SOME LONGITUDINAL HANDLING QUALITIES DESIGN GUIDELINES
FOR ACTIVE CONTROL TECHNOLOGY TRANSPORT AIRCRAFT

by

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This report contains a summary of the main conclusions and recommendations from extensive work performed by the Flight Mechanics Action Group on Handling Qualities (FM/AG01) of the Group for Aeronautical Research and Technology in Europe (GARTEUR). The work of this Action Group, which involved cooperation between research institutes of France (ONERA), Germany (DLR), the United Kingdom (RAE), and the Netherlands (NLR), was performed with the ultimate aim to establish handling qualities guidelines for future transport aircraft with advanced flight control and display systems.

The work of the Action Group started in 1982 with the consultation of aircraft industries within the participating countries concerning their opinion on anticipated manual control aspects for future transport aircraft. The underlying report may be regarded as the overall result of the work performed on the basis of this consultation, which resulted in a number of handling qualities guidelines.
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1. INTRODUCTION

In an international cooperation between research institutes of France (ONERA), Germany (DLR), the United Kingdom (RAE), and the Netherlands (NLR), extensive work has been performed by the GARTEUR Flight Mechanics Action Group on Handling Qualities GARTEUR FM/AG01 with the aim to establish handling qualities guidelines for future transport aircraft with advanced flight control and display systems, see Refs 1 to 9.

To this purpose, the Action Group, which was set up in 1982, first investigated the anticipated manual control tasks and control concepts for such aircraft via a questionnaire to the European aerospace industry. It was subsequently decided to perform a comprehensive study at the NLR moving-base piloted flight simulator.

Emphasis was put on the implications of the change in longitudinal handling qualities when reverting from a sophisticated primary fly-by-wire (FBW) flight control system (FCS) to a simpler backup FBW system having different, but still good, characteristics. (Industry had commented that the handling qualities of a future backup FBW system would be as good as those of current aircraft.)

After a limited preparatory pilot assessment study had been performed at the ONERA Flight Mechanics Facility in 1985 and 1986, the comprehensive piloted simulation study took place at NLR in October 1987. Reference 8 reviews this experiment and sets out the results in detail, including specific conclusions and recommendations.

The present summary report concentrates on the handling qualities design guidelines and generic conclusions deduced from the overall work of the Action Group. Section 2 presents some general conclusions as well as the design guidelines themselves. Section 3 then presents some concluding remarks and recommendations for further work. For a good appreciation of the reasoning that led to the experiment on which these guidelines have been based, appendix A presents a historical overview of the study; it also outlines the experiment at NLR.
2. HANDLING QUALITIES DESIGN GUIDELINES

2.1 General

The work of GARTEUR FM/AG01 culminated in a comprehensive piloted simulation study on the moving-base simulator of NLR in October 1987. The purpose of the study was to establish a basis for handling qualities design guidelines for future active control technology (ACT) transport aircraft. An outline of the experiment is given in appendix A. Detailed results from this experiment have been reported in reference 8.

A summary of the main results deduced from the reported experiment follows, subdivided into some general experimental results in section 2.2, and the handling qualities design guidelines in section 2.3. Each generic result or guideline is introduced by a short description of the background that led to it.

2.2 Generic experimental results

With respect to the setup of the experiment, it was concluded from the expressed pilot opinions that it is a viable concept for future FBW transport aircraft to be equipped with a Head-up Display (HUD) and controlled by means of a sidestick. Also the philosophy of a primary longitudinal FCS as mechanized in the reported experiment was well accepted by the pilots. Therefore:

(a) A future fly-by-wire FCS for transport aircraft can satisfactorily be mechanized as flightpath rate command/flightpath angle hold with associated auto throttle and bank compensation features, be controlled by means of a sidestick, and be equipped with a HUD.

Pilots readily accepted the changeover characteristics from the primary system to the flare system below 100 ft and, apart from the loss of sophistication, the changeover to the backup system at FCS failure.
(b) The dynamic changeover from an FCS based on flightpath control to a pitch control mode at flare, or to a backup pitch control system at FCS failure, can satisfactorily be mechanized as in the reported experiment: fading from flightpath to pitch control mode at flare, and instantly freezing parameter values and switching to the backup mode at FCS failure, followed by fading from primary to backup signals.

Although force versus displacement characteristics for pitch and roll control with the sidestick were harmonized, the pilots complained about overall harmonization problems due to different response and display characteristics, and different levels of system sophistication.

