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SUBSCALE FLIGHT TEST MODEL DEVELOPMENT AND TESTING AS A TOOL FOR UNCONVENTIONAL AIRCRAFT DESIGN

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ABSTRACT

This work has the objective to show development of a non-conventional subscale aircraft tests and compare a preliminary numerical analysis with wind tunnel tests. The subscale flight tests can be used as a low cost tool and that can improve the learning curve, considering the future aircrafts are characterized by the use of new technologies and radical configurations. For this validation was built the ITA-BWB aircraft, a single engine and tailless concept. This project demonstrates all steps of preliminary analysis with VLM software, preliminary flight tests and wind tunnel tests, where these data were used for simulations of specific maneuvers used in parameter identification. Finally, the simulations demonstrated consistency between the static derivatives acquired by VLM software and wind tunnel tests, which were used to estimate dynamic derivatives that allowed the simulation of specific maneuvers for subscale flight tests.

KEYWORDS: *Wind Tunnel, Subscale Flight Test, Stability and Control, Flight Mechanics, VLM*

NOMENCLATURE

α - angle of attack
ρ – Air density
S – Wing area
$\bar{c}$ – Aerodynamic mean chord
Kn – Static Margin
Φ – Bank angle
Ψ – Yaw angle
Θ – Pitch angle
C_D – Drag Coefficient
C_L – Lift coefficient
C_M – Longitudinal Moment Coefficient
Q – Dynamic pressure
q - Pitching rate
δe – Elevon deflection
C_{L0} – Lift Coefficient for α=0
CM0 – Moment coefficient for α=0

1. INTRODUCTION

1.1. Motivation

Nowadays, the need to reduce the emission of polluting gases in the atmosphere and noise pollution is the focus of research in the aeronautical industry, where the object of study is to increase the energy efficiency of aircraft. Until now a lot of effort is being done to increase the efficiency of propulsion systems, aerodynamic, structural parts of aircraft and aeronautical infrastructure.
Considering this context it is possible to observe that the use of conventional configurations reached his technological limit [1], which make the researcher thinking about the necessity of developing new configurations, new systems and new structural concepts.
When the current projects reach the technological limit, it will appear new aircraft configurations like Tailless, Box Wing, Twin Fuselage, C-Wing and others, but this concepts still in theoretical analysis and do not meet the technological maturity required to produce a full scale aircraft. Even though a small portion, it is known today that the aviation represents 2% of CO_2 emissions in the atmosphere [2]. This is not well seen by public thinking today, consequently these makes the regulatory agencies to concern about and establish rules and goals to decrease the pollution produced by the sector. To solve this problem it is need a multidisciplinary effort. This combination is compound by new technologies, more efficiency in operations, investing in infrastructure and investing in biofuels as shown in the Fig. 1.

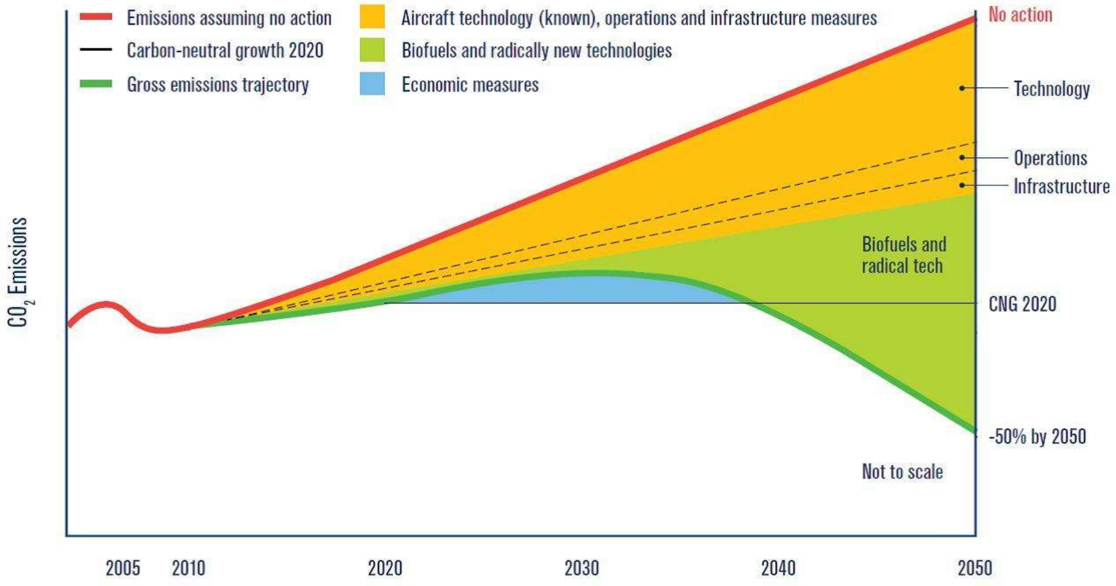

Figure 1 – CO2 emission reduction [2].

Considering this context it is possible to observe the evolution of the use of scaled models applying similarity criteria like wind tunnel tests and subscale flight tests like the figure below Fig. 2.

Figure 2 – Flexbird [3].

