A SYSTEMATIC APPROACH TO FLIGHT CONTROL LAW VALIDATION IN EARLY DESIGN STAGES

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Abstract. *This work proposes a set of validation/evaluation maneuvers to evaluate controller performance and robustness through simulation, thus helping to ensure that any redesign occurs in early stages of the development, if necessary. The main idea is to check the validity of the design model and controller, thus giving the user information on which criteria have been violated, as well as an indication of a possible solution to the problem detected during validation/evaluation. The importance of this work is to exhibit approaches which might reduce the complexity of control laws and the overall control system design project. To define a set of such maneuvers, specific aircraft mission and flight conditions are considered. The paper initially presents a brief overview on aircraft handling qualities. With the help of this background, an explanation is given why the chosen maneuvers are relevant to controller evaluation. After a justification of maneuver choice, an example is introduced to illustrate controller assessment. The case study considers a primary longitudinal control law design for a business aircraft. The overall goal of this work is to point out criteria to decide which maneuvers are important to evaluate a controller, that fit into a procedure for development which is the most general possible, independently of the type of controller used.*

Keywords*: Flight Quality, Flight Control Law, Aerospace Control, Control Design*

1. INTRODUCTION

When a modern aircraft is created, it is necessary to design a set of controllers that will help the new system to accomplish its mission. This set of rules is called Flight Control Law (FCL).

The success of a flight control law design depends, not only on aircraft dynamics (stability and control), but on how comfortable, safe and easily it is handled by the pilot. However, concepts like these, besides being subjective, are difficult to express in terms of control theory. During several years of research, criteria were developed that propose to link the pilot's assessment to design (Hodgkinson, 1999). In general, these criteria are characterized by analysis of the design result, off-line simulations and simulations with pilot-in-the-loop.

Flight and handling qualities are properties that certify how comfortably and precisely the airplane answers to pilot commands during a specific task. Because these properties are evaluated in terms of pilot opinions, it is necessary to find alternative quantitative descriptions to analyze them. This analysis takes into account the aircraft class, the flight phase category and the quality level required so that the aircraft dynamic characteristics accomplish their mission.

The FCLs are established with the development of the system, and should be structured such that the interactions can be done quickly and accurately at any stage of the design.

The most important decisions are made when the project philosophy is established. However, is not always possible to know all the variables involved in the process and it's only possible to discover a problem in advanced stages of the design.

In phases like flight simulation, the cost to redesign the gains is high and should be avoided. One possibility is to create a phase of validation in early design stages. The main idea is to specify important flight phases and define criteria and requirements to evaluate the controller. This work proposes to define a set of criteria and maneuvers that will be useful in the evaluation of the longitudinal controller in several flight phases.

This paper begins with a technical background to work together with an overview of handling and flight qualities. It will discuss the main considerations that justify the method chosen to evaluate the handling qualities criteria. After this, a brief introduction is given on the importance of the maneuvers in the validation of a flight control law design. The next section presents a case study to apply the proposed criterion. A few situations will be presented to assess the robustness criterion. Finally, conclusions until the actual point and next steps to -finalize this work are listed.

2. HANDLING AND FLIGHT QUALITIES

Both civil and military aircraft have frequently been using systems with augmented stability and complex commands to aim at improving the aerodynamic development and to decrease pilot workload and, consequently, supply a minimum of handling quality to the pilot.

George Cooper and Raymond Harper defined Handling Qualities (HQs), in 1969, as: "Those qualities or characteristics of an aircraft that govern the ease and precision with which a pilot is able to perform the tasks required in support of an aircraft role."

Mooij et al, 1982, goes on to split handling qualities into criteria and requirements. Handling qualities criteria are defined as design guidelines for use by control system designers and authorities, whereas the customer requirements for airworthiness have to be demonstrated to the certification authorities as having been met and may be supported by the criteria.

