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A Stochastically Optimal Feedforward and Feedback Technique for Flight Control Systems of High Performance Aircrafts

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Abstract

This paper focuses on a detailed description of a control technique, which has been successfully used in several advanced flight control systems research projects over the past decade. The technique, called Stochastically Optimal Feedforward and Feedback Technique (SOFFT), directly descends from optimal control, and in particular from Explicit Model Following Control (EMFC). Unlike the most used model following techniques, in SOFFT the feedforward and feedback control laws are designed independently of one another. Moreover, this technique relies on different levels of plant models, specifically, a simple plant model is used for the synthesis of the feedback control law, and another plant model, together with a "command" model, are used in the synthesis of the feedforward control laws. It is important to notice that the controller in its final form is nonlinear in nature. This is because the matrices that compose the plant and command models are constantly updated as the aircraft moves throughout the flight envelope, and at least two Algebraic Riccati Equations (ARE) are solved in real time to compute the feedback and feedforward gains.

List of Acronyms

SOFFT	Stochastically Optimal Feedforward and Feedback Technique
EMFC	Explicit Model Following Control
IMFC	Implicit Model Following Control
ARE	Algebraic Riccati Equation
HARV	High Angle of Attack Research Vehicle
MDA	McDonnell Douglas Aerospace
IFCS	Intelligent Flight Control System
WVU	West Virginia University
FDC	Flight Dynamics and Control
PID	Parameter Identification

1 Introduction

While the feedback control problem has been studied extensively, the feedforward control problem has received generally less attention [1]. In some optimal control techniques, such as IMFC and EMFC [2], the feedforward and feedback control laws are obtained by the optimization of a single criterion in which the performance of the feedforward and feedback control laws are jointly evaluated. This generally places conflicting demands on the control law, making it difficult to achieve at the same time all the objectives, such as, good closed loop stability characteristics (damping and bandwidth), attenuation of high frequency disturbances, desired response to input command, robustness to low frequency uncertainties and unmodeled nonlinearities. In other words, the optimization of a single criterion results in a compromise between the performance of the feedforward and the feedback components of the control system. As an example, when the cost function is optimized to provide good tracking characteristics, the controller usually has a high bandwidth with large feedback gains and poor noise attenuation [3].

The SOFFT approach [3,4,5] is directly related to Explicit Model Following Control, but unlike EMFC, it decouples the feedforward and feedback control design process by separating the feedforward and feedback control objectives.

As a result, compromise between these two part of the control system is no longer necessary. In particular, control objectives that relate the system response to input commands are mainly met by the feedforward controller, while objectives that relate closed loop damping and disturbance rejection are met by the feedback controller.

A different set of problems is raised by the fact that the system to be controlled (i.e. an high performance aircraft) is definitely nonlinear over the full operational range (i.e. flight envelope). Typically such a system cannot be controlled with satisfactory performance by a single linear controller.

During the last decade, a considerable research effort allowed the control community to figure out several ways of dealing with this situation. While boundaries between the different conceptual control categories tend to disappear as the research goes on, it can be said that the main approaches towards the control of nonlinear systems nowadays are: Inversion Based Control [6], Adaptive control [7], Gain Scheduling Control [8], and Optimal Control [2].

Although only recently Gain Scheduling control was given a rigorous framework, from a practical standpoint, it has definitely been the most used approach when dealing with

