DEVELOPMENT OF DESIGN STRUCTURE FOR ROBUST FLIGHT CONTROL LAW

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Abstract. *This work presents the development of a flight control law design structure, based on the H_∞ and μ synthesis theory. The design criteria includes usual robustness and performance requirements related to parameters uncertainty in the vicinity of the design point. In addition, the conventional mixed sensitivity design scheme is changed to comply with specific requirements of a flight control law design. These changes include the introduction of a feedforward path to reduce the phase delay at high frequencies and a perturbation in the plant input to avoid pole-zero cancellation. Typical uncertainties in the aircraft dynamics are introduced in the μ design. Using μ analysis, the closed loop performance and robustness are compared against a H_∞ design that does not consider the uncertainties in the design. The feedback loop and the weighting function adjustment are based on the C* flying qualities criterion, and analysis through other criteria are also briefly shown. The possibility of H_∞ and μ synthesis controllers satisfy the C* criterion is demonstrated. The resulting controller order is not excessive, what would make the implementation of a scheduled controller for the whole flight envelope practical. Furthermore, the robustness to the modeled uncertainties can be guaranteed.*

Keywords*: flight control, robustness, C*, feedback*

1. INTRODUCTION

This work focuses on flight control laws design structure, using H_∞ and μ synthesis, and also on robustness analysis. The goal is finding a robust control law that satisfies the design requirements not only in the design point, but also for a given combination of varying flight parameters. These variations are modeled as uncertainties in the Linear Fractional Transform (LFT) framework, and it shows to be an efficient way to incorporate the uncertainties in both μ synthesis and analysis. In order to evaluate the benefits of including the uncertainties in the design model, the results obtained for the μ synthesis are compared to the results of an H_∞ design that considers only the specifications for the nominal model.

The typical mixed sensitivity approach is modified to incorporate a feedforward path, commonly used in flight control systems, and also to avoid the problem of oscillatory poles cancellation. This structure also incorporates the C* flying qualities criterion. The analysis with other flying qualities criteria are shown in Siqueira et al. (2007).

1.1. H_∞ control

The H_∞ control design technique is formulated in the frequency domain, and is based on the optimization of a cost function written in terms of a H_∞ norm, defined as:

$$\|T_{zw}(jw)\|_\infty = \sup_w \bar{\sigma}\left(T_{zw}(jw)\right). \tag{1}$$

The design aims, employing output feedback, to find a controller that provides stability and performance robustness for a defined class of perturbations (Zhou, 1992). These perturbations can include uncertainties and modeling errors. Performance specification can include perturbation rejection, noise attenuation and reference tracking.

An augmented plant is used to introduce the stability and performance specifications, and also to define the perturbations. The typical augmented plant for the robust control problem known as mixed sensitivity includes the nominal plant *P* and the weighting functions:

• W_S weights the error signal. It acts on the sensitivity function *S*. Since *S* must be small for low frequencies to provide performance (e.g. disturbance rejection, small steady-state error), W_S must be great enough for low frequencies;

• W_{KS} weights the control signal, acts on *S* in series with the controller *K*, and must be great enough to avoid excessive controller gain;

• W_T weights the plant output. It acts on the complementary sensitivity *T*, which shall be small for high frequencies to keep the system stable in the presence of high frequency uncertainties. Hence, W_T must be large for high frequencies.

The feedback system sensitivity function *S* and the complementary sensitivity function *T* are defined by:

$$S = (I + G_n K)^{-1} \tag{2}$$

$$T = I - S = KG_n(I + KG_n)^{-1} \tag{3}$$

And the H$_\infty$ control problem can be formulated in terms of a minimization of a cost function $\|T_{zw}\|_\infty$, where

$$T_{zw} := [W_S S \;\; W_{KS} KS \;\; W_T T]^T, \tag{4}$$

or finding a small γ such that $\|T_{zw}\|_\infty \le \gamma$.

The above formulation is called closed-loop approach, and a major disadvantage is the cancellation of the plant resonant poles by the resulting controller zeros. This may be unacceptable if the plant resonant poles change, because these poles are no longer cancelled and the oscillation arises. This problem happens because the closed-loop specification is imposed without regard to the plant's characteristics, and can be avoided by using formulations which result in restraints on functions such as SG_n. In a typical commercial aircraft model there are two resonant modes (the short period and the phugoid), so this problem shall be considered. In Gatley et al. (2002), three weighting formulations are compared: The two-block mixed sensitivity is similar to the formulation shown above, and it exhibited significant degradation at off-design points, caused by the cancellation of the aircraft poles by controller zeroes. In contrast, the other formulations provided better robustness, but the adjustment of weighting functions is more complicated.

In Lin and Khammash (2001), H$_\infty$ *GS/T* design is employed to avoid pole-zero cancellations. This formulation is similar to the mixed sensitivity, but the reference input is multiplied by a small constant and a perturbation input is added to the control signal. The new functions to be minimized are SG_n e T, and it solves the polo-zero cancellations, but makes the weighting functions selection more difficult.