The handling qualities can be categorized based on the aircraft class (based on size, weight and maneuverability), flight phase categories and level of acceptability to complete the mission, as described in the Tab. 1:

Table 1. Aircraft classifications according to their class, flight phase and level of acceptability

Class	Class I – small, light aircraft	Class II – medium weight, low-to-medium maneuverability aircraft	Class III – large, heavy, low-to-medium maneuverability aircraft	Class IV - high maneuverability aircraft
Flight phase categories	Category A - non-terminal phase, involving rapid maneuvering, precision track and or flight path control	Category B - non-terminal phase, involving gradual maneuvering like cruise or climb	Category C - terminal phase, involving tight flight path control like landing or take-off	
Levels of acceptability to conclusion of mission	Level 1 - the flight qualities are clearly adequate for the mission flight phase	Level 2 - the flight qualities are adequate for the mission flight phase, but there is a significantly increase in pilot's workload or a loss of effectiveness	Level 3 - the aircraft can be controlled, however, due to significantly increase in pilot's workload mission effectiveness is seriously damaged	

While the HQs are dedicated to specify a set of rules that ensure the fulfillment of the mission with minimum safety and quality for pilot and crew, the Flight Qualities (FQs) are defined by Ashkenas, 1984, as "the aircraft property where the pilot can totally explore his potential and development during a large gamma of missions and tasks, without the aircraft limits produce any controllability problem in aircraft".

Considering the longitudinal motion, the FQs are related the two distinct characteristics: the short and the phugoidal period modes. The phugoid modes can be easily controlled by the pilot, while the short period modes, if not adequately managed during the design, can be critical in the maneuverability. Because of this, the behaviour of controller, pilot and aircraft must be consistent. It isn't admissible that an aircraft doesn't have good short period dynamics. Thus this paper focuses on in these characteristics to choose the appropriated handling quality criteria for them.

3. CRITERIA TO EVALUATE HANDLING QUALITIES

After a brief introduction about flight and handling qualities, the choice of relevant criteria and requirements is outlined in this session.

MIL-STD-1797A presents several criteria to evaluate handling qualities. But, this variety enables a variety of choices, and of when to use each criterion is not well understood. Thus the flight control designer, without a proper handling qualities background or without experience, might use too many criteria, incurring in overspecification and even obtaining contradictory results. A common example is the use of the CAP criterion with non-conventional response types.

According Saussié et al, 2006, the HQ criteria can be divided in three categories: modal, frequency and temporal criteria. The modal criteria deal essentially with the damping ratios of the aircraft natural modes: the phugoid and the short period modes. The Control Anticipation Parameter (CAP) is an additional criterion blending the natural short period frequency and the corresponding zero. The frequency criteria correspond to an analysis in the frequency-domain and the Bandwidth criterion is an example of this category. Finally, there are time-domain criteria such as the Gibson Dropback criterion. These criteria are chosen looking for those that provide a suitable measure of the pilot's ability to control the aircraft with precision.

The choice of criteria to evaluate the handling qualities must consider the importance of flexibility with respect to the allowable transfer functions of the aircraft dynamics. When a certain transfer function structure is assumed by the criterion, it must be ensured that the method is still valid if the flight conditions and the transfer function change. This kind of consideration is very important when the intention is to expand this analysis and create a method to evaluate any aircraft. Additionally, it has to be defined if the evaluation method considers the system in open or in close loop. A system is in closed loop when the influence of the pilot’s gain is considered. The bandwidth method was chosen here as the longitudinal handling quality criterion because besides not specifying a structure for the transfer function, it analyzes, for example, the range of gains allowed for the pilot transfer behavior, a close loop characteristic, from open loop data obtained from the Bode Diagram.

3.1. Bandwidth Method

The bandwidth is a classical term that has been used to describe system capability to follow an input in a range of frequencies.

