FLYING QUALITIES DESIGN FOR A FLY-BY-WIRE TRANSPORT AIRCRAFT IN THE LANDING FLIGHT PHASE

J.E. Gautrey and M.V. Cook

Flight Test & Dynamics Group
College of Aeronautics
Cranfield University, UK

Abstract

Fly-by-wire flight control systems are becoming more common in both civil and military aircraft. These systems can give many benefits but present a new set of problems, especially as they may drastically influence the pilot's perception of the aircraft's flying characteristics, compared with those of a classical transport aircraft. The paper presented here considers an approach to the design of fly-by-wire control laws for a generic regional transport aircraft.

An approach is described where flying qualities data obtained from past flying qualities studies was analysed, and a number of flying qualities requirements are formulated for the approach and landing flying qualities task for a transport aircraft. A number of different fly-by-wire control laws were designed using the design criteria derived from this data to provide a range of flying qualities characteristics which are representative of fly-by-wire transport aircraft currently in service.

These control laws were then evaluated with an ILS approach task to determine which was the most suitable control law. Pilot in the loop simulation was used in a fixed base engineering flight simulator for this purpose.

The results showed that the requirements could be used to design a number of different, but otherwise satisfactory, types of control law for the approach and landing task.

Copyright ©2000 by Cranfield University. Published by International Council of the Aeronautical Sciences with permission.

1 Introduction

Fly-by-wire flight control systems are becoming more common in both civil and military aircraft. These systems can give many benefits such as reduced cost and improved performance, but also present a new set of problems due to their increased complexity and the fact that they can drastically modify the pilot's perception of the aircraft's flying characteristics compared with those of classical transport aircraft. This paper considers the design of longitudinal fly-by-wire control laws for a generic regional transport aircraft for the approach and landing flight phase.

Since fly-by-wire control is a large subject area to cover, this paper concentrates on the design approach used for the longitudinal control laws and the background to the process. Results of evaluations made in an engineering flight simulator to validate the process are described. References are made to related issues to allow an interested reader to follow them up as desired. The principal reference for the design approach described here is reference [1].

2 Control Law Types

A number of fly-by-wire aircraft are currently in service, from airliners to fighter aircraft. Between them, these aircraft have a number of different control law types, or in other words, they have subtle differences in the aircraft’s response to a pilot’s input. Since the evaluation series described in this paper focuses solely on the longitudinal control laws, a list of common longitudinal control laws are given in Table 1, together with an example of an aircraft which uses that particular control law.

The characteristics of the longitudinal control laws given in Table 1 may be broken into two distinct groups. The short-term response is essentially the parameter which the pilot is controlling in the short term with the longitudinal inceptor, which for the size of aircraft considered here is approximately 5 seconds after the control input is made. The long-term response is the parameter that the pilot is controlling with the longitudinal inceptor in the longer term, which is defined as the period after the short-term dynamic response is complete.

To illustrate this point, consider a classical aircraft. The short-term response is pitch rate, therefore movements of the longitudinal inceptor generates pitch rate demands in the short-term, and the pilot will see the aircraft responding as he moves the inceptor. However, in the long-term, which is the response after the pilot has held the inceptor stationary for a period exceeding 5 to 10 seconds, the position of the inceptor determines the steady angle of attack. Therefore, the pilot may see the aircraft slowly changing its pitch rate, even with the inceptor fixed as the aircraft attempts to attain the desired angle of attack. This is different to the short-term response where the pilot effectively controls the pitch rate directly.

A reduced order, constant speed approximation to the response of a classical aircraft can be seen on Figure 1. Note that there is a steady state change in the angle of attack, and there is also a constant pitch rate and a constant rate of change of flight path angle, which remains steady after the initial response is complete. Since normal acceleration is proportional to rate of change of flight path (for constant airspeed), this also results in a step change in normal acceleration. The response shown here has identical short and long-term responses (after the initial transient is complete).