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nonlinear uncertain systems. Among the reasons for this success are its conceptual simplicity, the (apparent) possibility of inheriting a well established framework from the Linear Multivariable Control theory, and, last but not least, a long list of problems solved in the "real world" [8].
The control approach described in this paper can be safely described as Gain Scheduling since as the aircraft moves throughout the flight envelope, the matrices describing its linearized (local) model are continuously updated, and two ARE are solved to yield the most updated control gains. When the matrices of the linearized aircraft model are obtained from an identification process [9], the overall control system must be viewed as an Adaptive Control system.
NASA Langley sponsored the initial work on this approach, in 1992 [3]. As a result a variable gain SOFFT methodology was used to design a control system for the F/A-18 HARV (High Angle of Attack Research Vehicle) Aircraft which displayed excellent performance characteristics over the whole flight envelope both within simulation and flight testing [4]. Several extension were later investigated [5].
From 1995 to 1999 a NASA-Sponsored project named ***F-15 IFCS*** (Intelligent Flight Control System) was conducted by McDonnell-Douglas Aerospace (MDA) under the supervision of NASA Ames and Dryden. One goal of the project was the development and flight testing of a robust flight control system for the F15-ACTIVE aircraft (which is augmented with canards and thrust vectoring). The SOFFT was one of the investigated techniques along with a Setpoint Regulator and a Robust Servo Controller. After a detailed comparison, the SOFFT was chosen for implementation [5]. Flight tests conducted in 1999 showed that the SOFFT outperformed the previous existing controllers.
Within the prosecution of the above project, an approximate nonlinear model of the F15 dynamics has been built at WVU using a simulation code freely distributed for an academic design competition sponsored within the activities of the 1991 AIAA GNC conference [9]. The Matlab/Simulink based model has then been imported within the Flight Dynamics and Control (FDC) Toolbox providing the computational environment for this study.
On the basis of the available reports on the SOFFT technique from NASA and Boeing, a detailed Simulink implementation of the SOFFT was built for the above environment. This implementation has been used as an example throughout the paper.

2 Background : EMFC

The Explicit Model Following Control solves the general tracking problem using the Linear Quadratic Regulator (LQR) approach. This amounts to finding the closed loop control law that minimizes the error between the dynamics of the plant and a reference model:

$$\tilde{u} = \min \int_0^\infty ([H_x\tilde{x} - H_z\tilde{z}]^T Q [H_x\tilde{x} - H_z\tilde{z}] + \tilde{u}^T R \tilde{u}) dt$$

constrained to: (1)

$$\begin{bmatrix} \dot{\tilde{x}} \\ \dot{\tilde{z}} \end{bmatrix} = \begin{bmatrix} A_x & 0 \\ 0 & A_z \end{bmatrix} \begin{bmatrix} \tilde{x} \\ \tilde{z} \end{bmatrix} + \begin{bmatrix} B_x & 0 \\ 0 & B_z \end{bmatrix} \begin{bmatrix} \tilde{u} \\ \tilde{u}_z \end{bmatrix}$$

where A_x B_x C_x D_x H_x is the plant model and A_z B_z C_z D_z H_z is a "reference" model. Since the reference model is explicitly introduced in the equations the feedforward part of the resulting controller includes this model. The control input can indeed be expressed as:

$$\tilde{u} = -R^{-1}B_x^T P_{11}\tilde{x} - R^{-1}B_x^T P_{12}\tilde{z} = -K_x\tilde{x} - K_z\tilde{z} \quad (2)$$

where P is the solution of the Riccati equation. Due to the special structure of the problem, P is subject to a partition into two Riccati equations plus a Lyapunov equation.
Since the state and input variables in the problem usually represent deviations from a reference trajectory:

$$\begin{aligned} &\tilde{x} = x - x^*, \quad \tilde{z} = z - z^*, \\ &\tilde{u} = u - u^*, \quad \tilde{u}_z = u_z - u_z^* \end{aligned} \quad (3)$$

and since the "trajectory" is often a set point condition:

$$z^* = -A_z^{-1}B_z u_z^*, \quad x^* = -A_x^{-1}B_x u^* \quad (4)$$

by imposing also the constraint: $H_x x^* = H_z z^*$ we have:

$$\begin{aligned} u &= u^* + K_x x^* + K_z z^* - K_x x - K_z z^* \\ &= K_u u_z^* - K_x x - K_z z \end{aligned} \quad (5)$$

So the final control structure has two feedforward matrices and one feedback matrix.

3 SOFFT : Design Process

In the SOFFT approach, the design of the feedforward and feedback components is separated into two different stages.
A peculiar characteristic of this approach is the fact that , for the design of the feedforward part alone, two models are used: a command model and a reference plant model. The reference plant model is then forced to follow the signals coming from the command model, by designing a control law that minimizes the error between the two models.
The feedback part then addresses the problem of forcing the real plant to follow the behavior of the reference plant model. This two stages process could be viewed as a simple way to solve the linear servomechanism problem [1].