The alternative used in this work is summing a perturbation, multiplied by a gain, to the control signal in the conventional two-block mixed sensitivity. The goal is to adjust this gain to a value high enough to add a SG_n weighting to avoid pole-zero cancellations, but sufficiently small to allow a simpler weighting function selection. In the design with μ synthesis, the introduction of the uncertainties also contributes to avoid pole-zero cancellations.

1.2. μ synthesis and analisis

The structured singular value μ is a powerful tool widely used for robust control analysis and synthesis, especially for systems subjected to structured uncertainties, written as an LFT as shown in Fig. 1 (Zhou, 1998). The block Δ_p can represent model uncertainties and also stability and performance specifications, like in the H$_\infty$ design.

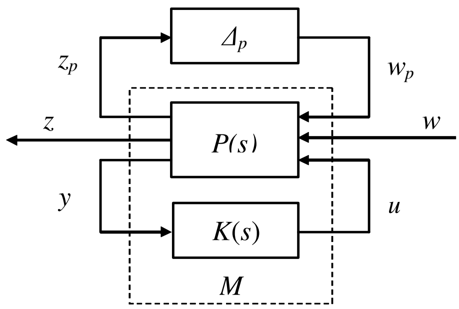

Figure 1. Control problem written as an LFT

With $\beta < 0$, the system shown in Fig. 1 has internal stability if and only if:

$$\sup_{\omega \in R} \mu_{\Delta_p}(M(jw)) \le \beta \tag{5}$$

Since the exact calculation of μ is hard, the bound values are usually employed, and the scaling matrix D is introduced to represent the uncertainty structure. D must be selected such that $D\Delta = \Delta D$.

And the μ synthesis can then be solved through an iterative minimization process known as D-K iteration:

$$\min_{stabilizing\ K} \quad \min_{stable,\ non-\min imum\ phase\ D(s)} \left\| \hat{D}(s) M \hat{D}(s)^{-1} \right\|_\infty \tag{6}$$

The minimization with fixed D is an H∞ optimization control problem, and the determination of D with fixed K involves fitting a stable, minimum phase, real-rational transfer function to the frequency-dependent scaling matrix D, obtained at a range of frequencies. Although fitting a high order transfer function to the function D can give better results, it will result in a higher controller order.

In Amato et al. (2004), μ synthesis is used for flight control law design, and a model matching methodology is applied to specify the flying qualities requirements. Besides the reference model, models for sensors, noise, actuators, gusts and shaping filters are added to the aircraft to shape the augmented plant. Although satisfactory results where obtained, the controller order is not informed. From the high order of the augmented plant, one can infer that it is also high, and this results in implementation problems. The goal in the present work is simplify the flight control problem setting to get a lower order controller without using order reduction algorithms, which can degrade the results.

1.3. LFT

The aircraft model is subjected to variations on parameters throughout the flight envelope. It is also subjected to uncertainties due to aerodynamic nonlinearities and limited precision of the aerodynamic model data. Another source of errors is the use of approximations to describe sensors, actuators, hydraulic systems, command transmission and structural modes. Even aircrafts of the same type can differ due to production tolerances.

The Linear Fractional Transformation (LFT) is an efficient tool for modeling uncertain systems in a structured way. Generally any linear time invariant system subjected to some kind of uncertainty can be described as in Fig 2.

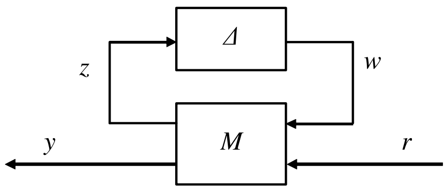

Figure 2. LFT representation of an uncertain system

In Fig. 2, M (Eq. 7) represents the relationship between the inputs w and r and the outputs z and y; M_{11} is the relationship between the external output(s) y and the external input(s) r, that is, the nominal model; Δ represents the uncertain parameters, and is usually restricted to a specified domain.

$$M = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix}. \tag{7}$$

This representation is known as upper LFT. The transfer function from y to r is given by:

$$y = F_U(M,\Delta)r = \left[M_{22} + M_{21}\Delta(I - M_{11}\Delta)^{-1}M_{12}\right]\ r \tag{8}$$

If the system is described in the state space form, with n uncertain parameters denoted by δ_i, $i = 1 : n$, $|\delta_i| \leq 1$:

$$\begin{aligned} \dot{x} &= (A_0 + A_1\delta_1 + \ldots + A_n\delta_n)x + (B_0 + B_1\delta_1 + \ldots + B_n\delta_n)r \\ y &= (C_0 + C_1\delta_1 + \ldots + C_n\delta_n)x + (D_0 + D_1\delta_1 + \ldots + D_n\delta_n)r \end{aligned} \tag{9}$$

