DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

NORTH ATLANTIC TREATY ORGANIZATION

SCIENCE AND TECHNOLOGY ORGANIZATION

AC/323(SCI-303)TP/1018

www.sto.nato.int

STO AGARDograph 300 **AG-300-V33**
Flight Test Technique Series – Volume 33

Flight Test Techniques for the Assessment of Fixed-Wing Aircraft Handling Qualities

(Techniques d'essai en vol pour l'évaluation des qualités de manœuvrabilité des aéronefs à voilure fixe)

This AGARDograph has been sponsored by the SCI Flight Test Technical Team (FT3) of the Systems Concepts and Integration Panel (SCI) of STO.

Published July 2021

Distribution and Availability on Back Cover

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

NORTH ATLANTIC TREATY ORGANIZATION

SCIENCE AND TECHNOLOGY ORGANIZATION

AC/323(SCI-303)TP/1018

www.sto.nato.int

STO AGARDograph 300 **AG-300-V33**
Flight Test Technique Series – Volume 33

Flight Test Techniques for the Assessment of Fixed-Wing Aircraft Handling Qualities

(Techniques d'essai en vol pour l'évaluation des qualités de manœuvrabilité des aéronefs à voilure fixe)

This AGARDograph has been sponsored by the SCI Flight Test Technical Team (FT3) of the Systems Concepts and Integration Panel (SCI) of STO.

Authored by

Hans-Christoph Oelker (lead Author), Timothy Cox

Joseph Duncan, Muharrem Fırat, Eren Topbaş

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

The NATO Science and Technology Organization

Science & Technology (S&T) in the NATO context is defined as the selective and rigorous generation and application of state-of-the-art, validated knowledge for defence and security purposes. S&T activities embrace scientific research, technology development, transition, application and field-testing, experimentation and a range of related scientific activities that include systems engineering, operational research and analysis, synthesis, integration and validation of knowledge derived through the scientific method.

In NATO, S&T is addressed using different business models, namely a collaborative business model where NATO provides a forum where NATO Nations and partner Nations elect to use their national resources to define, conduct and promote cooperative research and information exchange, and secondly an in-house delivery business model where S&T activities are conducted in a NATO dedicated executive body, having its own personnel, capabilities and infrastructure.

The mission of the NATO Science & Technology Organization (STO) is to help position the Nations' and NATO's S&T investments as a strategic enabler of the knowledge and technology advantage for the defence and security posture of NATO Nations and partner Nations, by conducting and promoting S&T activities that augment and leverage the capabilities and programmes of the Alliance, of the NATO Nations and the partner Nations, in support of NATO's objectives, and contributing to NATO's ability to enable and influence security and defence related capability development and threat mitigation in NATO Nations and partner Nations, in accordance with NATO policies.

The total spectrum of this collaborative effort is addressed by six Technical Panels who manage a wide range of scientific research activities, a Group specialising in modelling and simulation, plus a Committee dedicated to supporting the information management needs of the organization.

- AVT Applied Vehicle Technology Panel
- HFM Human Factors and Medicine Panel
- IST Information Systems Technology Panel
- NMSG NATO Modelling and Simulation Group
- SAS System Analysis and Studies Panel
- SCI Systems Concepts and Integration Panel
- SET Sensors and Electronics Technology Panel

These Panels and Group are the powerhouse of the collaborative model and are made up of national representatives as well as recognised world-class scientists, engineers and information specialists. In addition to providing critical technical oversight, they also provide a communication link to military users and other NATO bodies.

The scientific and technological work is carried out by Technical Teams, created under one or more of these eight bodies, for specific research activities which have a defined duration. These research activities can take a variety of forms, including Task Groups, Workshops, Symposia, Specialists' Meetings, Lecture Series and Technical Courses.

The content of this publication has been reproduced directly from material supplied by STO or the authors.

Published July 2021

Copyright © STO/NATO 2021
All Rights Reserved

ISBN 978-92-837-2337-0

Single copies of this publication or of a part of it may be made for individual use only by those organisations or individuals in NATO Nations defined by the limitation notice printed on the front cover. The approval of the STO Information Management Systems Branch is required for more than one copy to be made or an extract included in another publication. Requests to do so should be sent to the address on the back cover.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

AGARDograph Series 160 & 300

Soon after its founding in 1952, the Advisory Group for Aerospace Research and Development (AGARD) recognized the need for a comprehensive publication on Flight Test Techniques and the associated instrumentation. Under the direction of the Flight Test Panel (later the Flight Vehicle Integration Panel, or FVP) a Flight Test Manual was published in the years 1954 to 1956. This original manual was prepared as four volumes: 1. Performance; 2. Stability and Control; 3. Instrumentation Catalog; and 4. Instrumentation Systems. As a result of the advances in the field of flight test instrumentation, the Flight Test Instrumentation Group was formed in 1968 to update Volumes 3 and 4 of the Flight Test Manual by publication of the Flight Test Instrumentation Series, AGARDograph 160. In its published volumes AGARDograph 160 has covered recent developments in flight test instrumentation.