The airplane control bandwidth is critically important to a good handling and the FCS easily modifies it. The control of bandwidth is complicated by the fact that it varies according to the input-output variables involved. Control and handling difficulties may arise when the bandwidth of an input-output relationship is lower than it should be. Thus, all input-output bandwidth properties should be consistent with good handling and adequate stability margins.

The bandwidth is defined by the frequency where the phase margin is equal or higher than 45° and the gain margin is equal or higher than 6 dB. The Fig.1 represents this definition.

Concerns with the phase margin result from pilot observation data. To realize a tracking with 45° of phase margin, the situation requires the full attention from the pilot, although the maximum effort is not attained. The limit of 6 dB is due to experimental data showing that values less than 6 dB may induce undesirable Aircraft Pilot Coupling (APC), sometimes also called Pilot Induced Oscillation (PIO). PIO is an inadvertent and sustained oscillation that results from an abnormal interaction between the pilot and the aircraft. As this problem appears when the pilot tries to command the vehicle, such oscillations can be seen as instability of the closed loop control system.

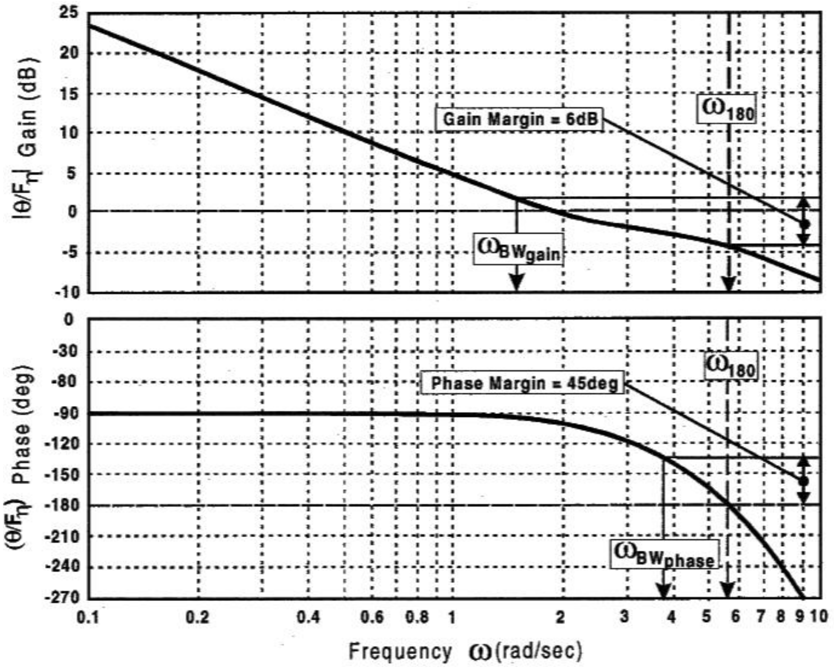

Figure 1. Bandwidth frequency definition (Hodgkinson, 1999)

The criterion is defined in Fig. 2 in terms of two parameters: the bandwidth frequency, ω_{BW}, and the phase delay, τ_p. The bandwidth frequency is the lower frequency among the frequencies of phase and gain margin. The phase delay is obtained by the following equation:

$$\tau_p = \frac{-\left(\theta_{2\omega 180^\circ} + 180\right)}{2\times(57{,}3)\times\left(\omega_{180^\circ}\right)} \tag{1}$$

Where:
ω_{180° (in rad/s) is the frequency where the phase angle is 180°.
$\theta_{2\omega 180^\circ}$ (in degrees) is the phase angle at the frequency given by twice ω_{180°.

The reason to use the parameter defined in Eq. (1) is that during the development of this criterion, it was perceived that the pilots were sensible to the shape of the phase slope in the frequency region close to ω_{BW}.

