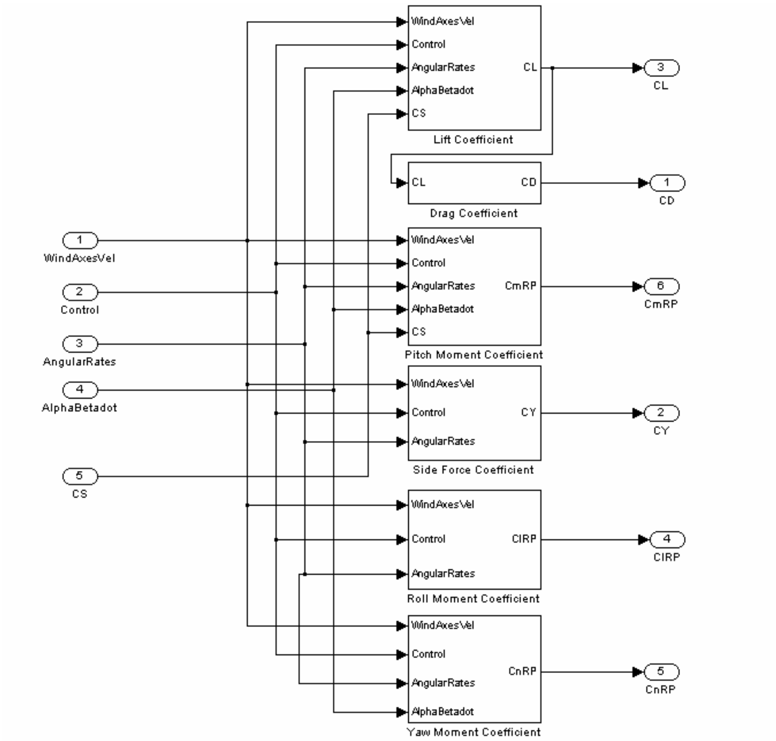

Figure 7 – Aerodynamics coefficients

3.1. Inputs

Maneuvers are used to identify and to estimate the parameters and to specific the entrances based in known signs. The parameters chosen consider the best way to excite the frequency interval desired. In the computational simulation of UAV is used the maneuver 2-1-1.

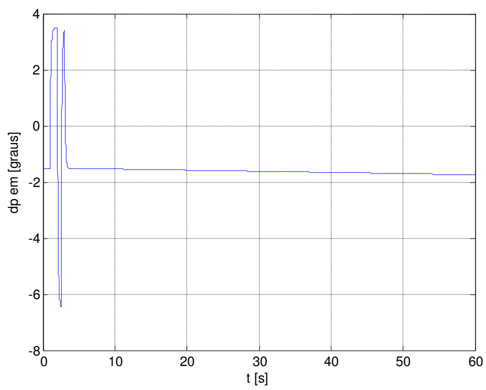

Figure 8 – Elevator Deflection

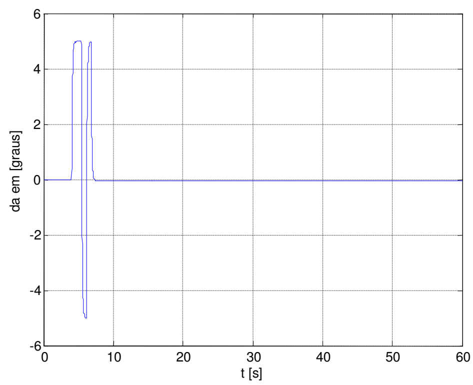

Figure 9 – Aileron Deflection

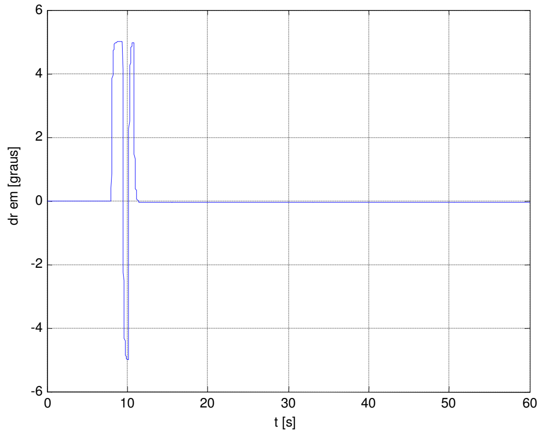

Figure 10 – Rudder Deflection

3.1. Results of simulation

The results of the simulation are shown in the figures from 11 to 18. These results were obtained using the data from tables 1 and 2.