The experimental analysis of physical prototypes it is an useful aeronautical project tool, if can complement the available knowledge in the initial project phase of an unconventional aircraft [4] and [5]. In this way it is possible to understand that this tool can maximize the knowledge of project during the phases of Conceptual Project and Preliminary Project where the committed cost represent 80% of the total budget of developing of an aeronautical project [6] and consequently can significantly reduce the risks related to maturity of the product minimizing the delays inherent to developing of non-conventional concepts.

Nowadays the development of conceptual is made by analytical tools, empirical and historical analysis, however this is not enough to the development of an innovative concept. The application of similarity criteria can be applied to reduced scaled models. The use of remotely piloted aircrafts has intensified, in this case is possible to identify dynamic parameters which are very important to development of unconventional concepts. This enables a faster maturity of the project, in the areas where the risk is too high, for example in flight mechanics and performance. It is very helpful to traditional project method of using historical data, add a methodology of a subscale model which minimizes the development costs and the risks of project. A proposed methodology is presented in the figure below Fig. 3.

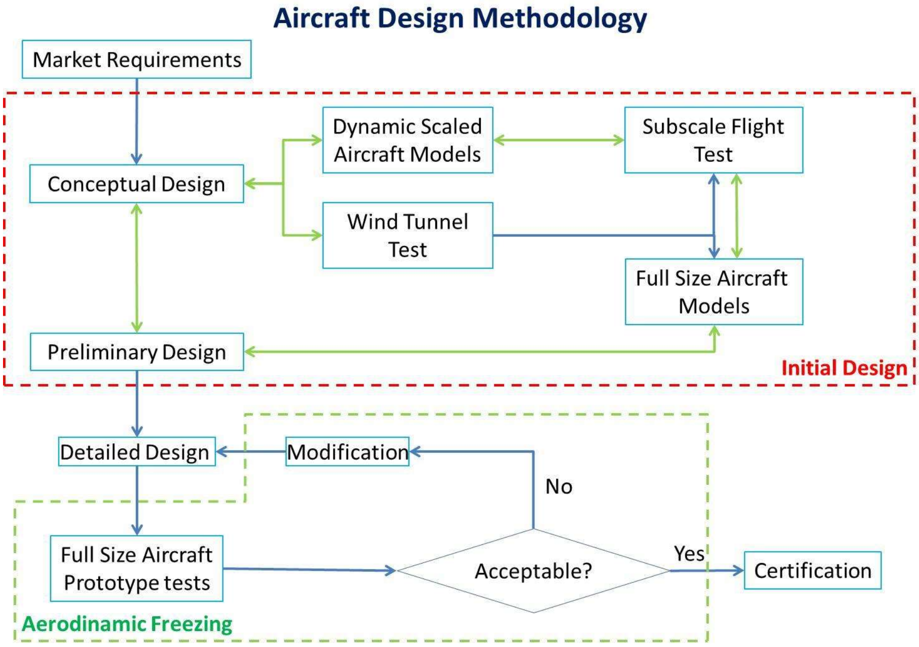

Figure 3 – Aircraft Design Methodology with subscale flight test.

Considering the economic potential that the subscale test can bring to the aeronautical industry, the present work will show the development of a subscale aircraft with a non-conventional concept which will be put to test in numerical analysis, wind tunnel tests and subscale flight tests.

1.2. Objectives

The present work has the objectives:

1) Propose a platform of non-conventional subscale as a tool to the development of aircraft;
2) Validate the technical viability of subscale flight tests with low cost data acquisition systems;
3) Compare and validate the theoretical data related to longitudinal movement using wind tunnel tests and with simulation.

2. THEORETICAL APLICATION

2.1. Similarity Criteria

Considering the scope of this work, there are several non-dimensional numbers to be discussed such as the Reynolds Number, Mach Number and etc, but for the application of subscale flight tests, the Froude Number will be used from the tests of the ship models, the Froude number was developed to provide a similarity criterion in order to compute the points of pressure and the non-dimensional shape of the waves created by the hull of the vessel [7].
This non-dimensional number ensures the gravitational and inertial effects with geometrical similarity and is expressed by the equation Eq. 1. Therefore, is possible to apply for a particular geometric scale, appropriate values of mass scale and inertia of the model.

$$Fr = \frac{u}{\sqrt{lg}} \tag{1}$$

The wind tunnel test has accuracy to determine the aerodynamic parameters. This result is due to years of development of data acquisition which allows the determination of up to six degree of freedom where the measurements can be in static situation or in dynamic situation. Usually static test are useful to acquiring the drag polar and static stability derivatives. The dynamic tests are focused in the acquisition of dynamic derivatives to use in the flight mechanic model. A wind tunnel test has a large infrastructure involved and this result in a high cost. To illustrate, the wind tunnel test presented here had a cost around U$ 100.000, while the model built had an approximate cost of U$ 2500, and their respective free flight tests would cost around U$ 3500. This values show the use of remotely piloted aircraft for parameter identification can significantly reduce the development cost of the project. To execute the subscale test correctly is necessary to understand the limitations. Even though the derivatives has almost the same value, the nonlinear portion of the curves do not have the same values. The lift curve it is an example of the linear part of the parameter is equal for both the full scale airplane and for subscale airplane, however CL_{MAX} do not are equal due to discrepancy of Reynolds number like shown in the Fig. 4. These data for example create disagreements near to the aircraft stall, like analysis of spin, landing performance and take off.

