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Flight-Path Tracking Control of an Aircraft Using Backstepping Controller

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Abstract

For transportation aircraft, the primary control objective for an autopilot system engaged during approach and landing is relative to the flight path tracking on the basis of highly simplified linear models of flight dynamics. The dynamics governing the flight path of an aircraft are in general highly nonlinear and involve complex physics for which no accurate models are available. In this paper a nonlinear model describing the longitudinal equations of motion in strick feedback form is derived. Backstepping is utilized for the construction of a globally stabilizing controller with a number of free parameters. It is implemented a controller with an internal loop controls involving the pitch rate of the aircraft and an external loop which includes angle of attack, path angle and pitch angle. Finally, nonlinear simulation results for a longitudinal model of a transportation aircraft are displayed and discussed.

Keywords: *backstepping, aircraft control, nonlinear control, Lyapunov stability*

1. Introduction

The design of flight control systems is a typical nonlinear control problem, due directly to the changes in aircraft dynamics with flight conditions and aircraft configuration. For this reason, a dynamic model that is stable and adequately damped in one flight condition may become unstable or at least inadequately damped in another one. In transportation aircraft, a lightly damped oscillatory mode may cause discomfort to passengers or make difficult the control of the aircraft for the pilot. For a combat aircraft, this condition may lead to more critical situation once the aircraft is inherently unstable due the maneuverability requirements and capability of attack.

In this paper we introduce an alternative for control separation; a backstepping controller is used to achieve global stability with an internal loop controls involving the pitch rate of the aircraft and external loop which includes angle of attack, path angle and pitch angle. A backstepping controller is proposed to solve the path angle stabilization problem of the aircraft transportation. Firstly, the full nonlinear longitudinal dynamics are described under consideration of external disturbances acting on path angle. Then, block backstepping controller.

Backstepping is a recursive procedure that interlaces the choice of a Lyapunov function with the design of the feedback control. The advantage of this technique is that it can from the stabilizing nonlinear terms rather than eliminating them. Backstepping has been applied to a number of different design taskes [7].

The goal of this work is to design a control law able to deal with the aircraft longitudinal dynamics, for all the normal operating regimes of the aircraft, with minimal information of the aerodynamic model. The controller must be able to make the system seek the references in the aerodynamic velocity and flight path angle, using as actuators the elevator deflections and the thrust level.

The main aim of this paper is to assess the respective performances of the nonlinear backstepping technique applied to the flight-path angle tracking control problem.

The paper is structured as follows: first, in section 2 is presented the longitudinal aircraft model equation. This aircraft represents a transportation aircraft like A320/A3XX and Boeing 737-200/300 this nonlinear control theory will control the aircraft rigid flight dynamics to achieve global stability.

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In the section 3, backstepping control design procedure is shown tracking four state variables. Finally, in the section 4 a numerical simulation is done to demonstrate

2. Nonlinear Aircraft Model

The longitudinal motion of an aircraft is well described by the following standard set of differential equations, the state variables, V (airspeed), γ (path angle), α (angle of attack), θ (pitch angle) and q (pitch rate), are depicted in Figure 1.

$$\dot{V} = \frac{1}{m}(-D + Tcos\alpha - mgsin\gamma) \tag{1}$$

$$\dot{\alpha} = \frac{1}{m}(-L + Tsin\alpha + mgcos\gamma) + q \tag{2}$$

$$\dot{\gamma} = \frac{1}{m}(-L + Tsin\alpha + mgcos\gamma) \tag{3}$$

$$\dot{\theta} = q \tag{4}$$

$$\dot{q} = \frac{M(\delta_e)}{I_y} \tag{5}$$

$\gamma = \theta - \alpha$ is the flight path angle, to which we shall return later. T is the engine thrust force and δ_e the elevator angle. Finally, L, D et $M(\delta_e)$ are the aerodynamics forces lift, drag and pitching moment and I_y is the inertial moment about y axis in body axes.

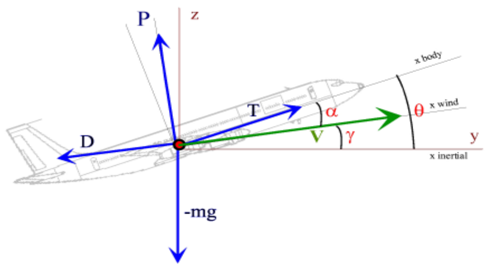

Figure 1. Definition of forces, moments and angles

As usual in aerodynamic forces and moments are computed through their non-dimensional coefficient, as follows:

$$L = \frac{1}{2}\rho V^2 C_L, \quad D = \frac{1}{2}\rho V^2 C_D, M = \frac{1}{2}\rho V^2 S\bar{c}C_m \tag{6}$$