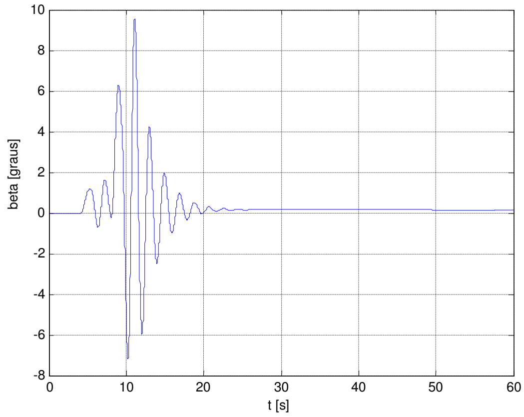

Figure 11 – Angle of sideslip

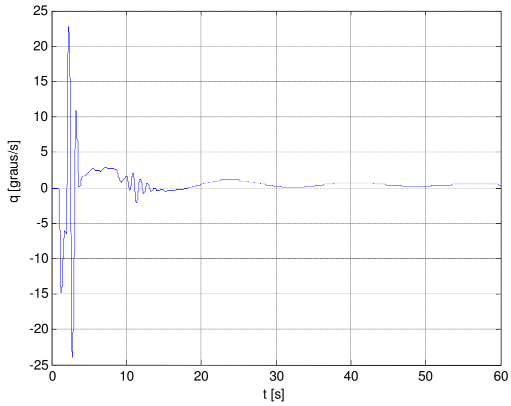

Figure 13 – Pitch rate

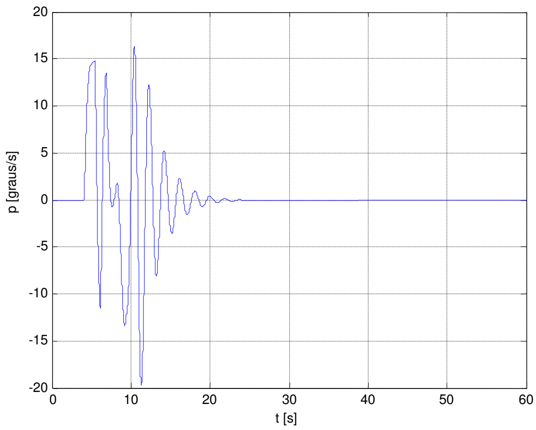

Figure 12 – Roll rate

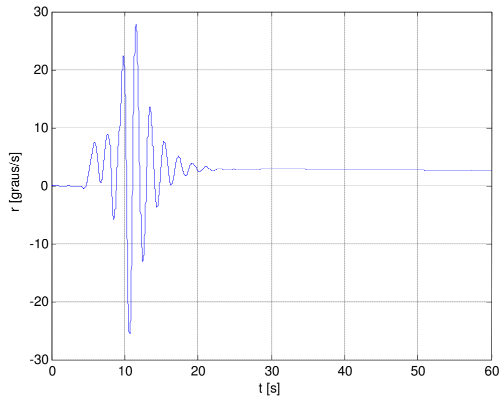

Figure 14 – Yaw rate

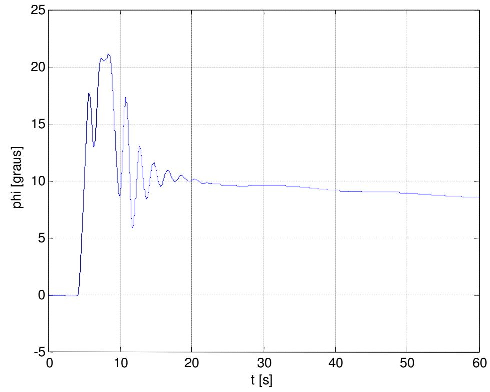

Figure 15 – Roll angle

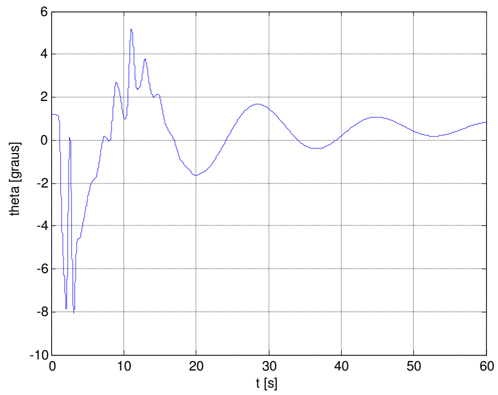

Figure 16 – Pitch angle

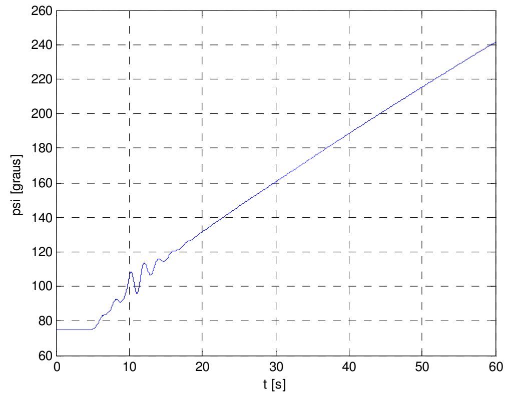

Figure 17 – Yaw angle

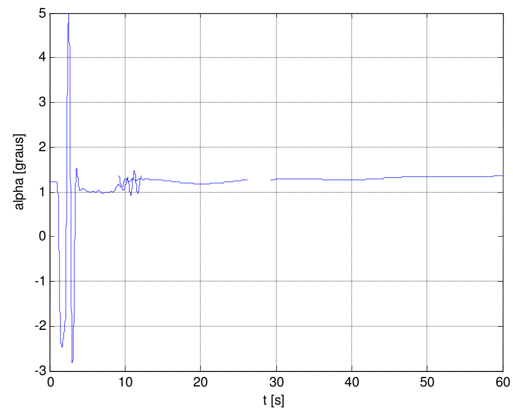

Figure 18 – Angle of attack

This results shows that the presented mathematic model is adjusted to analyze the stability of an aircraft. The analysis of these results showed that the considered simulator, considering the parameters of entrance (table 2), had the desired behavior, tending to stabilize the system in the studded cases.

4. CONCLUSIONS

The applications of UAVs have grown dramatically in many fields, and consequently, the use of simulation tools. These tools are used to analyze the dynamic behavior of UAV and had brought new possibilities to use the results, as control laws and planes and to reduce the schedule and risks.

There are amount of flight testing for complex aerospace systems, and the consistencies results in this studies are well-recognized benefits of these approaches. The experiments confirmed that our simulation, the results from six degrees of freedom dynamic were in accordance with the entrances data and control sign.

As future developments, we consider a necessity to insert external gust influences and other external disturbances to improve the capacity to analyze the aircraft behavior and take a turn for the better way to simulate.

5. REFERENCES

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