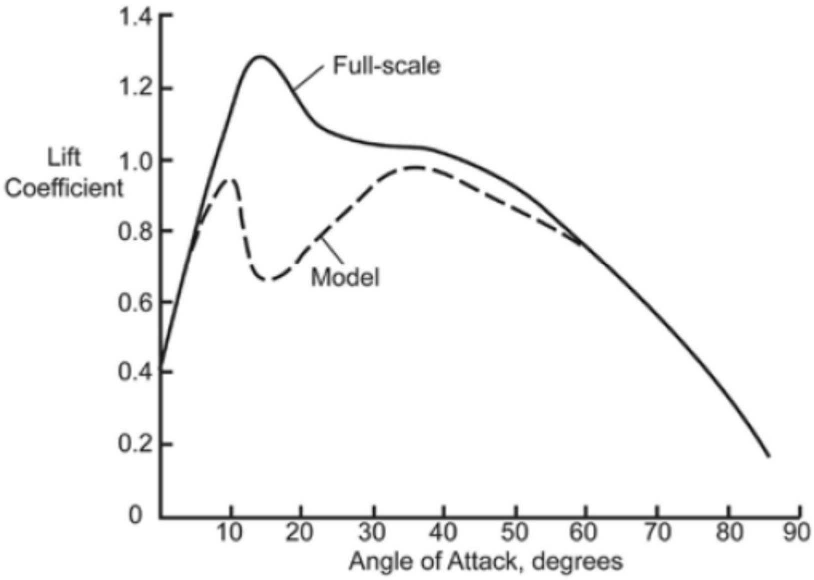

Figure 4 – Difference between high and low Reynolds Number [5].

The use of Froude number is the most used tests involving dynamic similarity. Nowadays, the cost of embedded acquisition systems can reach only U$ 500, this is enough to record flight data in maneuvers.

2.2. Vortex Lattice Method (VLM)

The Vortex Lattice Method (VLM) is a capable computational tool to determine the value of the aerodynamic parameter, where the main idea is to discretize a wing in a finite number of horseshoe vortex elements in span direction and in chord direction [8]. Usually the points of control are positioned in x at ¾ of local chord and the horseshoes vortex frontiers are positioned at ¼ of local chord. This method is based in the potential theory which does not predict the effects of boundary layer displacement and stall, generating only linear results.

2.3. Flight Mechanics

To describe the flight mechanics, it is necessary to define a coordinate system. One of the coordinate systems will be fixed in earth. The second coordinate system will be fixed at aircraft body. Both systems are elaborated using the right-hand rule as presented in the Fig. 5.
Using the coordinates systems is possible to describe the Euler angles. Then, three successive rotations are necessary. First rotation occur around the vertical axis z_1 where (x_1, y_1, z_1) -> (x_2, y_2, z_2). The second rotation θ happen around the axis y_2 where (x_2, y_2, z_2) -> (x_3, y_3, z_3). Ultimately the third rotation Φ occur around x_3 where (x_3, y_3, z_3) -> (x_b, y_b, z_b).

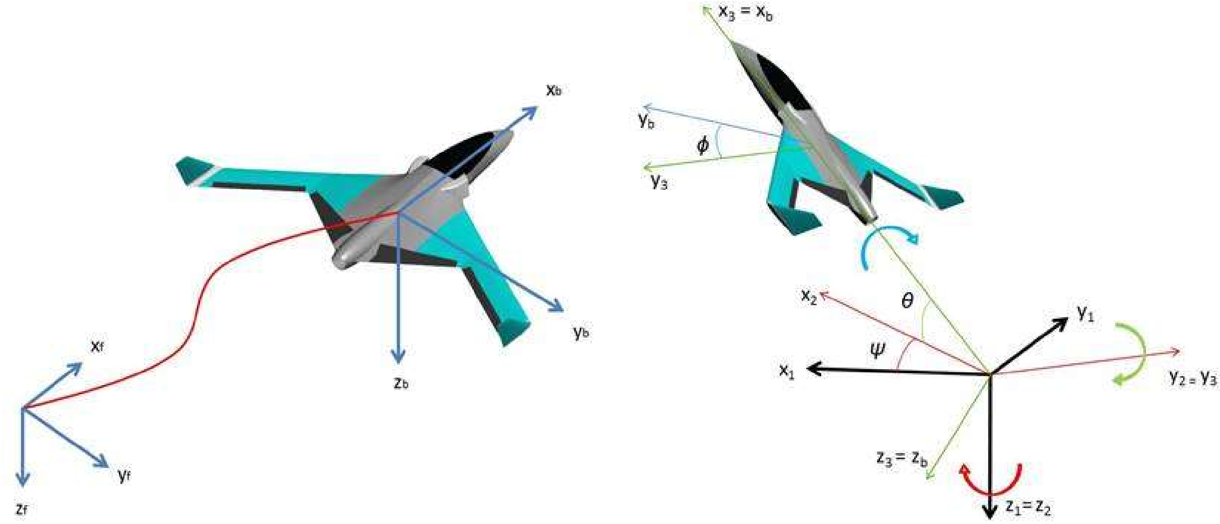

Figure 5 – Coordinate systems and Euler angles

The forces during flight at aircraft are composed by aerodynamic force, thrust force and gravitational force. These forces can be expressed by X, Y and Z, Tx, Ty and Tz and Wx, Wy and Wz respectively. They can be solved using the fixed coordinate system of the body. See Fig. 6.