In 1978, it was decided that further specialist monographs should be published covering aspects of Volumes 1 and 2 of the original Flight Test Manual, including the flight testing of aircraft systems. In March 1981, the Flight Test Techniques Group (FTTG) was established to carry out this task and to continue the task of producing volumes in the Flight Test Instrumentation Series. The monographs of this new series (with the exception of AG237 which was separately numbered) are being published as individually numbered volumes in AGARDograph 300. In 1993, the Flight Test Techniques Group was transformed into the Flight Test Editorial Committee (FTEC), thereby better reflecting its actual status within AGARD. Fortunately, the work on volumes could continue without being affected by this change.

Since that time, The Flight Test Editorial Committee has had a number of changes of identity which have in recent years been closely associated with a series of Task Group identities bearing the acronym FT3. This period has also seen FT3 migrate from the Air Vehicle Technology Panel to The Systems Concepts and Integration Panel reflecting the changing nature and focus of NATO Flight Testing. This AGARDograph is sponsored by FT3 against their current Task Group, SCI-305 Flight Test Technical Team (FT3).

An Annex at the end of each volume in both the AGARDograph 160 and AGARDograph 300 series lists the volumes that have been published in the Flight Test Instrumentation Series (AG 160) and the Flight Test Techniques Series (AG 300), plus the volumes that were in preparation at that time.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

Flight Test Techniques for the Assessment of Fixed-Wing Aircraft Handling Qualities

(STO-AG-300-V33)

Executive Summary

This AGARDograph focuses on flight test techniques for the evaluation of Flying Qualities and Handling Qualities. This evaluation plays an important role at the end of the development process of any aircraft. It is the final proof of performance of contractual operational requirements of the overall aircraft system.

As this testing is aimed at the verification of these capabilities of the overall aircraft all systems of the aircraft play a role. Their operational capabilities must be proven within their individual specifications prior to HQ testing. Their individual performance can have a major impact on HQ testing and resulting HQ performance.

This report gives a background and a guideline on how to set up tests for Flying Qualities and Handling Qualities for flight testing. For this a structured approach is described, basically with a ‘Step 1’ for open loop testing (no pilot interaction), a ‘Step 2’ for PIO resistance testing, and finally a Step 3 for closed loop (pilot interaction fully in the loop) and operational testing.

After introductory chapters on Flying Qualities and Handling Qualities, their basic understanding and evaluation methodologies, a catalogue of specific testing is given for all test stages. Selected practical examples show how it can be done operationally in the real world.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

Techniques d'essai en vol pour l'évaluation des qualités de manœuvrabilité des aéronefs à voilure fixe

(STO-AG-300-V33)

Synthèse

La présente AGARDographie se concentre sur les techniques d'essai en vol destinées à évaluer les qualités voilières et qualités de manœuvrabilité. Cette évaluation joue un rôle important à la fin du processus de mise au point de tout aéronef. Elle constitue la preuve de performance des choix effectués en matière de besoins opérationnels contractuels du système global d'aéronef.

Étant donné que ces essais visent à vérifier les capacités de l'ensemble de l'aéronef, tous les systèmes de l'aéronef y jouent un rôle. Leurs capacités opérationnelles doivent être démontrées dans le cadre de leurs spécifications individuelles avant les essais mesurant la qualité de manœuvrabilité. Les performances individuelles des systèmes peuvent avoir de grands effets sur les essais de qualité de manœuvrabilité et les performances qui en découlent.

Ce rapport fournit un arrière-plan et un guide sur la manière de configurer des essais relatifs aux qualités voilière et de manœuvrabilité pour les essais en vol. Pour cela, nous décrivons une démarche structurée, avec une étape 1 d'essais en boucle ouverte (sans interaction avec le pilote), une étape 2 d'essais de résistance au pompage piloté et enfin une étape 3 de boucle fermée (interaction du pilote totalement dans la boucle) et d'essais opérationnels.

Après les chapitres d'introduction sur les qualités voilières et les qualités de manœuvrabilité, leurs principes de base et leurs méthodologies d'évaluation, nous fournissons un catalogue des essais particuliers à chaque étape d'essai. Des exemples pratiques choisis indiquent comment les réaliser sur le plan opérationnel en conditions réelles.

Acknowledgements

This report is part of NATO-STO-SCI activity, Systems, Concepts, and Integration Panel. It is a sub-task of the “Flight Test Technical Team (FT3)”. Sponsors are David Wheaton (US Air Force, Engineering and Technical Management) and Oliver Brieger (formerly DLR Flight Test and now with Airbus Defence and Space Chief Engineer Combat Aircraft). Dave’s and Oliver’s support are highly appreciated.