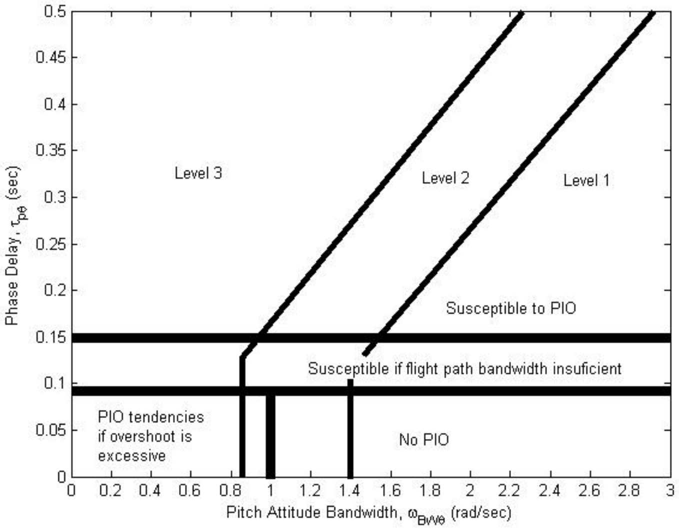

Figure 2. Definition of flight qualities bandwidth for pitch attitude

4. SET OF MANEUVERS TO VALIDATION OF FLIGHT CONTROL LAW DESIGN

To reduce the possibility of incompatibility between the subsystems, it was sought to increase integration between the stages of the design of an aircraft. The solution to this difficulty inside control engineering is the use of robust control. According to McRuer, 1994, “the traditional process of systems integration is to make individually designed subsystems work together on an aircraft, that is, to ensure compatibility and minimize adverse interactions. The new goal is to carry out concurrent multidisciplinary designs of the highly interactive systems in order to maximize aircraft performance, viewed in its broadest terms”.

The uncertainty around the operational environment and vehicle characterization are the largest obstacles for the designer. They produce the necessity of a design of gain scheduling so that control law can guarantee stability and performance. However, this design has a high cost for two reasons: the control law must be realized for any design point and a large number of evaluations must be done to guarantee stability and performance.

The robust control has as principal characteristic to maintain the performance and the stability even in the presence of uncertainties. In recent years, the techniques of robust control have undergone considerable advances. Among the advantages that these techniques provide, possibly the main one is the reduction in the number of design points for the gains of the control laws, since the laws of robust control cover a large area around an operation point in the flight envelope.

The final objective is not to obtain single satisfactory controllers, but exhibit approaches that reduce control law complexity and the overall control systems design cycle. Besides presenting this approach, it is intended to detail the justification for maneuver choice considering the evaluation purpose. Thus it will be possible expand the analysis proposed here to other evaluations.

The maneuvers chosen must assess the following characteristics along the flight envelope:

1. Availability of sufficient control power to maintain a steady state, straight and level flight, as well consistent steady state maneuvers consistent with the aircraft mission;
2. Proper following of transitions between flight conditions and from there to ground operation conditions (and vice versa) and flight.

Those characteristics need to be guaranteed even with an inoperative engine, as such failure can occur.

5. CASE STUDY

After defining the kind of control that will be used (in this case for longitudinal control), it is necessary to define the aircraft mission, the flight phases and flight conditions.

To exemplify the methodology presented in this work, models, data and other relevant case study considerations were taken from Cruz, 2008. Thus the following is assumed:

- Aircraft mission: Civil transport aircraft;
- Flight conditions: Described by Tab.2;
- Flight phases: Climb, approach, cruise, take-off and landing.

Table 2. Flight Conditions for the Case Study

Weight (kg)	CG (% MAC (1))
23224	10
44452	10
23224	40
44452	40

(1): MAC - mean aerodynamic chord

The aircraft configurations are described in the Tab. 3.

Table 3. Aircraft Configurations for Case Study

Altitude	Speed
0	1,3 Vs (1)
0	340 KCAS (2)
30900	1,3 Vs (1)
30900	340 KCAS (2)
51000	1,3 Vs (1)
51000	0,89 Mach

(1):Vs - stall speed; (2): KCAS - calibrated airspeed measured in knots.

