AN IMPLEMENTATION OF AN AIRCRAFT FLIGHT MECHANICS MODEL FOR FLIGHT CONTROL LAW STUDIES

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OVERVIEW

This paper presents the development and implementation of an aircraft flight mechanics model and a set of tools to be applied in flight control law studies. The objective is to provide students with: a structured approach to formulate flight control law problems; basic tools to develop new flight control law design techniques and applications; a common model to allow benchmarking of different techniques. The chosen model structure allows for minimum effort refinement, growth and change of modelled dynamics. The modelled aircraft presented herein is a long range high performance business jet. Aerodynamic, engine and inertia characteristics are modelled using calculations from traditional aeronautical engineering references. Trimming, linearization and simulating routines were implemented and results are presented, showing the effectiveness of the routines and highlighting a few distinctive features of the aircraft model representative of real aircraft. It is expected that this set of tools and its documentation will allow faster development and more relevant contributions of master students in flight control laws studies, bringing together academic exercises and practical problems and motivating students.

SYMBOLS

- $F_{x,A}$ Aerodynamic force in the x-axis
- $F_{y,A}$ Aerodynamic force in the y-axis
- $F_{z,A}$ Aerodynamic force in the z-axis
- L_A Aerodynamic moment in the x-axis
- M_A Aerodynamic moment in the y-axis
- N_A Aerodynamic moment in the z-axis
- S Wing area (m^2)
- $\bar{c}$ Wing mean aerodynamic chord (m)
- b Wing span (m)
- C_L Lift coefficient
- C_D Drag coefficient
- C_Y Lateral force coefficient
- C_l X-axis moment coefficient
- C_m Y-axis moment coefficient
- C_n Z-axis moment coefficient
- $_{WB}$ Subscript for forces and moments basic aircraft components contribution
- $\delta\xi$ Subscript for forces and moments contribution due to aileron deflection
- $\delta\eta$ Subscript for forces and moments contribution due to elevator deflection
- $\delta\zeta$ Subscript for forces and moments contribution due to rudder deflection
- δih Subscript for forces and moments contribution due to stabilizer deflection
- $_p$ Subscript for forces and moments contribution due to roll rate
- $_q$ Subscript for forces and moments contribution due to pitch rate
- $_r$ Subscript for forces and moments contribution due to yaw rate
- x State vector
- u Input vector
- y Output vector
- $_k$ Subscript for iteration number

1. INTRODUCTION

The event of aircraft featuring FlyByWire flight control systems can be considered a milestone in the aeronautical industry. The continuous advance made on digital computers resulted in increased processing capacity, allowing the use of more advanced closed loop flight control laws. This has deepened the interest on collaboration between aeronautical industry flight mechanics and flight control system departments and academic researchers working on control theory. However, some collaboration difficulties still arise due to different methods of work. Researchers and students in academy are more theoretically oriented while engineers in aeronautical industry prefer to rely on more empirical methods which can generate practical solutions (Fielding and Luckner[1]).

The complexity of flight control system application steadily increases, while control theory literature is continuously expanded with a vast set of different control techniques. Despite the interest the aeronautical industry has in the advances such techniques can generate, it hardly can afford the expense of developing all the available set of techniques to assess their gains. On the other hand, it is not practical for researchers and students to focus their attention on all the complexities and details inherent to an industrial project while researching advances in theory.

Thus it is desirable to create a common framework for flight control law studies which is sufficiently representative of industrial practice but is also sufficiently simple and general for control researchers and advanced students to produce representative results and conclude on the applicability of the techniques they intend to study within reasonable time and effort. Some particular contributions have been made towards this goal with very specific focuses. E.g.. Garteur Action Group FM(AG08) proposed two design challenges to evaluate Robust Control Methodology considering industrial use[2],[3].

