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H_{INF} LOOP-SHAPING CONTROLLERS FOR A FLEXIBLE AIRCRAFT

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Abstract: *The ever increasing competition on the aeronautical industry has been leading into major improvements regarding fuel consumption, engine performance and on flight controls systems, among others. One of most studied fields is the composite materials usage as, when correctly applied, it leads to major gains regarding the aircraft's structural weight and consequently into better fuel consumption figures. On the other hand, the ever increasing composite materials usage has a unique property: it brings the structure flexible modes closer to the rigid ones. Therefore, older techniques such as structural filtering cannot be used anymore. This results on the need of advanced filtering techniques, such as the ones provided by Robust Control. On this essay the longitudinal model of a military aircraft, the B1-Lancer, is deeply analyzed, integrating its structuralmodes into its rigid body dynamics in order to accurately design stability and control augmentation systems, through the Hinf Loop-Shaping Dynamic Robust Control Technique, considering up to three different control inputs: the tail deflection, which acts as an elevator, the control vane deflection, that mainly helps regarding gust-alleviation and the thrust levers, which serves as a fine-tuning input.*

Keywords: *control systems; robust control; flexible structures; augmentation systems; aeronautical engineering*

1. INTRODUCTION

For the last 40 years the aeronautical industry has been into fierce competition which means that manufacturers have to be ever improving their products, in order to get a better cost-to-benefit ratio at all times. This fact, lined up with the sudden rises of oil price has been leading into aircrafts with significantly smaller structural weight figures when compared to their predecessors. This happens due to the introduction of more sophisticated metallic materials and also composite ones. But nothing comes without a setback: this intense usage leads to an ever increasing interaction in between the rigid and flexible modes of the aircraft which leads to problems related to flying qualities, fatigue and aeroelastic instability, such as flutter.

On a modern aircraft complex control systems are extensively used. They are basically composed from a Stability Augmentation System (SAS) whose purpose lies on keeping the aircraft on an stabilized condition and returning it to the referred condition when it is subjected to any kind of disturbance, such as a gust wind; and also from a Control Augmentation System (CAS) which aims at optimizing aircraft’s performance when transitioning from a condition to another, such as changing the flight level or the heading direction, in order to flight a different route. These systems aim only at controlling the aircraft rigid body modes, as flying qualities would be severely handicapped if they would affect the flexible ones. Therefore, when the rigid modes are clearly apart from the flexible ones, a simple control signal filtering procedure is applied, normally generating the so called “notch filters”.

But when the aircraft presents a fair amount of structural flexibility (due to a series of factors such as the intense usage of composite materials) notch filters are no longer enough, as shown by Andrade (2006). Therefore, the introduction of an integrated model (incorporating both the rigid and flexible modes) for the control laws design is a highly desirable solution, but it requires some more advanced filtering techniques. That means that now, when designing augmentation systems for aircrafts, we will have integrated models and will be using techniques that will lead to higher order controllers. And as control systems synthesis preferably demand a low order controller that leads into the direction that they will probably have to go through an order reducing process (Lamas, 2008).

Taking into account all the control laws requirements for designing both the SAS and the CAS we normally find on the available literature two major chains, which are basically two major research areas on Control Engineering: Adaptive Control and Robust Control. The first one, even though it is a modern, high performance technique does not feature good performance indications regarding robustness, which is an essential concept when of designing SAS and

CAS for aeronautic engineered systems. That happens due to the fact that an aircraft is hardly ever identified (and therefore modeled) to its completion and also to the fact that there are associated uncertainties to some of the parameters that cannot even be estimated, as explained by Zhou and Doyle (1998). Therefore, the chosen control technique must be robust enough in order to deliver a good performance from a flying qualities point of view even if the system (aircraft) is subjected to any kind of disturbances, uncertainties and identification faults, among others.

On this essay, we will briefly review how a modern aircraft is modeled along its rigid and flexible modes. Also we'll try to understand the importance of having the flexible modes integrated into the rigid body dynamic of the aircraft.

Additionally, we'll introduce how the H_{inf} *Loop-Shaping* algorithm is generated and will also give a brief introduction of another H_{inf} Robust Control Technique, the HIFOO (H-Infinity Fixed-Order Optimization) algorithm, which was first introduced by Burke et al (2006).

Finally, and more importantly, we will evaluate the performance of some controllers designed (both SAS and CAS) with the H_{inf} *Loop-Shaping* algorithm mentioned above, considering up to three inputs into the system and also introducing the possibility of having the HIFOO control technique into the SAS control loop.

2. AIRCRAFT MODELING

On this session we are firstly going to present some important considerations regarding modeling a system due to be controlled. After that, we will discuss the simulation model due to be evaluated and present the B1-Lancer aircraft, considering the control inputs to be used.

2.1. System Modeling and its Importance

All control systems theory lies on the same basic principle: accurate modeling must be provided. Therefore, translating the physical reality into differential equations is as important as designing an efficient controller. And on the aeronautical industry case this has become even more important. Nowadays, the aerodynamic design of elements such as the wings, fuselage, tails, hyper-lift elements and control surfaces is becoming more specific at all times, which leads into an increasing complexity regarding their modeling.