(c) Harmonization between pitch and roll should include all aspects: sidestick, response and display characteristics, and system sophistication.

2.3 Guidelines

Future transport aircraft are likely to be equipped with fly-by-wire flight control systems with which pilots can directly control flight variables that are only controllable indirectly in most current aircraft. This means that the function of the controls is changed, and that the controlled parameter must be displayed to the pilot. Therefore, in such a situation the assessment of handling qualities of an aircraft/flight control system combination becomes inseparable from control and display characteristics. This leads to the following guideline:

**Guideline 1:** When assessing handling qualities, the complete system must be considered: including not only control laws, but also the characteristics of cockpit controls and displays.

The existing handling qualities criteria, which have been used here in the assessment of the various flight control systems, only consider the aircraft and control laws, without the characteristics of cockpit controls and displays. Therefore the following guideline emerges:
Guideline 2: When applying existing handling qualities criteria, be careful because they do not include the characteristics of cockpit controls and displays.

The existing longitudinal handling qualities criteria have been established for aircraft where the stick controls elevator or pitch rate, and in most cases are based on the pilot exercising inner-loop pitch control in order to obtain outerloop flightpath control. Although pitch attitude (or rate) remains a very important parameter for pilots judging the handling qualities of transport aircraft (e.g. passenger comfort considerations), such criteria are not directly applicable to flightpath control systems, even though they may appear to give valid measures of handling qualities levels.

Guideline 3: When applying any handling qualities criterion, care must be taken to ensure that its basis is compatible with the control system being studied. Specific criteria for flightpath control systems must be developed.

One of the investigated primary flight control systems featured discontinuities in the commanded flightpath angle when that was different from the actual flightpath angle at initiation of a longitudinal stick input. This was highlighted by the HUD and was disturbing with intentional inputs, but even more so when accidental cross-coupling from roll inputs occurred, especially in high turbulence.

Guideline 4: Flight control systems should not introduce step changes in demand if the pilot does not put in inputs of this type.

Ref. 8 proposes adaptations to the basis of ten existing longitudinal criteria, to make them applicable specifically to flightpath control systems. However, boundaries between handling qualities levels are only presented for one of these proposals.

Guideline 5: The adapted criteria presented in reference 8 should be applied to flightpath control systems. To ensure good handling qualities where handling qualities level boundaries are currently not available, care should be taken that the parameter values for such systems do not differ too much from
the data points for these adapted criteria in ref. 8.

Although the handling qualities of the backup systems were judged good by the pilots, the changeover at failure from the primary to the backup system was the main reason for the degraded handling qualities ratings for the backup systems. The pilots argued that the change in system sophistication was too big in the current experiment (especially mentioned were the loss of turn coordination and autothrottle functions, and the loss of the flightpath vector information in the HUD).

Guideline 6: If a primary FCS failure results in a changeover to a less sophisticated backup system, then the change in sophistication must be limited, as must changes in flight information displayed, to be acceptable to the pilots.

The study also addressed the simpler question of pilots' reaction to the change in basic handling characteristics on changeover to a different control mode, or backup system. Ref. 8 proposes that existing longitudinal criteria can provide the basis for measuring such changes in handling qualities. However, limits of acceptability have yet to be established.

Guideline 7: The measurement technique proposed in reference 8 should be applied to any sudden change in longitudinal FCS characteristics. To ensure good handling qualities, care should be taken that the magnitude of such a change is not substantially larger than indicated by the data points in ref. 8.

During the experiment, the pilots were frequently confronted with FCS failures, and hence were well trained to cope with the change in system sophistication. They were however worried about future day-to-day operation when failures only occur very rarely, and the pilots are likely to be less well trained. This leads to the following guideline:
Guideline 8: Crew training should highlight the consequences of the change in system sophistication at a failure in the primary FCS.

For the primary flight control systems under consideration, which were based on flightpath rate, an autothrottle was imperative. The pilot comments indicated that the autothrottle system used during the experiment was too slow. There are however no existing criteria for the design of autothrottles. Therefore:

Guideline 9: When use is made of an autothrottle, this system should be designed according to certain criteria (for which criteria should be developed).

3. CONCLUSIONS AND RECOMMENDATIONS

The GARTEUR Flight Mechanics Action Group on Handling Qualities started its work in 1982 with the ultimate aim to establish handling qualities design guidelines for future transport aircraft with advanced control and display systems. After extensive work, culminating in a comprehensive piloted evaluation study on the NLR moving-base flight simulator, the Action Group broadly succeeded in this aim but it is clear that further work is required.

