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Control Augmentation System and Auto Pilot using Backstepping Thecnique

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Abstract. *The main objective of this paper is to show the application of a nonlinear control technique in reference tracking for an aircraft control to a group of distinct variables. The technique selected to design the controller was the backstepping. The central idea of the backstepping technique is to design a controller recursively, with some state variable been consider a virtual control and having an intermediate control law designed for them. With the help of Lyapunov stability theory the backsteeping controller takes advantage of the Lyapunov control function characteristics to attain a global asymptotic stability. The design of the controller show in this paper pursuance a reference tracking for the longitudinal, lateral and directional axis through the angle of attack, load factor, velocity, altitude, sideslip angle and roll angle, all of them with one specific control structure.*

Keywords: *Nonlinear Control, Backstepping, Aircraft Control*

1. INTRODUCTION

With the advance of technology of micro processing, it is increasingly viable to ship control system that requires more computational effort, enabling the use of a greater variety of control techniques.

Today in the aircraft industry most of the control designs are based in linear techniques, nevertheless, aircrafts are nonlinear systems whose characteristics can vary according to the flight condition or aircraft configuration. Therefore, a gain calculated using linear control techniques that stabilizes the aircraft for a determined flight condition can be insufficient for other flight condition, a solution is to use a gain scheduler, whose main idea is to design a set of linear controllers for distinct flight conditions and interpolate the gain between them. The gain scheduler is the basic nonlinear technique.

As the market demands for a better performance with an improved fuel economy, a weight reduction, more controllability considering an expanded flight envelope, the system non linearities should be consider, and for that other nonlinear control techniques are attractive, one can cite dynamic inversion, sliding modes, and the $backstepping$, this paper will focus on the $backstepping$ technique.

The $backstepping$ control techniques were developed in the $90'$s decade by Petar V. Kokotovic in "The joy of feedback: nonlinear and adaptive". Control Systems Magazine, IEEE 12 (3): 7 —17 and Lozano, R.; Brogliato, B. em "Adaptive control of robot manipulators with flexible joints". IEEE Transactions on Automatic Control, 37 (2): 174 —181.

Recently, important research of backstepping technique for aircraft control is being done at Delft University (TUDelft), where "(Sonneveldt, 2010)", proposed the design of a Stability and Control Augmentation System (SCAS) for a modern fighter aircraft using an adaptive backstepping algorithm and handling qualities evaluation. Another work "(Henriquez, 2011)", in which a control system based on backstepping for a flexible medium transport aircraft was developed.

The objective of this technique is to design a stabilizing control for nonlinear system based on the Lyapunov stability theory.

2. AIRCRAFT MODEL

A valuable modeling is extremely important for the $backstepping$ control work in an adequate manner.

The aircraft model used in this work is the F-16 Fighter illustrate in "Fig. 1" and described by "(Stevens and Lewis, 2003)" and "(Sonneveldt, 2006)".

For the control design it was consider that the aerodynamics coefficients were represented as n-polynomials equations, this polynomials were calculated by "(Morelli, 1998)", the reason for that is because when boarding a control software, sometimes it is not viable to record all tables that reflects the behavior of the aircraft, so the polynomials approximation

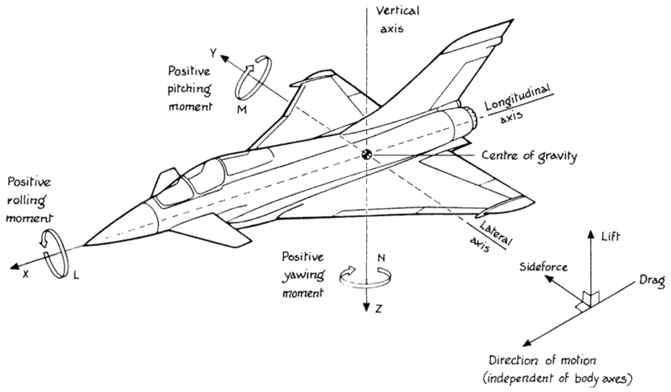

Figure 1. Aircraft Forces and Moments Representation

are an acceptable approximation. The control law shall be robust enough to not be influenced by the difference between the aircraft expected behavior and the aircraft real behavior.