The block M, that represents a linear uncertain model can be obtained in a known way (Mannchen, 2002):

$$\begin{bmatrix} \dot{x} \\ z_1 \\ \vdots \\ z_n \\ y \end{bmatrix} = \begin{bmatrix} A_0 & E_1 & \ldots & E_n & B_0 \\ G_1 & 0 & \ldots & 0 & H_1 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ G_n & 0 & \ldots & 0 & H_n \\ C_0 & F_1 & \ldots & F_n & D_0 \end{bmatrix} \cdot \begin{bmatrix} x \\ w_1 \\ \vdots \\ w_n \\ r \end{bmatrix} \tag{10}$$

where:

$$\begin{bmatrix} E_i \\ F_i \end{bmatrix} \cdot \begin{bmatrix} G_i & H_i \end{bmatrix} = \begin{bmatrix} A_i & B_i \\ C_i & D_i \end{bmatrix},\ r_i = rank\left(\begin{bmatrix} A_i & B_i \\ C_i & D_i \end{bmatrix}\right),$$

$$\Delta = \{diag(\delta_1 I_{r_i}, \cdots, \delta_n I_{r_n}), \delta_i \in R\} . \quad (11)$$

The uncertainties are represented by the inputs *w* and outputs *z*. and the block Δ.

Bates et al. (2003) examines alternatives for LFT-based uncertainty modeling. The technique applied in the present work, called numerical methods, is considered fast, easy to implement, and the conservatism can be reduced if the technique proposed in Mannchen et al. (2002) is used. This technique, called trends & bands, deals with multiple sources of uncertainty, and shows to be precise and practical. However, it is not used in the present work because a larger number of models would be necessary.

1.4. C* Flying qualities criterion

The C* flying qualities criterion was first published in 1965 and has been widely used. The C* parameter is the basis of the control law design of several aircraft in operation such as A320, A340, F16, F18 (Field, 1993)

The C* parameter is defined as a normalized sum of the load factor (n_z) at pilot's station and the pitch rate (q), multiplied by a constant $K_q = V_{CO}/g$:

$$C^* = n_z + K_q q \quad (12)$$

This parameter is a good indicative of the aircraft short period dynamics. It was postulated that at low speed, the most important cue for pilots is the pitch rate, whereas at high velocities the normal acceleration predominates. The speed V_{CO} was defined as a speed at which both cues have the same importance. V_{CO} should be obtained experimentally for each aircraft, but usually 122 m/s is adopted, then K_q = 12.4.

The C* flying qualities criterion defines envelopes in the time and frequency domains for the aircraft C* response to an input in the longitudinal control. Flight tests showed that a response contained within the envelopes is usually well accepted by the pilots. The envelope to be considered depends on the maneuvers and flight phase, as shown in Fig. 3. In this work, the boundary for optimum response is adopted as the design goal. For a transport aircraft the non-critical operation boundary is more reasonable, since precision track is not required, so this boundary is used for analysis.

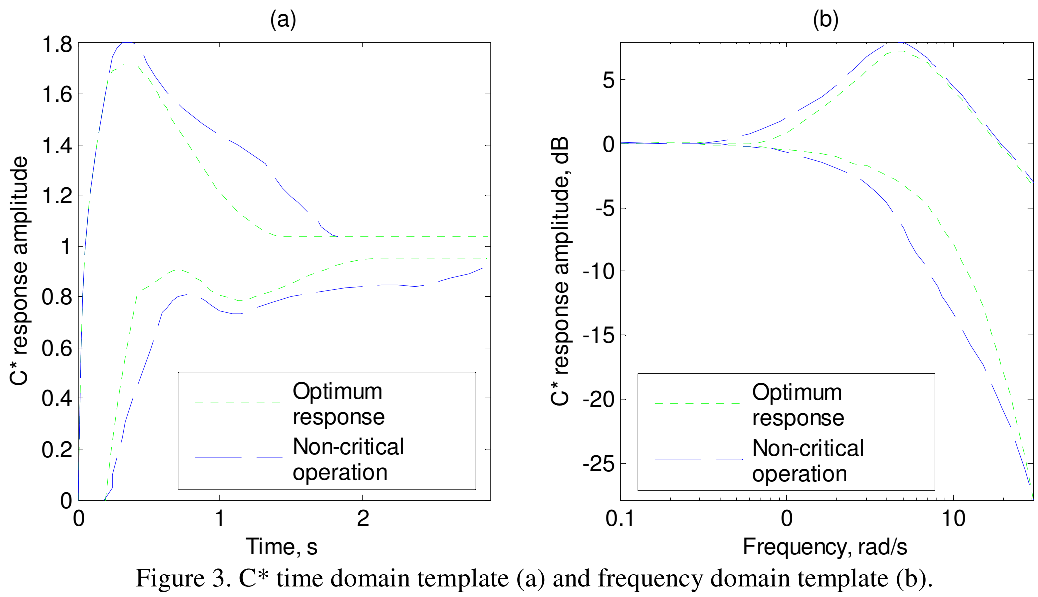

Figure 3. C* time domain template (a) and frequency domain template (b).

The good acceptance of the C* criterion as a flying qualities indicative led to the development of flight control laws based on this parameter (Field, 1993). The pilot longitudinal controller inputs acts as a C* reference, and the measured C* is obtained from pitch rate and load factor sensors. The elevator is used as actuator.

