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AGARD

ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT
7 RUE ANCELLE 92200 NEUILLY SUR SEINE FRANCE

AGARD ADVISORY REPORT No.279

Handling Qualities of Unstable Highly Augmented Aircraft

(Les Caracteristiques de Manoeuvrabilité des Aér
Instables a Stabilitk Augmentee)

NORTH ATLANTIC TREATY ORGANIZATION

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Handling Qualities of Unstable Highly Augmented Aircraft

(Les Caractéristiques de Manoeuvrabilité des Aéronefs Instables à Stabilité Augmentée)

This Advisory Report was prepared at the request of the
AGARD Flight Mechanics Panel.

North Atlantic Treaty Organization
Organisation du Traite de l'Atlantique Nord

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Preface

The flying characteristics and handling qualities of **all** types of aircraft are major items of interest in the activities of the AGARD Flight Mechanics Panel. A subcommittee of the Panel has specifically addressed this subject over a long period and initiated a questionnaire several years ago to determine the ongoing research, future plans and the need for additional activities in the area of aircraft handling qualities. Responses from interested organizations and institutions in the AGARD community indicated that the Item “Handling Qualities of Unstable Highly Augmented Aircraft” showed the first priority In response to this interest, the Panel formed a Working Group, WG-17, in 1987, consisting of specialists from all interested AGARD countries, to study this specific handling qualities subject.

The aim of the working group, within the context of unstable highly augmented aircraft, was to:

1. Exchange information, experience and opinions
2. Analyze the existing handling qualities design and assessment criteria, and where possible, present new aspects and approaches to these criteria.
3. Identify gaps and shortcomings in the relevant database.
4. Discuss the effects of automatic flight envelope limiting.
5. Condense the experience of the WG members into a set of lessons learned and recommendations
6. Identify areas for relevant research and discuss potential opportunities for cooperation in the conduct of the needed research.

Five working sessions were held at places of special interest for the activities of the group within the years of 1987—1989 at Dornier, Friedrichshafen, Germany; British Aerospace, Warton, United Kingdom; NASA Ames Research Center, Mountain View, CA United States; Avions Marcel Dassault-Breguet Aviation, Flight Test Center Istres, France; Aeronautics Militare, Flight Test Center Pratica di Mare Italy.

The final report was a team effort and consists of contributions from all of the members of the working group. AGARD has been most fortunate in finding these competent people willing to contribute their knowledge and time **in** the preparation of this document.

Horst Wiinnenberg
Member, Flight Mechanics Panel
Chairman, AGARD Working Group 17

Préface

Les qualités de vol et les caracteristiques de manoeuvrabilité des aironefs de tous types sont des questions dune importance majeure pour le Panel AGARD de la Mécanique du Vol. Ce sujet a été examine par un sous-comité spécifique du Panel sur une longue période. Il y a quelques années, ce sous-comité a diffusé un questionnaire afin d'identifier les travaux de recherche en cours, les travaux projetés et les besoins complémentaires dans le domaine des caractéristiques de manoeuvrabilité des aironefs. Les réponses recues des différents organismes et établissements concernés faisant partie de la communauté AGARDienne indiquaient comme point prioritaire "Les caracteristiques de manoeuvrabilité des aéronefs instables à stabilité augmentie". Pour répondre a l'intérêt manifesté à ce sujet, le Panel a créé, en 1987,un groupe de travail, le WG- 17,compose de spécialistes de tousles pays membres de l'AGARD ayant exprimé un intérêt pour ce sujet, afin de l'étudier.

Le groupe de travail a eu pour mandat, dans le cadre des aéronefs instables a stahilite augmentie:

1. D'échanger des informations, de l'expérience et des avis.
2. Danalyser les caractiristiques de manoeuvre existantes, ainsi que les crithes actuellement employes, et, prbenter, dans la mesure du possible, les nouveaux aspects et les nouvelles approches de ces critères.
3. D'identifier les éventuelles lacunes et insuffisances de la base de données appropriée.
4. De discuter des effets de la limitation automatique du domaine de vol.
5. De faire la synthèse de l'expérience des membres du groupe de travail sous forme de recommandations et d'enseignements a retenir.
6. Didentifierles domaines prometteurs pour defuturs travaux de recherche et discuter des possibilités de cooperation pour ce qui concerne la conduite des travaux en question.

Cinq seances de travail furent organisées dans des localités ayant un intérêt particulier pour le groupe pendant la période 1987—1990, auprès des établissements suivants: Dornier, Friedrichshafen, Allemagne; British Aerospace, Warton, Royaume-Uni; NASA Ames Research Center, Mountain View, Etats-Unis; Avions Marcel Dassault-Breguet Aviation, Centre d'essais en Vol, Istres, France; Aeronautica Militare, Flight Test Centre, Pratica di Mare, Italie.

Le rapport final résulte dun travail diquipe et est constitué de contributions fournies par tous les membres du groupe de travail.

L'AGARD peut être fier d'avoir trouve des personnes compétentes, qui ont bien voulu accepter de partager leurs connaissances et de consacrer le temps nécessaire a la préparation de ce document.

Horst Wunnenberg
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HANDLING QUALITIES OF UNSTABLE HIGHLY AUGMENTED AIRCRAFT

SECTION 1

SUMMARY AND OVERVIEW

1.1 SUMMARY

Demanding requirements for performance and handling qualities together with extended flight envelopes lead to use of new technologies like active control and control configured unstable vehicles. The review of the handling qualities issues of unstable aircraft which by necessity are highly augmented is the theme of this report. In general the handling qualities criteria for highly augmented stable aircraft are equally applicable to the specialized case of unstable aircraft. Accordingly, this report contains a review of existing highly augmented aircraft, both stable and unstable. Handling qualities criteria for both large and small amplitude longitudinal maneuvers are presented. Other areas of Interest are also considered: basic aerodynamic design, specific issues relating to the feel system and control sensitivity, evaluation techniques and the handling qualities design and evaluation process. The subjects of carefree handling, lateral-directional criteria and agility are presented in separate appendices. Where possible the lessons to be learned from the combined experiences of the working group are highlighted.

1.2 OVERVIEW

This document is directed at the special problems of vehicles which are highly augmented because they are statically unstable longitudinally. Statically unstable aircraft are not new; for example the Wright Flyer was statically unstable and the pilot provided the control "augmentation". As knowledge of the balance between stability and control improved, aircraft were balanced stable to allow safe piloted control for demanding or protracted tasks. Why do we again today relax stability? "If the designer is permitted to ignore the customer requirement for natural weathercock stability in pitch and In yaw, he will be able to produce configurations with substantially increased performance" (Pinsker, 1979). With today's technology we now have the advantage of actuation, sensor and computing devices to augment, with full authority, the pilot's effort. Demanding requirements for performance and handling qualities together with extended flight envelopes lead to use of new technologies like active control and control configured unstable vehicles, Benefits of task-tailored handling, carefree handling and automatic functions and control modes outweigh penalties like larger actuators with high power consumption, high sensor performance, redundant controls and demanding computer speed and capacity requirements.

Handling Qualities of these highly augmented vehicles are largely the designer's choice; however, the effects of any increased flight control system complexity on handling qualities should be transparent to the pilot. That is, the pilot should not be required to employ any control techniques that are unnatural or require special training. it should, therefore, not be necessary to distinguish between stable and unstable aircraft or even whether the aircraft is highly augmented, when specifying flying qualities. The stability of the basic design is immaterial to the pilot, who rightly expects low workload in an aircraft with full authority hardware and software.

Our Interest is, therefore, centered on **design** guidelines for good handling qualities in highly augmented aircraft because instability necessarily leads to high degrees of augmentation. Further, given the increased capability of modern electronic flight systems, the design goal for these "control-configured" aircraft should be "optimum" or desired handling qualities - in the heart of the Level 1 region.

Unlike the classic highly augmented aircraft, the handling qualities of the unstable highly augmented aircraft cannot degrade after failures to those of the basic aircraft. Instead, when failures occur the handling qualities do not change appreciably but the level of "protection" in the form of failure tolerance is reduced. For example, the X-29 technology demonstrator is highly unstable. With times to double amplitude in pitch of about 0.15 sec., it cannot be controlled by a pilot without augmentation. Following failures in its digital system, (either the system logic or the pilot can select alternate redundant sensors or the analog reversion system, with virtually no flying qualities degradation. As another example, the EAP aircraft has a core quadruplex system sensing rate and acceleration. Its angle of attack (AOA) sensing is only triplex, so after an AOA failure the pilot must respect additional flight limits, but still has good core flying qualities.

The purpose of this report is to present methods and criteria which have been found to be useful by members of this working group as design guides and for the evaluation of handling qualities of highly augmented aircraft. It is the unanimous opinion of the members that no one method or criterion is adequate by itself, and that several, or even all of the recommended criteria should be checked. Experience has shown that one metric may not show a deficiency that will be exposed by other criteria. Alternatively, a configuration that passes several of the proposed criteria has a high probability of being accepted as desirable by most pilots.

Criteria are presented for small and large amplitude maneuvering since it is important to account for both these aspects. In the latter case, nonlinear effects may be encountered which degrade the handling qualities (e.g. servo actuator rate limiting). Such degradations often occur as abrupt changes in the aircraft response, sometimes referred to as "handling qualities cliffs". The infamous Shuttle Pilot-Induced Oscillation (PIO) is an example of such a case.

The reader should be aware that there are several objectives that the working group specifically did not accomplish. First, we were specifically directed not to attempt to formulate an "AGARD Handling Qualities Specification". Detailed data correlations are not included in this report, as such correlations are contained in the references, and the collection, analysis, and codification of such data would be beyond the scope of this effort.

The term highly augmented appoars throughout the report. It is intended to refer to augmented aircraft which have significantly alterecl response characteristics compared to the same aircraft without augmentation. In control system jargon, this means that the loop gains are sufficiently high *so* that the closed loop poles are significantly different from the open loop poles. Of course, unstable aircraft which are augmented to be stable always fail into this classification.

The report is organized in a series of major sections in which the principal themes of this working group are presented followed by appendices in which important supporting informatiori and other areas of interest to this working group are reviewed. Details of the report organization are as follows:

- A review of existing highly augmented aircraft (stable and unstable) is given in Section 2.
- A unified method to match the shape of the response properly (i.e. type of augmentation) with the required mission tasks is presenled in Section 3. This section also contains some guidance on the proper choice of criteria for different response types.
- Handling qualities criteria recommended by the working group members are contained in Sections **4** (longitudinal small amplitude) and 5 (iongitudinal large amplitude).
- Considerations for the basic design of highly unstable airframes are presented in Section **6.**
- There is growing evidence that feel systems must be treated as a separate entity, i.e., not as an integral part of the augmented airplane. This is covered in Section 7 along with the important issue of control sensitivity. It is important to note that none of the criteria in this report include the effect of control sensitivity, and that it must be separately optimized.
- Evaluation techniques utilized in simulation, both ground-based and in-flight, and flight test are discussed in Section ***8.***
- The general handling qualities design and evaluation process is reviewed in Section **9** with particular emphasis on the important non-technical issues.
- The conclusions and recommendations of the working group members are presented in Section 10.
- An overview of the important subject of envelope limiting and carefree handling is presenled in Appendix A.
- Although the instabilities of interest are generally in the pitch axis, for completeness lateral-directional handling qualities are reviewed in Appendix B.
- Since agility and handling qualities are closely related subjects with considerable overlap, this subject was of particular interest within the working group. In fact, it may be argued that Ihe non-performance related aspects of agility are essentially handling qualities. This interesting subject is briefly discussed in Appendix C.

SECTION 2

A REVIEW OF THE DESIGN AND HANDLING QUALITIES OF HIGHLY AUGMENTED AIRCRAFT

2.1 INTRODUCTION

Modern flight control system designs use digital or analog computation techniques in combination with their advanced "fly-by-wire" technology to gain potential advantages such as improved mission performance and weight/cost reduction. With full-authority electronic augmentation systems, the designer literally has the capability to tailor the flying qualities of the aircraft as desired for each mission task. Typically, these advanced designs are complex and are characterized by "higher order" responses to the pilot's inputs. In many instances these additional control system dynamics, or higher order effects, which delay the initial response, created new flying qualities problems in the process of solving the old ones. For example, see References 2.1.1 to 2.1.4.

Early aircraft with advanced electronic flight control designs such as the Space Shuttle, F-16, YF-17, F-18 and Tornado exhibited significant flying problems during their development phases. Later aircraft such as the Rafale, the Mirage 2000, the EAP, and the X-29, for example, apparently incorporated advanced electronic flight control systems successfully and achieved satisfactory flying qualities. However, the recent unfortunate crash of the JAS 39 Gripen served notice that all the problems of advanced flight control design and development are still not totally understood.

Unstable aircraft are, by their nature, typically highly augmented and the problems exposed during the design and test of highly augmented more conventional aircraft are therefore important. The purpose of this section is to review briefly the design and flying qualities of several highly augmented aircraft with particular attention on those aircraft with inherent pitch instability.

2.1.1 References

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2.2 X-29 TECHNOLOGY DEMONSTRATOR

2.2.1 Aircraft Description

The X-29 is an interesting combination of integrated technologies which include extreme longitudinal instability and a forward-swept wing. A general description of the aircraft and the major flight test issues related to this unique aircraft are given in Reference 2.2.1. More detailed descriptions of the design concepts and the flight control system are given in References 2.2.2, 2.2.3, and 2.2.4.

The aircraft is nominally 35% unstable at subsonic speeds and is neutral to slightly stable at supersonic speeds. This level of instability translates into a worst-case time to double amplitude in pitch of approximately 0.15 sec - an unprecedented level of instability for a manned aircraft. Operation of the aircraft is therefore dependent on a sophisticated full-authority fly-by-wire flight control system. The flight control system consists of a three-channel synchronous system with three digital flight computers and an analog back up system using three analog computers. Dominant flight control parameters are sampled 40 times per second in the primary digital computers.

Control of the extreme instability made special demands on the X-29 flight control system design. For example, extensive lead compensation, high canard surface displacement and rate capability (about 100 deg/sec) were required. Traditional flight control system stability margins had to be halved to 3 db high-frequency gain margin and 22.5 degrees phase margin. Following one small gain change during the flight test program, the flight control system performed satisfactorily throughout the flight envelope with these reduced stability margins. It must be emphasized, however, that these reduced margins were allowable for the flight test of this unique technology demonstrator for which real time monitoring of the system performances was used on every flight.

2.2.2 Flight Control System Strategies

The primary digital flight control system is relatively complex: for example, the complete pitch control system is 48th order. Considering only the major features, the pitch control system reduces to about a 9th order system. The design strategies, simply stated, produced a rate command/attitude hold system for approach and landing: for the up-and away conditions, the flight control system was a "g" command system. For the landing case modest speed stability was provided. Technically, the up-and-away system used pitch rate, derived pitch acceleration and normal acceleration to produce a flight path rate command system. Suitable forward path gain scheduling with airspeed was used to produce a constant value of stick force per g.

2.2.3 Flying Qualities Summary

In general, the extreme pitch instability was transparent to the pilot. No significant flying qualities problems were found in the X-29 during flight test. Several changes were made to the flight control system, however, during the initial program in an attempt to achieve desired or "optimum" pitch flying qualities.

A significant feature of the X-29 flight control design is that the flying qualities in the pitch axis remain essentially constant after key sensor failures. The only change produced by these failures is in the level of redundancy within the flight control system. For example, X-29 pitch stability is achieved using pitch rate feedback from a set of 3 primary and 3 secondary gyros. Up to 4 failures can be tolerated without degradation in the longitudinal stability or flying qualities. An additional failure causes loss of the aircraft.

Lateral flying qualities were good to excellent (Level 1) throughout the development test phase and will not be reviewed in any detail since the unstable longitudinal axis is the primary focus of this report. The only significant change during the program was to increase the maximum roll rate to fighter values. One interesting feature of the X-29 flight control system is the relatively large equivalent time delay present in both pitch and roll axes. The original control system time delays measured from a stick force input were: pitch ~180 millisec and roll ~230 millisec. A large contributor to these delays was the relatively slow feel system design. The second-order feel system had a natural frequency of 18 rad/sec in pitch and 13 rad/sec in roll. Equivalent time delay contributions from the feel system were approximately 80 millisec and 100 millisec repectively. The good lateral flying qualities achieved despite the large equivalent time delay are inconsistent with expectations based on the Military Specifications and previous flying qualities evidence. This apparent anomaly is discussed further in Section 7 and reviewed in References 2.2.5 and 2.2.6.

The longitudinal flight control system evolution (Reference 2.2.7) involved three significant changes which directly affected up-and-away flying qualities:

1.) Original System
The pitch flying qualities were judged to be level 2 (PR~5) because of sluggish initial response and large stick throws (~10 inches total). Control harmony was a problem because of the more responsive roll axis.

2.) Stick Modification
The longitudinal stick throw was reduced by half and the stick force gradient in the feel system was changed to 8 lb/inch from 4 lb/inch. Stick force per g was held constant by appropriate forward path gain changes. Equivalent time delay was reduced by 30 millisec with the increase in feel system natural frequency to ~ 26 rad/sec.
Flying qualities improved to level 1 to 2 (PR ~ 3 to 4). Slow initial pitch response was still a minor deficiency.

3.) Initial Response Improvement
The initial pitch acceleration was increased by a factor of two using a design method based on the Neal-Smith Criterion (Reference 2.2.9). This change to the-flight control system (Reference 2.2.8) was accomplished without disturbing the control system inner loops. Pitch flying qualities were noticeably improved and in the desired area (PR~2). Control harmony was good and the aircraft was a solid Level 1. Pilot ratings of 1 to 2 were achieved.

Approach and landing flying qualities were typically judged to be Level 1 to 2 (PR - 3 to 4) and no design effort was made in this area. The only change made during the program was to include a modest increment of speed stability at the typical approach and landing speeds.

2.2.4 Some Lessons To Be Learned

A complete review of the X-29 program including the second phase directed at high angle of attack using the #2 aircraft is given in Reference 2.2.10. Some of the important lessons to be learned from this program are:

- For highly unstable aircraft, which are by nature necessarily highly augmentd, the overall "health" of the aircraft is best judged by the stability of the flight control system. For the X-29 program a real-time capability was developed to evaluate key flight control stability measures. This flight test technique allowed for an efficient envelope expansion process and ensured aircraft safety.
- During the development phase of a highly-unstable, control-configured aircraft such as the X-29, the flight control verification and validation process never stopped. Potentially disastrous single-point failure paths and basic flight control design flaws were exposed after over 100 flights had been flown.
- Vigorous testing of the flight control system in the ground simulator is essential to the safety of the flight test program. This process must include large amplitude inputs which may be unrealistic from a normal flight perspective, but are potentially representative of off nominal high stress tasks in the aircraft. This type of agressive testing is particularly important if the flight control design contains non-linear elements such as rate limiters.

2.2.5 Summary Comments

Despite an extreme instability in pitch and a relatively complex flight control system design, the X-29 proved to be a pleasant and easy aircraft to fly. Modifications to the flight control system were made to achieve "desired" (PR - 2) fighter flying qualities and not because of any significant problems. The extreme instability necessitated a relaxation of the typical flight control design stability margins but this compromise did not adversely affect the flight control system or the flying qualities.

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2.3 FLY-BY-WIRE JAGUAR, EAP AND EFA

This section reviews the development of the FBW Jaguar, the Experimental Aircraft Program (EAP) and the European Fighter Aircraft (EFA).

2.3.1 Flight Control Law Review

The pitch control laws of the FBW Jaguar, EAP and EFA are ail based on a core integral pitch rate demand digital quadruplex flight control system (FCS) with no alternative reversion system. For normal operation, enhanced modes are used to provide optimum task oriented handling. On the FBW Jaguar this took the form of a pitch rate and angle of attack demand system, whereas on the EAP and EFA the demand mode remains pitch rate for near-steady flight, but changes progressively to normal acceleration or angle of attack as the appropriate limits are reached. The latter retain the integrator path to obtain very close control of these limits. These modes are optimized for system stability and disturbance rejection, while piloted handling qualities are optimized by command prefiltering defined by different criteria. The lateral directional ones use conventional non-Integral roll rate demancl and yaw rate plus sideslip augmentation, again using roll command prefiltering for response optimization. The overall effect of this design approach is to achieve an extremely high level of attitude stability coupled with highly responsive control in both the pitch and roll axes.

2.3.2 Instability

The control law techniques were developed for the initially stable FBW Jaguar in a series of increasingly unstable configurations, achieved by aft ballast and large wing root strake extensions. The maximum Instability level gave a time to double amplitude of 0.25 seconds. The necessity 'lo ensure sufficient stability margins in tho presence of aerodynamic uncertainties led to the concept of margin robustness by specification of simultaneous gain and phase margin boundary areas rather than unique points (see Section 6).

The EAP is substantially more unstable with 0.18 seconds to double amplitude in the worst case, and EFA will be generally similar. Practical instability limits are associated with the need to accommodate a very wide range of stores with significant effect on stability, and with the use of sufficient integrator gain to ensure that structural limits are not transiently exceeded.

2.3.3 FCS Complexity

The same basic pitch control law structure has proved to be very satisfactory for all these examples; that is the classical proportional plus integral demand error feed-forward with the addition of phase advance filtering to maximize stability margins. Optimal design methods continue to be considered, but standard classical methods have proven to be entirely adequate even for the dual pitch control surfaces of EAP/EFA. Successful positive maneuver limiting was achieved on FBW Jaguar by a combined pitch rate/angle of attack demand mode, but this experience led to the use of separate, parallel demand modes on EAP/EFA in pitch rate, angle of attack and normal g. These are blended from one to another as a function of stick cornmand amplitude and flight condition to achieve the desired handling and carefree limiting functions, and each has the same dynamic response and stability margin characteristics.

The other feature which has remained unchanged is the use of command path filtering to optimize the piloted handling qualities. Already used in a simple form on Tornado, this was initiated before first flight of the FBW Jaguar to overcome the sluggish flight path response characteristic of a high gain rate command/attitude hold systern. It has been developed further on EAP to encompass task-tailored and gross maneuver responses, maintaining uniform behavior through aerodynamic non-iinearities and fast response with no overshoot of structural limits. Being outside the feedback closed loop path, there are no constraints imposed by stability margin or other closed loop problem areas other than avoidance of saturation effects. The resulting filter is in general more complex than the basically rather simple stability augmentation loops. Despite the major design effort required, the results fully justify the additional work.

2.3.4 General Handling Comments

The control law structure described above provides a combination of high and well damped attitude stability, precise small amplitude and rapid large amplitude control, and excellent disturbance rejection. The ability to tailor all aspects of the handling, requiring the application of many alternative design criteria, enables the achievement of light, responsive handling with good sensitivity, complete freedom from PIO, and accurate and comprehensive limiting for carefree handling.

2.3.5 Development and Lessons To Be Learned

Although these techniques and associated criteria have evolved gradually and increased their scope, no major change has been necessary in principle. The principal lessons to be learned are as follows:

- In addition to conventional small-perturbation linearized analysis of whatever methodology, it is absolutely essential to employ complete, non-linear and dynamically very accurate models in both computer and flight simulation and to exercise them in an extreme manner to uncover all possible consequences of saturation effects, as these may be catastrophic.
- As a corollary of the first lesson, it is essential to maintain a total engineering grasp of all the contributing factors to each response characteristic, and never to leave unexplained any facet of the handling behavior.

2.4 MIRAGE 2000 AND RAFALE A DEMONSTRATOR

2.4.1 Mirage 2000 Control Laws

The flight control system of the Mirage 2000 is designed and built by AMD-BA (Avions Marcel Dassault-Breguet Aviation). The maiden flight of the first prototype occurred on March 10, 1978. Main features of the Mirage 2000 FCS are as follows:

- Full authority on all surfaces. No mechanical backup.
- Quadruplex analog redundancy for each critical element.
- High performance actuators.
- Controls: 4 elevons, 1 rudder, 2 leading edge slats,
  2 air-intake adaptation devices
- Main functions implemented:
    - Aerodynamic configuration optimization
    - Air-intakes adaptation
    - Longitudinal and lateral stabilization
    - Longitudinal and lateral command shaping
    - Automatic protection against loss of control (spin departure)
    - Automatic protection against excessive structural loads (excessive normal load factor)

2.4.2 Rafale A Demonstrator

The flight control system of the Rafale is designed and built by AMD-BA. The maiden flight of the Rafale A Demonstrator occurred on July 4, 1986. Main features of the Rafale A Demonstrator are as follows:

- Full authority on all surfaces and engines.
  No mechanical back-up.
- Digital processing (large data processing capability)
- Quadruplex redundancy for each critical element.
- Data processing: 3 digital channels, 1 analog back-up channel
- Automatic reconfiguration independence with the level of integrity of the different subsets (sensors, processor, actuators)
- High performance actuators
- Controls: 6 elevons, 1 rudder, 2 canards, 6 leading edge slats, 2 air brakes, 2 engines
- Main functions implemented
    - Automatic aerodynamic configuration optimization
    - Longitudinal and lateral stabilization
    - Longitudinal and lateral command shaping
    - Velocity stabilization
    - Damping of on-ground modes (on "gear modes")
    - Automatic protection against loss of control (spin departure)
    - Automatic protection against excessive structural loads (excessive normal load factor)

2.4.3 Instability Limitations

For combat aircraft there is no practical limitation in longitudinal (or lateral) instability for any reason such as handling qualities or technological constraints. Both the Mirage 2000 and the Rafale are statically unstable subsonically. For the Rafale the time to double amplitude is on the order of 400 millisec. So, the amount of instability may be considered as a consequence of the aircraft optimization for its specific missions. (See References 2.4.1 and 2.4.2.)

2.4.4 Connections Between Different Design Aspects

It must be kept in mind that the FCS has to be optimized not only for handling quality considerations, but also in close correlation with:

- Structural design
- Human pilot physical tolerance (loss of consciousness)
- Air intakes and engine tolerance

(See References 2.4.3, 2.4.4, 2.4.5 and 2.4.7.)

2.4.5 Mirage 2000 Experiment

The nature of FBW systems (especially digital ones with their very flexible software) causes the augmentation functions of the aircraft to change and evolve very rapidly with significant improvements in capability and in performance. Some pilot demands are met satisfactorily, however, the changes bring potential for new demands to light. In this dynamic situation, flying qualities criteria have to be adapted rapidly as well. (See References 2.4.2, 2.4.3 and 2.4.7.)

To illustrate the previous statement, flight test development of the Mirage 2000 flight control system revealed that:

- Traditional handling qualities requirements were easily met.
- Pilots quickly expanded their demands to include total carefree handling.
- The latter demands have been met in three successive steps with progressive refinements as follows:

  Step 1 - Implementation of an automatic flight envelope limiter (angle of attack envelope and load factor envelope).

  Step 2 - Splitting of the previously defined flight envelope into two flight envelopes:
    - The limit envelope: the pilot is entitled to go beyond the envelope limits in case of emergency (to avoid crashing for instance), the outcome of which could be some permanent structural distortions.
    - The ultimate envelope: Exceeding the envelope limits would involve the loss of aircraft.

In terms of the man-machine interface, the limit envelope is implemented on the stick using a so-called "elastic stop". This stop can be overcome by the voluntary action of the pilot. The ultimate envelope is then implemented by the mechanical unexceedable stop.

Step 3 - Adaptation of the flight envelope according to the actual configuration of external stores using manual pilot selection.

(See References 2.4.2, 2.4.3, and 2.4.4.)

2.4.6 Actuator Management

The modern combat aircraft - especially the Rafale - has many surfaces available for each function (stabilization, dynamic behavior adaptation under pilot control, etc. for both longitudinal, lateral and combined functions) and each actuator shares its authority between several functions. Therefore, there are two complementary kinds of problems to be solved:

- First, the "optional" use by each function of the different available surfaces. The main goals are then: efficiency, (i.e. economy of aggregate surface motion), appropriate decoupling (when requested), and continuity of effects (i.e. optimizing transients during mode changes).
- Second, the appropriate allocation of the total authority of each surface to the different functions. In case of conflict, it is absolutely necessary to have a hierarchical priority management and to provide the essential functions with sufficient authority.

The priority management has to cope with all inputs, whether they be from large pilot commands, atmospheric disturbances or combinations of these inputs. (See References 2.4.6 and 2.4.7.)

2.4.7 Robustness

Robustness, an essential quality of a flight control system, compromises between the necessity for tolerating many configurations (mainly external stores) and hardware and software complexity. (See Reference 2.4.7).

2.4.8 Role of Simulation

Practical experience in FCS development shows that many FCS evolutions arise from improved knowledge of the "natural" (unaugmented) aircraft aerodynamics. Therefore:

- Models used have to be as accurate as possible.
- Non-linear effects have to be taken into account.
- Appropriate simulation tools (both non-real time and real time) must be available
- The use of linear techniques (including frequency domain techniques and pole placement techniques) is limited to the very initial phases of the FCS development.

2.4.9 "On the Limits" Handling Qualities Development

When a high augmentation system is implemented, the handling qualities criteria problem is strongly pushed away to the on limits conditions. In fact, "classical" piloting problems are resolved by:

- Aerodynamic peculiarities being smoothed out by FCS modifications
- Stability
- Uncoupled control
- Respect of behavior in the time-domain standards

In these conditions, piloting problems mainly deal with the edge of the envelope: small amplitude piloting conditions near the edge of the envelope, and large amplitude piloting conditions from and to the envelope edges. Developing FCS for satisfactory operation then implies that:

- Models are satisfactory in these limit conditions.
- Non-iinear methods and tools are operated.
- Criteria are expressed in the time domain
- Simulation (non-real time and real time) is extensively used

2.4.10 References

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2.5 TORNADO

2.5.1 Tornado Command and Stability Augmentation System (CSAS)

The Tornado was designed to be stable in both pitch and the lateral/directional axes. However, the stability is marginal and the aircraft has generally Level 2 to 3 Handling Qualities (HQ) when flown in the mechanical mode: this is the second backup mode. From the beginning, the Tornado was designed to be flown with a full time, full authority Control and Stablity Augmentation System (CSAS). The CSAS is triple redundant analog with a direct electrical link as the first back-up mode and mechanical drive as the second backup.

For the pitch CSAS the stick position is sensed via a non- linear gearing and the output signal, interpreted as a pitch rate command feeds:

- The Maneuver Demand (MD) loop of the normal mode via a stick path filter and a stick gain scheduler.
- The direct electrical link (In normal operations the direct link is blocked)
- Lateral/Directional CSAS for compensation as required.

The pitch command signal to the MD loop is filtered and scheduled as a function of dynamic pressure. The feed-back signal is sensed by a rate gyro unit and passed through a noise filter and then shaped in the main control and phase-advance filters before it is summed with the stick command signal. The error signal so produced is transmitted to the taileron actuator servo via a further dynamic pressure dependent gain and a structural notch filter. Signals derived from airbrake and flap position sensors are summed in to compensate for moments produced by these devices. Limiters are used to prevent Saturation of the taileron actuators and to ensure Sufficient actuator travel remains to accommodate a simultaneous roll command. This feature was incorporated in the design following a flight incident in which a combined pitch and roll PIO developed because the taileron actuators ran to their limit at slightly different rates, inducing an uncommanded rolling motion which the pilot was not able to correct due to a lack of excess actuator authority.

In the roll axis, roll rate is commanded by the pilot's stick position. The command signal follows two paths:

- The manoeuvre demand (MD) loop via a stick gain scheduler and a stick path filter.
- The Roll Direct Link which in full CSAS mode operates in addition to the MD loop. In the case of a second failure in the MD loop, the MD loop is faded out while the direct link remains operative.

In the MD, loop roll rate is sensed by a rate gyro unit and routed through a Structural filter and a noise filter before it is summed with the stick command signal. The error signal is then fed to the taileron and spoiler actuator servos via a phase advance filter with a dynamic pressure dependent gain. The roll CSAS also provides roll to yaw cross-feeds.

2.5.2 Handling Qualities

During the development phase of the Tornado aircraft a pitch PIO problem was uncovered during the landing phase after considerable flight test hours. The source of this problem was traced to excessive time delay in the form of phase lag in the pitch axis. Modification of the pitch filtering solved the problem. As noted, this problem did not surface during Initial testing but came to light under a special combination of conditions and pilot inputs. This situation again emphasizes the need for constant vigilance and for vigorous initial tests which include large and perhaps non-optimum pilot inputs.

The latest development version of the CSAS described provides basically Level 1 handling qualities throughout the operational flight envelope of the Tornado. However, because of hardware constraints some PIO tendencies remain at low to medium speeds for high gain tasks requiring large and rapid pilot inputs. These tendencies were discovered during flight test and were not apparent during the development process. The PIO tendencies as well as other instabilities discovered during flight test were mainly caused by rate and acceleration limits in the system which caused excessive phase lag for abrupt medium to large inputs.

This experience stresses that during the development of fly-by-wire aircraft a thorough evaluation and simulation has to be accomplished. It is important that the process must account for all rate limits and non-linearities in the system and their effects for large inputs in all axes, singly and in combination. This procedure has not normally been considered realistic, but the lessons of the Tornado Indicate the requirement for these tests.

2.6 F-16 (YF-16)

2.6.1 Aircraft Description

The F-16 has evolved since its first flight in February 1974 as the YF-16 lighweight fighter prototype into an Impressive and versatile fighter aircraft. The purpose of this brief review is to present details relevant to the theme of this report. A review of the design details of the YF-16 is presented in Reference 2.6.1.

The F-16 utilizes a full-authority, fly-by-wire flight control system featuring a sidestick controller. A quadruple redundant analog flight control system design strategy was used until the development of a digital version of this system in recent F-16C models. The basic airframe is slightly unstable subsonically with a time to double amplitude in pitch on the order of 1.5 secs. in the worst flight condition. it is interesting to note that one of the advantages of this relaxed static stability - smaller tail size - was removed when a larger tail was incorporated in the early F-16A production models. The larger tail was incorporated primarily to improve the aircraft departure resistance and recovery at high angles of attack.

In summary, the F-16 represented a somewhat daring advance in the fighter aircraft evolution process. Eventually the side stick, the relatively simple advanced fly-by-wire flight control system design and the unstable airframe merged effectively to create an outstanding fighter aircraft. References 2.6.2 and 2.6.3 provide some background to F-16 FCS evaluations.

2.6.2 Development Review

Perhaps not surprisingly, considering the pioneering nature of the F-16 program, the development phase had some significant problems which provide suitable lessons for the future. On the first high speed taxi test of the YF-16. the pilot inadvertantiy became airborne and experienced a severe lateral PIO. He wisely decided to fly out of the unexpected problem and made the unscheduled first flight of the program. This spectacular event is well documented in Reference 2.6.4. As a result of this near catastrophic flight, the lateral gains for small inputs were reduced by a significant factor.

The original design for the side stick was a fixed no-motion stick. Ultimately, the stick was revised to include a small degree of movement in both the pitch and roll axis. Although this change in stick characteristics was not as significant as the large lateral gain reduction, the Inclusion of limited motion resulted in an improvement in handling qualities, particularly In the landing phase. Reference 2.6.5 substantiates the need for some motion in the sidestick and does, in fact, recommend more motion than presently incorporated into the F-16 design. A discussion of the Importance of controller feel system characteristics is presented in Section 7.

2.6.3 Lessons To Be Learned

The major lesson to be drawn from the YF-16 development experience is centered on the “first flight” lateral PIO problem. Clearly, the lateral gains were much too high. Since the design involved a novel side-stick control, previous design experience was not available for reference. Accordingly, the ground simulator was used as a design tool - the gains were selected on the basis of evaluations In a simulator which could not replicate the real world accelerations or visual scene.

Simply staled, the lesson is: do not use ground Simulators to tune up the responsiveness of the aircraft. The resulting gains will be too high in flight. If there are no available design guidelines then design on the conservative side and provide the flexibility in the initial flight control design to change the key gains easily. Recent examples, such as the JAS-39 Gripen indicate that this lesson is not completely understood.

2.6.4 References

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2.7 F-18 (YF-17)

2.7.1 Aircraft Description

The present F-18 fighter aircraft is an outgrowth of the YF-17 lightweight fighter prototype which was a competitor against the YF-16 and eventually the loser in the lightweight fighter competition. The YF-17 which first flew in 1974 was a highly augmented aircraft which utilized a full-authority analog CAS design operating with a conventional mechanical control system.

The F-18, on the other hand, used an advanced (for its time) quadruple redundant digital flight control design with a mechanical backup mode for emergency pitch and roll control. This F-18 design, which represented an extensive modification to the original YF-17, was highly augmented but the basic airframe retained static stability throughout its flight envelope. For example, the pitch rate response to pilot stick force was over 50th order. More details of the F-18 flight control design and the pre-first flight evaluations in the NT-33 in-flight simulator are given in Reference 2.7.1. Although neither of these aircraft were unstable, the development process for each aircraft provides several interesting lessons for review.

2.7.2 YF-17 Development Review

The original YF-17 design used a prefilter model technique in the pitch axis and was developed using a shophisticated ground simulator. Prior to first flight the approach and landing flying qualities were evaluated on the NT-33 variable stability aircraft. This evaluation showed that the pitch flying qualities were very poor - "cliff like" degradations in the form of a large pitch PIO occurred near touchdown. The large equivalent time delay introduced by the low frequency prefilter was the source of the problem. Revising the design to reduce the time delay significantly produced a solid Level 1 aircraft. The details of the YF-17 evaluation and an analysis of the flying qualities using the Neal-Smith criterion are presented in Reference 2.7.2 and discussed further In subsection 4.5.4. in its final form, the YF-17 was an excellent aircraft from a flying qualities perspective.

2.7.3 F-18 Development Review

The F-18, which first flew in 1979, represented a major revision of the YF-17 to meet Navy requirements. A major feature of this revision was the incorporation of the quad digital fly-by-wire control system which retained a mechanical reversion mode for emergency pitch and roll control. The FCS design features were a relatively complex design (over 50th order in pitch power approach mode, for example) and, unfortunately, considerable equivalent time delay. Despite the use of in-flight simulation to evaluate the power approach flying qualities, the F-18 emerged from its development process with less than adequate handling qualities. The final in-flight simulations were used in the main to evaluate the sensitivity of the design to time delay and to evaluate overall safety aspects. Some of the details of this evaluation are reported in Reference 2.7.1.

The initial versions of the F-18 were characterized by an abrupt PiO-prone lateral response both during in-flight tasks such as refueling and carrier landings. Pitch response was sometimes unpredictable with a tendency to PIO evident in tight tests. After several major revisions to the FCS design, including switching from force to position commands, the F-18 emerged as an excellent flying aircraft. It is truly a fighter-pilot's aircraft which possesses virtually carefree handling characteristics including no low-speed AOA limits. The evaluation of the F-18 is summarized in Reference 2.7.3 in the context of the general lessons to be learned from the early fly-by-wire aircraft.

2.7.4 Lessons To Be Learned

The following lessons can be drawn from the YF-17 and F-18 programs:

- In the YF-17 case the potentially disastrous effects of large prefilter equivalent time delays was not evident during ground simulations. Exposure of this problem required in-flight simulation and actual landing tasks.
- The need for a team approach was evident in the F-18 development process where the Initial design was solely the responsiblity of the digital control experts. A successful evolution of the FSC occurred when experts from the flying qualities/aerodynamics areas were Included in the design team.

2.7.5 References

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2.8 SPACE SHUTTLE

2.8.1 Vehicle Description

The Space Shuttle is clearly a unique vehicle with a very large flight envelope and represented a significant challenge for the flight control designer. it is mildly statically unstable in pitch during the landing phase with an aft c.g. where the time to double amplitude is on the order of 2.5 sec. The configuration Includes a delta platform with a large elevon which results in an instantaneous center of rotation near the cockpit in the landing phase. Finally, the large elevon surfaces are difficult to move rapidly with realistic hydraulic demands. Surace rate limiting is therefore a potential problem during high gain tasks such as touchdown.

A complete description of the Shuttle FCS is beyond the scope of this review. Reference 2.8.1 and 2.8.2 provide some insight into the FCS design. In simple terms the FSC is a quad digital system with no mechanical backup. The design is relatively complex and equivalent time delay has been an ongoing concern and a factor in the vehicle's flying qualities.

2.8.2 Development Review

The flying qualities problems observed during the initial free flight trials and the in-flight simulations (References 2.8.1 and 2.8.2) were related to high equivalent time delay (in the 200-250 millisec range), surface rate limiting and the lack of pitch/roll priority logic.

Attempts to actively control the vehicle in the final phases of the landing approach produced overcontrol and finally PIO problems in pitch. Any large rapid inputs produced surface rate limiting which then rapidly lead to a divergent PIO. In the PIO problem observed during the landing in free-flight #5 rate limiting in pitch effectively locked out the lateral axis which then caused severe lateral control problems. Recall that all of these problems are intensified by the unusual center of rotation feature of this configuration. Changes to improve or compensate for the Shuttle flying qualities problems were:

- Inclusion of a priority logic for pitch and roil commands to the elevons.
- Redistibution of filters from the forward path to the feedback path to reduce time delay.
- Inclusion of a PIO suppressor (Reference 2.8.2) which helped to prevent divergent PIO due to rate limiting and thus avoid the major problem near touchdown.
- Extensive training for the pilots to avoid closed-loop control inputs near the ground. The pitch control System is essentially a rate command attitude hold type system which lends Itself to an open-loop strategy for landing. Inclusion of a HUD and better external visual guidance also helped the pilots perform the landing task in an open-loop fashion.

The Shuttle has evolved into a very impressive vehicle which performs a very difficult series of mission tasks satisfactorily. Potential flying qualities difficulties have been minimized through training and several relatively minor FCS modifications. Major changes in a complex mature vehicle like the Shuttle are somewhat impractical. Reference 2.8.3 presents the results of several design studies to address more directly the Shuttle flying qualities issues.

2.8.3 Lessons To Be Learned

Several lessons can be drawn from the Shuttle experience:

- The original design criterion for the Shuttle (Reference 2.8.3) limited the allowable pitch rate overshoot. This design contraint dictated that the sluggish angle of attack and therefore flight path response of this vehicle could not be altered. Such a design contraint is not consistent with previous flying qualities results.
- Early use of in-flight simulation during the FCS design and development process would have been beneficial and perhaps highlighted the potential pitch flying qualities problems related to time delay and rate limiting early enough for modifications to be incorporated.
- Surface rate limiting is clearly a major problem which can be the final factor which sends the vehicle over a latent flying qualities "cliff". Exposure of these sequential factors requires vigorous realistic ground and in-flight simulator testing.

2.8.4 References

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2.8.2 Weingarten, N.C., "In-Flight Simuition of the Space Shuttle (STS-1) during Landing Approach With Pilot-Induced Oscillation Suppressor", Calspan Report No. 6339-F-2, December 1979.

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2.9 GENERAL ASPECTS OF THE X-31 FLIGHT CONTROL SYSTEM

2.9.1 Introduction

The objective of the X-31 program is to demonstrate "Enhanced Fighter Maneuverability (EFM)". EFM is a composition of capabilities which will improve close air combat effectiveness in a future all-aspect environment without significantly degrading the ability to successfully conduct beyond-visual-range (BVR) air combat. The EFM capability is comprised of:

- post stall (PST) maneuverability
- steep descent capability
- enhanced agility in low speed envelope
- enhanced decoupled fuselage aiming
- enhanced deceleration
- enhanced negative g capability

The flight control system (FCS) will allow infiight demonstration of the beneficial effects of EFM. As a demonstration system, the FCS uses military specifications as guides for design and development. The X-31 FCS is a full fly-by-wire system without any backup system, providing stability and control for an aerodynamically unstable configuration throughout the flight envelope. The FCS is effectively a guad digital system which uses three active digital computers and a 4th identical "lie breaker" computer. The main elements of the FCS are flight control computers, rate gyros, accelerometers, angle of attack and sideslip sensors, air data computer, inertial sensor unit and control surface actuators. A thrust vector system will permit the X-31 to retain directional and attitudinal control, even when its aerodynamic surfaces become ineffective due to post stall flight condition. The thrust vectoring (TV) consists of three paddles which can move into the exhaust stream to deflect it to any direction commanded. The paddles can deflect the effective thrust force up 'to 10 degrees

2.9.2 Longitudinal Control Law

The X-31 is unstable in pitch with a time to double amplitude on the order of 0.2 sec in the worst flight condition. In the longitudinal axis angle of attack and pitch rate are used as proportional feedback signals to maintain stability and damping of the aircraft motion. These feedback signals are shaped with appropriate notch filters to suppress the feedback of structural modes. Lead-lag filters are used to satisfy the gain- and phase-margins as required in MIL-F-9490D in the critical high dynamic pressure subsonic flight regime.

In the feedforward path, which includes an integral path, the stick position commands angle of attack for speeds below the corner speed and normal acceleration above the corner speed. The normal acceleration command is converted with a stored aerodynamic lift table and the estimated weight of the aircraft to an equivalent angie of attack command for this flight condition. Thus, angle of attack is commanded throughout the flight envelope, with a variable stick gain depending on flight condition and estimated weight.

The direct link uses angle of attack command to read out the trimmed trailing edge flap and canard position from tables which are optimized for minimum drag at low angle of attack and control power at high angle of attack flight conditions. An integral feedback of commanded minus sensed angle of attack to trailing edge flap and canard is used to account for c.g. travel and aerodynamic uncertainties in the trim tables. This delta angle of attack signal as well as delta pitch rate signal mutiplied with the proportional feedback gains are distributed to trailing edge flap, canard and thrust vectoring paddles. The distribution of the feedback to the different control surfaces is designed in a way that the most effective surface has to do most of the work. During flight in the conventional flight envelope the thrust vectoring can be switched off. In that case, the feedback signals to the thrust vectoring paddles is redistributed to trailing edge flap and canard in a way that the small amplitude behavior of the aircraft remains nearly unchanged.

2.9.3 Lateral Directional Control Laws

In the lateral directional part of the control system sideslip, roll rate and yaw rate are the proportional feedback signals. As in the longitudinal part, there are also notch- and lead-lag filters used to shape the feedback.

The lateral stick position commands a wind axis roll rate, which is converted to body axis roll and yaw rate with angle of attack and sideslip. At high angle of attack, this leads mainly to a body axis yaw rate command. The pedal deflection commands a sideslip angle whose maximum value is scaled with flight condition and angle of attack. At high angle of attack, the pedal command is totally faded out.