More information related to aircraft model can be obtained from Cruz and Kienitz, 2007.

The requirements are established considering a Class II-L (medium weight land based aircraft). Level 1 handling qualities for flight phases in category B are required as described in MIL 8785C. The chosen class is compatible with the aircraft used in the case study while the handling quality levels is representative of a primary longitudinal control law in up and away phases.

Considering the aircraft dynamics and the specifications described above, the transfer function from elevator (δ) to attitude (θ) given in Eq. (2) was obtained.

$$\frac{\delta}{\theta} = \frac{1.332 \cdot 10^{-5} s^3 - 1.601 s^2 - 1.19 s - 0.04698}{s^4 + 1.452 s^3 + 3.052 s^2 + 0.04694 s + 0.08311} \qquad (2)$$

To plot the Bode Diagram, determine the bandwidth and analyze the handling quality, it is necessary to specify a delay time. Two distinct situations were considered: one where a specific delay time was fixed and the flight conditions were varied and, another situation where the flight condition was fixed and the delay time was varied.

For the first case, four situations were considered with delays of 10 ms, 50 ms, 100 ms and 150 ms. Fig. 3 and Fig. 4 represent the results for 10 ms and 50 ms, and the Fig. 5 and Fig. 6 for 100 ms and 150 ms.

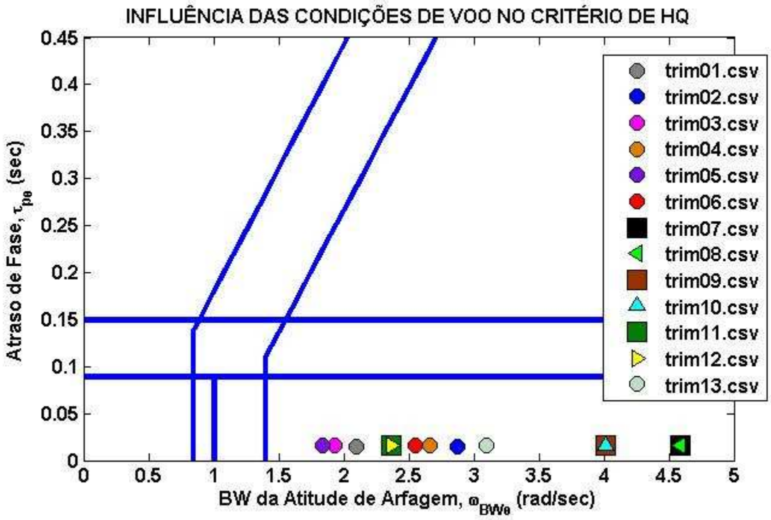

Figure 3. Influence of the flight conditions in the handling quality criteria according bandwidth method for a delay time of 10ms

In this Figure it is possible to perceive that, for low delay time, the aircraft performance is the same, although the flight conditions have been varied. The phase delay is, basically, the same for all conditions. For the situations described by Fig.3, the aircraft is PIO free and the handling quality is Level 1.

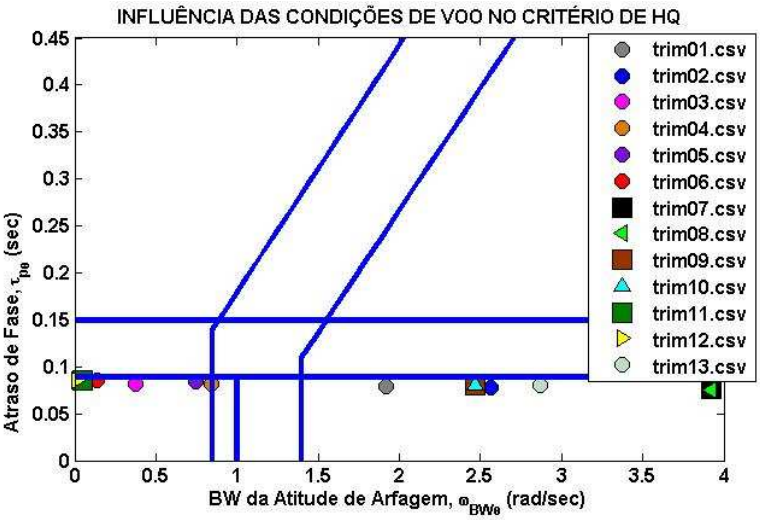

Figure 4. Influence of the flight conditions in the handling quality criteria according bandwidth method for a delay time of 50 ms