The “Fig. 2” and “Fig. 3” shows the difference between the coefficients C_{nr} and C_x considered in the aircraft and in the control law.

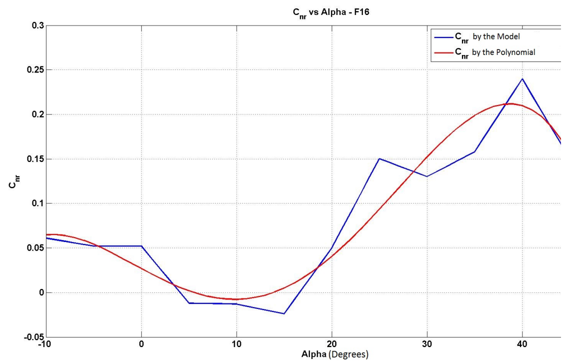

Figure 2. C_{nr} Comparison

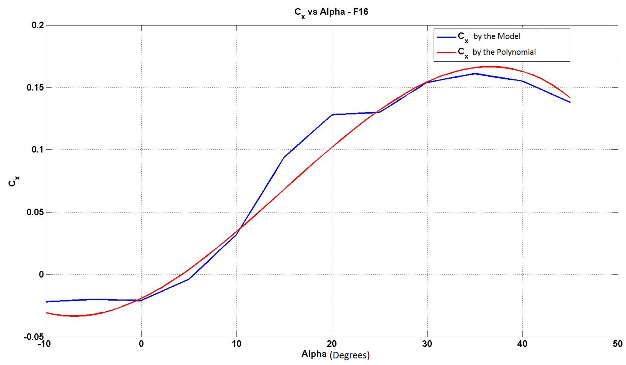

Figure 3. C_x Comparison

3. BACKSTEPPING DESIGN

The nonlinear $backstepping$ technique is centered in the Lyapunov stability theory. The name $backsteeping$ is due to the recursive nature of the control design method. The method begins with the scalar equations that are separated by a great number of integrators from the output variables and ŚŠtake a steep backŠŠ to the input variables. At each steep a $virtual control$ is calculated, and in the final steep the real control law is found.

A Important characteristic of the $backstepping$ method is it flexibility, for example, is a design choice which non linearities should be consider and which non linearities should be removed.

The $backstepping$ technique can be summarized in three repetitive steps:

- 1. Introduce the virtual control and state error, rewriting the state equation according to these errors.
- 2. Choose a control Lyapunov function, and consider it as a final stage
- 3. Choose a stabilizer term for the virtual control that makes the control Lyapunov function stable.

3.1 Three Axis Simultaneous Control

For the design of a controller that acts in the three axis from the aircraft simultaneous (longitudinal, lateral and directional axis) the variable chosen the angle of attack, sideslip angle and roll angle. The virtual controls are related to the roll rate, the pitch rate, the yaw rate, the pitch angle and the yaw angle represented as $x_1 = [\alpha, \beta, \phi]^T$, $x_2 = [p, q, r]^T$, $x_3 = [\theta, \psi]^T$. The control of the aircraft is reached through the deflection of the surfaces, the elevator, the aileron and the rudder, represented as $u = [\delta_e, \delta_a, \delta_r]^T$.

With the help of ”(Stevens and Lewis, 2003)” and ”(Duke *et al.*, 1988)” we can describe the system equations as:

$$\begin{aligned}
\begin{bmatrix} \dot{\alpha} \\ \dot{\beta} \\ \dot{\phi} \end{bmatrix} &= \frac{1}{m.V}\begin{bmatrix} -\frac{\sin(\alpha)}{\cos(\beta)}.(T + C_x.\overline{q}.S) + \frac{\cos(\alpha)}{\cos(\beta)}.C_z.\overline{q}.S \\ -\cos(\alpha).\sin(\beta).(T + C_x.\overline{q}.S) + \cos(\beta).(C_y.\overline{q}.S) + \sin(\alpha).\sin(\beta).C_z.\overline{q}.S \\ 0 \end{bmatrix} \\
&+ \begin{bmatrix} -\cos(\alpha).\tan\beta & 1 & -\sin(\alpha).\tan(\beta) \\ \sin(\alpha) & 0 & -\cos(\alpha) \\ 1 & \sin(\phi).\tan(\theta) & \cos(\phi).\tan(\theta) \end{bmatrix} . \begin{bmatrix} p \\ q \\ r \end{bmatrix} \\
&+ \frac{\rho.S}{4.m}\begin{bmatrix} 0 & -\frac{\sin(\alpha)}{\cos(\beta)}.C_{xq}.\overline{c} + \frac{\cos(\alpha)}{\cos(\beta)}.C_{zq}.\overline{c} & 0 \\ \cos(\beta).C_{yp}.b & -\cos(\alpha).\sin(\beta).C_{xq}.\overline{c} - \sin(\alpha).\sin(\beta).C_{zq}.\overline{c} & \cos(\beta).C_{yr}.b \\ 0 & 0 & 0 \end{bmatrix} . \begin{bmatrix} p \\ q \\ r \end{bmatrix} \\
&+ \frac{\rho.V.S}{2.m}\begin{bmatrix} -\frac{\sin(\alpha)}{\cos(\beta)}.C_{x\delta e} + \frac{\cos(\alpha)}{\cos(\beta)}.C_{z\delta e} & 0 & 0 \\ -\cos(\alpha).\sin(\beta).C_{x\delta e} - \sin(\alpha).\sin(\beta).C_{z\delta e} & \cos(\beta).C_{y\delta a} & \cos(\beta).C_{y\delta r} \\ 0 & 0 & 0 \end{bmatrix} . \begin{bmatrix} \delta_e \\ \delta_a \\ \delta_r \end{bmatrix} \\
&+ \frac{g}{V}\begin{bmatrix} \frac{1}{\cos(\beta)}.(\sin(\alpha).\sin(\theta) + \cos(\alpha).\cos(\phi).\cos(\theta)) \\ \cos(\alpha).\sin(\beta).\sin(\theta) + \cos(\beta).\cos(\theta).\sin(\phi) - \sin(\alpha).\sin(\beta).\cos(\phi).\cos(\theta) \\ 0 \end{bmatrix}
\end{aligned} \tag{1}$$

$$\begin{aligned}
\begin{bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} &= \begin{bmatrix} I_2.p.q + I_1.q.r + I_3.C_r.\overline{q}.S.b + I_4.C_n.\overline{q}.S.b \\ I_5.p.r + I_6(p^2 + r^2) + I_7.C_m.\overline{q}.S.\overline{c} \\ -I_2.q.r + I_8.p.q + I_4.C_r.\overline{q}.S.b + I_9.C_n.\overline{q}.S.b \end{bmatrix} \\
&+ \frac{\rho.V.S}{4}\begin{bmatrix} I_3.C_{rp}.b + I_4.C_{np}.b & 0 & I_3.C_{rr}.b + I_4.C_{nr}.b \\ 0 & I_7.C_{mq}.\overline{c} & 0 \\ I_4.C_{rp}.b + I_9.C_{np}.b & 0 & I_4.C_{rr}.b + I_9.C_{nr}.b \end{bmatrix} . \begin{bmatrix} p \\ q \\ r \end{bmatrix} \\
&+ \overline{q}.S.\begin{bmatrix} 0 & I_3.C_{r\delta a}.b + I_4.C_{n\delta a}.b & I_3.C_{r\delta r}.b + I_4.C_{n\delta r}.b \\ I_7.C_{m\delta e}.\overline{c} & 0 & 0 \\ 0 & I_4.C_{r\delta a}.b + I_9.C_{n\delta a}.b & I_4.C_{r\delta r}.b + I_9.C_{n\delta r}.b \end{bmatrix} . \begin{bmatrix} \delta_e \\ \delta_a \\ \delta_r \end{bmatrix}
\end{aligned} \tag{2}$$

$$\begin{bmatrix} \dot{\theta} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} 0 & \cos(\phi) & -\sin(\phi) \\ 0 & \frac{\sin(\phi)}{\cos(\theta)} & \frac{\cos(\phi)}{\cos(\theta)} \end{bmatrix} . \begin{bmatrix} p \\ q \\ r \end{bmatrix} \tag{3}$$