The commanded rates and sideslip are compared with the sensed values. These deltas are then used, after scaling with the feedback gains, to command differential flap, rudder and thrust vectoring paddles. When thrust vectoring is switched off, a redistribution similar to the longitudinal axis will be performed. In addition, cross axes feedback loops are included to compensate for the moments introduced by airplane inertia and engine momentum during maneuvers.

2.10 GENERAL COMMENTS

This brief review of several advanced aircraft designs including new aircraft such as the X-31 serves as background and confirmation that highly augmented aircraft require special design considerations. As clearly stated in Reference 2.2.6, the versatility of fly-by-wire technology, which typically now exploits the power of the digital computer, can improve handling for both maneuverable military aircraft and larger, efficiency oriented transports, such as the A320 fly-by-wire aircraft. The design engineer can largely tailor the aircraft response with little dependence upon the airframe's basic characteristics including high levels of static instability. However, this increased freedom and design power has meant more complexity because the designers often produce responses of much higher order compared to classical aircraft. As shown by our examples, the result can sometimes be an analytical nightmare and result in an aircraft with unacceptable or even dangerous handling qualities. Potential problems associated with advanced flight control systems, which are particularly pertinent to unstable aircraft, include non-linear effects such as control surface saturation, the need for redundancy and fail-safe contingencies and inherent time delays.

Before discussing the typical problem areas associated with highly augmented aircraft which, of course, are directly related to unstable aircraft, a few additional comments are in order.

2.10.1 Control System Redundancy and Handling Qualities

Unstable aircraft such as the X-29 require a high level of flight control system redundancy in order to satisfy the necessary fail-safe criteria for safety. The level of augmentation, and therefore. the handling qualities for such aircraft often remain unchanged throughout the various control failure states. For example, the handling qualities of the X-29 remain essentially unchanged in pitch in the face of up to four pitch gyro failures. The aircraft would be lost on the next failure.

In general therefore. the emphasis for unstable control system design should be biased towards the desired or "optimum" handling qualities regions (Pilot Rating -2). This situation is somewhat in contrast to the past where most of the effort was directed towards defining the minimum acceptable handling qualities boundary (PR -6.5) for failure cases.

2.10.2 Level 2 and 3 Still to be Considered?

For fly-by-wire transport aircraft, reliability and safety are the prominent issues in addition to performance. This requires flight control systems architectures which are at least quad-redundant throughout, Existing systems have these redundancy levels, e.g. Space Shuttle. Airbus 320. in these cases, Level 1 flying qualities only need to be considered for design because failure cases which degrade system performance can be taken as extremely remote, and on the other hand the flight envelope may be easily restricted by automatic means to be well within the range of good behaving aerodynamics.

For combat aircraft one does accept higher risk levels. Performance, even at the edges of a large envelope, is a design driving issue, and in most cases, leads to requirements conflicting with controllability and flying qualities needs. The smaller scale of combat aircraft makes vital system components, e.g. pitot static pickoffs and airstream detection devices, more vulnerable to outside influences like bird strikes, because even for a quad-redundant layout, the pickoffs may have to be placed close together out of other design constraints, e.g. mounting of radar, FLIR, gun. In addition, system functions can be degraded or destroyed by war damage. All the above leads to situations where reversionary modes have to be designed into the system, e.g. revert to fixed gains, partial feedback, restructured control laws. The stability levels remaining may not satisfy the needs of Level 1 flying qualities throughout the required flight envelope. Some of the burden to fly the aircraft has to be put back to the pilot confronting him with Level 2 or even Level 3 flying qualities.

In combat, pilots make a much more violent use of their aircraft converting even to a "bang bang" type control strategy for aircraft with "carefree" flight control systems. This feature combined with the higher frequency of the eigenmotion or the shorter time to double amplitude can drive systems, specially actuating systems, to their technical limits which in turn may lead to bad flying qualities or even expose flying qualities cliffs. Therefore, for combat type aircraft occurrence of level 2 or level 3 flying qualities cannot be totally avoided. However, the primary stabilization aspects of the FCS system design for a highly unstable aircraft such as the EAP (EDA), Rafale or Swedish JAS 39 Gripen must remain functional for aircraft survival. In these cases, the basic flying qualities remain reasonable for the center of the envelope flying. As noted in this subsection, consideration must still be given to handling qualities degriadation or the loss of the "carefree" aspects of the design under certain failure conditions. Even though the main emphasis for highly augmented designs:, Particularly for the highly unstable cases, should be focussed on the "optimum" or desired flying qualities regions (PR - 2) there may be conditions where Level 2 or 3 flying qualities are encountered.

2.10.3 System Architecture

For fighter aircraft in up and away flight, the typical flight control system architecture is g command at high speed changing to angle of attack command for low speed. in some cases, such as the EAP and the European Fighter Aircraft development, pitch rate command is the choice for small demands at moderate speeds. Auto trim is a general feature of all designs. In the approach and landing phase, a rate command attitude hold system in pitch is often used. in most cases, some form of speed stability is typically incorporated. More conventional classic response shapes are the system of choice from the pilot's viewpoint.

in summary, the handling qualities potential offered by advanced full-authority electronic flight control systems is enormous. Early adventures with this advanced technology approach to FCS design revealed serious problem areas. The examples of the Space Shuttle, YF-16, YF-17 and F-18 illustrate the extent of these early difficulties. Recent experience continues to yield mixed results. Unstable aircraft such as the Rafale, the EAP and the X-29 are complex, highly augmented aircraft which have exhibited good to outstanding handling qualities. Other recent examples such as the JAS 39 Grippen indicate that not all the lessons of the past are fully appreciated. The major causes of handling quailties problems in the world of highly augmented aircraft are highlighted in the foilowing section

2.11 HANDLING QUALITIES PROBLEM AREAS

2.11.1 introduction

It is not possible to state clearly a set of recommendations which can be used to avoid handling qualities problems. There are really two broad areas of concern: technical design issues and the more philosophical non-technical issues related to human behavior and interaction. The broader non-technical issues are discussed in Section 9 in which the flight control system and handling qualities development process are reviewed.

The technical issues are somewhat interrelated which makes the definition of rigorous recommendations difficult. However, major problem areas can be identified. Control system time delays and the effects of control system non-linearities such as surface rate limits are clearly major issues. These areas and the general subject of control sensitivity selection are discussed in the following subsections.

2.11.2 Time Delay

For the pilot it is crucial that the subconscious relationship between brain, hands and desired aircraft response be retained. Significant time delay between pilot input (typically stick position, refer to Section 7) and aircraft response can affect this instinctive closed loop and lead to handling qualities problems. Time delays as low as 150 miilisec can noticeably affect the pilot’s ability to perform precision tasks such as air-to-air tracking or landing.

Complexity in itself does not cause handling qualities problems. In the past examples, system complexity typically resulted in time delay because of additional dynamics in the flight control system forward path. If the connection between controller and control surface is essentially direct, the pilot can operate instinctively in an attempt to achieve the desired response. The pilot wants a correlated initial acceleration in response to his input. When this correlated acceleration is not present, the pilot loses his instinctive capability and in most cases significant handling qualitles problems in the form of PIO’s typically result.

“Time delays”, described or quantified by whatever means, seem invariably to have been attributable to one simple factor. This factor is the introduction in the control laws of excess phase lag between the stick command output and the actuation input, creating an acceleration lag which is absent in conventional aircraft. Lag introduced by an actuator is inevitable but is small enough to be unnoticed. Additional control law acceleration lag is unnecessary and can always be eliminated by attention to the control structure.

As noted in Reference 2.11.1 and 2.11.2, there is strong evidence that the allowable time delay is a function of the initial response shape or control sensitivity. Larger time delay thresholds appear to be allowable for less abrupt responses. As is usuaiiy the case, handling qualities problems are generally caused by multiple interrelated factors. The allowable time delay appears to be a function of at least the task and the initial response shape.

In summary, complex systems can be designed and successfully flown if the time delay problem is avoided by effectively providing a direct path from controller to control surface.

2.11.3 Control System Non-Linearities (Rate Limits)

System saturation in the form of position, rate and possibly acceleration limits, is sometimes unavoidable. However, if actuator limits are reached during the response of an unstable airframe, the stabilization is effectively lost and the aircraft will usually go out of control. The effects of rate limiters in any part of the flight control system must therefore be evaluated. Typically these evaluations are done on suitable simulators. To perform an adequate evaluation requires that the FCS be agressively excercised even to the point of incorporating tasks which may appear to be unrealistic but in fact are representative of the off-nominal stressed situation where rapid large control inputs may be required. As an example, interitional large glide path errors should be introduced lo require large rapid corrective inputs on final appraoch. Although in the "real world" a new approach would be initiated in the face of such a large initial error, this task may be very revealing and essential to the evolution of a safe design.

Loss of controi in pitch can also occur even when saturation occurs in a roll response if the same control surfaces are used. It is essential to ensure that such saturation interaction effect!; cannot take place whatever extreme command inputs are made in pitch roil and yaw. Suitable control axis priority logic must be part of the design.

Because there are practical limits to the maximum actuation rates possible if large weight penalties are to be avoided, "upstream" rate limiting is feasible when properly applied. Simple stick command rate limits can be varied as a function of flight condition or response amplitude so that surface rate saturation is just avoided in full stick applications. Sustained inadvertent oscillatory inputs should be avoidable by control law design techniques to enhance PIO resistance, but even if deliberately excited, the signal attenuation largely compensates the additional lag and the PIO resistance is effectively maintained. it is essential however, that such an upstream rate limit is applied to all elements if gross changes in behavior are lo be avoided.

In a stable axis, the augmentation may be adversely affected by actuator rate limiting, even though the alleviation in gain due to rate limiting can be favorable to some extent. Significant actuator acceleration limiting can have a drastic effect, however, creating a sudden jump in phase lag and an increase in gain sometimes known as a "jump resonance". The reduction in PIO resistance or stability margin may be very severe when large control reversals are made. Although actuators always have an acceleration limit, this has no handling implication when sufficiently high, because it then occurs only at frequencies well beyond those of interest to the pilot.

2.11.4 Control Sensitivity

The selection of the appropriate level of controi sensitivity (initial acceleration per inch or pound) has been a factor in handling qualities problems of aircraft with new controllers such as the YF-16 and potentialiy the JAS-39 Gripen. in the case of a new controller design, the guidelines of the past are not easily applied and the Temptation is to make the selection using a ground simulation.

The near disaster of the initial "flight" of the YF-16 is a clear example of the folly of this practice. Do not optimize control sensitivity of a new design using only ground simulation. In these cases, the use of in-flight simulation would appear to be a mandatory part of the aircraft development process.

2.11.5 References

2.11.1 Berthe, C.J., Knotts, L.H., Peer, J.H., and Weingarten, N.C., "Fly-By-Wire Design Considerations," SETP Cockpit Magazine, October, November, December 1988.

2.11.2 Monagan, S.J., Smith, R.E., and Bailey, R.E., "Lateral Flying Qualitiesof Highly Augmented Fighter Aircraft," AFWAL-TR-81-3171, January 1982.

SECTION 3

UNIFIED APPROACH TO THE EVALUATION OF HANDLING QUALITIES

3.1 INTRODUCTION

Work accomplished during the past several years to improve fixed and rotary wing handling qualities specifications has resulted in a systematic approach which can be utilized to insure that all pertinent factors have been accounted for. These factors are summarized as follows:

- The characteristic shape of the aircraft response to commands should be matched to the required tasks. Control mode switching may be required.
- The aircraft response characteristics should account for the degree of divided attention required of the pilot. This is especially important for single pilot operations.
- Different criteria should be invoked for small amplitude and large amplitude maneuvering.
- The effect of displays should be accounted for, especially when operating at low altitude in poor visibility.
- Several criteria should be utilized to perform handling qualities evaluations of an existing aircraft, or to design the control laws for a new or modified aircraft. Some criteria only apply to certain Response-Types, and this should be accounted for (see Section 4).
- The overall pilot rating is a result of the handling qualities in each axis. Two or three marginally acceptable ratings in each axis will usually result in an unacceptable overall rating.

Space does not allow a complete description of the methodology, and only a brief description is contained herein. A more complete review is contained in Reference 3.1.1, and was used as a guide to the complete revision to the military rotorcraft specification in Reference 3.1.2.

3.1.1 References

3.1.1 Hoh, Roger H., Unifying Concepts for Handling Qualities Criteria, AIAA Paper No. 88-4328, August 1900.

3.1.2 Anon, Handling Qualities Requirements for Military Rotorcraft, ADS-33C, August 1989, United States Army Aviation Systems Command, St. Louis, MO.

3.2 DEFINITIONS

The proposed methodology for unifying handling qualities analyses is based on certain procedures, definitions and terminology. These are summarized in the following paragraphs.

3.2.1 Mission-Task-Elements (MTEs)

One of the most important lessons from flying qualities experiments during the past 20 years has been that the task must be well defined, including what constitutes "desired" and "adequate" performance on the Cooper Harper Handling Qualities Rating (HQR) scale (see Reference 3.2.1). Therefore, it is essential that all the proposed missions be subdivided into specific handling qualities tasks, which are defined as "Mission-Task-Elements" (MTEs).

An example of the importance of rigorously defining the MTEs can be appreciated from an experiment wherein one pilot assigned an HQR of 1 and the other a 10. The first pilot evaluated the characteristics of a SCAS that allowed maneuvering at higher angles-of-attack than were previously possible with the subject aircraft. He found the flying qualities in the extended angle-of-attack region to be excellent -- HQR-1. The second pilot explored the departure characteristics of the new system and found them to be uncontrollable -- HQR-10. Why did this experiment produce a 1 and a 10 from two experienced test pilots? Because they evaluated different tasks (MTEs in the new jargon). It is important that the MTEs represent the lowest common denominator in terms of piloting requirements.

3.2.2 Response-Type

The response of highly augmented airplanes depends on the nature of the feedbacks and feed-forwards used in the automatic flight control system (AFCS). For example, some common Response-Types are Attitude-Command-Attitude-Hold (ACAH), Rate-Command-Attitude-Hold (RCAH), or combinations of feedbacks which make an airplane look "Conventional". The intent of defining Response-Types is to catalog generic input/output characteristics, not to define the AFCS structure. The use of labels such as ACAH has the advantage of describing the response, and the disadvantage of implying that the feedbacks and feedforwards commonly associated with the label are being addressed. We have chosen to retain the more descriptive labels at the risk of possible confusion, as illustrated by the following example. The flight control system shown in Figure 3.2.1 has attitude feedback and is sometimes referred to as an "attitude system". However, the integrator in the input path can cause the response to have the characteristics of a Rate Command Attitude Hold "Response type" (RCAH).

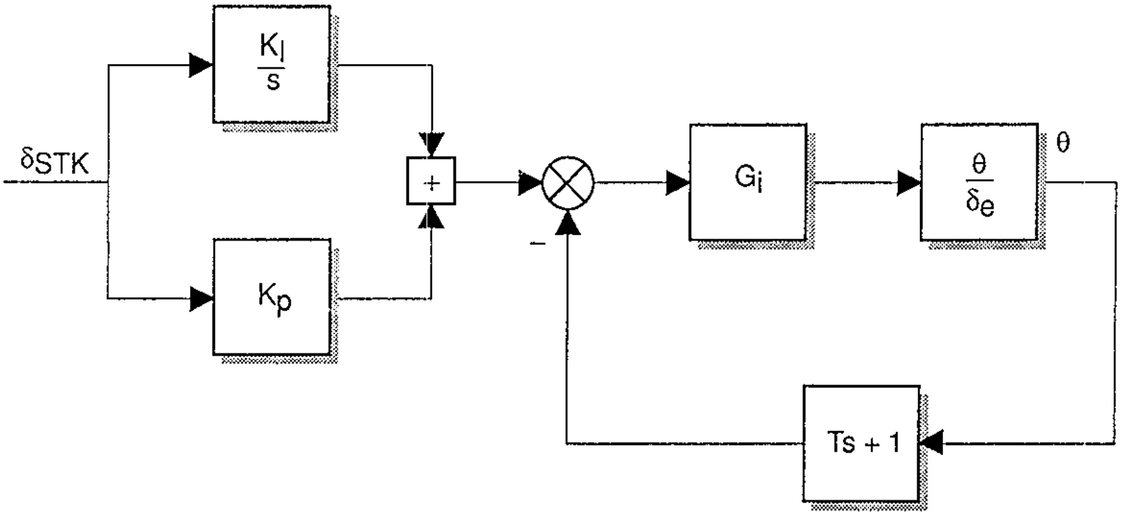


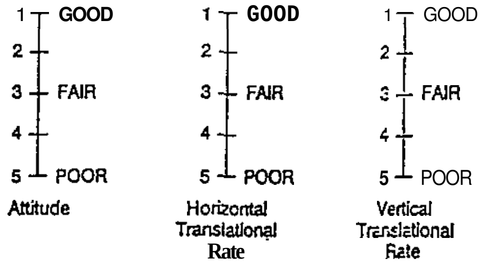
Figure 3.2.1 Example of an "Attitude System" Classified as Rate-Command-Attitude-Hold (RCAH)

3.2.3 Usable Cue Environment (UCE)

The minimum stabilization required to achieve an acceptable level of workload increases as the pilot's usable cue environment (UCE) is degraded. The UCE consists of the outside world plus cockpit displays and/or vision aids. A methodology has been developed to account for this in Reference 3.1.2 via the scales shown in Figure 3.2.2. The VCR scale allows the pilot to rate the visual environment, while the UCE values determine the appropriate Response-Type, or in some cases, define a need for a different level of dynamics within a Response-Type category (see References 3.1.2 or 3.2.2 for details). The UCE methodology applies to near-earth operations where the pilot is flying with respect to out-the-window cues in poor visibility. It is currently well developed for helicopters, but not for fixed-wing applications. Typical fixed-wing tasks where UCE is a factor are low visiblity landings and terrain following.

3.2.4 Divided Attention

Divided attention operation refers to requirements on the pilot to perform tasks not directly associated with control of the aircraft. An example of a divided attention task would be terrain following, terrain avoidance, plus navigation, and operation of aircraft systems and/or weapons systems while manually flying the aircraft. In such cases, the mid and low frequency characteristics of the aircraft are important. i.e. frequencies below ω_{BW} or ω_{sp}. The criterion in Figure 3.2.2 is used in the recently revised rotorcraft specification to define the required stability of the mid/low frequency modes. For mission tasks where the pilot can devote essentially full attention to aircraft control, low frequency instabilities are allowed. If significant periods of divided attention are required, the minimum damping ratio of low frequency modes is 0.35 (dotted line in Figure 3.2.3).

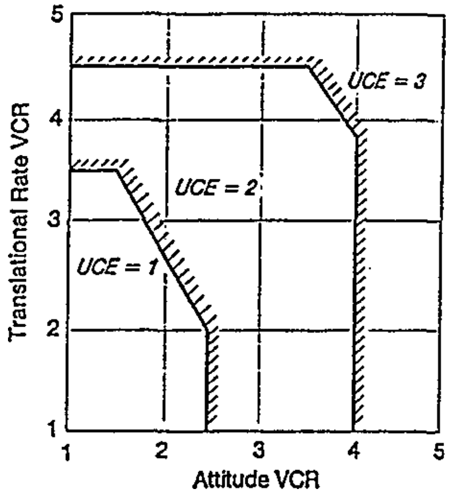


DEFINITIONS OF CUES

X = Pitch or roll attitude and lateral, longitudinal, or vertical translational rate.

Good X Cues:	Can make aggressive and precise X corrections with confidence and precision is good.
Fair X Cues:	Can make limited X corrections with confidence and precision is only fair.
Poor X Cues:	Only small and gentle corrections in X are possible, and consistent precision is not attainable.

a) Visual Cue Rating (VCR) Scale to be Used When Making UCE Determinations



b) Definition of Usable Cue Environments

Figure 3.2.2 Definition of Useable Cue Environment Used in New Rotorcraft Specification

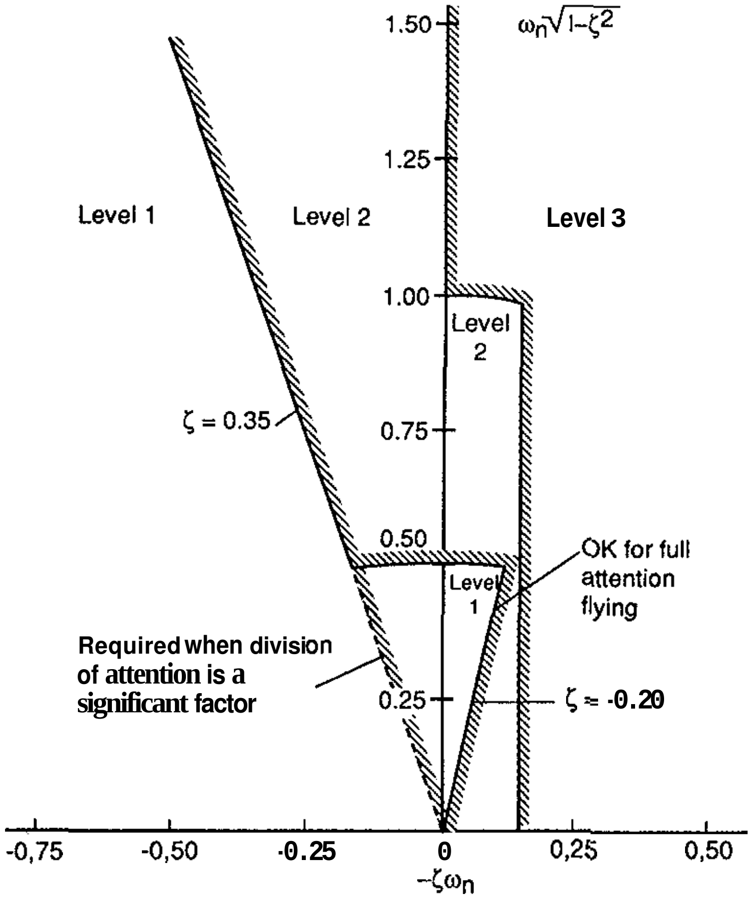


Figure 3.2.3 Limits on Pitch and Roll Oscillations as a Function of Required Pilot Division of Attention

3.2.5 Maneuver Amplitude

Most handling qualities criteria apply to small amplitude closed loop tracking. However, this distinction is rarely made, and the criteria are used for maneuvering at all amplitudes, sometimes with poor results. Therefore, in this proposed unified methodology, the applicable criteria are specified in terms of maneuver amplitudes: small and large. Criteria for these regions are discussed in Sections 4 and 5 respectively.

3.2.6 References

3.2.1 Cooper, George E., and Robert P. Harper Jr., The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities, NASA TN D-5153, April 1969.

3.2.2 Hoh, Roger h., David G. Mitchell, et.al., "Background Information and User's Guide for Handling Qualities Requirements for Military Rotorcraft", USAAVSCOM Technical Report 89-1-008.

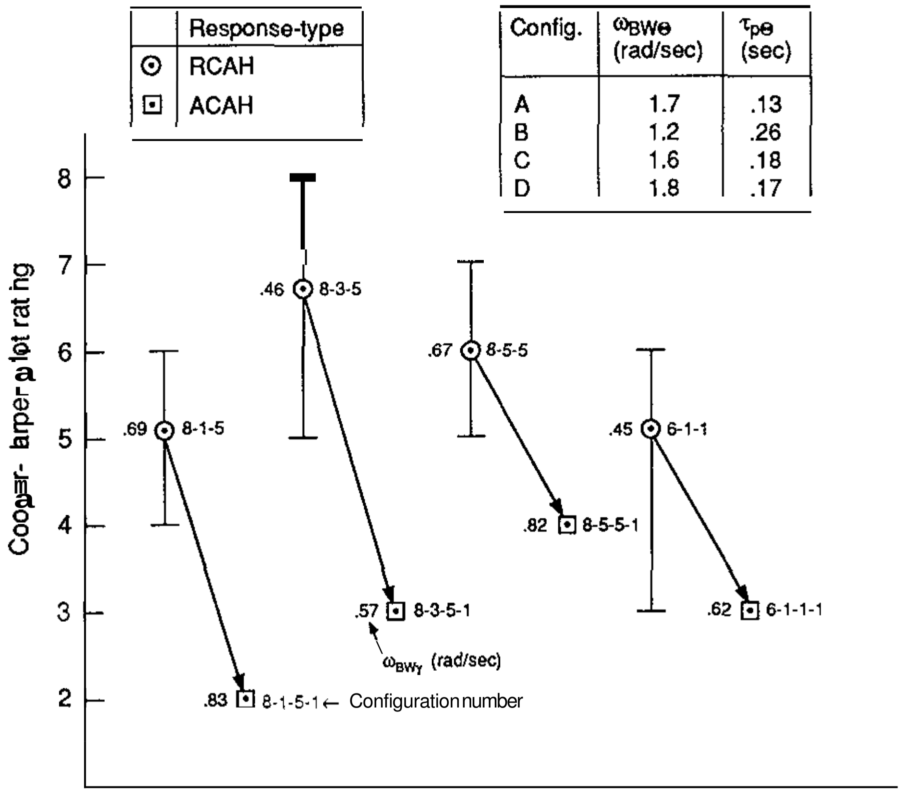
3.3 SELECTING THE PROPER RESPONSE-TYPE

Studies have shown that there are certain generic response shapes that enhance the ability of the pilot in the performance of one or more elements of the aircraft mission. Therefore, an important first step in the design of a flight control system is to properly match the "Response-Types" to the "Mission-Task-Elements". An example of the pros and cons of several Response-Types for the approach and landing task is given in Table 3.3.1.

RESPONSE-TYPE	ADVANTAGES	DISADVANTAGES
Conventional Airplane	Well accepted flare characteristics	Lightly damped phugoid mode. Requires trimming to change airspeed during the approach Angle-of-attack sensing required . gust sensitivity problems.
Rate Command/ Attitude Hold (RCAH)	No trimming required to accomplish airspeed changes during the approach.	Not as desirable for flare. Not Level 1 if $1/T_{q} < 1/T_{\theta 2}$ Tendency to float in flare Tendency for airspeed Control problem; during the approach (associated with division of attention).
Attitude Command/ Attitude Hold (ACAH)	Highly desirable flare Characteristics.	Requires trimming during approach.
Flight Path Command/Flight Path Hold	Highly desirable flare characteristics.	Requires trimming during approach. May result in excessive speed bleedoff for unpowered approach in windshear. Sensing requirements more complex than for ACAH.

Table **3.3.1** Competing Response Types for Landings in many cases, the selection of a Response-Type which is not the best one for the task produces acceptable, but not desirable flying qualities. Prior to fly-by-wire aircraft, it was not possible to develop task tailored flight control systems, and the pilots simply learned to live with less than optimum flying qualities for some tasks. One of the prime advantages of the new technology Is the possibility for tailoring the flying qualities to the piloting tasks. An example of how the choice of the proper Response-Type can affect flying qualities can be seen from the data in Figure 3.3.1 from the precision landing experiments conducted on the USAF/Calspan variable stability TIFS aircraft (see References 3.3.1 and 3.3.2). Here it can be seen that a significant improvement in pilot opinion occurred by changing to an Attitude Command Response-Type, even though the dynamics (bandwidth) were essentially constant. It is interesting to note that the Airbus A-320 switches from a Rate Response-Type to an Attitude Response-Type at an altitude of 50 feet, just prior to the landing flare.

The Response-Types are defined in terms of the generic control response characteristics associated with known augmentation schemes. For example, the fundamental properties which identify the Response-Types in Table 3.3.1 are summarized below and in Figure 3.3.2.



Notes:

1) Bandwidth and Phase Delay were essentially unchanged between Rate and Attitude Response-Types

2) Attitude was obtained from Rate Response-Type by inserting a Washout Pre-Filter at the Output of the Cockpit Controller

3) Test Designed to Evaluate Control Laws for a Generic Transport (193,000 LB Gross)

Figure **3.3.1** Flight Test Results Showing Effect of Changing from Rate to Attitude Response-Type

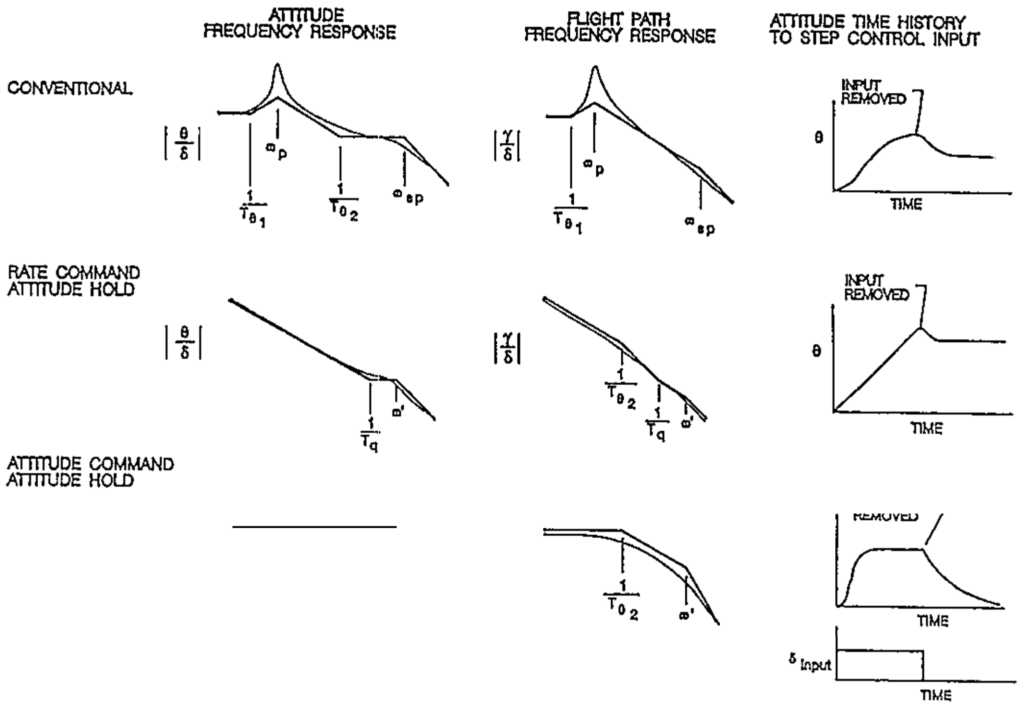


Figure **3.3.2** Generic Characteristics of Three Response-Types

3.3.1 Conventional Airplane

- Short period and phugoid modes are well separated and easily identified. The phugoid mode is typically lightly damped, with an oscillation that occurs at constant angle-of-attack.
- The Bode plot of flight path response to longitudinal controller Inputs Is K/s between the phugoid and short period modes.
- The time response of pitch attitude to a step controller Input increases monotonically in the short term, and returns to trim when the controller is released.

3.3.2 Rate Command Attitude Hold (RCAH)

- Phugoid dynamics are eliminated
- Attitude numerator defined by $1/T_q$ instead of $1/T_{\theta 2}$.
- Flight path frequency response is K/s^2 between $1/T_{\theta 2}$ and $1/T_q$, when $1/T_q >> 1/T_{\theta 2}$.
- Time response of pitch attitude increases monotonically to a step controller input, and holds attitude at point of release.

3.3.3 Attitude Command Attitude Hold

- Attitude response is proportional to controller input with some lag (defined by ω').
- Steady flight path change is proportional to controller input with lag defined by $1/T_\theta$
- Time response of pitch attitude to a step controller input is a constant attitude, which' returns to trim when input is removed.

3.3.4 Important Characteristics

Some important characteristics of these Response-Types are summarized as follows:

- The RCAH Response-Type introduces flight path lag if $1/T_q$ is much greater than $1/T_{\theta 2}$.
- The above noted flight path lag does not exist for the Conventional Response-Type, i.e. $1/T_{\theta 2}$ does not appear in the γ/δ response.

- Augmenting the short period frequency increases the flat stretch between $1/T_{\theta 2}$ and ω' and hence the pitch rate overshoot for a conventional Response-Type. Too much of this results in excessive drop-back (see Section 4).
- The relationship between attitude and flight path discussed above, and shown in Figure 3.3.2, is fundamental to the CAP boundaries used in the Lower Order Equivalent System (LOES) criterion discussed in Section 4. Hence, that criterion should not be applied if the Response-Type is not Conventional. In practice, the LOES/CAP criterion usually works for RCAH, since problem configurations usually exhibit excessive equivalent time delay. However, misleading results may occur, and other criteria should be utilized if the Response-Type is not conventional.
- Application of the LOES/CAP criterion to an ACAH Response-Type is incorrect.

There has been considerable debate in the flying qualities community as to the need for pitch rate overshoot for good flying qualities. The characteristics discussed above allow the flight control system designer to determine the need for pitch rate overshoot in terms of first principal requirements. For example, if the value of $1/T_{\theta 2}$ is low, pitch rate overshoot is needed to augment the flight path response, and conversly if it is not small, pitch rate overshoot is not necessary. Hence, it may not be possible to achieve good flying qualities with an RCAH Response-Type if $1/T_{\theta 2}$ is low. In such a case, the designer may elect to augment to Conventional dynamics by the use of angle-of-attack feedback (to augment the short period frequency), or by the use of an ACAH Response-Type.

It is extremely important to pay careful attention to the method used to switch between flight control system modes. Inadequate switching logic can negate any advantages due to task tailoring. In the case of the A-320, the switching is accomplished automatically at a reference altitude, which is natural for the landing task. The flight control system design used for the European Fighter Aircraft (EFA) blends between a conventional Response-Type and a RCAH Response-Type as a function of stick position and airspeed as follows:

- At low airspeed and aft stick, a feedback is dominant producing a Conventional Response-Type.
- At moderate airspeeds and stick positions, a proportional plus integral feedback of pitch-rate is employed, i.e., an RCAH Response-Type.
- At high airspeeds, the RCAH Response-Type is retained and the command gain is scheduled to produce a constant stick-force-per-g. These modes are blended in and out so that at some airspeeds and stick positions a combination of Conventional and RCAH exists. Experience with the prototype aircraft (British Aerospace EAP) has indicated that this is not a problem.

In some cases, a manual switch may be more desirable, and the human factors associated with location of the mode-switch controller, and annunciation of the current mode must be carefully accounted for. Since there has been very little research in this area, it is usually necessary to perform basic human factors research during the system development process.

3.3.5 References

3.3.1 Berthe, C.J., Chalk, C.R., and Sarrafian, S., "Pitch Rate Flight Control Systems in the Flared Landing Task and Design Criteria Development, NASA CR 172491, Oct. 1984.

3.3.2 Weingarten, Norman C., Berthe, Charles J., Jr., Rynaski, Edmund G., et. al., "Flared Landing Approach Flying Qualities. Volume I, Experiment Design and Analysis", NASA CR 178188, Dec. 1986.

3.4 COMBINED AXIS PILOT RATINGS

The combined effect of degraded handling qualities in each axis of control is not addressed in any of the specifications. There is, however, an empirical formula which seems reasonably effective as a method to predict the overall aircraft flying qualities in terms of the HQRs in each axis.

$$R_m = 10 + \frac{-1^{(m+1)}}{8.3^{(m-1)}} \prod^{m} (R_i - 10)$$

Where

R_m = the predicted overall pilot rating
R_i = the pilot rating in a given axis
m = the number of axes rated

This equation has been investigated in a motion base piloted Simulation experlemnt (Reference 3.4.1) with good results. it is interesting to note that the predicted effect of two 5s in a two-axis task is a 7, and two 3s is approximately a 4. That is, the effect of combined axes becomes more important as the handling qualities in each axis degrade.

3.4.1 References

3.4.1 Mitchell, David G., Aponso, Bimai L., Hoh, Roger H., "Minimum Flying Qualities, Volume I: Piloted Simulation Evaluation of Multiple Axis Flying Quaiioties", WRDC-TR-3125, January 1990.

3.5 PITCH RATE OVERSHOOT

Pitch rate overshoot is not an end in itself but reflects the ratio of the transient angle of attack rate to the steady flight path angle rate. This is determined by the parameter $T_{\theta 2}$ and the short period frequency and damping or its equivalent. The overshoot ratio increases generally with wing loading and with altitude. Typically its absence is associated with a sluggish flight path response and with some overshoot in attitude, which can lead to overdriving or "digging in" especially if the response bandwidth is low. The K/S-like attitude response in which the nose appears to "follow the stick" always contains some pitch rate overshoot. However, excellent small-amplitude target tracking can be achieved with a deadbeat pitch rate response of sufficient bandwldth, and the conflicting requirements for fast target acquisition can be resolved by amplitude-dependent filtering as demonstrated by the AFTI/F-16 and the RAE ACT Hunter. The EAP and FBW Jaguar probably represent the limits of the wide range of acceptable attitude behaviour that are possible in the landing approach, both having satisfactory flight path response. The EAP has a high value of $1/T_{\theta 2}$, and the control law provides an essentially deadbeat attitude response whereas the FBW Jaguar has a smaller value of $1/T_{\theta 2}$ and the control law is designed to provide a large pitch rate overshoot with substantial attitude dropback. The reason for using increased pitch rate overshoot on an aircraft with low $1/T_{\theta 2}$ is discussed in Section 3.3.

3.6 TIME DELAYS AND PHASE DELAY

Excessive values of these parameters can be directly attributed to control law lags introduced between the pilot command inputs and the corresponding control surface actuation input signal. These additional lags are absent in conventional aircraft, where the pitch and roll accelerations essentially follow the stick commands instantaneously. Proper attention to the control law structure is necessary to eliminate unnecessary lag.

SECTION 4

LONGITUDINAL CRITERIA FOR SMALL AMPLITUDE PRECISION ATTITUDE AND FLIGHT PATH CONTROL

4.1 INTRODUCTION

Criteria that have been found to be useful for the prediction of flying qualities of aircraft in the performance of small amplitude precision tracking tasks are briefly discussed in this section. The intention is to familiarize the reader with these criteria; details related to data correlations are left to the appropriate references.

Experience has shown that several criteria should be utilized in the evaluation of the handling qualities of an existing aircraft, and in the development of a new flight control system. For example, the upper limit on the Bandwidth is defined by the Dropback criterion. In some cases, one criterion will expose a handling qualities deficiency that others do not. It is also important to understand the regions of validity of a given criterion. For example:

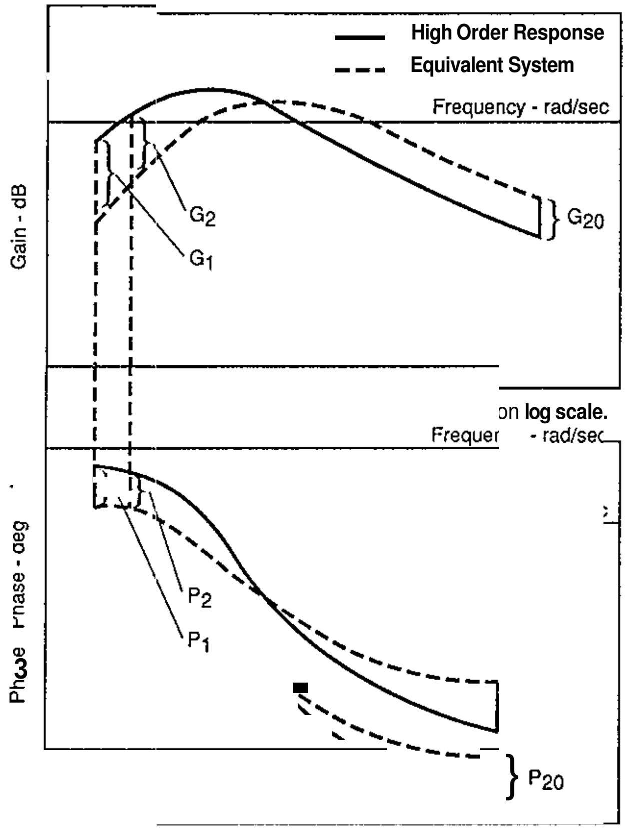
- The Lower Order Equivalent Systems Control Anticipation Parameter (CAP) boundaries are valid for airplanes with a classical Response-Type (see Section 3). The method usually works for Rate Response-Types, since the culprit is often time delay, which is essentially equivalent to the more general phase-rate and phase-delay parameters. However, application of the CAP criterion to an attitude command system will produce completely misleading results.
- The proper bandwidth must be selected for the Neal-Smith criterion, or, perhaps more appropriately, the bandwidth must be systematically varied to examine flying qualities trends.
- The dropback criterion only applies to rate systems where the effective stick-free static stability is zero, i.e., where the stick must be returned to zero to stop the pitch rate.
- The attitude variations must be reasonably small for all of these criteria to apply (on the order of plus or minus five degrees in pitch and 10 degrees in roll). Criteria for larger amplitude maneuvering are contained in Section 5.
- The criteria generally apply to the linear region of control. If significant nonlinear operation is encountered, it must be accounted for by using describing function techniques, or by other methods discussed in Section 5. It should be noted that significant nonlinear control for small amplitude tracking is in itself a warning of unacceptable flying qualities.
- None of the criteria in this section properly account for control sensitivity and feel system dynamics. These factors must be accounted for separately as discussed in Section 7.

4.2 LOW ORDER EQUIVALENT SYSTEMS (LOES)

The equivalent system approach takes mathematical models of aircraft with complex stability and control augmentation systems and reduces them to simple low order form. This method allows flying qualities analysis, design and real-time simulation with direct reference to familiar unaugmented dynamics. Many matching techniques have been used, with equal success. For analytical evaluation of a design, a frequency response match of the low order transfer function by a direct search method has been shown to reduce longitudinal dynamics effectively, using a cost functional as shown in Figure 4.2.1. For longitudinal dynamics, short period pitch rate and normal load factor (measured at the instantaneous center of rotation) responses to longitudinal commands are simultaneously matched with the spacing of frequency response data similar to that shown in the figure. The resulting values of short period damping and frequency are then compared with current specifications, such as MIL-F-8785C or Mil Standard 1797.

4.2.1 Rationale Behind Criterion

Augmented longitudinal dynamics are typically modeled by very high order responses with many modes. In attempting to apply early Military Specifications on low order modal parameters, control system designers frequently used a single 'dominant' mode from the high order response. This proved inappropriate because other modes contributed significantly. The equivalent system matching technique, using a low order aircraft model plus a time delay, was explored by Difranco and Neal and Smith and Stapleford, et al (References 4.2.1, 4.2.2, and 4.2.3). In Reference 4.2.4 the criterion was developed as a reliable method of determining damping and frequency for specification compliance. An equivalent delay not only greatly improved the match, but also strongly degraded pilot ratings (Figure 4.2.2). The LOES method was established as an interim way of determining the low order modal terms need for specification compliance; however, it eventually became part of MIL-F-8785C. It was



Minimize Cost Functional (mismatch) = $\sum_{i=1}^{20} (G_i^2 + WP_i^2)$; $W = 0.02$

Figure 4.2.1 Optimizing Cost Functional for Equivalent System Determiriation

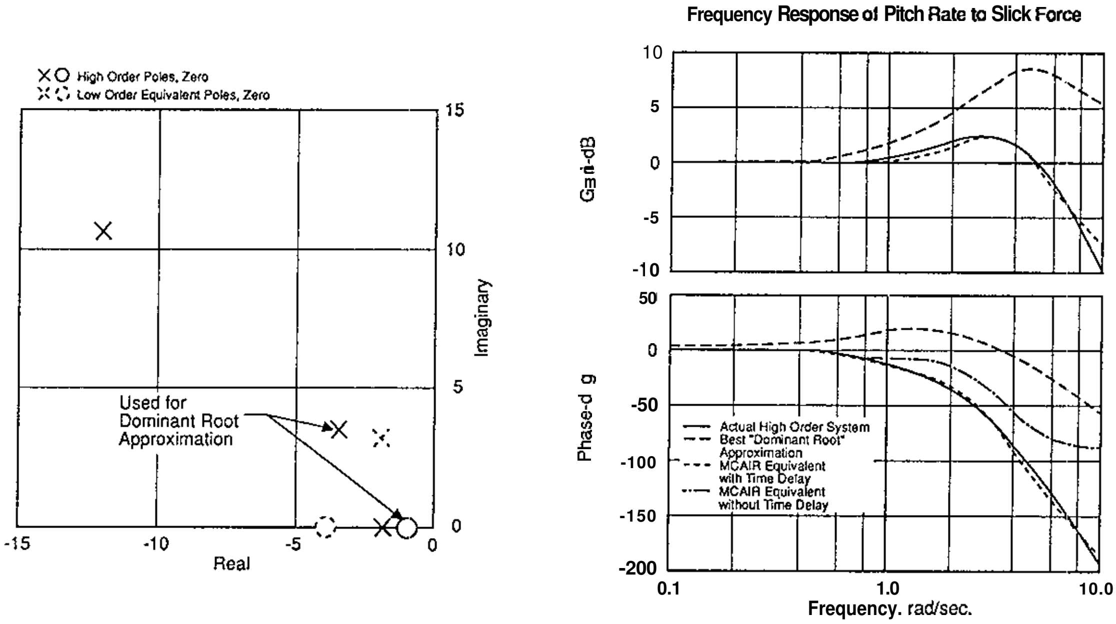


Figure 4.2.2 Pole-Zero and Frequency Response Comparison of High Order System, Dominant Root Approximation and Low Order Equivalent

also required for demonstrating compliance with equivalent phugoid, lateral-directional, V/STOL and CCV model criteria. References 4.2.5, through 4.2.11 are some examples of equivalent system appilcations.

4.2.2 Guidance for Application

Matching is quite robust, to the extent that hand matching can be used in event of computer failure. As a quick check, equivalent time delay can be estimated directly from the phase curve (see discussion of τ_p under bandwidth Section 4.3). Application to actual aircraft flight responses has emphasized that frequency domain equivalent system methods are far easier to handle than any step time history interpretations of the method. Fast Fourier results from flight test distribute more frequency points at higher frequencies as compared with Figure 4.2.2, so some correction may be required to capture the character of the low frequency response. Some users (Reference 4.2.12) have recommended shifting the frequency range of match to straddle the equivalent short period frequency. When normal load factor responses from flight data are used, care must be exercised to allow for effects of sensor location (see Reference 4.2.12).