However, when a full order classical response is considered, the long-term response is a little different, as shown on Figure 2. There is still a step change in angle of attack, however the pitch attitude and flight path angle responses are now oscillatory in the long-term (which is the phugoid mode). Therefore, constant (and in fact, zero) pitch rate and normal acceleration does not occur until the phugoid has damped out, which can take a number of minutes. This response has pitch rate demand characteristics in the short-term and angle of attack demand characteristics in the long-term.

It may be seen that the response during the first 5 seconds on both Figure 1 and Figure 2 is identical. For the responses shown, this is defined as the short-term period.

Finally, note that the C* control law has not been listed in Table 1. C* is not strictly a control law type, however it is sometimes used to classify a control law which has a mixture of normal acceleration demand and pitch rate demand characteristics. In addition, note that some of the control law types given in Table 1 have both short and long-term characteristics, whilst others only have a short-term characteristic specified. The control laws with both short and long-term characteristics generally require trimming of some sort, whilst those which only have a short-term characteristic specified generally do not require any form of trimming action by the pilot.

All of the control law types listed in the table are known as rate-demand control law types since a step input produces an aircraft response which more or less has a constant pitch rate response in the short-term. This type of control law was deemed most suitable for the approach and landing task by Field [2], whose work preceded the evaluation program described here. The other common group of control laws has what is known as attitude-like properties, where a step input made by the pilot causes a response, which approximates a step change in pitch attitude. Again, Field deemed these to be less suited to the ILS approach task [2], although it has since been shown that they can have a large benefit when used in the landing flare [1].

3 Flying Qualities Criteria

In order to analyse the response of an aircraft to assess whether a pilot would find the response acceptable, flying qualities criteria are used. A number of these criteria are available, which have been developed over a long period of time, mainly to facilitate the design of the flight control system for fly-by-wire aircraft.

The criteria selected for use in this study have been taken from the many different criteria used over the past years, and include the Control Anticipation Parameter (CAP) criterion, a derivation of it called the Generic Control Anticipation Parameter [3] (GCAP), the Gibson criteria and the Bandwidth criterion. In addition, modifications were proposed to some of these criteria in order to make them more applicable to fly-by-wire transport aircraft. Details of these modifications may be found in reference [1].

The criteria listed were used for two distinct purposes. Firstly, they were used to compare the characteristics of the different configurations, or specified aircraft / control law combinations, contained within the flying qualities programmes listed in Table 2. These criteria are known as analysis criteria. Secondly, trends shown by the application of the criteria were found, which were used to design the control laws for the engineering flight simulator evaluations described below. These trends produced target values for a number of critical parameters, and the criteria used for designing individual control laws are known as design criteria.

The criteria considered are listed in Table 3, together with a brief description. Further information pertaining to these criteria may be found within references [1], [4] and [5].

4 Analysis of past flying qualities programs

The criteria described within Table 3 were used to analyse the data contained within the flying qualities evaluation programmes listed in Table 2.

Use was made of the Cooper Harper Rating scale (CHR) [1] contained within the references to the past flying qualities programmes to determine whether the evaluating pilots rated a particular configuration well or badly.

4.1 Results

After analysing the results of past flying qualities programmes, it can be seen on Figure 3 that there are significant differences between the results from the different programmes, and also between the results from configurations analysed in moving base, fixed base and in-flight simulators.

The minimum value of the Cooper-Harper Rating, presented on the vertical axis, gives the configuration that received the best rating by an evaluation pilot. Figures 3a, 3c and 3e show the CAP values for a fixed base, moving base and in-flight simulator respectively. Table 4 shows the desirable range of CAP values for the three figures. It can be seen that the desirable value of CAP depends on the type of simulator being used for the evaluations, indicating that pilots evaluating identical aircraft configurations in different types of simulator would rate the configurations differently. According to current flying qualities standards [13], the desirable range of CAP values varies between 0.16 and 3.6.