3.1 FF Design using EMFC

Since the aim of the SOFFT feedforward design is to minimize the error between the dynamics of command model and reference plant model, the EMFC is a very appropriate framework to be used. Moreover, since the feedforward part will be implemented as an unique digital block, there is no need to worry about noise attenuation or large feedback gains. The cost function can then be chosen just to provide good tracking characteristics.

So, letting A_x B_x C_x D_x H_x be the reference plant model and A_z B_z C_z D_z H_z the "command" model, if we follow the steps from (1) to (5) then we come up with three feedforward matrices K_u K_z K_x that allow the reference plant model to follow the behavior of the command model.

This way of designing the feedforward gains requires the solution of an ARE, or, exploiting the structure of the problem, two ARE's and one Lyapunov equation. If this is to be done in real time, the computational cost can easily become prohibitive.

3.2 FF Design using Perfect Tracking

Another way of computing the feedforward gains descends directly from the Dynamic Inversion control approaches.

Indeed, if we define the error to be minimized as:

$$e \triangleq H_x x - H_z z \tag{6}$$

by imposing the constraint: $H_x x^* = H_z z^*$ we already have that the error is zero in the "set point condition". A way to ensure that the error remains zero is to design a control law that forces the time derivative of the error to remain zero:

$$\begin{aligned} \dot{e} &= H_x \dot{x} - H_z \dot{z} \\ &= H_x A_x x + H_x B_x u - H_z A_z z - H_z B_z u_z = 0 \end{aligned} \tag{7}$$

So, if $H_x B_x$ is full column rank, (as is often the case when the dimension of e is less than or equal to the dimension of u) then the control law:

$$u = (H_x B_x)^+ (-H_x A_x x + H_z A_z z + H_z B_z u_z) \tag{8}$$

is such that the error remains at zero. In some cases, (minimum phase plants with $H_x B_x$ is full column rank) this control law is the limit case of an EMFC design with a vanishing R in (1).

From (8), adopting negative feedback convention we have the three feedforward matrix gains:

$$\begin{aligned} K_x &= +(H_x B_x)^+ H_x A_x, \\ K_z &= -(H_x B_x)^+ H_z A_z, \\ K_u &= -(H_x B_x)^+ H_z B_z \end{aligned} \tag{9}$$

If HB is square, as is often the case, then the pseudo-inverse becomes the standard inverse. In any case, the solution of the Riccati equation is avoided. This is exactly the reason that lead to the adoption of this method in the IFCS [5].

The price to pay for this gain in computational resources is that the perfect tracking approach, as any inverting control law, works only for minimum phase plants. Indeed, a closer look reveals that the error is kept equal to zero by moving the poles of the feedforward dynamics to the zeros of the following model:

$$\begin{aligned} \begin{bmatrix} \dot{\tilde{x}} \\ \dot{\tilde{z}} \end{bmatrix} &= \begin{bmatrix} A_x & 0 \\ 0 & A_z \end{bmatrix} \begin{bmatrix} \tilde{x} \\ \tilde{z} \end{bmatrix} + \begin{bmatrix} B_x (H_x B_x)^+ \\ 0 \end{bmatrix} \tilde{u}' \\ e &= \begin{bmatrix} H_x & -H_z \end{bmatrix} \begin{bmatrix} \tilde{x} \\ \tilde{z} \end{bmatrix} \end{aligned} \tag{10}$$

So, if the reference plant model (which in our case is time varying since A_x B_x C_x D_x H_x are a function of the state) happens to be such that the system in (10) is non-minimum phase, then the whole feedforward part will be unstable.

Although this instability was never observed in simulation, it would be very desirable to exclude such a case before actually implementing the control laws. Perhaps a μ-analysis with real structured uncertainties over A_x B_x C_x D_x H_x could pinpoint if this instability of the feedforward part can actually take place.