Also, it must be considered that the competition on the aeronautical industry has become as strong as ever on the recent years, mainly due to the entrance of new players on the market and due to economic aspects. This leads into the search for new ways of getting a better cost per seat-mile on any aircraft produced which puts an emphasis on every aspect of the whole process of designing an aircraft: optimizing the structure, the aerodynamics and consequently increasing the modeling and control systems performance requirements. For example, as it has been mentioned on this work's introduction the usage of composite materials has been leading into the flexible modes of an aircraft getting too close to the rigid body ones which makes notch filters inefficient and therefore requires a more sophisticated control technique.

One last aspect that must be considered is regarding the system order. A full-order model for an aircraft has 12 rigid-body states, each of these described by a first order differential equation. When we consider the influence of the flexible modes into the model, the system order is going to grow as each flexible mode is normally described by a second order differential equation. This leads to an extremely important conclusion: the bigger the number of flexible modes to be considered, the higher will the controllers order be, which will get the closed-loop system to an even higher order.

Considering all the aspects just mentioned it is clear that the modeling engineer is as responsible as ever: he/she must be able to accurately choose which flexible modes must be taken into consideration for each situation and the ones which only need to act as a high-frequency design limitation.

2.2. B1-Lancer Modelling

For this essay we will consider the B1-Lancer aircraft, which is a high-subsonic military machine and that has been deeply studied. We'll consider its longitudinal axis, and will from then work on designing a control system architecture which integrates both the SAS and CAS into one structure which will be called Stability and Control Augmentation System (SCAS).

The adopted model for the SCAS design is derived from the full rigid body model presented by Waszak and Schmidt (1988). Additionally we follow the reference's different approach: it presents the natural frequency and the damping ratio for two longitudinal flexible modes and also a generalized model which includes the influence of the flexible modes on the aircraft's motion. Therefore we can consider a flexible aircraft model for the longitudinal degrees-of-freedom with one structural mode in straight, horizontal flight. The equations of motion are

$$\dot{u} = -qw - g\sin\theta + X \tag{1}$$

$$\dot{w} = uq + \cos\phi\cos\theta + Z \tag{2}$$

$$\dot{q} = \underline{M} \tag{3}$$

$$\ddot{\eta}_z = -2\zeta\omega\dot{\eta}_z - \omega^2\eta_z + Q_{\eta_z} \tag{4}$$

where u and w are surge and plunge velocities in the body-reference axes, respectively; q is the pitch rate ϕ and θ are the Euler angles of the aircraft; η, ζ and ω are the generalized coordinate, damping and frequency for the structural mode, respectively; and X, Z, $\underline{M}$ and Q_η are the aerodynamic forces, moment and generalized force, respectively, whose expressions are given bellow on Eq. (5-8):

$$X = \frac{\rho V_A^2 S}{2}\left(C_{x_0} + C_{x_\alpha}\alpha + \sum_{k=1}^{m} C_{x_{\delta_k}}\delta_k\right) + \frac{\rho V_A^2 S\bar{c}}{4}\left(C_{x_q} q + C_{x_{\dot{\alpha}}}\dot{\alpha}\right) + T_x \tag{5}$$

$$Z = \frac{\rho V_A^2 S}{2}\left(C_{z_0} + C_{z_\alpha}\alpha + \sum_{k=1}^{m} C_{z_{\delta_k}}\delta_k + C_{z_{\eta z}}\eta_z\right) + \frac{\rho V_A^2 S\bar{c}}{4}\left(C_{z_q} q + C_{z_{\dot{\alpha}}}\dot{\alpha} + C_{z_{\dot{\eta}_z}}\dot{\eta}_z\right) + T_z \tag{6}$$

$$\underline{M} = \frac{\rho V_A^2 S\bar{c}}{2}\left(C_{m_0} + C_{m_\alpha}\alpha + \sum_{k=1}^{m} C_{m_{\delta_k}}\delta_k + C_{m_{\eta_z}}\eta_z\right) + \frac{\rho V_A^2 S\bar{c}^2}{4}\left(C_{m_q} q + C_{m_{\dot{\alpha}}}\dot{\alpha} + C_{m_{\dot{\eta}_z}}\dot{\eta}_z\right) + M_T \tag{7}$$

$$Q_{\eta_z} = \frac{\rho V_A^2 S\bar{c}}{2}\left(C_0^{\eta_j} + C_\alpha^{\eta_j}\alpha + \sum_{k=1}^{m} C_{\delta_k}^{\eta_z}\delta_k + C_{\eta_z}^{\eta_z}\eta_z\right) + \frac{\rho V_A^2 S\bar{c}^2}{4}\left(C_q^{\eta_z} q + C_{\dot{a}}^{\eta_z}\dot{\alpha} + C_{\dot{\eta}_z}^{\eta_z}\dot{\eta}_z\right) \tag{8}$$

where C_{x_α} is, for example, the aerodynamic stability derivate associated with the variable α, δ_k is the deflection/variation of control input k, ρ is the air density, V_A is the aircraft's velocity, S is the planform area, $\bar{c}$ is the mean aerodynamic chord and T_x, T_z and M_T are the forces due to the aircraft's traction.