Many discussions about whether to fix or free the numerator term if matching the pitch response alone (see Reference 4.2.13 for background) were settled arbitrarily by enforcing simultaneous matching of pitch and normal load factors, thereby essentially fixing the term. These discussions were not mathematical but physical, because they were in truth arguments about whether attitude, flight path or both should be considered. The LOES method (or CAP for that matter) could not settle the arguments because insufficient data existed.

Reference 4.2.14 documents an in-flight experiment to validate the question of equivalence. It contains guidance on flight evaluation of augmented dynamics (see also Reference 4.2.15) and introduces envelopes of allowable mismatch. References 4.2.16, 4.2.17 and 4.2.18 document comparisons of LOES methods with other approaches. Reference 4.2.19 discusses how to include feel system dynamics in the equivalent time delay. Reference 4.2.20 describes identification of equivalent parameters from flight time history records.

4.2.3 References

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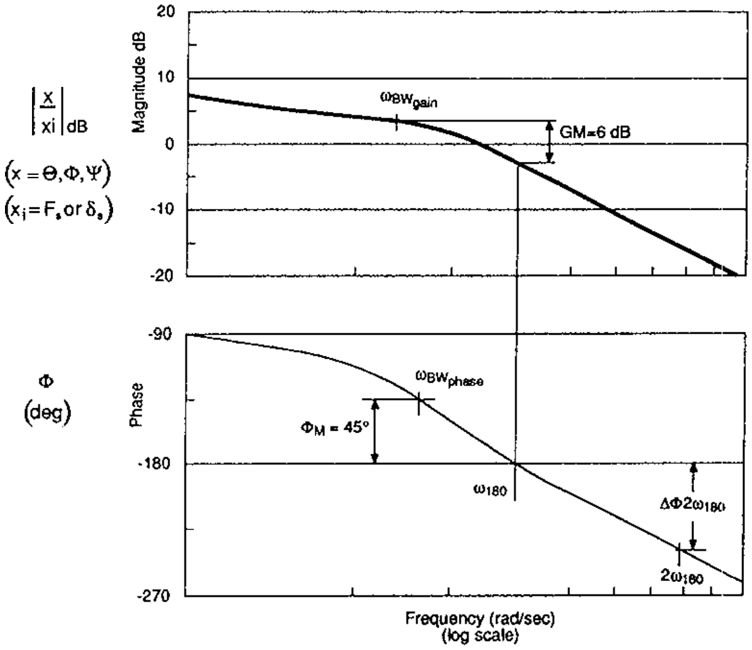
4.3 BANDWIDTH CRITERION

4.3.1 Description of Criterion

Bandwidth is indicative of the highest frequency at which the pilot-airplane loop can be closed without threatening stability (i.e. encountering a Pilot-Induced Oscillation [PIO]). Specifically, it is defined from the Bode plot of the augmented airplane, as the frequency where the phase margin is 45 degrees, or where the gain margin is 6 dB (see Figure 4.3.1). For tasks where flight path control is an important factor (e.g. landing), it is necessary to specify the bandwidth of both the attitude and flight path. The generic shapes of the bandwidth boundaries for pitch attitude and flight path control are shown in Figure 4.3.2. The Bandwidth criterion is described in more detail in Reference 3.2.2 and 4.3.1.



Phase Delay:

$$\tau_p = \frac{\Delta\Phi\, 2\omega_{180}}{57.3\,(2\omega_{180})}$$

Note: if phase is nonlinear between ω_{180} and $2\omega_{180}$, tr shall be determined from a linear least squares fit to phase curve between ω_{180} and $2\omega_{180}$

Rate Response-Types:
ω_{BW} is lesser of $\omega_{BW\,gain}$ and $\omega_{BW\,phase}$

Attitude Command/
Attitude Hold Response-Types (ACAH):
$\omega_{BW} = \omega_{BW\,phase}$

Figure **4.3.1** Defiinition of Bandwidth and Phase Delay

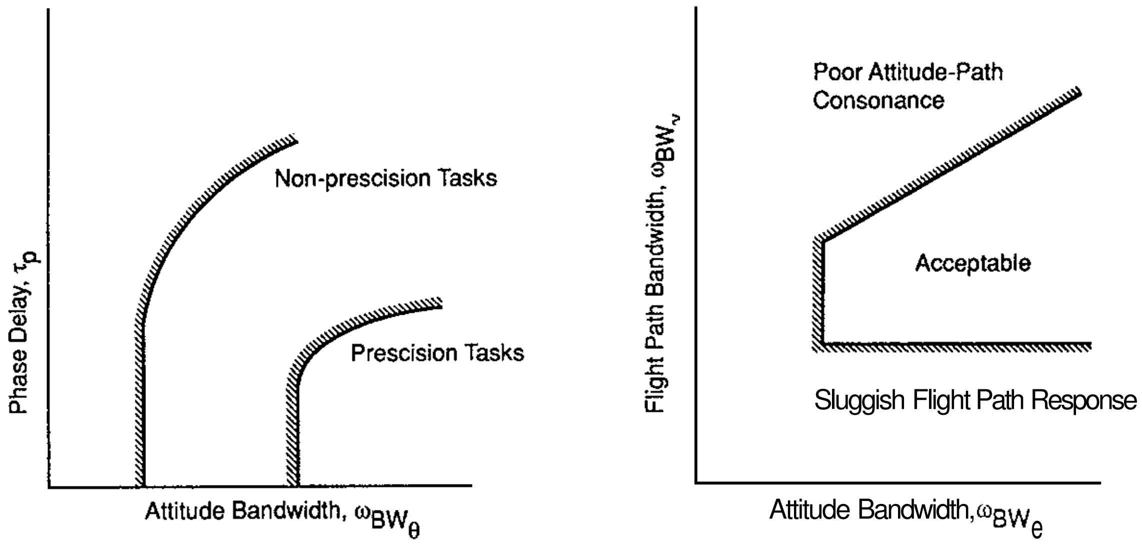


Figure 4.3.2 Generic Shape of Attitude and Flight Path Bandwidth Criteria

4.3.2 Rationale Behind Criterion

Physically, the Bandwidth is a measure of the frequency below which the pilot can follow all commands, and above which he cannot. The characteristic frequency of the effective commands depends on the task, and hence the bandwidth boundaries are task dependent. Most configurations are phase margin limited, i.e. the phase margin Bandwidth is lower than the gain margin Bandwidth. Bode plots for configurations which are gain margin limited tend to be PIO prone and exhibit a "shelf" such as shown in the example in Figure 4.3.1.

The Bandwidth criterion consists of two parameters, bandwidth (ω_{BW}) and phase-delay (γ_p). The phase-delay parameter is a measure of the shape of the phase curve at frequencies above the bandwidth frequency. That is, the phase curve drops off more rapidly for "large values" of phase delay than it does for "small values". Hence, phase-delay is a measure of the slope of the phase curve in the vicinity of -180 degrees. An important caveat is that it is a frequency weighted slope. That is, for the same phase-slope, the value of phase-delay will be higher for low values of ω_{180}. Physically, this implies that a steep phase slope is more important when ω_{180} occurs at low frequency, than if it occurs at frequencies above the region of piloted crossover. The phase-delay parameter, τ_p can be shown to be very similar to the Lower Order Equivalent System time-delay parameter, τ_e (see Section 4.2) and to the phase-rate parameter (Section 4.4). In fact, the phase-rate and phase-delay parameters can be shown to be numerically identical if the phase-rate slope is taken between the 180 degree frequency and twice that frequency.

4.3.3 Guidance for Application

The upper boundary of the flight path bandwidth criterion (Figure 4.3.2) represents excessive flight path response such as might occur if the gain is set too high on a direct lift control flap or spoiler. Increasing the flight control system feedback or feedforward gains to achieve increased values of attitude bandwidth (or equivalent short period frequency) may result in increased dropback (due to increased pitch-rate overshoot). Hence, it is important to check the dropback criterion in Section 4.7 when augmenting an unstable or sluggish airplane to high values of bandwidth (or equivalent short period frequency).

The primary advantages of the Bandwidth criterion are that it applies to all Response-Types, and hence is ideal for highly augmented aircraft, and it is easily calculated from a Bode or Nichols plot of the higher order system. On the negative side, the calculation of bandwidth from flight test records requires a Fast Fourier transform on data which contains sufficient power at the frequencies of Interest. Experience has shown that even benign maneuvers usually contain sufficient power. For example, excellent Bode plots of the Shuttle attitude transfer function have been obtained from landing flare data. More conventionally, the bandwidth is calculated from frequency sweeps as discussed in Reference 4.3.1.

4.3.4 References

4.3.1 Military Standard, Flying Qualities of Piloted Vehicles, MIL-STD-1797 (USAF), March 1987.

4.4 PHASE RATE CRITERION

Phase rate is the slope of the phase curve around the neutral stability point, i.e. $(d\phi/d\omega)_{\omega} = 180^\circ$. It has been found empirically to have a strong relationship with the features which tend to promote PIO. These features consist of a low frequency with correspondingly low pitch acceleration, which can lead the pilot to employ excessive gain, resulting in a large response amplitude at the PIO frequency. A high phase rate appears; to negate efforts by the pilot to break out of a PIO, since any increase in crossover frequency due to "tightening up" results in a rapid decrease in phase margin.

The Phase Rate criterion has been used in the European Fighter Aircraft Handling Qualities Specification (unpublished) to insure good closed loop precision tracking characteristics.

It can be shown that the phase rate criterion is proportional to the phase delay parameter (τ_p), which is part of the Bandwidth criterion (see Section 4.3) if the phase slope in Figure 4.3.1 is taken between the 180° and twice the 180° frequency. For that special case, $(d\phi/d\omega)_{\omega} = 180^\circ = 2\tau_p$.

4.5 NEAL-SMITH CRITERION

4.5.1 introduction and Background

The Neal-Smith closed loop (i.e. pilot-in-the-loop) criterion was originally developed for highly augmented fighter aircraft performing precision tracking tasks (Flight Phase Category A). A later attempt to extend the criterion to the approach and landing task (Flight Phase Category C) was successful. In the initial work a faulty assumption was made that the landing task was a low gain, undemanding task relative to a fighter tracking task. Subsequent evidence from simulation programs and the LAHOS program (Reference 1) indicated that the flare and touchdown phase of the landing task was indeed a demanding, high gain task.

Complete details on the criterion are contained in Reference 4.5.2. Briefly, the criterion assumes a simple closed-loop pitch attitude tracking task as shown in Figure 4.5.1. The pilot block in the closed loop should be viewed, more properly, as a pitch attitude compensator since even though the form of the "pilot model" used is representative, the model was not experimentally confirmed. The criterion represents a "flying qualities test" and as such is not dependent on the accuracy of the "pilot model" assumed.

The criterion assumes a certain "performance standard", or degree of aggressiveness, with which the "pilot" closes the loop. This standard is defined in the frequency domain as a bandwidth frequency (ω_β). This bandwidth is task dependent; the value for a particular task is determined heuristically using pilot rating and comment data to obtain the best overall correlation with the criterion parameters. For a given desired bandwidth, the "loop is closed" and the compensator, or pilot model, parameters are varied to yield the best overall closed-loop performance. A more general application of the criterion involves reviewing a suitable range of bandwidth frequencies.

The criterion output parameters are the pilot compensation (workload) required and the resulting closed-loop performance as measured by the maximum value of closed-loop resonance($|\theta/\theta_c|_{max}$). Low frequency performance is constrained by limiting the "droop" up to the bandwidth frequency. These criterion parameters are illustrated in Figure 4.5.2. Application of the Neal-Smith criterion consists of the following steps:

- Specify the bandwidth or range of bandwidths appropriate for the task; must be determined for each task by data correlation.
- Adjust pilot model parameters, the compensation, (using a fixed value of time delay) to meet the "performance standard" set by the bandwidth requirement.
- Measure the closed-loop compensation required (pilot workload) and the closed-loop maximum resonance ($|\theta/\theta_c|_{max}$).
- Typically, pilot workload is measured by the phase angle of the Compensation required at the bandwidth frequency [$\measuredangle_{pc}$].
- Plot measuredvalues against Neal-Smith flying qualities boundaries to evaluate the flying qualities. Boundaries for the original tracking data are shown in Figure 4.5.3; typical pilot comments around the Neal-Smith parameter plane are illustrated In Figure 4.5.4.

In the original analysis (Reference 4.5.2), a pilot time delay of τ_p = 0.3 sec was assumed and a maximum droop of -3 dB was imposed. For the flight condition most representative of a fighter tracking and maneuvering environment, a bandwidth of 3.5 radlsec was selected.

The required analysis can be performed by hand or using a digital computes program. A Nichols Chart technique forms the basis of the analysis to yield the necessary closed-loop parameters. A Nichols Chart solution using a desired bandwidth of 3.0 radlsec is illustrated in Figure 4.5.5.

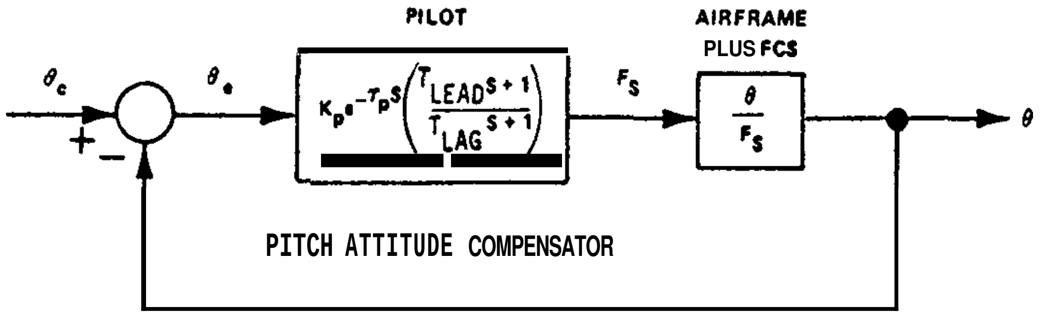


Figure 4.5.1 Criterion Pitch Tracking Task

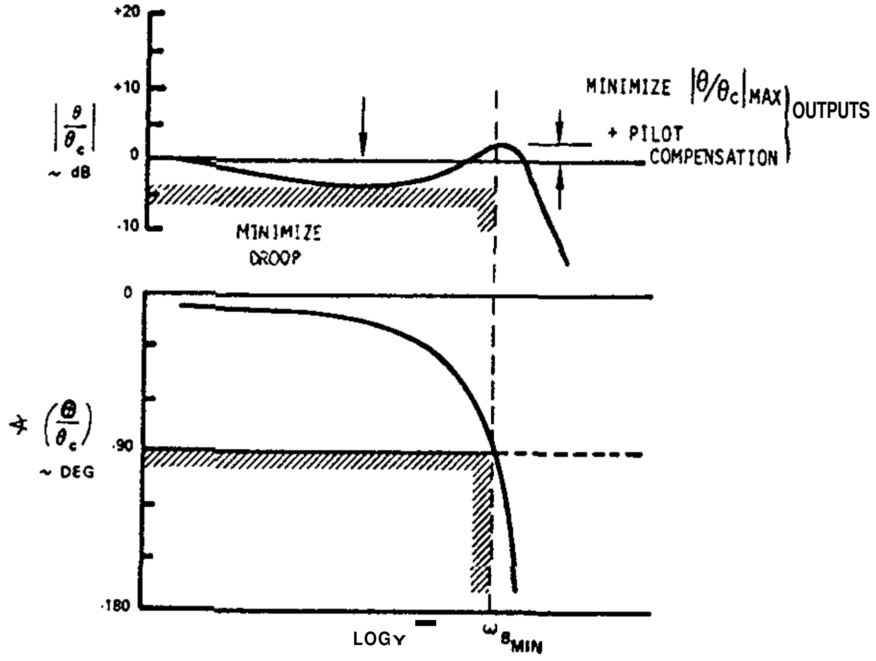


Figure 4.5.2 Neal-Smith Criterion Parameters

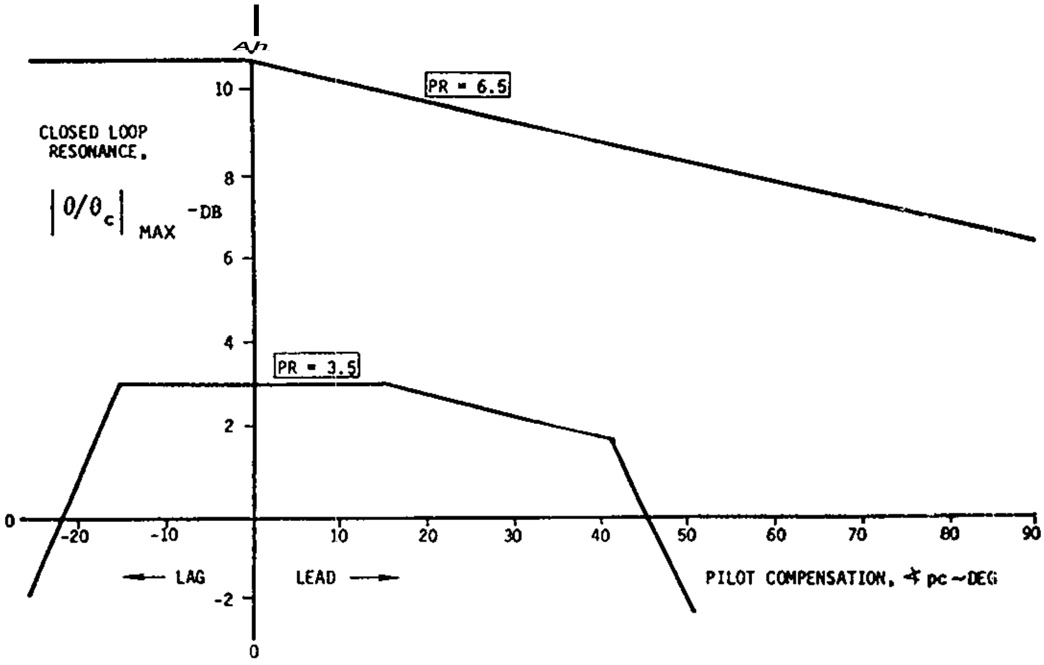


Figure 4.5.3 Neal-Smith Parameter Plane

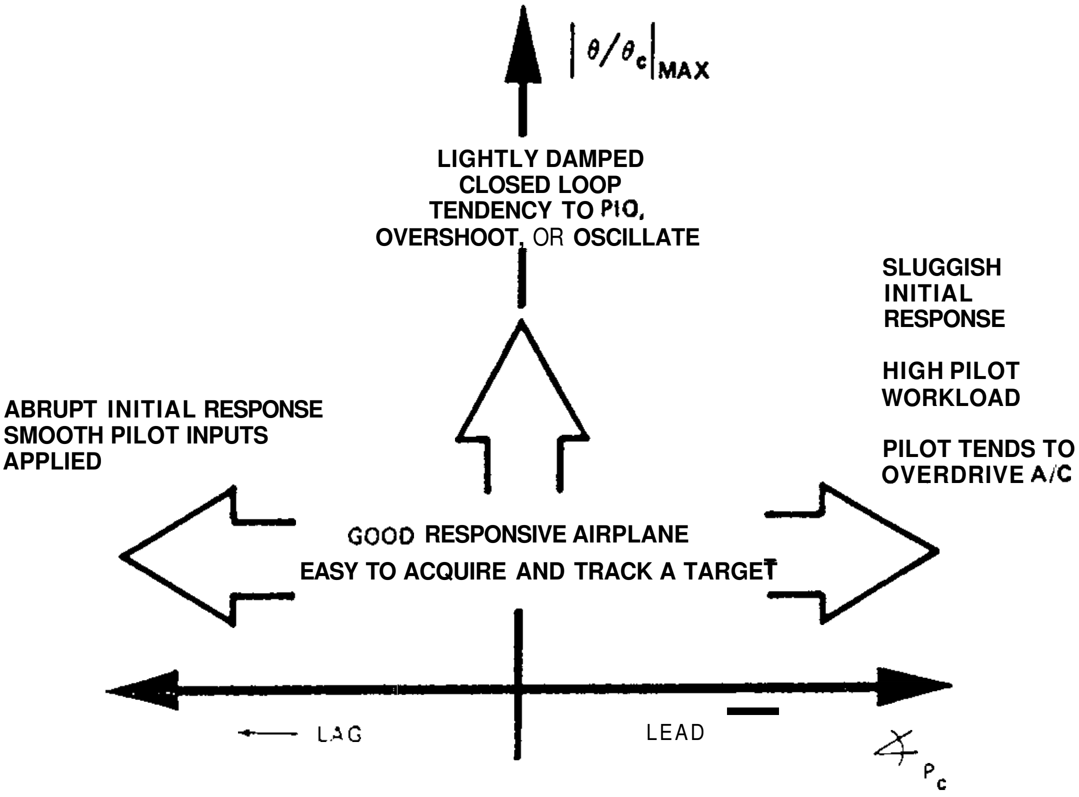


Figure 4.5.4 Typical Pilot Comments

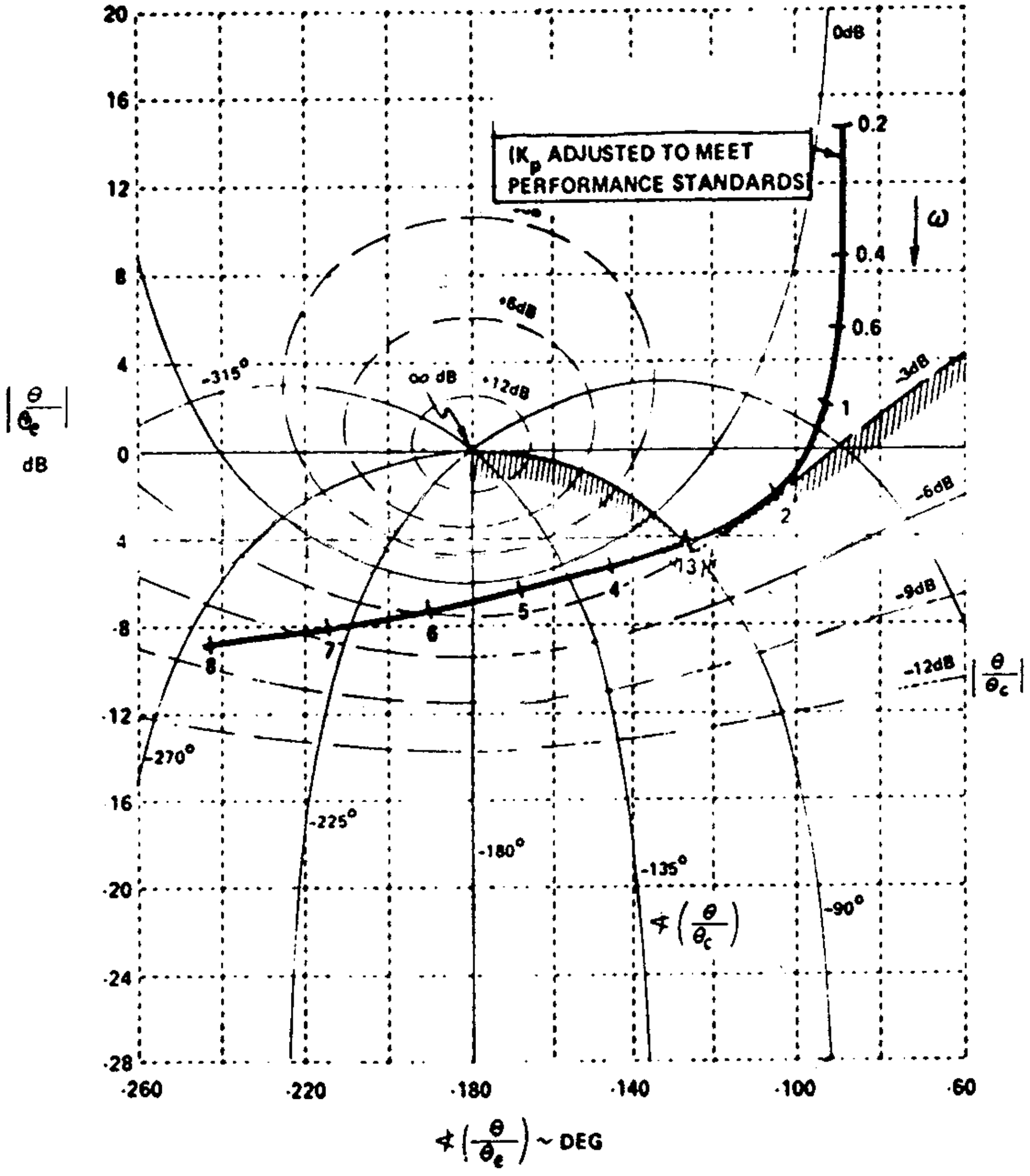


Figure 4.5.5 Typical Amplitude-Phase Curve Overlayed on a Nichols Chart (Configuration with High ω_{sp})

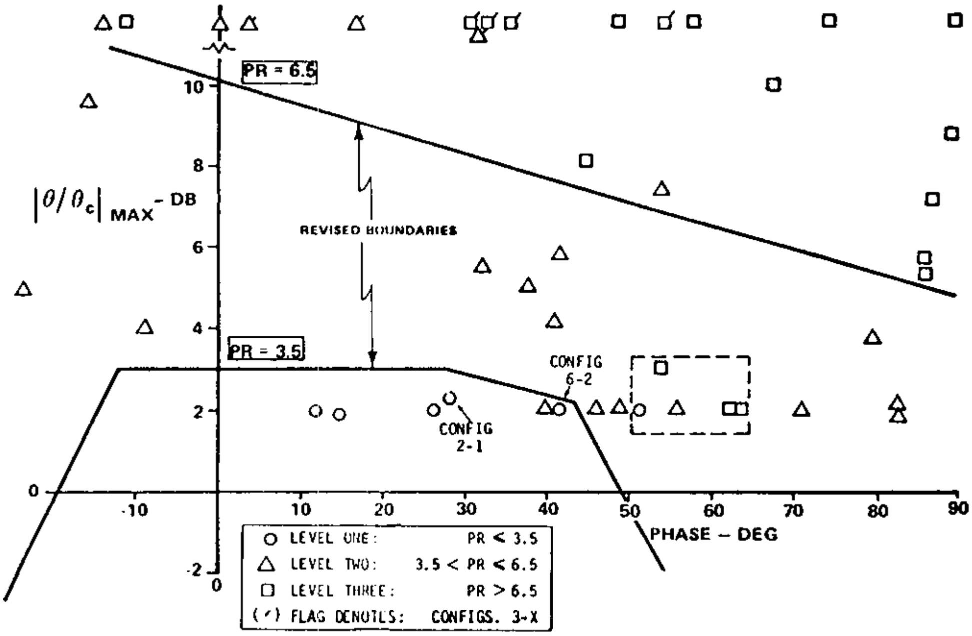


Figure 4.5.6 LAHOS Data - 3dB Droop Criterion Relaxed, ω_B □ 3.0 radlsec, τ_p □ 0.2 sec.

4.5.2 Evaluation of the Criterion

A review study of landing flying qualities evaluation criteria for augmented aircraft (Reference 4.5.3) recommended revisions to be basic criteria parameters and the task related bandwidth values. These revisions were based on a revisit with the data base from LAHOS and the original data base. The revisions were:

- Pitch compensator (pilot) time delay of 0.2 sec (vice 0.3 sec in the original version).
- Approach and landing task bandwidth of 3.0 radlsec.
- Fighter tracking task bandwidth of 4.5 radlsec.

In addition the flying qualities boundaries were slightly modified as shown in Figure 4.5.6 which includes the LAHOS data points. Perhaps of greater importance in the study was the recognition that the performance of a (given configuration, in terms of resonance, as bandwidth is varied is a more important factor. Poor designs exhibit flying qualifies “cliffs” which are equivalent to large non-linear changes in resonance with small changes in pilot technique (bandwidth).

4.5.3 Configuration Sensitivities to Criterion Parameters

It is clear that some aircraft dynamic combinations are particularly sensitive to changes in task environment or piloting technique. in this context, sensitive means that large changes in flying qualities can occur with different pilots or with small changes in the task standard of performance. For these aircraft, large variations in pilot ratings for the same task are common. Indeed, the measure of a good aircraft is its insensitivity to pilot techniques or small task variations. From a flying qualities requirement viewpoint, application of the criterion at a specific bandwidth is likely required; however, from a design criterion viewpoint, evaluation of the changes in performance over a realistic range of bandwidths provides the more important information. This point is illustrated in detail in Reference 4.5.3.

There is, therefore, another dimension to the criterion plane: suitable sensitivity parameters are required. From the pilot point of view, this sensitivity reflects the degree of difficulty he has in "adapting" (compensating) as the task requirements change rapidly.

4.5.4 Practical Application of the Criterion

The importance of the performance trends with bandwidth variations is clearly illustrated in Figure 4.5.7. The original flight control system for the YF-17 as flown in the NT-33 In-flight simulator exhibited very poor flying qualities and was significantly changed prior to first flight. The trends of closed-loop performance with increasing bandwidth are non-linear and show a very large degradation of performance as bandwidth is increased above 2 rad/sec. This Sensitivity to changes in bandwidth or pilot technique is a definite indication of flying qualities problems which would not be evident if the evaluation was done at only one value of bandwidth. in contrast, the changes in YF-16 performance with the same increases in bandwidth are linear and show that while some improvements are warranted there are no lurking "cliffs".

4.5.5 Use of the Criterion as Part of a Design Methodology

During the recent flight tests of the X-29A forward swept wing technology demonstrator aircraft, a series of design changes were made to the pitch axis aimed at improving the initial pitch response. Pilot complaints were centered on a sluggish initial pitch response and excessive control throw which lead to control harmony problems. As a first step, the longitudinal stick travel was cut in half while maintaining the same stick force per g. This change resulted in much Improved vehicle fiylng qualities. The final goal was to show that fighter-type initial response characteristics could be designed into the highly unstable X-29A aircraft. An iterative design methodology was developed which used the Neal-Smith criterion as a guideline to affect the desired increase in pitch acceleration (Reference 4.5.5). Important features of this design method were that the existing control system architecture was retained and the stability and robustness of this unique aircraft were maintained.

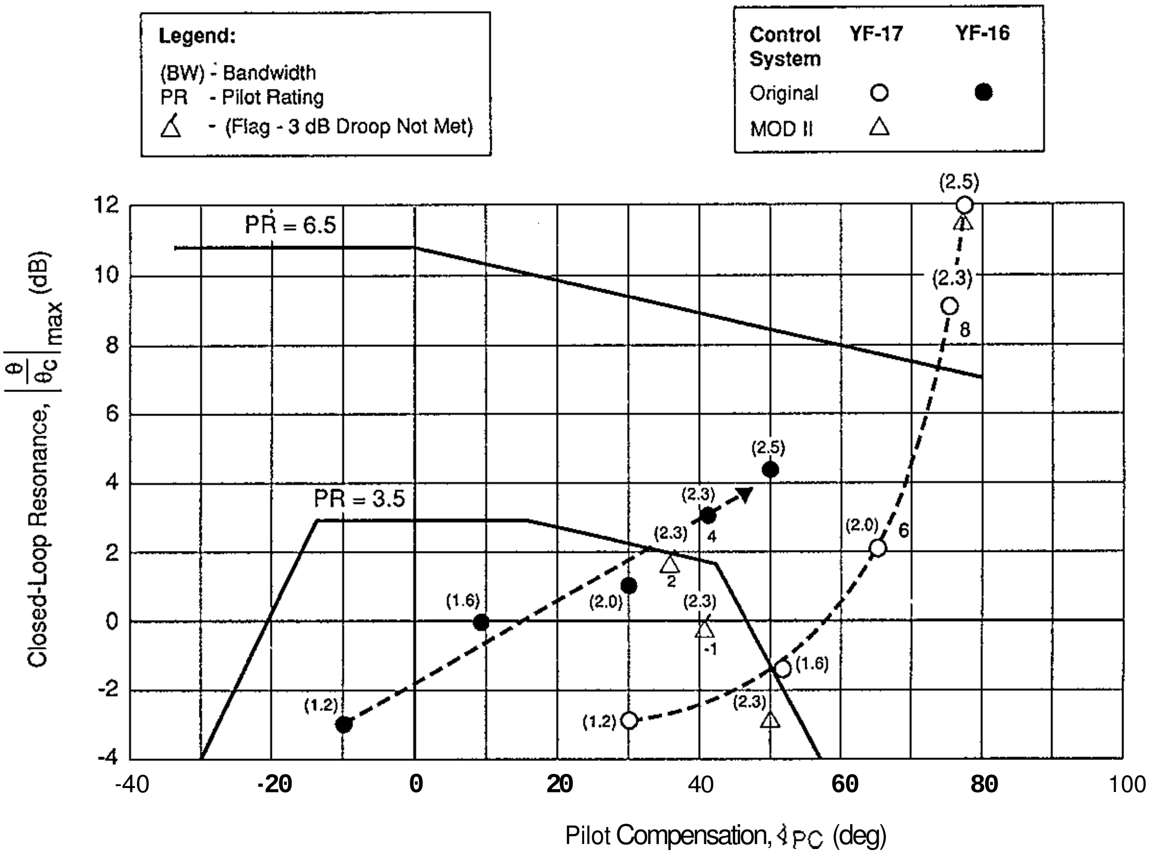


Figure 4.5.7 Correlation of YF-16 and YF-17 with Original Neal-Smith Criterion (Landing Approach)

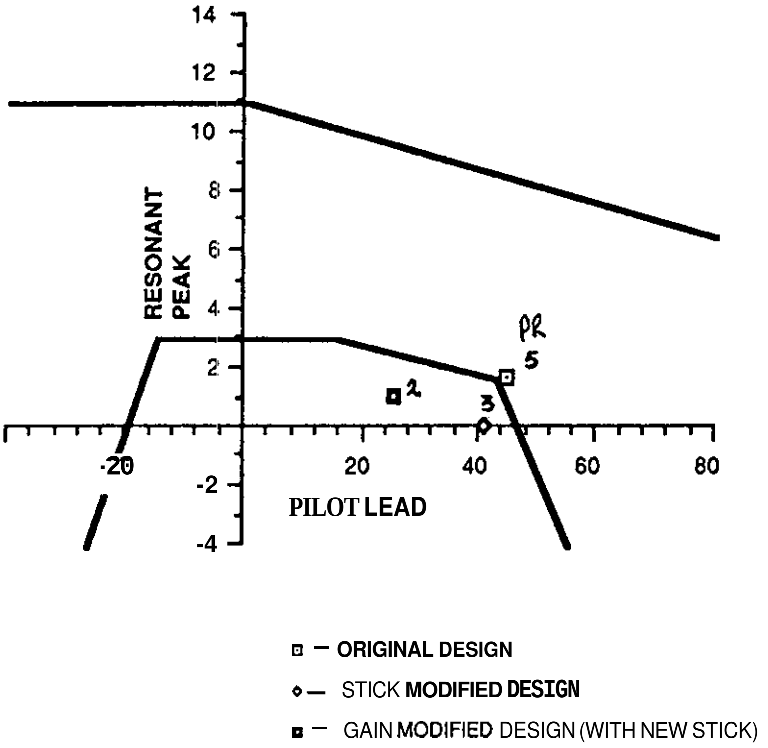


Figure **4.5.8** Neal-Smith **Analysis** on X-29A Development Configurations **(Theta/Force)**

This procedure provided a practical means for improving the flying qualities of the X-29A without excessive re-design. The pitch acceleration was increased **100%** while retaining good precise pitch control and good stability margins. The X-29 cases are plotted on the Neal-Smith plane in Figure 4.5.8 using the original criterion parameters. The projected improvements of the X-29 pitch flying qualities conform reasonably well with the average pilot ratings from flight test.

4.5.6 Summary Comments

The following comments on the Neal-Smith criterion are found in Reference 4.5.3 in which several applicable flying qualities criteria are compared.

- Desirable Features:
  - Good pitch landing and fighter tracking flying qualities discriminator; exposes bad aircraft consistently.
  - Parameter plane dimensions are directly related to typical pilot comments.
  - Provides a design target area which guarantees good flying qualities if met regardless of system complexity.
  - Evaluation of aircraft's longitudinal maneuvering response characteristics can be done in one step; eliminates "combination of bads" question present in other criteria and military specification.

  ideal as a design criterion since "sensitivity" of the aircraft dynamic system to changes in task performance standard or pilot technique can be explored effectively.

  The potential exists that the criterion (or any of the linear handling qualities criteria for that matter) could also be used to evaluate systems with non-linear elements. This process would involve obtaining frequency response data for a range of pilot input magnitudes just as in flight test using fast fourier transform techniques. The results of the analysis for various input magnitudes could then be used to indicate the handling qualities trends during high-gain large amplitude tasks which might occur during off-nominal high stress situations.

- Undesirable Features:
  - Application of the criterion is relatively complex although it can be done efficiently and consistently using the digital computer program.
  - Although not of a concern for typical highly augmented designs, the Criterion does not predict pitch landing flying qualities accurately for lightly damped unaugmented aircraft.
  - Requires an additional "adaptability" metric to evaluate properly aircraft which are sensitive to task variations or changes in pilot technique. The criterion does, however, lend itself to such an application as a design guideline.
  - Cannot accurately evaluate systems with non-linear elements, although the potential exists to use the criterion for various size inputs using frequency sweep data.
  - Requires selection of appropriate bandwidth from flight test data for use as a specification method

4.5.7 References

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4.5.3 Radford, R.C., Smith, R.E., and Bailey, R.E., "Landing Flying Qualities Evaluation Criteria for Augmented Aircraft," NASA CR 163097, August 1980.

4.5.4 Smith, R.E., "On the Evaluation of the YF-16 and YF-17 Aircraft Using Longitudinal Maneuver Response Criteria," Calspan, Flt Research Memo No. 510, November 1975

4.5.5 Bosworth, J.T. and Cox, H.C., "A Design Procedure for the Handling Qualities Optimization of the X-29A Aircraft," AIAA 89-3428, Boston, Mass., August 1989.

4.6 FREQUENCY DOMAIN CRITERION

4.6.1 Brief Description of Criterion

The criterion defines limits for the normalized open loop transfer function of pitch attitude, etc., due to stick deflection delta/es in a Nichols diagram (Figure 4.6.1). Normalizing means in this context that the transfer function under test has to be shifted up or down by varying the gain until it runs through 0 db at -110 deg phase lag. Because the Nichols diagram contains no constraints for the frequency range allowed, Figure 4.6.2 gives the required bandwidth for the flying qualities levels L1, L2, L3 for flight phases A, B. and C.

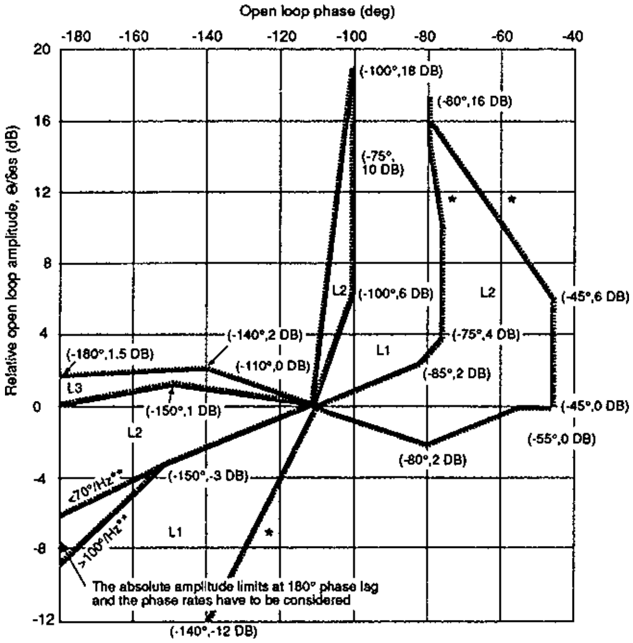


Figure 4.6.1 Pitch Attitude Frequency Response Limits

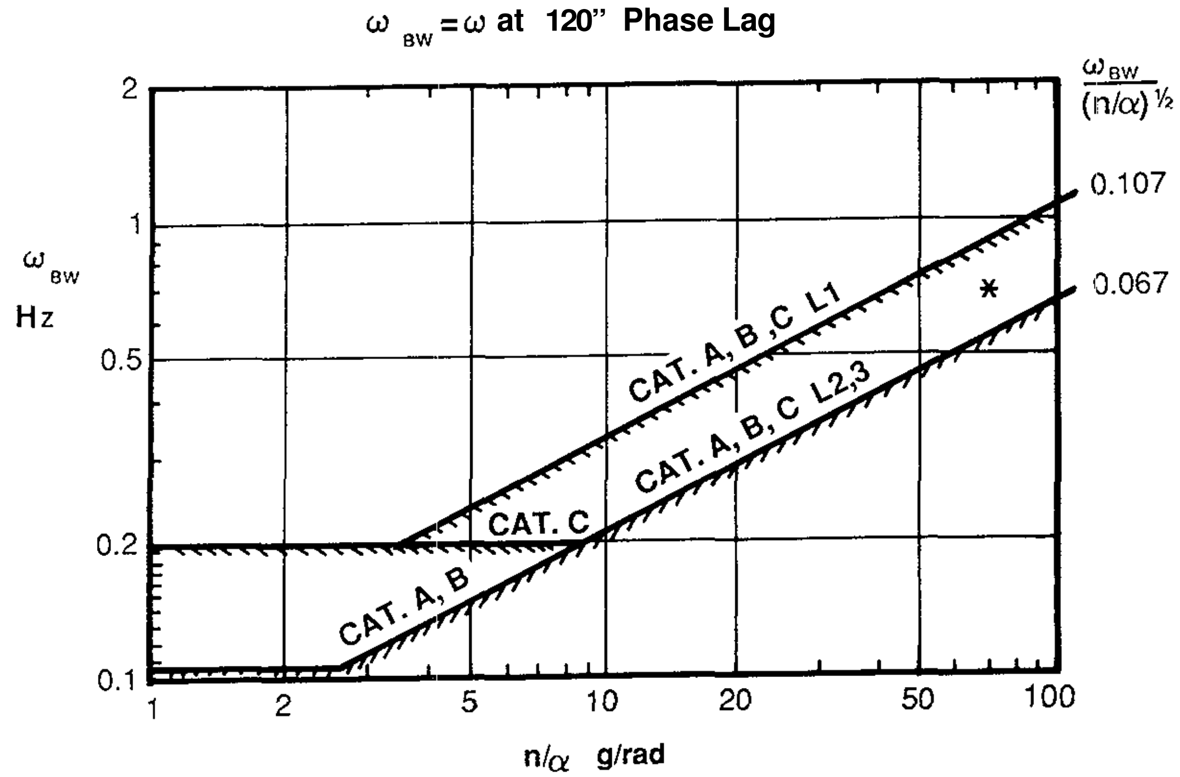


Figure **4.6.2** Pitch Attitude **Response** Bandwidth

The boundaries identified by asterisks (*) in Figure 4.6.1 are applicable only where provision is made for precision attitude control for fine tracking at small stick inputs. In this case the boundaries identified by the asterisk in Figure 4.6.2 need not be observed for stick inputs of less than 10 mm (0.4 inch) for center stick controllers.

For the boundaries identified by a double asterisk (**), additional criteria apply for the not normalized transfer functions pitch attitude due to stick deflection. At the frequency where phase lag of pitch attitude to cockpit control displacement is 180 deg. for levels 1, 2 and 3:

- The rate of change of phase lag shall be less than 16 deglradlsec (100deg/Hz) or if greater, then the phase rate at 190 and 200 degrees phase lag shall be significantly less than 16 deglradlsec (100deg/Hz).
- The amplitude shall be less than a maximum of 0.022 deg/N (0.1deg/lb) or 0.03 deg/mm for a phase rate of 16 deglradlsec (100deg/Hz), increasing to 0.036deg/N (0.16deg/lb) or 0.05 deg/mm for a phase rate of 11 deglradlsec (70deg/Hz) or less if omega 180 > = 1.0Hz.

4.6.2 Rationale Behind the Criterion

Full authority flight control systems led to total system (aircraft plus flight control system) transfer functions of significantly higher order than those on which the short period pitch axis criterion of MIL 8785B Reference (4.6.1) was based.

In particular the effects of the phase shift of more than *180* deg which is normally exhibited by the higher order systems was not covered in Reference 4.6.1. Moreover, there may be moro dominant modes which could be addressed as "short period modes". To overcome these problems, Brauser, Diederich and Roger (MBB) Reference 4.6.2 developed, based on the principles in Reference 4.6.1, criteria in the frequency domain, one of these being the predecessor of the criterion proposed here. This predecessor mapped the short period criteria of MIL 8785B into the frequency domain, thus defining boundaries for the transfer function pitch attitude due to stick input instead of defining the transfer function by its roots and zeros. The criterion was subsequently presented to an international audience! at the AGARD Flight Mechanics Panel Symposium on "Criteria for Handling Qualities of Military Aircraft" in April 1982 (Reference 4.6.3). in 1985-1986 Dornier, under government contract, undertook a simulation study in which among others the criterion developed by MBB was correlated with pilot ratings gained from air-to-air close-in combat. This exercise showed the basic validity of the approach chosen. However, some modifications to the boundaries proved to be necessary and were proposed by Dornier.

Furthermore, Dornier combined the "Diederich" criterion with a criterion proposed by Gibson (Reference 4.6.4) which was also formulated in the frequency domain and presented in a Nichols plot. DLR subsequently compared the criterion with the Neal-Smith database (Reference 4.6.6) again finding good correlation. in addition, the combined criterion was checked by Gibson (British Aerospace) against his flying qualities database collected mainly from the fly-by-wire Jaguar and the experimental aircraft (EAP) programs. in the course of joint discussions Dornier, DLR and British Aerospace developed the final version of the criterion, which also serves as one of the design guidelines for the development of the longitudinal flying qualities of the European Fighter Aircraft (EFA).

4.6.3 Guidance for Application

The criterion was designed for the evaluation of closed-loop flying qualities involving small stick inputs, i.e. it is applicable to judging the precision tracking behavior of combat aircraft for flight conditions where essentially linear behavior can be assumed. Regions of high angle of attack may have to be excluded.