Figures 3b, 3d and 3f show the same configurations, but analysed using the GCAP criterion, with Table 4 giving the desirable range of GCAP values. Although here is still a difference in the most desirable value, depending on the type of flight simulator used, the range of desirable values for each of the parameters is now reduced. This indicates that the GCAP criterion may be more selective compared to the CAP criterion, and hence a

better design criterion. The full set of results, plus analysis, may be found in reference [1].
The desired values for the criteria parameters used as design criteria are shown in Table 5. These are the values that were found to give the lowest Cooper-Harper Rating for each particular criterion. The main observations found from the studies were;

The CAP criterion

- Can be used for aircraft having classical response characteristics
- Is commonly specified as a criteria to be used in military flying qualities standards
- Does not often apply to unconventional response characteristics since a classical short period mode may not exist

The GCAP criterion

- Is essentially untested.
- Gives better results than the CAP criterion for unconventional response characteristics since higher order lead/lag terms are taken into account.

The Neal-Smith Criterion

- Shows a significant difference between the desirable characteristics for moving base simulators, fixed base simulators and in-flight simulators
- Only considers the pitch attitude response

Gibson's Dropback Criterion

- May be used with any rate-like response characteristic.
- Was not taken account of in pole-placement trials, and would have shown some bad configurations.

More detailed comments may be found in reference [1].

4.2 Summary of Control Law Design Requirements

As previously discussed, control law design requirements have been derived from the analysis of these flying qualities investigations. The design requirements derived for control laws used in the approach and landing task for a generic regional aircraft are summarised in Table 5.

5 Engineering Flight Simulator Trials

A series of trials were carried out using a model of a relaxed stability 100 seat generic regional aircraft in a fixed base engineering flight simulator. This aircraft in its unaugmented state is referred to as the baseline aircraft.

A number of control law types were designed and implemented for the baseline aircraft, as listed in Table 1. They represent a sample of the different types of control law in common use in Fly-By-Wire aircraft. The control laws were all designed to the same set of control law independent criteria, i.e. criteria that could be applied to any of the control law types considered.

By adopting this approach, it was envisaged that the most suitable control law type could be identified, since differences between the control law types should be due solely to the type of control law used, and not to the way in which the control law was designed.

A total of five evaluation pilots were used in the trials programme – one pilot, the principal pilot, evaluated all of the configurations. An additional four pilots evaluated some, but not all of the different configurations presented.

A series of analysis metrics were used to rate the aircraft / control law combination. The Cooper Harper Rating scale was used as the primary analysis tool for assessing pilot opinion. The Bedford Workload Scale [14] was used to give n indication of the workload experienced by the pilot and the Pilot Induced Oscillation scale was used to formally quantify any PIO tendencies in the aircraft / pilot combination.

The control laws were evaluated with an ILS task to determine which was the most. Pilot-in-the-loop simulation was used for this study in a fixed base engineering flight simulator. The results are summarised briefly below, and also describe the effects of using an autothrottle on the pilot's perception of the aircraft's flying qualities.

In addition to the ILS approach task, a Windshear penetration task and a formation-flying task were also considered. More details of these studies can be found in reference [1].

5.1 Results from the Simulator Trials

The results from the simulator trial can be found in Table 6 for the different control law types evaluated. The results presented are overall Cooper Harper Ratings for the approach and landing task, both with and without autothrottle considered.

Further results were obtained, including pilot comment cards, and these can be found in references [1], [4] and [5].

5.2 Discussion from the Simulator Trials

From the results presented in Table 6, it can be seen that all of the control laws were rated well (with a Cooper Harper Rating of 3 or less, which is in the Level 1 flying qualities region) compared to the baseline aircraft, which was rated a Level 2 aircraft. In addition, analysis of the pilot comment cards showed that the pilots seemed to be satisfied with the manner in which the control laws performed, and did not make comments such as “too sluggish” or “too abrupt”, suggesting that the control laws were well designed.

Hence, it is suggested that firstly, the differences between the different control laws evaluated were due to the response characteristics of the control laws themselves. In other words, the fact that the pilot was evaluating a configuration with normal acceleration response characteristics compared to a configuration with pitch rate response characteristics, for example.

Secondly, the comments made by the pilots indicated that the control law independent design requirements can be applied to a variety of rate-like control laws as these comments did not indicate that improvements to the control laws would be required.