3.3 Feedback Design

The design of the feedback control is performed independently from the feedforward control design by using a standard output feedback LQR synthesis on the feedback plant model A,B,C,D :

$$\tilde{u} = \min \int_0^\infty (\tilde{y}^T Q \tilde{y} + \tilde{u}^T R \tilde{u}) dt$$

constrained to: (11)

$$\begin{bmatrix} \dot{\tilde{x}} \\ \tilde{y} \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} \tilde{x} \\ \tilde{u} \end{bmatrix}$$

where the input, state, and output variables are deviations from a reference trajectory u^* x^* y^* , which in this case is supplied by the feedforward part, and in particular by the input state and output of the "reference" plant model:

$$\tilde{x} = x - x^*, \quad \tilde{u} = u - u^*, \quad \tilde{y} = y - y^* \tag{12}$$

The following ARE involving the matrices A,B,C,D,Q,R is solved:

$$
\begin{aligned}
&A^T X \ + \ XA \\
&- (XB \ + \ C^T QD)(R + D^T QD)^{-1}(B' X \ + \ D^T QC) \\
&+ C^T QC \ = \ 0
\end{aligned} \tag{13}
$$

The solution 'X' is used to calculate the following state feedback matrix:

$$K = \ (R + D^T QD)^{-1}(B^T X \ + \ D^T QC) \tag{14}$$

since we have access only to the output vector y rather than to the state x , we have to build an equivalent output feedback matrix, this can be done with the following formula:

$$K_y = K(C - DK)^+ \tag{15}$$

Assuming that C-DK is full column rank, $u = -K_y y$ is equivalent to $u = -Kx$. As a matter of fact, equation (15) is obtained by substituting $-Kx$ to u into the equation $u = -K_y(Cx+Du)$, eliminating x, and solving for Ky.

3.4 General Structure

The SOFFT general structure that results from the described design process is the one shown in the picture below, with one feedback matrix and three feedforward matrices:

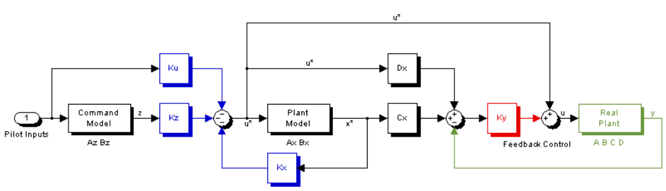

Figure 1

4 Nonlinear Extension

As pointed out in the introduction, a single linear controller can hardly cope with the nonlinear behavior exhibited by an aircraft over the whole flight envelope. Adaptation was the chosen way to deal with this situation, infact, one of the main goal of the F15-IFCS project was the development of a flight control concept involving the use of parameter identification (PID) algorithms able to estimate in real-time the aerodynamic coefficients of the aircraft.

So, as the aircraft moves throughout the flight envelope, the non-dimensional stability and control derivatives are estimated. If the estimation satisfies certain "quality requirements" [9] then these parameters are used to compute new values for most of the matrices that compose the models used both in the feedback and in the feedforward part. Then the feedforward gains K_u K_z K_x are computed following the perfect tracking procedure, and the feedback matrix K_y is computed by solving an ARE.

As a result, another (inherently nonlinear) feedback loop appears in the control system, which can be easily visualized by the blue bottom links in the picture below:

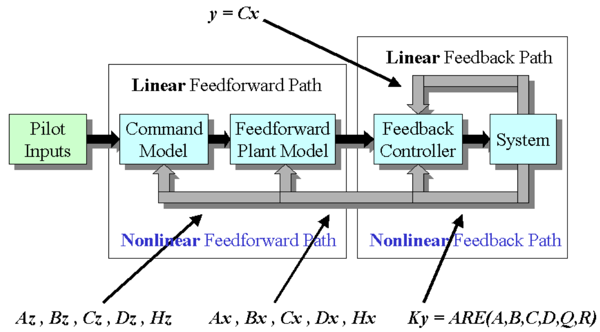

Figure 2

Even in the easier case for which the matrices of the controller are scheduled directly from the state variables, as it was for the F-18 HARV, the stability of such a system cannot be easily guaranteed [8]. Since in our case the feedback matrices are the result of an estimation process, (so a lot more state variables enters in the description of the system), followed by rearrangement into state space form, inversions (feedforward) and ARE solution (feedback), it definitely can be said that analytical tools like the Lyapunov stability criteria become useless, and the system cannot be guaranteed to be stable or even bounded at least with the tools presently available.