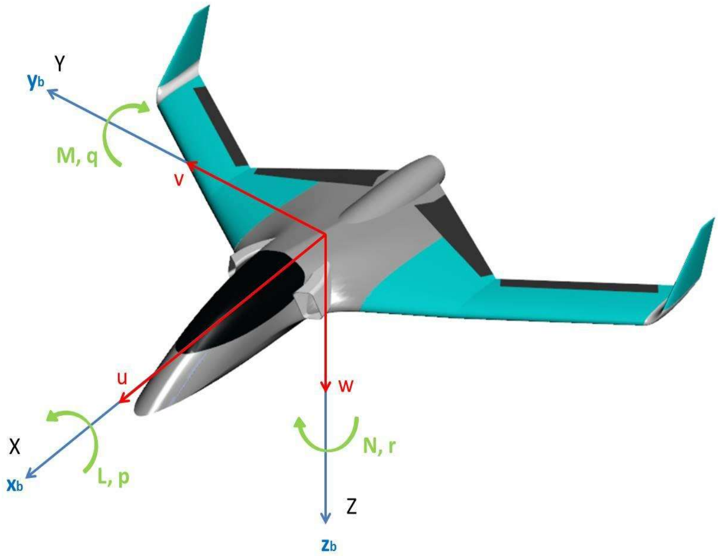

Figure 6 – Aircraft Forces, Moments and Velocities

To the study of aircraft flight mechanics is important to study the relation between forces, moments, and speeds which compose the six degree of freedom. The equations are shown below according to [9].

Force Equations:

$$X - mgsin(\theta) = m\dot{u} + qw - rv \quad (2)$$

$$Y - mgcos(\theta)\sin(\emptyset) = m\dot{v} + ru - pw \quad (3)$$

$$X - mgcos(\theta)\cos(\emptyset) = m\dot{w} + pv - qu \quad (4)$$

Moment Equations:

$$L = I_x\,\dot{p} - I_{xz}\dot{r} + qr\,(I_x - I_y + I_{xz}\,pq) \quad (5)$$

$$M = I_y\,\dot{q} + rq\,(I_x - I_z) + I_{xz}(p^2 + r^2) \quad (6)$$

$$N = -I_{xz}\dot{p} + I_z\dot{r} + pq\,(I_y + I_x) + I_{xz}qr \quad (7)$$

Looking to the given aerodynamic forces and moments, these are described in function of dynamic pressure (Q), reference area (S) by means of follow equations:

$$Z = C_z QS \quad (8)$$
$$X = C_x QS \quad (9)$$
$$M = C_m QS\bar{c} \quad (10)$$

Where:

$$Q = \frac{\rho V^2}{2} \quad (11)$$

3. TEST AND RESULTS

3.1. Numerical Analysis

Based on geometric parameters, the wing of ITA-BWB was built in VLM environment for analysis of aerodynamic forces and moments. The geometric volume of the cockpit region wasn't modeled for preliminary studies. For the validation of the subscale test proposed, it was modeled wings in 1/1 scale and in modeled scale. The Fig. 7 shows a comparison between the curves of the two models.

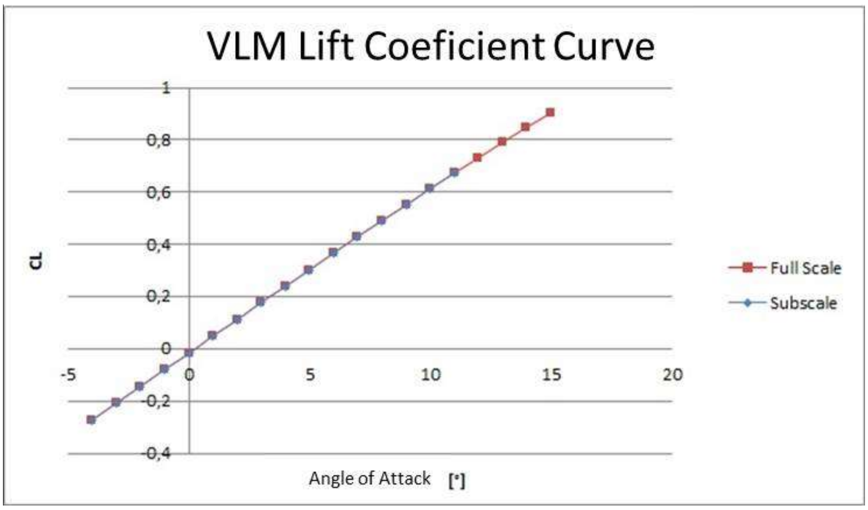

Figure 7 – Comparison between high and low Reynolds Number

Before to execute the flight test, it is necessary to estimate the controls and stability derivatives of the aircraft. This derivatives will contribute in the physical model of the aircraft behavior. To make feasible the parameters identification, it is necessary to know which frequencies must be excited during the maneuvers in flight. This work do not have the objective to determine the longitudinal parameters of the subscale aircraft, however the data collected will be used in future work.