2. MODELING

2.1. Linear model, flight envelope and uncertainties

The linear model has four state variables: airspeed (V), angle of attack (α), pitch angle (θ) and pitch rate (q). The model input considered in the design is the elevator deflection δ_e. The outputs are the states and the computed C* parameter. Although the C* is described as a blend of load factor and pitch rate, the feedback of this parameter can lead to low frequency instability. The reason is that n_z response shows a low frequency non-minimum phase zero, which is not desirable because it imposes performance limitations. To avoid this problem, the n_z is replaced by the acceleration a_z in the generation of the C* parameter.

The linear model is obtained from numeric linearization of a nonlinear model in level flight, cruise configuration. The linearizations are performed in a nominal point, and also in a set of adjacent points that are considered perturbed models. The nominal point corresponds to a mid-speed cruise, at a medium altitude, with average cg position, weight and load distribution. Variations of ±20 knots, ± 2000 ft were introduced for the perturbed models, in combination with the allowable weight, cg and load distribution limits.

The design of a scheduled flight control law to cover the whole flight envelope is left as a future work. Lin and Khammash (2001) present scheduled flight control laws obtained from robust control designs. Generally the task of scheduling robust controllers is complicated by the relatively high order, and the present work aims to limit the resulting controller order. It is also expected that the robust controller covers a wider envelope than a conventional one, reducing the number of controllers to schedule.

The uncertainty model takes directly into account two conditions in the above defined flight envelope: the nominal and the critical. The latter is defined as the linear model with the greatest singular values of the difference of the state space matrix relative to the nominal case. So, the singular values $\sigma_i \dots \sigma_{i\ n+n_{y,u}}$ are calculated for the *i-th* case as:

$$U\begin{bmatrix} \sigma_{i\ 1} & & \\ & \ddots & \\ & & \sigma_{i\ n+n_{u,y}} \end{bmatrix} V^* = \begin{bmatrix} A_i & B_i \\ C_i & D_i \end{bmatrix} - \begin{bmatrix} A_{no\min al} & B_{no\min al} \\ C_{no\min al} & D_{no\min al} \end{bmatrix} \tag{13}$$

where

$n_{u,y}$ is the largest between number system inputs and outputs and n is the number of states

Among the 32 combinations of extreme values for the five unknown parameters, the case with increased speed and altitude, reduced weight, c.g. afterwards and maximum fuel loading shows the highest values for Eq. (13), and this case is chosen as the critical. It was seen that the phugoid poles show the largest deviation from the nominal among all cases.

Since the perturbation Δ is limited in modulus in Eq. (11), in order to reduce the conservatism the design model was defined as the mean between the nominal and the critical cases, and the uncertainty was defined as the deviation to cover the critical and nominal cases from the design model. Therefore, the uncertainty model covers a set of plants ranging from the nominal to the critical case.

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \frac{\left(\begin{bmatrix} A_{crit} & B_{crit} \\ C_{crit} & D_{crit} \end{bmatrix} + \begin{bmatrix} A_{nom} & B_{nom} \\ C_{nom} & D_{nom} \end{bmatrix}\right)}{2} + \frac{\left(\begin{bmatrix} A_{crit} & B_{crit} \\ C_{crit} & D_{crit} \end{bmatrix} - \begin{bmatrix} A_{nom} & B_{nom} \\ C_{nom} & D_{nom} \end{bmatrix}\right)}{2}\Delta \tag{14}$$

$$\Delta = \delta\begin{bmatrix} I & 0 \\ 0 & I \end{bmatrix}, -1 \le \delta \le 1,\ \delta \in \Re\,. \tag{15}$$

2.2. Augmented plant

The block diagram for the proposed augmented plant is shown in Fig. 4. The inputs include the C* reference r and the disturbance d. The weighted outputs are z_1, z_2 and z_3, similar to the mixed uncertainty problem. The uncertainty model is represented by the inputs w_p and outputs z_p and the dotted path. The error signal e (between the reference and the measured C* parameter) is sent to the controller, which generates the control signal u.

The feedforward path is introduced through the gain K_{FF} to provide a direct link (no dynamics) between the pilot input and the actuator. Satisfactory results were obtained with $K_{FF} = 0.0006$. The feedforward compensation gain FF_{comp} avoids that the controller counteracts the effect of the feedforward for high frequencies. This gain is set equal to element of the aircraft state space model D from elevator to C*.

The gain K_{pert} is set to 0.001, and with this value, the adjustment of the weighting functions is intuitive, while the resulting controller zeroes does not match the oscillatory aircraft poles. The gain K_D is an additional degree of freedom for the uncertainty (Moreira, 1998), but is kept as identity matrix.