This paper presents the implementation of an aircraft dynamic model built in Simulink and a set of tools to be applied in flight control law studies. The objective is to provide: a structured approach to formulate flight control law problems; basic tools to develop new flight control law design techniques and applications; a common model to allow benchmarking of different techniques. This is expected to be the first step on creating a common framework for flight control law studies within ITA Aero and Mechanical Engineering and Computer and Electronic Engineering masters programs.

The next chapter presents a discussion on the aspects to be considered in the design of any flight control law intended to have at least basic practical value. Chapter 3 discusses the aircraft model itself and its structure. Chapter 4 presents the tools supplied with the model. The conclusion and next steps envisioned in this work are presented in Chapter 5. The references considered in this paper are listed in Chapter 6.

2. FLIGHT CONTROL LAW DESIGN

In modern aircraft, several functions are allocated to the flight control system, such as pitch, roll and yaw control, envelope protection, load alleviation, high-lift surfaces control, airbrakes control[1]. Nevertheless, according to Fielding and Luckner[1], pitch, roll and yaw axes controls are still the primary functions related to the flight control system. There are three aircraft aspects which should be considered in flight control law design of primary functions: the aircraft mission; the aircraft flight envelope; the aircraft configurations.

The aircraft mission can be thought of as a composition of different tasks or flight phases. In a commercial aircraft, any flight can be divided in flight phases such as takeoff, climb, cruise, approach, landing and an eventual go around. In some military aircraft, it is not so simple to define sequential flight phases, yet any flight can be described as a composition of a finite number of mission task elements. Each flight phase or each mission task element might demand different performance from the primary flight control system functions. In a military aircraft, mission task elements such as close flight formation, air-to-air combat and air-refueling require more agility and precision in controlling the aircraft than a terminal mission task element, such as landing, which in turn is more demanding in precision than cruise, for example[1]. All this different requirements have to be considered in the flight control law design.

The flight envelope can be seen as a range of flight conditions the aircraft is designed to be subjected to so as to accomplish its missions. The relevant flight conditions from a flight control law design stand point include speed, Mach number, altitude, angle of attack, angle of sideslip, load factors, angular velocities, etc.

Aircraft configuration can vary in many ways, both within a flight and throughout different flights. For instance, during the flight of a military aircraft, both aerodynamic and mass configuration change, as flaps are deployed or retracted, fuel is burnt or weapons are deployed. Throughout an aircraft life cycle, the same commercial airplane can perform either a fully loaded revenue flights or ferry flights back from maintenance.

The way these three aspects are combined is of fundamental importance for flight control law design[1]. Military norms predict the following steps to define handling qualities requirements which affect flight control laws[4],[5]:

- Defining the aircraft mission in terms of task elements or flight phases;
- Defining the aircraft class, based on its mission and size;
- Defining the aircraft flight envelope, composed of an operational flight envelope, a service flight envelope and a permissible flight envelope;
- Defining configurations and associating them with flight phases or mission task elements;
- Defining requirements for each mission task element or flight phase as a function of the aircraft class and the desired handling quality level, defined for the aircraft normal state and for failure states;

Despite the existing regulations for commercial aircraft do not present such detailed quantitative requirements [6],[7], the approach aircraft manufacturers use is very similar[1]. However, commercial aircraft requirements tend to drive the design to produce excellent handling qualities for operation within the aircraft normal flight envelope allowing progressive degradation towards the limit envelope of the aircraft.

From this discussion, it should be clear that the following issues should be considered to design any flight control law with practical application interest:

- A set of requirements representative of the aircraft mission task element considered;
- A flight envelope for the flight control law;
- A set of aerodynamic and mass configurations;
- An aircraft dynamic model which is representative of the entire set of configurations in the flight envelope defined.

3. THE AIRCRAFT MODEL

In order to obtain a dynamic model representative of an aircraft in its entire flight envelope and for all possible configurations it is necessary to consider all the physics involved. Examples of such aircraft models were presented by the Garteur Action Group FM(AG08) in the scope of the Robust Flight Control Design Challenge[2],[3], and also by Cavalcanti and Papini, during Embraer 170 Jet development[8].