The equation “Eq. (1)”, “Eq. (2)”,“Eq. (3)” can be rewritten as “Eq. (4)”:

$$\begin{cases} \dot{x_1} = f_1(x_1) + f_{1a}(x_1, x_3) + g_1(x_1, x_3).x_2 + g_{1a}(x_1).x_2 + h_1(x_1).u \\ \dot{x_2} = f_2(x_1, x_2) + f_{2a}.x_2 + g_2(x_1).u \\ \dot{x_3} = f_3(x_3) \end{cases} \tag{4}$$

Before the backstepping method is applied some assumptions are consider:

- **Assumption 1** The desired trajectory $x_1^d = [\alpha^d, \beta^d, \phi^d]$ are bounded as:

$$||[x_1^d, \dot{x}_1^d, \ddot{x}_1^d]|| \leq c_d \tag{5}$$

where $c_d \in \Re$ is a know constant and ||.|| denotes the 2-norm of a vector or matrix.

- **Assumption 2** The true airpeed and Dunamic pressure are constant, that is:

$$\dot{V}_T = 0, \dot{\overline{q}} = 0 \tag{6}$$

- **Assumption 3** The magnitude of θ is bounded as:

$$|\theta| \leq \theta_m < \frac{\pi}{2} \tag{7}$$

- **Assumption 4** There exist positive constants α_m and $\beta_m \in \Re$ such that g_1 and g_2 are invertible

- **Assumption 5**The control surface deflection has not an effect on the aerodynamic force component

$$h_1(x_1) = 0 \tag{8}$$

An Error function is defined for the system as follows:

$$\begin{aligned} z_1 &= x_1 - x_1^d \\ z_2 &= x_2 - x_2^d \end{aligned} \tag{9}$$

Its derivatives are:

$$\begin{aligned} \dot{z}_1 &= \dot{x}_1 - \dot{x}_1^d = f_1(x_1) + f_{1a}(x_1, x_3) + g_1(x_1).x_2 + x_2 - \dot{x}_1^d \\ \dot{z}_2 &= \dot{x}_2 - \dot{x}_2^d = f_2(x_1) + f_{2a}(x_1).x_2 + g_2(x_1).u - \dot{x}_2^d \end{aligned} \tag{10}$$

A candidate Lyapunov function is chosen then for the z_1 error, The simples choice for a Lyapunov function is the quadratic function, as by itself it is positive defined, "(Khalil, 2002)". the chosen function is:

$$V(x) = \frac{1}{2} z_1^2 \tag{11}$$

And its derivative is:

$$\dot{V}_1 = \dot{z}_1.z_1 = z_1.(f_1(x_1) + f_{1a}(x_1, x_3) + g_1(x_1).x_2 + x_2 - \dot{x}_1^d) \tag{12}$$

To have a stabilizing control law, the derivative of the Lyapunov function shall be negative defined, and for that to happen the following equation is consider:

$$f_1(x_1) + f_{1a}(x_1, x_3) + g_1(x_1).x_2 + x_2 - \dot{x}_1^d = k_1.z_1 \tag{13}$$

Through "Eq. (13)" the x_2^d is defined as:

$$x_2^d = g_1^{-1}.(-k_1.z_1 - f_1(x_1) - f_{1a}(x_1, x_3) + \dot{x}_1^d) \tag{14}$$

Now, a candidate Lyapunov function is chosen for the z_2 error:

$$V_2 = \frac{1}{2}.z_1^T.z_1 + \frac{1}{2}.z_2^T.z_2 \tag{15}$$

And its derivative is:

$$\dot{V}_2 = \frac{\partial V_2}{\partial z_1}.\dot{z}_1 + \frac{\partial V_2}{\partial z_2}.\dot{z}_2 \tag{16}$$