3.2. Wind Tunnel Tests

The wind tunnel tests was realized in the *Laboratório Aerodinâmico Subsônico TA-2* (Subsonic Aerodynamic Laboratory), located at IAE, São José dos Campos as shown in the Fig. 8. This tunnel has a closed circuit and a section of 2,1 m of high, 3 m wide and 3 meters long, being able to perform subsonic tests with maximum speed of 127 m/s with turbulence equal to 0.7%. The uncertainty of this tunnel are around of 0,2% for speed, 0,2% for aerodynamic forces and 0,3% for aerodynamic moments. Were executed tests in two different speeds which cover the flight envelope, the values were 20 m/s and 40 m/s with the objective to identify the existence of different aerodynamic effects for both speeds. The tests included the forces and moments in six degree of freedom, where the angle of attack changed from -5° until 26°. At longitudinal tests it was applied $-5º$ of deflection in all surfaces of control of the wing, called elevons, this configuration had the goal to study the variation of derivatives in moment, lift, and drag. This test was also done with the aircraft inverted at roof of the tunnel in order to correct the measure errors due to the interference between the mast and the model.

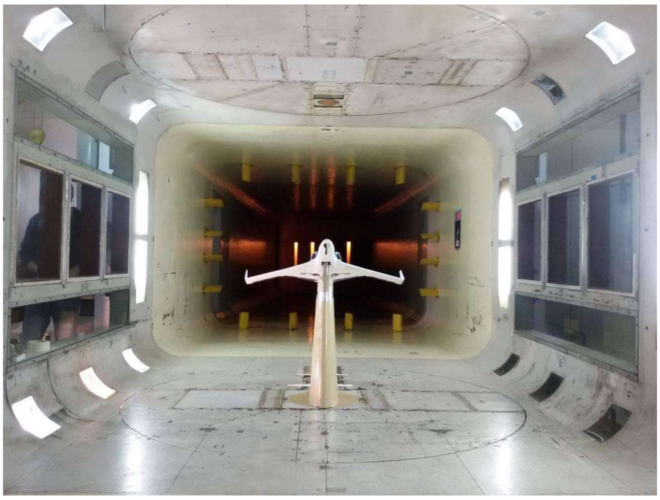

Figure 8 – Wind Tunnel test lay-out.

The Fig. 9 shows the lift data found in the test without the elevator deflection. Without to check the numerical data, can be verified a phenomenon of Vortex Lift at high values of angle of attack due to a second stall near to values of angle of attack between 17º and 25º at speed of 40 m/s. To the same test speeds, were executed tests with elevator deflection δe=-5º with the objective of get values of control derivatives of the aircraft. An important point to discuss is the determination of the value of the C_{L0} of the model that show variation for both speeds tested and don't match with the calculated values by VLM. The variation of the value in the test can be due of a possible gap in the fastening system. This point will be discussed in the analysis of the longitudinal moment curve. How the VLM analysis does not include the friction effects, probably this could be a factor that generates the difference between these values.

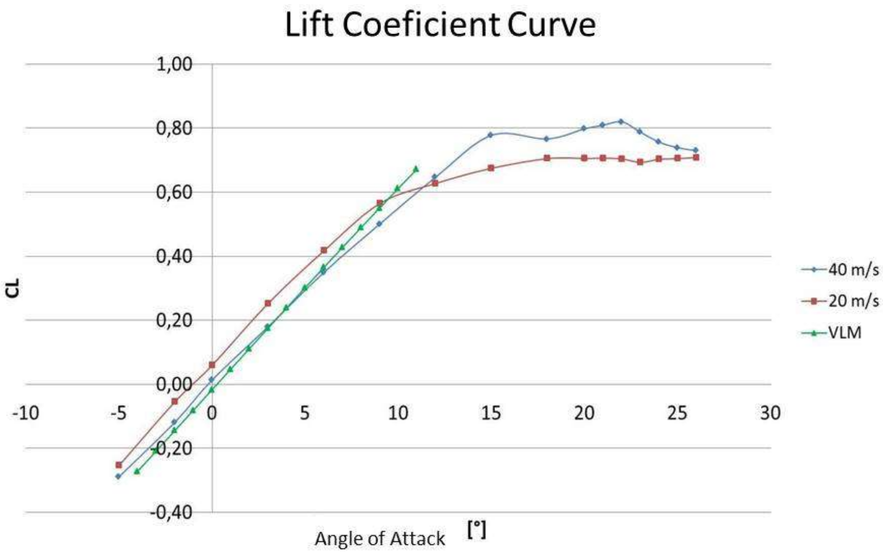

Figure 9 – Lift coefficient curve.

The aircraft moment curve was measured with respect to the fixation of the mean mast and the data are presented in the Fig. 10.

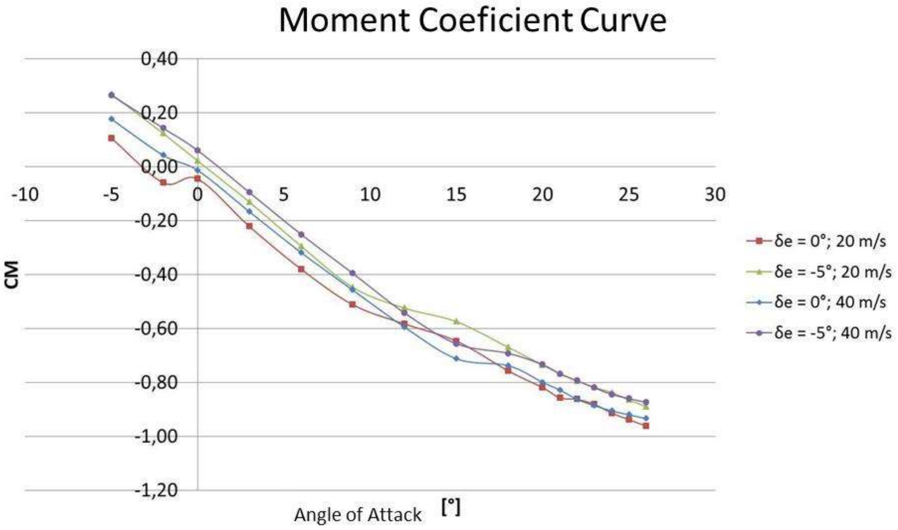

Figure 10 – Moment coefficient curve.