This section presents the model which is one of the main focuses of this paper. Section 3.1 presents the structure adopted for the flight mechanics model discussed in this paper, while section 3.2 presents the particularities of the aircraft used and its modeling

3.1. The Model Structure

The model developed in this work has the purpose of supporting flight control law design studies. It focuses on aircraft dynamic and does not present flight control system or sensors modeling. Matlab/Simulink is used to implement the model. The model top view is presented in FIG 1. Its inputs and outputs are presented in TAB 1and TAB 2.

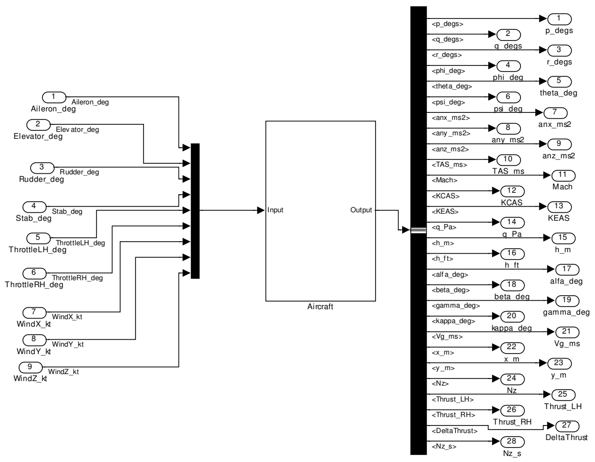

FIG 1. Aircraft simulation model top view.

TAB 1. Aircraft simulation model inputs.

N.	Symbol	Name	Description
1	$\delta\xi$	Aileron_deg	Aileron deflection
2	$\delta\eta$	Elevator_deg	Elevator deflection
3	$\delta\zeta$	Rudder_deg	Rudder deflection
4	δih	Stab_deg	Stabilizer deflection
5	rT1	Throttle_LH_deg	Left hand throttle lever position
6	rT2	Throttle_LH_deg	Right hand throttle lever position
7	w_x	WindX_kt	Wind X component
8	w_y	WindY_kt	Wind Y component
9	w_z	WindZ_kt	Wind Z component

The approach used in the implementation is very similar to that described by Garteur Action Group FM(AG08)[2] and Cavalcanti and Papini[8]. I.e., the model is structured in terms of physical objects and phenomena, rather than signals. Data buses are used to concentrate communication. Its internal structure is presented in figure FIG 2.

There are nine main blocks in the internal structure. Block "Inputs" does the conversion between practical engineering units used in the inputs and SI units, adopted through all the internal communication of the model. Block "CalculateAirspeed" calculates airspeed magnitude, airspeed orientation and airspeed components. Block "Equations of Motion" comprises the entire set of rigid body equations of motion. Block "Engine" calculates the engine thrust, its components and its moments. Block "MassProperties" calculates the aircraft's weight, centre of gravity and inertias. Block "Aerodynamic" calculates aerodynamic forces and moments based on airspeed, command deflections, angular velocity and centre of gravity position. Block "Weight" calculates the gravity force acting upon the aircraft and its orientation in relation to body coordinates. Block "Atmosphere" calculates the atmosphere properties. Block "Outputs" concentrates all the data, already in practical engineering units, sent from all the other blocks into a single data bus.

TAB 2. Aircraft simulation model outputs.

