DEVELOPMENT OF A CONCURRENT LOW-COST, REAL-TIME FLIGHT SIMULATOR: FLIGHT DYNAMICS AND AERODYNAMIC MODELS

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Abstract. This program, which is aimed to the development of a low-cost reconfigurable flight simulator to be used by both military and civil aeronautic institutions of Argentina, began in April, 2007, joining efforts of R&D groups of five National Universities (Córdoba, La Plata, Buenos Aires, La Pampa and Bahía Blanca) and a Ministry of Defense R&D Center (CITEFA), and under the sponsorship of the National Agency for Science and Technology Promotion (Agencia Nacional de Promoción Científica y Tecnológica). In addition of the main purpose, also it is intended to join efforts from several academic groups which were working isolated in different organizations.

The project, which is called Academic Flight Simulator, has been conceived with the main targets of: to get the know-how about own theoretical subjects of this area, and to train an interdisciplinary workgroup which is responsible to take this project ahead. The work is focused in three main areas: Flight Dynamics Model, Topographic Environment Model and Motion Platform. Targets for each area have been specifically defined, giving us the possibility to make their work easier and to give them a high independence of the rest. Their work implies to develop physical, data and control models associated which specific subjects and from these models algorithms and software applications are being developed. It is also purpose of the project to adapt a general simulation device (actually operative at CITEFA's facilities) in order to be able to use it as a test platform for different components that arise as a result of the work of each area.

This paper presents a Tensor 6-DOF Flight Dynamics model, which is intended to form the core of this system; it is discussed indepth, presenting the theoretical description of the Tensor Flight Dynamics model, as well as its implementation; also included is the description of the main coordinate systems used.

Development of the aerodynamic databases is also presented, oriented to two main aircraft types: a multi-role fighter (based in the known characteristics of the Dassault M2000) and a generic military jet trainer. At this stage of the project, engineering methods are the main ones used for calculations; the results obtained are used as a baseline for the aerodynamic coefficients, leaving for further stages the refinement of calculations, i.e. via CFD algorithms.

Keywords: Flight simulation, Flight Dynamics Modeling

1. INTRODUCTION

During year 2005, the need for the aeronautical community of Argentina of the developing of mathematical models for Flight simulation was evident. Most of the simulation work in both military and civil aeronautic fields is actually being performed in specific commercial off-the-shelf simulators, which in turn, since they are closed, proprietary systems, implies costly and difficult upgrades for any hardware or specification change. Moreover, academic job is carried through the use of specific software, developed in isolated efforts by R&D groups, according to their needs, and without any further prospective.

In view of this situation, and under sponsorship of the National Agency for Science and Technology Promotion (Agencia Nacional de Promoción Científica y Tecnológica) by mean of the project PAE2004-22614, started this program in April, 2007, joining efforts of R&D groups of five National Universities (Córdoba, La Plata, Buenos Aires, La Pampa and Bahía Blanca) and a Ministry of Defense R&D Center (CITEFA).

The project, which is called Academic Flight Simulator, has been conceived with the main targets of update the know-how about theoretical subjects of this area, as well as to train an interdisciplinary workgroup which is responsible to take this project ahead. The work is focused in three main areas: Flight Dynamics Model, Topographic Environment Model and Motion Platform. Targets for each area have been specifically defined and it has given us the possibility to make their work easier and to give them a high independence of the rest. Their work implies to develop physical, data and control models associated which specific subjects, developing the necessary algorithms and software applications.

This paper presents the Flight Dynamics model used in the project; it includes its tensorial formulation, which proved to be accurate, fast and easy to implement, while being mathematically rigorous and elegant. Also the models of the aerodynamic databases are presented, showing some of the results obtained, as well as some interesting results obtained from simulations for two types of planes considered.

2. FLIGHT DYNAMICS MODEL

Flight Dynamics, of course, has been historically treated as a classical mechanics problem, hence Goldstein (1959) and Landau and Lifschitz (1960) have provided us the theoretical framework for any analysis since late '50s to present. In the specific area of Flight Dynamics, the road has been paved by such authors as Perkins & Hage (1949) and Etkin

(1959, 1972), who were references for any aeronautical engineer for decades. Etkin, in fact, introduced the matrix treatment, as well as the digital calculations in the analysis. This treatment, together with the inclusion of quaternions as parameters for attitude description (i.e. Surber 1961, Ickes 1970 and Halijak 1978), formed the mainstream of the Flight Dynamics modeling up to late '80s.

The astonishing increase in computing power worldwide available from `90s to date, allowed the direct treatment of the Flight Mechanics in a tensor way (Zipfel, 2000), which was selected for this development.