During the design phase of an aircraft project, the transfer function of pitch attitude response to stick deflection is readily available as an equation and can therefore easily be compared to the criterion and the additional features, e.g. phase rate between -150 deg and -200 deg phase, can be computed as local gradients. For flight test derived transfer functions more care is needed around the area of -180 deg phase and suitable mean values of the phase rate have to be derived because of the occasional poor quality of flight test data especially near and beyond the -180 deg. phase.

If the right hand side level 1 limit above 0 db is violated excessive drop back leading to pitch bobble is indicated whereas violation of the left hand limits points to sluggish aircraft behavior resulting in overshoots. infringement of the left hand limits of Level 1 below 0 db suggests that the design may be pilot induced oscillation prone.

Feasibility of the criterion in the high angle of attack region will be demonstrated by the X-31A program. The original Diederich criterion was used in the design of this experimental aircraft up to high angles of attack. Otherwise the criterion compares well with databases as given in References 4.6.5 and 4.6.6 as well as with details of more recent unpublished experience with the above mentioned experimental aircraft designs of British Aerospace.

4.6.4 References

4.6.1 Military Specification, Flying Qualities of Piloted Airplanes, MIL-F8785B (ASG), 16 Sept. 1974
4.6.2 K. Brauser, L. Diederich, W. Roger, Steuerbarkeitskriterien zur Bewertung der Manovriereigenschaften moderner Hochleistungsflugzeuge, MBB/FE301/S/R/1505, 22 Dec. 1980.
4.6.3 W. Neuhuber, L. Diederich, K. Brauser, Handling Qualities Criteria for Longitudinal Control. AGARD CP 333. Aor. 1982
4.6.4 Gibson,' Handling Qualities' for Unstable Combat Aircraft, ICAS 86-5.3.4 1986
4.6.5 Chalk, C.R., et al., Background information and User Guide for MIL-F-8785 (ASG), AFFDL-TR-69-72, Aug. 1969
4.6.6 Neal. T.P. and Smith, R.E., And inflight investigation to Develop Control System Design Criteria for Fighter Airplanes (Vol I and ii), AFFDL-TR-70-74, Dec. 1970

4.7 DROPBACK CRITERION

The attitude response widely recognized as optimum for compensatory closed-loop tracking is Ws, that is with pitch rate purely proportional to stick input. The attitude appears to follow the stick and remains fixed at the value existing when the input is removed. This cannot be exactly realized in practice, but the equivalent result can be achieved after a transient disturbance. Attitude dropback is then defined as the case when the altitude moves back towards a previous value when the input is removed, as shown in Figure 4.7.1.

The problem of "pitch bobble" in tracking is directly related to the effect of bandwidth. While a fast flight path response is desirable for target acquisition, and is achieved by a high short period frequency, the consequence is usually a large dropback. The attitude response becomes very difficult to stop exactly on target. On the other hand, zero nominal dropback can be achieved by reduced short period frequency and bandwidth, but the attitude transient may be prolonged to the extent that fine predictability is lost. if the bandwidth is sufficiently low, the attitude will overshoot the expected value, and this gives the feeling of "digging in", leading to an overdriving tendency.

The qualitative effect of a given value of dropback is influenced by the pitch rate overshoot ratio, effectively the ratio of initial angle of attack rate to the steady flight path angle rate. The higher this ratio is, the more step-like the dropback appears, being associated generally with high bandwidth. These characteristics generally become more pronounced with increasing altitude because of the changing relationship of pitch rate and angle of attack. Their Importance is related to the task requirements. For general maneuvers and flight path tasks, they have little significance unless fairly extreme, a factor also influenced by the quality of the flight path information presented to the pilot. For precision tracking, very small values of dropback or overshoot are optimum when combined with high attitude bandwidths. This can be achieved by command filtering at the expense of flight path bandwidth.

Successful application of this filtering technique has been demonstrated on the AFTI-F-16, NASA F-8, RAE ACT Hunter, F-15 S/MTD, and EAP, and it will be used on EFA. The conflict with flight path control has been resolved in most of these examples by an amplitude-dependent filter optimizing attitude for small commands and flight path for large commands.

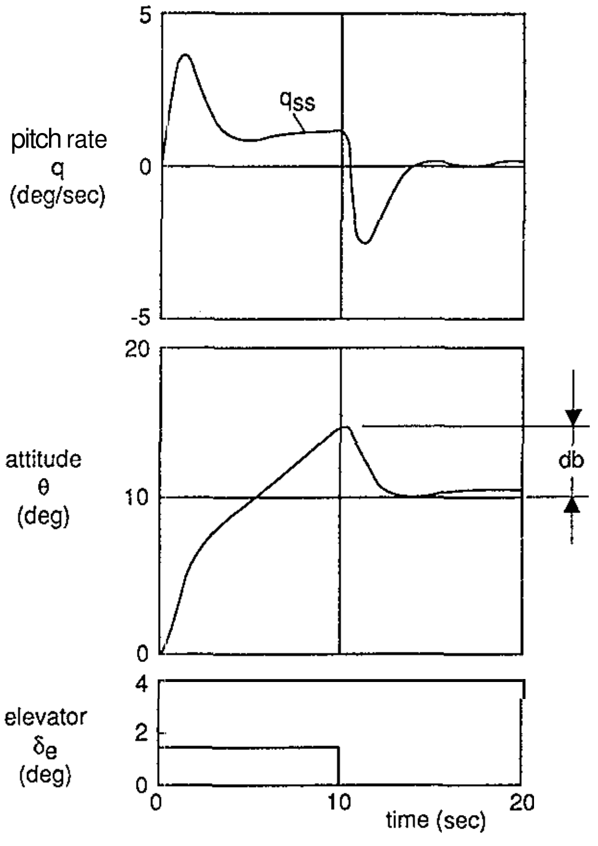


Figure 4.7.1 Definition of Attitude Dropback

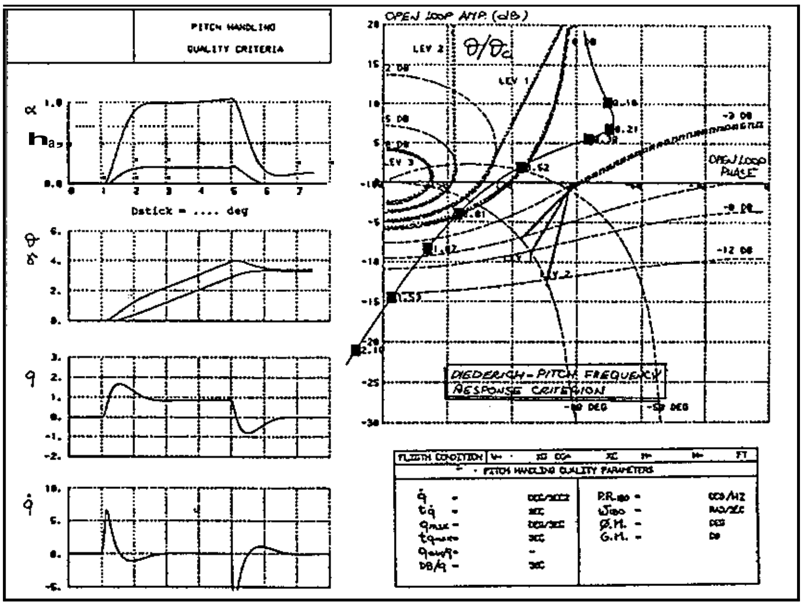
As a rule-of-thumb, the following design limits on dropback have been found to lead to good flying qualities.

$\frac{db}{\bar{q}_{ss}} \leq .25$ precision tracking; $\frac{db}{\bar{q}_{ss}} < 1.0$ landing

4.8 APPLICATION OF SOME LONGITUDINAL HANDLING QUALITIES CRITERIA FOR HIGHLY AUGMENTED AIRCRAFT TO AMX AIRCRAFT

AMX is a subsonic dedicated attack aircraft developed within the framework of a joint Italian-Brazilian program. It is a basically stable aircraft with a quasi-conventional FCS. in fact, it has been provided with a limited authority SAS which only marginally affects the flight characteristics, and the flight control is achieved by a three axes fly-by-wire system managed by a digital flight control computer along with conventional electrohydraulic lines. From the flight mechanics standpoint, it has been designed using basically the MIL-F8785-C requirements as design criteria, but for some specific tasks the MIL Specification proved insufficient to fit the flying characteristics, so the need for more demanding requirements arose.

More modern criteria have been applied in the areas of longitudinal and lateral-directional precision tracking tasks, to cope with our operational problems and prevent PIO tendencies. Both frequency and time domain criteria gave good results. For the longitudinal maneuvering characteristics, in general AMX shows good handling qualities and is in agreement with the MIL-F8785-C Specifications. Nevertheless in the context of our activity supporting the flight trials, we had some concern relating to the precision tracking task in some particular flight conditions. Figure 4.8.1 shows the longitudinal time and frequency response evaluation for one flight condition of interest.



MACH = 0.4
MEDIUM ALTITUDE

Figure 4.8.1 Typical Longitudinal Time and Frequency Responses

At the $M=0.4$ flight condtion illustrated in Figure 4.8.1 there were difficulties during precision tracking tasks but correlation with the military specification predicted good flying qualities. Comparison with the dropback criterion at several flight conditions as shown in Figure 4.8.2 does, however, indicate the degraded flying qualities observed in flight at $M=0.4$. In the landing condition the frequency response criterion was used with good success to prevent any PIO tendency.

4.8.1 References

4.8.1 Bava, R., "Flying Qualities Experience on the AMX Aircraft", AGARD Flight Mechanics Panel Symposium, Quebec, Canada, October 1990.

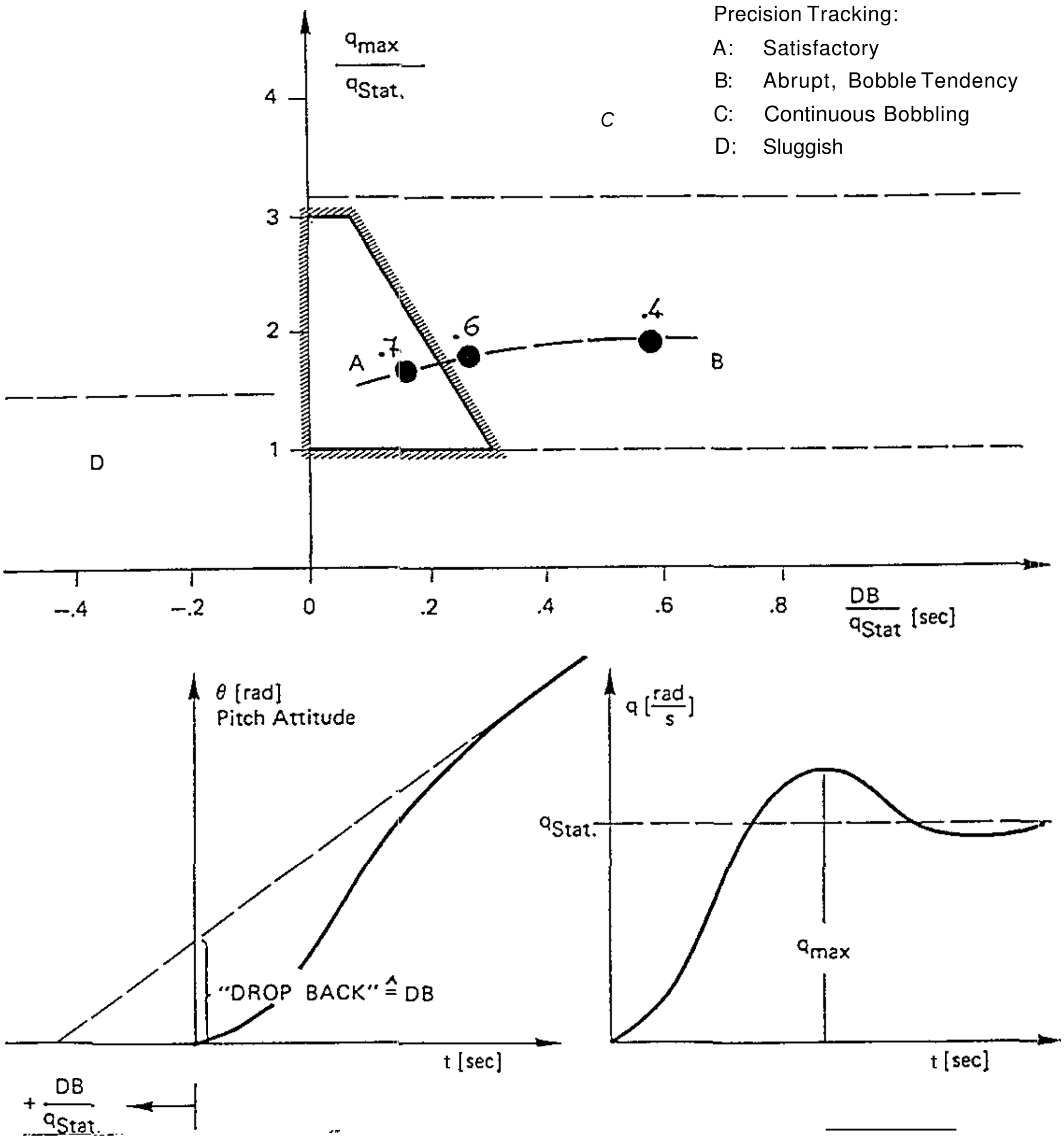


Figure 4.8.2 Comparison with the Dropback Criterion

4.9 TIME DOMAIN VS. FREQUENCY DOMAIN CRITERIA FOR PRECISION CONTROL

Although we have shown examples of time response criteria, in general the specification of handling qualities for precision tracking with aircraft attitude is best accomplished with frequency based criteria. These criteria emphasize features directly related to the piloted loop closure. Time domain criteria have been found to be more appropriate for use with lower frequency phenomena such as pursuit tracking, flight path control, etc. Most time domain criteria for attitude control are based on a step or boxcar input. Such inputs emphasize the mid and low frequency characteristics, at the expense of the response in the region of piloted crossover, which tends to be suppressed to the origin.

A moving-base piloted simulation experiment was conducted on the NASA Ames Vertical Motion Simulator specifically to compare rise-time type criteria vs. the Bandwidth criterion. The tasks were 1) to hover a VSTOL over a point on the deck of a ship in Sea State 3, and 2) to land on that point. Four configurations were formulated which had Identical Bandwidth, but exhibited wide variations in rise-time due to changes in the damping ratio. ACAH was used because of known problems with simulator validity for Rate Response-Types. The step input time responses and corresponding pilot ratings for the tested configurations are given in Figure 4.9.1. The pilot ratings are essentially invariant in spite of a wide variation in rise time, indicating that Bandwidth is a more appropriate metric than rise time for the prediction of handling qualities for small amplitude precision tracking tasks. In addition to these results, the time domain criteria had other shortcomings as follows:

- The Level 1 values of rise time involved very small values (order of .05 sec.).
- Slight variations in the shape of the "step" input caused significant changes in the rise time.
- Rise time data obtained from flight tests were not repeatable, due to the input shaping problem noted above, atmospheric disturbances, and problems with establishing ideal initial conditions.
- The important slope of the phase curve must be estimated from the effective transport time delay which is suppressed to the origin.

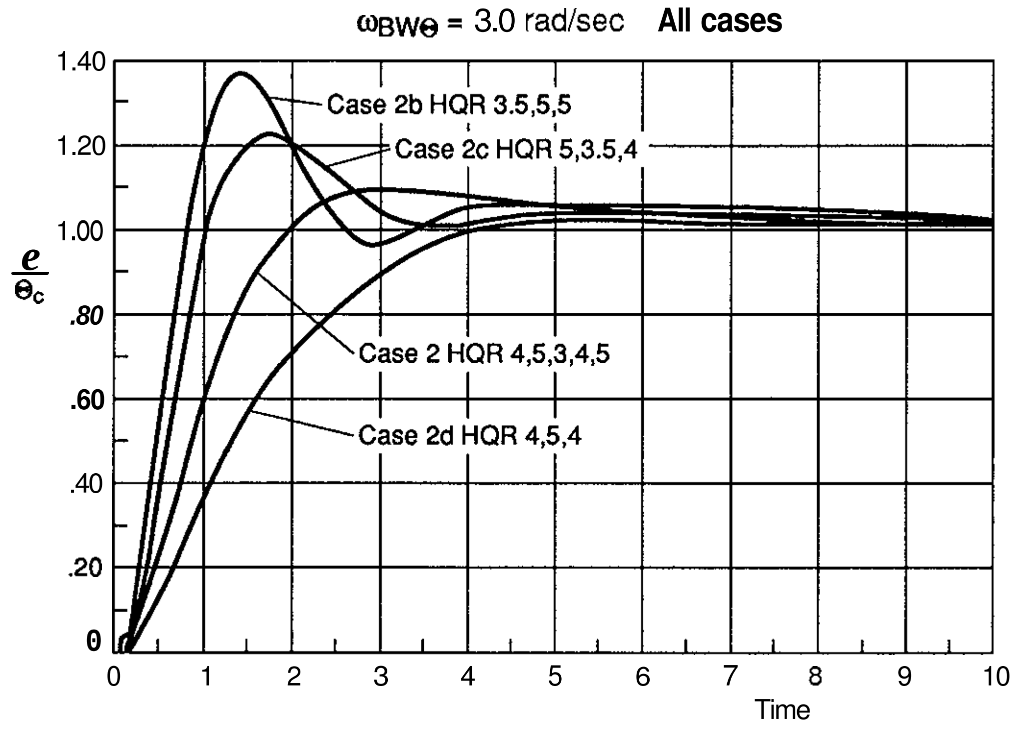


Figure 4.9.1 Illustration of Insensitivity of Pilot Rating to Rise Time - Bandwidth is Constant

While frequency domain criteria are generally more applicable, there has been some success with time domain criteria within experiments. For example, the transport handling qualities work accomplished in Reference 4.9.1 showed considerable success in correlating handling qualities ratings with time response envelopes. For the unified flying qualities method presented herein, frequency domain criteria are recommended for small amplitude, precision, closed-loop tasks, such as precision landings, air refueling. formation flying, etc. However, the dropback criterion should also be checked to ensure that the augmentation has not resulted in excessive overshoot. Time domain criteria have been found to be particularly applicable to low frequency and/or large amplitude response characteristics, such as are discussed In Section 5.

4.9.1 Reference

4.9.1 Mooij, H.A., Criteria for Low-Speed Longitudinal Handling Qualities of Transport Aircraft with Closed-Loop Flight Control Systems, National Aerospace Laboratory NLR, Amsterdam, September 1984.

4.10 RELATIONSHIPS BETWEEN THE VARIOUS CRITERIA

Many features of the foregoing criteria are related. The phase slope, phase delay and equivalent delay parameters for example are not only aimed at the same augmentation phenomenon, they are often numberically similar. Short period equivalent frequency and the Neal-Smith lead parameter have also been shown to bo very closely related (Reference 4.2.16). To be effective, a criterion should address features of the augmented response that are known to affect flying quailties. Figure 4.10.1 indicates how each criterion addresses each response feature.

Longitudinal Criteria - Overview

HR - Characteristics	AUGMENTED RESPONSE FEATURE					COMMENTS	
	SHORT TERM				LONG TERM		
Criterion	Rapidity/ *Sluggishness*	Oscillatory *Characteristics*	High Frequency *Phase Lag*	Sensitivity	Path/ Attitude	Experience With Non-longitudinal AXIS & Problems	Potential for Further R&D Activities
Neal - Smith	Pilot Lag/ Lead	Closed Loop Resonance (PIO)	- Closed Loop Resonance - Sensitivity of solution to bandwidth	Separately specified	Separately specified		TBD
Bandwidth VS. Phase Delay	Bandwidth	Low Bandwidth especially due to gain margin limit	Large phase *delay or gain* margin limit		T_{02} *OR* ω_{BW_Y}	*All Axes*	Used for all *axes in 8501* upgrade
Equivalent Systems	Frequency	Damping	Equiv. time delay		Lumped in together cap.	- Lateral - Directional - RCAH, ACAH	**Has been** used to interpret existing 8785 requirements
Gain, phase margin	Phase margin	Gain margin	Gain margin/ phase margin	Gain margin	$T \Theta \infty$ Phase margin	None	TBD
OCM (Optimum Content Model)	Pilot Lag/ Lead	Closed Loop resonance	TBD	Separately specified	Separately specified	Extensive exploratory work	Has been used for wide variety of exploratory applications
Gibson	Uses effective frequency	Uses effective damping	Phase rate at -180 deg.		Uses path delay as separate parameter	**TBD**	**TBD**

Figure 4.10.1 Longitudinal Criteria Overview

SECTION 5

MODERATE AND LARGE AMPLITUDE LONGITUDINAL HANDLING QUALITIES CRITERIA

5.1 INTRODUCTION

Most new handling qualities criteria apply to small amplitude closed-loop tracking. However, this distinction is rarely made, and the criteria have been used for maneuvering at all amplitudes, sometimes with poor results. The ability of fly-by-wire technology to tailor the handling qualities for different tasks has also focused attention on the need for separate small and large amplitude response criteria.

Physical limitations will usually prevent the achievement of identical response characteristics at all amplitudes. At angles of attack near the stall, lift slope variations alter the relationship between attitude and flight path, so that conventional parameter metrics become meaningless. The pitch down control margin at the stall may be quite small on unstable aircraft, and non-linear pitching moments are also commonplace, so that the response characteristics can depend both on direction of the control input and on the initial condition. Actuation rate limits alter the acceleration characteristics, and introduce a hard limit for unstable aircraft because feedback stabilization, and therefore control, will usually be lost.

5.2 CURRENT SPECIFICATIONS

There are currently no formal specifications for large amplitude maneuvering for fixed-wing aircraft. However, the rotary wing specification (ADS-33C, see Reference 3.1.2) includes a criterion for moderate amplitude maneuvering and this is discussed below in Section 5.4. The standard limits on frequency and damping define the normal acceleration and consequently the flight path response, and are certainly applicable for moderate amplitudes within the linear response range. Moderate and large amplitude criteria are required to insure that rapid degradations in handling do not occur at the onset of non-linear operation such as actuator rate limiting.

Current studies of agility have resulted in a number of metrics related exclusively to large or maximum amplitude maneuvers. All are essentially functions of the time to achieve some change in steady state by means of a rapid transient response. These are discussed further in Appendix C.

5.2.1 <u>References</u>

5.2.1 Gibson, John C., Handling Qualities for Unstable Combat Aircraft ICAS 86-5-3-1, 1986

5.3 CURRENT FLY-BY-WIRE AIRCRAFT

The basic pitch control laws are designed to satisfy the conventional Mil. Std. 1797 flight path requirements expressed as frequency and damping. In one example, (the F-15 STOL/Maneuvering Technology Demonstrator) this was done by the low order equivalent system method. in highly unstable aircraft such as the EAP and EFA, optimum handling can be achieved by adding command filtering to the basic regulated response. It is most convenient to satisfy flight path requirements directly, using boundaries such as those in Figure 5.3.1 converted directly from the Mil. Std. 1797 requirements. These can be applied to calculated responses without low order matching.

The frequency response bandwidth of a conventional aircraft, which is discussed in Section 4, is related to the flight path angle time delay as shown in Figure 5.3.2.

For good maneuverability a high bandwidth is necessary, but this could lead to attitude bobble or excessive attitude dropback which is unsatisfactory for precision tracking. In Section 4 it is shown that high bandwidth for good target acquisition can be retained with optimized small amplitude pitch tracking by use of amplitude dependent command filtering. For large amplitude maneuvers with full stick inputs, non-linear computer simulation is used with the qualitative goal of achieving the fastest possible response within actuation rate limits, reaching but not exceeding the structural envelope or controlled flight departure limits. Despite generally small initial pitch down control moment in unstable aircraft at high angles of attack, recovery to level flight can be made as fast as the pitch up by the use of a suitable command structure.

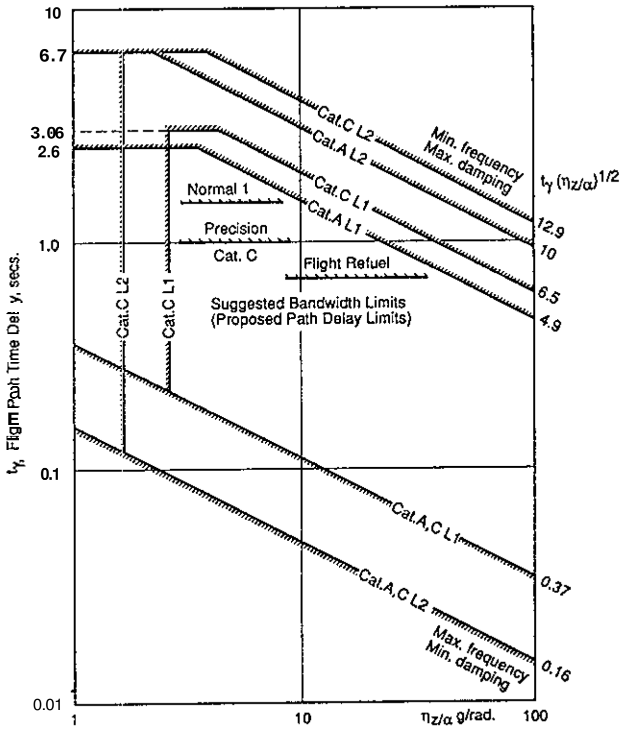
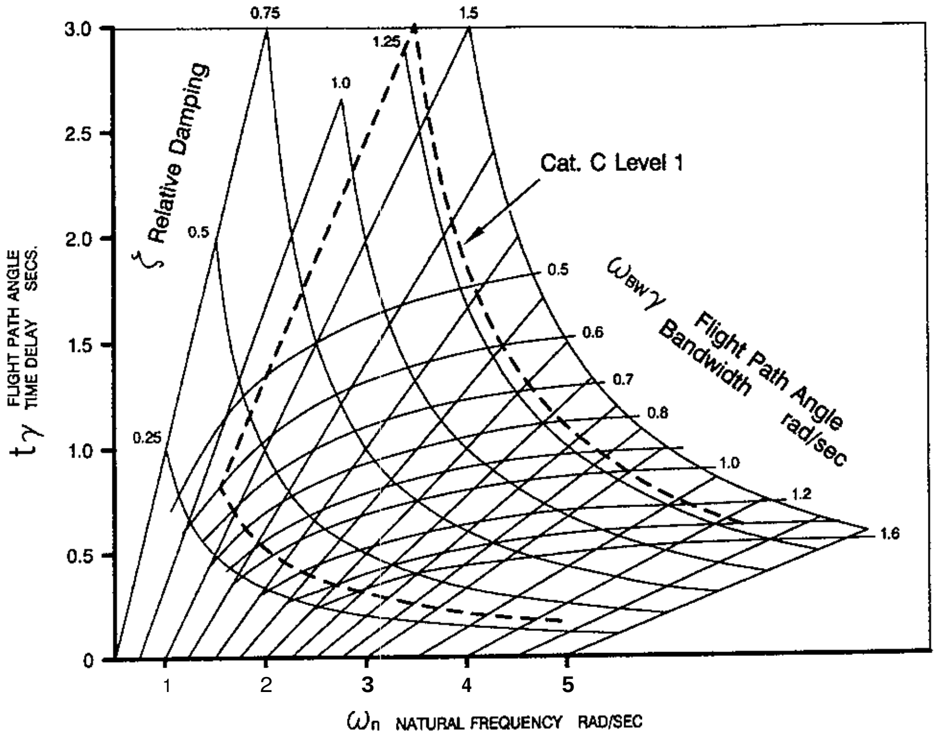


Figure 5.3.1 Transformed Frequency and Damping Boundaries



$\omega_{BW\gamma}$ = Frequency at which phase lag is 135 degrees

Derived from $\zeta = \frac{1}{2}\left[\left(\frac{\omega}{\omega_n}\right)^2 - 1\right] \frac{\omega_n}{\omega} \tan \phi$

t_γ = Effective delay in step time response

Figure 5.3.2 Flight Path Angle Bandwidth

While general criteria for gross maneuvers are not available, the basis from which both small and extreme amplitude responses are developed is the nominal moderate amplitude control system.

5.4 ATTITUDE QUICKNESS CRITERION

This criterion was formulated to apply to moderate amplitude maneuvering, defined here as pitch attitudes over ± 5 degrees and roll attitudes over ± 10 degrees about trim. It accounts for the fact that the bandwidth must decrease as the maneuver amplitudes increase, to keep accelerations within reasonable limits, and to avoid actuator rate limiting. The parameter. $p_{pk}/\Delta\phi$, termed "attitude quickness" turns out to be an ideal solution since it is a time domain equivalent to bandwidth, and thereby represents a direct extension to the small amplitude precision tracking criterion. The equivalence between bandwidth and attitude quickness is valid as long as the input is single sided (pulse or boxcar) as shown in Figure 5.4.1 (see Reference 3.2.2 for details). Therefore, it is important that the test inputs used for comparison with the criterion boundaries be essentially one sided (i.e., the cockpit control should not reverse sign from the trim value). Experience has shown that open loop pulse inputs of increasing magnitude work best.

Criterion boundaries have not been developed for fixed wing aircraft. However, the general shape of such boundaries can be seen in Figure 5.4.1.

Physically, bandwidth and $p_{pk}/\Delta\phi$ are measures of the crispness of the response. The extension to larger amplitudes allowed by the attitude quickness criterion provides an excellent measure of agility. The need for such a measure was apparent during an agility conference held at Edwards AFB (Reference 5.4.1). There it was noted that the best criteria involved the time to change attitude through specified angles, but that such criteria were inherently closed loop in nature. As a result, they tended to be overly sensitive to the tolerance of the final attitude, and to individual pilot technique. The $p_{pk}/\Delta\phi$ parameter is a measure of the quality of the closed loop response, and has the desirable feature of being based on open-loop testing.

'The parameter $p_{pk}/\Delta\phi$ is used in this discussion to represent the form of the criterion. The ratios $F_{pk}/\Delta\theta$ and $r_{pk}/\Delta\psi$ are used to set boundaries on the pitch and yaw axes, respectively.

Based on Open Loop Boxcar inputs of Varying Duration and Amplitude.

Is Analogous to Bandwidth, Except it applies to Larger Amplitude Maneuvers.

Definition of Criterion Parameters, and expected Shape of Boundaries is shown below.

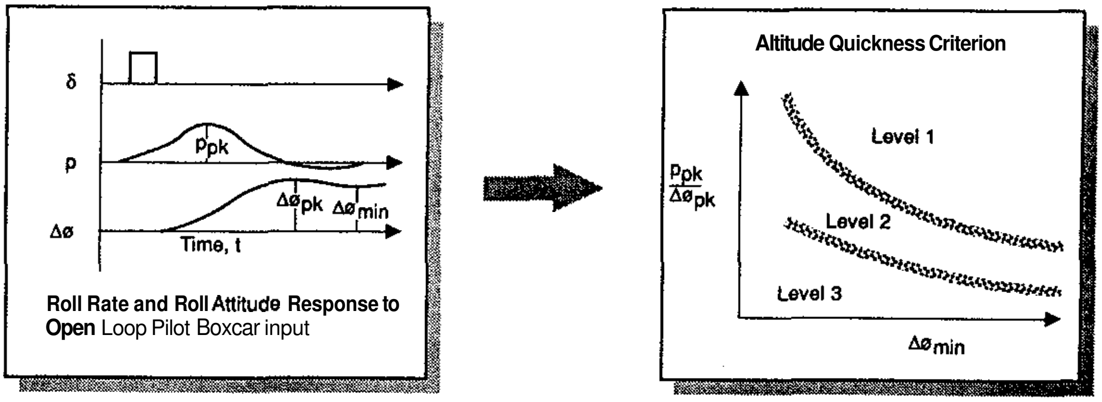


Figure 5.4.1 Attitude Quickness Criterion as a Moderate Amplitude Agility Requirement

5.4.1 References

5.4.1 Lt. Alan Lawless, "AFFTC Agility Metric/Flight Test Workshop", Edwards AFB. March 1988

5.5 NON-LINEAR SIMULATION

Accurate modeling of system and aerodynamic non-linearities and of all hardware dynamics is essential for the development of large amplitude response characteristics. This requirement applies equally to computer and piloted simulations, which should use the same models. The process;is largely empirical and depends strongly on tho experience of the designer and pilot to uncover the possibilities for loss of control or limit exceedance. It will generally be possible to develop a standardized routine of test inputs, but these will not always find the most critical case and there is no substitute for perseverance in attempting to catch the system out. To ensure complete robustness, no input or combination of inputs can be considered too extreme.

5.6 BIFURCATION THEORY

Available mathematical tools and optimal methods are derived from linear systems through various linearisation techniques, and are unsuitable for the analysis of large amplitude responses which are inherently non-linear.

A new methodology has been developed for this purpose, based on the bifurcation or catastrophe theory, which allows a systematic analysis of angles of attack such as stalllspin departures, arid can give useful information for the subsequent recovery. The method has been validated recently to yield very good correlation between predic'lion of spin departures and flight test results on an Alpha-Jet aircraft (References **5.6.1** through **5.Ei.3).**

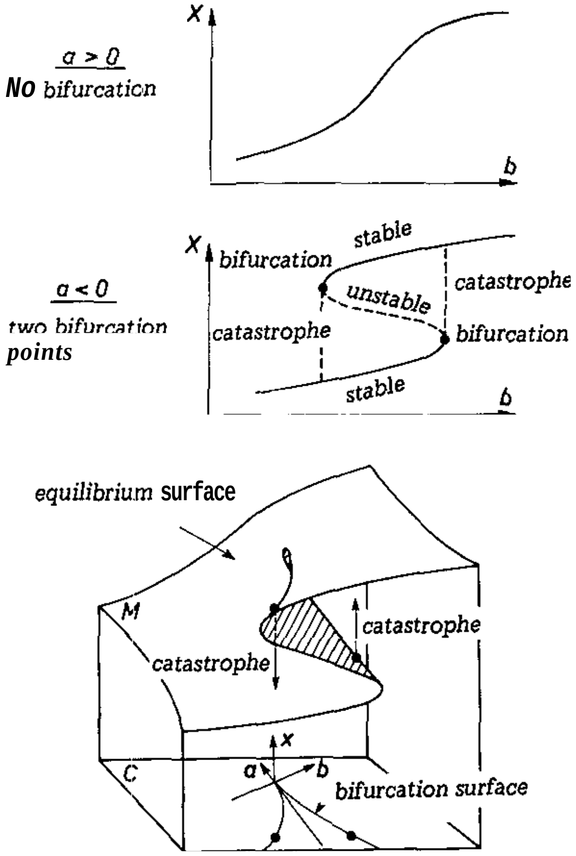


Figure 5.6.1 Map of Equilibrium Solutions

This theory can be illustrated briefly with a scalar non-linear example of the form: $\dot{x} = -x^3 + ax + b$). The map of equilibrium solutions of this equation, defined by $0 = (x^3 + ax + b)$, is represented in terms of parameters a and b of the system in Figure 5.6.1. Associated with the computation of the eigenvalues of the jacobian matrix related to all the equilibrium solutions, the behavior of the non-linear system can be derived easily as functions of variations on its parameters a and b. Thus the method allows a prediction of jumps in the solutions according to the variations on parameters.

More generally, the computation of the bifurcation surface, defined as the map in the space of parameters where there are jumps in equilibrium solutions, provides a powerful means for a non-linear behavior analysis of the system. This notion of bifurcation, which is presented here in the single case as discontinuities related to equilibrium solutions, concerns a wider class of steady-state solutions of the system such as periodic solutions or limit cycles, or quasi-periodic solutions, or chaotic motion.

5.6.1 References

5.6.1 Guicheteau, Ph., "Application de la Theorie des Bifurcations a l'Ètude des Pertes de Conlroie sur Avion de Combat", AGARD CP-319, Oct. 1981
5.6.2 Guicheteau, Ph., "Bifurcation Theory Applied to the Study of Control Losses on Combat Aircraft", Recherche Aerospatiaie, no. 1982-2 (Engiis Edition of ONERA publication)
5.6.3 Guicheteau, Ph., "Bifurcation Theory in Flight Mechanics - An Application to a Real Combat Aircraft", 14th ICAS Congress, Stockholm, 9th-14th Sept. 1990

SECTION 6

IMPACT OF UNSTABLE DESIGN AND HIGH ANGLE OF ATTACK ON THE REQUIREMENTS FOR THE AERODYNAMIC CONFIGURATION

6.1 INTRODUCTION

From the very beginning, all the design phases of "New Generation" fighter aircraft are dominated by the attempt to find an optimum balanced concept within the constraints of maximum performance, defined mass figures and limited costs. The field of performance especially encompasses aspects in at least three dimensions, which may be titled "Mission-, Point- and Maneuver Performance." Requirements derived from these different items are often rather contradictory.

A suitable tool to overcome some of the contradicting requirements is the introduction of Unstable Design in pitch which has remarkable effects on performance as demonstrated in Figure 6.1.1. The trim characteristics of the *sample* aircraft (*i.e.* a tail-less configuration; the principles apply for any tailed configuration as well) show that the stable version will have negative slopes in the pitching moment-lift diagram for controls fixed. Therefore, it is necessary to trim the configuration with negative (i.e. upwards) flap deflections. An unstable design with the center of gravity aft of the aerodynamic center, has a positive $\partial c_m / \partial c_L$ (and $c_{m\alpha}$) slope and therefore requires positive (i.e. downwards) flap settings for trim. The sketch of the polars in the lower part of Figure 6.1.1 shows the resulting beneficial effect on trimmed performance data. Typical supersonic fighter wings are characterized by a relatively small aspect ratio and high leading-edge sweep. Especially for those, the induced drag for a given lift coefficient is much smaller with positive than with negative flap deflections. This leads, on one hand, to a remarkable reduction in overall drag at a desired turn rate and, on the other, to a much larger trimmed maximum lift coefficient. If the full technically feasible potential of unstable design is used, then relative to a conventionally stable aircraft maximum lift can be increased by roughly 25% and induced drag at a typical lift Coefficient for maneuver (say $C_L = 0.7$) can be reduced by about 20%. This means that unstable configurations when designed for the same performance requirements and under the same flight mechanical constraints, will be much smaller than

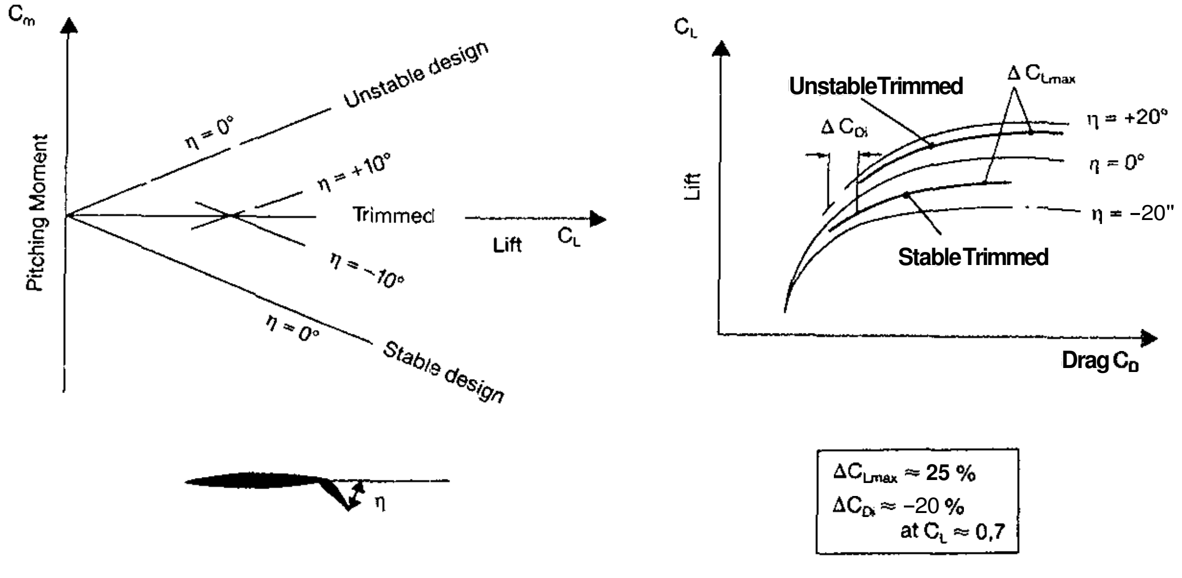


Figure 6.1.1 Effect of Destabilization on Performance

their stable "brothers" as shown in Figure 6.1.2. A reduction in combat mass (including internal fuel) of about 18%, a smaller required thrust of about 16% and a reduction in wing area of about 18% can be achieved as demonstrated by detailed studies. But, it has to be kept in mind that, a pure optimization for maximum point performance (i.e. sustained and instantaneous turn rates) which requires maximum lift or minimum drag respectively may not be advantageous for a desired superior agility, because the preloaded aerodynamic controls do not leave enough power to initiate and stop maneuvers in a way which lead to sufficient handling qualities (Reference 6.1.1).

Handling qualities at high angle of attack have always been considered as an important factor in flight safety. Departure and spin are the results of loss of control at high angles of attack. Therefore, all design requirements prefer an aircraft with an easily perceptible stall approach (stick-shaking or aircraft buffet), high departure resistance and an easy recovery technique. The general trend to enlarge the operational flight envelope for present and future fighters towards higher angles of attack and lower dynamic pressures leads very quickly to the absolute limits of pure aerodynamic control devices. Hence these flight regimes may not be exploited operationally unless additional control power is provided by thrust. In the recent past some experimental programs (F-18 High Alpha Technology Program, X-29 Program, X-31A Program) have been launched, which are dedicated to demonstrate the operational advantages in an air-to-air combat environment using high angle of attack maneuvering. Flight testing of these aircraft will result in a better insight into handling qualities requirements for flying and maneuvering at high angle of attack.

6.1.1. References

6.1.1 Beaufrere, Henry L., et.al., Control Power Requirements for Statically Unstable Aircraft, AFWAL-TR-87-3018, June 1987

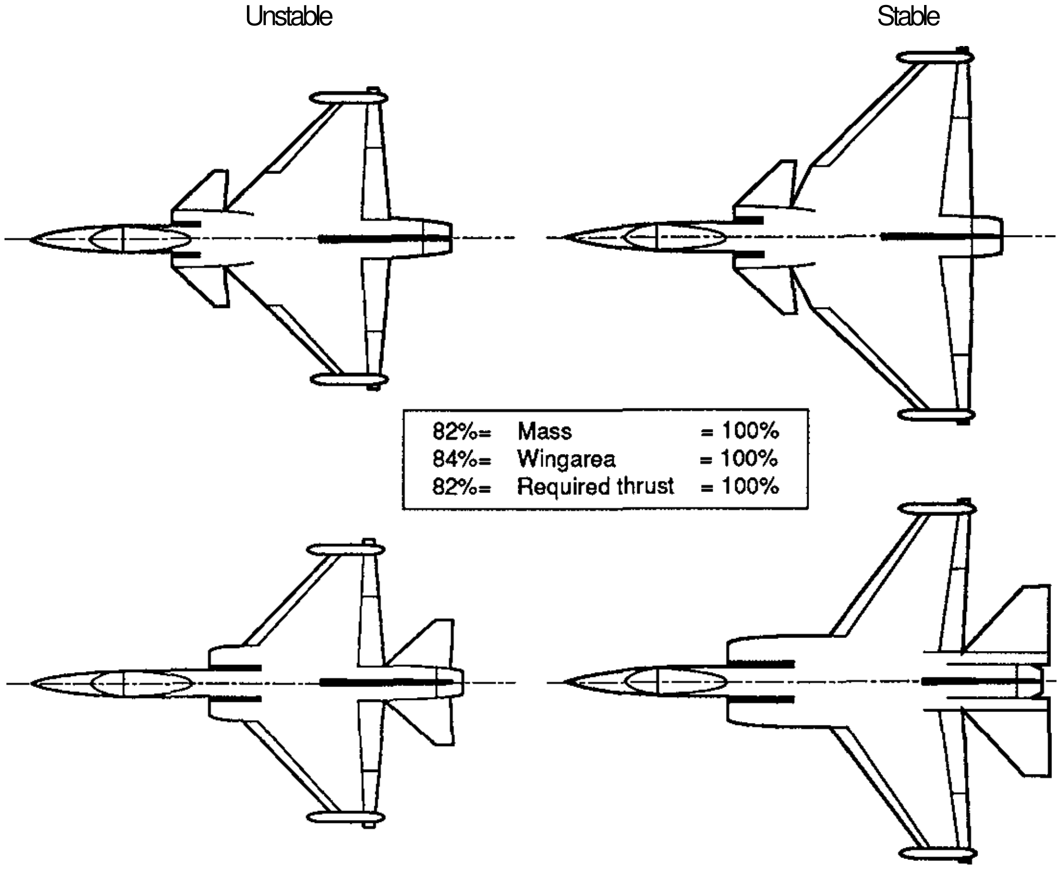


Figure 6.1.2 Effect of Optimum Design on Aircraft Size

6.2 RATIONALE FOR THE NECESSITY OF ADDITIONAL FLIGHT MECHANICAL DESIGN CRITERIA

As already mentioned above, the tool "Aerodynamic Instability" has broadly been applied by the overall design people to modify the rellation between point performance and mass properties. On the other hand, usually no notice is taken of the fact that the introduction of desired instability levels will have major impacts on the required control margins which are necessary to satisfy the high demands on maneuver performance including key characteristics like agility, handling and ride qualities.

The comparison in Figure 6.2.1, taken from a generic simulation study, shows, for example, that a 50% reduction of pitch recovery margin at high angles of attack (this minimum allowable margin forms an essential corner stone for unstable configurations) will require excessive pitch down power (400%) at low angles if identical time to pitch down is specified. So, if such relations are neglected at the beginning of a definition or development phase when more thorough considerations about the design of the flight control system (soft/hardware) and about the flight mechanical requirements are necessary, the unpleasant consequences of these incomplete design procedures are evident:

- Too large dynamic design instabilities (introduced for the sake of point performance) and/or local pitch-up zones lead to insufficient safety margins (phase/gain margin).
- A sluggish pitch response has to be implemented to prevent over-shoots.
- Loaded control/trim surfaces (scheduled for the sake of point performance) exhibit reduced pitch efficiencies and/or control power especially at medium and high angles of attack.
- Large positive symmetrical flap settings (necessary for maximum lift) reduce avallable roll control power.
- Control surface schedules required from the various disciplines are contradictory (Point performance optimum /= Maneuverability optimum |= Load alleviation optimum).
- Carefree handling requirements reduce the angle of attack envelope promised by the basic aerodynamic characteristics of the chosen configuration.