In addition, the following observations were made;

- Autothrottle caused a major decrease in workload for the augmented aircraft
- Autothrottle caused a major increase in workload for the baseline (unaugmented) aircraft, with reduced static stability
- An aircraft with desirable pitch characteristics allow the pilot more time for airspeed control
- Pilot is most sensitive to manoeuvre margin, rather than static margin, although he is aware of static margin effects

6 Conclusions

The following conclusions may be drawn.

- Flying qualities differences exist between identical configurations evaluated in fixed, moving base and in-flight simulators
- The control law independent design requirements appeared to be successful, since the benefits of the different laws appeared to be due to the differences in control law type and not to the response characteristics associated with a particular control law type

References

[1] Gautrey J E. *Flying Qualities and Flight Control System Design for a Fly-By-Wire Transport Aircraft*. EngD Thesis, Cranfield University, September 1999.

[2] Field E J, *Flying Qualities of Transport Aircraft: Precognitive or Compensatory?*, PhD Thesis, Cranfield University, June 1995.

[3] Gautrey J E; Cook M V, A generic control anticipation parameter for aircraft handling qualities evaluation, The Aeronautical Journal, Vol. 102, No. 1013, March 1998.

[4] Gautrey J, *Generic regional aircraft flying qualities for the approach and landing task*, CoA Report 9701, Cranfield University, 1997.

[5] Gautrey J E, Generic regional aircraft flying qualities for the windshear and formation flying tasks, CoA Report 9710, Cranfield University, 1998.

[6] Field E, *A piloted simulation investigation of several command concepts for transport aircraft in the approach and landing*, CoA Report 9401, Cranfield University, February 1994.

[7] Mooij H A, *Criteria for low-speed longitudinal handling qualities of transport aircraft with closed-loop flight control systems*, Martinus Nijhoff Publishers for the NLR, 1985.

[8] Radford R C; Smith R E, Approach and Landing Flying Qualities Requirements, Flying Qualities Design Criteria, *AFFDL Flying Qualities Symposium*, AFWAL-TR-80-3067, May 1980.

[9] Rossitto K R; Hodgkinson J, Longitudinal and lateral-directional flying qualities investigation of high-order characteristics for advanced-technology transports, AIAA 93-3815, 1993.

[10] Rossitto K F; Hodgkinson J; Williams T M; Leggett D B; Bailey R E; Ohmit E E, Initial result of an in-flight investigation of longitudinal flying qualities for augmented, large transports in approach and landing, *AIAA Guidance, Navigation and Control Conference, Monterey California*, AIAA 93-3816, August 1993.

[11] Preston J D; Rossitto K R; Hodgkinson J, Comparison of results from an in-flight and ground-based simulation of longitudinal flying qualities for augmented, large transports in approach and landing, *AIAA Atmospheric Flight Mechanics Conference*, AIAA 94-3489, 1994.

[12] Rossitto K R; Preston J D, Results of a simulator investigation into the effects of the instantaneous center of rotation on approach and landing flying qualities, *AIAA Atmospheric Flight Mechanics Conference*, AIAA 94-3510, 1994.

[13] Anonymous, *Military Standard - Flying Qualities of Piloted Aircraft*, MIL-STD-1797A, January 1990

[14] Roscoe A H; Ellis G, *A subjective rating scale for assessing pilot workload in flight: a decade of practical use*, Royal Aerospace Establishment TR90019, March 1990.