Substituting "Eq. (9)", "Eq. (10)" and "Eq. (14)" in "Eq. (16)", and making $\dot{V}_2$ negative definite the control law can be obtained:

$$\begin{aligned} u \;=\; & g_2^{-1}.(-k_2.z_2 - z_1.(g_{1a}(x_1) + g_1(x_1, x_3)) - f_2(x_1, x_2) - f_{2a}(z_1).x_2) + \frac{\partial x_2^d}{\partial x_1}.\dot{x}_1 \\ & + \frac{\partial x_2^d}{\partial x_3}.\dot{x}_3.x_2 + g_1(x_1, x_3)^{-1}.(k_1.\dot{x}_1^d + \ddot{x}_1^d) \end{aligned} \tag{17}$$

The gains shall obey $k_1 > 0$ and $k_2 > 0$ to guarantee that the Lyapunov control functions are asymptotically stable.

3.2 Load Factor Control

Taking advantage of the control law found in "Eq. (17)" a load factor (n_z) controller is designed, as the load factor is represented by "Eq. (18)", and thus a selected approach for the controller design is to estimate an angle of attack based on a n_z request, the estimated angle of attack is the α^d, and it can be replaced as the track reference in "Eq. (17)" considering only the longitudinal axis

$$N_z = \frac{\overline{q}.S}{m.g}.C_z(\alpha, \delta e) \tag{18}$$

3.3 Altitude Control

For the altitude control control design, one more "steep back" is taken from previous controller, "Eq. (17)", only in the longitudinal axis, the variable that will track a reference is the H, and is defined by "Eq. (19)"

$$\dot{H} = V.\sin(\theta - \alpha) \tag{19}$$

Adopting the follow assumption:

- **Assumption 6** The track angle (γ) is very small:

$$|\gamma| \leq 3^{\circ} \rightarrow \sin(\gamma) = \gamma \tag{20}$$

So the resultant state equation is:

$$\dot{H} = V.(\theta - \alpha) \tag{21}$$

As before, an error function and its derivative can be defined as:

$$\begin{aligned} z_h &= H - H^d \\ \dot{z}_h &= V.(\theta - \alpha) - \dot{H}^d \end{aligned} \tag{22}$$

The following Candidate Lyapunov Function is chosen:

$$\begin{aligned} V_h &= \tfrac{1}{2}.z_H^2 \\ \dot{V}_H = z_h.\dot{z}_H &= z_H.(-V.\alpha + V.\theta - \dot{H}^d) \end{aligned} \tag{23}$$

From "Eq. (23)" as $\dot{V}_H$ is forced to be negative definite a value from α is calculated and inserted in longitudinal part of "Eq. (17)"as x_1^d. The "Eq. (24)" explicit the α^d for a desirable reference in H

$$\alpha^d = -\frac{k_H.z_h + V.\theta - \dot{H}^d}{V} \tag{24}$$

The gain shall obey $k_1 > 0$, $k_2 > 0$ and $k_H > 0$ to guarantee that the Lyapunov control functions are asymptotically stable.

3.4 Velocity Control

The Velocity control design is focused in controlling the motor thrust through the thrust lever, π, Adopting the follow assumption:

- **Assumption 7** The thrust (T) is directed related to the thrust lever:

$$T = C_t(H, V).\pi \tag{25}$$

The $backstepping$ design for the velocity control does not need any $''virtual\ control''$, it is calculated from:

$$\begin{aligned} \dot{V} \quad = \quad & \frac{\cos(\alpha).\cos(\beta)}{m}.C_T.\pi + \frac{\cos(\alpha).\cos(\beta).\overline{q}.S}{m}.(C_x + \frac{\overline{c}.q}{2.V}.C_{xq}) \\ & + \frac{\sin(\beta).\overline{q}.S}{m}.(C_y + \frac{b.p}{2.V}.C_{yp} + \frac{b.r}{2.V}.C_{yr}) + \frac{\sin(\alpha).\cos(\beta).\overline{q}.S}{m}.(C_z + \frac{\overline{c}.q}{2.V}.C_{zq}) \\ & + g.(-\cos(\alpha).\cos(\beta).\sin(\theta) + \sin(\beta).\sin(\phi).\cos(\theta) + \sin(\alpha).\cos(\beta).\cos(\phi).\cos(\theta)) \end{aligned} \tag{26}$$