However, it is also fair to say that if the dynamics of the "nonlinear feedback loop" evidenced by the bottom links in figure 2, is considerably slower than the dynamics of the "linear feedback loop", and if the PID algorithm works well and yields linear matrices that are (at least locally) a reasonable representation of the true system dynamics, then one can expect that the stability and performance proprieties of the typical local linear controller should carry over to the overall nonlinear closed loop system [8].

The next sections will be devoted to a more detailed description of the design of the actual lateral and longitudinal controllers.

5 Example: Longitudinal Design

The command models were designed to emulate the conventional F15 S/MTD command models. For the longitudinal channel, this second order filter was used:

$$q_{cmd} = \frac{K_{lon}\omega_{sp}{}^2(s + L_\alpha)}{s^2 + 2\zeta_{sp}\omega_{sp}s + \omega_{sp}{}^2}\delta_{lonstk} \tag{16}$$

In state space form (Az, Bz, Hz) :

$$\begin{bmatrix}\dot{\bar{q}}_{cmd}\\ \ddot{\bar{q}}_{cmd}\end{bmatrix}=\begin{bmatrix}0 & 1\\ -\omega_{sp}^2 & -2\zeta_{sp}\omega_{sp}\end{bmatrix}\begin{bmatrix}\bar{q}_{cmd}\\ \dot{\bar{q}}_{cmd}\end{bmatrix}+\begin{bmatrix}0\\ K_L\omega_{sp}^2\end{bmatrix}\delta_{lonstk}$$
$$q_{cmd} = \begin{bmatrix}L_\alpha & 1\end{bmatrix}\begin{bmatrix}\bar{q}_{cmd}\\ \dot{\bar{q}}_{cmd}\end{bmatrix} \tag{17}$$

where ω_{sp} K_{lon} L_a are scheduled with mach, alpha, altitude and the derivative Cza, and $\xi_{sp} = 0.8$.
The longitudinal plant model (A_X B_X C_X D_X H_X) has a one input, 7 states, 2 outputs :

$$\begin{bmatrix}\dot\alpha\\ \dot q\end{bmatrix}=\begin{bmatrix}A_{LG11} & A_{LG12}\\ A_{LG21} & A_{LG22}\end{bmatrix}\begin{bmatrix}\alpha\\ q\end{bmatrix}+\begin{bmatrix}B_{LG12}\\ B_{LG22}\end{bmatrix}\delta_c+\begin{bmatrix}B_{LG11}\\ B_{LG21}\end{bmatrix}\delta_s$$
$$\ddot\delta_c = -\omega_{nc}^2\delta_c - 2\zeta_c\omega_{nc}\dot\delta_c + \omega_{nc}^2 x_c$$
$$\dot x_c = -\omega_{c1}x_c + K_{c1}\omega_{c1}\alpha_f$$
$$\tau_f\dot\alpha_f = \alpha_p - \alpha_f \tag{18}$$
$$\tau_p\dot\alpha_p = \alpha - \alpha_p$$
$$\begin{bmatrix}a_z\\ q\end{bmatrix}=\begin{bmatrix}C_{LG11} & C_{LG12}\\ 0 & 1\end{bmatrix}\begin{bmatrix}\alpha\\ q\end{bmatrix}+\begin{bmatrix}D_{LG2}\\ 0\end{bmatrix}\delta_c+\begin{bmatrix}D_{LG1}\\ 0\end{bmatrix}\delta_s$$