Control Law Type	Currently used in …	Short-term Response	Long-term Response
Classical Response	most, if not all, non Fly-By-Wire Aircraft	Pitch rate demand	Long-term response is trimmed angle of attack
Pitch Rate	Boeing C-17	Pitch rate demand	
Normal Acceleration	Airbus A320, A330 and A340	Normal acceleration demand	
Normal Acceleration with trim to Airspeed	Boeing 777	Normal acceleration demand	Long-term response is trimmed airspeed

Table 1 : Some typical current Fly-By-Wire Transport Aircraft control law types

Programme	Type of Simulator	Reference
Field's Thesis	Fixed Base Simulator	[2]
Field CoA 9401	Fixed Base Simulator	[6]
Mooij's Thesis	Moving Base Simulator and In-Flight Simulator	[7]
NASA TR 80 3067	Moving Base Simulator	[8]
McDonnell Douglas : Internal Research & Development		
AIAA 93-3815	Moving Base Simulator	[9]
AIAA 93-3816	In-Flight Simulator	[10]
AIAA 94-3489	Moving Base Simulator and In-Flight Simulator	[11]
AIAA 94-3510	Moving Base Simulator	[12]

Table 2 : Flying Qualities Programmes under Investigation

Criterion	Description
Control Anticipation Parameter	Places limits on the short period frequency or manoeuvre margin of the aircraft.
Generic Control Anticipation Parameter:	This is a criterion proposed by the author as a result of earlier related work that took the ideas behind the Control Anticipation Parameter and extended them so that they would apply to aircraft with an unconventional response characteristic. As it is a "new" criterion, more information may be found in reference [3].
Low Order Equivalent Systems analysis:	LOES analysis was not used for this work, but performs frequency matches to obtain a low order system with an equivalent frequency response of a high order system over a specific frequency range.
Gibson's Dropback:	Places limits on the characteristics of the pitch attitude response to an elevator step input. It was modified for the purposes of this work, as described in reference [1].
Sturmer's Pitch rate Sensitivity:	This criterion places limits on the pitch rate sensitivity. Some modifications were made to account for the higher control forces experienced with transport aircraft.
Gibson's Attitude Frequency Response:	Places boundaries on the Nichols plot of pitch attitude.
Bandwidth:	Places limits on the gain and phase margins for the pitch attitude and flight path angle responses.
Gibson's Phase Rate:	Specifies the maximum rate of change of pitch attitude phase with frequency at the crossover point.
Neal-Smith:	Uses a pilot model to give compensation to obtain a specified pitch attitude frequency response characteristic, and places limits on the characteristics of the required compensation.

Table 3 : Flying Qualities Criteria

Range of desirable	Fixed-Base Simulator	Moving-Base Simulator	In-Flight Simulator
CAP	0.15-0.75	0.25	0.45-0.7
GCAP	0.3-0.65	0.25	0.6-0.7

Table 4 : Range of Desirable CAP and GCAP Values for Different Types of Flight Simulator

Criterion	Desirable Value	Rationale
GCAP	0.6 rad /s^2/g	Ensures that the pitch attitude to normal acceleration response is desirable
Pitch Attitude Dropback	0.5	Ensures that there is not too much lead or lag in the flight path angle response
Short-term Mode Natural Frequency	1.5 rad/s	Ensures that only a small amount of lead/lag compensation is required to meet the GCAP requirement
Short-term Mode damping ratio	0.7	When applicable, ensure that the short-term mode damping ratio is sufficient to give a well damped pitch response.
Long-term Mode Damping ratio	0.15	When applicable, ensure that the long-term mode damping ratio is sufficient to prevent problems in stabilising airspeed.
Maximum initial pitch acceleration	0.6 deg/s^2/lb	Ensures desirable control forces for a medium sized transport aircraft
Airspeed Stability		When static stability is required, 1 lb control wheel force is required to hold the aircraft 3 knots “off-trim”
Flare Control Forces	N/A	The response in the flare shall be modified so that it has attitude-like properties

Table 5 : Flying Qualities Design Requirements for the Approach Task for a Transport Aircraft

Control Law	Median CHR without AutoThrottle	Median CHR with AutoThrottle
Unaugmented Aircraft (Baseline)	3.5	3.5
Angle of Attack	3	2
Pitch Rate	3	2.5
Normal Acceleration	2.5	2
Normal Acceleration with Trim to Airspeed	3	2