The equation "Eq. (26)" can be rewritten as "Eq. (27)":

$$\dot{x}_V = f(x_V) + h(x_V).u \tag{27}$$

As before, an error function and its derivative can be defined as:

$$\begin{aligned} z_V &= x_V - x_V^d \\ \dot{z}_V &= f(x_V) + h(x_V).u - \dot{x}_V^d \end{aligned} \tag{28}$$

The following Candidate Lyapunov Function is chosen:

$$\begin{aligned} V_V &= \tfrac{1}{2}.z_V^2 \\ \dot{V}_V &= z_V.\dot{z}_V = z_V.(f(x_V) + h(x_V).u - \dot{x}_V^d) \end{aligned} \tag{29}$$

From "Eq. (29)" as $\dot{V}_V$ is forced to be negative definite the control law for velocity control is calculated as:

$$u = \frac{k_V.z_V - f(x_V) + \dot{x}_V^d}{h(x_V)} \tag{30}$$

The gain shall obey $k_V > 0$ to guarantee that the Lyapunov control functions are asymptotically stable.

3.5 Final controller structure

The control structure for the design projects in the previous section is represented by "Fig. 4". It is worth noting that the longitudinal control can be switched between the load factor or altitude control, the choice of which will be active is a pilot decision, the pilot can decide to be in the loop, load factor control, or use an autopilot control, altitude control.

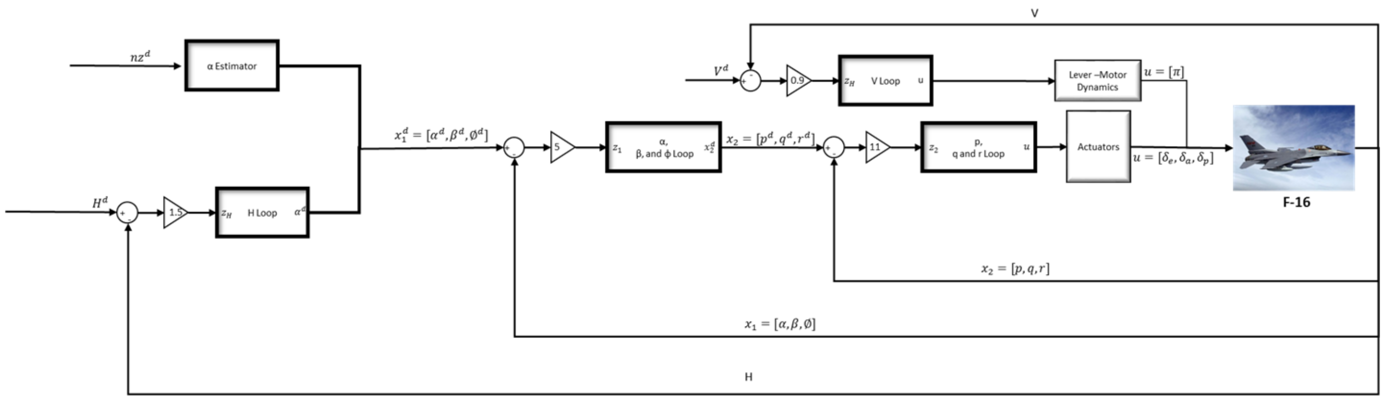

Figure 4. Backstepping Controller Representation

4. SIMULATION

During the simulation the following gains where adopted: $k_1 = 5$, $k_2 = 11$, $k_H = 1.5$ and $k_V = 0.9$.

For the α, β and ϕ controller, the aircraft was trimmed in a condition where $cg = 0.35\%$; $Altitude = 900m$ and $TrueAirspeed = 250m/s$, then a reference in α and ϕ were simultaneously changed and β hold its value (zero degrees). The result of aircraft tracking this references is displayed in "Fig. 5", "Fig. 6" and "Fig. 7" for α, β and ϕ respectively, and the effort of the control surfaces, elevator, aileron and rudder, to attain this track is displayed in "Fig. 8".