This model includes the short term F15 dynamics, the canard actuator model, the canard scheduling with the attack angle, the attack angle sensor dynamics, and the normal acceleration output equation. H_X is the row vector [0 1]. For what concern the numerical value of the parameters, ω_C = 43 rad/sec, ξ_C = 0.4, ω_{C1} = 66 rad/sec, τ_f = 20 sec, τ_p = 40 sec and K_{c1} is a function of mach, alpha, and altitude.
Rearranging the command and plant models in state space format (at each step) the 3 feedforward control matrices K_X, K_Z and K_U using the perfect tracking approach formulas as indicated in the previous sections. For the longitudinal case H_xB_x is scalar; thus the (pseudo) inverse is trivial.
The plant model for the feedback design is a simplified version of the plant used for the feedforward design, where all of the dynamics relative to the alpha sensor and canard actuators are neglected, the canard schedule with alpha is approximated by a constant gain, and the integral of q is considered as a state in order to have zero steady state error in the q regulation:

$$\begin{bmatrix}\dot\alpha\\ \dot q\\ q\end{bmatrix}=\begin{bmatrix}A_{LG11}+K_{c1}B_{LG12} & A_{LG12} & 0\\ A_{LG21}+K_{c1}B_{LG22} & A_{LG22} & 0\\ 0 & 1 & 0\end{bmatrix}\begin{bmatrix}\alpha\\ q\\ \int q\end{bmatrix}+\begin{bmatrix}B_{LG11}\\ B_{LG21}\\ 0\end{bmatrix}\delta_s$$
$$\begin{bmatrix}\int q\\ a_z\\ q\end{bmatrix}=\begin{bmatrix}0 & 0 & 1\\ C_{LG1}+K_cD_{LG2} & C_{LG2} & 0\\ 0 & 1 & 0\end{bmatrix}\begin{bmatrix}\alpha\\ q\\ \int q\end{bmatrix}+\begin{bmatrix}0\\ D_{LG1}\\ 0\end{bmatrix}\delta_s \tag{19}$$

Given an unitary R matrix and a Q matrix such as:

$$Q = k_q\begin{bmatrix}0.6 & 0 & 0\\ 0 & Q_{nz} & 0\\ 0 & 0 & 1\end{bmatrix} \tag{20}$$

where k_q and Q_{nz} are scheduled respectively with dynamic pressure and alpha, it is possible to compute (at each step) the feedback control as indicated in the previous sections

6 Example : Lateral Design

The command models used for the lateral-directional dynamics are:

1) roll rate command from lateral stick:

$$p = \frac{K_{lat}}{\tau_r s+1}\delta_{latstk} \tag{21}$$

2) beta and yaw rate command from pedal:

$$\begin{bmatrix}\beta\\ r\end{bmatrix}=\begin{bmatrix}1\\ -\dfrac{Y_\beta}{V_t}\dfrac{s-Y_V}{Y_V}\end{bmatrix}\frac{K_{dir}\omega_{dr}^{\ 2}}{s^2+2\zeta_{dr}\omega_{dr}s+\omega_{dr}^{\ 2}}\delta_{pedal} \tag{22}$$

where beta and r are used to generate a "total directional command" Y_{cmd}:

$$Y_{cmd} = \begin{bmatrix}K_{\beta_{cmd}} & K_{rs_{cmd}}\end{bmatrix}\begin{bmatrix}\beta\\ r_s\end{bmatrix} \tag{23}$$

In state space form (Az, Bz)

$$\begin{bmatrix}\dot\beta\\ \ddot\beta\\ \dot p\end{bmatrix}=\begin{bmatrix}0 & 1 & 0\\ -\omega_{dr}^2 & -2\zeta_{dr}\omega_{dr} & 0\\ 0 & 0 & -1/\tau_r\end{bmatrix}\begin{bmatrix}\beta\\ \dot\beta\\ p\end{bmatrix}+$$
$$\begin{bmatrix}0 & 0\\ 0 & \omega_{dr}^2K_{dir}\\ K_{lat}/\tau_r & 0\end{bmatrix}\begin{bmatrix}\delta_{latstk}\\ \delta_{pedal}\end{bmatrix} \tag{24}$$

Since $K_{\beta cmd}$ = 1, Krs_{cmd} = -0.2, $Y_v = V_t/Y_\beta$ then the Hz matrix equation reduces to:

$$\begin{bmatrix}p_{cmd}\\ Y_{cmd}\end{bmatrix}=\begin{bmatrix}0 & 0 & 1\\ 1-0.2Y_V & 0.2 & 0\end{bmatrix}\begin{bmatrix}\beta\\ \dot\beta\\ p\end{bmatrix} \tag{25}$$