Where ρ is the air density, S is the reference wing surface, $\bar{c}$ is the mean chord and L, D and M are the lift, drag and pitching moment coefficients. Moreover, we consider the following models for the drag and moment coefficients [1, 2].

$$C_D = C_{D_0} + K_1 C_L + k_2 C_L^2 \tag{7}$$

$$C_m = C_{m_0} + C_{m_\alpha}\alpha + C_{m_q}q + C_{m_{\delta_e}}\delta_e \tag{8}$$

Where C_{D_0}, K_1, k_2, C_{m_0}, C_{m_α}, $C_{m_q}$and $C_{m_{\delta_e}}$ are aircraft aerodynamic coefficients, and δ_e is the elevator angle. in this work C_{D_0}, K_1, k_2, C_{m_0}, C_{m_α} and C_{m_q} are considered to be unknown parameters, $C_{m_{\delta_e}}$while is known.

3. Backstepping

Consider a dynamic system:

$$\dot{x}_1 = f(x_1) + g(x_1)x_2 \qquad (9)$$

Where $x_1 \in \Re, x_2 \in \Re$ are state variables and $u \in \Re$ is the control input.

The control objective [x] to this dynamic system is to design a control law such that the state x_1 can be stabilized at 0, a supposed global asymptotically stable equilibrium with null input $(f(0) = 0)$, furthermore it can observed that x_2 can be regarder as a virtual (or mediate) control input for the dynamics x_1, the dynamics of x_2 is controlled by the real control input u. This is an important feature to make use of for the following control law synthesis. Now, suppose that there exists a control law [5].

$$x_2 = \xi(x_1) \qquad (10)$$

$$\dot{V}_1(x_1) = \frac{\partial V_1}{\partial x_1}\big(f(x_1) + g(x_1)\xi(x_1)\big) \le -W_1(x_1) \qquad (11)$$

Where $W(x_1)$ is positive definite function. Then the whole dynamics can be expressed as:

$$\dot{x}_1 = f(x_1) + g(x_1)\xi(x_1) + g(x_1) + g(x_1)z \qquad (12)$$

$$\dot{z} = w \qquad (13)$$

Where,

$$z = x_2 - \xi(x_1) \qquad (14)$$

$$w = u - \dot{\xi}(x_1) \qquad (15)$$

With,

$$\dot{\xi}(x_1) = \frac{\partial \xi}{\partial x_1}(f(x_1) + g(x_1)x_2) \qquad (16)$$

Then, the Lyapunov function condidate of the full system is given by [9]:

$$V(x_1, z) = V_1(x_1) + \frac{1}{2}z^2 \qquad (17)$$

The time derivative of $V(x, z)$ is given by:

$$\dot{V}(x_1, z) = \frac{\partial V_1}{\partial x_1}\big(f(x_1) + g(x_1)\xi(x_1)\big) + \frac{\partial V_1}{\partial x_1}g(x_1)z + zw \qquad (18)$$

Substituting the inequality of Equation (9) and Equation (10) into Equation (14) yields:

$$\dot{V}(x_1, z) \le -W(x_1) + \frac{\partial V_1}{\partial x_1}\, g(x_1)z + zw \qquad (19)$$

By an edequate choice of w, such as:

$$w = -\frac{\partial V_1}{\partial x_1}g(x_1) - kz \qquad (20)$$

Where is positive constant, the full system is globally asymptoticallt stable since it satisfies the following condition:

$$\dot{V}(x_1, z) \le -W(x_1) - kz^2 \qquad (21)$$

Finally, sibstituting Equation (7) and Equation (11) into Equation (16) yields the effective control input:

$$u = \frac{\partial \xi}{\partial x_1}(f(x_1) + g(x_1)x_2) - \frac{\partial V_1}{\partial x_1}g(x_1) - k\big(x_2 - \xi(x_1)\big) \quad (21)$$

4. Controller Design

The main objective of the controller is to track slow states $V, \alpha, \theta$and γ. But the problem is divided in two parts. The first one is the control of α, θ and γ, this problem can be viewed like a two-scaletine approach because the fast states q is used as control input as is proposed in Lee et al. (2001) [8]. the second part is the control of V, accordingly to achieve this objective is proposed a first order backstepping using the throttle setting inputs [3, 4].