N.	Symbol	Name	Description
1	p	p_degs	Roll rate
2	q	q_degs	Pitch rate
3	r	r_degs	Yaw rate
4	ϕ	phi_deg	Bank angle
5	θ	theta_deg	Pitch angle
6	ψ	psi_deg	Heading angle
7	a_{nx}	anx_ms2	X-accelerometer measure
8	a_{ny}	any_ms2	Y-accelerometer measure
9	a_{nz}	anz_ms2	Z-accelerometer measure
10	V_a	TAS_ms	True Airspeed
11	M	Mach	Mach Number
12	KCAS	KCAS	Knots Calibrated Airspeed
13	KEAS	KEAS	Knots Equivalent Airspeed
14	$\overline{q}$	q_Pa	Dynamic Pressure
15	h	h_m	Altitude (m)
16	h	h_ft	Altitude (ft)
17	α	alfa_deg	Angle of attack
18	β	beta_deg	Angle of sideslip
19	γ	gamma_deg	Flight path angle
20	χ	kappa_deg	Track angle
21	V_g	Vg_ms	Ground speed
22	x	x_m	X-coordinate
23	y	y_m	Y-coordinate
24	N_z	Nz	Normal load factor (body axes)
25	F_{Ex1}	Thrust_LH	Left hand engine thrust
26	F_{Ex2}	Thrust_RH	Right hand engine thrust
27	ΔF_{Ex}	DeltaThrust	Thrust asymmetry
28	$N_{Z,S}$	Nz_s	Normal load factor (stability axes

Model parameters are initialized through external Matlab scripts. The scripts load all the necessary variables in the workspace when run. A main script is run to call all other initialization scripts, which are structured like the Simulink aircraft model itself.

This structured approach for the model and its initialization is very useful, since the same model structure can be used for different aircraft or for adopting different levels of complexity in the modeling. For example, if one is to represent another aircraft, he or she will only have to change the initialization parameters, or, in the worst case, change blocks such as aerodynamics, engines and mass properties.

The equations used in the model are heavily based on the work by Garteur Action Group FM(AG08)[2]. Rigid body equations of motion, coordinate transformations, airspeed calculation, atmospheric properties and gravity force are exactly the same presented in sections 2.3.2, 2.3.3, 2.3.7 and 2.3.8 from [2], respectively. Aerodynamic, engine and mass properties modeling are very particular to the modeled aircraft and are described in details in the next section. The considered set of equations leads to the states depicted in TAB 3.

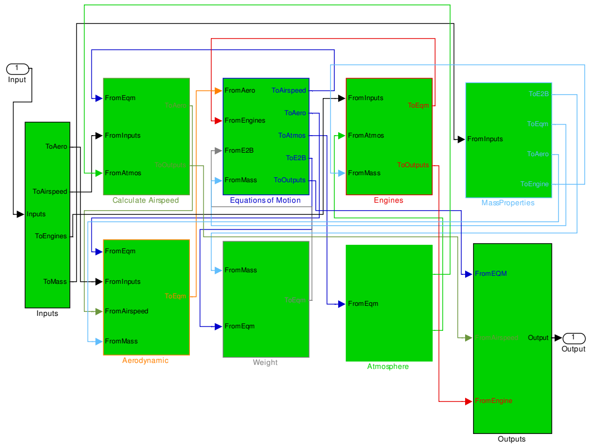

FIG 2. Internal structure of the aircraft simulation model.

TAB 3. Aircraft simulation model internal states.

N.	Symbol	Name	Description
1	u	u_ms	Longitudinal velocity
2	v	v_ms	Lateral velocity
3	w	w_ms	Normal velocity
4	p	p_rads	Roll rate
5	q	q_rads	Pitch rate
6	r	r_rads	Yaw rate
7	ϕ	phi_rad	Bank angle
8	θ	theta_rad	Pitch angle
9	ψ	psi_rad	Heading angle
10	x	x_m	X-coordinate
11	y	y_m	Y-coordinate
12	z	z_m	Z-coordinate
13	-	engine1_F	First state of engine 1
14	-	engine1_{F1}	Second state of engine 1
15	-	engine2_F	First state of engine 2
16	-	engine2_{F1}	Second state of engine 2

3.2. The Modeled Aircraft

The modeled aircraft is a long range high performance business aircraft representative of airplanes such as Dassault Falcon 7X, Bombardier Global Express XRS or the Gulfstream G550. The aircraft geometry, mass and engine properties were defined upon data, presented in Jane's All the Worlds Aircraft[9]. The modeled airplane basic data is presented in table TAB 4.