Compared with Fig. 3, the Fig. 4 had an increase in the differences among the flight conditions characteristics. Part of them (trim01, trim02, trim07, trim08, trim09, trim10 and trim13) is, although PIO free, going to PIO susceptibility spot. On the other hand, another group of flight conditions has their bandwidth reduced. This causes PIO prone behavior if the overshoot is excessive. The increase in phase delay resulted in a decrease in handling quality level (Level 3).

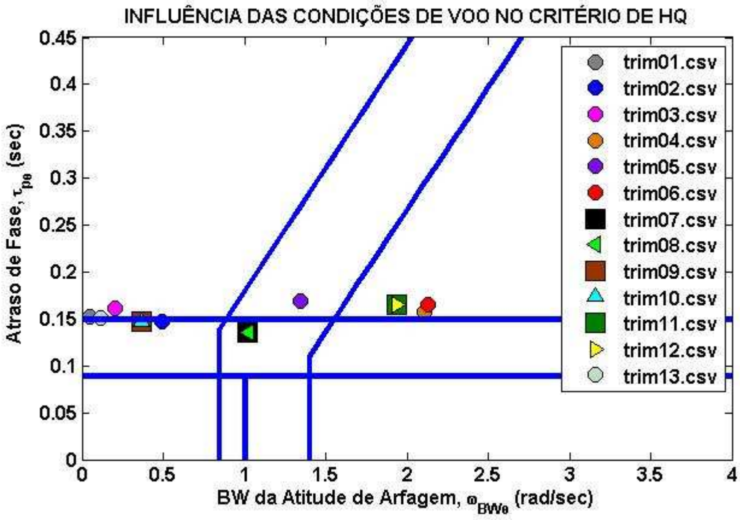

Figure 5. Influence of the flight conditions in the handling quality criteria according bandwidth method for a delay time of 100 ms

If the flight condition is inside the PIO prone spot and handling quality level is Level 3, the delay time shouldn't be allowed. In Fig. 5 the conditions trim01, trim02, trim03, trim09, trim10 and trim13 describe such situation. All the simulations refer to the landing flight phase, thus critical to the pilot, another reason that justifies their avoidance.

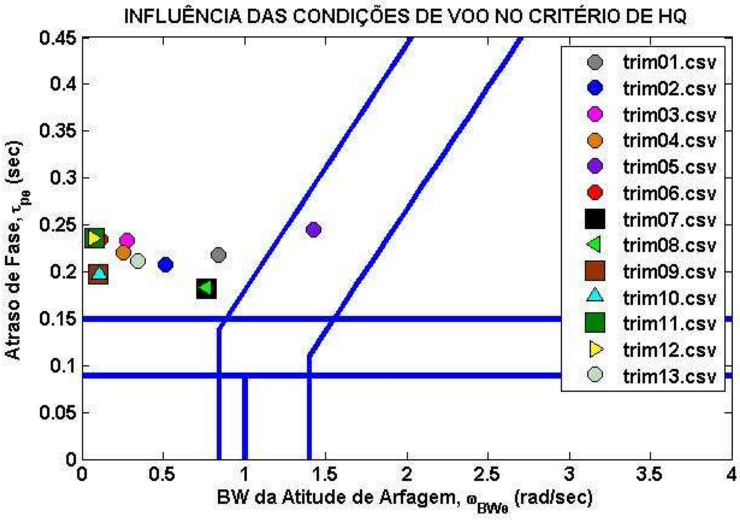

Figure 6. Influence of the flight conditions in the handling quality criteria according bandwidth method for a delay time of 150 ms

In the last situation described in here, Fig. 6, all the conditions, except the condition trim05, are in the worst case (PIO prone and level 3 of handling quality).