4.1. Control of the Flight Path Angle

The backstepping procedure to be applied can be viewed as two-timescale approach because the fast states are used as control inputs for the slow states α, θ and γ intermediately. However, this methodology considers the transient responses of the fast states and, therefor does not require the timescale separation assumption. First, it is necessary replace the aerodynamic forces and moments into the state equation. The dynamics of flight-path angle are written as [11, 12]:

$$\dot{\gamma} = \frac{1}{m}(-L + Tsin\alpha + mgcos\gamma) \quad (22)$$

The first step of a backstepping approach consists in difining the output output error which is given here by:

$$z_\gamma = \gamma - \gamma_d \quad (23)$$

Where γ_d is the desired flight-path angle. Then the error dynamics of flight-path angle is given by:

$$\dot{z}_\gamma = \dot{\gamma} - \dot{\gamma}_{ref} \quad (24)$$

A Lyapunov function for γ is given by:

$$V_\gamma = \frac{1}{2}z_\gamma^2 \quad (25)$$

Its time-derivative is then given by:

$$\dot{V}_\gamma = \dot{z}_\gamma z_\gamma \quad (26)$$

With:

$$\dot{V}_\gamma < 0 \quad (27)$$

$$\dot{z}_\gamma = -k_3 z_\gamma \quad (28)$$

Since:

$$\dot{\gamma} = -k_3 e_1 + \dot{\gamma}_d = V_{2d} \quad (29)$$

At the second step the new error given by:

$$z_{2\gamma} = \dot{\gamma} - \gamma_{2d} = \dot{\gamma} - k_3 z_1 + \dot{\gamma}_d \quad (30)$$

Its time-derivative is then given by:

$$\dot{z}_{2\gamma} = \ddot{\gamma} - \ddot{\gamma}_{2d} = \ddot{\gamma} + k_3\dot{z}_1 + \ddot{\gamma}_d \quad (31)$$

With:

$$\dot{z}_\gamma = z_{2\gamma} - k_3 z_\gamma \quad (32)$$

Such that:

$$\ddot{\gamma} = -z_\gamma - k_4 z_{2\gamma} - k_3\dot{z}_\gamma + \ddot{\gamma}_d \quad (33)$$

$$\ddot{\gamma} = -(k_3 + k_4)z_{2\gamma} - (1 - k_3^2)z_\gamma + \ddot{\gamma}_d \quad (34)$$

Afin d'éliminer cette erreur, la fonction de Lyapunov augmentée d'un autre terme qui contient une nouvelle erreur

$$V_{2\gamma} = \frac{1}{2}z_\gamma^2 + \frac{1}{2}z_{2\gamma}^2 \quad (35)$$

Its time-derivative is then given by:

$$\dot{V}_{2\gamma} = z_\gamma\dot{z}_\gamma + z_{2\gamma}\dot{z}_{2\gamma} \quad (36)$$

$$\dot{V}_{2\gamma} = -k_3 z_\gamma^2 + z_{2\gamma}\left(\dot{z}_{2\gamma} + z_\gamma\right) \quad (37)$$

With:

$$\dot{V}_{2\gamma} < 0 \quad (38)$$

$$z_\gamma + z_{2\gamma} = -k_4 z_2 \quad (39)$$

Finally, the effective control of flight path angle given by:

$$\ddot{\gamma} = f(\alpha, \gamma, T, L, m, V) \quad (40)$$

It appears that the backstepping approach is far from being straigh forward and that such an inttricate construction should be tested through fully to provide confidence in its performances.

5. Simulation Results

In this section, simulation results of the controllers developed are shown and demonstrate the performance of this control law.