During the preparation, this report was reviewed by colleagues from several nations. Their valuable comments have been highly appreciated. A special thanks goes to John Manke (USAF 412 Test Wing, Flight Test Engineer), Heinz Spoelgen (Airbus Defence and Space, Test Pilot), Paul Kelly (BAE Systems, Flight Test Engineer), Oliver Trujillo (Airbus Defence and Space, Flight Test Engineer), and Col. A.Y. Barbaros Demirbaş (Retired, Turkish AF, former Head of the 401st Development Test Squadron).

A final overall review was performed by John Hodgkinson. His comments were highly appreciated. He contributed thoughts on the usage of simulators and mentioned the examples about C-17 testing.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

Preface

Flight testing of aircraft Handling Qualities is the final step in a sometimes long and tedious certification effort of an aircraft. The overall process is governed by general flight test safety measures. The test contents with regard to Handling Qualities heavily depends on requirements given by the relevant certification authority and/ or customer specification.

A safe and successful execution of a Handling Qualities flight test program is mainly governed by experience provided by the test centre and their engineering and test crews. The main purpose of this report is to bring together experience from various test centres and test engineers. The intention is to provide a guideline for future projects.

This report is the result of a team effort. As lead author I received valuable support by my co-authors, Tim Cox, Joey Duncan, Muharrem Fırat, and Eren Topbaş. Almost all communication in the team was carried out vie e-Mail, only occasionally via telephone (due to time shifts), and only once in a face-to-face meeting which still could not be attended by all team members.

At this point I would like to thank all team members for their valuable contributions and discussions. Without these this report would not have been possible.

Hans-Christoph Oelker.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

Biographical Sketches

HANS-CHRISTOPH OELKER

Dr. Hans-Christoph Oelker is a flight test engineer with some 30 years of experience in development flight testing at the Manching Flight Test Centre which today belongs to Airbus Defence and Space. He gained his experience with Eurofighter and Tornado in various flight test tasks in flight physics mainly with Handling Qualities testing. Within the Airbus organisation he holds the title Expert Flight Physics. From his education he holds a Dipl.-Ing. in Aerospace Engineering and a Dr.-Ing. in Aerodynamics from Technical University of Braunschweig. He started his career in industry with Dornier Luftfahrt GmbH which today is part of Airbus.

TIMOTHY COX

Timothy H. Cox received a bachelor's degree in aerospace engineering from the University of Illinois in 1985. Since that time he has worked primarily in the flight controls and dynamics branch at NASA Armstrong Flight Research Center supporting flight programs such as: Drones for Aerodynamic and Structural Testing (DAST), X-29A, National Aerospace Plane (NASP), SR-71 Linear Aerospike Research Experiment, X-38, F-15 Quiet Spike, HTV-2, and most recently X-59. Research emphasis has included flight dynamics and handling qualities of high speed flight, including simulation and flight research on hypersonic applications, the SR-71, and the TU-144. In addition, he led a two year NASA wide effort to assess the capabilities of Uninhabited Aerial Vehicles (UAVs) for civil use.

JOSEPH DUNCAN

Mr. Duncan is a Performance and Flying Qualities Technical Expert at the US Air Force Test Center, Edward Air Force Base. He has worked wide ranging programs with primary roles in envelope expansion, stores certification, and AutoGCAS testing on platforms such as F-15SA, F-16, and EuroHawk, along with support and review roles in Global Hawk, F-22, F-35, B-1B, T-7A, and several other projects. His specific areas of expertise are in flight controls testing, handling qualities evaluation, and high angle of attack testing. He holds a Bachelor's and Master's degree in Aeronautics and Astronautics from the University of Washington.

MUHARREM FIRAT

Lt.Col. Muharrem FIRAT has a bachelor of science in Electronics engineering at Turkish Air Force Academy. Being an operational pilot he has participated in various national and international exercises and operations. After graduated as a test pilot, he has involved in many air to ground and air to air weapon development and integration projects at Turkish Air Force 401st Flight Test Squadron. He also has conducted CS-23 and CS-25 type aircraft certification and avionics modernisation test flights. Currently he works as Squadron Commander of the 401st FTS. He has more than 3500 hours of flight hours with 27 types of aircraft.

EREN TOPBAŞ

Eren TOPBAŞ is a flight mechanics engineer in TÜBİTAK SAGE with experience in vehicle design and certification. His main area of expertise is in the development of air vehicles to be certificated to platform aircraft and flying/handling qualities testing during the store certification phase. He graduated as an experimental flight test engineer and has a master of science degree in mechanical engineering from Middle East Technical University. He is currently a Ph.D. candidate at the same department of the University.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