Once we have mathematically presented the model due to be used, we can determine which control inputs are on the B1-Lancer, which are displayed on Figure 1 and described bellow:

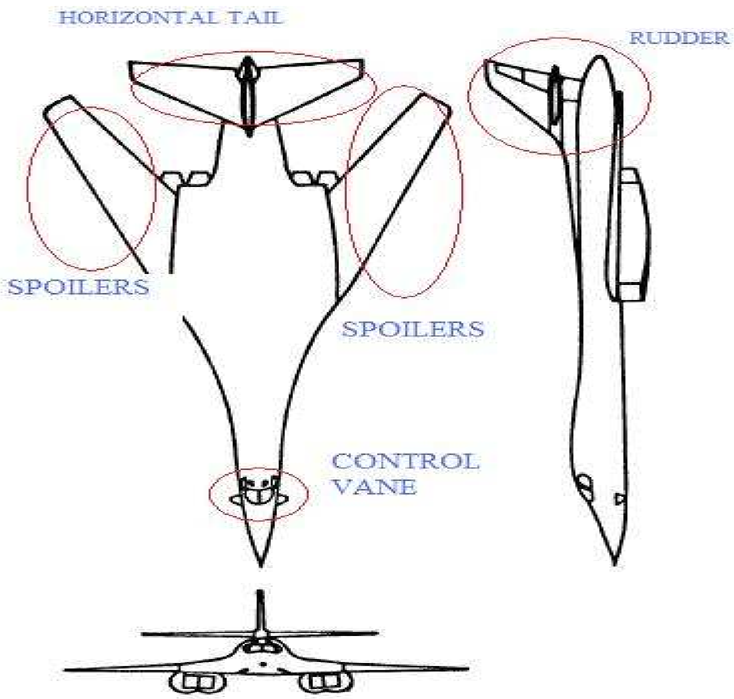

Figure 1. The B-1 Lancer and its control surfaces

- The horizontal tail deflection, δ_t, through which it is possible to control the pitch attitude of the aircraft;
- The differential horizontal tail deflection, δ_{DH}, through which it is possible to control the rolling attitude of the aircraft;
- The spoilers deflection, δ_S, which helps to control and trim the aircraft's rolling attitude together with the horizontal tail differential deflection;
- The rudder's upper and lower deflection, δ_{RU} and δ_{RL}, through which the yawing attitude of the B1-Lancer is controllable;
- And the control vane deflection δ_{CV} which mainly helps alleviating loads into the aircraft when it is subjected to disturbances of any kind.

For the aircraft's longitudinal motion we consider as controller inputs the horizontal tail deflection δ_t and the control vane deflection δ_{CV}. Additionally, as a last control input, we can consider the thrust levers. By providing different traction ratings, they can help finding better flight conditions, so that the aircraft can optimize its mission targets, such as fuel consumption, flight time, among others. Also, for military aircrafts they can be used differentially so that they can help into some maneuvers.

Considering all the aspects mentioned above, we can infer that the approach presented sets a clear and extremely important advantage over the previous ones: the designed controllers will consider the influence of the flexible mode dynamics that are included on the aircraft model, which gives the engineer more freedom when searching for the best control law for a given situation. This advantage will be explored on the forthcoming sections.

3. ROBUST CONTROL

On this session we will briefly introduce the importance of Robust Control, mainly linking it to modeling uncertainties and verifying how the plant parameter variations problem can be solved through Robust Control usage. Secondly, we will present the H_{inf} *Loop-Shaping* algorithm, mainly concentrating on its practical aspects. Finally, we will take into consideration the HIFOO algorithm and show how it differentiates from the *Loop-Shaping* one.

3.1. Uncertainties and Robust Control

As we have already stated, controllers are designed based on a mathematical model of a physical system. This model tries to be as accurate as possible, but as shown by Zhou and Doyle (1998) there is no mathematical model that can represent 100% a physical reality. This leads into a very important conclusion: for control systems design, the engineer must use tools that support the possible divergences in between the real and the mathematical model.

For some systems these divergences can be negated which is fact that leads into the Adaptive Control direction, as this theory allows the controller to adjust its parameters in real time in order to maximize control-loop performance. But within the aeronautical industry this is not a particularly commonly used technique: aircrafts are extremely complex machines and the translation of their dynamics into mathematical equations is extremely difficult. Also, we have to bear in mind that modern aircrafts have to withstand severe certification processes and, for them not to lose performance along its operational envelope, a more spread Control Technique has to be used.

Mathematically speaking, as it has been demonstrated throughout Section 2, the equations that describe the aircraft's motion are nonlinear. Therefore we must use linearized models over a set of operating points, determine optimal control gains on each of them, tabulate and schedule them using microprocessors, so that we are always using the most adequate control law, no matter where we are inside the operational envelope. This approach would solve the given problem, but the fact that the modeled parameters are subjected to uncertainties leads to another consideration: we must design a controller that will be robust enough to manage all the parameters variation and still deliver a close-loop response within the specifications. But as it's not possible to stabilize the plant for all parametric uncertainties, the control engineer must be able to pick which parameters whose uncertainties must be considered and then design a control law that will be able to withstand these uncertainties.