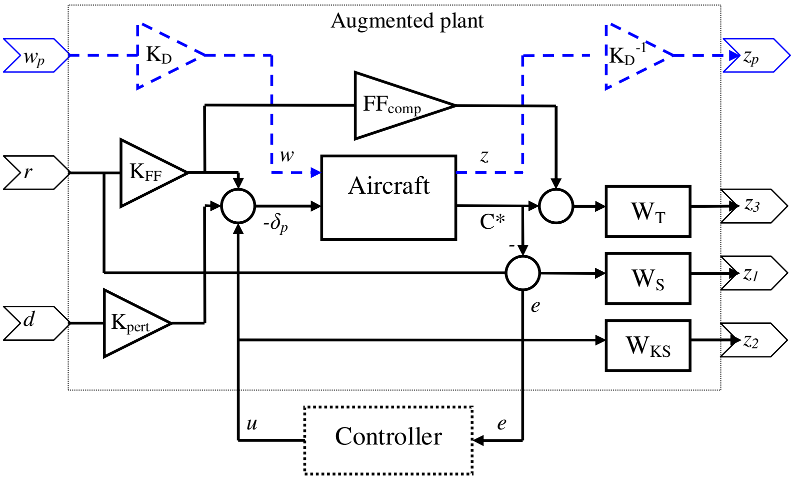

Figure 4. Block diagram for the proposed augmented plant

The weighting functions are adjusted to comply with the frequency domain C* criterion, as shown in Fig 5. The function W_S is selected to provide an upper bound for the C* frequency response, which is given by 1 minus the inverse of the function W_S^* (shown in the upper right part of Fig. 5). This relation comes from Eq. (3), and W_S^* is similar to W_S, except by the fact that it includes the additional limitation on S, that is $S < 1$ if there are no poles in the right-half plane. This is a reasonable assumption in the range frequencies of the C* criterion. The function W_T is selected such that its inverse provides an upper limit to keep T (the C* response) inside the C* envelope. In fact, the bandwidth specified by both functions is slightly smaller than the C* criterion, but this decision was taken to reduce the influence of the actuator and time delays that are not directly considered in the design. The function W_{KS} is kept as 0 since the control signal is considered satisfactory. W_S and W_T functions are both first order:

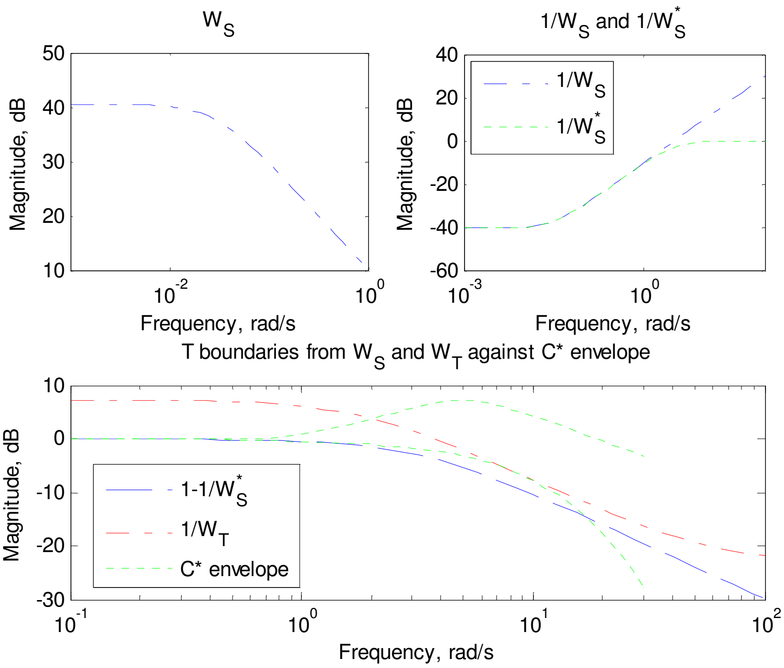

Figure 5. Weighting function selection to comply with C* criterion

3. RESULTS

3.1. H$_\infty$ controller design

The H$_\infty$ controller is obtained from using the structure and weighting functions shown in the previous section, excluding the uncertainty model (the dotted path of Fig. 4). The resulting system functions are shown in Fig. 6, and it can be seen that the specification written as weighting functions are met. The result of changes in the design variables was clearer for the H$_\infty$ design.

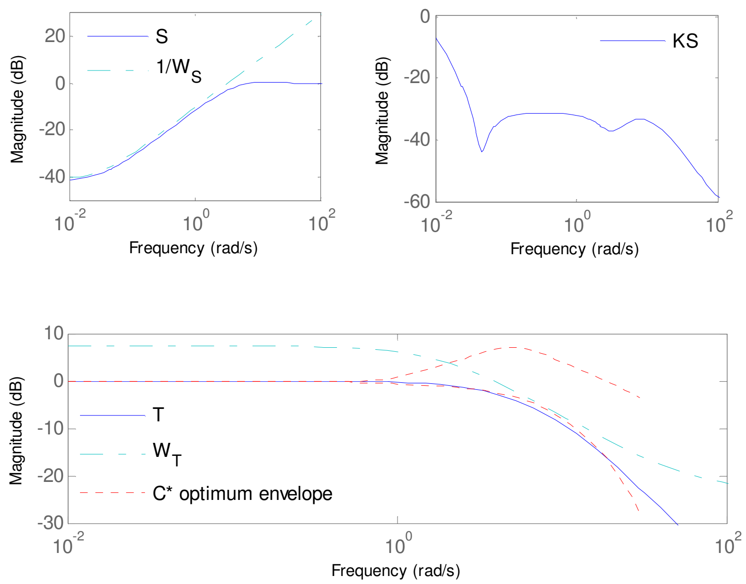

Figure 6. System functions obtained with H_∞ controller against the weighting functions.