Table 6 : Cooper Harper Ratings for Different Control Laws

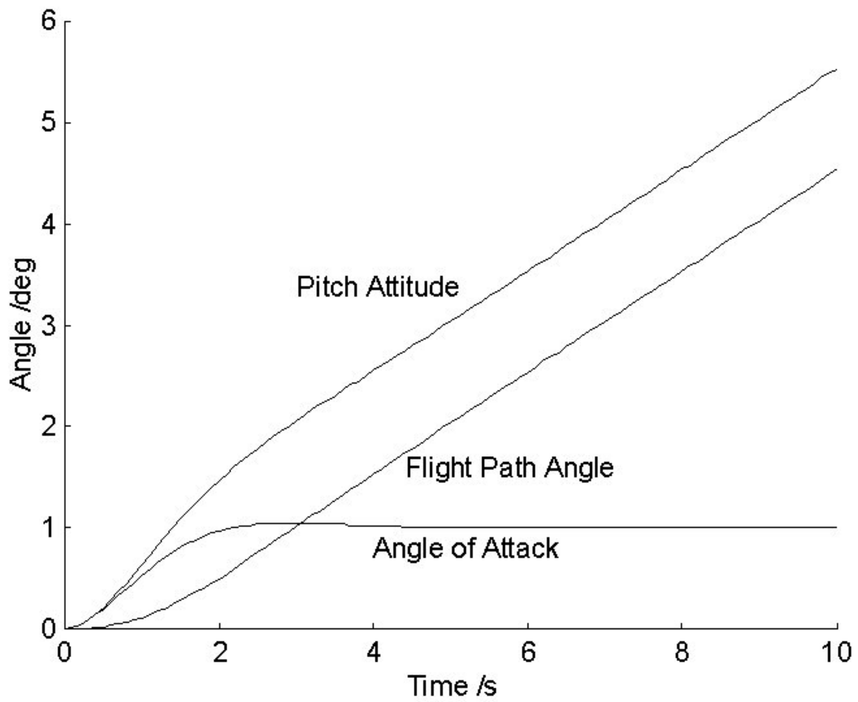

Figure 1 : Constant Speed approximation response to an elevator step input.

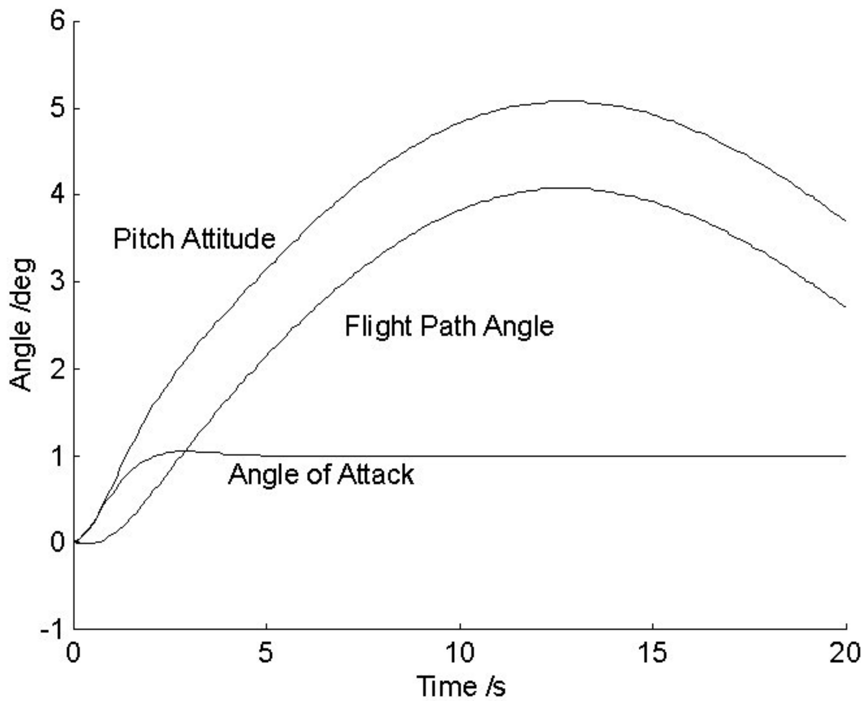

Figure 2 : Full order aircraft response to a step elevator input.