Suppose that the nominal model used for the controllers design is

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx \end{aligned} \tag{9}$$

which has a transfer function

$$G(s) = C(sI - A)^{-1} B \tag{10}$$

However, due to operating point changes the actual aircraft perturbed motion is described by

$$\begin{aligned} \dot{x} &= (A+\Delta A)x + (B+\Delta B)u \\ y &= (C+\Delta C)x \end{aligned} \tag{11}$$

where the plant variation matrices are given by ΔA, ΔB and ΔC, which represent uncertainties over the parameters that compose the model of the aircraft such as its mass, stability derivatives, lift/drag coefficients, inertial moments and engine/thrust model. We can show that this results in the transfer function

$$\begin{aligned} G^{'}(s) &= G(s) + \Delta G(s) \\ \Delta G(s) &= C(sI-A)^{-1}\Delta B + \Delta C(sI-A)^{-1}B + C(sI-A)^{-1}\Delta A(sI-A)^{-1}B \end{aligned} \tag{12}$$

where second order effects have been neglected. Hence, we apply the algorithm present by Lewis and Stevens (2004) and therefore are able to design robust controllers over a range of operating points that do not require gain scheduling. Finally, it’s important to note that the algorithm presented on the given reference does not consider the flexibility of the aircraft structure, which further tightens high-frequency bounds for the controller design, and that we will consider on this essay.

For the reasons presented above, we will consider a Robust Control technique for designing SCAS for aircrafts, as it inherits the properties mentioned above.

3.2. $\mathbf{H_{inf}}$ *Loop-Shaping*

H_{inf} controllers belong to a class which contains the most used robust controllers. And one of the most used techniques for the H_{inf} is the *Loop-Shaping* algorithm whose proposal is to design a controller $C(s)$ so that the closed-loop system presents a desired transfer function $G_d(s) = G(s)C(s)$, where $G(s)$ represents the open-loop system and $G_d(s)$ represents the closed-loop one. This is an extremely powerful technique because with it almost any closed-loop system response is achievable, the engineer only having to bear in mind the physical realization of the controller.

The H_{inf} *Loop-Shaping* design technique is essentially a two stage design process. Firstly, the open-loop system is augmented by a pre and a post-compensator, in order to generate a desired shape to the open-loop singular values frequency response. After that, the shaped plant is robust stabilized using the H_{inf} optimization. But as the controller design derives from an augmented plant, the controller will tend to have a higher order than if it was designed from a non-augmented one. Therefore, the engineer will have to bear in mind if the tools that he has at his/her disposal are enough to make the controller realizable. But, as hardware engineering has significantly evolved throughout the last few years, this problem has come to a lesser extent.

For this essay, we’ll consider the *loopsyn* MATLAB function which basically puts into practice the algorithm introduced and detailed by Skogestad and Postlethwait (1996) and also mentioned by Zhou and Doyle (1998).

3.3. HIFOO

As we stated, there is a lot of work and research on the H_{inf} control theory. This has generated many interesting results and one of those is the HIFOO (H-Infinity Fixed Order Optimization) MATLAB package, which was created by Burke et al. (2006) and further improved by Millstone (2006). This package has been created aiming at providing a powerful and user-friendly tool for computing reduced-order controllers of linear systems. It has been built upon powerful methods for non-convex and non-smooth optimization and it tries to generate controllers that not only robustly stabilize the given plant, but also that provide the local optimization on at least one of several provided objective functions.

The fact that the HIFOO algorithm provides a local optimized solution means that for every time that it is run, it will generate a different controller that even though might satisfy the objective functions and the robustness criteria’s, it may not satisfy other performance requirements, which can lead to the engineer having to run an iterative process.

For this essay, the HIFOO function will be explored as a support algorithm and we will be aiming to check at to what extent it can help to fine-tune the performance generated by the H_{inf} *Loop-Shaping* Robust Control Technique.

4. SCAS DESIGN AND SIMULATIONS

On this section we will cover the design of the SCAS control structures considering the assessment that has been made over the previous sections. Firstly, we’ll briefly introduce the structures that are due to be used. Secondly, we will make some assumptions, regarding the control system design, such as control surfaces actuators, for example. Finally we will present the simulations, already considering the designed controllers, firstly showing the full order SCAS which will be followed by reduced order structures that can still deliver the same level of performance and still do have a lower complexity.

4.1. Control Architectures

As we have been mentioning, this essay mainly deals about the performance of a SCAS designed with the H_{inf} *Loop-Shaping* technique; but also we are going to consider the HIFOO technique, which generates two different control strategies to be taken into account, shown by figures 2 and 3 respectively.

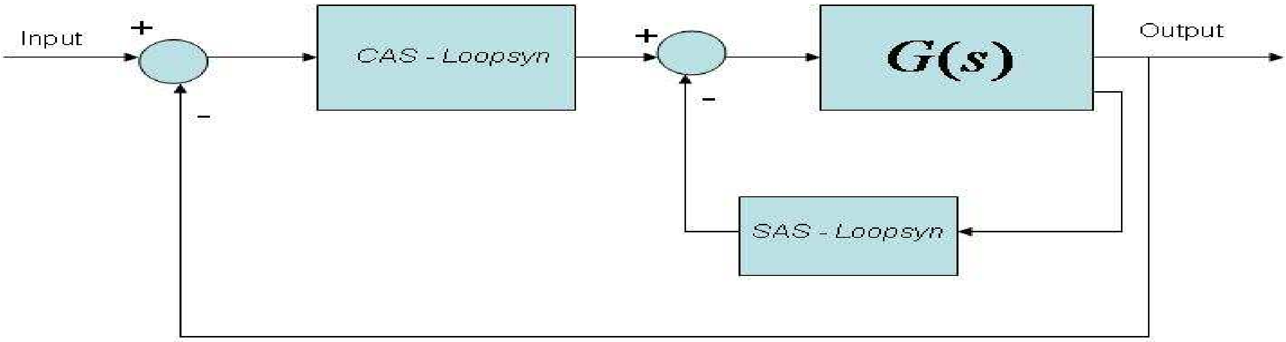

Figure 2. SCAS Primary Architecture – H_{inf} *Loop-Shaping* SAS + *Hinf Loop-Shaping* CAS

