DYNAMIC INVERSION-BASED ADAPTIVE AIRCRAFT CONTROLLER

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Abstract. *The Dynamic Inversion (DI) control strategy has been established as one of the most important in the design of fly-by-wire flight control laws: since in these applications the model structure is well known, superior performance can be obtained by using DI. Basically, through DI the designer can impose a desired aircraft flight response to pilot input by canceling out the aircraft natural dynamics. There are however 2 problems here: a) in order to simplify the dynamic inversion, the results in the literature usually suppose uncoupled lateral-directional and longitudinal dynamics, and b) performance can be degraded if there is no perfect dynamic canceling, due for instance to parameter variation. This paper addresses both problems and the 2 main contributions are: 1) no model simplification is supposed, i.e., the fully coupled 6DOF model is employed for the DI design, and this is accomplished by adequate use of symbolic processing, and 2) an adaptive controller is implemented in order to compensate parameter variations, which can include control surfaces degradation.*

Keywords: *DI, Aircraft Control, Adaptive Control, Flight Control System.*

1. INTRODUCTION

Amongst the nonlinear control strategies for aircrafts, that based on DI (Dynamic Inversion) has a long trend of success in aeronautical applications, where it has shown to be effective. Details about this strategy can be found in Stevens and Lewis (2003), and basically it can be classified as input/output linearization via feedback, see Slotine and Li (1991) for details. It is also adequate for use in adaptive control, due to its simple structure, in both classical and advanced approaches (based in neural networks), as summarized in Sing and Steinberg (1996), Steinberg (2001) and Rysdyk and Calise (2005).

The application of DI to flight control demands the use of a nominal model, which is typically a simplified one. This corresponds, for instance, to the applications reported in Steinberg (2001) and Stevens and Lewis (2003). It would be advisable, however, to avoid such simplifications at the very beginning of the design. Apparently the complexity of the nonlinear flight dynamics explains the lack of works in these directions so far, but nowadays this limitation is not a severe one anymore, due to the availability of symbolic processing, encapsulated in commercial softwares such as Matlab and Mathematica. Moreover, even supposing that no simplification has been considered in the design phase, there remains a point to be dealt with: since DI is taylored for a nominal dynamics, performance degradation can occur in case where there are dynamic variations, which may occurs when there are parameters variations, such as mass, or failure in the control surfaces, such as aileron hard over.

This paper addresses both issues: a) symbolic processing, via Mathematica, is employed to obtain the information required for implementing the DI control strategy, without the need for simplification, and b) an adaptive control strategy of the indirect type is employed for parameter estimation. Simulations results are reported and discussed. This paper is organized as follows: in section 2 the DI control strategy is summarized, and section 3 deals with the symbolic processing used for calculating the matrices required for dynamic inversion. The design of the indirect adaptive control strategy is described in section 4. Simulations results are presented in section 5, followed by the conclusions in section 6.

2. DI CONTROLLER

The DI flight control strategy is designed by considering two sets of equations. The first one composes the inner loop and deals directly with the aircraft angular rates. The second one is an outer loop linking the sideslip angle with the yaw angular rate. The basic diagram is shown in Fig. 1.