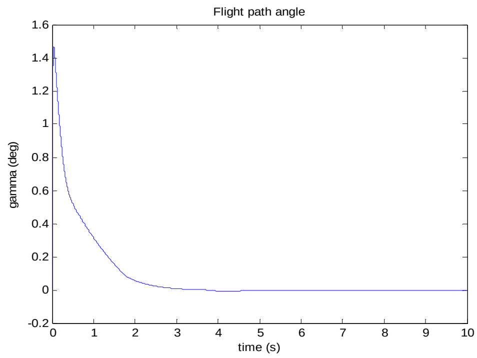

Figure 2. Flight path angle γ

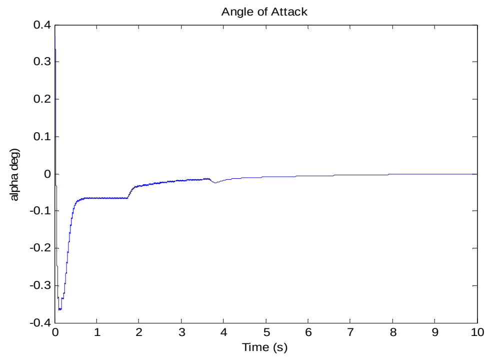

Figure 3. Angle of attack α

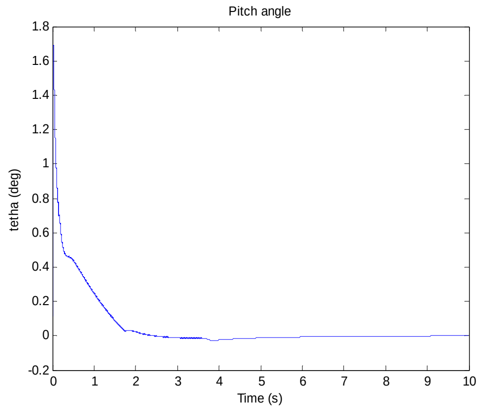

Figure 4. The pitch angle θ

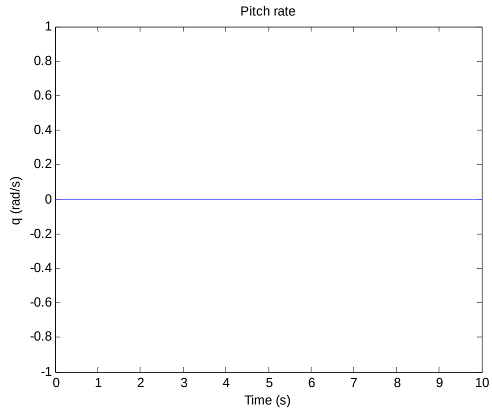

Figure 5. Pitch angle rate q

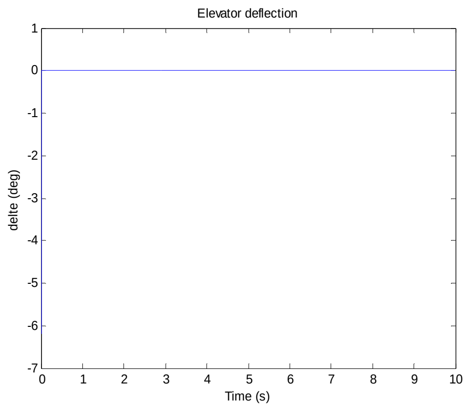

Figure 6. Control inputs: elevator deflection δ_e

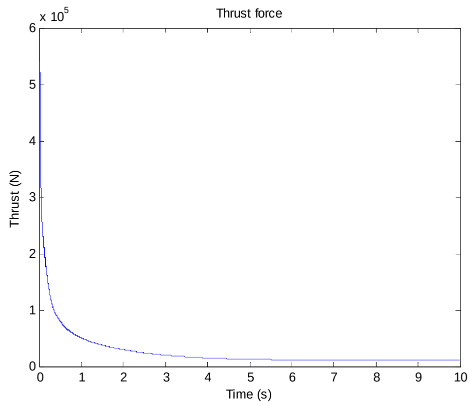

Figure 7.Control inputs: elevator throttle setting δ_{th}

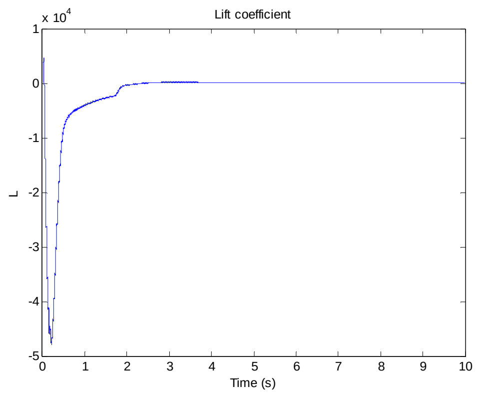

Figure 8. The lift force L

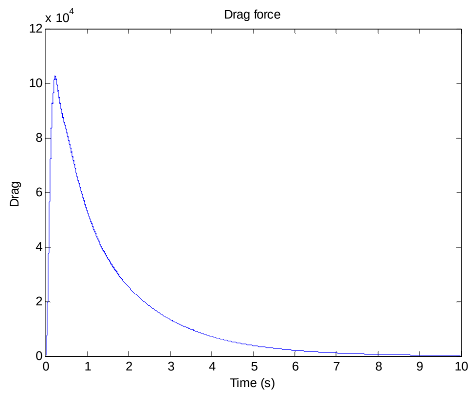

Figure 9. The drag force D

6. Conclusion

In this paper nonlinear backstepping technique was used to design law to be applied in a nonlinear aircraft model. A controller was proposed to track α, θ and γ using angular rate as intermediate, thus, it is possible control a slow dynamics using the fast dynamics. With this controller applied the error exponentially converges, then system can be globaly stabilized or reach a new equilibrium state.

We have addressed the path angle control problem for a transportation aircraft. A nonlinear model describing the longitudinal motion in strick feedback format was derived, carefully selecting the states includes and making proper approximations. A backstepping control law was designed recursively in three steps, resulting in a nonlinear controller with five free parameters. The closed loop stability of the error states and the parameters of backstepping technique are examined by the Lyapunov theory, and it is shown that the error expontially converge to a compact set whose size is ajustable by the design parameters. Finally, a nonlinear simulation of an aircraft maneuver is performed to demonstrate the performance of the proposed control laws.

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