As many of the points mentioned above will affect specifications already contractually fired, the situation may be insoluble.

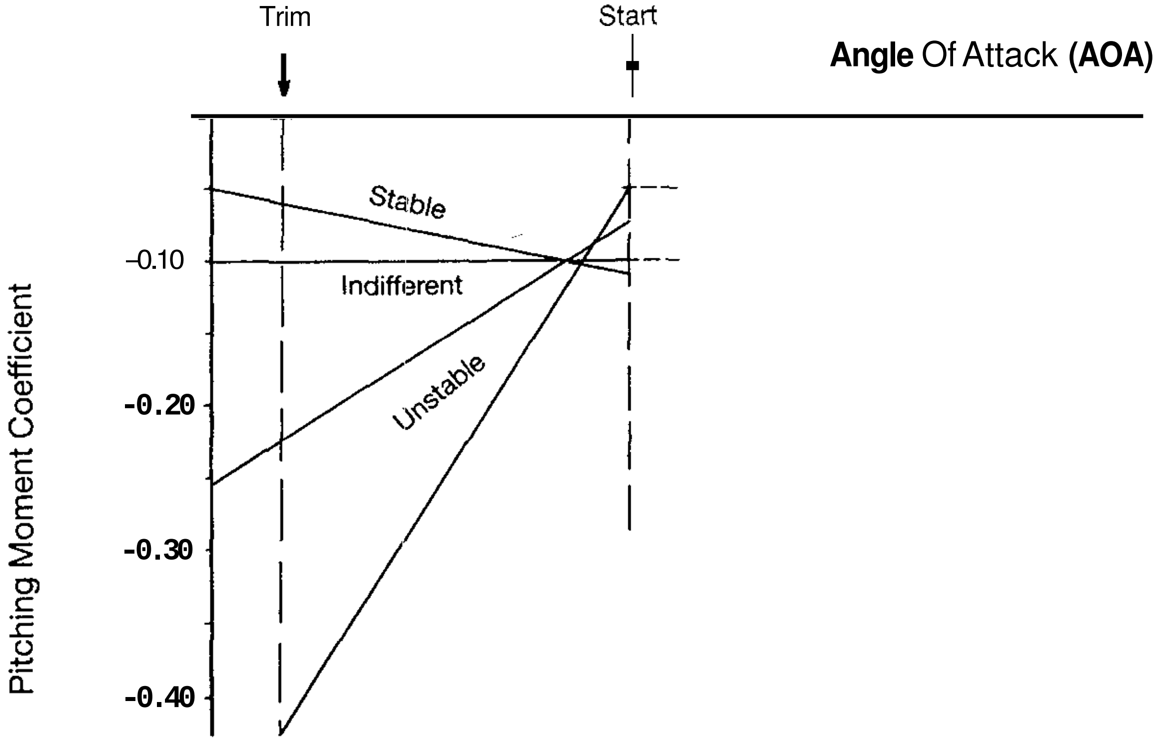


Figure 6.2.1 Nose Down Pitching Moment Plots Yielding Identical Time to Pitch Down from "Start AOA to "Trim "AOA"

In any case such an unfavorable coincidence of facts can be avoided if an integrated design procedure is used from the very beginning. This implies, that a set of flight mechanical criteria is available which translates the most important aspects derived from Handling Agility and Safety into aerodynamic requirements

6.3 SCOPE OF THE REQUIREMENTS AND CRITERIA

The criteria to be developed shall generate the necessary link between the disciplines of control law design, flight mechanics and aerodynamics within the pre-development phases of modern fighter aircraft. In order to achieve complete design cycles considering mass, overall performance, cost and risk properties, it is necessary to enlarge the idea of "performance" by including agility, handling and ride quality requirements and by introducing essential aspects from the safety point of view. The criteria may have to be based on simplified assumptions but must be convertible into aerodynamic characteristics to enable the design team:

- to define feasible aerodynamic instability levels
- to fix trim schedules which leave sufficient control power in pitch, roll and yaw
- to optimize the basic aerodynamic pitch and lateral- directional characteristics In the wind tunnel (for example, allowable local pitch-up and required minimum lateral stability characteristics)
- to size and position the control surfaces

Therefore, the overall control margin requirements must consider the three basic aspects listed below:

- Control Authority is defined as the total control moment which is available from all the moment producers about one specific axis. According to the individual reliability of the controllers the sum of moments may be split into different parts. The safety related tasks have to be fulfilled with highly reliable moment producers -typically, aerodynamic surfaces with redundant hydraulic actuators. Using the remaining controllers or remaining control authority, the operational (agility) requirements must be met.
- Control Deflection Rates must be large enough to avoid the saturation of actuator rates which causes phase loss in the control loops. This phase loss reduces stability margins as defined in MIL-F-9490D and the PIO (Pilot induced Oscillation) resistance of the vehicle. The describing function of the rate limitation (Figures 6.3.1 and 6.3.2) can be used as an instrument for calculation of "large amplitude" phase and gain margins.
- For both, authority and rate, limitations due to hinge moments or other load restrictions have to be considered.

MIL-F-8785C (Reference 6.3.1) defines the basic requirements for control margins and in Flying Qualities of Piloted Vehicles MIL-Prime Standard and Handbook (Reference 6.3.2) a detailed qualitative requirement is given as follows:

> "Control authority, rates and hinge moment capability shall be sufficient to assure safety throughout the combined range of all attainable angles of attack (both positive and negative and sideslip). This requirement applies to the prevention of loss of control and recovery from any situation for all maneuvering, including pertinent effects of factors such as pilot strength, regions of control-surface-fixed-instabiiity, inertial coupling, fuel slosh, the influence of symmetric and asymmetric stores, stalllpost-stalllspin characteristics, atmospheric disturbances and aircraft failure states, maneuvering flight appropriate to the failure slate is to be included. Consideration shall be taken of the degree of effectiveness and certainty of operation of limiters, c.g. control malfunction or mismanagement, and transients from failures in the propulsion, flight control and other relevant systems".

Application of this requirement in conjunction with handling quality requirements during the design of modern fighter aircraft leads to a great number of independent control margin requiremenis. The absolute values of the required control power however differs for each aircraft configuration and its flight envelope. Therefore, specific margins cannot be defined exactly and rough approximations have to be used as given in the next sections.

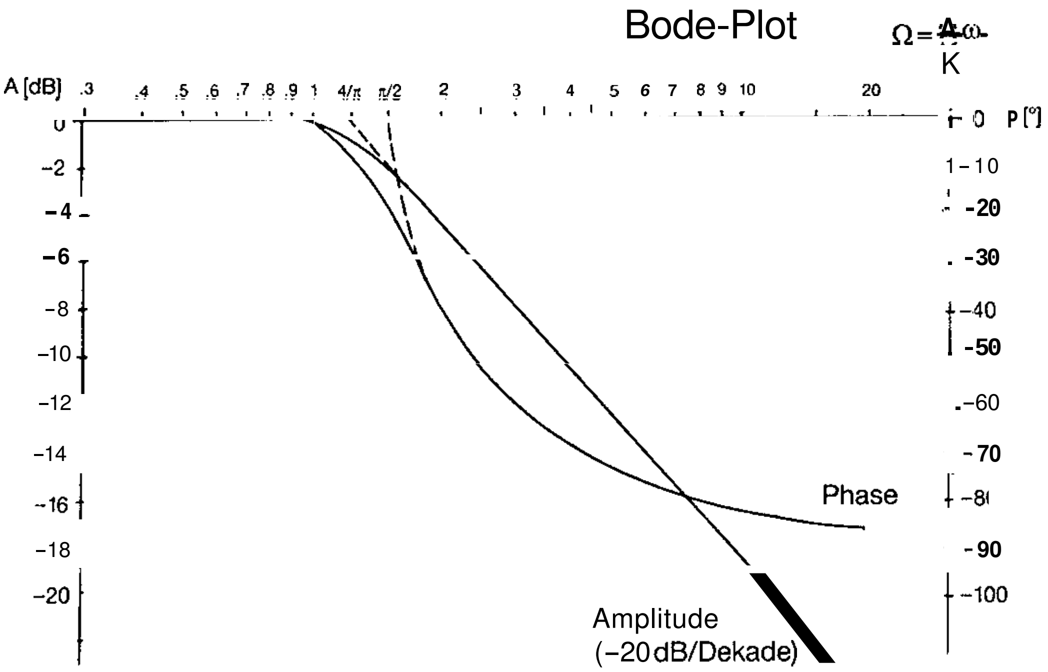


Figure 6.3.1 Describing Function of the Rate Limitation

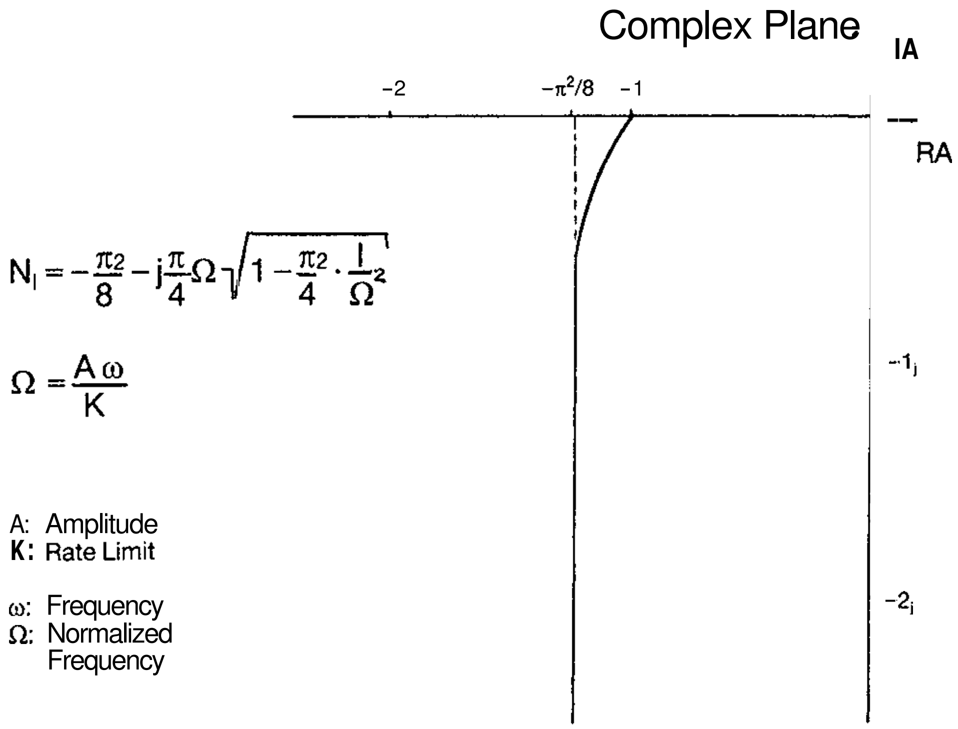


Figure 6.3.2 Negative inverse Describing Function

6.3.1 References

6.3.1 Military Specification, Flying Qualities of Piloted Vehicles, MIL-F-8785C November 1980

6.3.2 Military Standard, Flying Qualities of Piloted Vehicles, MIL-STD-1797 (USAF), March 1987

6.4 DESIGN CRITERIA AND REQUIREMENTS AVAILABLE UP TO NOW

In the recent past at least some experience and studies have been published (References 6.3.2, 6.4.1, 6.1.1, 6.4.2, 6.4.3) which give the opportunity to fix some numbers for the control power to be installed.

6.4.1 Pitch Control Power

The summary in Figure 6.4.1 (taken from References 6.4.2, 6.4.4 and 6.1.1) presents a set of formulas and relationships which should lead to necessary pitch control margins for the preliminary design phases of a modern fighter aircraft. in detail the following aspects have to be reviewed and numbers have to be settled:

- Control Power Related to Flying Quality
  For a given CAP (Control Anticipation Parameter, as defined in MIL-F-8785C and the desired normal acceleration range the required control power can be calculated depending on aircraft inertia and dynamic pressure. It should be mentioned that this control power is independent of the static stability of the airplane. For maneuvering above maximum lift, angle of attack has to be used instead of normal acceleration. Here no requirement for the dominant eigenvalue exists up to now. But as a first guess, the required short period frequency for low angle of attack at the desired flight condition can be used.
- Control Power to Maintain Stability
  Using a simplified linear two degrees of freedom transfer function. the necessary control power to stabilize the aircraft at the desired angle of attack after a maximum pitching maneuver can be calculated according to Figure 6.4.1. For highly unstable aircraft the lags and delays introduced by flight control hardware will increase the necessary control power. Therefore, a analysis with the full system should be done to confirm or increase the control power calculated with the simplified equation.
- Control Power to Counteract Gust and Turbulence
  The control power in a gusty and turbulent environme[illegible] is mainly [illegible] b[illegible] the [illegible]k coefficients of the flight control system. They are themselves a function of the static stability and control effectiveness. An approximation for the required control power is given in Figure 6.4.1.
- Control Power for Inertia Compensation During Rolls
  It is a physical law, that during rolling and yawing motions of the aircraft pitching moments will be induced due to inertia coupling and gyroscopic effects of the engine. This moment depends only on rotational rates and inertias and can easily be calculated from the roll rate requirements and the configuration data as shown in Figure 6.4.2. At low dynamic pressure and high angles of attack even with low roll rates, a large pitch down moment in terms of c_m is required. This is the reason why this requirement is one of the design drivers for pitch down capability.
- Control Power for Nose [illegible]wn Stall Recove[illegible]y
  This safety relate[illegible] [illegible]nent is usually automatically fulfilled if the requirements regarding flying qualities at high angles of attack are met, because the control power for maneuvering will be at least twice the control power for recovery. In Reference 6.3.2 a net pitch restoring moment $|c_m|$ of not less than 0.1 is suggested to be used as a requirement. in the normal case, however, where the aerodynamic control power needs augmentation with thrust vectoring to get acceptable flying qualities at low speed and high angles of attack, the safety related "stall recovery" requirement shall be accomplished with the highly reliable aerodynamic surfaces.
- [illegible]ontrol [illegible]ower fo[illegible] Nosewh[illegible] Off Prior to Desired Takeoff Speed
  [illegible]his requirement will settle the [illegible]nimum airspeed wh[illegible] lift-off of the nosewheel is possible

Some other experiences have been published (Reference 6.4.1) where pitch control margins are suggested which combine some of the different contributions, discussed above in a single number. For "Nose Down Stall Recovery", "Potential for Stabilization Purposes", "Sufficient Handling Qualities", and for "Counteracting of Gusts", a minimum pitch acceleration capability of $|\theta| \leq -0.3$ rad/sec^2 is recommended at high angles of attack as indicated by the constant part in Figure 6.4.2. It is assumed, however, that this margin will only be sufficient if the local instability level is less than the chosen basic instability. In addition, the inertial coupling term has to be considered as indicated in the figure.

Another attempt has been made in 6.4.2 to define the required pitch control power in terms of required moment M and moment onset rate $\dot{M}$ as a function of instability T_2 (time to double amplitude of basic aircraft). The charts of Figure 6.4.3 should be valid for all tail concepts within the CAT.A flight phases. The recommendations have been evaluated considering the requirements of Figure 6.4.4. In particular the safety aspects with respect to control law design, Level 1 CAT. A handling qualities in pitch and good gust response characteristics may be achieved if the boundaries of Figure 6.4.3 are avoided by a proper design. Furthermore, realistic hardware assumptions for sensors, filters, computers and actuators have been made in this study which lead to the sharp limits due to phase/gain margin in the relevant graphs.

6.4.2 Roll/Yaw Control Power

The requirements of roll and yaw control power may be handled together because in almost all the cases combined deflections are needed to perform *lateral/directional* maneuvers.

- Control Power Related to Flying Qualities
  The control power needed to fulfill the flying quality requirements is either settled by the control power for sideslip command (initial acceleration) or the control power needed to fulfill the roll time constant requirement in a wind axis roll. As sketched in Figure 6.4.5 the requirements for the yaw and roll controllers can be derived from the relevant MIL-spec criteria for Roll Mode Time Constant τ_R and Time-to-Bank. For aircraft which are designed for high angle of attack *maneuvering*, the yaw control power derived from roll will be more stringent because the inertia ratio I_z^2/I_x^2 is considerably larger than 1 (for modern
  5 to
- Control Power to Maintain Stability
  In this case, requirements similar to those for the pitch axis can be used. At high igl of attack, however, most of the airplane configurations lose aerodynamic yaw control power; therefore, controlled maneuverability can only be maintained with thrust vectoring. The reliability of thrust vectoring is, up to now, not high enough to handle a safety critical item. For this reason, a stable lateral-directional aircraft configuration is recommended for high angle of attack flying. Applicable criteria to achieve this goal have been developed ($C_{n\beta dyn}$, LCDP etc.) and are broadly used in spite of the fact that they may not always be valid at high angles of attack (References 6.4.1 and 6.4.5). An attempt to overcome some of the deficiencies related with $C_{n\beta dyn}$ and LCDP is presented in Reference 6.4.3 where the criteria have been modified by the introduction of dynamic derivatives.
- Control Power to Counteract Crosswind, Gusts and Turbulence
  In addition to the pitch axis requirements, the control power for osswind landing has to b added, but this has no influence on the high angle of attack control power requirements
- Control Power for Inertia Coupling Compensation
  Similar to the pitch axis, rolling and yawing moments induced by inertia g and by gyroscopic effects of the engines have *to be* taken into account and cancelled by the available control power. As illustrated in 6.4.3, the most challenging effect is introduced by an additional yaw acceleration due to a combined roll/pitch maneuver. This effect may increase the requirements for the rudder efficiency by a considerable amount and aggravate the situation especially at high angles of attack.
- Control Power to Cover Engine Failure
  This classical requirement for twin engine fighters should be considered in any case in order to define the "Minimum Control Airspeed" V_{MC}.

Flying Quality	$\Delta\delta_{FQ}/\Delta n_c = 57.3\ CAP'/M_\delta$ deg/g (for $T_{eff} \le 0.05$)
Stabilization	$\Delta\delta_{stab}/\Delta n_c = 57.3\ \frac{g}{U_0} \cdot \frac{1/T_{sp_1} \cdot 1/T_{sp_2}}{M_\delta \cdot 1/T_{\theta_1}}$ deg/g (linear, 2 DOF)
Turbulence	σ_δ/σ_w fn of M_α, M_δ, $\omega_{sp_{cl}}$, $\zeta_{sp_{cl}}$, structural modes - most severe at low $\bar{q}$ - $3\sigma_\delta$ and σ_w for severe turbulence recommended
Sensor Noise	σ_δ/σ_s fn of K_s, K_F, ω_s, $1/T_a$, $\omega_{sp_{cl}}$, $\zeta_{sp_{cl}}$, $\omega'_{p_{ol}}$
Flying Quality	$\dot{\delta}_{FQ}/n_c = 57.3\ CAP/(M_\delta \cdot T_{eff})$ for desired CAP
Stabilization	$\dot{\delta}_{stab}/n_c < \dot{\delta}_{FQ}/n_c$ if FCS stability margins OK & $\frac{1}{T_{eff}} > \omega_c$ $\dot{\delta}_{stab}/n_c$ fn of $1/T_{eff}$, $1/T_{sp_1}$, $\omega_{sp_{cl}}$, $\zeta_{sp_{cl}}$
Turbulence	$\sigma_{\dot{\delta}}/\sigma_w$ fn of $1/T_a$, $\omega_{sp_{cl}}$, $\zeta_{sp_{cl}}$, M_δ - Most severe at low $\bar{q}$ - $3\sigma_{\dot{\delta}}$ recommended for control margin
Sensor Noise	$\sigma_{\dot{\delta}}/\sigma_s = K_s K_F \cdot$ fn (ω_s, $1/T_a$ and, for low $\omega_{sp_{cl}}$: $\omega'_{sp_{ol}}$, $\omega_{sp_{cl}}$, $\zeta_{sp_{cl}}$) - These parameters are not all independent - $3\sigma_{\dot{\delta}}$ recommended for control margin

Δn_c is the commanded increment of normal acceleration

$1/T_1$ is the unstable pole of the transfer function (negative; 1/sec)

$\omega'_{sp_{ol}}$ is the 2-deg-of-freedom product of the poles, 1/sec

$\omega_{sp_{cl}}$ and $\zeta_{sp_{cl}}$ are the closed-loop frequency and damping ratio of the short-period mode

CAP is $\dot{q}_0/\Delta n_\infty$, CAP' is $\dot{q}_{max}/\Delta n_\infty$

ω_s is the sensor bandwidth

K_s, K_F are the sensor and forward-loop gains

σ_s, σ_w are the rms intensities of sensor noise and vertical gusts

ω_c is the crossover frequency of the $\dot{\delta}/n_c$ transfer function

T_{eff} is the effective time constant of command-path plus forward-path control-loop elements (such as prefilters and actuators)

T_a is the time constant of the actuator ram

Figure 6.4.1 Required Control-Margin Increments

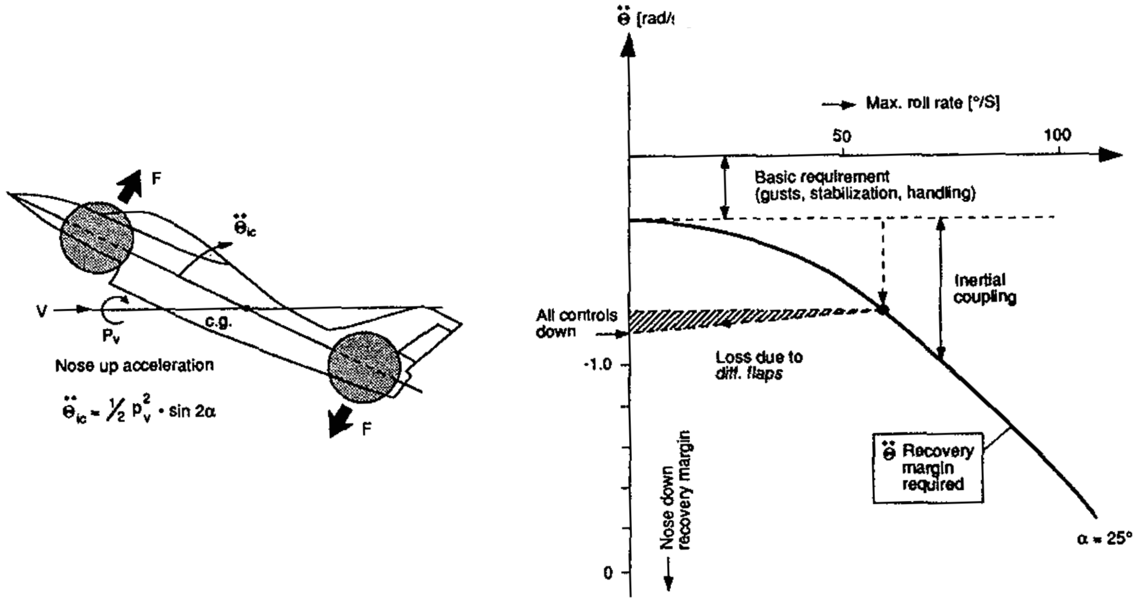


Figure 6.4.2 Definition of Pitch Recovery Margin at High Angles of Attack by Roll Rate Requirement

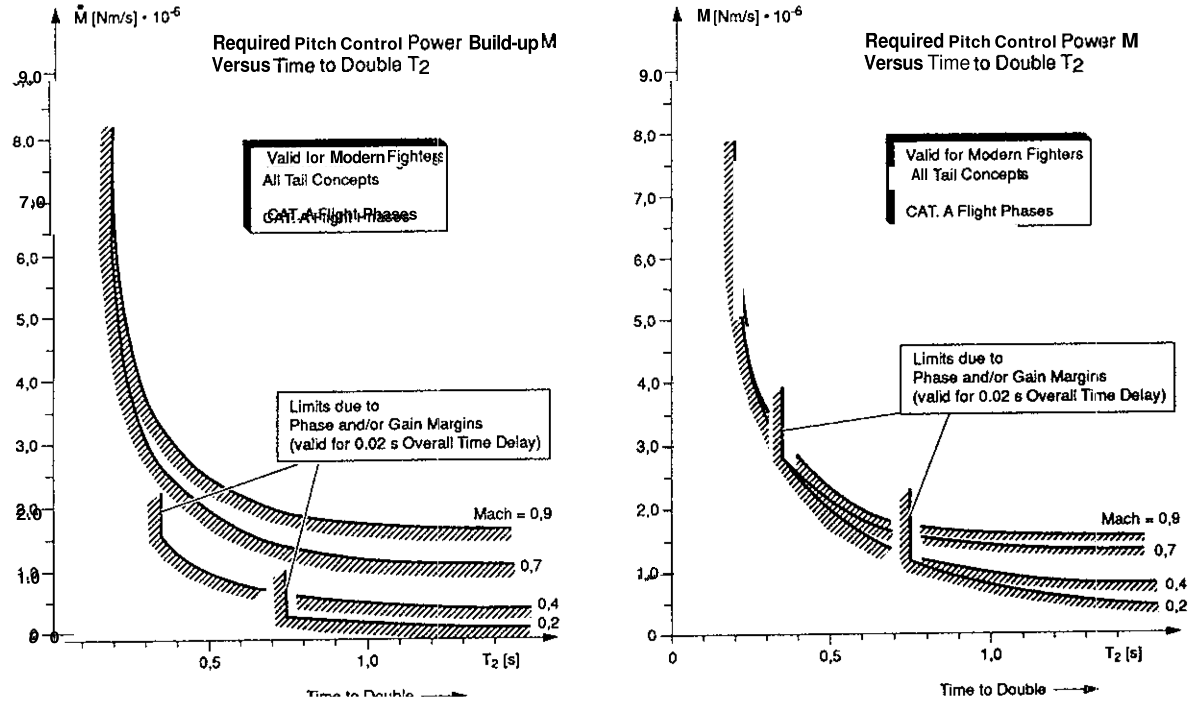
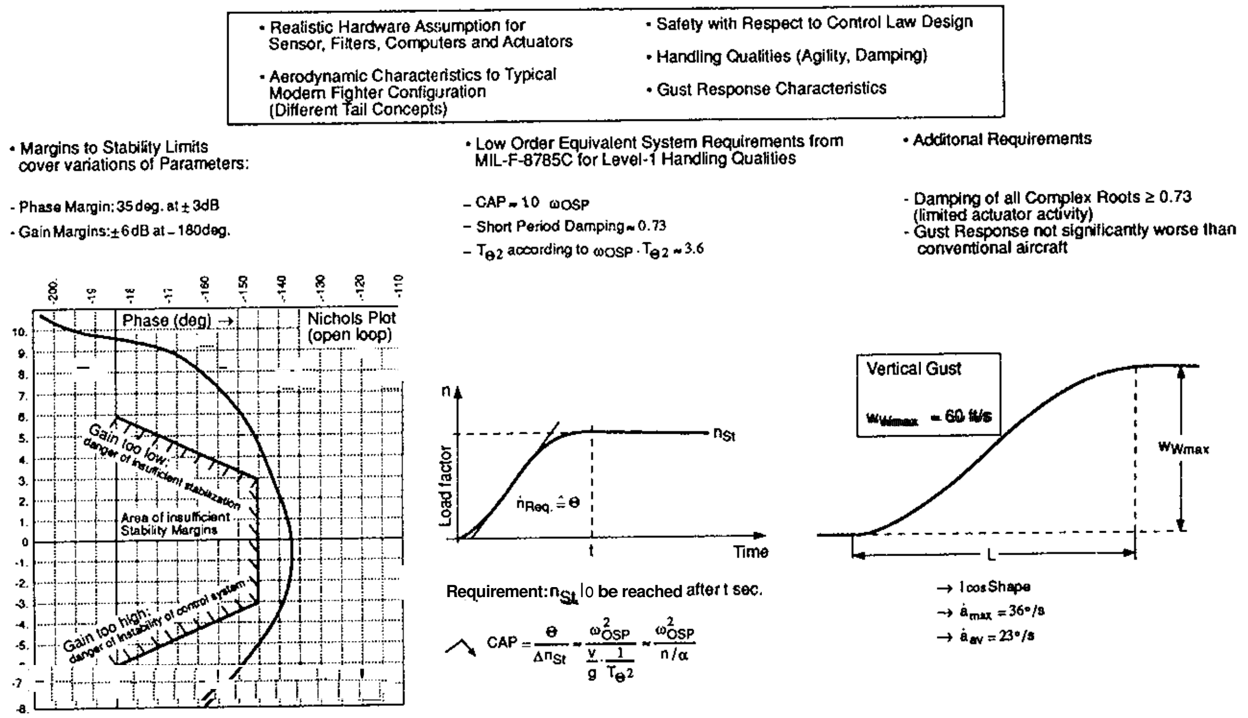


Figure 6.4.3 'Criteria for Pitch Control Power



- Realistic Hardware Assumption for Sensor, Filters, Computers and Actuators
- Aerodynamic Characteristics fo Typical Modern Fighter Configuration (Different Tail Concepts)
- Safety with Respect to Control Law Design
- Handling Qualities (Agility, Damping)
- Gust Response Characteristics

- Margins to Stability Limits cover variations of Parameters:

- Phase Margin: 35 deg. at ± 3dB
- Gain Margins: ± 6 dB at – 180 deg.

- Low Order Equivalent System Requirements from MIL-F-8785C for Level-1 Handling Qualities

- $CAP \approx 10\ \omega_{OSP}$
- Short Period Damping ≈ 0.73
- $T_{\Theta 2}$ according to $\omega_{OSP} \cdot T_{\Theta 2} \approx 3.6$

- Additonal Requirements

- Damping of all Complex Roots ≥ 0.73 (limited actuator activity)
- Gust Response not significantly worse than conventional aircraft

Requirement: n_{St} to be reached after t sec.

$$CAP = \frac{\dot{\Theta}}{\Delta n_{St}} \approx \frac{\omega_{OSP}^2}{\frac{V}{g} \cdot \frac{1}{T_{\Theta 2}}} \approx \frac{\omega_{OSP}^2}{n/\alpha}$$

→ 1 cos Shape
→ $\dot{a}_{max} = 36°/s$
→ $\dot{a}_{av} = 23°/s$

Figure 6.4.4 Aspects Considered in the Requirements for Pitch Control Power

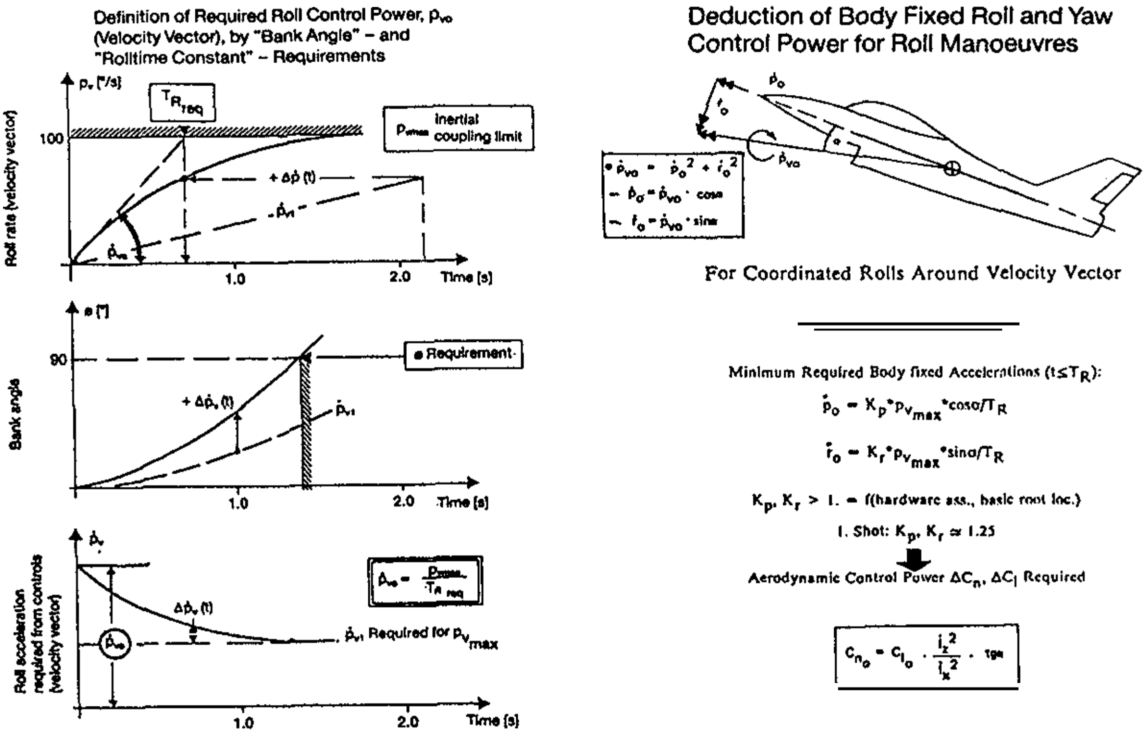


Figure 6.4.5 Requirements for Roll and Yaw Control Power

6.4.3 References

6.4.1 G. Wedekind, P. Mangold, Integration of Aerodynamic, Performance, Stability and Control Requirements into the Design Process of Modern Unstable Fighter Aircraft Configurations, AGARD Lecture Series 153

6.4.2 P. Mangold, "Integration of Handling Quality Aspects into the Aerodynamic Design of Modern Unstable Fighters," AGARD Symposium on Flying Qualities, Quebec, October 1990.

6.4.3 J.R. Chody, J. Hodgkinson, A.M. Skow, Combat Aircraft Control Requirements for Agility AGARD Fluid Dynamics Papel Symposium, Madrid 1989

6.4.4 Woodcook, Robert J., A second Look at MIL-Prime Flying Quality Requirements, AGARD Lekture Series No. 157

6.4.5 H.D. Greer; Summary of Directional Divergence of Several High Performance Aircraft Configurations, NASA-TN D-6993 (1972)

6.5 NEED FOR FURTHER RESEARCH

The summary of flight mechanical criteria which can and have to be used within the pre-design phases of modern fighters, shows that no homogeneous set of requirements is available up to now. In particular, the impact of unstable design and of high angle of attack maneuvering are not covered sufficiently. Therefore, further research is urgently needed to develop criteria which show the inter-relationship between attainable flying qualities, design instability and required control power within the several flight phase categories or angle of attack regions. Points of main emphasis, which should be addressed in any case, are listed below:

6.5.1 Pitch Axis

- Required pitch control power and pitch control build-up rate for sufficient maneuver capabilities, stabilization and acceptable gust response.
- Allowable minimum time-to-double to guarantee safety (Phase/Gain margins) and sufficient augmented stability levels.
- Information about maximum trim rate as a percentage of maximum surface rate.
- Additional pitch control power required to cancel coupling effects (roll into pitch).

6.5.2 Lateral/Directional Axis

- Required **roll/yaw** control power and **roll/yaw** control build-up rate for ...
  ...stabilization or stability augmentation
  (ζ_{DR}, ω_{DR} design goal)
  ...**sufficient maneuver** capabilities
  (τ_R; $\sigma(t)$)
- **Requirements** for the basic root locations (most unstable root; characteristics versus sideslip) to guarantee safety (phase/gain margins) and sufficient augmented stability levels.
- Necessary combination of roll and yaw control power at high angles of attack required for coordinated rolls.

6.5.2 Criteria Development

Furthermore, it will be important that all the criteria to be developed are easily convertible into aerodynamic requirements, once assumptions about mass, Inertias, actuator rates and main dimensions have been agreed. Parameters which could be handled within the early design phases are summarized in the following listing:

- Pitch Axis
  - Minimum control moment coefficient ΔC_m versus $C_{m\alpha}$
  - **Minimum** control moment derivative $C_{m\delta}$ versus $C_{m\alpha}$
  - Recovery moment C_{mR} near C_{Lmax}
  - Information about feasible control surface (trim) schedules
- Lateral/Direction Axis
  - **Minimum** control moment coefficients ΔC_l, ΔC_n versus $C_{n\beta dyn}$ for trimmed conditions.
  - Minimum control moment derivatives C_l, $C_{n\delta}$ versus $C_{n\beta dyn}$ for trimmed conditions.
  - **Minimum** requirements for combined roll-rudder effectiveness at high angle of attack
  - information about maximum allowable symmetrical flap deflection (feasible trim schedules)

SECTION 7

FEEL SYSTEM DYNAMICS AND CONTROL SENSITIVITY

7.1 INTRODUCTION

This section deals with feel system dynamics and control sensitivity as they impact the overall handling qualities of the flight vehicle. Traditionally these characteristics were set as functions of the control surfaces of the vehicle, their reflected hinge moments, aerodynamic damping and the anticipated strength of the human pilot (stick/tab gearing). With the advent of powered or power assisted controls in the early fifties this intimate relationship to the aerodynamics of the control surface was lost, and designers found themselves having to replace the classical relationships between control deflection and stick force artificially. Even in the early days of artificial feel systems attempts were made, with varying degrees of success, to modify the force/feel characteristics both to aid the pilot in terms of enhanced handling qualities, or to assist the structural designer in limiting pilot imposed loads on various parts of the aircraft. These early systems were characterized, generally, by the fact that the stick deflection was stili proportional to control surface deflection, the characteristic varied being the relationship between deflection and applied force. Within this constraint, the forces were tailored by a variety of mechanical devices such as 'q' bellows, springs, dash-pot dampers and bob weights. The recent moves towards fly-by-wire or fly-by-light control systems has completely separated pilot's controller from the control surface motion and therefore the designed must now ensure that the force to position characteristics of the stick are properly matched to the dynamics of the augmented aircraft. All previous restrictions have disappeared, even that of making the controller position the Input to the flight controlled system (e.g. the **F-16** uses applied force as the Input to the flight control system). Thus for highly augmented aircraft, Including naturally unstable machines, the stick dynamics have become a discrete element In the total pilot-in-the-loop chain. The Interaction of the pilot with the flight control system via such a dynamic system Is not well understood at this point. However, recent experiences in a variety of research programs have provided a degree of insight into the subject as noted below.

7.2 FEEL SYSTEM DYNAMICS

7.2.1 Definition

For the purpose of this document the feel system is defined as "that dynamic element of overall control system which translates the pilot's applied force Into a control system input". This definition does not make a prior assumption that the stick Itself has motion, but it permits consideration of an isometric controller.

7.2.3 Existing Database

At present, there does not exist a definitive and consistent database against which the design of control stick characteristics for use with fly-by-wire systems may be established. There are, however, a series of case studies which offer some guidance in this area. Amongst the most significant of these are studies conducted on the NT-33 and observations made in X-29 program. Extensive In-flight studies into control system characteristics conducted in the Canadian variable stability Bell 205 helicopter also provides some insight into this area which should be applicable to fixed wing installations, at least in the low speed regime.

7.2.4 Pilot and Feel System Interaction

In the fundamental task of controlling his vehicle, the pilot needs to know not only the magnitude of his Input in any given axis, but that it is such that he may achieve a desired response from the machine. The bio-kinesthetic feed-back, which gives him this knowledge, processes controller acceleration, velocity and displacement and this is translated Into the requirement to apply a specific force in a given direction. In addition, aircraft motions may couple inertially into the force-feel system causing various uncommanded motions (the roll ratcheting phenomenon and "arm bobweight" PIO are examples). Considering the cockpit controllers in this way suggests a prima face case for considering their dynamics as a part of the overall dynamic environment of the aircraft. if the question of feel system dynamics has not to this point attracted great Interest In the handling

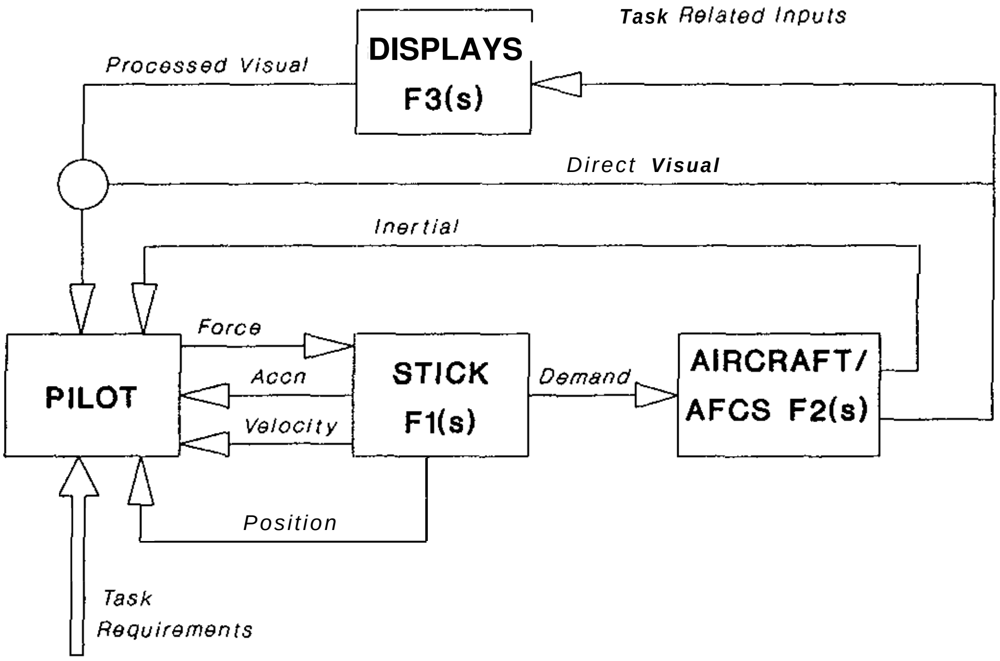


Figure 7.2.1 Generic Relationship Between Control Stick and Total Task Environment

qualities community, it is because they have generally been designed with frequency responses so much higher than that of the overall vehicle that it is the dynamics of the pilot that have been limiting rather than those of the controllers. The Influence of the controllers has therefore been only those of extraneous high order effects, beyond the frequency range of interest to the human pilot and effectively transparent to him. Occasionally controllers of limited bandwidth have been installed with their own specific effects. As shown in Figure **7.2.1,** there is a complex interaction between the pilot and the aircraft and its environment for a given task. The feel system is clearly an element in this process whose contribution can be important but is at this date not totally understood.

7.2.5 Changes in Controller Design

The arguments in the previous paragraph apply specifically to the traditional large displacement center mounted stick. Recent developments, however, have seen a move away from this type of installation towards small displacement center or side mounted sticks and here the situation may well change. The frequency limiting characteristics of the human operator observed when making large physical motions with a relatively large muscle group is not nearly so marked when he is using a small displacement device with a much more limited muscle group and even less so if the device is force sensing. Here effects of mismatching the frequency content of the pilot's input with the response type and bandwidth of the aircraft control system have, on occasion, become intrusive and detrimental to the handling qualities of the aircraft.

7.3 THE X-29 EXPERIENCE

Recent experience in the **X-29** flight test program supports the contention that the feel system is a discrete dynamic element with a special role in the flying qualities of the aircraft. The handling qualities of the original **X-29** (also discussed in Section **2.2)** were much better than predicted. To Investigate this situation, the lateral axis was selected for special attention since this channel was not complicated with other issues as was the case in pitch. In the lateral case a large equivalent time delay from a stick force input (approx. **230** millisec) should have resulted in Level 3 handling qualities based on existing axilitary specifications. However, reasonably detailed handling qualities evaluations of the real aircraft consistently showed solid Level 1 handling qualities. A unique feature of the X-29 control system was the relatively slow feel system. In the lateral axis the natural frequency of the feel system was 13 rad/sec which contributed approximately 100 millisec to the overall equivalent time delay. This observation raised several questions:

- Does the feel system element act as a filter which alters the shape of the aircraft response and affects the sensitivity of the overall system to time delay?
- Is the feel system truly a unique dynamic element which the pilot can to some degree discount since he has access to both input (force) and output (position)?

In an attempt to answer these questions and to study the general interaction of the feel system and flight control system dynamics, a rather detailed experiment was performed using the NT-33 in-flight simulator (Reference 7.3.1). Unfortunately, the results of the experiment are not definitive and further analysis is in progress. Some observations from the X-29 experience and general experience in the In-flight simulator demonstration flights can, however, be presented:

- As noted in References 7.3.1 and 7.3.2, time delays resulting from the feel system dynamics are not as significant as those produced in the flight control system itself.
- Systems with low frequency feel systems are more tolerant of equivalent time delay than those with higher frequency feel systems. This observation is consistent with existing evidence that, in general, the threshold of tolerable time delay is a function of the abruptness of the response shape.
- Reference 7.3.1 suggests that feel systems with natural frequencies less than 10 rad/sec severely degrade pilot-in-the-loop performance. For center stick installations feel system frequency should be 20 rad/sec or higher when possible.
- The present Military Flying Qualities Specification (Reference 7.3.3) time delay requirements are not generally applicable, particularly when a low frequency feel system is present. In addition, allowable time delay appears to be a function of initial response shape (control sensitivity).
- Even when the feel system is not in the forward path, as in a force command control system mechanization, its dynamics still have considerable impact on closed loop performance (References 7.3.1).

7.3.1 References

7.3.1 Bailey, R.E. and Knotts, L.H., "Interaction of Feel System and Flight Control System Dynamics on Lateral Flying Qualities," Caispan Report No. 7205-26, May 1989.
7.3.2 Smith, R.E. and Sarrafian, S.K., "Effect of Time Delay on Flying Qualities: An Update", Journal of Guidance, Control, and Dynamics, Vol 9, October 1986.
7.3.3 Military Standard, Flying Qualities of Piloted Vehicles. MIL-STD-1797 **(USAF),** March 1987.

7.4 THE CANADIAN BELL 205 EXPERIENCE

7.4.1 Background

Over the Past four years the Canadian Bell 205 in-flight simulator has been used for extensive studies of control systemcharacteristics aimed at providing a database for the recent update of MIL-H-8501, the Military Helicopter Flying Qualities specification. A wide range of control systems were studied varying in both bandwidth and response types (Rate command, rate command/attitude hold, attitude command and velocity command). Both conventional control sticks and a variety of integrated side sticks were used.