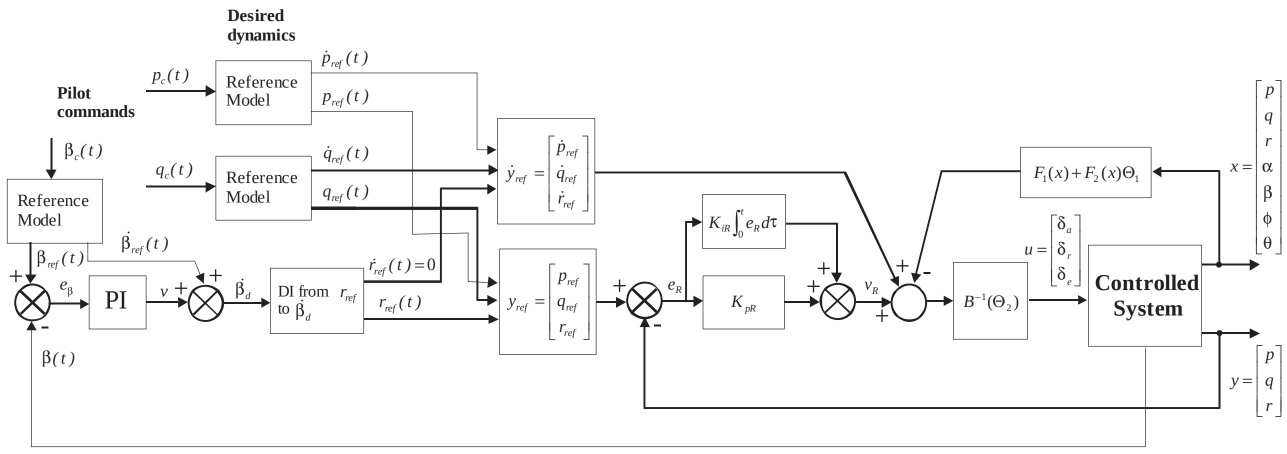

Figure 1: Baseline aircraft flight control system based on DI

All dynamic inversions are made by supposing a standard x-y-z flat earth, rigid body and symmetrical airplane six-degree-of-freedom dynamic model. The six-degree-of-freedom aircraft dynamics can be expressed as, (Steven and Lewis, 2003)

$$
\begin{aligned}
\dot{p} &= \frac{-(-I_y I_z + I_z^2 + I_{xz}^2)qr + I_z(I_{xz}pq + \bar{q}SbC_l) + I_{xz}((I_x - I_y)pq + \bar{q}Sl_s C_n}{I_x I_z - I_{xz}^2} \\
\dot{q} &= \frac{\bar{q}Sl_\mu C_m - I_{xz}\left(p^2 - r^2\right) + \left(I_z - I_x\right)pr}{I_y} \\
\dot{r} &= \frac{I_{xz}(I_{xz}pq - (I_x - I_y + I_z)qr + \bar{q}Sl_s C_l) + I_x((I_x - I_y)pq + \bar{q}Sl_s C_n)}{I_x I_z - I_{xz}^2} \\
\dot{\alpha} &= -\frac{\bar{q}S}{mV\cos\beta}C_L + q - \tan\beta\left(p\cos\alpha + r\sin\alpha\right) \\
&+ \frac{g}{V\cos\beta}\left(\cos\phi\cos\theta\cos\alpha + \sin\theta\sin\alpha\right) \\
\dot{\beta} &= \frac{\bar{q}S}{mV}C_{Y_{WIND}} + p\sin\alpha - r\cos\alpha + \frac{g}{V}\cos\beta\sin\phi\cos\theta \\
&+ \frac{\sin\beta}{V}\left(g\cos\alpha\sin\theta - g\sin\alpha\cos\phi\cos\theta\right) \\
\dot{\phi} &= p + \tan\theta\left(q\sin\phi + r\cos\phi\right) \\
\dot{\theta} &= q\cos\phi - r\sin\phi
\end{aligned}
\tag{1}
$$

where $C_{Y_{WIND}} = C_Y \cos\beta + C_D \sin\beta$. In addition, C_L, C_D and C_Y are the lift, drag and side aerodynamic forces coefficients, and C_l, C_m and C_n are the rolling, pitching and yawing aerodynamic moment coefficients, respectively.

In the equation (1), α and β are the angle-of-attack and the angle-of-sideslip of the aircraft, respectively. The angular rates along the body axes are p, q and r, and ϕ and θ are respectively the roll and pitch angles. These variables compose the state vector,

$$x = [\,p \quad \mathrm{q} \quad \mathrm{r} \quad \alpha \quad \beta \quad \phi \quad \theta\,]^{\mathrm{T}}. \tag{2}$$

The aerodynamics coefficients and, consequently, the aerodynamic forces and moments, are function of the states of the vehicle and also function of the aerodynamic control surface deflections. For the flight controls problem in this work, three aerodynamic control surfaces are assumed: the aileron, δ_a, for lateral control; the rudder, δ_r, for directional control; and the elevator, δ_e, for longitudinal control, composing the input vector $u = [\,\delta_{\mathrm{a}} \quad \delta_{\mathrm{r}} \quad \delta_{\mathrm{e}}\,]^{\mathrm{T}}$. These control surfaces are directly used in the inner linearization loop to control the output variables, assumed to be $y = [p, q, r]$.