TAB 4. Modeled airplane basic data

Passengers (tipical)	MTOW (kg)	M_{MO} (Mach)/ V_{MO} (KCAS)	Range (NM)	Operational ceiling (ft)
8-19	44452	0.89/340	6150	51000

The modeling of the aircraft forces and moments acting upon it is defined by the equations below.

$$
(1)\quad
\begin{aligned}
F_{xA} &= \bar{q}S(-C_D\cos\alpha + C_L\sin\alpha)\\
F_{yA} &= \bar{q}SC_Y\\
F_{zA} &= \bar{q}S(-C_L\cos\alpha - C_D\sin\alpha)\\
L_A &= \bar{q}SbC_l\\
M_A &= \bar{q}S\bar{c}C_m\\
N_A &= \bar{q}SbC_n
\end{aligned}
$$

The aerodynamic forces and moment coefficients in the expressions given in (1) are defined according to the following equations:

$$
(2)\quad
\begin{aligned}
C_L &= C_{L,WB}(\alpha) + C_{L,\delta\eta}\delta\eta + C_{L,\delta h}\delta h + C_{L,q}\frac{q\bar{c}}{2V}\\
C_D &= C_{D,WB}(\alpha) + C_{D,\delta\eta}\delta\eta + C_{D,\delta h}\delta h\\
C_Y &= C_{Y,WB}(\beta) + C_{Y,\delta\zeta}\delta\zeta + C_{Y,r}\frac{rb}{2V} + C_{Y,p}\frac{pb}{2V}\\
C_l &= C_{l,WB}(\beta) + C_{l,\delta\xi}\delta\xi + C_{l,\delta\zeta}\delta\zeta + C_{l,r}\frac{rb}{2V} + C_{l,p}\frac{pb}{2V}\\
C_m &= C_{m,WB}(\alpha) + C_{m,\delta\eta}\delta\eta + C_{m,\delta h}\delta h + C_{m,q}\frac{q\bar{c}}{2V}\\
C_n &= C_{n,WB}(\beta) + C_{n,\delta\zeta}\delta\zeta + C_{n,r}\frac{rb}{2V} + C_{n,p}\frac{pb}{2V}
\end{aligned}
$$

The calculation of the aerodynamic parameters in the left hand side of equations (2) is based on traditional airplane design references. First, an equivalent geometry for the modeled airplane is defined according to ESDU[10]. It is presented in FIG 3. Then, the aerodynamic coefficients and derivative coefficients are calculated according to ESDU Aerodynamic Series[10] and Roskam[11].

The maximum takeoff weight and the basic operating weight are used as the maximum and the minimum weight allowed, respectively. The centre of gravity range is assumed to be from ten percent to forty percent of the wing mean aerodynamic chord. The inertias of the aircraft are calculated based on a method developed by Roskam, which is based on the use of similar aircraft historical data[12]. Inertia variations due to weight are considered in this model.

The engine modeling is exactly the same as the one used in section 2.3.6 of reference Garteur, except that the parameters are different. The mapping between throttle and thrust at sea level is linear. The maximum thrust comes from Jane's[9] and an arbitrary idle thrust is assumed. The engine orientation and engine arms in relation to the centre of gravity are defined according to the equivalent geometry presented in FIG 3.

4. THE SUPPORTING TOOLS

In order to support control law studies with the model, a set of supporting tools was developed. The three main components of this set of tools are the trimming routine, the linearization routine and the simulation routine.