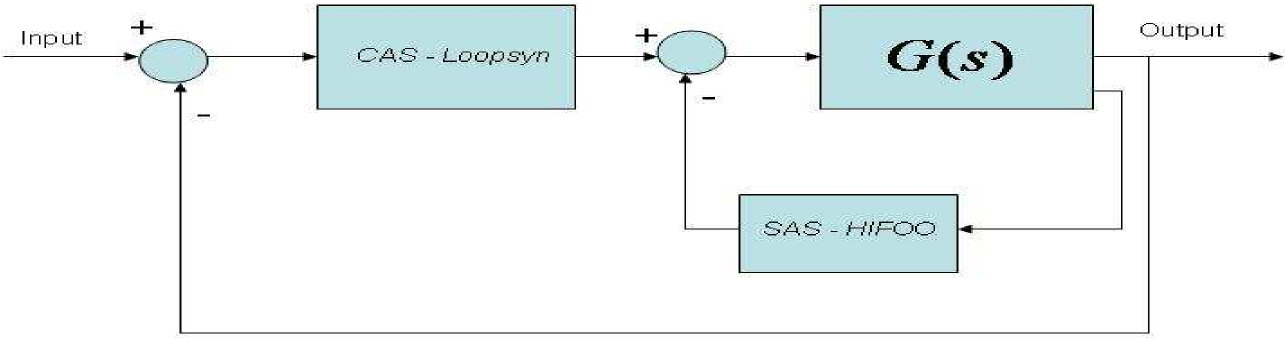

Figure 3. SCAS Alternative Architecture –HIFOO SAS + *Hinf Loop-Shaping* CAS

Having two different control architectures, we will make some considerations regarding the control systems design and that will follow with the performance evaluation mainly from the primary architecture, observing the H_{inf} *Loop-Shaping* algorithm performance and comparing it with the one generated by the alternative architecture.

4.2. Design Assumptions

For designing the proposed SCAS based on the control architectures shown above, we need to state some assumptions, in order to be able to compare the designed controllers with each other.

- The horizontal tail deflection has been limited to 50 degrees (± 25 degrees) and its rate of deflection has been limited to 60 degrees per second. Additionally, it has been considered an actuator which has been modeled as a first degree low-pass filter with time constant of approximately 49.5 ms;
- The control vane deflection has been limited to 50 degrees (± 25 degrees) and its rate of deflection has been limited to 120 degrees per second. For the vanes, it has also been considered an actuator which has been modeled as a first degree low-pass filter with time constant of approximately 49.5 ms;
- The thrust levers have been modeled so that its increasing/decreasing rate would be of 10% per second, which means that they can go from zero to full power in 10 seconds. Additionally, their actuation has been modeled by first degree low-pass filter with time constant of approximately one second;
- The first longitudinal flexible mode $(12.57 rad/s)$ has been integrated into the aircraft model. The second longitudinal flexible $(21.17 rad/s)$ has been mainly used as a high frequency boundary for the designed controllers;

- The possible noise and uncertainties derived from the measurement sensors have been neglected;
- For the high frequency limitations (considering the second longitudinal flexible mode), it has been used the methodology presented by Lewis and Stevens (2004)
- For the low frequency limitations (considering the influence of gust winds as per the MIL-HDBK-1797 regulations), it has been used the methodology presented by Lewis and Stevens (2004) and further develop by Silvestre (2007).
- For the SCAS simulations we have considered the B1-Lancer to be on straight leveled flight at an altitude $H = 1500m$ and with a true air speed $V = 200m/s = 720km/h$ and a commanded reference input of a 1 degree/second pitch rate.

4.3. Full Order Controllers

On this session we'll present and analyze our firstly designed SCAS: we'll consider the full-order controllers generated by the *Loopsyn* MATLAB function, two of those having been fully designed (both the SAS and the CAS) with the referred function and two of those having been designed with the alternative strategy in mind: the SAS with the HIFOO algorithm (static solution – 0 order) and the CAS with the main solution, the H_{inf} *Loop-Shaping*.

Each of the mentioned control architectures is going to be tested and analyzed on two different scenarios: one with two control inputs (the horizontal tail deflection and the control vane deflection) and the second one with only one input, the primary horizontal tail deflection. Our objective with those trials is to check how big will be the performance handicap when we design a controller considering that the plant has fewer inputs, which will generate a lower-order controller, which is a characteristic of the H_{inf} *Loop-Shaping* algorithm. It's also worth noting that although it had been initially considered to add a third control input to the aircraft, earlier simulations indicated that including the thrust levers into the control-loop wouldn't give any benefits in terms of performance and/or would alleviate the load into the other control inputs. So, any simulations considering the thrust levers have been omitted on this essay.