3. SYMBOLIC PROCESSING FOR 6DOF DI CONTROLLER

Therefore, by using equation (1) and Mathematica for symbolic mathematical processing the inner linearization loop becomes linear in aerodynamic derivatives Θ_1 and Θ_2

$$\dot{y} = F_1(x) + F_2(x)\Theta_1 + M(u)\Theta_2 \tag{3}$$

were

$$F_1 = \begin{pmatrix} \dfrac{q\left(-I_x I_{xz} p + I_{xz} I_y p - I_{xz} I_z p + I_{xz}^2 r - I_y I_z r + I_z^2 r\right)}{I_{xz}^2 - I_x I_z} \\ \dfrac{\left(-I_x + I_z\right) pr + I_{xz}\left(-p^2 + r^2\right)}{I_y} \\ \dfrac{q\left(-I_x^2 p - I_{xz}^2 p + I_x I_y p + I_x I_{xz} r - I_{xz} I_y r + I_{xz} I_z r\right)}{I_{xz}^2 - I_x I_z} \end{pmatrix} \tag{4}$$

the last 2 terms in (3) are the contributions of the aerodynamics characteristics of the aircraft, including the aerodynamic control surfaces. These portions depend on the modeling of C_L, C_D and C_Y and C_l, C_m and C_n as a function of the aircraft model states and inputs. They are omitted here, since they are quite large expressions.

4. INDIRECT ADAPTIVE CONTROL

In order to introduce adaptability into the flight control system shown in Fig. 1, an indirect adaptive control strategy of the certainty equivalence type is used, see Goodwin and Sin (1984) for details. Although it is a classical control law, its use here is indeed recommended since by using symbolic processing it is possible to obtain equation (3), which is linear in the unknown parameters. In (3) we also have

$$F_1(x) \in R^{3x1},\ F_2(x) \in R^{3x11},\ \Theta_1 \in R^{11x1},\ M(u) \in R^{3x5},\ \Theta_2 \in R^{5x1} \tag{5}$$

with

$$x = [\,p, q, r, \alpha, \beta, \phi, \theta\,], \quad y = [p, q, r],$$

$$\Theta_1 = [C_{l0}, C_{l\beta}, C_{lp}, C_{lr}, C_{m0}, C_{m\alpha}, C_{mq}, C_{n0}, C_{n\beta}, C_{np}, C_{nr}]$$
$$\Theta_2 = [C_{n\delta a}, C_{l\delta a}, C_{n\delta r}, C_{l\delta r}, C_{m\delta E}]$$

$$u = [\delta_a, \delta_r, \delta_e]$$

In the discrete time domain, it is possible to obtain the linear regression model

$$\dot{y}(k+1) = \Phi(k)\Theta(k) \tag{6}$$

and any identification method for obtaining the parameter estimates can be used, as for instance the least squares method. Additionally, a modification is introduced in the adaptive controller, in order to improve its integrity: the parameter estimation is not applied to the full parameter values, but actually for their variations around the nominal values. This also simplifies the performance evaluation, since the nominal performance is recovered by making the parameter estimates equal to zero.

5. SIMULATION RESULTS

The adaptive inversion-based adaptive aircraft controller was simulated with Matlab/Simulink, and at first the performance of the baseline DI controller, shown in Fig. 1, was considered and good results were obtained, thereby indicating that the symbolic procedure for designing the DI controller was properly implemented. This baseline control represents the best which can be achieved. It should also be highlighted that the commanded signals are not directly delivered to the control system, since some flight quality parameters must be satisfied, see Hodgkinson (1999) for details. Hence, the command signal is first properly prefiltered and then delivered to the control system. Therefore, the performance should be evaluated by taking into consideration only the reference and the measured signals, which stand for the system outputs.

Now the adaptive capability is investigated. For this, the parameters Θ_1 and Θ_2 are decreased by 5% and increased by 40%, respectively, i.e., a mismatching between the nominal model used in the DI design and the true aircraft dynamics is simulated. The corresponding commanded, reference and measured signals are shown in Fig. 2, fort both the baseline and adaptive controllers.