Table of Contents

	Page
AGARDograph Series 160 & 300	**iii**
Executive Summary	**iv**
Synthèse	**v**
Acknowledgements	**vi**
Preface	**vii**
Biographical Sketches	**viii**
Table of Contents	**ix**
List of Figures	**xii**
List of Tables	**xv**
List of Acronyms and Abbreviations	**xvi**
List of Nomenclature	**xviii**
Author Contact Information	**xix**
Chapter 1 – Introduction	**1-1**
Chapter 2 – Fundamental Aspects of Aircraft Handling Qualities in Flight Test	**2-1**
2.1 Evaluation of Handling Qualities: The Final Step in the Overall Envelope Expansion Process	2-1
2.2 Flying Qualities vs. Handling Qualities	2-7
2.3 Examples for Flying Qualities	2-9
2.4 Mishaps Caused by Adverse Pilot-Vehicle Interactions	2-13
2.5 The Pilot-Vehicle-System of Highly Augmented Aircraft	2-16
2.6 Pilot Gain or High Gain and Low Gain Pilots	2-18
2.7 Flying Qualities and Handling Qualities Evaluation	2-18
2.8 Overall Remark	2-19
Chapter 3 – Evaluation of Handling Qualities	**3-1**
3.1 Qualitative Evaluation of Handling Qualities (Qualified Evaluation by Pilots)	3-1
3.2 “Open Loop” versus “Closed Loop” Analysis Methodology	3-9
3.3 Quantitative Evaluation with Linear Criteria	3-12
3.4 Quantitative Evaluation with Non-Linear Criteria	3-17
3.5 Criteria Reflecting Pilot Modelling	3-18
3.6 Discussion on Rating Scales and Criteria	3-22

3.7 Flight Clearance Based on HQ Criteria 3-22
3.8 Overall Remark 3-25

Chapter 4 – Flight Test Methods 4-1
4.1 Phase 1 Testing (Control Law Familiarisation) 4-2
4.1.1 Background of Control Law Familiarisation 4-2
4.1.2 Control Law Familiarisation Manoeuvre Descriptions 4-2
4.1.3 Control Law Familiarisation Manoeuvre Execution 4-10
4.2 Carefree Handling Trials (Intermediate Test Step) 4-11
4.3 Phase 2 Testing (PIO Resistance Testing) 4-14
4.3.1 Simple Pilot-in-the-Loop Manoeuvres 4-14
4.3.2 Pilot Technique Methods 4-16
4.3.2.1 KLONK Technique 4-16
4.3.2.2 Handling Qualities During Tracking (HQDT) 4-17
4.3.3 Specific Synthetic Target Techniques 4-22
4.3.3.1 GRATE/ATLAS Technique 4-22
4.3.3.2 Boundary Avoidance Tracking 4-23
4.4 Phase 3 Testing (Operational Handling Qualities Assessment) 4-26
4.4.1 Air-to-Air-Refuelling (AAR) 4-26
4.4.1.1 Hose-Drogue AAR 4-28
4.4.1.2 Boom AAR 4-32
4.4.2 Air-to-Air Tracking (AAT) 4-34
4.4.3 Basic Fighter Manoeuvres (BFM), Gross Manoeuvring 4-36
4.4.4 Descent, Approach, and Landing (DAL) 4-39
4.4.5 Formation Flying (FF) 4-46
4.4.6 Ground Attack Manoeuvring (GAM) 4-47
4.4.7 Take-Off and Climb-Out (TOC) 4-48
4.5 Standard Evaluation Manoeuvres (STEM) 4-51
4.6 Principal Test Matrix (How to Use this Catalogue?) 4-54
4.6.1 Initial Flight Envelope Expansion 4-55
4.6.2 Control Law Familiarisation (Phase 1) 4-55
4.6.3 PIO Resistance Testing (Phase 2) 4-56
4.6.4 Operational Testing (Phase 3) 4-57
4.6.5 Some General Test Matrix Considerations 4-58
4.7 Flight Safety Test Considerations 4-59

Chapter 5 – Practical Experiences 5-1
5.1 Phase 1 Testing (The Value of Open Loop Testing) 5-1
5.2 Some Aspects of Carefree Handling Testing 5-7
5.3 Phase 2 Testing (The Challenges of PIO Resistance Testing) 5-8
5.3.1 Some Aspects about the Usage of Tools 5-8
5.3.2 Experiences with the KLONK Technique 5-9
5.3.3 Experiences with the HQDT Technique 5-11
5.3.4 Experiences with the Boundary Avoidance Tracking (BAT) Technique 5-15

5.3.5 Other Techniques 5-17
5.3.6 Experiences with PIO Resistance Testing More Generally 5-22
5.4 Phase 3 Testing (The Challenges of Operational Testing) 5-23
5.4.1 Practical Aspects from Various Projects 5-23
5.4.2 Experiences from Aerial Refuelling 5-28
5.4.3 Experiences from External Stores Integration 5-33
5.4.3.1 Overview 5-33
5.4.3.2 Approach for HQ Testing for External Store Integration 5-35
5.4.3.3 HQ Flight Test Techniques for Store Integration 5-36
5.4.3.4 Experiences 5-37
5.4.4 Experiences with Operational HQ Testing More Generally 5-40