On last note before showing and analyzing the simulation results is that the desired closed-loop system will be given by $G_d(s) = C(s)G(s) = \dfrac{1}{s^2 + s}$.

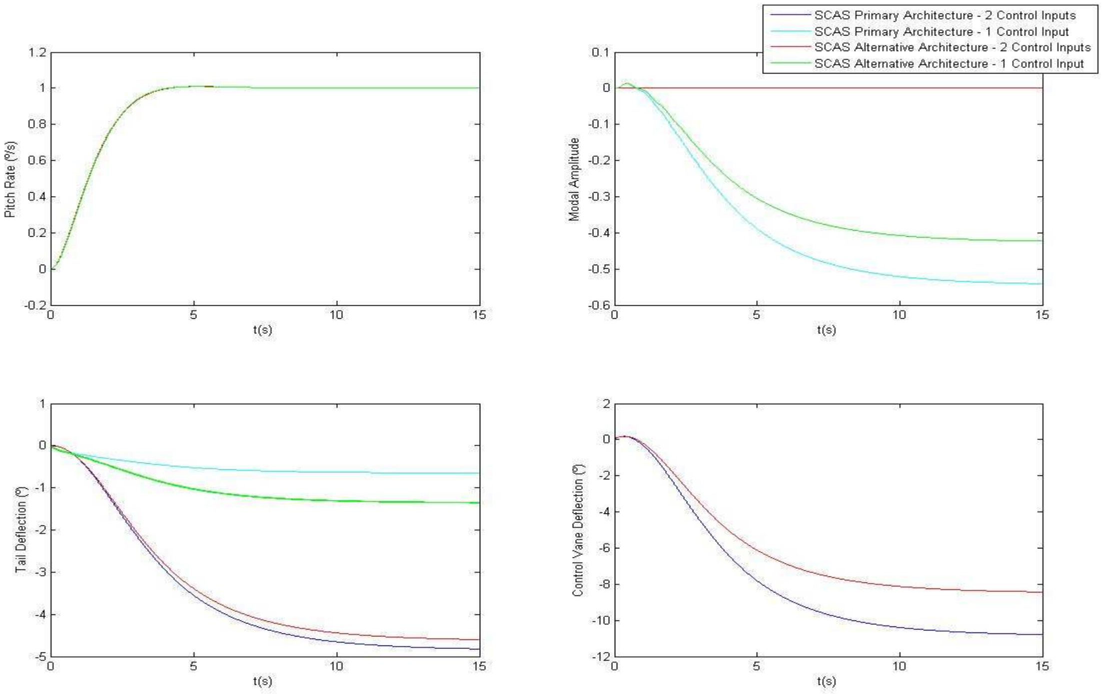

Figure 4. Full Order SCAS – Primary and Alternative Strategies – Time Domain Analysis

The time-domain analysis leads us to some interesting observations. Firstly, it's quite clear that all full-order controllers lead to excellent tracking performance as show by the pitch rate graphic. And secondly it can be observed that the algorithm when considering two control inputs leads to an almost null modal amplitude, which is not the case when the control vane usage is scraped. Here, it's worth noting that the modal amplitude corresponds to the generalized coordinate for the first longitudinal structural mode, which is proportional to the physical excursion of the structure. This result is very peculiar because on different situations it will be better to waste a bit more on the control cost and then have a better response regarding the structural deflection. On others, it will be better that use one less input and compromise a little bit the internal performance system: this is an engineer's choice that will need to be analyzed separately for each application. Finally it's worth noting that the usage of the HIFOO algorithm for the SAS design hasn't brought any significant advantage/disadvantage in terms of performance, still proving itself also to be a good solution.