2.1. Tensor form of the Flight Equations

The Flight Dynamics Model presented here is based on Zipfel (2000), so we will skip the full tensor development, presenting here the General Flight Equations:

The Newton's Second Law, which governs the translation of the aircraft (in fact, of any material body), takes the form:

$$m^B D^I v_B^I = f \tag{1}$$

being

m = mass of the body v = velocity f = external force and super and super and I denoting that we refer to body and Inerror

and super- and sub- indices B and I denoting that we refer to body and Inertial Frame, respectively

In a similar manner, the rotational behaviour of the airframe, expressed from Euler equations, and, as usual, referred to the body c.m., takes the form:

$$\left[I_{B}^{B}\right]^{B}\left[\frac{d\omega^{BI}}{dt}\right]^{B} + \left[\Omega^{BI}\right]^{B}\left[I_{B}^{B}\right]^{B}\left[\omega^{BI}\right]^{B} = \left[m_{B}\right]^{B}$$
(2)

were

 $\left[I_{B}^{B}\right]$ = Inertia tensor

 $\left[\frac{d\omega^{BI}}{dt}\right] = \text{angular acceleration of the body w.r.t. the Inertial frame, referred to body axes}$ $\left[\Omega^{BI}\right]^{B}, \left[\omega^{BI}\right]^{B}, \left[p, q, r\right] = \text{angular velocity of the body w.r.t. the Inertial frame, referred to body axes}$

 $[m_B]^B$ = external moment, in body axes

As in the previous equation, super- and sub- indices B and I denoting that we refer to body and Inertial Frame, respectively.

2.2. Coordinate Systems

As usual, several coordinates systems are used in this simulation; here we will only show the most significant ones; they are developed in detail in Perkins (1949), Etkin (1959-1972), Stevens (2000) and Zipfel (2000) :

- **Body frame.** With origin at vehicle cm, axes aligned with vehicle reference directions. The "x" axis points through the nose of the vehicle and lies with the downward-pointing "z" axis in the plane of symmetry. The "y" axis out of the right wing
- Vehicle wind-axes frame. Needed to specify the aerodynamic forces and moments. The angles that are used are the angle of attack (alpha) and the sideslip angle (beta). The origin of the system is at the c.m. of the vehicle. The "x" axis is parallel and in the direction of the velocity vector of the cm of the vehicle with respect to the air. The angle of attack is denoted by α when measured to the fuselage reference line from the projection of the relative wind on the body *x-z* plane. It is positive when the relative wind is on the underside of the aircraft. The sideslip angle is denoted by β and is measured to the relative wind vector from the same projection. It is positive when the relative wind is on the relative wind vector from the same projection. It is positive when the relative wind is on the right side of the airclane.

Vehicle stability-axes frame. The "x" axis is parallel and in the direction of the projection of the velocity vector (relative wind) on the symmetry plane. The "y" axis and the "z" axis are the same as in the body fixed system.



Figure 1. Body and wind axes, and aerodynamic angles.

- **Local level coordinate frame**. The Earth is presumed an inertial frame. The "x" and "y" axes are into the horizontal plane. The "x" axis points north and the "y" axis points east. The "z" axis points downward.
- **Flight-path coordinate frame**. It relates the velocity vector of the vehicle wrt Earth, to the geographic system. The "x" axis is parallel and in the direction of the velocity wrt Earth, and the "y" axis remains in the plane tangential to Earth. Two angles relate the velocity coordinates to the geographic system. The heading angle χ , measured from north to the projection of the velocity into the local tangent plane; and the flight path angle γ , measured from the tangent plane to the velocity vector.



Figure 2. Local level and Flight path coordinate frames.

2.3. Matrix Implementation

The force and moment equations (1) and (2), considering the flat earth as the inertial frame, take the classical form (Etkin 1972, Zipfel 2000)

$$m\left[\frac{dv_{B}^{E}}{dt}\right] + m\left[\Omega^{BE}\right]^{B} \left[v_{B}^{E}\right]^{B} = \left[f_{aer}, f_{prop}\right]^{B} + m\left[g\right]^{B}$$
(3)

and

$$\left[I_{B}^{B}\right]^{B}\left[\frac{d\omega^{BE}}{dt}\right]^{B} + \left[\Omega^{BE}\right]^{B}\left[I_{B}^{B}\right]^{B}\left[\omega^{BE}\right]^{B} = \left[m_{B}\right]^{B}$$

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(4)

where

g = gravity acceleration vector

Super-index *E* denoting the Earth as Inertial Frame, and sub-indexes *aer* and *prop* are used to denote aerodynamic and propulsion forces, respectively