Chapter 6 – Summary 6-1

Chapter 7 – References 7-1

Annex A – AGARD and STO Flight Test Instrumentation and Flight Test Techniques Series A-1

1 Volumes in the AGARD, RTO and STO Flight Test Instrumentation Series, AGARDograph 160 A-1
2 Volumes in the AGARD, RTO and STO Flight Test Techniques Series, AGARDograph 300 A-3

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

List of Figures

Figure		Page
Figure 2-1	Schematics of Flight Envelope Boundaries	2-2
Figure 2-2	Schematics of Stepwise Envelope Expansion Process	2-3
Figure 2-3	Structured Approach for Testing FQ and HQ	2-5
Figure 2-4	Schematic Distinction between Flying Qualities and Handling Qualities	2-8
Figure 2-5	Short Period Excitation Together with Simple Model Response	2-10
Figure 2-6	Lateral Axis Excitation for Aerodynamic Data Gathering	2-11
Figure 2-7	Unfavourable Airframe Pilot Interaction	2-12
Figure 2-8	YF-22 PIO Event	2-14
Figure 2-9	Influence of Different Pilot Behaviour on Dynamics of an Air-to-Air Tracking Manoeuvre	2-16
Figure 3-1	Sequence of Pilot Rating Decisions	3-2
Figure 3-2	Major Category Selection and Definition	3-3
Figure 3-3	Cooper-Harper Pilot Rating Scale	3-3
Figure 3-4	Summary of Definitions from the Original Cooper-Harper Report	3-4
Figure 3-5	Example of Typical Task Description	3-5
Figure 3-6	USAF Test Pilot School PIO Rating Scale	3-7
Figure 3-7	Exemplary Pilot Evaluation Sheet	3-8
Figure 3-8	Thumbprint Criterion	3-10
Figure 3-9	A Typical Result for Determination HQ Rating Boundaries	3-11
Figure 3-10	Generic Pitch Axis Time Response with Regard to a Step Input at t = 0	3-13
Figure 3-11	Typical Graph for Application of the CAP Criterion	3-14
Figure 3-12	Flight Test Data for the CAP Criterion During Early Flying Period of Eurofighter	3-15
Figure 3-13	Schematic Diagram Explaining the Bandwidth Criterion	3-16
Figure 3-14	Jump Phenomenon Due to Rate Limiting in the Transfer Function of the Closed System	3-17
Figure 3-15	Variables Affecting the Pilot-Vehicle-System	3-18
Figure 3-16	Schematic Representation of McRuer's Crossover Model	3-19
Figure 3-17	Neal-Smith-Criterion, Pilot Model as Part of Closed Loop System	3-20
Figure 3-18	Neal-Smith-Criterion, Overall System Transfer Function with Optimisation Parameters	3-20

Figure 3-19	Neal-Smith-Criterion, Evaluation Diagram	3-21
Figure 3-20	Schematic Overview of the General Flight Clearance Process	3-23
Figure 3-21	Schematic Overview of the Flight Mechanics Clearance Process	3-24
Figure 4-1	Frequency Sweep Schematics	4-4
Figure 4-2	Schematics of Amplitude Frequency Relationship	4-17
Figure 4-3	On-Ground Lamp Pattern for GRATE and ATLAS Technique	4-23
Figure 4-4	Maximum Attainable Performance (Left), Decreasing Boundaries (1 to 6) Driving Performance to Find the Maximum Attainable Performance (Right) [41], [42]	4-24
Figure 4-5	T-38 Target Aircraft Markings for Pilot and Camera Used in HAVE BAT	4-24
Figure 4-6	NF-16D HUD Task Used in BAT DART	4-25
Figure 4-7	Example of “Hose-Drogue” Air-to-Air-Refuelling	4-27
Figure 4-8	Example of “Boom” Air-to-Air-Refuelling	4-27
Figure 4-9	Schematic System Diagram Tanker-Receiver-Pilot-Receiver-Aircraft	4-28
Figure 4-10	Schematics of Result of an AAR Refuelling Box Exploration	4-29
Figure 4-11	Boom AAR, Box Pattern of Boom Tip	4-33
Figure 4-12	Boom AAR, Bow Tie Pattern of Boom Tip; Regular, Reverse Pattern	4-33
Figure 4-13	Typical First Flight Test Regimes	4-55
Figure 4-14	Generic Test Matrix for Phase 1 Flight Tests	4-56
Figure 4-15	Generic Test Matrix for PIO Resistance Testing	4-57
Figure 5-1	Example of Roll Ratcheting in C-17 Aircraft Flight Test	5-2
Figure 5-2	NASA F-15B in Flight with Quiet Spike Attached	5-3
Figure 5-3	Evaluation of CAP Criterion for NASA F-15B Quiet Spike Aircraft	5-3
Figure 5-4	NASA F-15B Quiet Spike, Analysis of Supersonic Yaw Stability Derivative $c_{n\beta}$.	5-4
Figure 5-5	X-29 Test Aircraft	5-5
Figure 5-6	In-Flight Envelope Expansion Methodology for X-29	5-5
Figure 5-7	Schematics of Real-Time Comparisons between Linear Predictions and Flight Data	5-6
Figure 5-8	X-38 Test Aircraft	5-6
Figure 5-9	X-38 Real-Time Stability Margin Calculation for Elevator Loop	5-7
Figure 5-10	Carefree Handling Envelope Expansion	5-8
Figure 5-11	Sample of Completed Pilot Information Sheet	5-10