Before any computation it is necessary to notice a phenomenon similar to a backlash at negative low angles. Probably the fastening device of the model has not been adjusted properly or his respective project wasn't enough to avoid gaps during the pitch movement of the model. To calculate this derivative, it was considered the linear region of the curves.

3.3. Longitudinal Flight Mechanics Simulation

In order to check the derivatives obtained in the wind tunnel test and to ensure the integrity of the aircraft in the first flight, it was realized some simulations.
Another dynamic derivatives were estimated and a simulation was realized to observe the behavior of the aircraft for a given CG. Thus, it was acquired the values C_{L0} = 0,09 and C_{M0} = 0,01, considering a static margin K_n=15% and longitudinal inertia of I_{yy}= 0,049 kg m^2.
For the simulation inputs it was also calculated the longitudinal derivatives, the values are presented in the table 1. The values of C_D are calculated using the Eq. 12.

Table 1: Longitudinal static and dynamic derivatives

	CD	CL	CM
α	-	3,14	-0,47
$\hat{q}$	-	2,51	-0,66
$\hat{\dot{\alpha}}$	-	-1,37	-0,73
δe	-	-0,91	0,16

Considering the sum of the longitudinal coefficients, we have:

$$C_D = C_{D0} + K_1 C_L + K_2 {C_L}^2 \qquad (12)$$

With the values of these derivatives and with the models presented in section "Flight Mechanics" it was built an algorithm in *Matlab* which is capable of simulate the behavior of the model. The following simulations and the analysis were performed considering the linear region of the forces and moments curves. The first simulation lasted five seconds and the altitude considered was the same of the city of São José dos Campos, H= 1300 m , with a speed of V=30m/s at straight and leveled flight and an initial perturbed alpha = 10º. Initially it was found the values of longitudinal dynamic poles shown in Table 2.

Table 2: Dynamic Longitudinal Poles

Real Part	Imaginary Part
-4,85	+14,54 i
-4,85	-14,54 i
-0,05	+,46 i
-0,05	-0,46 i

From the initial data it was computed the initial conditions for angle of attack α= 1,22°, elevator deflection δe= -3,48° and power ratio of 20,6% of engine level.
The behavior presented by aircraft was stable during the simulation showing that the pilot will not have many difficulties during the parameter identification flight test campaign. It would be prudent to check the flight quality according to aircraft configuration, level flight and flight phase. Although the model is a subscale aircraft, the representativeness of flying qualities must be better understood because the piloting is external and visual. In this case some behaviors cannot noticed by the pilot. The Fig. 11 shows the data of the aircraft previously described.