From Figs. 3, 4, 5 and 6 it is seen that the increase of delay time leads to an increase in the tendency of PIO and a decrease of the handling quality level. Some flight conditions allow large delay times, even if PIO susceptibility appears. But, this admissibility depends on the flight phase. Cases where maximum pilot attention is required need off-line analysis.

In the analysis of delay time influence on handling quality criterion is interesting to verify that the greater the bandwidth, the greater will be the delay time accepted for the aircraft, considering the requirements to avoid PIO.

Taking into account the influence of the delay time in the degradation of the handling quality criterion is very important. Harper and Cooper, in 1986, showed that pilots were sensible to the shape of the phase slope in the regions close to ω_{BW}. Because of this, the analysis of the influence of delay time on the handling quality criterion is necessary. An increase in delay time yields a decrease in bandwidth and an increase in phase delay. This influence may lead to a change in the choice of ω_{BW}. Here, this analysis was done for two flight conditions. In Fig. 7 and 8 the variations of bandwidth, ω_{BW}, and phase delay, τ_p, are shown. In both cases the delay time is varied in steps of 20 ms, from 10 ms to 200 ms.

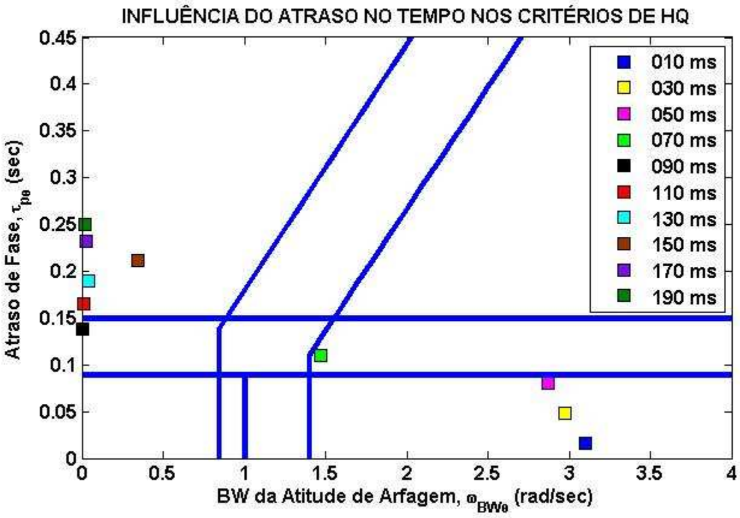

Figure 7. Influence of the delay time in the handling quality criteria according bandwidth method for flight condition 13

With the condition trim03 it can be perceived that the system had, in the first moment, its bandwidth reduced (check the performance of flight condition with 10ms and 30ms of delay). The bandwidth continued reducing until it reached phase delay close to $\tau_p \approx 0,15$s. Then, the bandwidth increased, but it didn't reach Level 1 of handling quality.

The next figures show with more clearness the behavior of aircraft dynamics response.