Figure 5-12	Typical HUD Tracking Pattern	5-11
Figure 5-13	HQDT Set-Up at SAAB and FMV	5-12
Figure 5-14	Time Histories of 1g Low-Speed Attitude HQDT Case	5-13
Figure 5-15	Frequency Domain Analysis for the 1g Low-Speed Attitude HQDT Case	5-13
Figure 5-16	Frequency Domain Analysis for the 1g Low-Speed Attitude HQDT Case with Pilot Compensation	5-14
Figure 5-17	Flight Path Boundary Profile [42]	5-16
Figure 5-18	Correlation between Boundary Value and CHR	5-17
Figure 5-19	NASA NF-15B Research Aircraft, Tail Number 837	5-18
Figure 5-20	Typical Formation Flight Time History	5-18
Figure 5-21	Duty Cycle Measurements for Pitch Stick	5-19
Figure 5-22	Analysis of Duty Cycle Measurements During Air-to-Air Tracking	5-20
Figure 5-23	ROVER Model Conditions Block for Flag Computation	5-21
Figure 5-24	ROVER Evaluation of Modern-Day Fighter	5-21
Figure 5-25	SR-71 Bank Angle and Heading Change Requirements	5-24
Figure 5-26	SR-71 CHR for the Vertical Plane Altitude Manoeuvre	5-25
Figure 5-27	SR-71 Comparison of Time Histories	5-25
Figure 5-28	NASA F-18 HARV During High AoA Testing	5-26
Figure 5-29	NASA F-18 HARV High AoA Manoeuvres	5-26
Figure 5-30	NASA F-18 HARV Wind Axis Bank Angle Overshoots after 90 deg Wind Axis Bank Angle Change	5-27
Figure 5-31	NASA F-18 HARV Bandwidth Criterion Application	5-27
Figure 5-32	AAR Refuelling Envelopes of Two Different Tanker Aircraft	5-31
Figure 5-33	Comparison of Real-World and Fused Reality Scene	5-32
Figure 5-34	Enhancement of Visual Cues	5-32
Figure 5-35	A Sample of Change of Directional Stability with External Store at M = 1.6	5-34
Figure 5-36	A Sample of Change of Longitudinal Stability with External Store at M = 1.6	5-34
Figure 5-37	External Store Loading Configuration, Open Loop Pitch Excitation Test Pitch Rate Time History	5-38
Figure 5-38	Asymmetrical External Store Loading Configuration, Take-Off Test-Time History	5-39
Figure 5-39	Asymmetrical External Store Loading Configuration, Take-Off Test Yaw Rate Time History	5-40
Figure 5-40	Illustration of Visual Cues Definitions, Lateral Displacement Target, Formation Target	5-42

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

List of Tables

Table		Page
Table 4-1	Sequence of Test Manoeuvres for Control Law Familiarisation Phase 1	4-10
Table 4-2	A Collection of Open Loop Carefree Handling Manoeuvres	4-12

List of Acronyms and Abbreviations

AAR	Air-to-Air Refuelling
AAT	Air-to-Air Tracking
ADS	Air Data System
AFFTC	US Air Force Flight Test Centre
AGARD	Advisory Group of Aeronautical Research and Development
AGL	Above Ground Level
AoA	Angle of Attack
AoS	Angle of Sideslip
APC	Aircraft-Pilot-Coupling
Appr	Approach
ARSAG	Aerial Refueling Systems Advisory Group
ATP	Allied Tactical Publication
BACH	Bank Angle Capture and Hold
BAT	Boundary Avoidance Tracking
BFM	Basic Fighter Manoeuvre
CAP	Control Anticipation Parameter
CAS	Calibrated Air Speed
CFD	Computational Fluid Dynamics
CFH	Carefree Handling
CG	Centre of Gravity
CHR	Cooper-Harper-Rating according to CHR Scale (Figure 3-3)
DAL	Descent, Approach, and Landing
EAS	Equivalent Air Speed
FBS	Full Back Stick
FCS	Flight (dynamics) Control System
FFT	Fast Fourier Transformation
FFS	Full Forward Stick
FMV	Swedish Defence Materiel Administration
FOD	Fear of Death
FQ	Flying Qualities
FRS	Full Roll Stick
FTT	Flight Test Technique
fwd	forward
GAM	Ground Attack Manoeuvring
GARTEUR	Group of Aeronautical Research and Development in Europe
GCA	Ground Control Assistance
GCCM	Gentle Course Changing Manoeuvre
GPS	Global Positioning System
HARV	High Alpha Research Vehicle
HMI	Human-Machine-Interface
HUD	Head-Up-Display
HQ	Handling Qualities