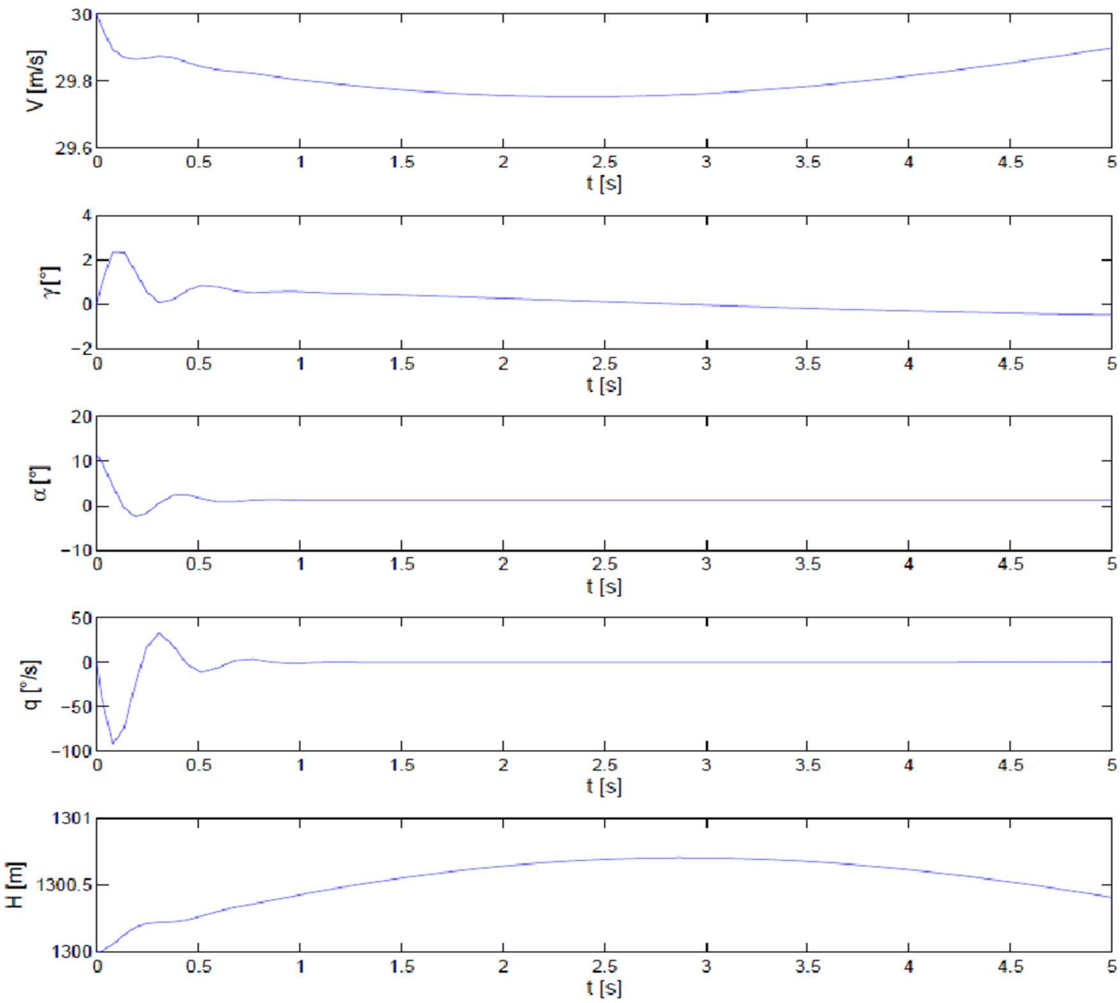

Figure 11 – Longitudinal dynamics response: Short Period

In a preliminary analysis it can be verified that the angle of attack variation, the variation of path angle and the variation of pitch rate is damped after approximately one second, showing the effectiveness of the damping in Short Period.
To check the consistency of the control derivatives, it was simulated a simple maneuver of pull up. After two seconds of simulation it was applied a command δe= -10° and it was sustained a constant traction. The answer of the aircraft is represented by the Fig 12.

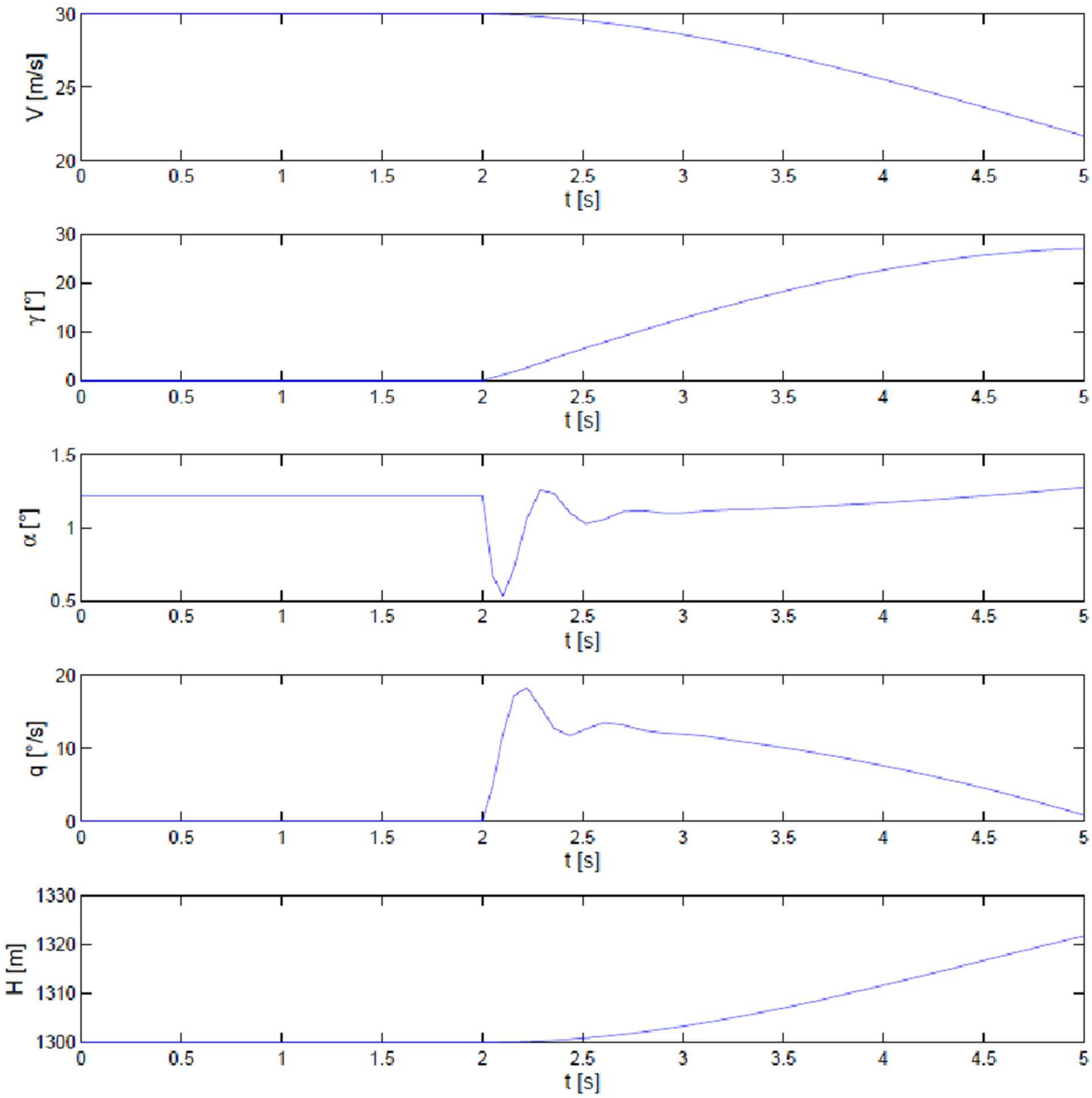

Figure 12 – Longitudinal pitching response.