7.4.2 General Observation

Early in the program it was recognized that feel system dynamics had a significant impact on the handling qualities of the aircraft under evaluation. For center sticks, the stick characteristics needed to be optimized ofr the specific control system type, while for the side sticks, the stick filter characteristics were varied to provide the same optimization. This necessity was caused essentially by the same types of observations noted in various fixed wing studies that limited the abruptness of response acceptable to the pilot in high gain tasks. Generally, the less augmented the aircraft is (i.e. the lower the response type in terms of Section 3 methodology), the higher the bandwidth of the feel system needs to be. This fact is best illustrated by the stick filter (first order, low-pass) break points used with a force sensing side stick for various control response types as given in Table 7.4.1. These filter settings were those required to maintain Level 1 handling qualities across the response types.

The control systems were also flown with a large displacement center stick, the characteristics of which were adjusted empirically to suit the aircraft model under study. Unfortunately, although the center stick settings qualitatively followed those used with the side-stick, it was not possible to document its dynamics well enough to publish.

The main difficulty and degrading characteristic encountered due to unmatched center stick characteristics seemed to be due to an excessively abrupt or 'spikey' response if the feel system had too high a natural frequency. When the natural frequency was too low, two effects were noted 'from pilot comments: a sluggish response and a perceived lack of sensitivity. The former case produced a proneness to a form of PIO not related to the classical case of a pilot attempting to control a system with excessive lag, but rather an uncontrollable bio-inertial feed-back of aircraft motion due to the 'arm bobweight' effect. At extreme mis match, the excessively slow stick produced classic PIO tendencies In high-gain tasks (e.g. precision hover, much akin to fixed wing formation flying). With the side sticks in use the effects were broadly the same, except that the bio-inertial feed back oscillation tended to be higher in frequency, exciting potentially damaging airframe/transmission modes rather than causing significant attitude perturbations.

7.4.3 Ad Hoc Experiments

informal ad hoc experiments were conducted when developing simulations for control system indicated several significant points:

- Producing a stick with significantly under damped characteristics (for the purpose of obtaining a flat response to high frequency) was acceptable provided the natural frequency exceeded the bandwidth of the augmented aircraft by a factor of at least 2.5 and the damping ratio remained above **0.4.**
- The combined characteristics of stick plus any stick filter should not exhibit significant (30 degrees) phase lag at frequencies lower than the bandwidth of the augmented aircraft.
- The Influence of non-iinearities in the feel system can be very significant, as can those of its static characteristics. The relationship between break out force and spring gradient has proved to be critical with displacement type side sticks, to the extent that a change in the break out force from 0.3 to **0.6** lb was sufficient to degrade the handling qualities of a solid Level **1** rate response aircraft to Level 2 when it occurred in conjunction with a low spring gradient. When using a center stick, the conflicting requirements of spring gradient (adequately low to permit the sustained inputs required with some response types) and bandwidth, which lowers with spring gradient at a given level of damping, sometimes made it difficult to construct a suitably matched feel system for any given set of aircraft characteristics.

RESPONSE TYPE	FILTER **(Rad/Sec)**
Unaugmented	**16**
Rate Command	**16**
RCAH	12
Attitude Command	**4**
Translational Rate Command	0.5

Table 7.4.1 - Break-Points for Side-Stick Filter As Used On Canadian Bell 205

7.4.4 Specific Experimental Data

A recent series of studies, References **7.4.1** and **7.4.1,** has indicated quite positively that:

- When using a displacement controller, the bandwidth criteria need only be met by the slick displacement to attitude describing function and that the force to attitude characteristics are of far less significance than had previously been thought.
- Contributions to Effective Time Delay due to control stick dynamics are largely transparent to the pilot and as such should **be** discounted.
- Underdamped sticks should be avoided for a variety of reasons. If the stick is of low natural frequency they cause significant arm-bobweight effects and can lead to a classic low frequency PIO; at high frequency they are prone to bio-inertial feedback, possibly

exacerbated by neuromuscular resonance and can generate the 'roll racheting' phenomena or excite aircraft structural modes.

- There is a suggested boundary, from handling qualities considerations only, of about 9.0 radlsec for natural frequency and 0.5 for damping ratio.
- Even though sticks as low as 9.0 radlsec were assessed as Level 1 when used in conjunction with a Rate Command control system, pilot performance in a roll tracking task degraded slightly as Equivalent Time Delays (defined at $2\xi/\omega_n$), generated in the feel system, Increased from 30 to 370 ms.
- Pilot's are very sensitive to time delays caused by stick signal processing prior to the inner stabilization loops, these are seen as a degraded vehicle response and the HQR assignments confirmed that the stick displacement (prior to signal processing) to attitude characteristics dominate the pilot's perception of the handling qualities.
- Stick displacement do not need to be large for the beneficial effect of the compliance to be achieved. In Reference 7.4.2 two stick models, both having spring gradients of 9.0 lblIn and a maximum displacement of +/-1.25 in. were rated solidly Level 1 except when underdamped.

These findings are generally in accordance with previous fixed wing studies In this are, particularly those reported in Reference 7.4.3, with the exception that the natural frequency boundary is somewhat lower. This could be due to a difference between flight and fixed base simulation effects, or the different levels of maneuvering performance between the helicopter and the fixed wing models used to generate the data in 7.4.3.

7.4.5 References

7.4.1 Baillie, S.W. and Morgan, J.M., "An In-Flight Investigation Into the Relationships Among Control Sensitivity, Control Bandwidth and Distrubance Rejection Bandwidth Using a Variable Stability Helicopter:, Paper #61, Fifteenth European Rotocraft Forum, Amsterdam, Sept. 1989.

7.4.2 Morgan, J.M., "An Initial Study into the Influence of Control Stick Characteristics on the Handling Qualities of a Fly-by-Wire Helicopter", Paper #18, AGARD-FMP Symposium on Flying Qualities, Quebec City, Oct. 1990.

7.4.3 Johnston, D.E. and Aponso, B.L., "Design Considerations of Manipulator and Feel Characteristics In Roll Tracking", NASA CR-4111, Feb. 1988.

7.5 COMMENTS ON FEEL SYSTEM DYNAMICS

While there is a distinct lack of definitive numerical data on which to base recommendations, there is sufficient evidence to indicate that the dynamic characteristics of the feel system to be used in any fly-by-wire environment must be given careful consideration as a separate element of the overall system design. However, it currently appears that it is not sufficient or correct to treat the feel system as an integral part of the augmented aircraft dynamics. This clearly defines an area for further research: in particular it appears important that we improve our knowledge of the pilot's internal 'weighting matrix' for closing loops around the feel system, and how that may adapt under changing conditions of magnitude and frequency.

7.6 CONTROL SENSITIVITY

7.6.1 Current Situation

A primary weakness in the current requirements is the lack of adequate specification of control sensitivity. None of the criteria for attitude control (Equivalent Systems, CAP, Bandwidth, etc.) Include the effect of control sensitivity but inherently assume that it is separately optimized. The importance of control sensitivity tends to be disregarded for two reasons:

- It is assumed that the control gearing can be easily changed, especially with a fly-by-wire aircraft.
- It is a function of the task and the characteristics dynamics (equivalent short period, Bandwidth, etc).

Avery large, and therefore expensive, database would be required to formulate a quantitive control sensitivity criteria, especially considering that side stick, center stick, isometric and compliant controllers must be considered.

7.6.2 General

Even the most experienced and perceptive test pilots have great difficulty determining the effects of control sensitivity. Excessively high values look like low damping and produce PIO prone systems which will receive comments to that effect (few, if any, pilots will isolate the problem as excessively high control sensitivity). Similarly, systems containing very low control sensitivity will receive comments related to overly sluggish response. The control sensitivity should logically be over the band of in which the pilot is most sensitive to aircraft response. Since, by definition, the pilot is operating in the crossover region, it is gain in that e that should be specified. Unfortunately, none of the existing handling Qualities ic include such a requirement, primarily because the necessary data is not available.

The MIL-STD-1797 **(USAF)** includes the product of the stick sensitivities at low and high frequencies

$$\frac{F_e}{n_{zss}} \cdot \frac{\ddot{\theta}_o}{F_{es}}$$

as the criterion, where F_e/n_{zss} is measured as the quasi-steady stick force per 'g' and $\ddot{\theta}_o/F_{es}$ is defined at very high frequency. Since the product of these parameters does not uniquely specify the gain of the response in the region of pilot crossover, it is not judged to be a generally valid measure of the control sensitivity for highly augmented aircraft.

SECTION 8

HANDLING QUALITIES EVALUATION TECHNIQUES

8.1 INTRODUCTION

The handling qualities evaluation is a very important part of the overall flight control system development process (see Section 9). For determining the flight characteristics of highly augmented aircraft there are basically two methods:

1. Evaluation using pilots under operational conditions (Piloted Simulation and Flight tests).
2. Numerical Handling Qualities Evaluation using mathematical models of the aircraft.

The first method enables:

- investigation of pilot-aircraft interaction;
- testing under real environmental conditions;
- mission dependent evaluation;
- collection of pilot information on system behavior and pilot workload.

Due to the above reasons this method forms the basis for evaluation of flight characteristics in all new aircraft developmental programs. However, this requires extensive flight testing, which in turn is time consuming, as each flight test results in pilot comment which are valid only for that particular flight condition, configuration, and mission under test. This is true not only for flight tests, but also for piloted simulations which are frequently carried out in parallel during different stages of new aircraft development.

Modern aircraft development, especially development of highly augmented aircraft, requires comprehensive evaluation of flight characteristics for various controller modes, loadings, and operational missions. These, in turn, have to be evaluated at several points in the flight envelope. Therefore, it is important to supplement these findings with those obtained from numerical handling qualities evaluation techniques (method 2). This method has made significant progress during the last 20 years, mainly due to the rapid advances in digital computers and data processing engineering. It now forms an essential part of the total flight characteristics evaluation process in all new aircraft developmental programs. To cater to the expanding flight envelope of modern aircraft, It is possible today (using this technique) to evaluate flight characteristics online in real time. One advantage of using this method is its dependence on mathematical models of the aircraft, which are available right from the Initial phase of a developmental program, for e.g. theoretical estimates, wind tunnel data etc.. These mathematical models need to be subsequently upgraded and validated against flight test data when available. System Identification techniques can be used to model the flight test data.

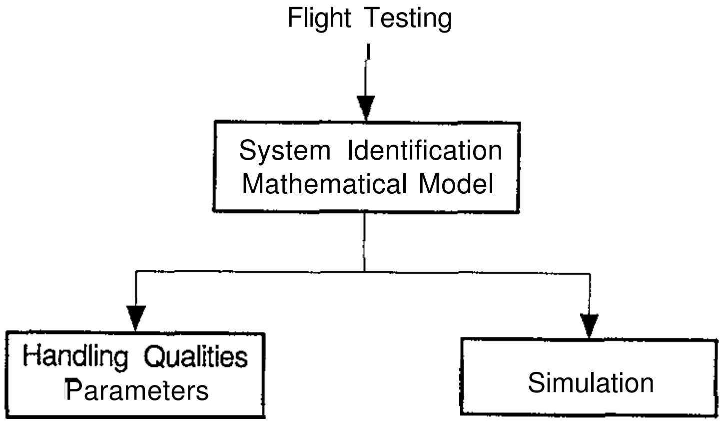


Figure **8.1.1** System Identification Application in particular, system identification is essential for all handling qualities investigations of complex aircraft systems (highly augmented unstable aircraft subjected to simultaneous deflection of various control surfaces) as it can provide the necessary mathematical models which are essential for simulation and handling qualities analysis. System indentification procedures should therefore be used to extract modeling information right from the initial flight tests, not only to validate existing mathematical models, but also to arrive at a single model for simulation and handling qualities analysis (Figure 8.1.1).

8.2 BASIC HANDLING

The pilot flying the aircraft will be faced with a number of handling characteristics, which result from the discrete static maneuver and dynamic behavior of the aircraft in its pitch and roll/yaw axes throughout the useabie flight envelope. To cover all of the intended flight phases typical for the role of the aircraft, clean, gear, and flaps configurations and external stores configurations have to be tested in the entire c.g. range as well.

The purpose of the flight tests is to obtain qualitative and quantitive data of the basic static and dynamic characteristics:

- to demonstrate the dynamic and static stabilities are acceptable to the pilot;
- to show the aircraft meets speciiied stability and control requirements;
- to provide basic aerodynamic data for the mathematical modeling for simulation;
- to correlate wind tunnel estimates with the flight test results.

Aircraft having an angle of attack limiter in the flight control system (carefree handling) will be tested when flying ai the angle of altack limit and in maneuvers where the limit is exceeded intentionally. More information can be found in References 8.2.1 to 8.2.4.

8.2.1 References

8.2.1 Aircraft Assessment arid Acceptance Testing, AGARD Lecture Series No. 108.
8.2.2 Military Standard, Flying Qualities of Piloted Vehicles, MIL-STD-1797 (USAF), March 1987.
8.2.3 Stall/Post-Stall/Spin Flight Test Demonstration Requirements for Airplanes, MIL-S-83691A USAF.
8.2.4 Flight Test Techniques, AGARD Conference Proceedings No. 452.

8.3 OPERATIONAL HANDLING QUALITIES EVALUATION

8.3.1 The Role of Simulators

In the flight control development process simulators play an important role. But the designers and the flight test team must be aware of the advantages and limitations of the simulators available to them.

Ground-based simulators can be very effective even in the early stages of the design, if one realizes their limitations. Current ground-based simulators can essentially give an exact replication for tests involving flight under instrument flight conditions or nonprecise visual tasks. They suffer from limitations of visual and motion cueing. Visual limitations affect, in particular, high gain tasks such as landing, in-flight refueling. etc.. These limitations consist not only of field of view, but also of fine detail representation and time delay effects. The motion systems of ground simulators are inherently limited and require washouts to recenter the linkage. The lack of correlation between the visual and the motion systems frequently results in motion sickness in experienced test pilots. On the other side, motion becomes a necessity for flying qualities work when the pilot station is far removed from the aircraft rotation center, as is the case in most large aircraft, or other situations where cockpit accelerations are high with control inputs. in these cases, cockpit motions that result from angular acceleration and high maneuverability provide strong cues to the pilot and will greatly affect closed-loop flying qualities.

in particular, in the above cases, in-flight simulators are considered to be mandatory for optimizing flight control systems. in-flight simulators are able to provide the pilot with the real scene i.e. visual and motion cues; “one of the general assets of the in-flight simulator is that it places the pilot in a real environment with the attendant pilot gain“. But the flight test engineer should be aware that one problem of all current in-flight simulation (e.g. variable stability NT-33, TIFS, ATTAS) are the limited flight envelopes that can be covered and therefore they are limited in obtaining data, particularly for aggressive maneuvering. Also, time delays due to actuator bandwidth and computer system can produce problems.

In the development process, both ground-based and In-flight simulators should be used in a complementary way. The test team must be aware that both types of simulators require accurate mathematical models. Verification of the ground-based and the in-flight simulators have to take place prior to the handling qualities evaluations experiments.

An excellent example how these simulation tools should be integrated into the development of a complex highly augmented unstable aircraft is given by the conduct of the X-29 evaluation and test.

8.3.2 Test Techniques For Small Amplitude Tasks

The design of operational handling qualities flight test programs for fighter aircraft may be derived from a list of mission events that are elements of the intended role as outlined for example in Table 1 of the Military Specification MIL-F-8785C, MIl-STD-1797 or in other documents from which useful information can be taken.

From mission analyses, the test techniques may be divided into small amplitude maneuvering (SAM) precision tasks and moderate to large amplitude maneuvering (LAM) tasks. SAM tasks mostly result from the flight phases which require precise control characteristics using frequent and Small control inputs. LAM tasks are characterized by full stick inputs with high angle excursions and body-fixed rates in order to achieve gross attitude and flight path corrections.

To investigate the stability of the total system (pilot + aircraft) small amplitude precision tasks are designed to force the pilot into a high gain which normally Identifies deficiencies due to time delays. Typically, the flight test techniques will differ considerably from the real mission tasks to provide consistent and repeatable numerical data and pilot ratings. To assure, on the other hand, similarity of the test maneuvers to the mission phases, typical conditions of the real mission tasks have to be retained, e.g. precision fine tracking of target aimpoints in air-to-aidground and formation tasks. Further details about preparation and conduct of flight tests for small amplitude precision tracking can be found in Reference 8.3.1. Sophisticated air-lo-air and air-to-ground test methods are described in subsection 8.3.5.

8.3.3 Tests Techniques for Moderate and Large Amplitude Tasks

Close-in dog fighting generally requires aircraft maneuvering capabilities that cannot be tested and evaluated by applying conventional stability and control flight test techniques. Instead, maneuvers that are typical for the role of the aircraft have to be adopted to flight test the corresponding handling qualities (H.Q.). To minimize the degrees of freedom or number of parameters Involved without losing significance for H.Q. purposes, the combat test maneuvering should be tailored to take place in one-vs-one engagements within visual range. A target aircraft with comparable characteristics as far as handling and performance is concerned shall be Involved and flown by highly experienced crews. The maneuvers of the test aircraft shall be such as to outmaneuver the opponent with large amplitude maneuvers, to reach his six o'clock position and shortly track him precisely within the lethal range of the test aircraft's short range missile andlor gun equipment.

Basic Fighter Maneuvering

Basic information about the coarse maneuvering of the aircraft can be evaluated by using the typical combat maneuvers that can be flown by the test aircraft alone or against a target aircraft, e.g. windup turns, left/right, with smooth to abrupt G-onset; turn reversals in high-G break turns, unloaded; high-G barrel rolls, over the top, underneath, smoothly/abruptly/uncoordinated; maximum negative G - max. positive G maneuver, vertical plane; split 8 maneuver; slice turns; vertical reversals (pitch back); oblique loop turns; defensive spirals; Yo-Yo maneuvers, high/low.

Complex Air Combat Maneuvering Tasks

Complex air combat maneuvering is needed to investigate the combination of coarse and fine tracking maneuver capabilities as well as energy management. The tests will be flown with a capable target aircraft which will maneuver defensively but may also counteract offensively if deemed appropriate. For the investigation of handling qualities of the aircraft, avionic system capabilities should be disregarded and therefore the engagements should take place within the visual range and should involve only one threat aircraft,, All of the maneuvering, both of the test aircraft and the target aircraft, will be aimed to achieve position advantage for a short range missile or gun tracking solution. Typical air combat maneuvering tasks are parallel engagement, head-on pass engagement, multiple fight maneuver sequences. Futher details can be found in Reference 8.3.1.

One-vs-one alr combat engagements involving various types of target turned out to be able to provide almost 100% of the Information needed to characterize dog fight handling qualities. Multiple aircraft, two-vs-two and other combinations of alr combat engagements will not contribute much to the handling qualities evaluations since significant increase in the control requirements will be present in most of the cases. But, if - on the other hand -tactical and weapon systems aspects (radar, missile launch techniques. tactics) art?of primary interest, multiple aircraft engagements may have to be included. However, the procedures to be used in these cases are beyond the scope of this paper.

8.3.4 Evaluation Using Pilot Opinions

in handling qualities studies, the human pilot is an active part of the overall pilot-vehicle system and therefore, only pilot evaluation assesses the interaction between pilot-vehicle performance and total workload in performing the mission. The common method of assessing handling qualities stili relies heavily on subjective evaluations by experienced test pilots. To assist pilot and experimenter, rating scales and questionnaires are often used. The most often used Handling Qualities Rating Scale is referred to as Cooper-Harper Scale.

To indicate the reason for handling qualities ratings, additional scales have proven useful in the past, such as Turbulence Rating Scale, Pilot Confidence Rating, Pilot induced Oscillation Scale, and Buffet Rating Scale. in addition, Effort Rating Scales can be used to determine the individual amount of effort which the pilot has to provide for performing specified subtasks (Reference 8.3.3). The introduction of scales for assessment purposes has not reduced the importance of the comments of the pilots. The number of evaluation pilots participating in an experiment should be as high as possible. Experience have shown thalt as a minimum three pilot are required to achieve consistent pilot opinions. instructions to evaluation pilots are of extreme importance. A written instruction in the form of a Briefing Guide is a well-proven method to prepare the pilots properly prior to the execution of the experiments. A good example is the Briefing Guide proposed by Cooper and Harper.

Before flying the pilots should be orally briefed on the general experiment purposes and test/simulation. The evaluation pilots should not be informed about the configuration flown. Each evaluation pilot should execute pre-evaluation flights to become familiar with the configuration. During these flights pilots adapt their control strategy to the test configuration and the task. Experience has shown that at least 5 test runs should be carried out to be sure that pilot ratings are independent of learning effects. A quick-look method is helpful in controlling the test on-line. A typical example from helicopter flight testing for such a procedure is shown in Figure 8.3.1 (Reference 8.3.4). For the slalom flight task a score factor is computed which should be nearly constant during the evaluation runs. During the experiment, all signals of interest should be recorded on a digital recorder for further analysis with high sampling rate. For handling qualities investigation, these should include aircraft states, control surface motions, pilot activity, control system signals, and tracking deviation. The data obtained from handling qualities experiment.s are as follows:

- objective data of onboard recorded data
- subjective data generated by applying the different rating scales and questionaires.

For the analysis of objective data, several program packages exist which enables the user to analyze the flight test data. The procedure for the analysis of data measured during the experiment is shown in Figure 8.3.2. It includes analysis in the time and frequency domain (see subsectiori 8.4.5)

Experience has shown that neither the objective data (performances and control activities), nor the subjective data (Cooper-Harper Ratings, Effort Ratings) alone are sufficient for a clear and unambiguous assessment of handling qualities. Pilots who perform the task with less effort in trade for lower performance (e.g. larger tracking deviations) can come up with good Cooper-Harper ratings and effort ratings. Contradictory to this, pilots who aim for very precise tracking can come up with high performances but poor ratings. It therefore depends on the experience of the test engineer to combine the different results and to draw the right conclusions from the experiment.

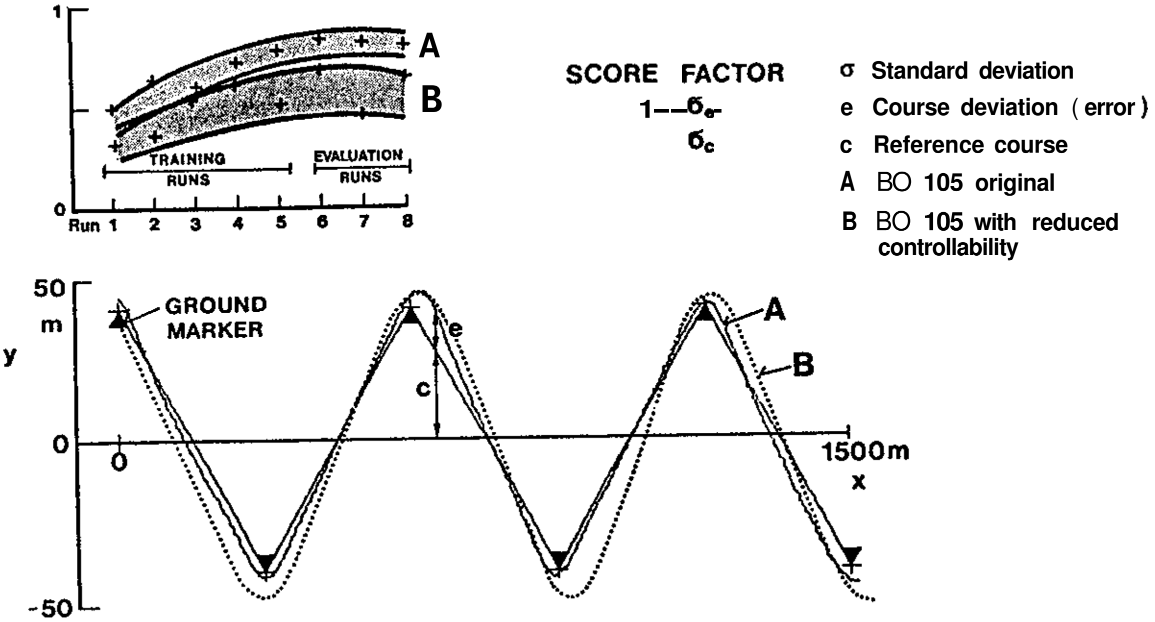


Figure 8.3.1 Check of Pilot Training Status

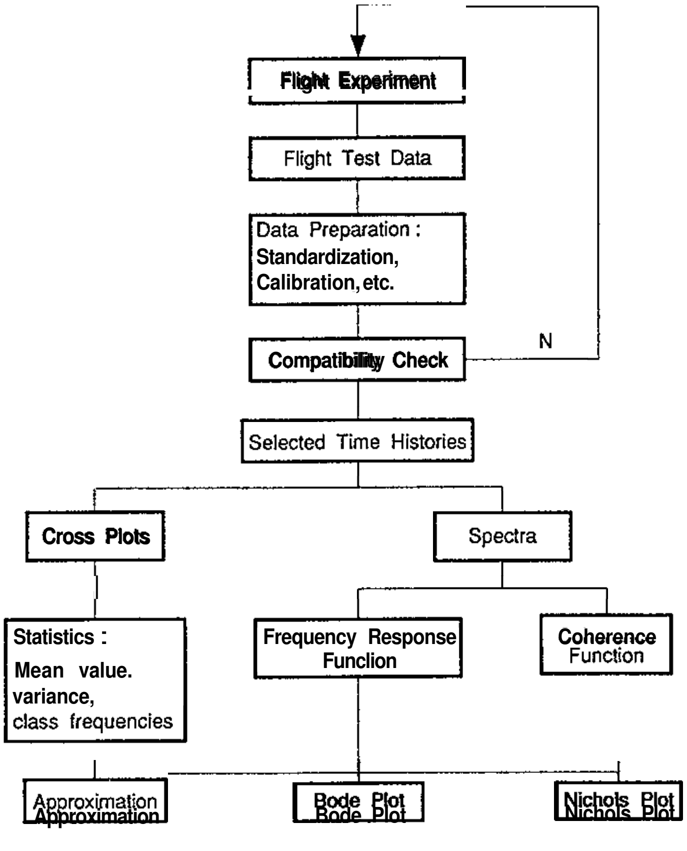


Figure 8.3.2 Flight Test Data Analysis

8.3.5 Special Evaluation Techniques

The increasing complexity of highly augmented aircraft calls for sophisticated pilot-in-the-loop handling quality test and evaluation techniques. The use of suitable test maneuvers in combination with tracking test techniques offers one solution for optimizing the flight control system to the Operational requirements of the aircraft.

Both techniques, SIFT - System identification From Tracking and GRATE - Ground Attack Test Technique. offer potential solutions for gaining quantitive insights into pilot-in-the-loop handling qualities, identifying the inflight characteristics of the flight control system under operational condition (which may differ from the modeled and ground-tested characteristics), and for determining mathematical aircraft models by applying system identification methods. The most important characteristics of the test techniques discussed below are that they are pilot-in-the-loop, mission oriented techniques, and that they provide quantitive as well as qualitive results.

1. SIFT - System identification from Tracking

SIFT test techniques (System identification from Tracking) have been developed at the US Air Force Flight Test Center (AFFTC), Edwards AFB (Reference 8.3.5). They include both special flight test techniques and data analyses procedures, see Figure 8.3.3.

The SIFT data analysis techniques include the use of spectral estimation methods to identify linear frequency response transfer functions of the entire airplane, (airplane response to pilot input), or some smaller part of the whole airplane. The frequency response data may be used **for** analyzing handling qualities in terms of such developed criteria as equivalent systems, Neal-Smith, Ralph Smith, and Bandwidth. The advantage to the SIFT test techniques is that the quantitative frequency response data and the various criteria comparison results may be correlated with the qualitative pilot comments to provide significant insight into handling qualities characteristics. Because all of the data were obtained during the same pilot-in-the-loop, mission oriented maneuvers, the correlation of qualitative and quantitative results is especially valuable.

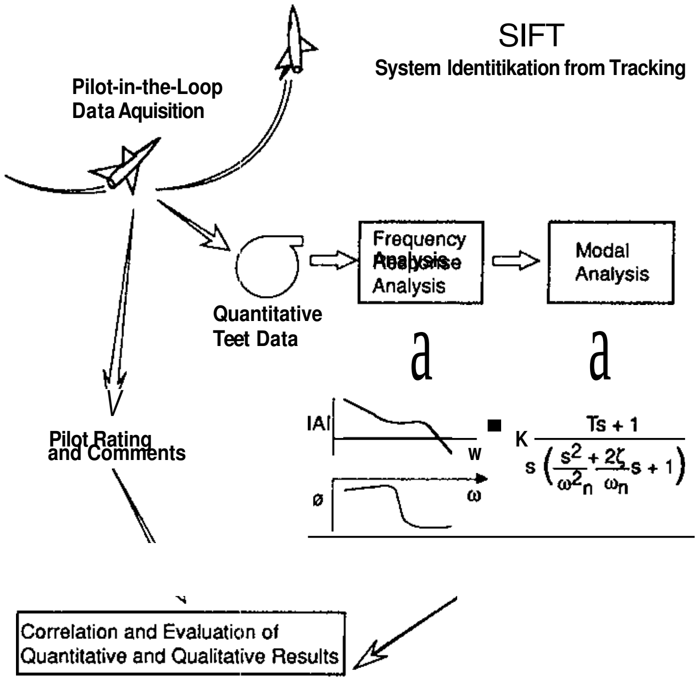


Figure **8.3.3** Schematic Outline of the SIFT Pilot-in-the-Loop Handling Qualities Test Techniques

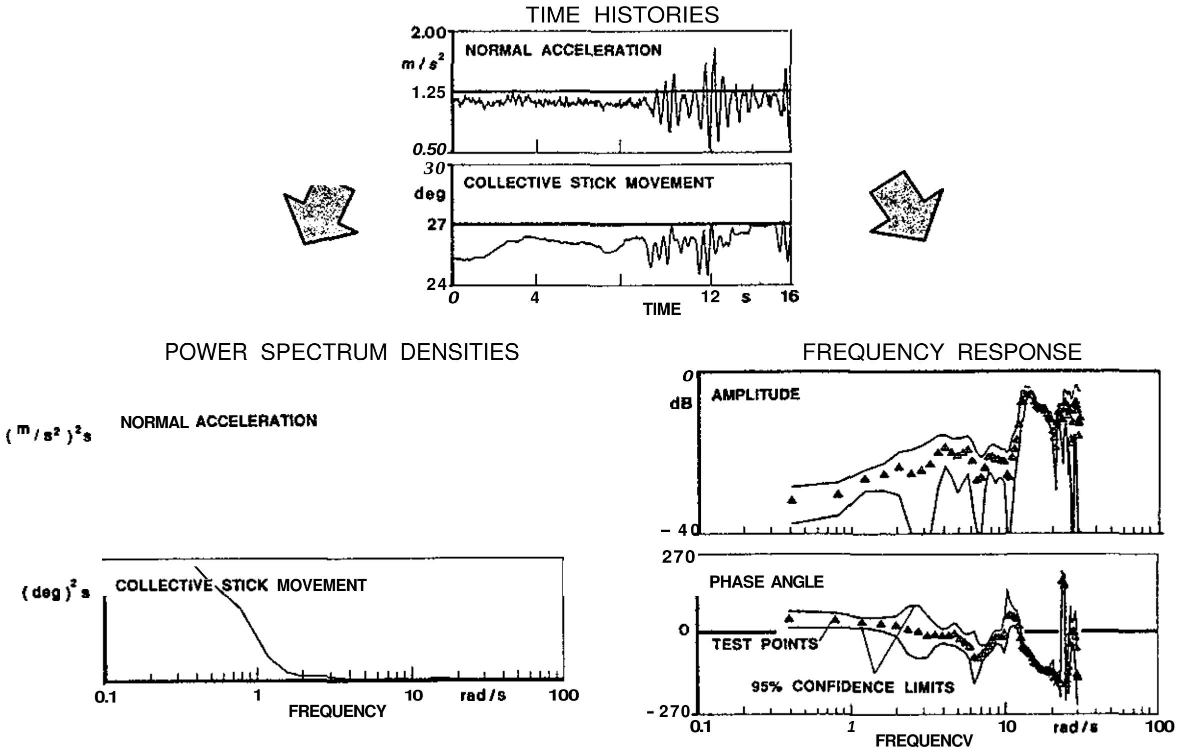


Figure **8.3.4** Time Histories with Starting PIO, Power Specfral Densities and Transfer Function from Reference **8.3.6**

There have been several applications of SIFT techniques, e.g. (1) the discovery of previously unsuspected coupling from lateral-directional axes into the pitch axis during air-to-air tracking turns, and (2) the investigation of pilot reports of PIO (Pilots induced Oscillation) using the SIFT techniques.

Another example shows the application of SIFT techniques to rotorcraft flight test data (Reference 8.3.6). This example deals with a PIO which occurred during landing approach of a large helicopter with a suspended load. Data evaluation using the SIFT techniques showed that a bad combination of eigenfrequencies from the helicopter and the suspended load causes a very poorly damped eigenmode. As illustrated, measured time histories, power spectral densities and frequency response functions from rotorcraft flight test data are presented in Figure 8.3.4. The PIO-tendency of the system investigated can be clearly identified from each of these diagrams.

2. GRATE - Ground Attack Test Technique

The GRATE technique has been developed by DLR (German Aerospace Establishment) to test highly augmented aircraft in the final phase of a ground attack mission (Reference 8.3.7). An illustration of the GRATE techniques including the test setup of the test equipment is shown in Figure 8.3.5. The technique involves the precise location of a series of target lights which sequentially illuminate during the simulated ground attack. The light sequences are designed in the frequency domain to provide a high bandwidth input signal to the system. The pilot attempts to track the light targets, and the response of the pilot-aircraft system is recorded on the flight data recorder and in the Images on the Head-Up Display (HUD) film. Additionally, the pilot provides a handling quality assessment in form of Cooper-Harper ratings.

Upon completion of the test flights, the recorded flight data, HUD film, and pilot ratings can be assimilated, permitting correlations between subjective ratings, mission performance metrics such as aiming speed and accuracy, and aircraft flight control characteristics. For mission parameter calculations, HUD data are evaluated including the position of pipper and the illuminated lamp (see Figure 8.3.6).

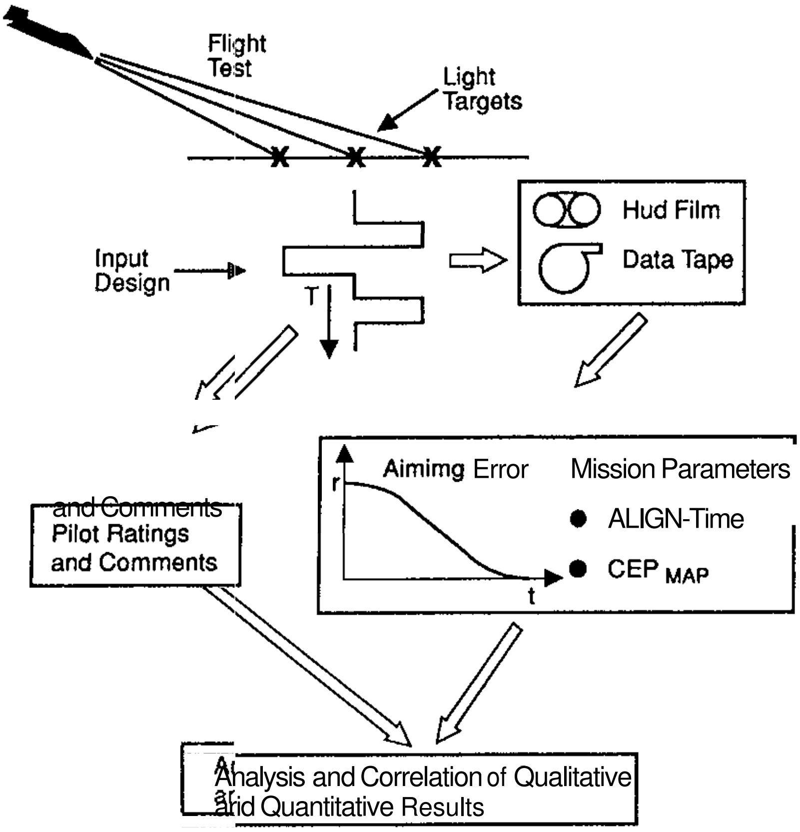


Figure 8.3.5 Schematic Outline of the GRATE Technique

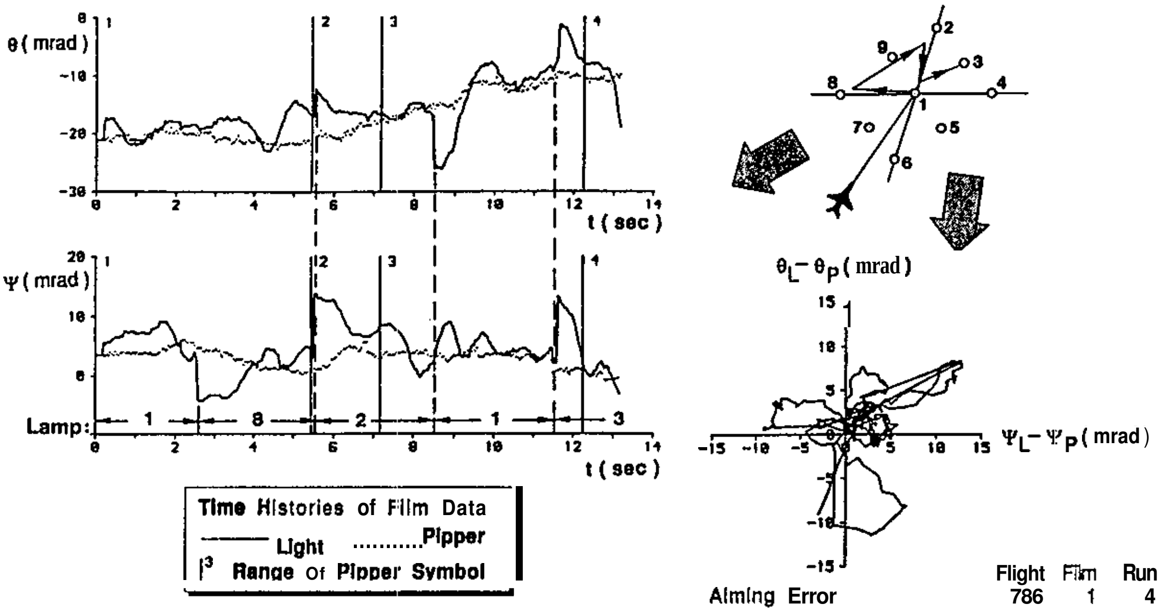


Figure 8.3.6 Typical Plots of Film Data

The first application was a series of flights with the Direct Side Force Control Alpha-Jet at WTD 61 in Manching. A preliminary analysis correlating pilot ratings with aiming align-time and circular error probable (CEP) is reported in Reference 8.3.7. The results from simulations of GRATE using the Large Amplitude Multimode Aerospace Research Simulator (LAMARS) at AFWAL in Dayton show that the pilot ratings under GRATE appear less susceptible to inconsistencies caused by varying turbulence levels than the conventional method of pilot-commanded step functions.

A functional equivalent of the GRATE system was developed by NASA Ames-Dryden Research Facility for use at Edwards Air Force Base, USA. This system, known as the Adaptable Target Lighting Array System (ATLAS) was flight tested and used in several flight test programs for assessing the handling qualities of widely different fighter-type aircraft such as NT-33A, TF-104, X-29A etc.

8.3.6 References

8.3.1 Wiiheim, K, "Evaluation Techniques for Highly Augment Aircraft:, DLR-FB 90-35, 1990.
8.3.2 Cooper, G.E., Harper, R.P., "The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities", AGARD Report 567, April 1969.
8.3.3 Wilhelm, K., Schafranek, D., "In-Flight investigation of Landing Approach Flying Qualities of Transport Aircraft with Relaxed Static Stability", DFVLR-FB 84-11, March 1984.
8.3.4 Pausder, H.J., Sanders, K., "DFVLR Flying Quality Research Using Operational Helicopters", Vertica, Vol. 10, No. 1, 1986.
8.3.5 Twisdale, T.R., Ashurst, T.A., "System Identification from Tracking (SIFT), a New Technique for Handling Qualities Test and Evaluation (Initial Report)", AFFTC - TR-77-27, November 1977.
8.3.6 Buchacker, E., Experience with System Identification from Tracking (SIFT), Flight Test-Techniques at the German Air Force Flight Test Center, AGARD FMP Symposium on Criteria for Handling Qualities of Military Aircraft, Fort Worth, TX USA, April 1982.
8.3.7 Koehler, R., Buchacker, E., Biezad, D.J., "GRATE - A New Flight Test Tool for Flying Qualities Evaluations", AGARD-CP-452, Flight Test Techniques, Edwards AFB, 1988.

8.4 USE OF SYSTEM AND PARAMETER IDENTIFICATION FROM FLIGHT TESTS

8.4.1 introduction

Numerical handling qualities evaluation is dependent on mathematical models of the aircraft. The model has to cover all parts of the aircraft which contribute to the handling qualities, and therefore it must include not only the equations of motion and the aerodynamic forces and moments, but also substystems like FCS (flight control system), engine dynamics, actuator dynamics, etc. These mathematical models are based in the initial phase on theoretical estimates, wind tunnel data, and preliminary design data, but have to be upgraded and validated against flight test data as new date become available.

System Identification Technique (Figure 8.4.1) is therefore essential for all numerical handling qualities investigations of complex aircraft systems as it can provide the necessary mathematical models. The system identification framework can be divided into three major parts:

- Installation of tnstrumentation and Filters which cover the entire flight data acquisition process including airborne or ground based digital data recording.
- Flight test techniques which are related to selected aircraft maneuvering procedures in order to optimize control inputs.
- Analysis of flight test data which includes the determination or validation of the structure of the mathematical model of the aircraft and an estimation of a set of parameters which minimizes a cost function derived from the response errors.

8.4.2 Instrumentation

A high quality of the instrumentation system is essential for parameter estimation accuracy. To satisfy the need for specialized documentation in the field of sophisticated flight test instrumentation, the AGARD Flight Mechanics Panel has initiated the publication of a series of monographs on selected subjects of flight test instrumentation. Within this AGARD Flight Tests instrumentation Series, several volumes provide valuable information on instrumentation system design for parameter identification purposes (References 8.4.1, 8.4.2). An overview is given in paper 4 of AGARD LS104 (Reference 8.4.3)

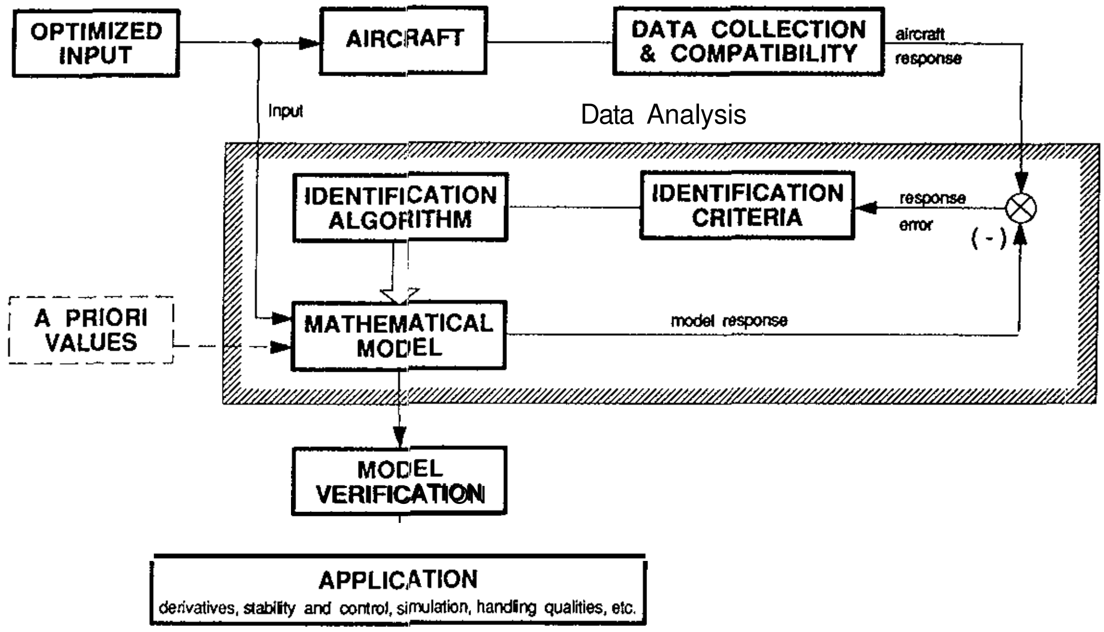


Figure **8.4.1** System Identification Procedure and Utilization

8.4.3 Maneuver Design and Input Design

The importance of adequate design of flight test maneuvers for parameter identification purposes Is well recognized. The reliability of aircraft parameter extraction from flight test maneuvers depends heavily on the amount of information available in the response. Therefore, the shape of the control Inputs should be chosen such that they excite each pertinent mode of the aircraft dynamics as much as possible. Generally, in order to excite all the modes of the aircraft response equally well, It Is mandatory to design and apply specific optimum inputs for all available control surfaces of the alrcraft. The design of optimum input signals can be performed both in the frequency and time domain considering system criteria and estimation error criteria. Evaluations, practical applications and performance comparisons on inputs are discussed In Paper **3** of Reference **8.4.3**.

8.4.4 Determination of Mathematical Models

The stability and control analysis of augmented aircraft usually deals with the aircraft model at two levels of integration. The first level deals with the bare airframe. It involves only vehicle aerodynamics and kinematics. At the second level, the flight control System (FCS) is included in the model. These considerations include issues of sensor characteristics, control system laws, computing time delays and actuator characteristics. The problem of identifying the aerodynamic parameters for the unstable highly augmented aircraft in principle is the same as for a conventional aircraft. However, this can lead to typical problems of closed loop system identification related to identifiability and accuracy. Independent control surface inputs are mandatory because high correlation of different control surface deflections (e.g. canard and trailing edge flaps) can occur with FCS engaged (see **X-29, X-31A** experience). **As** a result the input design with respect to the augmented aircraft is more complicated and will be of a higher level to achieve control surface deflections "optimal" for parameter identification of the bare airframe model.