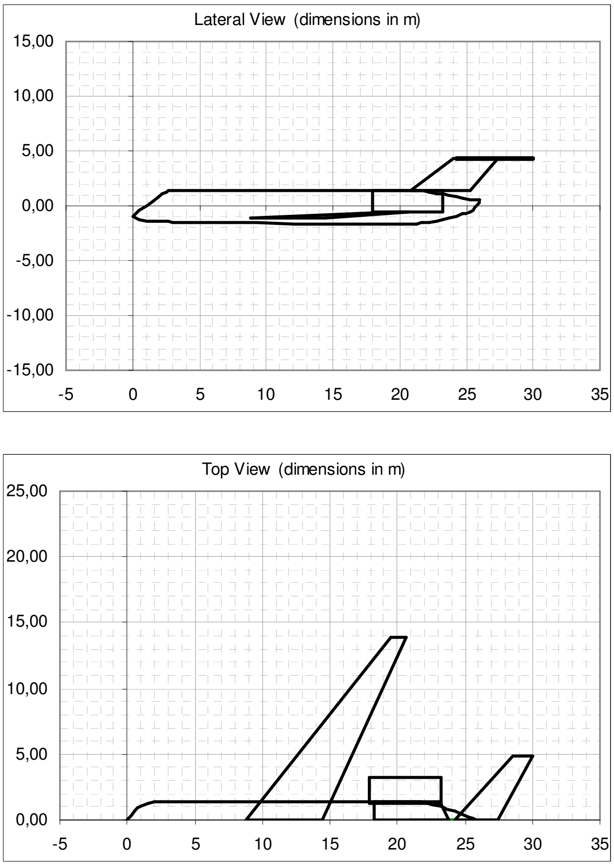

FIG 3. Modeled aircraft equivalent geometry.

The trimming routine is a Matlab function which uses a multivariable Newton-Raphson algorithm. The trimming routine extracts an input table from a comma separated file. This table contains the values of frozen inputs, frozen states, desired outputs and state derivatives desired to be null. The routine uses this information and the model to create a set of nonlinear equations of the form:

(3) $$\begin{aligned} \dot{x}_{Freeze} &= F_{Freeze}(x,u) = 0 \\ y_{Freeze} &= G_{Freeze}(x,u) = K \end{aligned}$$

They are then solved by the multivariable Newton-Raphson algorithm, which obtains the derivatives for its Jacobian matrix numerically using routine “limodv5.m” from Matlab as given in (4).

(4) $$J = \begin{bmatrix} \dfrac{\partial F_{Freeze}}{\partial x_{Float}}(x,u) & \dfrac{\partial F_{Freeze}}{\partial u_{Float}}(x,u) \\ \dfrac{\partial G_{Freeze}}{\partial x_{Float}}(x,u) & \dfrac{\partial G_{Freeze}}{\partial u_{Float}}(x,u) \end{bmatrix}$$

The Newton-Raphson algorithm then iterates the expression below to find the solution:

(5) $$\begin{bmatrix} x_{k+1} \\ u_{k+1} \end{bmatrix} = \mu \cdot J^{-1} \cdot \left(\begin{bmatrix} 0 \\ K \end{bmatrix} - \begin{bmatrix} F_{Freeze}(x_k, u_k) \\ G_{Freeze}(x_k, u_k) \end{bmatrix} \right)$$

The trimming routine returns the trimmed inputs, states and outputs.

Linearization routine also uses the Matlab routine “linmodv5.m”. The routine is generally used after a successful trimming. It uses the trimmed states and inputs as its own inputs. Matlab routine “linmodv5.m” is then used to obtain the derivatives of outputs and state time derivatives in relation to state values and input values exactly as in equation (4). From all the derivatives, a small set of derivatives of interest is selected while the rest is ignored. This set is selected considering the inputs, outputs and states of interest. This leads to the linear formulation below.

(6) $$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx + Du \end{aligned}$$

The matrices A, B, C and D are then linearly transformed to reflect the set of states and outputs in TAB 5 (longitudinal) and TAB 6 (latero-directional), which is generally more useful for control laws. The resulting matrices A, B, C and D are the outputs of the routine and can be used to flight control law design or linear analysis then.