3.2. μ synthesis controller design

The μ synthesis is performed with the same augmented plant. The maximum allowable order of the function that fits the scaling matrix *D* is set to zero, the frequency optimization range is set to [10^{-5}, 10^{3}]. Although better results were obtained accepting higher orders for the *D* fitting transfer functions, the controller order increases from 6 to about 20, and the implementation becomes not viable without order reduction. Although the selected frequency range is slightly high, and leads hard computing, it allows satisfactory results in the frequency of interest for flying qualities. The resulting closed-loop frequency sensitivity, complementary sensitivity and control signal response for a C* reference are shown in Fig. 7. The weighting functions are not satisfied for frequencies under 0.01 rad/s and above 10 rad/s, but the results are still satisfactory, since the performance specifications were stringent and this range of frequencies is not relevant for flying qualities.

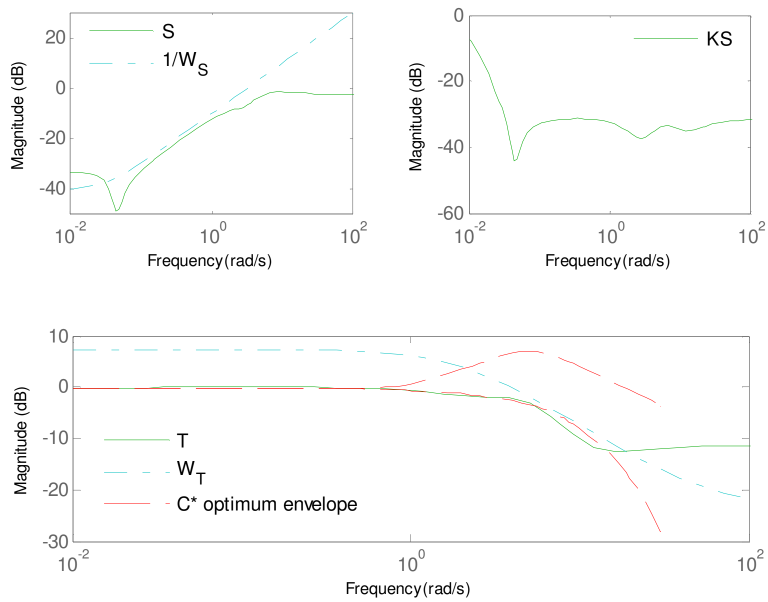

Figure 7. Weighting functions and resulting closed-loop functions

3.3. Controller frequency response

For a first comparison between the H_∞ and the μ controllers, the Bode plot of both is shown in Fig. 8. The H_∞ controller shows higher gain for low frequencies, and higher roll-off for high frequencies. These characteristics provide better performance for the closed loop (smaller steady-state error and less noise). On the other hand, the μ controller has a smoother response, due to the absence of oscillatory zeroes, as shown in the next section.

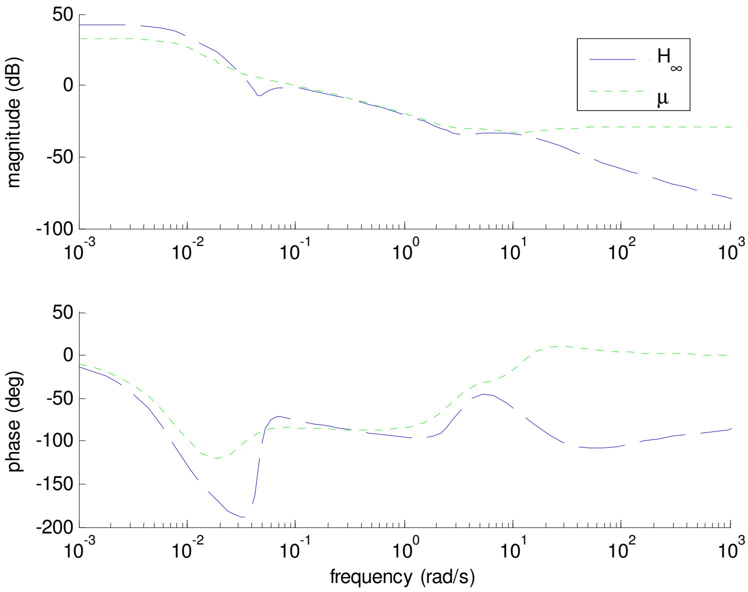

Figure 8. Bode plot for both controllers

3.4. Controller poles and zeroes

The pole-zero map for the controllers is shown in Fig. 9 with the plant poles and zeroes of the plant. The values in the scales are not shown to protect the information. It can be seen that the H_∞ controller zeroes are very close to the short period and phugoid plant oscillatory poles, although he introduction of the perturbation in the augmented plant through the gain K_d prevents the exact match.

For the μ controller, the zeroes are more distant, resulting in better robustness regarding the plant oscillatory poles. This better result for the μ controller is due to the introduction of the uncertainties in the design model.