In the past decade, a number of estimation techniques for the identification of aircraft parameters from flight tests have been developed, which can be used on a routine basis. With some modifications, these techniques can also be applied in the analysis of unstable highly augmented aircraft dynamics. in principle, they include the so called equation error and output error method. From the latter, the maximum likelihood procedure is widely accepted as a valuable method for parameter estimation. An impressive practical experience has been gained with this method for a large number of different classes of flight vehicles (Reference 8.4.4). in Reference 8.4.3, a somewhat different approach has been followed. In this so called two-step method, at first, the flight path of the aircraft is accurately reconstructed based on the redundant information of inertial and air data. in a second step the identification of the aerodynamic model can take place.

8.4.5 System Analysis

In modern aircraft development, the numerical handling qualities evaluation using mathematical models of the aircraft system forms an essential part. This system analysis process consists of computation and estimation of handling qualities parameters and includes the comparison with boundaries and criteria given in the literature.

In the last decade a number of computer programs have been developed for the evaluation and analysis of linear and non-linear systems. Such software packages in general contain a computer-aided application of classical control theory methods for linear system analysis and control system design and evaluation, transfer function representations in the form of Bode, Nichols, Nyquist, and power spectral density plots. In the time domain the calculation of responses to step, block, and stochastic inputs for linear and nonlinear systems are available (also see Figure 8.3.2). in addition, these programs allow an evaluation of the handling qualities criteria.

8.4.6 References

8.4.1 Wuest, W., "Pressure and Flow Measurement", AGARD Flight Test Instrumentation Series, Voi 11, Agardograph 160, 1980.
8.4.2 Stieler, B., Winger, H., "Gyroscopic instruments and their Application to Flight Testing", AGARD Flight Test instrumentation Series, Voi. 15, Agardograph 160, 1982.
8.4.3 Parameter identification, AGARD Lecture Series No. 104.
8.4.4 Iliff, K.W., Maine, R.E., "Identification of Dynamic Systems. Applications to Aircraft. Part 1: The Output Error Approach", AGARD Flight Test Techniques Series Volume 3, Agardograph 300, 1986.

8.5 CONCLUDING REMARKS AND RECOMMENDATIONS

- With increasing complexity of the FCS, application of in-flight simulation during the development process is mandatory. Optimization of the FCS via ground-based Simulation is no longer productive for such systems due to the increased significance of inaccuracies.
- It has been shown that for developmental flight testing of complex FCS, it is essential to have a suitable pilot-in-the-loop simulation facility on-site which can be used back-to-back to flight tests.
- The use of pilot-in-the-loop mission oriented evaluation techniques offer the only solution for pilot/system integration and optimization. Techniques like GRATE, SIFT and Air Combat Maneuvering have proven their effectiveness in this process and should therefore become standard for handling qualities evaluations.
- To ensure success during evaluation, the rules covering test definition, use of rating scales, and creation of suitable supportive pilot comment cards must be followed.
- Unrealistic evaluation tasks way be required in any simulation, ground or flight, to explore latent flying qualities problems. For example, large intentional task errors which would not be acceptable in the operational world may be necessary to create a realistic pilot stress or gain level.
- Care should be taken to assure that the mathematical models used for simulation and handling qualities analysis remain equivalent throughout the test program, and that these models continue to be upgraded as new data become available.
- System identification is the only method capable of providing the necessary mathematical models for simulation and evaluation of the system under test with the accuracy needed for handling qualities analysis.
- Application of system identification methods requires (1), the installation of a high quality instrumentation system, (2) the availability of properly-designed flight test programs and maneuver inputs, and (3) robust and well-designed data processing and analysis techniques.
- Special attention should be devoted for developing system identification methods in areas where non-linear (aerodynamic) effects are important such as high angle of attack, high angular rates and transonic Mach number.

SECTION 9

THE DESIGN AND EVALUATION PROCESS

9.1 INTRODUCTION

The design and evaluation process for the development of any new aircraft is a very complex evolution which involves the combined effort of contributors from many technical disciplines. A block diagram of the general process is shown in Figure 9.1.1.

The weighting of each block within the development process is a function of the aircraft design. More conventional designs benefit from a large foundation of experience and data and therefore the degree of iteration and reliance on the simulation - modification - flight test loop would be less than for a more radical design. The whole process, whatever the nature of the design, is in part a discovery process. This discovery process involves all the elements of the development process: from wind tunnel and computational fluid ciynamic (CFD) tests, through application of various design criteria, simulation and finally flight test. The flight test phase for a new design, particularly those with unstable airframes and sophisticated flight control systems, is rarely limited solely to validation of our predications but also involves discoveries which must be fed back into the iterative process to ensure the evolution of a good aircraft. The X-29 high angle-of-attack flight test program illustrates this point. For this unique configuration with its high-gain FCS active, the final answers in the sensitive high angle-of-attack arena required flight test. The details of this phase of the X-29 test program are reported in Reference 9.1.1 and 9.1.2.

The remainder of this section is devoted to a summary of the lessons to be learned both general and specific from the review process undertaken by the working group and the experience of the working group members.

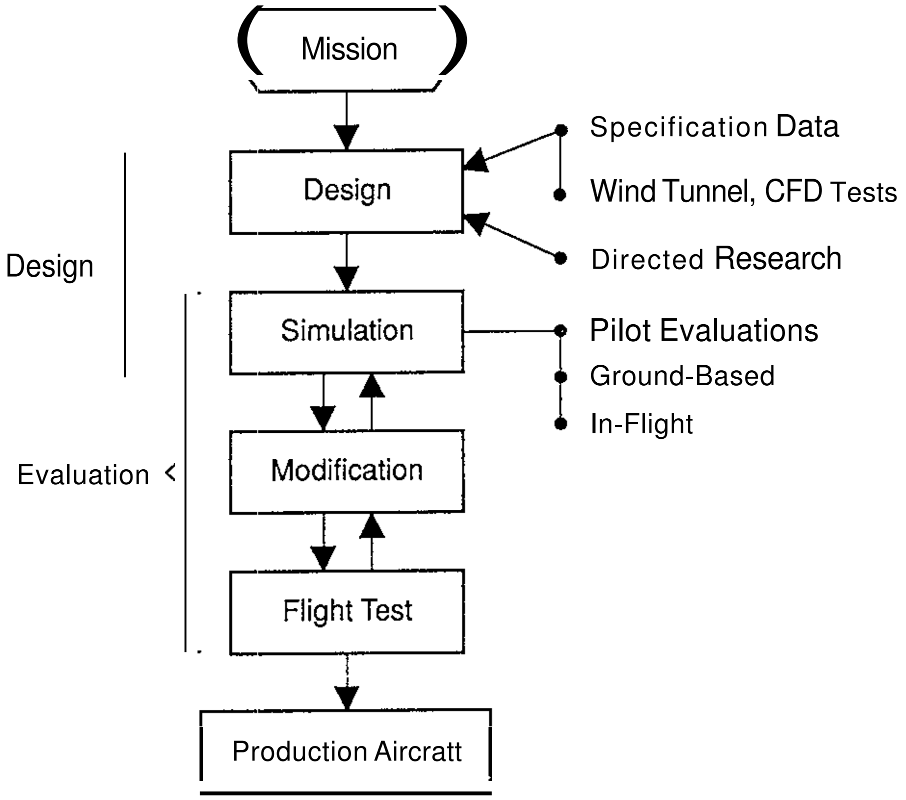


Figure 9.1.1 Handling Qualities Development Process

9.1.1 References

9.1.1 Walchli, L.A. and Smith R.E., "Flying Qualitles of the X-29 Forward Swept Wing Aircraft", AGARD Flight Mechanics Panel Symposium on Flying Qualities, Quebec, October 1990.

9.1.2 Pellicano, et ai, "X-29 High Angle-of-Attack Flight Test Procedures, Results, and Lessons Learned", Society of Flight Test Engineers 21st Symposium, August 1990.

9.2 GENERAL LESSONS TO BE LEARNED

This general review of the important philosophical or non-technical issues in the handling qualities development process is largely quoted from Reference 9.2.1 which Itself is an outgrowth of the WG-17 meetings (also see Reference 9.2.2).

9.2.1 The Problem

The flying qualities of recently designed highly augmented aircraft have not always lived up to the hopes of their designers. The industry has seen some success, but has also encountered:

- Loss of control during takeoff in more than one Instance
- Loss of control in landing, in several instances ranging from identification of the problem In an In-flight simulator, to actual aircraft being damaged or even totally destroyed.
- Difficulty in in-flight refueling, resulting even in airplane damage.
- Expensively-developed systems Installed but remaining inactive, either because they failed to meet operational requirements or because they simply degraded the flying qualities they were supposed to enhance.
- Total system redesign as almost a rule rather than an exception, Increasing system development cost manyfold.
- Cancellation of an entire airplane project due to the expense and intractability of the augmentation system development.
- Failure of an expensive "one-shot" destructive test to obtain the needed data because augmentation systems did not allow the pilot to position the test aircraft precisely.
- Removal of respected organizations from development teams because of stubborn resistance of the augmentation system to development progress.
- Loss of aircraft sales.

Why would these problems occur in a discipline that has traditionally attracted some of the industry's best and highest educated talent? There is no simple or single answer of course; however, we believe there are common threads in these problems that are revealed when the process of system development is examined.

9.2.2 The Process

The design and evaluation of the augmentation system of a new aircraft is very complex. After the mission objectives have been specified, the iterative design process begins, by combining theoretical design methods with results from wind tunnel tests. As soon as a sufficient data base is available, simulations (both off-line and on-line) become important tools. One very important feature of the real-time simulation activity is the pilot. From the flying qualities standpoint, his importance is self-evident. However, his presence ensures a constant feedback to help integrate all the design disciplines, from the early design to the final flight test phase. The flying qualities community therefore, with its special responsibility to interpret pilot ratings and comments, must implement its piloted evaluation procedures especially carefully.

9.2.3 The Team

The development process depends on inputs from many technical disciplines. In addition to flying qualities engineers and pilots, there are designers, controls engineers, "control lawyers", flight test engineers and test pilots. Specialists on aerodynamics, actuation, computer hardware, system architecture, applications software, real-time software, avionics, human factors, various subsystems, structural dynamics and many other disciplines are required. Program managers and accountants should also be added to this list. It is not surprising that in such a group there is a tendency towards autonomous action, The process cannot however tolerate such action - a team approach is essential. An ordered, iterative process among simulation, modification and flight test must be continuous to ensure a good final product.

As noted by Berthe et ai (Reference 9.2.3), "more flight control system problems are caused by human behavior than for technical reasons". The behavioral factor often Interferes with the development process and causes technical inputs or issues to be missed or misdirected, to the point that serious problems are created. Often the technical issues in development problems can be traced to behavioral issues.

The initial development phase of an early production fighter digital flight control system serves to illustrate this point. Since this system was to be an advanced quadrupiex digital design, those who best understood the vagaries of the digital world were effectively given control of the design process. The handling qualities staff, though aware of potential problems due to augmentation systems, were not included in the process. Only later, when the aircraft's poor handling qualities emerged, were the specialists consulted. Bringing the disciplines together finally resulted in an excellent flying aircraft, both from the pilot's handling point of view and from the digital design point of view. Therefore, realizing the need for clear communications and evaluation of technical inputs from all sources would have reduced the number of costly iterations. In today's jargon, the flying qualities staff were asked to "inspect the quality in" rather than teaming with others in the greatly preferable approach to "design and build the quality in". This is not to say that inclusion of the flying qualities engineers, or of any other discipline, is a guarantee of success. In that particular instance, the necessary flying qualities research had been done to provide answers for the problems encountered. Teamwork is not a substitute for a technology base. Validated criteria and methods are still needed.

Of course, our problem here is riot unique - the need to establish a multidisciplinary team for intensely technological activities has emerged as a prime behavioral management challenge for many other current industries and products. Success or failure can determine the future of whole industries or even of nations.

9.2.4 The Role of the Pilot

The test pilot is a pivotal part of the team who must join with its members to produce quality evaluation results. However, the pilot can be one of the largest obstacles to an effective evaluation process. if he is particularly skilled (a "golden glove") and cannot relate to the general pilot population, his results can be misleading. He must also be willing to cooperate in the process defined and agreed to by the team. He must learn the pilot rating scale and comment card and use them as agreed upon. He must also be willing to discuss and perhaps modify his approach to the tests following detailed discussion with the team about particular evaluation interpretation problems.

From the pilot's perspective, there must be an atmosphere on the test team that encourages him to present his opinions. Management cannot create an atmosphere of "shoot the messenger" should the pilot bring bad tidings, and expect the development to succeed. Despite the pressures of schedules and cost it must be possible to get the facts, good or bad, to the surface for evaluation. Again here, a behavioral issue overshadows technical considerations.

Reliable evaluation of the design by the pilot and the engineers to determine its flying qualities is aided by Cooper and Harper's original work (Reference 9.2.4) which summarizes the proper techniques, including test definition, use of the rating scale, and suitable pilot comment cards.

9.2.5 The Role of Simulation

As mentioned above, simulation is a vital part of the development process, and one that has evinced some pitfalls. A short but incomplete list of the chief lessons to be learned would include the following:

- Do not optimize the control system on the ground simulator. Typically, over-responsive, potentially dangerous flying qualities can result.
- Unrealistic piloting tasks in the ground simulator may be needed to expose realistic potential piloting problems. For example, simulator tasks requiring full amplitude stick commands, though unrepresentative of routine flight, may reveal lurking flying qualities "cliffs".
- For ground simulation, exact replication may not, in fact, be a good simulation. For example, it might be useful to simulate rocks or 'electronic sticks' on the runway to enhance the reality of a visual system. These enhancements may provide the cues required for a correct evaiuation of the aircraft.

- In-flight simulation has a definite place in the development process. Particularly with new designs which are unsupported by a data base, use of in-flight simulation is essential to the process.
- The development process must include test and verification of the various mathematical and simulation models. One development of an angle-of-attack limiting system was based on a deficient aerodynamic model. necessitating a redesign following flight test.

9.2.6 The Communication Challenge

As summarized in Berthe et al (Reference 9.2.3), all team members must understand each other's problems and the design limitations. Unilateral decisions made by one specialty frequently cause problems that permanently plague the whole endeavor. in summary, the success of an augmentation system development process depends on the correct blend of technical data, documented specifications, documented methods, and pilot evaluation. There is a strong behavioral element to the whole process, to which the management in particular must be sensitive. From the flying qualities viewpoint, the guidelines for proper organization and conduct of piloted evaluations are, like the flying qualities specifications, vitally important and reasonably well documented but unfortunately rarely followed. Communication is the cornerstone on which the development process is built. Without a continuous effort in this area by all team members the process will not work.

9.2.7 References

9.2.1 Hodgkinson, J., Potsdam, E.H., and Smith, R.E., "Interpreting the Handling Qualities of Aircraft with Stability and Control Augmentation", AIAA-90-2825, August 1990.
9.2.2 Smith, R.E., "Evaluating the Flying Qualities of Today's Fighter Aircraft," AGARD-CP-319, Oct. 1981
9.2.3 Berthe, C.J., Knotts, L.H., Peer, J.H., and Weingarten, N.C., "Fly-By-Wire Design Considerations," SETP Cockpit Magazine, October, November, December 1988.

9.3 SPECIFIC LESSONS TO BE LEARNED

The specific lessons to be learned which apply to the design and development of highly augmented aircraft are contained In the various sections of this report. Our general purpose In this report has been to share the lessons from the past in the hope that the mistakes of the past will not be repeated in the future. Unfortunately, the records show that the important messages from "the technical history book" were not always reviewed by the next development team as they worked intensively on their new program. For this reason the term "Lessons to be Learned" has been used throughout this report rather than "Lessons Learned".

SECTION 10

CONCLUSIONS AND RECOMMENDATIONS

AGARD Flight Mechanics Panel Working Group 17 reviewed the current State of handling qualities criteria and the flight control system design process for unstable, highly augmented aircraft. The major conclusions and recommendations from this multi-national effort are as follows:

10.1 MAJOR RESULTS

Several proven longitudinal handling qualities are available to allow successful initial definition of flight control laws that produce good pitch handling qualities for longitudinally unstable aircraft. The criteria developed for stable aircraft are equally applicable to the unstable case since the desired responses from a pilot's perspective are identical.

Although the criteria reviewed differ in their details and the presentation of the data, they, in fact, deal with common phenomena. The recommendation of the Working Group is that all these available criteria be explored to maximize insight into a particular flight control design.

The development lessons from the past strongly suggest that these handling qualities analyses and supporting simulation evaluations should be undertaken as a continuing part of the development process rather than as a response to observed handling qualities problems with the final product.

10.2 GAPS OR INCONSISTENCIES

There are, not surprisingly, some inconsistencies among the various criteria reviewed in this report. A partial list would include:

1. More data are needed to substantiate the trade-offs between attitude and flight path requirements. Specifically more direct flight path control criteria are required.
2. The Control Anticipation Parameter boundaries require better definition or replacement with separate attitude and flight path requirements.
3. A detailed validation of the impressive Gibson criteria, in particular the dropback criterion, is required.
4. More specific, task-oriented data are needed to define the desired response characteristics for a variety of mission tasks since the capability now exists to create very precise task tailored control laws.
5. There is a need for more data within the Level 1 areas to define properly the "optimum" or desired flying qualities regions since modern control laws can and should be designed to achieve these goals.
6. More definition is needed to define the best response type for particular mission tasks.
7. There is a strong suggestion that time delay measures should be made relative to stick position rather than stick force. More data are required to clarify this feel system issue. Majority opinion also indicates that force command systems should be avoidled.

10.3 RECOMMENDATIONS FOR USE OF THIS DOCUMENT

This document is not a specification or an evaluation of methods or criteria. It simply documents the data- and idea- gathering of a number of individuals. Its best uses would be:

- as background and guidelines to development of a specification for a specific aircraft.
- as background to general specifications like MIL-F-8785C and MIL Std 1797.
- as an aid to planning future research.

10.4 FINDINGS OF THE WORKING GROUP AND FUTURE TRENDS

Though future trends are difficult to predict, they include stealth technology (B-2, F-117, YF-22 and -23, etc.) and thrust vectoring (YF-22, X-31, F-15 SIMTD, F-18 HARV, etc.). The basic principles of design for good flying qualities apply no less to these configurations than to more conventional ones. The pilot should have at his disposal responses that allow rapid, precise control, and tho responses should meet the same criteria as more conventional types.

The implementation of the control laws is the chief challenge for the emerging configurations. The Working Group did not specifically address this issue for future designs, but the consensus is that the present foundation of criteria and lessons from the past provide an adequate starting point.

10.5 NEEDS FOR FUTURE RESEARCH

Specific needs for future research include data-gathering to allow resolution of the gaps and inconsistencies listed in 10.2. Cooperative efforts among AGARD countries are one possible approach. A cooperative program should meet the following criteria:

- Geared to resolving gaps/inconsistencies of common interest or to establishing criteria for emerging aircraft of types to be operated by several member nations.
- Maximizing efficiency by utilizing the best resources of nations in the team.
- Maximizing shared learning by involving all nations members equally in appropriate phases of the effort
- Demonstrating economy of operations, i.e. less cost per nation than a solo effort would cost.

Several nations possess resources that complement those of other nations, including variable stability aircraft, simulation and analytical skills.

10.6 FOLLOW-ON ACTIVITIES

Working Group 19, on Functional Agility, has already been established as an outgrowth of Working Group 17.

APPENDIX A

ENVELOPE LIMITING AND CAREFREE HANDLING

A.1 INTRODUCTION

The question of "to limit or not to limit" is complex and still controversial as discussed In Reference A.1.1. Several present fighter aircraft such as the F-18 and F-14 have no angle of attack limits which Indicates that essentially carefree aerodynamic designs are now possible. The Introduction of digital flight control systems provides the capability to design very specific angle of attack/load factor limiters as a function of many parameters. These factors would appear to Indicate that limiters, if required, need not be absolute, across the envelope limiters as was the case In early examples such as in the F-16 aircraft. There is also a growing body of pilot opinion against the contraints of absolute limiters. The desire is to be able to cross the boundary of the permissible flight envelope as needed during emergencies (hitting the ground) or combat and, at the very least, have the degradation in aircraft flying characteristics be graceful. Graceful in this context would mean no sudden departures if special pilot handling is used (for example, no lateral stick inputs).

For example, the world famous "cobra" maneuver in the Russian SU-27 and MIG 29 aircraft is a testimonial to their excellent high angle of attack pitch aerodynamics. Each of these aircraft have angle of attack limiters which are normally active at F-16-like values (about **25** deg. AOA). The pilot can exceed the limiter under special circumstances and pitch point to very high angles of attack. He must, however, not use lateral-directional control inputs in these maneuvers to be successful.

The application of envelope limiting in several current and projected aircraft designs is reviewed in the following subsection.

A. 1.1 References

A.1.1 McKay, K. and Walker, M.J., "A Review of High Angle of Attack Requirements for Combat Agility", AGARD Flight Mechanics Symposium, Quebec, October 1990.

A.2 F-15/F-16 EXPERIENCE

The F-15 and F-16 represent contrasting design solutions to the problem of air superiority maneuvering.

The F-15 is stable in pitch, while the F-16 is unstable with a deep stall. Because of the F-15's stability, pilots can maneuver it without regard for loss of control. However, the aircraft is easy to 'over-g' and a voice warning system has been Installed to help prevent structural damage due to vigorous maneuvering. The F-16, on the other hand, Is statically unstable with a deep stall and weak directional stability at high angles of attack. Consequently, the F-16 is equipped with an angle-of-attack limiter and a load factor limiter. The limiters, however, are functionally reliable enough to allow rapid, full-deflection commands by the pilot, in contrast to the move tentative commands required in the F-15. Paradoxically, this piloting experience has given the F-16, in spite of its high-angle-of-attack aerodynamics problems, a reputation for desirable carefree handling compared with the F-15. An interesting side effect of the F-16 absolute limiter in combination with a small-amplitude force sidestick is that the incidence of g-induced loss of consciousness is higher in the F-16 than in the F-15, which can actually produce theoretically much faster load factor onset rates.

A.3 ASPECTS FOR TRANSPORT AIRCRAFT

Even the most advanced transport aircraft, which are equipped with sophisticated "Fly-by-Wire" flight control systems, are not specifically unstable designs, and therefore they, in principal, don't fit into the scope of this working group. However, it was thought to be of interest to discuss briefly a few important items.

Concerning the limiting and flight envelope protecting system of the airbus, A- 320, as an example, there are three main aspects;for the system definition: to protect the aircraft against overstressing, stall and passengers discomfort. This leads to a larger number of limiting functions, the mechanization of which includes an integration of the thrust control into the system. To illustrate this situation, the following list gives an example of typical limiting and protecting functions:

- Angle of Attack limitations depending on the configuration and flight condition.
- Positive and negative pitch attitude protection, different for high and low speed conditions.
- Vertical load factor protection depending on flap position.
- High speed and Mach number protection different for neutral stick and stick-forward commands
- Bank angle protection different in normal flight and after overspeed warning

A.4 THE B-1B ANGLE-OF-ATTACK LIMITER - A LESSON TO BE LEARNED

The interim flight control system used on the B-1B utilized an open-loop integrator in combination with a series feel system for angle-of-attack limiting. inputs to the integrator only occurred when the angle-of-attack exceeded the defined limit. Values of angle-of-attack above that limit were integrated and fed to the elevator servo-actuator in a sense to produce a nose down pitching moment. Since a series mechanization was used, the down elevator was not reflected by any stick motion, and the nose down moments appeared to be uncommanded. in principle, this would be an emulation of a natural aerodynamic stall. However, the system proved to be unsatisfactory despite considerable efforts at fine-tuning using ground-based simulation. The fundamental drawback was that the output of the integrator tended to saturate the elevator servo-actuator, especially when operating at high gross weights. Such saturation occurred for even slightly prolonged application of moderate load factor (say 1.4 g), e.g. level 45 degree banked turn, and pull-out from a dive. Activation of the integrator resulted in an uncommanded pitch-down which sometimes led to a complete loss of control. The scenario was as follows. The pilot would apply aft stick to recover from the dive with no apparent result since the aircraft could only pull very small values of load factor on the angle-of-attack limit. Additional aft stick was then applied resulting in continuous integration which saturated the elevator servo in the nose-up direction, resulting in an uncontrollable departure (fortunately always on the simulator). in other cases, an uncommanded pitch oscillation occurred (simulation and in flight) while operating in 1 g flight at or near the angle-of-attack limit. This was determined to be a result of a limit cycle above and below the alpha limit which turned the integrator on and off. Sometimes these oscillations diverged to the point where a departure occurred (simulation only). Fortunately, this integrator was not included in the final version of the B-1B flight control system.

The lesson to be learned was that even with considerable tweaking and fine-tuning, the combination of an open-loop integrator and a series feel system proved to be unacceptable as a method of envelope limiting

A.5 MIRAGE 2000/RAFALE CAREFREE HANDLING DESIGN PHILOSOPHY

A.5.1 General Objectives - Reduced Pilot Workload

- Pilot work-load reduction hence pilot will devote all his attention to the mission accomplishment. For example: in air-combat, the pilot is more involved in all the strategic and tactic combat aspects.
- Piloting simplification for some of the mission phases by "bang-bang" piloting or "piloting on limits" (more especially in combat).

A.5.2 Carefree Handling Actuality

Today, because of Fly-By-Wire implementation, "classical" piloting problems are resolved:

- Aerodynamic particularities are smoothed out by the flight control system.
- Stability
- Uncoupled control
- Respect of behavior in the time-domain standards
- Under these conditions, pilots adapt their requirements and think that Flight Control Systems must provide them with all necessary protection which means the cancellation of all the flight control rules referring to the aircraft flight envelope monitoring.

A.5.3 Flight Envelope to be Considered

Limits corresponding to the ~~control loss~~: deep stall, spinning start. divergent **rolling:**

- Aerodynamic state monitoring: Angle of attack, sideslip, air-speed.
- Monitoring of the dynamic **behavior** In some maneuvers: roll rate. ...

The limiting flight envelope relies on the flight configuration: flight condition (altitude, Mach number), aerodynamic aircraft configuration (external loads, surfaces deflection), inertial configuration (external loads, fuel situation).

- **Limits** corresponding to the excessive structural stress: Monitoring of parameters such as: load factor, roll rate. etc...
- **Engine(s)** limitations
- Limits corresponding to the weapon delivery conditions
- Limits corresponding to the pilot's stamina
  - In steady state conditions, load factor monitoring
  - In transient conditions, load factor rate monitoring
- Distinctions are to be made between:
  - The limit envelope: The pilot **is** entitled to go beyond the envelope limits **in** emergericy **case (to avoid** crashing for instance) the outcome of which could be some permanent structural distortions.
  - The ultimate envelope: Exceeding the envelope limits would Involve the aircraft **loss.**

A.5.4 Carefree Handling General Criteria

- On the overall piloting commands, the reachable envelope has to be as extensive as possible without exceeding the limit envelope.
- From a specific and intentional pilot's command, the reachable envelope could be extended. Then, It will be as extensive as possible without exceeding the ultimate envelope.

Example: The pilot can exceed an "elastic stop" so that the obtained load factor results In an exceedance of the limit structural loads (to avoid crashing for instance).

These requirements lead to transient overshoots **in** load factor to achieve maximum achievable aircraft performance.

5.5 Handling Realization

- Control of **the aircraft response time** history
  - Use of feedback and feedforward functions
  - Use of appropriate non-linear techniques
  - Use of model-following techniques
- Accurate **adaptation** to the flight conditions
  - Altitude, air-speed
  - External loads

A.5.6 Cafefree Handling (CFH) Under Low Maneuverability Conditions

- Under very low maneuverability conditions (very low air-speed), the aircraft can to be in any angle-of-attack and sideslip condition ($-180° < \alpha \leq +180°$, $-90° < \beta \leq +90°$).
- The pilot cannot put himself under very low maneuverability conditions inadvertently.
- Under very low maneuverability conditions, the aircraft behavior does not rely on the Flight Control System in a significant way.
- Under very low maneuverability conditions, the flight opportunities mainly rely on temporary behavior during recovery.

A.5.7 Summary Comments

1. Today, carefree handling functions provide the combat aircraft with opportunities regarded as absolutely necessary by the pilots.
2. CFH functions must insure protection against:
   - Control loss
   - Excessive structural stress
   - Undesirable effects on the **engine(s)**
   - Undesirable effects on the weapon delivery conditions
   - Undesirable effects on the pilot's stamina

3. CFH functions can be obtained with existing Flight Control Systems, without additional architectural complexity (only "classical" sensors).
4. CFH functions development represents a great part of the Flight Control System development. In the same way, the corresponding data processing work-load represents a very important part of Flight Control System computer work-load.
5. CFH functions involve quite an evolution on the art of the combat aircraft piloting (piloting on limits) and on physiological consequences for the pilot.
6. For a CFH aircraft, handling qualities mainly rely on the structural strength and pilot resistance.
7. CFH functions allow some aircraft development tasks reduction (spin studies).

A.6 EAP/EFA - CAREFREE HANDLING PHILOSOPHY

The essential feature of the carefree handling philosophy for these aircraft is that regardless of the combination of pilot command inputs in any or all axes, the aircraft should be able to reach but not go outside the defined limits of the structural strength envelope or departure-free handling. The intention is to relieve the pilot completely of the task of safeguarding the aircraft while in high workload combat situations, and to be able to exploit its performance and agility to the absolute maximum without requiring exceptional skill. For at "last luck" avoidance of collision with the ground or with another aircraft, an additional aft stick override travel is provided through a large incremental breakout force which commands greater than limit load g.

The achievement of this aim requires a substantial design effort with full non-linear computer and simulator modeling. The design is refined by a continuous interaction between calculation and piloted simulation, aiming eventually at the most critical input sequences and the control law adjustment required to maintain the limits. In this respect, the method of handling optimization by command prefiltering is exceptionally well suited to the carefree handling design process.

APPENDIX B

LATERAL DIRECTIONAL FLYING QUALITIES CRITERIA FOR HIGHLY AUGMENTED AIRCRAFT

6.1 LATERAL DIRECTIONAL PROBLEMS RELATED TO HIGHLY AUGMENTED AIRCRAFT

The lateral directional aspects of flying qualities have received less attention by the working group since instability effects are usually confined to the pitch axis. Highly augmented aircraft, however, are designed to perform in an extended flight envelope, where high angles of attack are attained and inertia coupling is present. Phenomena like pilot induced oscillations in roll have surfaced as well as high frequency oscillations due to neuromuscular lag feeding from the pilot (roll ratcheting).

These problems are not taken into account in the present military specifications, but can be highlighted using available analysis techniques such as the extension of the dropback method to the roll axis (Reference B.1.1).

Another aspect which has become more important, in relation to highly augmented aircraft, is the orientation of the roll axis during large amplitude and agile maneuvers. When rolling about an axis other than the wind axis, sideslip generation induces a deterioration in the dutch roll characteristics possibly causing departure.

Roll performance characteristics are presently expressed in terms of time to roll versus :service and operational flight speeds and load factor. A modification of required speeds and load factors for level 1 and 2 appears to be necessary due to the highly augmented characteristics of the aircraft and the short time constants which do not allow the pilot to pay attention to the present airspeed and load factor sequences.

A proper dutch roll dipole cancellation is still necessary and recent experiments validate the capability of the Northrop criteria in associating the dutch roll damping with the ratio ω_ϕ/ω_d. Due to limited experimental data base availability, the next sections provide some qualitative suggestions of problem areas and those aspects of lateral directional flight qualities which could be of importance to highly augmented aircraft.

B.1.1 Roll Axis Selection

Of some importance in designing modern flight aircraft is the definition of the axis about which the aircraft should roll during maneuvers within the flight envelopes. In older fighters, without any interconnection between ailerons and rudder, the orientation of the roll axis was fixed by masslinertia properties, aerodynamic coefficients and control effectiveness. Modern flight control systems, however, make it possible to select the roll axis within the physical limits, according to pilot's desire during the various flight phases, maneuvers and agility requirements.

The roll axis is presently not defined in any of the military specifications e,g, see Reference **B.1.2. Its** desired orientation varies, for example, for turns and roll-out for flight path modification, barrel rolls to slow down and ailerons roll to start a split S.

The most frequent use is for turn entry or exit. With respect to the direction of flight, a roll axis tilted up corresponds to adverse yaw (nose lagging the turn entry) in stability axes; while a nose-down tilt indicates proverse yaw

Rolling about any axis other than the flight path will generate sideslip, thus influencing dutch roll motion. Even departure from controlled flight at high angle of attack may be possible. Studies have shown that a major contributor to departure is the $P\alpha$ term in the side-force equation, which doesn't exist during rolls around stability axis. However, the cockpit is higher above a flight-path-aligned roll axis at high angles of attack. The results are unusual responses to roll control Inputs like lateral acceleration and visual slowing, e.g., of a runway threshold.

Also rolling about the flight path at high angle of attack creates a flywheel effect producing an Incremental pitching moment which has to be considered during the basic aerodynamic design.

All things considered, it appears best to generate and measure the roll motion in stability axes, examining the results carefully at high angle of attack, where the difference between body and stability axes is greatest. in order to achieve the needed roil performance it may be necessary to accept some uncomfortable lateral acceleration.

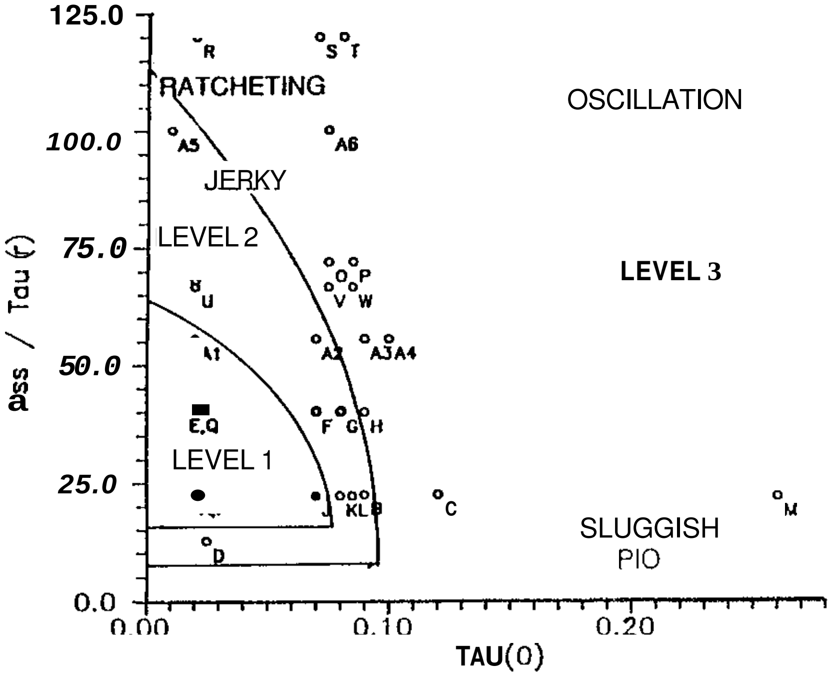
B.1.2 Roll Characteristic in Tracking

insight gained with the LATHOS experiment (Reference 6.1.3) has led to a slight modification in the MIL-STD-1797, with a limit on minimum roll lime constant (see Reference B.1.2). These results are supported by the fact that some modern aircraft equipped with high augmentation have too small time constant and experience an excessive lateral sensitivity and roil ratcheting.

Avery important parameter, surfaced during the analysis of the LATHOS data, is the effect of control sensitivity which, combined with extended maneuverability and increased roll rate demand produced the appearance of familiar pilot induced Oscillations in roll during tracking and landing.

The use of well tested methods, such as the dropback (References B.1.1 and B.1.4) has proven very valuable once the control sensitivity is taken into account. The extension to the lateral case requires the use of metrics such as roll rate overshoot τ_o, and initial acceleration P_{ss}/τ_r, (functions of time delay and roll time constant respectively) to be able to identify Level 1 configurations as shown in Figure B.1.1).

PIO can also be identified from bank angle frequency response information. Phase rate and phase lag at crossover are capable of separating good configurations from those that are PIO prone as shown in Figure B.1.2. Boundaries in the frequency response Nichols plots can be suggested as in Figure B.1.3 even though experimental validation is required before implementation of the dropback as an official analysis tool.

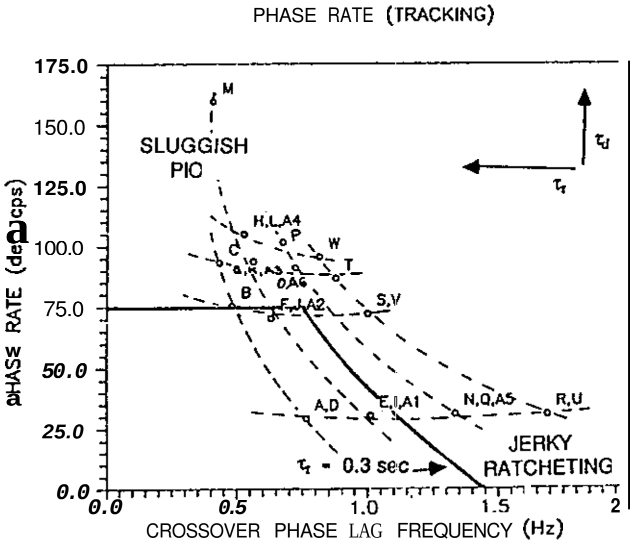


PARAMETERS USED

τ_o = Roll rate overshoot time. Function of time delay

p_{ss}/τ_r = Initial acceleration. Function of roll time constant

Figure B.1.1. Trim Response Boundary Levels for Roll Tracking



- Phase rate

Excellent metric for PIO

PIO condition

- $p_r > 60^\circ$/cps
- Magnitude > -10 db

- Level 1 boundaries clearly identifiable as a function of time delay τ_d, roll time constant τ_r, phase rate p_r

Figure B.1.2 Phase Rate Based on Level 1 Boundaries for Roll Tracking

[illegible] ll ratcheting problems that surfaced u[illegible]g th[illegible] LATHOS expe[illegible]t, althou[illegible]g[illegible] not as critical per se as [illegible]), can be identified f[illegible] r[illegible] t[illegible] [illegible] of the [illegible] ration frequency response [illegible] is a by [illegible] machine interaction, it can be excluded when the [illegible] crossover frequency lies outside of the 10-20 rad/sec [illegible] region

[illegible] in th[illegible], a general approach such as [illegible] dropback is suggested for the analysis of tracking handling qualities in roll, keeping in [illegible] that control sensitivity [illegible] t be accounted for ([illegible] 7 [illegible] more [illegible] on [illegible] ontrol sensitivity) and that, if [illegible], [illegible] related to t[illegible] delay and roll time constant can be [illegible] highlight levels [illegible] f handling qualities

B.1.3 Lateral-Directional Tracking Requirement

The primary late[illegible] task is the control of the [illegible] angle by use of lateral s[illegible] Th[illegible]e eq[illegible]ival[illegible]nt [illegible] g the dynamics of this task can be [illegible] the high order system over the frequency range from 0.1 [illegible] to 10 ra[illegible] ed on the [illegible] of [illegible] the [illegible] angle to [illegible] the dutch roll to [illegible] control (Reference B.1.5):

$$\frac{p}{F} \qquad \frac{{}_{\delta a s}\, s(s \quad +2\zeta_\phi\omega_\phi s+3_\phi)e^{\quad s}}{(s+1/\tau_s)(s+1/\tau_R)(\quad +2\zeta \qquad s+\omega_d^2}$$

When the complex dipole cancels ($\omega = \omega_d$; [illegible] ζ_d) the roll rate response is not contaminated by [illegible] xcu[illegible] in the dutch-roll mode [illegible] the [illegible] bel[illegible] Whe[illegible] not [illegible] la[illegible] directional precision task both in the open and close[illegible] loop [illegible] severely a[illegible]ted [illegible] tential met[illegible] that can be applied in this case is the [illegible] (see Reference B.1.6). To cancel the [illegible] r[illegible], [illegible] rite[illegible] uses the [illegible] nitu[illegible] ratio ω_ϕ/ω_d and the real axis location of the zero with respect to the [illegible] roll pole $\zeta_\phi\omega_\phi/\zeta_d\omega_d$.

The cancellation depends mainly on the values of ω_ϕ and ω_d and to a lesser extent on ζ_ϕ and ζ_d. Hence the importance of ω_ϕ/ω_d as a parameter which determines proverse ($\omega_\phi/\omega_d > 1.$) or adverse($\omega_\phi/\omega_d <$ 1.) yaw tendency during the roll control.

The importance of the $\omega\ /\omega_d$ parameter is felt mainly in closed loop tasks. When the zero of p/Fas transfer function lies in the lower quadrant with respect to the dutch-roll pole, the closed-loop damping increases when the pilot (pure gain) closes a bank angle error to aileron loop. Conversely, it can be shown that when the zero lies in the upper quadrant with respect to the dutch-roll pole, when the pilot applies aileron inputs proportional to bank error the closed-loop damping decreases up to destabilize the system (pilot induced oscillation). Finally, when ζ_d becomes large, the effect of the pole-zero location decreases because the variation in damping due to ω_ϕ/ω_d effect is small relative to the augmented damping.

Figure **B.** 1.4 compares level 1 and level 2 boundaries mapped Into ω_ϕ zero location for several dutch-roll poles with the Northrop requirements on the complex plane for the same dutch roll poles. An Important aspect of the requirement is that it implicitly accounts for the usable zero location areas in the complex plane due to ω_d and ζ_d increase.

All the Interactions caused by this quadratic pair are lumped under the general heading of ω_ϕ/ω_d and $\zeta_\phi\omega_\phi/\zeta_d\omega_d$ effects. however several other parameters play an important role in the totality of effects, such as $1/\tau_r$, $1/\tau_s$, τ_{sp}, $|\phi/\beta|_d$. For this reason the application of the requirement implies quite a number of guidelines which must be considered. The roll, spiral and dutch roll mode MIL requirements should first be met as well roll time delay, moreover small to medium values of $|\phi/\beta|_d$ are preferred.

It has been shown that pilot rating correlations with the parameter ω_ϕ/ω_d exhibit different trends as a function of $|\phi/\beta|$ especially with low ζ_ϕ and ζ_d leading to:

$\omega_\phi/\omega_d = 1.8$ for $|\phi/\beta|_d$ small

$0.75 < \omega_\phi/\omega_d < 1.0$ for $|\phi/\beta|_d$ medium to large

For large ζ and ζ_d as such as for highly augmented aircraft meeting level 1 requirements, $\omega_\phi = \omega_d$ is generally prefefred.

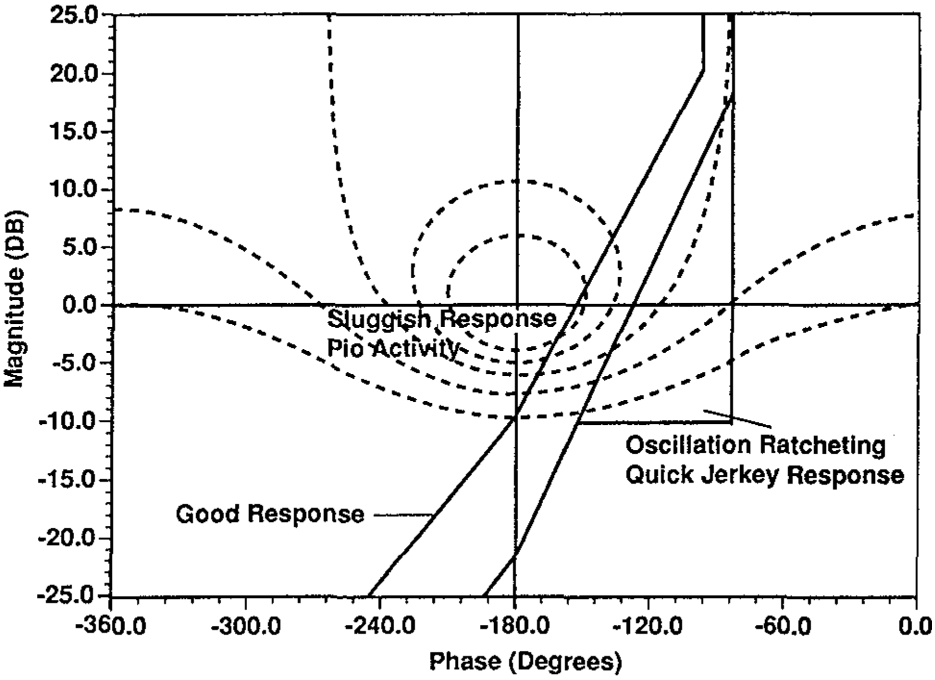


Figure **B.1.3** Bank Angle Frequency Response Boundaries for PIO Detection

A limited fixed base simulation of the lateral directional tracking criterion has been carried out using an AMX aircraft. The AMX is a subsonic dedicated attack aircraft, basically stable with a quasi-conventional FCS. It has been provided with a limited authority SAS which affects only marginally the flight characteristics. The flight control system consists of a three axis fly-by-wire system managed by a digital FCC along with conventional electrohydraulic lanes. Several FCS configurations have been considered, the nominal along with the degraded states. These configurations, all for the same flight condition (one of the most critical) have been reported in Figure B.1.5.

The simulation activity was performed using Aeritalia's fixed base simulator. A formation flight was simulated with respect to a lead aircraft flying in the same direction and whose image was computer generated. The pilot was asked to maintain the fixed vector displayed on the HUD exactly on the nozzle of the model in level flight or in a 45 deg bank turn maneuver. Of course during the whole maneuver (30 sec) the yaw control was free and minimum use of longitudinal control was recommended.

The average and integral errors on lateral and vertical translation and roll rotation as well the lateral and the longitudinal stick activity were monitored to provide a measure of the pilot capability to track the aircraft, to be used as a comparison term among the various cases and to establish a correlation with the analytical prediction (lateral directional tracking criterion).