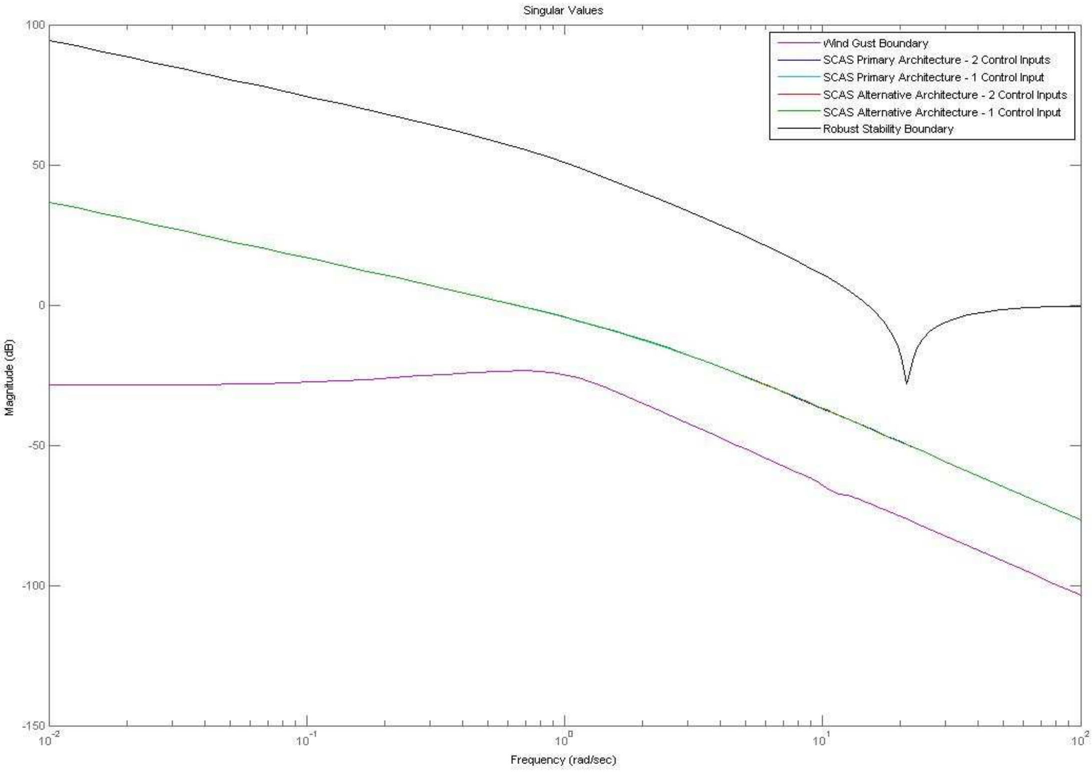

Figure 5. Full Order SCAS – Primary and Alternative Strategies – Frequency Domain Analysis

Analyzing the frequency domain performance of the system, it can be verified that the usage of different techniques and the usage of a different number of control inputs, have not made a significant difference into the stability margins regarding the wind gust limitations and the robust stabilities constraints, which puts back an emphasis into the time domain analysis for the full-order controllers. This conclusion is pretty important: by choosing the desired closed-loop transfer function through the H_{inf} *Loop-Shaping* algorithm it has been possible to get a tailor-made frequency response for the given constraints, which gives the engineer the freedom of choosing any of the full-order controllers, his choice being only a fine-tuning one, depending on the situation.

4. 4 Reduced Order Controllers

Now that the full-order controllers have been designed, we will be taking a look into reducing their respective orders in order to check if it is possible to maintain the very good performance that has been seen on the previous analysis while at the same time having a "smaller" controller. There, we will take each of the full-order controllers designed on the previous session in order to verify if one of the architectures has a better performance when compared to the other and if the number of control inputs has any influences of the results.

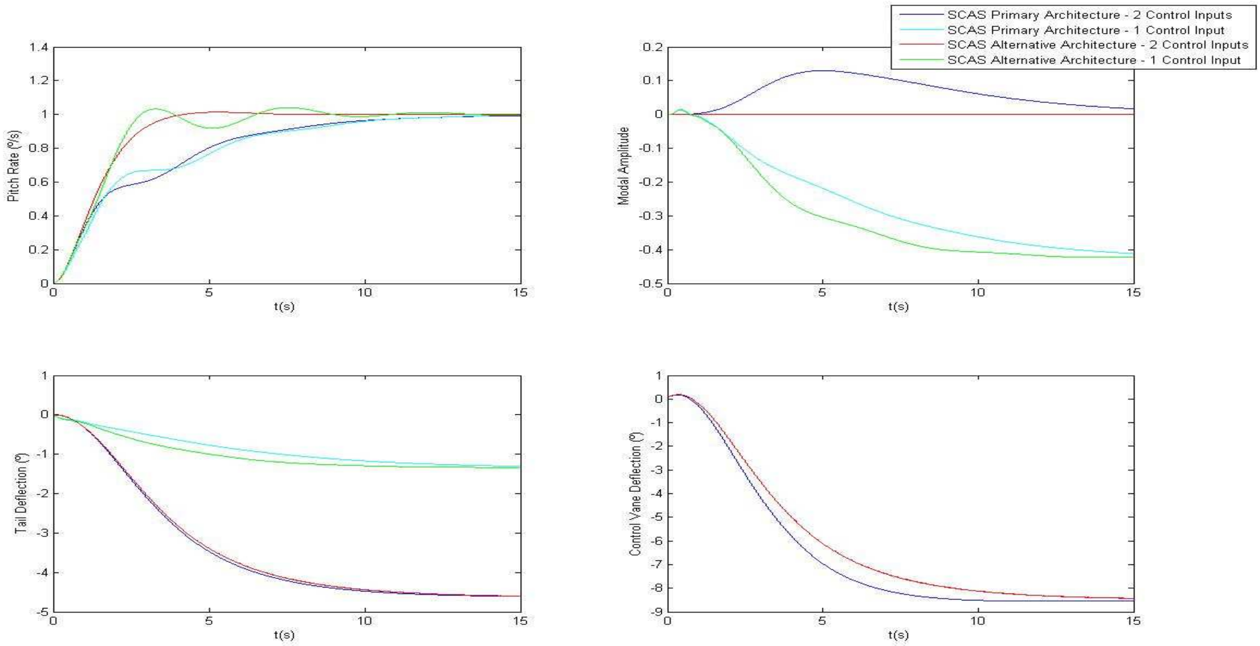

Figure 6. Reduced Order SCAS – Time Domain Analysis

The original full order controllers had order 17 (two control inputs) and 11 (one control input), respectively. Using the MATLAB *reduce* function it has been possible significantly reduce the order of the originals controllers. The controllers designed for the 2 control inputs systems had their orders lowered from 17 to 10, whereas the controllers designed for the one input control systems had their orders more than halved, from 11 to 4.