The lateral-directional plant model (A_x, B_x, C_x, D_x) has 2 inputs, 3 states, and 3 outputs consisting in the dutch roll dynamics of the plant with mixed inputs. The Hx matrix equation is instead:

$$\begin{bmatrix} p \\ Y_{Xcmd} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ K_{\beta_{cmd}} & 0 & K_{rs_{cmd}} \end{bmatrix} \begin{bmatrix} \beta \\ p \\ r \end{bmatrix} \quad (26)$$

As in the previous cases, the 3 feedforward control matrices were calculated using the 'perfect tracking' approach formulas. This time $H_X B_X$ is a 2 by 2 matrix thus an inverse must be calculated at each step.For what concerns the feedback design, R is still unitary, while Q is chosen as:

$$Q = k_q \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0.2 & 0 \\ 0 & 0 & 0.01 \end{bmatrix} \quad (27)$$

As for the longitudinal case the feedback control is computed at each time step using the formulas in section 4.

7 Example : Simulink Implementation

The Simulink implementation of the full blown nonlinear controller was challenging for two main reasons. First of since at the time only Matlab 5.3 was available, a complete matrix support for Simulink had to be built. Second, an important requirement was that the code had to be readily "autocodable", thus excluding any possible use of the Matlab interpreter to solve matrix equations (i.e. ARE). The following picture shows the upper level diagram of the longitudinal SOFFT.

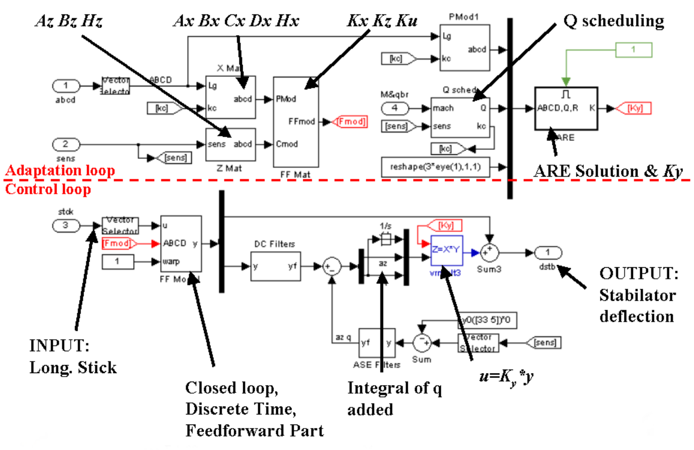

Figure 3

8 Example : Simulation Results

As an example of the level of tracking that this kind of controllers can provide, the response to a doublet in the lateral stick channel is shown in figure 4.

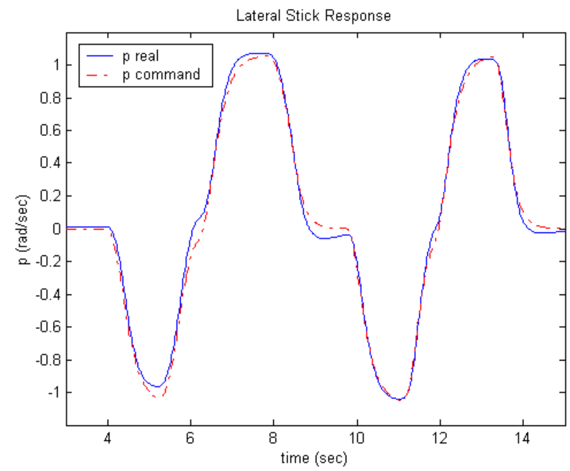

Figure 4

9 Conclusions

A technique successfully used for the control of two high performance aircraft over the last decade has been described in detail throughout this paper. The peculiarities of this technique were discussed, and examples of its direct application were given.

Acknowledgements

The authors wish to thank the unknown reviewers for some very interesting comments, which due to space constraints have been addressed only partially, but could be the subject of future research.

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