HQDT	Handling Qualities during Tracking
HQR	Handling Qualities Rating
HW	Hardware
ICR	Instantaneous Centre of Rotation
INS	Inertial Navigation System
IR	Infra-Red
IVSI	Instantaneous Vertical Speed Indicator
KCAS	Calibrated Air Speed in Knots
KEAS	Equivalent Air Speed in Knots
Ldg	Landing
Level 0	Top Aircraft System Level
LOES	Low Order Equivalent System
Ma	Mach Number
NATO	North Atlantic Treaty Organization
OLOP	Open Loop Onset Point
PED	Pedal Input
PIO	Pilot-in-the-Loop-Oscillation
PIOR	PIO Rating according to USAFTPS Rating Scale (Figure 3-6)
PVS	Pilot-Vehicle-System
RC	Roller Coaster
ROVER	Real-Time Oscillation Verifier
SCI	NATO STO Systems, Concepts, and Integration Panel
SHSS	Steady Heading Side Slip
STEM	Standard Evaluation Manoeuvre
STO	NATO Science and Technology Organisation
STP	Stick Pitch Input
STR	Stick Roll Input
SW	Software
TMP	Test Management Program
USAFTPS	US Air Force Test Pilot School
VCAS	Calibrated Air Speed
WLB	Work Load Build-up
WUT	Wind Up Turn

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

List of Nomenclature

α	Angle of attack
θ	Longitudinal attitude
η	Elevator deflection
ζ_{SP}	Damping ratio for short period
ω_C	Crossover frequency
ω_{SP}	Undamped natural frequency short period
$C_{n\beta}$	Directional stability derivative
E_{XX}	Accumulated power spectral density
K_P	Pilot gain
K_Q	Gain factor, pitch axis
n_z	Longitudinal load factor
S_{XX}	Power spectral density
T_{P1}	Lead time constant
T_{P2}	Lag time constant
X_K	Spectral density
Y_C	Open loop airframe transfer function (controlled system)
Y_P	Open loop pilot describing function

Author Contact Information

Name:	Dr.-Ing. Hans-Christoph Oelker (Principal Author)
Mailing Address:	Airbus Defence and Space Flight Test Centre D-85077 Manching GERMANY
Email:	hans-christoph.oelker@airbus.com (until January 2022) hans-christoph@oelker.eu (from January 2022 onwards)

Name:	Mr. Timothy Cox (Contributing Author)
Mailing Address:	NASA Armstrong Flight Research Center Edwards Air Force Base, CA UNITED STATES
Email:	timothy.h.cox@nasa.gov

Name:	Mr. Joseph Duncan (Contributing Author)
Mailing Address:	USAF 412 Test Wing 307 East Popson, Bldg 1400, Rm 102 Edwards AFB, CA, 93524 UNITED STATES
Email:	joseph.duncan.2@us.af.mil

Name:	Lt. Col. Muharrem Fırat (Contributing Author)
Mailing Address:	Turkish Air Force 401st Development Test Squadron 1st Main Jet Base Eskişehir TURKEY
Email:	m-firat@hvkk.tsk.tr

Name:	Mr. Eren Topbaş (Contributing Author)
Mailing Address:	TÜBİTAK SAGE Pk. 16 Mamak 06261 Ankara TURKEY
Email:	eren.topbas@tubitak.gov.tr

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

Chapter 1 – INTRODUCTION

This report is part of the AGARD-AG-300 series on Flight Test Techniques. Therefore, the focus will be on flight test techniques relevant to evaluating Flying Qualities (FQ) and Handling Qualities (HQ) rather than on theoretical deductions about FQ and HQ criteria and their widespread application in aircraft design processes. It rather tries to give background and a guideline on how to test Flying Qualities and Handling Qualities during flight.

A clear distinction between what is meant when using the terms “Flying Qualities” and “Handling Qualities” will be given in Section 2.2. Here, in anticipation of this chapter, a brief distinction is drawn between the two terms: the term “Flying Qualities” generally addresses bare airframe dynamics as visible to the pilot. It is meant as an uncontrolled airframe reaction to any excitation, be it an inceptor input or a gust. In case of an augmented aircraft, it means uncontrolled reaction of aircraft plus controller dynamics. The term “Handling Qualities” addresses the dynamics of the Pilot-Vehicle-System (PVS) within a dedicated task.