The aircraft tracked the new reference in α and ϕ in a satisfactory way, and managed to maintain β fixed in the zero possition. The surface response is also satisfactory.

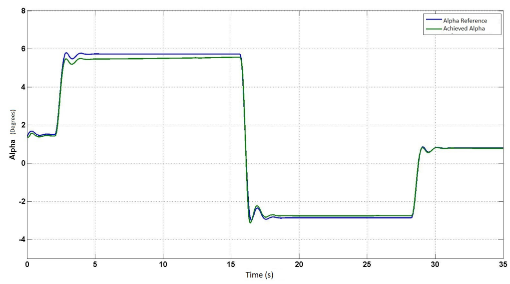

Figure 5. Response of the Aircraft for a Reference in the Angle of Attack

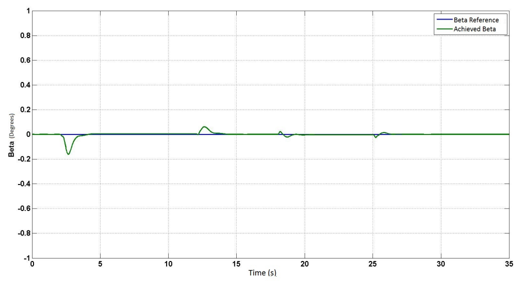

Figure 6. Response of the Aircraft for a Reference in Sideslip Angle

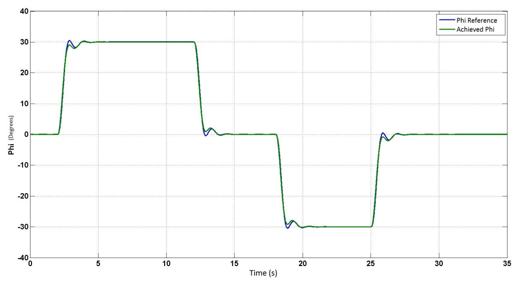

Figure 7. Response of the Aircraft for a Reference in Roll Angle

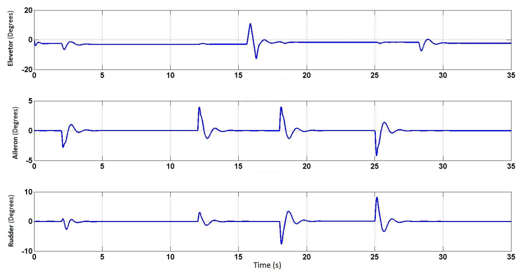

Figure 8. Response of the Surfaces to Track a Simultaneous Change in Angle of Attack and Roll Angle

For the load factor, n_z, controller, the aircraft was trimmed in a condition where $cg = 0.35\%$; $Altitude = 4500m$ and $TrueAirspeed = 175m/s$, then a simulated pilot n_z demand was applied. The result of the aircraft tracking this new demand is displayed in “Fig. 9”, and the effort of the control surfaces, elevator, to attain this track is displayed in “Fig. 10”.

The aircraft tracked the new n_z demand in a satisfactory way. The surface response is also satisfactory, seen that it didn′t need to reach the elevator maximum deflection.

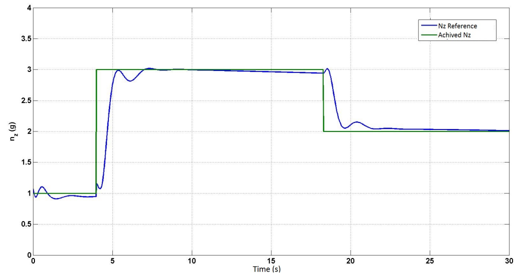

Figure 9. Response of the Aircraft for a Reference in Load Factor

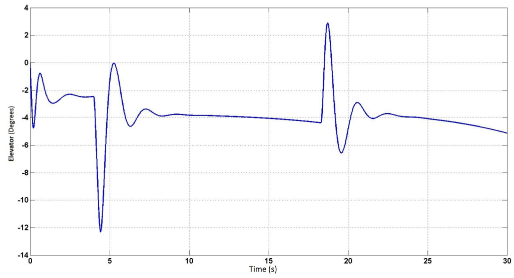

Figure 10. Response of the Elevator to Track a Change in Load Factor

For the Altitude, H, controller, the aircraft was trimmed in a condition where $cg = 0.35\%$; $Altitude = 4500m$ and $TrueAirspeed = 175m/s$, then after a short while the altitude reference was changed, with a requiring a negative rate, $\dot{H} = -20$. The result of aircraft tracking the new altitude is displayed in “Fig. 11”, and the effort of the control surfaces, elevator, to attain this track is displayed in “Fig. 12”.