During the pull up the pitch rate becomes positive, the speed of aircraft decreased and the altitude went up. This simulation represents an appropriate behavior to the maneuver.
A doublet maneuver was also performed with the objective to excite the frequency of short period. After five seconds of simulation, with initial conditions of H=1300 m and V=30 m/s, it was applied a pitch down delta in the elevator of δe = 10° during 0,16 s, after it was commanded a pitch up delta of δe = -10° during 0,16s and finally the elevator returns to initial position. So it was possible to obtain the answer shown in Fig. 13.

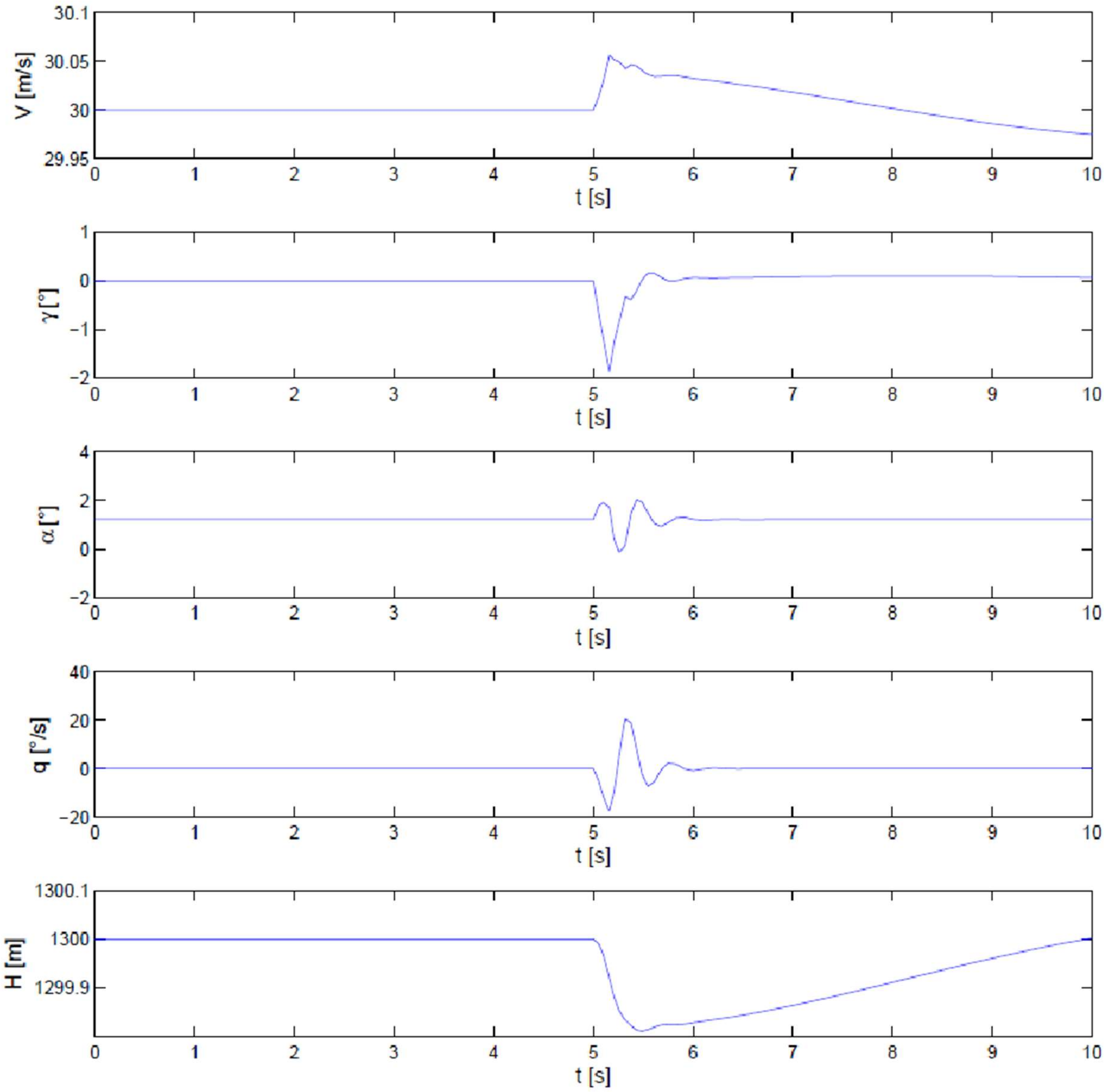

Figure 13 – Doublet maneuver response.

4. CONCLUSION

The present work demonstrated the technical feasibility of using VLM software to estimate the static stability values derivatives and consequently to assist in the preliminary simulations of flight mechanics for an unconventional aircraft. Subscale flight tests will be performed to determine the values of dynamic derivatives, helping to develop new design techniques, minimizing the time and cost of new concept development.

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