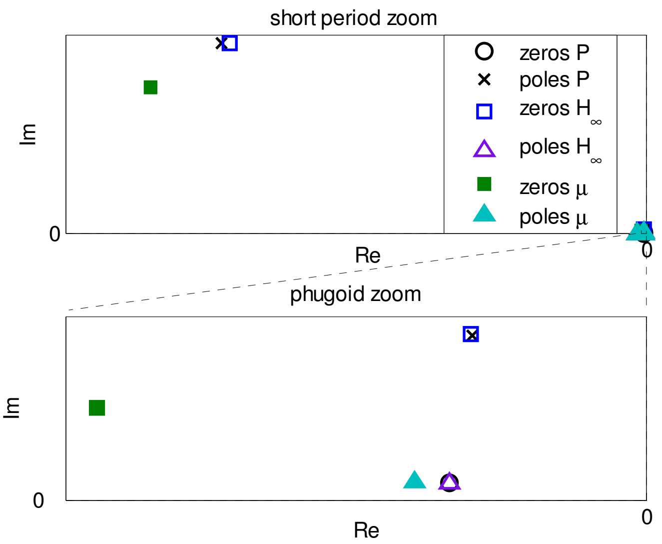

Figure 9. Pole-zero diagram for the plant (P) and the controllers (K).

3.5. C* time domain criterion

To evaluate the accomplishment of the C* flying qualities criterion considering a more realistic scenario, a first order approximation of a 50 ms time delay and a fist order system with pole at 24 rad/s are included in the simulation model to represent the typical system delay and the elevator actuator, respectively. The result of this simulation is shown in Fig. 10 for both controllers, considering the nominal, the critical and the other cases considered in Section 2.1.

Both controllers show robustness regarding the introduction of the actuator pole and the time delay, and the C* criterion is marginally met. It is worth to remember that the weighting functions were defined as a compromises between complying with the C* criterion and reducing the bandwidth.

While the responses for closed loop with the μ controller are similar for the nominal and critical cases, the response for the H_∞ controller a higher overshoot can be seen only for the critical case. It shows clearly the oscillatory poles of the plant are cancelled by the H$_\infty$ controller for the nominal mode, but as these poles are shifted in the critical case, the closed loop response can be significantly changed.

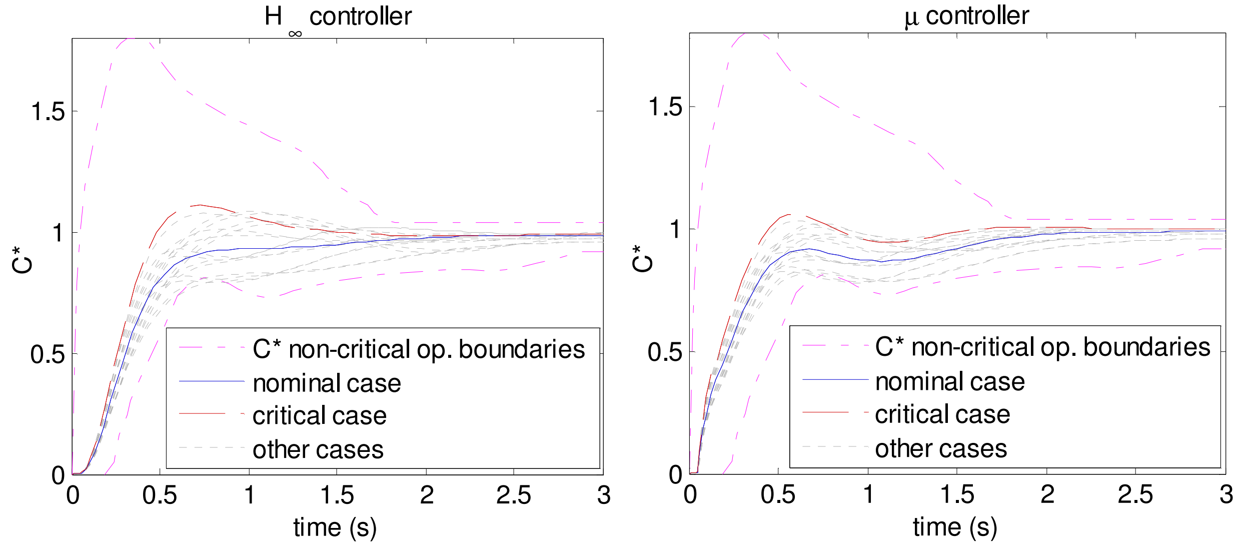

Figure 10. C* response for the closed loop with both controllers.

3.6. Gain and phase margin

Figure 11 shows the Nichols diagram for the system with both controllers. It is a classical measure of the closed loop robustness, and in the aeronautical industry, gain and phase margins of 10 dB and 45° are usually required. It can be seen that both controllers comply with this robustness specification for all the models considered. The μ controller is more robust according to this analysis, since it shows higher margins for all cases.