TAB 5. Final Inputs, States and Outputs of the Longitudinal Linear Models

Inputs	States	Outputs
$\delta\eta$	V_a	V_a
δih	α	α
$engine1_F$	q	Q
$engine2_F$	θ	θ
w_x		U
w_z		W
		N_x
		N_z

TAB 6. Final Inputs, States and Outputs of the Latero-Directional Linear Models

Inputs	States	Outputs
$\delta\xi$	β	β
$\delta\zeta$	p	P
$engine1_F$	r	r
$engine2_F$	ϕ	ϕ
w_Y		v
		N_Y

The simulation routine is the most simple of the three routines. It builds input vectors from the sum of the trimmed inputs vector and the perturbation input vectors. It runs a Simulink simulation using the input vectors and then returns the simulation output.

In the following paragraphs, model and tools usage is exemplified. TAB 7 presents a set of mass configurations for the basic model. TAB 8 presents a number of different flight conditions for linearization of the models, considering the configurations in TAB 7. The model is trimmed in the combinations of these conditions and configurations. FIG 4 shows the results in terms of angle of attack and stabilizer values as a function of airspeed.

TAB 7. Mass configurations used to illustrate use of tools

Weight (kgf)	CG (%MAC)
23224	10
44452	10
23224	40
44452	40

TAB 8. Flight conditions used to illustrate use of model tools

Altitude	Speed
0	1.3Vs
0	340 KCAS
30900	1.3Vs
30900	340 KCAS
51000	1.3Vs
51000	0.89 Mach

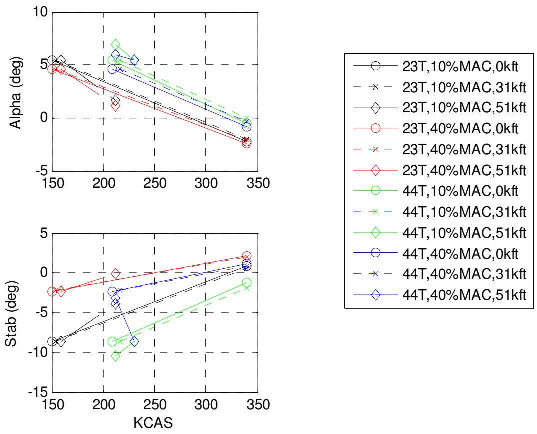

FIG 4. Angle of attack and stabilizer deflection values for trimmed conditions.

The model is then linearized using the linearization routine in all the trimming points. FIG 5 and FIG 6 present the poles and zeroes for all the longitudinal and latero-directional linear models respectively. The results show some realistic aircraft features, such as a case of unstable phugoid in FIG 5 (23224kgf, 40%MAC, 0ft, 1.3V_S), and unstable spiral modes in all the latero-directional models.

Simulations of the linear model is then made and compared with results from the nonlinear simulation routine, considering the same inputs. These simulations are presented in FIG 7 and FIG 8 for elevator and aileron inputs, respectively. They show no difference between the results from the nonlinear model and those from the linearized models.

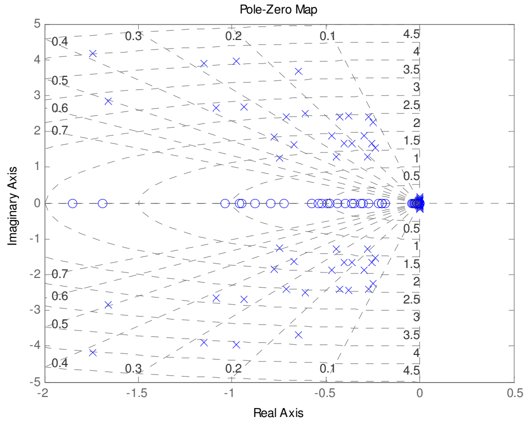

FIG 5. Poles and zeroes of pitch rate linear model response to elevator inputs.