The aircraft tracked the new altitude reference in a satisfactory way, with the desirable negative rate.. The surface response is also satisfactory, seen that it didn′t need to reach the elevator maximum deflection.

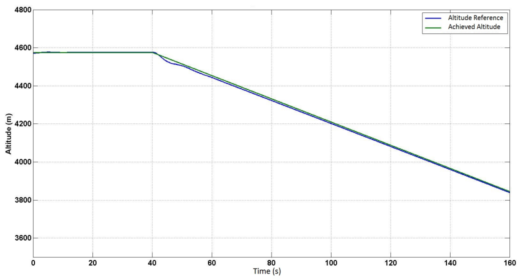

Figure 11. Response of the Aircraft for a Reference in Altitude

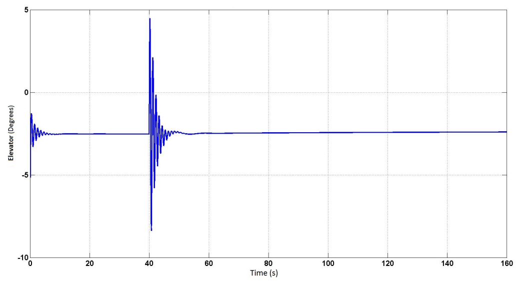

Figure 12. Response of the Elevator to Track a Change in Altitude

For the Velocity, H, controller, the aircraft was trimmed in a condition where $cg = 0.35\%$; $Altitude = 4500m$ and $TrueAirspeed = 175m/s$, then after a short while the velocity reference was changed. The result of aircraft tracking the new velocity is displayed in “Fig. 13”, and the effort of the thrust lever to attain this track is displayed in “Fig. 14”.

The aircraft tracked the changes in the velocity reference in a satisfactory way.

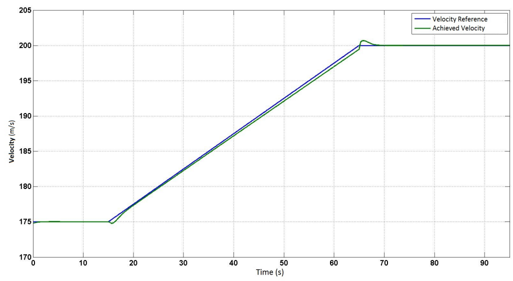

Figure 13. Response of the Aircraft for a Reference in Velocity

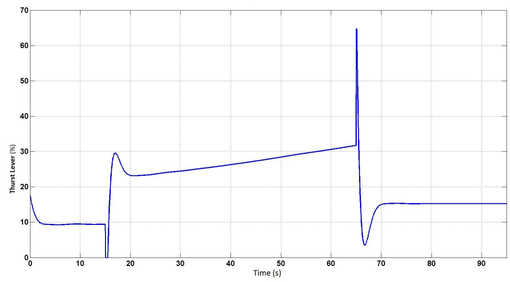

Figure 14. Response of the Power Lever to Track a Change in Velocity

5. CONCLUSION

The *backstepping* is a powerful tool to aircraft design control, because it allows to track any state(measured or estimated), by handling the force, moment e movement equations.The same *backstepping* technique can be used to perform different control objectives, and the same structure, showed in “Fig. 4” can be used in different aircrafts, demonstrating the flexibility of the method. Today in the industries there are none know applications of the *backstepping* method, however, as the market demands for more precise controls, where the nonlinearities of an aircraft must be taken in account, the *backstepping* became a feasible solution.

6. ACKNOWLEDGEMENTS

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