The main conclusions of the work performed by the Action Group have resulted in the guidelines detailed in the previous section. Recommendations for further work evolve from the less than satisfactory characteristics of the lateral/directional FCS, and the loss of augmentation features and some HUD information at the moment of failure, which might have influenced the results of the reported longitudinal study:

a. With the present aircraft model and longitudinal flight control system, design an improved lateral/directional control system taking into account new control concepts which fully exploit the capabilities provided by the fly-by-wire technology. Assess them, in a piloted simulation, so as to establish a basis for low-speed lateral/directional handling qualities guidelines for transport aircraft. This study should include the effects of reversion to a backup system on failure.
b. Develop a full HUD format and associated head-down displays as an integrated part of the FCS for use with (a) above.

c. Return, following the above, to a further longitudinal handling qualities study including an improved autothrottle. This work would resolve some of the questions left unanswered by the present study. In particular a broader variation of system parameters would provide the basis for more well defined design guidelines.

Finally, it can be remarked that the Action Group considers the presented conclusions and guidelines the result of a fruitful cooperation between research institutes of the four European countries involved.
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APPENDIX A: HISTORICAL OVERVIEW OF THE STUDY

In 1982, an Exploratory Group of research representatives from aerospace institutions in the countries participating in CARTEUR (Group for Aeronautical Research and Technology in EUROpe), being France, Federal Republic of Germany, The Netherlands, and The United Kingdom, concluded that an Action Group was required to establish a basis for the handling qualities guidelines for future Active Control Technology (ACT) transport aircraft (Ref. 1). It was concluded, that the main objective for the recommended Action Group would be the buildup of handbook-type information on design flying qualities guidelines through systematic simulation research of a matrix of conceivable aircraft/flight control system characteristics including the possible failure states. The Group based this conclusion on the views and common interest areas concerning a number of topics within several organizations within the four nations which were inventoried in 1980 and 1981.

The necessary research subjects according to the Exploratory Group were:
1. Definition of piloting tasks, present and future.
2. Definition of workload levels and required performance levels.
4. Appraisal of analytical methods describing the pilot/aircraft system.
5. Demonstration procedures.
6. Evaluation of concepts for future ACT primary flight control.

Although most of the topics could be tackled by Research Establishments, the Exploratory Group strongly recommended that Industry be consulted and/or involved wherever possible.

The findings of this Exploratory Group, reported in reference 1, resulted in the establishment of an Action Group in 1982. The objective was to establish a basis for the handling qualities guidelines to be applied to future transport aircraft, particularly taking into account the influence of advanced flight control systems. The expression 'design guidelines' was chosen in accordance with the firm intent not to deal with certification criteria in the present studies.
The Terms of Reference for this Flight Mechanics Action Group on Handling Qualities of GARTEUR have been incorporated in an appendix A of reference 2. According to the Statement of Work of these Terms of Reference the work performed in the first year was aimed at the definition of present and future manual control piloting tasks (Task-1) on the one hand and the evaluation of available analytical methods describing the pilot/aircraft system (Task-2) on the other hand. Reference 2 can be considered as the formal report on Task-1 and Task-2. The information provided therein led to a recommendation for the execution of a comprehensive flight simulator programme aimed at the generation of handling qualities guidelines for future transport aircraft equipped with advanced flight control systems (Task-3).

With respect to Task-1, aircraft industries within the participating countries were approached with a questionnaire. From the responses to this questionnaire and from discussions held within the Action Group it was concluded that manual control will be performed only in a few flight phases: takeoff, (emergency) approach and landing, and go-around. The application of fully electrical primary flight control systems (with an electrical backup system) in transport aircraft is foreseen, allowing for aircraft designs with higher aerodynamic efficiency due to relaxed static stability. Improvement in handling qualities will be achieved by application of fly-by-wire flight control systems.

With respect to Task-2, it was concluded that within the participating institutes ample methods, mainly in the form of computer programs, are available for describing the pilot/aircraft system.

For the Task-3 investigation recommended in reference 2, it was decided to concentrate on the handling qualities during the terminal flight phases of a heavy transport aircraft with reduced longitudinal static stability and equipped with a fly-by-wire flight control system controlled by a sidestick. A prime topic would be operation with a backup flight control system, assuming failure of the primary flight control system. In particular, the investigation would study the implications of the change in handling qualities when reverting from a manual mode of a sophisticated primary FCS to a simpler backup system having different, but still good, characteristics. It was proposed to use the moving-base flight
simulator facility of the National Aerospace Laboratory (NLR) for this investigation. For future fly-by-wire transport aircraft, it was anticipated by the Action Group that, in the primary mode, the pilot would directly control the flightpath angle, whereas in backup mode he would revert to direct control over pitch angle.