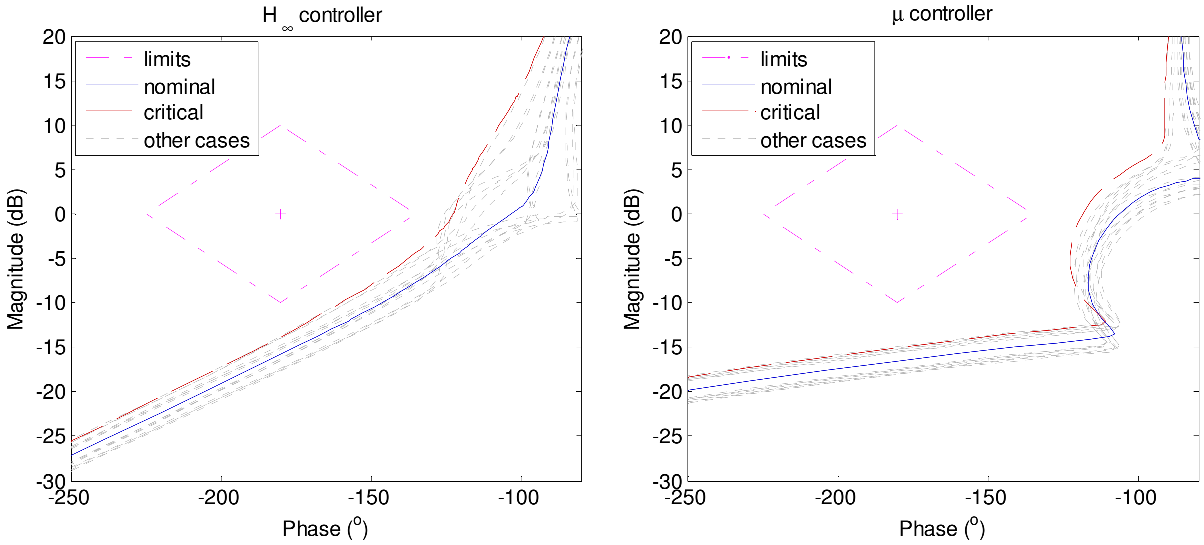

Figure 11. Nichols diagram of the system for both controllers, with actuator and delay models included.

3.7. Stability and performance robustness analysis using μ synthesis

In this section, both controllers are evaluated using μ analysis, regarding some properties of the closed loop, which also includes typical actuator and time delay models. In the upper part of Fig. 12, the results for the nominal performance are shown. For the H$_\infty$ controller, the upper bound of μ is smaller than 1 for almost all frequencies and it can be said that the performance specified by the weighting functions is met, disregarding small degradations caused by the introduction of the actuator and the time delay models. From the higher values observed for the μ controller for frequencies smaller than 0.03 and higher than 20 rad/s, it can be said that the specifications are not met in these ranges, but these frequencies are outside the range considered for flying qualities.

The robust performance analysis in the same figure shows that the performance with both controllers is degraded when the considered perturbation is included, but this degradation can be considered small and outside the range of frequencies of interest. Near the phugoid frequency (~0.1 rad/s), the H$_\infty$ controller clearly shows higher degradation.

In the robust stability test (lower part of Fig. 12) the value of the upper bound is much smaller for the μ controller, what shows that this controller keeps the system stable for perturbations with higher magnitudes, yet both controllers shows stability robustness with respect to the considered uncertainty.

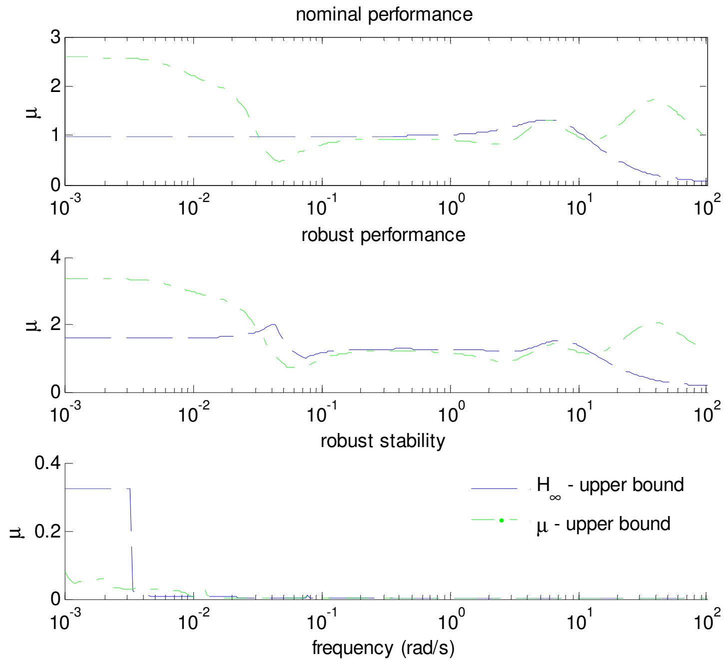

Figure 12. μ analysis for the closed loop with both controllers.

4. CONCLUSIONS

The results for both controllers are considered satisfactory, and the proposed augmented plant propitiates a clear procedure for the adjustment of the design requirements. As expected, the introduction of the uncertainties in the design provides better results in terms of stability robustness, at the cost of some degradation in the nominal performance. It was shown that the conventional design-redesign cycle can be reduced with the use of modern robust control tools, and the analysis can be more efficient.

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