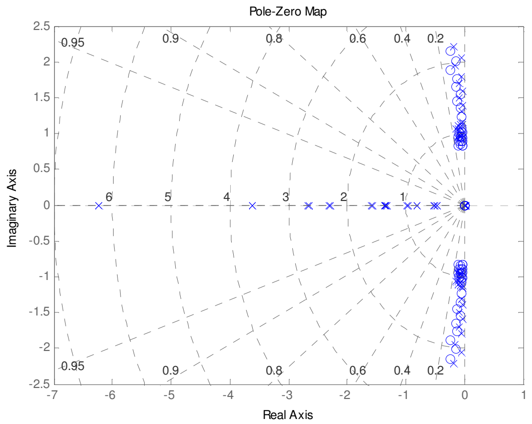

FIG 6. Poles and zeroes of roll rate linear model response to aileron inputs.

5. CONCLUSION

An aircraft model and a set of tools for flight control law studies were presented. Both, the model and the control tools were developed with the intent of providing: a structured approach to formulate flight control law problems; basic tools to develop new flight control law design techniques and applications; a common model to allow benchmarking of different techniques. The model presents features that are representative of real life aircraft. The tools perform basic tasks necessary for any flight control law design process: trimming, model linearization and simulation.

This work will be continued to include details of the flight control system in the model, such as sensors, actuators and time delays. Other possible contributions to this work are the definition of model blocks as libraries and the creation of configuration control features for the model. It is believed that this will further contribute to provide Embraer Engineering Specialization Program and ITA Aero and Mechanical Engineering and Computer and Electronic Engineering master program students with an adequate platform to develop flight control law studies.

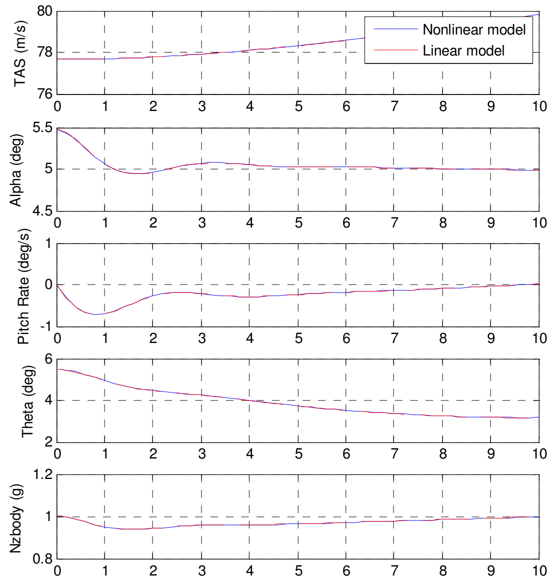

FIG 7. Nonlinear model and linear model response to elevator step input (23224 kgf, 10% MAC, 0ft)

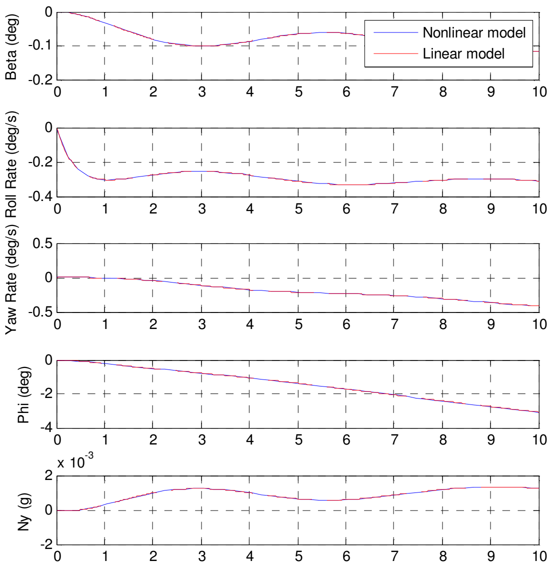

FIG 8. Nonlinear model and linear model response to aileron step input (23224 kgf, 10% MAC, 0ft)

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