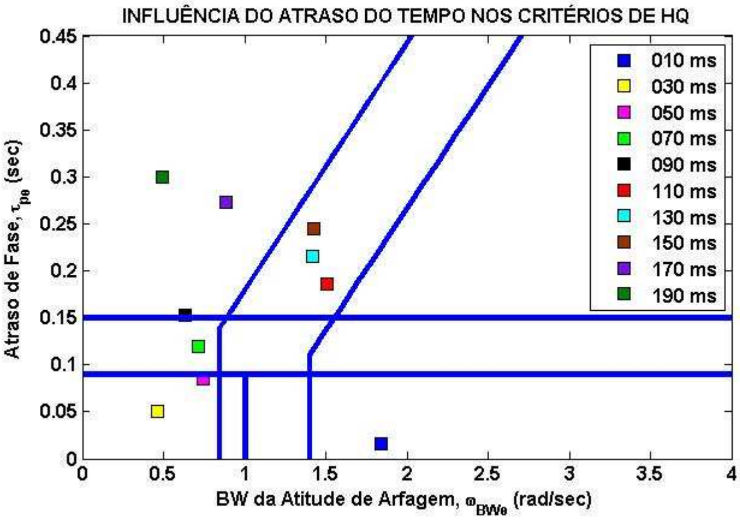

Figure 8. Influence of the delay time in the handling quality criteria according bandwidth method for flight condition 05

The figure above shows a "tendency" of decrease in bandwidth for some delay times (PIO free, PIO prone if overshoot excessive or PIO prone). In these sections there is a tendency to decrease the bandwidth, but in the next sections, the bandwidth increases along the section then decreases again. The bandwidth decreases slower than the phase delay increases, so the aircraft behavior is going swiftly to the section where the PIO susceptibility is high.

In Figure 9 the influence of delay time on increasing "PIO prone" behavior and decreasing HQ is higher than in previous cases.

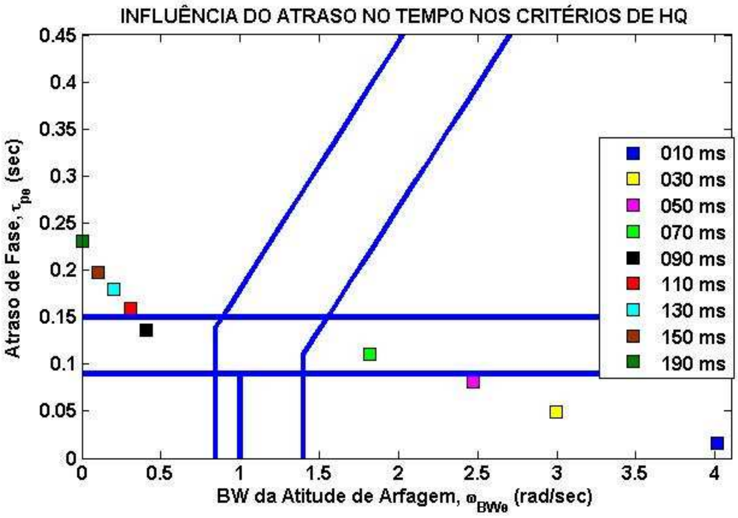

Figure 9. Influence of the delay time in the handling quality criteria according bandwidth method for flight condition 09

Although the BW is decreasing faster than in other situations, the worst case is reached with the same delay time (≈90ms). Unlike the other conditions (trim03 and trim05), this was the condition in which the aircraft remained in the region free of PIO with the largest delay. The downside of it is that it has less flexibility of time delay, when we changed the bandwidth.

6. CONCLUSIONS AND FUTURE WORKS

Focusing on longitudinal control for the sake of exemplification, this work proposes a set of criteria and maneuvers to evaluate handling qualities. One available criteria was chosen and evaluated that was considered of more relevance to the purpose of this work. A routine was developed that evaluates both the influence of variation in terms of flight conditions as well as of delay time.

With just these two types of analysis, it was possible to verify the influence of these two parameters on the bandwidth criterion, which gives relevant information on PIO susceptibility.

In ongoing work, it is intended to determine a set of maneuvers that will describe a scenario to further evaluate proposed controllers. The main idea is the correlation between the conventional analysis, by the handling qualities criteria, and the simulation. Such analysis can become an important phase in a flight control design, since a deeper understanding of the behavior of the system in the initial stages of the design can further reduce the possibility of future redesign, reducing production costs.

7. ACKNOWLEDGEMENTS

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