The integration of Eqs. (3) and (4) yields the location of the aircraft c.m. and its angular position, respectively. Denoting

$$\left[\omega^{BE}\right]^{B} = \left[p, q, r\right] \tag{5}$$

and using the classical quaternion formulation (as given, for example, by Surber 1961, Ickes 1970, Halijak 1978, and reviewed by Zipfel 2000 and Stevens & Lewis 2003), we obtain the following set of differential equations:

$$\begin{bmatrix} r \\ q_{0} \\ r \\ q_{1} \\ r \\ q_{2} \\ r \\ q_{3} \end{bmatrix} = \begin{bmatrix} 0 & -p & -q & -r \\ p & 0 & r & -q \\ q & -r & 0 & p \\ r & q & -p & 0 \end{bmatrix} \begin{bmatrix} q_{0} \\ q_{1} \\ q_{2} \\ q_{3} \end{bmatrix}$$
(6)

Defining

 $q_0, q_1, q_2, q_3 =$ quaternion components

and the rotation matrix between body and local-level systems

$$[T]^{BL} = \begin{bmatrix} q_0^2 + q_1^2 + q_2^2 + q_3^2 & 2(q_1q_2 + q_0q_3) & 2(q_1q_3 + q_0q_2) \\ 2(q_1q_2 + q_0q_3) & q_0^2 - q_1^2 + q_2^2 - q_3^2 & 2(q_2q_3 + q_0q_1) \\ 2(q_1q_3 + q_0q_2) & 2(q_2q_3 + q_0q_1) & q_0^2 - q_1^2 - q_2^2 + q_3^2 \end{bmatrix}$$
(7)

being $[T]^{BL}$ = rotation matrix between body and local-level systems

Equations (3), (4) and (6) form the complete set of ordinary differential equations to be integrated, task which is performed via a 4th Order Runge-Kutta algorithm (Schilling and Harris,2000).

4. AIRCRAFT MODELS

As main aircrafts models used in this development, we took that of a multirole combat aircraft, based in the known characteristics of the Dassault Mirage 2000, and a military trainer, in the class of FMA IA-63, CASA C101 or Aeritalia M211. These planes were selected due their characteristics (i.e the M2000 configuration is both modern and relatively simple to model and analyze, while the military trainer presents interesting problems in transonic flight).

Main characteristics for the fighter type are:

- Low, thin delta wing, 58° leading edge sweep, 3% maximum thickness, area ruled fuselage.
- Two section elevons and leading-edge slats on wings.
- Fixed strakes over intake ducts and wing-mounted air-brakes.
- Vertical tail, no horizontal tail.
- Single turbofan power plant with afterburning; variable air intakes, with movable half-cone center body.
- Maximum Mach number 2.2, 20000m service ceiling, g limits of +9.0/-3.2 (+11.0/-4.5 ultimate).

While those for the trainer are:

- Unswept shoulder-mounted, supercritical wing; leading-edge sweep of 5 degrees and an anhedral of 3 degrees.
- Hydraulically powered ailerons and single-slotted Fowler flaps on the wings.
- All-moving downward sloping tailplane.

- Sweptback fin with an integral rudder.
- Single 1587 kg (3500 lb) Honeywell TFE731-2C-2N turbofan mounted in the central fuselage.
- Max level speed: 745 km/h (402 kts), service ceiling: 12 900 m (42 320 ft), g limits: +6/-3.

Based in these configurations, we will present some of the models used for aerodynamic predictions.

4.1. Aerodynamics

The terms of aerodynamic forces and moments given in eqs. (3) and (4) are, as usual (see Etkin, 1972, Zipfel, 2000, and Stevens & Lewis, 2003), modelled trough the use of nondimensional aerodynamic coefficients; in this project, they are modelled as functions of the attack and yaw angles, as well as Mach and Reynolds numbers and control deflections; the coefficients included in the model are:

- Longitudinal coefficients CD,CL, Cm, CN, and CA
- Static derivatives CLα, Cmα, Cyβ, Cnβ, Clβ
- Dynamic derivatives CLq, Cmq, CLad, Cmad, Clp, Cyp, Cnp, Cnr Clr
- Increments due to control deflections and high lift devices D(CL), D(Cm), D(CLmax), D(CDmin), D(CDI),

These coefficients, grouped in matrices and dimensionalized, are used to calculate the forces and moments acting on the aircraft. The matrices used by the models are:

Longitudinal coefficients matrix

$$\begin{bmatrix} CD\\ CL\\ CM \end{bmatrix} = \begin{bmatrix} CD_{basic} & 0 & 0 & CD_{\partial elev}\\ CL_{basic} & CL_q & CL_{d\alpha/dt} & CL_{\partial elev}\\ CM_{basic} & CM_q & CM_{d\alpha/dt} & CM_{\partial elev} \end{bmatrix} * \begin{bmatrix} 1\\ Q.c\\ (d\alpha/dt).c\\ \partial elev \end{bmatrix}$$

Where the subindex *basic* denotes the sum of zero angle of attack values and the α -dependent term