But contrary to what was seen on the full-order controllers, the time domain analysis now presents a major difference in terms of performance can be seen in between the primary and the alternative architectures. The usage of the HIFOO on SAS-loop made for a better response on time domain than when the H_{inf} *Loop-Shaping* technique was fully used. It can be seen that the alternative one gives a faster response even if deflects less the control inputs (on the 2 control inputs systems), using less energy. Also, the same faster performance can be seen on the 1 control inputs systems, which have the setback of introducing oscillations on their response due to the absence of the control vane which helps the aircraft to respond more smoothly.

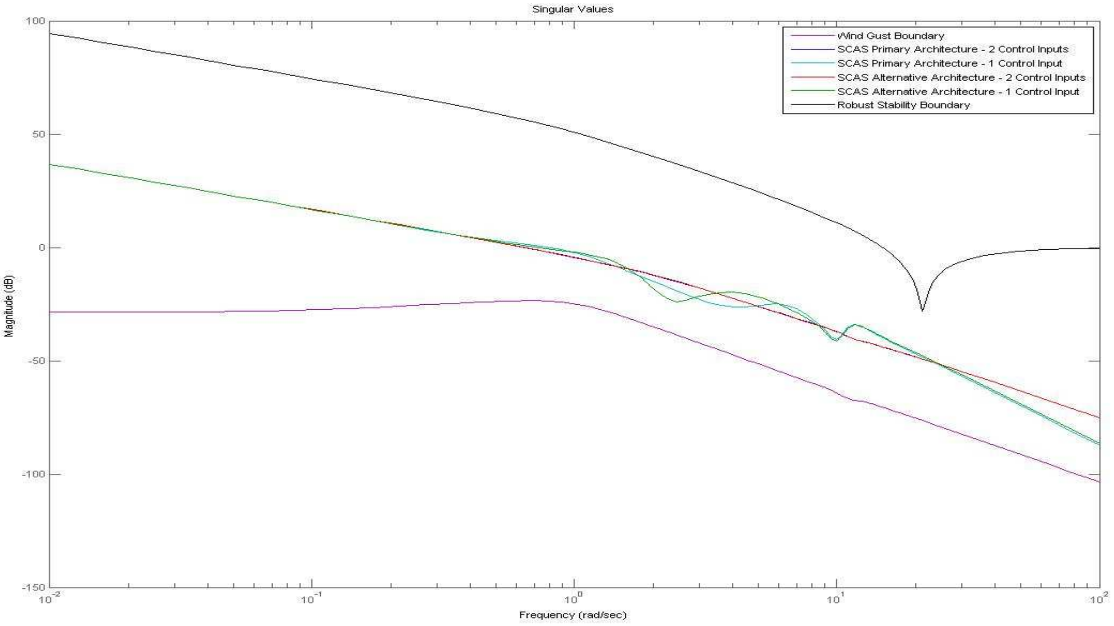

Figure 7. Reduced Order SCAS – Primary and Alternative Strategies – Frequency Domain Analysis

Now, considering the frequency-domain response, we also observe responses that are different from the ones seen for the full order controllers, but that corroborates with the time domain analysis. It was possible to significantly lower the order of the SCAS and keep the desired closed-loop plant when using 2 control inputs. When using just one, the shape of the closed-loop response, could not be kept, but still provides good margins regarding the robustness of the system and limitations regarding possible gust winds.

Therefore we are now able to get to a few valuable contributions of this essay. It's possible to combine:

- The H_{inf} *Loop-Shaping* algorithm;
- The HIFOO (H-Infinity Fixed Order Optimization) algorithm;
- And an order reduction algorithm.

Putting all the strategies above together can allow the Control Engineer to design a controller that has a high level of robustness, that has a fast and efficient tracking performance and that has a lower than usual order, which is highly desirable and extremely important contributing towards better control design techniques.

5. CONCLUSION

Throughout this essay, we have tried to put together many important aspects of Control Systems (SAS and CAS) design for Aeronautical Engineering, coming from an early introduction which leads to understand how specific the referred designs have become.

Section 2 specified the aspects around the importance of efficiently modeling a system to be controlled, in our case an aircraft. This was followed by the presentation of the B1-Lancer, its control inputs and its specific characteristics.

Section 3 went into the Robust Control Theory aspects, importance and why it's regularly used for SCAS for aircrafts, as it still withstands an advantage over Adaptive Control. Also, two different techniques were presented, one as prime selection for this essay and other as an alternate one.

And finally, on Section 4 the simulations considering the modeled system on Section 2 and the controllers designed bearing Section 3 in mind, were shown and analyzed. And we could come to an interesting set of conclusions: the H_{inf} *Loop-Shaping* algorithm is an extremely powerful tool as it can generate any closed-loop response desired by the control engineer. But the essay's main contribution came when the referred technique was combined with the HIFOO technique and applying an order reduction algorithm. It has been observed that when they are put together they can generate a fast and robust closed-loop lower order system, which is highly desirable on modern aeronautical applications.

6. ACKNOWLEDGMENTS

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