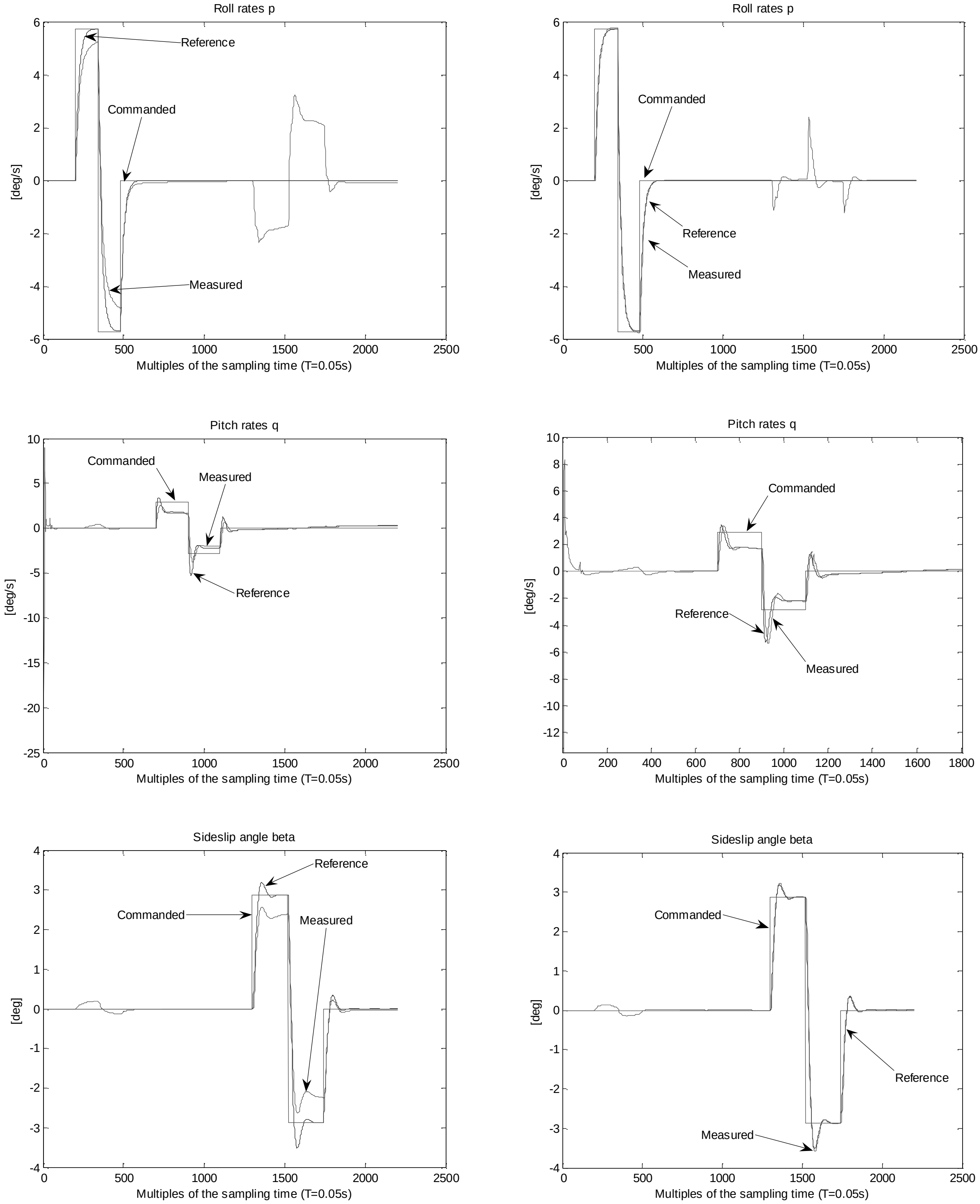

Figure 2. Signals commanded by the pilot, reference signals and measured signals, for the baseline (first column) and the adaptive controller (second column)

The first column in Fig. 2 shows that the baseline DI controller does not cope well with the mismatch between the nominal model employed for design and the actual plant. On the other hand, the performance of the adaptive controller is adequate, since the error between the reference and the measured signals are small.

6. CONCLUSIONS

This paper has investigated the application of the DI strategy for implementing flight control systems. The 2 main contributions are: a) use of symbolic processing for designing the baseline DI controller, thereby removing the usual simplifications required in the literature, and b) use of an indirect adaptive control strategy to account for model mismatches or failures. From the simulations, the expected conclusion can be drawn: if there is a considerable mismatch between the nominal model used for designing the baseline DI controller and the actual aircraft dynamics, then there can be considerable performance degradation. However, when the adaptation is introduced, the tracking errors are considerably reduced. Both the baseline DI controller and the indirect adaptive controller discussed in this paper have already been tested with a more sophisticated Embraer regional aircraft model, and the results will be reported elsewhere.

7. ACKNOWLEDGEMENTS

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