The pilot comments for the different conditions plotted in Figure B.1.5 were:

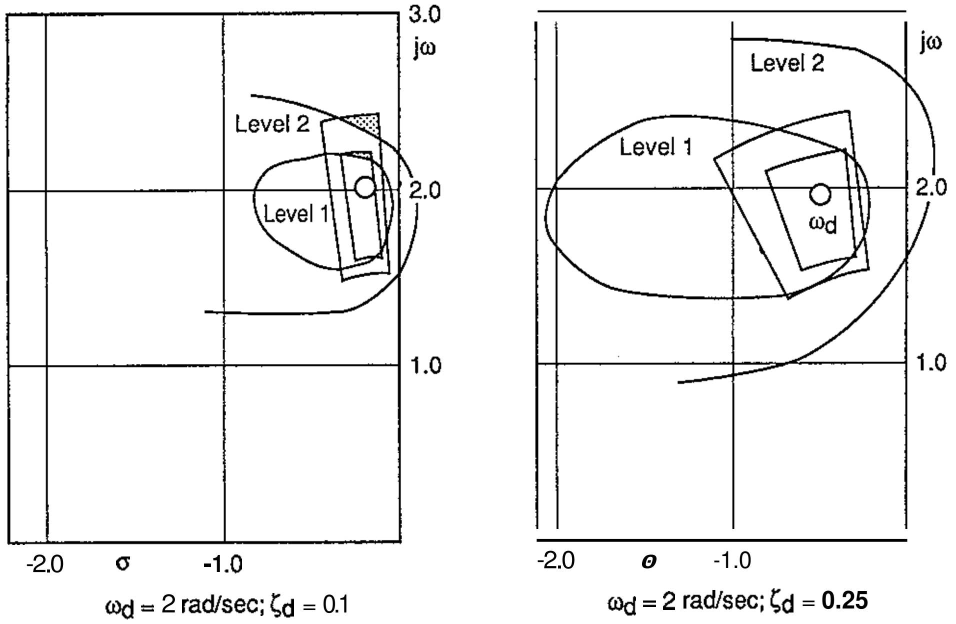
1. FULL FCS: not easy to control in roll due to the sluggish roll response but acceptable.
2. C/F OFF: difficult to control for the roll and yaw oscillation developed during the task (cross-feed off).
3. R/D OFF: easier than 1 because the faster roll response and the possibility to quicker stop the bank angle (roll damper off).
4. Y/D OFF: very difficult to perform the tracking task because of the divergent oscillations (yaw damper off).
5. R/D + Y/D OFF: the same as 4.
6. C/F + R/D OFF: yaw oscillation, the roll control seems easier than 2.
7. C/F + Y/D OFF: strong yaw oscillations, similar to 6.
8. C/F + R/D + Y/D OFF: more difficult than 6 because the higher oscillation in roll and yaw.
9. $G = 2/3 * G$: easier than 1 (reduced gain aileron/spoiler).

The average error of the different FCS cases was compared in Figure B.1.6 and in general a good correlation with pilot comments was found. The nominal condition (full FCS) has been found slightly difficult to control due to the sluggish roll response even if the roll time constant meets the level 1. A better situation has been found for Conditions 3 and 9, in fact, with R/D off, lower roll time constant leads an iimprovement for the roll control and this influences the pilot opinion. The worst cases were conditions 4 and 5 because of the low damping (level 2) and $\omega_\phi < \omega_d$ leading to pilot induced oscillation. Points 6 and 7 with $\omega_\phi < \omega_d$ were considered conditions quite difficult to control but they were found to satisfy level 2 of handling qualities unlike the boundaries in the criterion.

A general agreement has been found between the pilot opinion and the analytical predictions based on the lateral-directional tracking criterion. The left hand limits of the above criterion seems to better define the tracking difficulty, while, according to our investigation, the exact position of the right hands limits is disputable.

B.1.4 Residual Modes

Highly augmented aircraft are usually capable of meeting dutch roll damping requirements for cat. A combat phase. Even though excellent behavior in turbulence can be attained, recent experience with the F-20 (Reference B.1.7) has shown degradation in gun aiming characteristics due to a small nose slice or drift after target acquisition. This was attributed to the effects of the washout filter time constant, producing a residual drift in rudder command. The minimum dutch roll frequency was 2 rad/sec with damping between 0.5 and 0.8. After the excitation of the dutch roll by lateral control, sideslip settled after a few seconds, adjustment of filter and dutch roll frequency cured the problem.



$\omega_d = 2$ rad/sec; $\zeta_d = 0.1$

$\omega_d = 2$ rad/sec; $\zeta_d = 0.25$

Figure B.1.4 Level 1 and 2 Boundaries Comparison Between MIL-87858 and Northrop Criterion

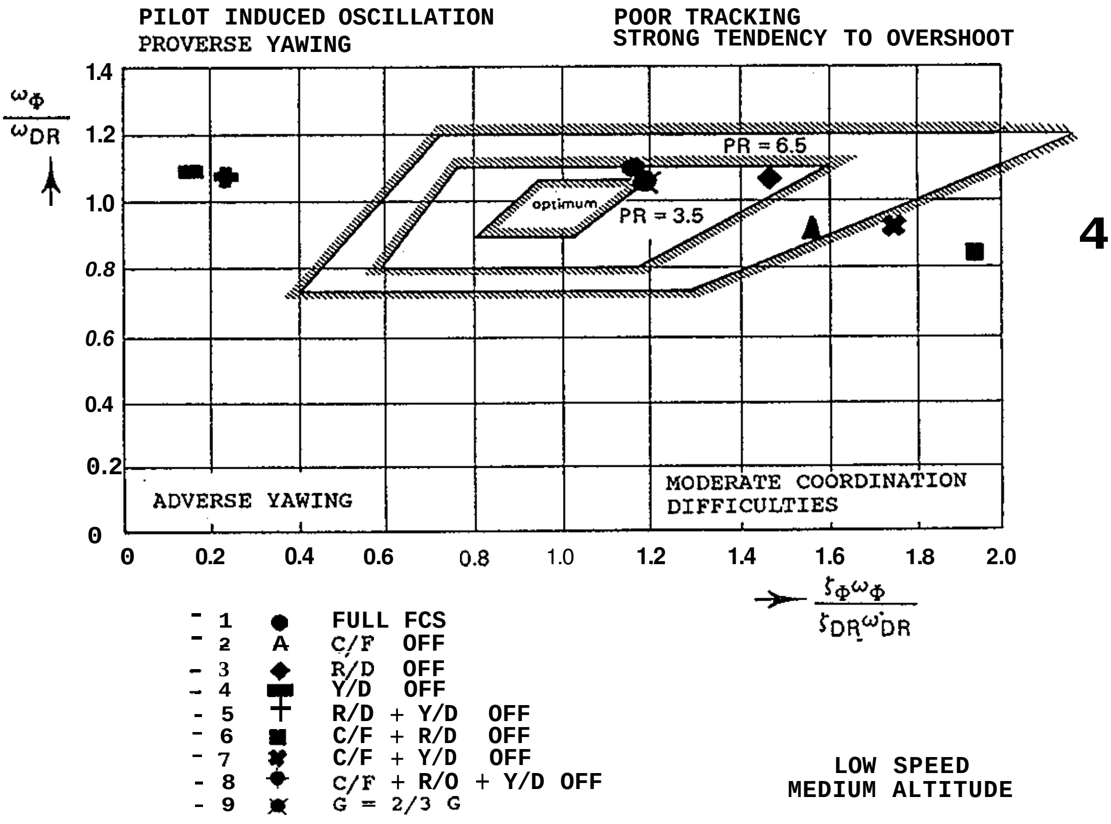
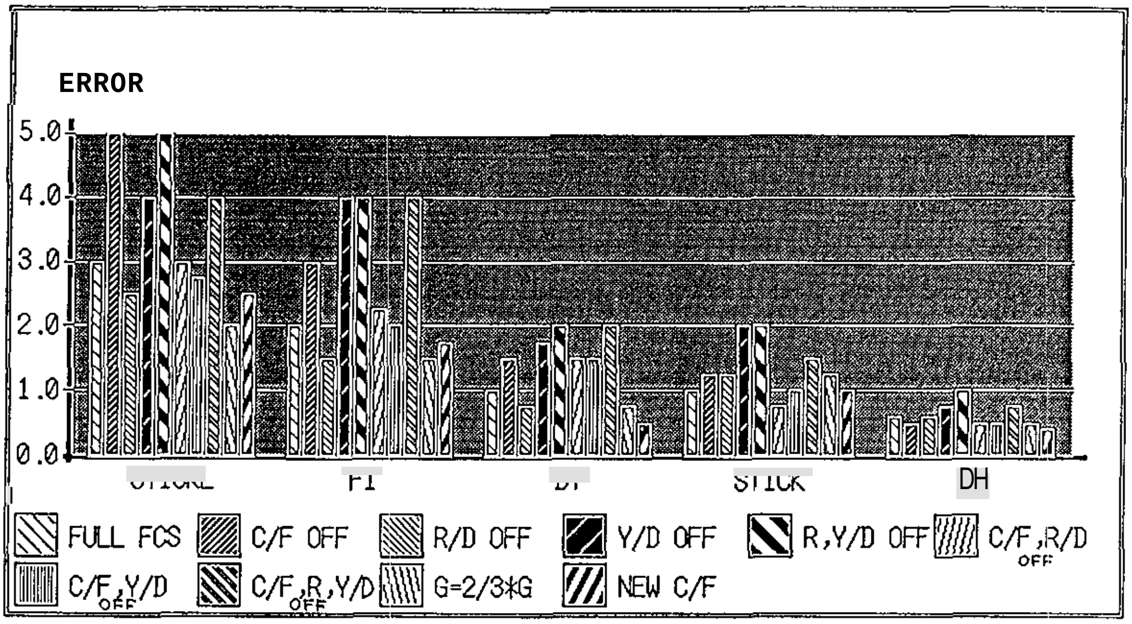


Figure B.1.5 AMX Simulation Handling Qualities Levels



F.C.S. : flight control system
C/F : cross-feed
R/D : roll-damper
Y/D : yaw-damper
G=2/3*G: reduced gain aileron/spoiler

LOW SPEED
MEDIUM ALTITUDE

Figure B.1.6 AYX Simulation Tracking Error Results

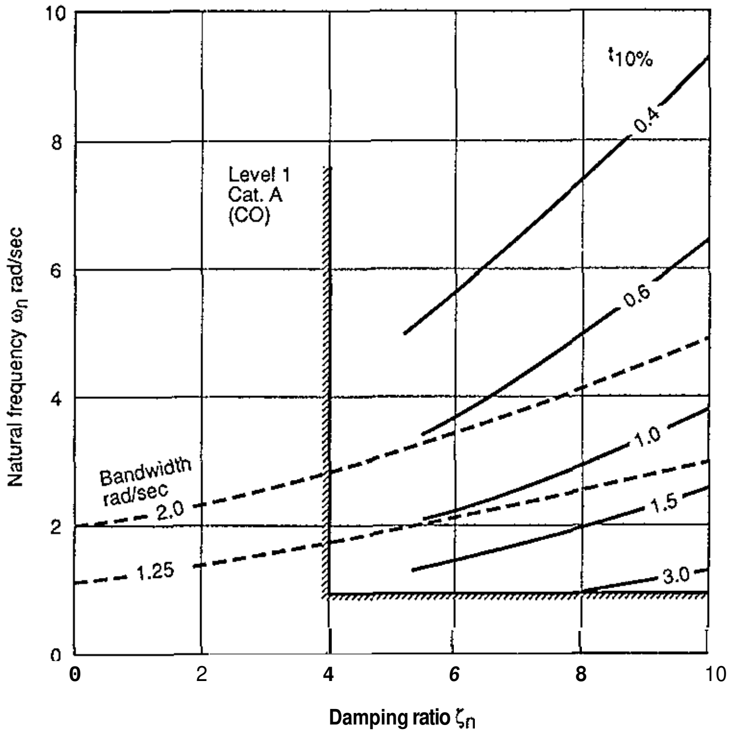


Figure B.1.7 Dutch Roll Characteristics

The presence of long settling time is shown in Figure B.1.7 as responses to a 10% initial dutch roll disturbances and to a 90% demanded sideslip. The level 1 minimum bandwidth boundary of 1.25 rad/sec is shown. Both metrics require the frequency to be increased with higher damping to compensate for for the increased sluggishness indicating possible inadequacy of standard cat.A limits.

B.1.5 References

B.1.1 Innocenti, M., Thukral, A.J., "Roll Response Criteria for High Maneuverable Aircraft Using Gibson's Method", AIAA Atmospheric Flight Mechanics Conference, Boston, MA, August 1989.

B.1.2 Hoh, R., and others, "Proposed MIL Standard and Handbook - Flying Qualities of Air Vehicles", AFWAL-TR-82-3081, 1982.

B.1.3 Monagan, S.J., and others, "Lateral Flying Qualities of Highly Augmented Aircraft", AFWAL-TR-81-31B1, Vol. I and II, June 1982.

B.1.4 Gibson, J.C., "Piloted Handling Qualities Design Criteria for High Order Flight Control Systems", AGARD-CP-333, April 1982.

B.1.5 Hodgkinson, J, LaManna, W.J. "Equivalent System Approaches to Handling Qualities Analysis and Design Problems of Augmented Aircraft", AIAA Atmospheric Flight Mechanics Conference, Hollywood, FL, August 1988.

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B.1.7 Iloputaife, O., Ma, L., "Handling Qualities Design of a Northrop High Performance Fighter", AIAA Paper 88-2450, 1988.

APPENDIX C

AGILITY OVERVIEW AND OVERLAP WITH HANDLING QUALITIES

C.1 INTRODUCTION

The writers include an overview of agility in this document for several reasons. First, aerodynamic instability has been "sold" partially as a way to achieve greater agility (though the reader will have gathered from our comments that the buyer should beware of some of these claims). Second, it is, however, certainly true that the focus on transient responses is at the heart of both agility and handling qualities studies. Next, because agility technology is still emerging, we need to define our current perspective of its role.

Finally, the writers strongly feel that the handling qualities community should embrace and play a leading role in the development of agility technology.

C.2 PAST FIGURES OF MERIT FOR COMBAT PERFORMANCE

"Point Performance" and "Energy-Maneuverability" (E-M) have been widely used as measures of merit for air to air combat design and analysis. Up to the early 1950's, fighter aircraft were mainly limited to the use of guns and rockets. Because of the relative length of the air combat (on the order of minutes), "Point Performanco" parameters were mostly adequate to comprehensively describe and compare the fighters' combat capabilities.

A more balanced way to evaluate close combat effectiveness became necessary when jet propulsion, sensors exceeding the pilot's eyes' performance, and rear aspect IR missiles were introduced, greatly expanding the weapon system capabilities and allowing much wider combat envelopes. "Energy-Maneuverability" (E-M) concepts were therefore developed as a complement to the "Point Performance", providing the possibilily for comparisons and trade-off analysis between management of the aircraft energy level (SEP to be converted in speed andlor altitude variations) and maneuvering sustained performance (STR, etc...).

C.3 THE NEED FOR AGILITY

In a close combat (Reference C.3.1 and C.3.2), the development of effective all-aspect missiles and of integrated avionics and weapons sensors, which allow off-boresight acquisition and launch, now obviates the need to maneuver to the opponent's tail position; the launch aircraft needs only to be within missile range and generally pointed at the target to effectively fire a weapon. The new generation of digital flight control systems reinforces such capabilities by allowing every aircraft to be designed for ideal flying qualities, even to be tailored around specific combat tasks.

Offensively, this emphasizes the need to rapidly and precisely move the nose of the aircraft to point (as required by the weapons) and shoot, even accepting some degradation in energy status. Defensively, similar transient capabilities are essential for evasive maneuvers.

The dynamics of the close combat engagements have been therefore significantly increased, being now characterized by fast and large variations of speed, altitude, load factor and attitude, all implying coarse use of stick and throttle. In order to point the nose quickly, acquire and track a target, to be the first to effectively launch a weapon and to disengage at will in a multi-target environment, the pilot may have to achieve completely different flight conditions in the minimum time, aiming to minimize turn radius, maximize turn rates or change plane in the most dynamic way.

"Point Performance" and "Energy-Maneuverability" are not sufficient anymore to represent the fast transients required by a fighter, and it has been necessary to search for new figures of merit (or "metric") in order to analyze those new capabilities and to derive proper operational tactics.

Such a new metric is the "Functional Agility".

A significant amount of work is however presently ongoing with respect to the operational utilization of agility in a realistic threat scenario. Although the initial results do not seem to be In total agreement within each other in terms of absolute numbers (mainly depending on the combat simulation program adopted), it has been shown as a general trend that increases in Agility, achievable through "relatively" low cost improvements in aerodynamics or FCS design philosophies, could result in combat effectiveness increases similar to those achieved through very costly performance related improvements, such as STR or Thrust level.

C.3.1 References

C.3.1 Hamilton, W.L., and Skow, A.M., "The Impact of All-Aspect Weapons and Advanced Avionics on Fighter Maneuverability Requirements", Eidetics Study Report 85-10, May 1985.

C.3.2 Fristachi G., "Identification and Ranking of Factors Influencing the Effectiveness of Air to Air Fighters", AC\243 (Panel 7, RSG 16) D\3 Vol. I, 1989.

C.4 FUNCTIONAL AGILITY

Functional Agility is a measure of the time to change aircraft state with precision and control and to achieve a valid weapon employment.

The goal of this new metric is to merge airframe capabilities with the dynamics of the sensors, the data processing, the decision finding process, and the weapons aiming, management and delivery for close-in engagements.

Although considering that the employment of the weapon system as a whole will have a mutual influence on the aircraft handling qualities, all ongoing studies on agility agreed that the most proper approach to the problem was to initially confine the research on the overlap between handling qualities and the more "Flight Mechanical" aspect of the agility, i.e. the Airframe Agility.

C.5 AIRFRAME AGILITY DEFINITIONS

Despite the fact that the proper "tool" to study agility is still to be identified and several metrics have been proposed, a common categorization has been agreed to in terms of flight path and nose pointing agility. This approach recognizes that each one of the metrics under debate emphasizes different aspects of the overall agility issue.

C.5.1 Flight Path and Nose Pointing Agility

In this context Flight Path Agility (Maneuverability) can be defined as the ability to change direction and magnitude of the velocity vector (i.e. flight path, involving states such as load factor and vertical and horizontal displacements) with precision and control, being representative of the movement of the aircraft center of gravity.

The Nose Pointing Agility (Controllability) can be defined as the ability to change magnitude and direction of the lift vector (i.e. nose pointing, involving states such as pitch, heading and bank angles) with precision and control, being representative of the aircraft rotations around its center of gravity.

It must be noted that all of the agility definitions specifically address the precision of the end state.

C.5.2 Pitch, Torsional and Axial Agility

For a more complete understanding and utilization of the agility concept, Airframe Agility can be categorized also by the type of controls used, as Pitch, Torsional and Axial Agility.

Pitch Agility is a measure of the capability to move the aircraft nose in the longitudinal plane with precision and control, i.e. a measure of the time required to pitch to maximum lift, to unload to zero g or to rapidly achieve a desired attitude, angle of attack, or load factor variation.

Torsional Agility addresses the time to change heading and bank angle with precision and control under loaded conditions.

The fighter's rapidity to decelerate to best performance speeds can determine the outcome of an engagement, while its rapidity to achieve minimum drag conditions while "spooling up" to max power may determine a successful disengagement or ability to intitiate multiple reengagements with significant maneuver potential: Axial Agility is a measure of such capability to rapidly change the aircraft: energy state (speed/altitude) starting from any initial condition.

C.6 AGILITY METRICS; OVERVIEW OF CURRENT PROPOSALS

in the mid 80's, several studies on Agility started. These lacked, however, the necessary coordination and therefore resulted in different or even diverging research directions, with the consequent development of a wide range of different metrics.

Only recently a coordinated effort was initiated, sponsored by the USAF. One of the most interesting initial outcomings of this coordination is a "big picture" view of all studies, from which it is already possible to deduce that the Agility issue is far more complex than expected. This complexity does justify the coexistence of a whole set of conceptually different metrics and theories. Some of these are described below.

General Dynamics (Reference C.6.1) has proposed the Dynamic Speed Turn (DST) plots, which are actually a recombination of the widely used "dog-house" plot. By crossplotting its limit lines, two different plots can be derived, showing the aircraft acceleration/deceleration potential in the whole airspeed spectrum both at 1 g and at maximum loaded conditions (Figure C.6.1). Total airspeed loss/gained and average turn rate over the time needed to perform a defined maneuver can be derived from these plots, together with optimum maneuvering limits (e.g. AOA) to be used in order to avoid too heavy perfromance degradation while dynamically maneuvering.

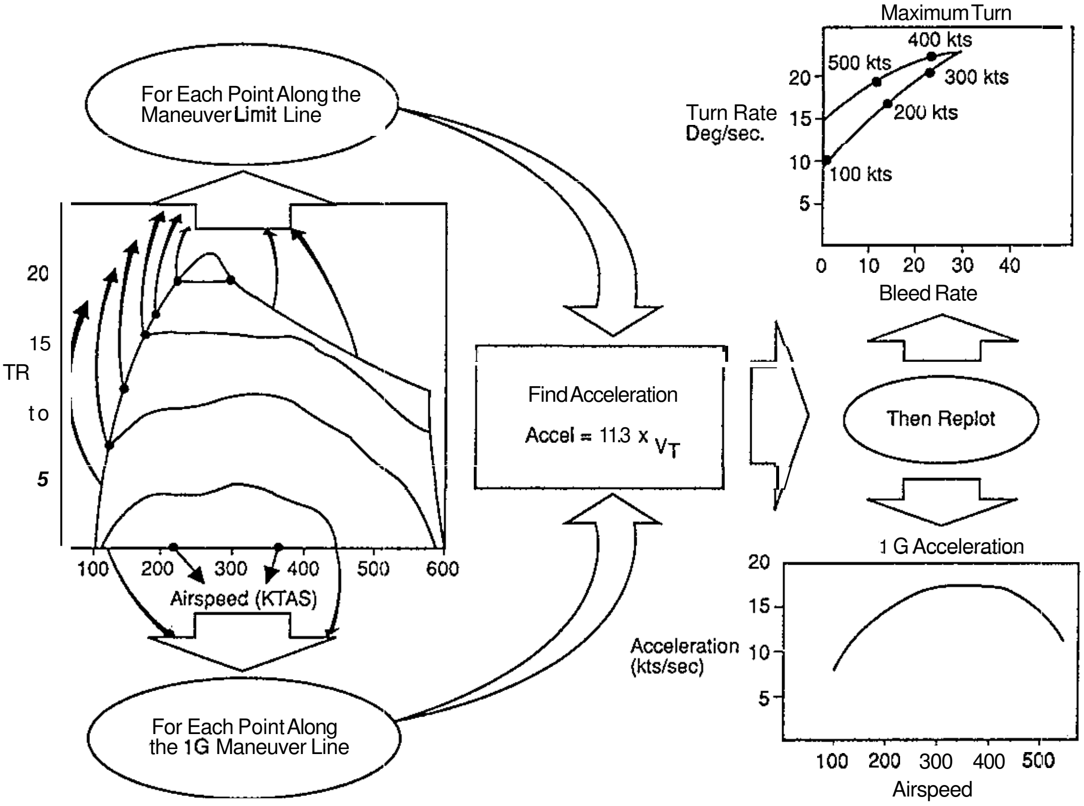

Figure C.6.1 Dynamic Speed Turn (DST) Plots

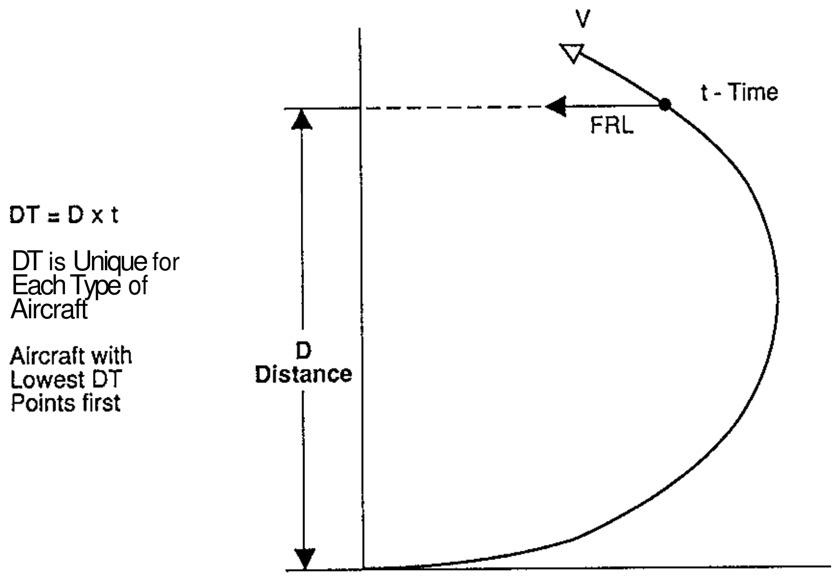

Figure C.6.2 Definition of Point-and-Shoot Parameter

Northrop (References **C.6.2** and **C.6.3)** is proposing a metric called "Distance/Time" (DT), derived multiplying the cross-distance and the time needed by an aircraft to turn its Fueslage Reference Line (FRL) by 180° in a level turn (Figure **C.6.2).** This parameter, characterizes the aircraft's capability to maximize average turn rate and minimize total turn radius in a minimum time. It is intended to give insight into the aircraft's "Point-and-Shoot" performance, **i.e.** its capability to be the first to point its all-aspect weapons at an opponent, achieved by (Figure **C.6.3)** minimizing the combination of "total" turn radius (D) and total time to perform a 180° turn (T). The DT metric can be used to directly compare Point-and-Shoot capabilities of two opposing aircraft in their whole flight envelopes, by calculating the DeltaDT for given values of mutual headings. A similar parameter, possibly used in the same way as DT, has been recently proposed by Northrup (Reference **C.6.4)** with the aim of quantifying the torsional agility from a more operational point of view, by multiplying the cross-distance and the time needed to complete roll reversal maneuvers at various load factors.

The Eidetics (Reference **C.6.5)** approach to a metric for Torsional Agility combines turn rate and roll rate capabilities into a Dynamic Roll or "Turn Agility" term, defined as the aircraft Turn Rate (TR) divided by the time required to change bank angles by 90° (and stop) while maintaining the TR. This metric, plotted vs Specific Excess Power (Ps), could possibly provide an understanding of the mutual maneuvering capabilities of two aircraft better than the standard Ps vs TR plots. e.g. showing that in some conditions (Figure **C.6.4**), although a higher sustained turn rate is available, aerodynamics or flight control related aspects could detract from such potential, by actually denying an advantage in lateral maneuvering capabilities. The Eidetics proposal for an Axial Agility metric is the "Power Onset Rate", defined as the increment of Specific Excess Power (DeltaPs) from minimum powerlmaximum drag to maximum powerlminimum drag divided by the time necessary to change configuration (engine spool-up, speed brakes in, etc..); conversely, a "Power Loss Rate" parameter reflects the DeltaPs between max powerlmin drag and min powerlmax drag divided by the time to make the change. Both parameters are a measure of the aircraft's capability to rapidly change energy state independent of lift-induced drag. When plotted against Turn Rate, indications of the aircraft capability to achieve energy variations while in maneuvering flight can be deduced, clearly highlighting, also, any air intake or enginelairframe integration problem in the whole AOA range.

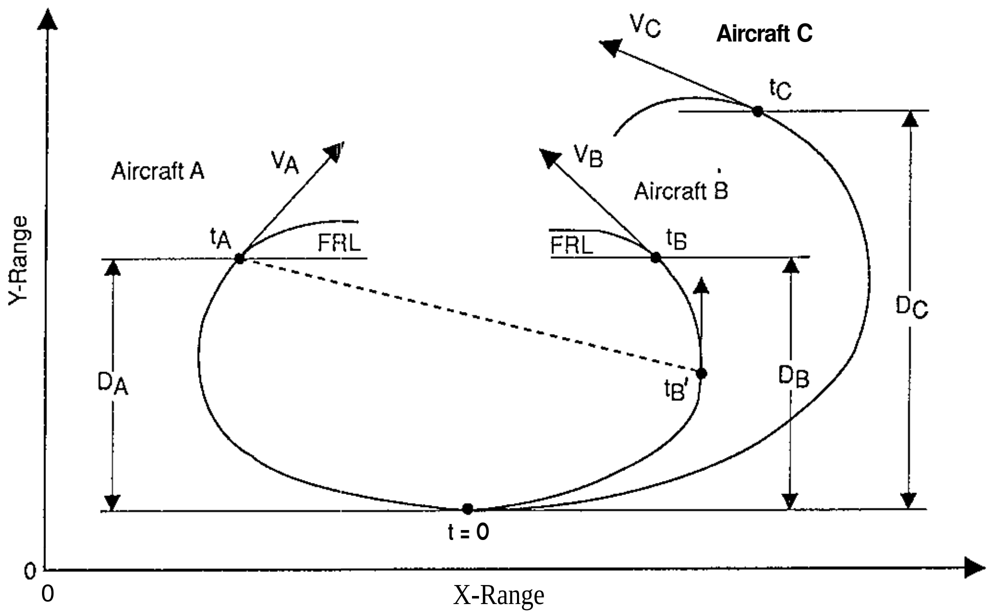

Figure C.6.3 Point-and-Shoot Trajectories

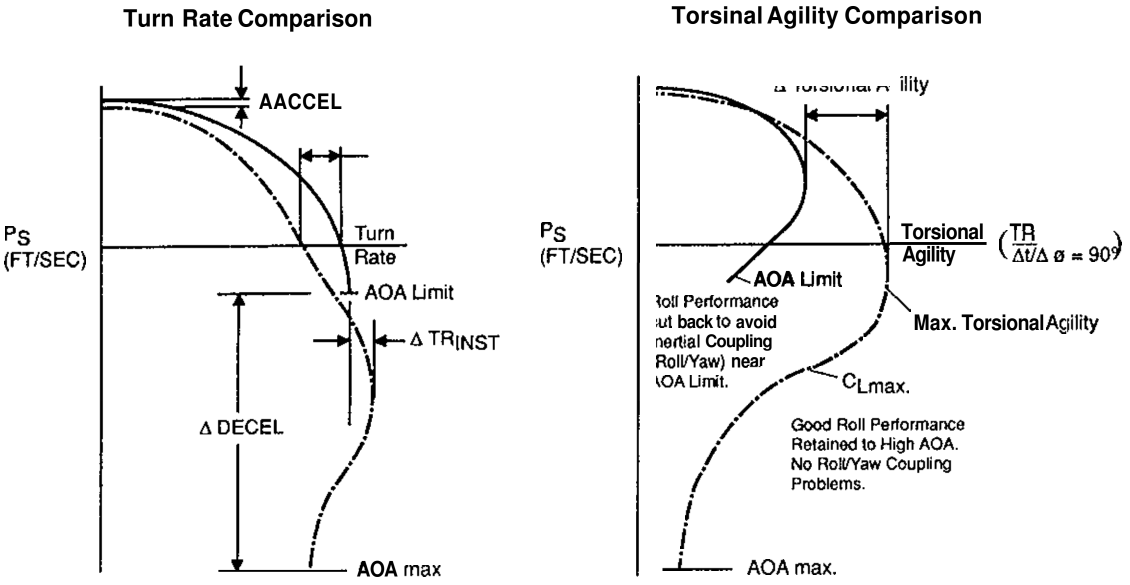

Figure C.6.4 Turn Rate and Torsional Agility Comparisons

While the above metrics tend to derive "global" capabilities, usually related to the whole length of the maneuvers, MBB (Reference C.6.6) proposal is primarily focused on instantaneous capabilities, depicting "acceleration" terms related to the Instantaneous center of curvature of the aircraft trajectory.

With the idea of bringing together all proposed metrics into a unique picture, the USAF FDL (Reference C.6.7) starts with the "user's point of view" that in the real world the pilot's task in a close combat can be either to achieve an instantaneous performance (e.g. jinking or missile avoidance maneuvers), an actual change in position parameters (e.g. to point-and-shoot) or a more global change in state variables, with a closer consideration of the development of the tactical situation over a certain length of time. In this light, the timeframe has been proposed as the main identifier, such that all above proposed metrics could fall within a classification either of "instantaneous, Small Amplitude or Large Amplitude Task Agility" using time constants respectively of "instant, 1-2 secs. and 10-20 secs".

To complete such a "big picture view", the USAF FDL also proposed an additional metric, the "Energy-Agility" to correlate magnitude of state variation, time (or rate) of variation and the energy penalty paid to accomplish the maneuver: such a metric could therefore be exploited by the ratio between a general parameter expressing the rate of state change and the energy loss, both as integrals over the whole maneuver time (Figure C.6.5). In some respects, such a metric could also be considered as a complement to the previously analyzed metrics, seen now In terms of "tasks"; applying the Energy-Agility integral approach, the Northrop and the Eidetics proposed metrics could therefore be seen respectively as "Angle" and "Range/Closure" tasks.

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C.6.2 Kalviste, J., "Point-and-Shoot Agility Parameter", Minutes of AFFTC Agility Workshop, Edwards AFB, March 1988.

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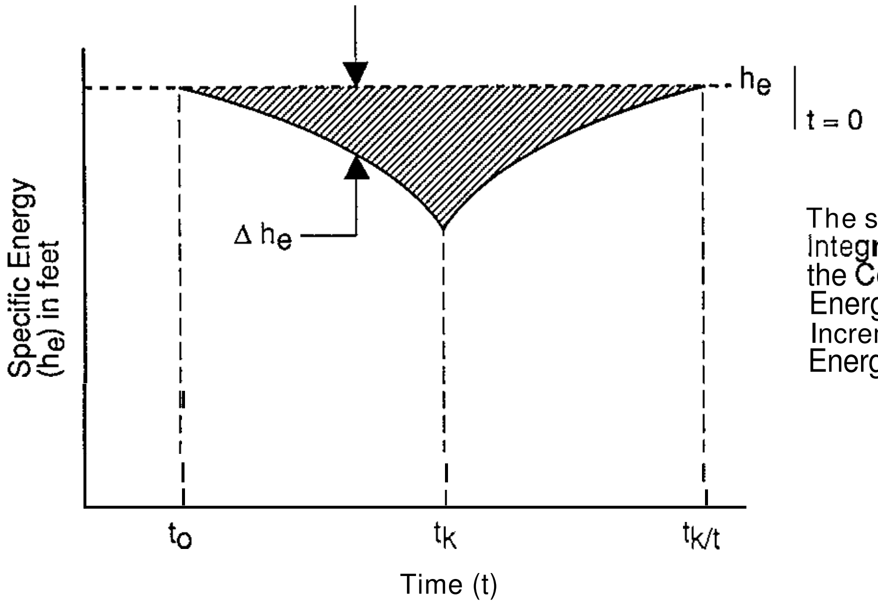

The shaded Area is the Integratio Product of the Compromised Energy and the Time Increment Spent at Each Energy Level or. . .

$. . . \int \Delta h_e \, dt$

Figure C.6.5 "Energy-Agility" Concept

C.7 AGILITY MEASURES vs. FLYING QUALITIES CRITERIA

There are many correspondences between the study of transient agility and the study of flying qualities. Both examine steady and transient response characteristics, and flying qualities engineers have long been the custodians of transient response quality determination. Agility specifications must take into account the flying qualities requirements discussed in this report. Agility for a completed aircraft design can be calculated using the usual simulation models which, however, are complex and of high dimension. Currently, engineers are also using simplified methods and criteria to gain insight into the agility potential of aerodynamic configurations. These methods, which are like low order equivalent systems, are called Equivalent Potential Agility (EPA) models.

C.7.1 Pitch Agility

There is no explicit official specification for time-to-pitch or maximum pitch rate and time to reach a desired angle of attack. Pitch flying qualities are defined by the Control Anticipation Parameter (CAP) or by using pitch bandwidth. Those parameters are intended to ensure not only sufficient performance but also sufficient precision. The addition of a time to pitch to the Standard would **be** worthwhile.

The requirement to stop or arrest the pitch motion is certainly operationally realistic, but from the measurement standpoint, judgement or an agreed-upon criterion is required to define the maneuver end point. Perhaps the response should be broken down into performance (in the manner of current time-to-time roll requirements) and precision (as currently governed by modal and frequency response parameters).

As an example of a flying qualities parameter which is similar to a transient agility measure, Chalk defined At, at time for pitch rate to reach its first steady slate value, as $\Delta t = \frac{g}{V_T}\,\frac{1}{CAP}$

Using simple EPA models, Figure C.7.1 compares agility quantities to the CAP requirements. The figure implies that very high pitch agility, however desirable from the theoretical operational point of view, might not be acceptable to pilots because of excessive abruptness. The definition of Level 3 flying qualities includes inability to perform the operational task.

In the nonlinear pitching moment plot of Figure C.7.2, the nose-up pitch control power is strong. However, in the angle of attack (AOA) region of instability, the aircraft has progressively **less** nose-down pitching moment. Should the full-nose-down pitching moment plot cross the axis and return, as in Figure C.7.3, there is a stable trim point at very high AOA. This deep stall reduces nose-up agility because the nose-up pitch excursions must be limited severely to prevent entry into the deep stall. This characteristic is also discussed in Section 6 of this report. Reference C.7.1 discusses how real-world actuation and the need to meet flying qualities requirements can offset these results.

C.7.2 Axial Agility

Apart from the specialized coupling of thrust and pitch on some configurations there are no generic lessons on axial agility for unstable aircraft. Early experience on the F-4K aircraft showed that improved stick free stability was one way to compensate for engines that responded too slowly for precise flight path control.

C.7.3 Lateral (Torsional) Agility

Combat range results and actual wartime experience have shown that an aircraft with the capability to roll rapidly, especially at loaded or high angle-of-attack conditions has a significant advantage. An aircraft with good lateral agility can fight more equally, and even defeat, an aircraft with significantly higher traditional measures of energy maneuverability. Figure C.6.4 shows one proposal for presentiing lateral (or "torsional") agility data for two aircraft. One aircraft has an advantage in energy maneuverability, seen in the plot of specific excess power versus turn rate, on the left of the figure. When lateral agility is added to the comparison, on the right side of the figure, a more complete view of the other aircraft's qualities emerges. For this comparison, torsional agility is defined as turn rate divided by time to bank ninety degrees and stop. By adding the agility measure to the traditional energy meneuverability comparison, insight and depth are added to the comparison of combat effectiveness.

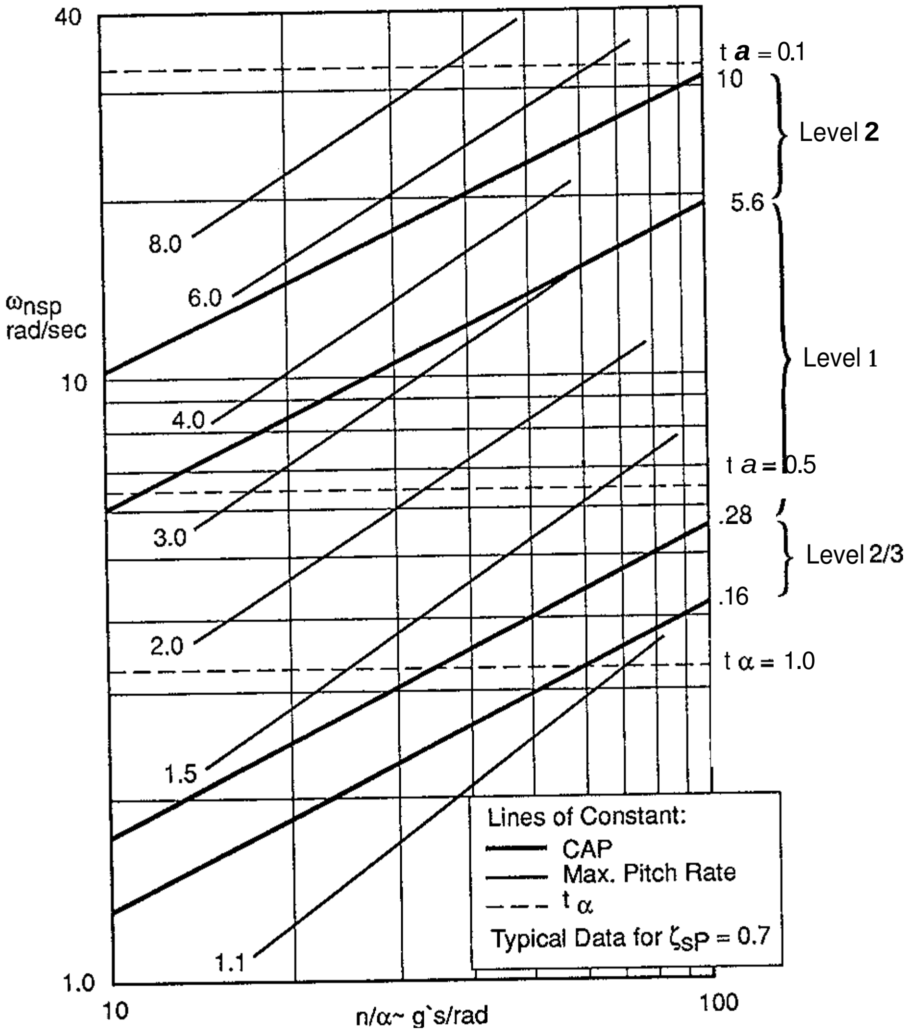

Figure C.7.1 Comparison of Maximum Pitch Rate and Time to Angle of Attack With Control Anticipation Parameter

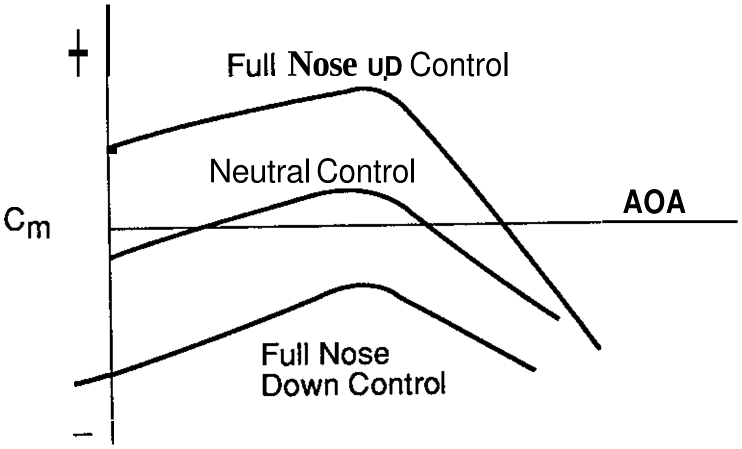

Figure C.7.2 Pitching Moment Versus Angle of Attack for Typical Fighter with Relaxed Static Stability

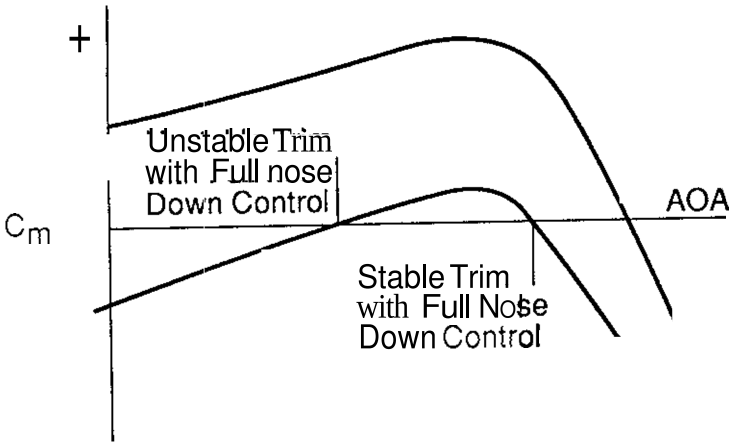

Figure C.7.3 Pitching Moment Versus Angle of Attack for Fighter with Deep Stall

C.7.4 Agility/Flying Qualities Overlaps

There is clear overlap between agility metrics and flying qualities requirements. Some flying qualities requirements are performance-oriented in the manner of agility metrics. Some agility metrics are precision-related in the manner of flying qualities requirements. The methodologies also overlap because accurate determination of very short term aircraft response is key to both technologies. Simplified models are being used for both (including equivalent systems and EPA models for example). The vast background of flying qualities analysis, including the current ideas on models of drastically reduced dimension, appears largely applicable. However, while quantitatively very similar, agility and flying qualities are not necessarily qualitatively evaluated similarly. For example, the Cooper-Harper pilot opinion rating scale does not provide a direct measure of agility per se, only of task peformance. And yet the quantitative nature of agility is an essential foundation of the flying qualities requirements. There is, therefore, a need to collect a significant data base in order to derive support for numerical specification requirements that account for both agility and flying qualities.

C.7.5 References

C.7.1 Hodgkinson, J., and Cord, T., "Relationship Between Flying Qualities, Transient Agility and Operational Effectiveness of Fighter Aircraft", AIM-Atmospheric Flight Mechanics Conference Proceedings, Aug. 1988.

C.8 OPEN AREAS AND PROPOSALS FOR FURTHER ACTIVITY

As seen through this whole chapter, the agility issue is far from being comprehensively developed and analyzed; coordinated research efforts have just started, and many aspects, both in the developmental and in the application areas, need to be more deeply investigated or are even still to be approached.

Even remaining confined, at the moment, to the flight mechanics core disciplines, it is still necessary to:

- develop theories and metrics,
- quantify requirements,
- find correlation with combat effectivenessand, possibly, identify new (or more proper) tactics,
- develop specialized flight test techniques,
- identify possible new technology requirements,
- identify optimal trade-offs between weapon system, airframe capabilities and pilot in the loop aspects.

All the above topics have been analyzed by the Working Group 17 and resulted in the drafting of a pilot paper proposing to the Flight Mechanics Panel body the terms of reference for a dedfcated working group on agility. As a result of this proposal a new agility working group has been created.

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4. Abstract

Demanding requirements for performance and handling qualities together with extended flight envelopes lead to use of new technologies like active control and control configured unstable vehicles. The review of the handling qualities issues of unstable aircraft which by necessity are highly augmented is the theme of this report. In general the handling qualities criteria for highly augmented stable aircraft are equally applicable to the specialized case of unstable aircraft. Accordingly, this report contains a review of existing highly augmented aircraft, both stable and unstable. Handling qualities criteria for both large and small amplitude longitudinal maneuvers are presented. Other areas of interest are also considered: basic aerodynamic design, specific issues relating to the feel system and control sensitivity, evaluation techniques and the handling qualities design and evaluation process. The subjects of carefree handling, lateral-directional criteria and agility are presented in separate appendices. Where possible the lessons to be learned from the combined experiences of the working group are highlighted.

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