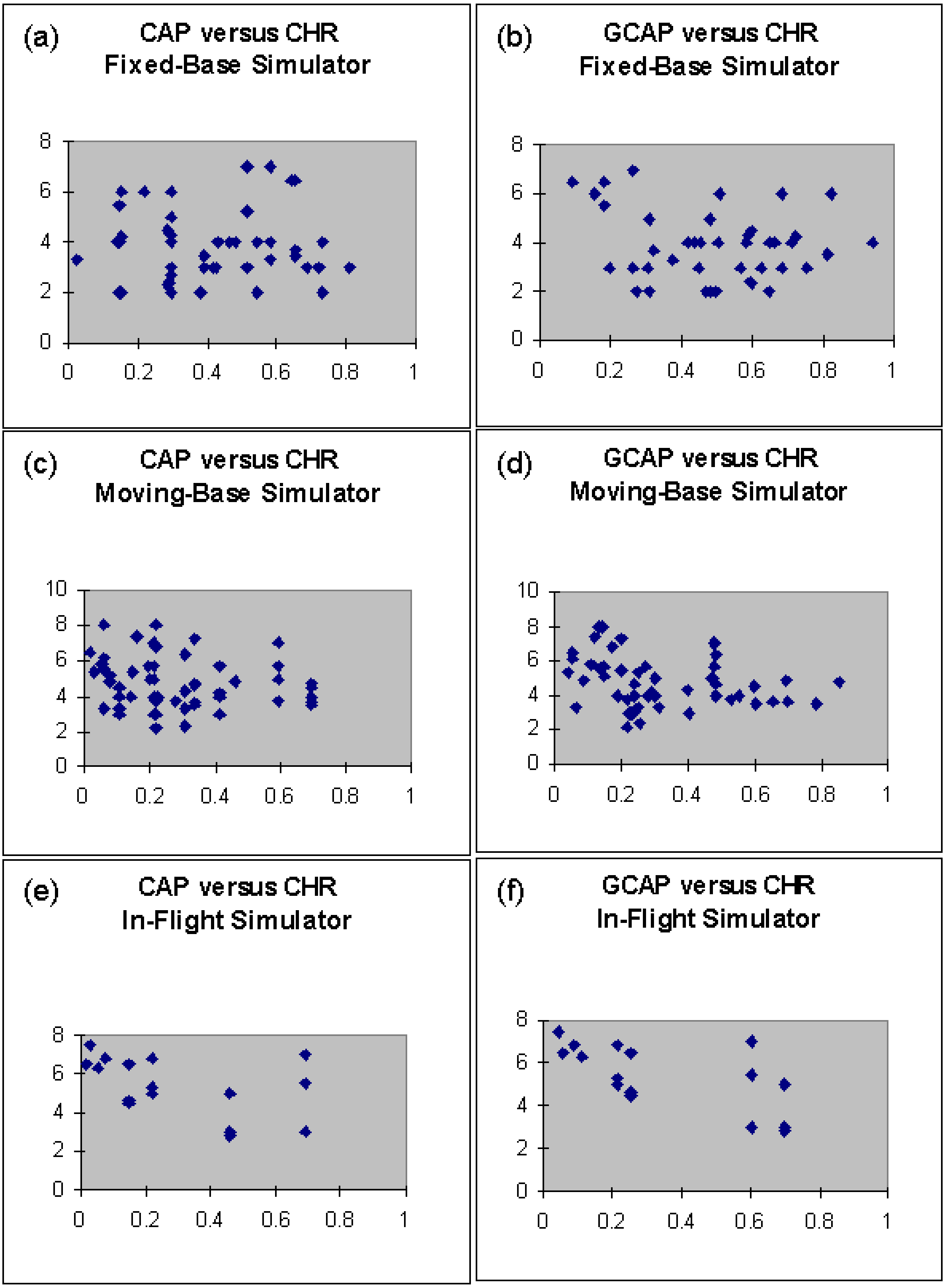

Figure 3 : Flying qualities criteria results for the past programmes analysis (with CHR on the vertical axis).