Lateral-directional coefficients matrix

$$\begin{bmatrix} CY\\ CN\\ Cl \end{bmatrix} = \begin{bmatrix} CY_{\beta} \ CY_{p} \ 0 \ 0 \ CY_{\partial rud.} \\ CN_{\beta} \ CN_{p} \ CN_{r} \ CN_{\partial ail.} \ CN_{\partial rud.} \\ Cl_{\beta} \ Cl_{p} \ Cl_{r} \ Cl_{\partial ail.} \ Cl_{\partial rud.} \end{bmatrix} * \begin{bmatrix} \beta\\ P.b\\ R.b\\ \partial ail.\\ \partial rud. \end{bmatrix}$$

All of them are calculated for different conditions of speed and altitude. For the aerodynamic model of the fighter we have: Mach 0.1, 0.3, 0.6, 0.9, 1.2, 1.5, 1.8, 2.1 and 2.4; Altitudes 0, 10000 and 20000 meters, making a total of 27 data groups. For the trainer we have: Mach 0.2, 0.4, 0.6 and 0.8; Altitudes 0, 5000, 10000 and 15000 meters making a total of 16 data groups. The objective of this scheme is to cover the whole flight envelope with data in order to perform the interpolations for the requested flight condition.

Due to the large amounts of data needed, at this development phase of the program mainly engineering methods are used, such as those presented in Hoak and Finck, 1974, although more detailed calculation methods (i.e. panels and/or CFD Navier-Stokes integration) are previewed for next phases of the project.

Figures 3 to 5 shows the effects of mach over drag and pitch stiffness and damping coefficients for the fighter, showing in fig. 6 the pitch behaviour obtained, for a control pulse as function of flight Mach number.



Figure 3 - Fighter - Mach effects on Drag







Figure 5 – Fighter - Mach effects on pitch damping



Figure 6. – Fighter response to an elevator pulse

It is shown the subsonic intrinsic instability typical of most modern fighters, as well as the high degree of supersonic stability, also typical of delta wings. It must be noted that these simulations were used to design a longitudinal stability augmentation system for the real time hands-on piloting of the model.

The trainer model, with its supercritical wing and low tail length, also showed an interesting longitudinal behaviour, in the proximity of M=0.7, as can be seen in figs. 7. This reduction in the trimmed pitch stiffness is also typical of those type of wing sections, as shown by Longo et al. (1983)



Figure 7 - Trainer - Mach effects on pitch stiffness

The pitch damping coefficients as function of Mach number are shown at fig. 8, while the lateral ones are at fig. 9.



Figure 8 - Trainer - Mach effects on pitch damping



Figure 9 – Trainer - Mach effects on lateral derivatives

Figures 10 and 11 show the lateral-directional response to a rudder doublet for different Mach numbers, showing the coupling between lateral and directional channels as around M=0.6; dumping effect prevent divergent behaviour up to M=0.605, becoming the divergence evident at M=0.61; these results, which are, of course, obtained without the consideration of any stability augmentation system, are being used for the design of one, necessary for human piloting of the simulator.







Figure 11 – Trainer Roll rate vs. time at different Mach numbers

Figure13 show the effects of the c.g. position on the longitudinal stability of the trainer aircraft. The simulations were run at M=0.56 and three c.g. positions: 10%, 20% and 25% of the mean aerodynamic chord. The airplane is artificially trimmed during the first 10 seconds. Then the control stabilization system is turned off, and an elevator doublet is performed (+-5 degree, 1sec. period). Results show that the airplane is stable for c.g. positions of 10% and 20% becoming unstable for the 25% location. The difference in the final angle of attack for stable cases is explained in the fact that before the doublet it is artificially trimmed to maintain Mach number, while after the manoeuvre it finds an slightly different equilibrium condition.

Angle of attack Alpha vs. time



Figure 13 - Angle of attack vs. time at M=0.56 for different c.g. locations

5. CONCLUSSIONS

The Flight Dynamics model used for the development of the Academic Flight Simulator was presented, including a brief mathematical treatment of it; the matrix form of flight equations, including the definition of attitude by means of quaternions, were also shown, as they were implemented in the simulation code.

The Aerodynamic model was also discussed, from the point of view of its organization, rather than the methods used to obtain the coefficients; this was done this way due to the project necessity for a complete, although only approximate, aerodynamic database to test integration issues, leaving the precise calculations for further stages. In fact, the aerodynamic models of both configuration described here are being generated to be introduced in some CFD codes (both public-domain and in-house developed), as well as the searching of documentation about similar configurations in order to cross-check the results.

Some of the most interesting results of these preliminary simulations are also shown, since they illustrate some typical behaviour of the planes considered.

We consider that the work performed up to date in this subject may serve as a good basis for the development of a modern, reconfigurable, low cost Flight Simulator, which is the final goal of this project; further analysis and tests will confirm this hope.

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