Some concern was expressed by Industry that the results aimed at by the Action Group could possibly develop into additional requirements to be applied by the certifying authorities. However, the Action Group was convinced that the application of ACT brings with it such wide possibilities that useful, generally applicable, handling qualities guidelines will be necessary for the design of ACT transport aircraft, and could be generated as a result of the proposed flight simulator experiment (Task-3).

Initially, the recommended comprehensive simulator investigation was planned to take place in 1985. However, no flight simulator suitable for this investigation was available within the GARTEUR countries during 1985, so the Action Group made a new recommendation which was accepted by the Group of Responsables for Flight Mechanics of GARTEUR. This was that in 1985 a preparatory investigation should be performed at the ONERA flight mechanics facility, before undertaking the comprehensive simulation at NLR in 1986.

The purpose of this preparatory investigation, of which the Test Plan is detailed in reference 3, was to design and validate a harmonized primary flight control and display system for the later comprehensive investigation, by undertaking a limited pilot assessment. This preliminary investigation was performed in the fixed base simulation setup of the ONERA Flight Mechanics Laboratory. During the initial phase of this investigation, executed in 1985, one primary FCS layout was evaluated with various sets of gains. The results of this initial phase are presented in reference 4.

The pilot comments during the initial phase of the preliminary investigation, see reference 5, highlighted areas of the primary longitudinal flight control system that required some degree of redesign before the full study at NLR could be performed. Duly, the longitudinal system was redesigned during the summer of 1986. For the follow-on study, a backup longitudinal flight control system was also designed, as required for the NLR study. The modified primary (called
system A) and newly designed backup systems were exercised on the ONERA simulator during a shakedown phase in autumn 1986. The design work and simulator shakedown are fully described in reference 5.

For this shakedown phase, it had been decided to display the commanded flight-path angle to the pilot. This highlighted a fundamental problem because the mechanization of system A caused the locking and unlocking of the flightpath hold term. An alternative system (called system B) was designed to alleviate this possibly disliked feature. This system B provided a continuous method of implementing the flightpath hold. This required a somewhat more complex system, but retained similar basic principles and the same gains as system A. This additional design study and its shakedown at ONERA are also described in reference 5.

The above longitudinal flight control systems, two primary and one backup, were flown by evaluation pilots during the follow-on study at ONERA in early 1987. Apart from the pilot comments on the obvious limitations of the experiment, it was concluded (Ref. 5) that the objectives had been met, and that a sound basis had been established for the study at NLR. The conclusions and recommendations with respect to this study formed the background for much of the contents of the Test Plan for the comprehensive simulator experiment at NLR (Ref. 6). This Test Plan contains a detailed description of the aircraft to be simulated (incl. control and display systems, cockpit layout, and environmental conditions) and the way in which the investigation would be organized (checkout phase, evaluation phase, and data acquisition and analysis).

The relaxed longitudinal static stability aircraft was flown in the circuit through a sidestick, using both head-up and head-down displays including flightpath information. As noted above, the two alternative primary longitudinal flight control systems provided flightpath rate command with flightpath angle hold. Both smoothly changed to a pitch-rate mode for flare and landing. All these primary systems provided bank compensation and an autothrottle. On failure a step change to one of two possible pitch-rate backup systems occurred, and the flightpath display was removed. The backup systems had no bank-compensation or autothrottle. One lateral system, providing roll rate command with bank angle hold, was used throughout and did not change on failure.
The two primary longitudinal flight control systems and two backup systems (and hence four possible changeovers at FCS failure) were evaluated on the NLR movingbase flight simulator in October 1987. The data obtained from this comprehensive piloted simulation study, which involved 3-day evaluation periods for pilots from each of the four participating countries, are presented in reference 7, together with the changes relative to the Test Plan that were introduced during an initial checkout.

The results from the complete handling qualities investigation executed by the CARTEUR Flight Mechanics Action Group on Handling Qualities are discussed in the Final Report in reference 8. Preliminary results were presented on the AIAA Atmospheric Flight Mechanics Conference in Minneapolis, USA, in August 1988. This paper has also been published as reference 9. The final handling qualities guidelines and recommendations for further work are presented in the present report.