The report is organised into four major chapters. After this introduction (**Chapter 1**), **Chapter 2** will show how the evaluation of Flying Qualities (FQ) and Handling Qualities (HQ), respectively, is part of the overall flight envelope expansion for a new or a modified already existing aircraft. As envelope expansion can be a very long process, touching all aircraft systems: this chapter will focus on how FQ and HQ evaluations are embedded into the overall process. The chapter begins with a discussion of the difference between FQ and HQ, leading to the definitions to be used in this report. The discussion will be further illustrated with distinctive examples of how testing for FQ and HQ can reveal system shortcomings or how system shortcomings can be revealed on a “ride along” basis during systematic testing. This also includes unfavourable pilot-vehicle-system interactions commonly known as Pilot-In-the-Loop-Oscillations (PIO).

Chapter 3 reviews the process of evaluation of FQ and HQ. The well-known Cooper-Harper-Ratings scale (CHR) will be introduced, and its usage will be explained. Also, a rating scale to evaluate Pilot-Vehicle-System (PVS) oscillations will be given. Further examples will explain how the evaluation process works from the design aspect, during the aircraft development process. Finally, the derivation process for a flight clearance will be sketched.

Chapter 4 mainly contains a catalogue of various test methods to be applied for FQ and HQ testing. At the end of the chapter a guideline on how to use the catalogue will be given; this includes flight safety considerations.

Finally, based on the previous contents, **Chapter 5** presents different practical applications of FQ and HQ testing, as applied to the different test phases. This is to illustrate to the reader how FQ and HQ testing is experienced in “real life”.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

Chapter 2 – FUNDAMENTAL ASPECTS OF AIRCRAFT HANDLING QUALITIES IN FLIGHT TEST

A very important part of the acquisition process for a new aircraft is the requirements definition process. During this activity, amongst many other discussions and negotiations, the procuring agency, together with the contractor(s) and responsible test organisations, negotiate a common test philosophy on how to evaluate the new air vehicle in flight test. The evaluation of handling qualities will be one important part of such a test philosophy. This process results in a collection of handling qualities specifications and requirements for this new aircraft. In some cases, a special handling qualities definition document will result[1] from these negotiations; in other cases, the MIL-Standard (e.g., Ref. [1][2]) serves as basis for a requirements document. Flight testing of handling qualities will be performed on the basis of one of these documents.

2.1 EVALUATION OF HANDLING QUALITIES: THE FINAL STEP IN THE OVERALL ENVELOPE EXPANSION PROCESS

Flight testing an aircraft is the last big step in a (sometimes rather long) development process. It contains many tests for all systems making up a highly integrated, high-performance aircraft. When it comes to testing flying qualities or handling qualities in general all other systems of an aircraft must be fully tested and operationally ready. Thus, the aircraft must be ready to go for any operational manoeuvre as requested by the overall specification. Flying qualities, and especially handling qualities, can be affected by the performance of any other aircraft system. Flying qualities and handling qualities are these disciplines which are only totally visible at “Aircraft Level 0”, the top system level.

Flight testing in general can be separated into two major steps. In **step one** (e.g., maiden flight and envelope expansion beyond) testing is aimed at looking after all systems. It is to show that all sub-systems that together make up such a complicated system like an aircraft are operating as they are designed to operate. This part is also often called the system integration part: the integration of all sub-level systems into one Level 0 (aircraft level) overall system. System integration is the endeavour to align the different design outcomes of various different sub-system design processes into one integrated and functioning overall system. Testing for system integration is done at various levels of complexity on ground (rigs and other simulators as well as on aircraft) and in the final stage in flight with the operational overall system. The final outcome of this first step (system integration) is an aircraft that can be operated in the requested envelope, being **fit for flying**, and even more important being **safe to fly**.

Once this has been achieved, the **second step** goes into requirement verification. Here it will have to be proven that customer-given performance requirements for various systems are fulfilled in satisfaction of the overall specification, respectively, the contract. Thus, verifying the aircraft as being **fit for operational use**. Within the scope of this report, testing for flying qualities and handling qualities at the end of the development chain plays an important part in requirements verification. At the very end, only satisfactory fulfilment of all requirements, sometimes in a close dialogue between contractor and customer, entitles the contractor to finally issue a bill to the customer.

Let us go back to the first step. Once a new aircraft design gets airborne for the first time, the required envelope will have to be explored cautiously in a stepped manner in order not to endanger the crew or the test article itself at any time. For this, flight test centres have established stringent processes to ensure that flight safety is always taken care of properly.

[1] Normally this type of document is confidential between customer and contractor and not open to the public.

[2] This version is available freely via the Internet at various locations. There may be other and newer versions of this specific MIL-STD which are not available freely.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

Most relevant flight envelope boundaries for a safe envelope expansion process are given in **Figure 2-1**. The diagram shows a typical flight envelope in terms of altitude and Mach number. In the low-speed regime, it is governed by the achievable maximum lift, the lift boundary. In high altitudes maximum available thrust or limitations to the environmental control system limit the aircraft. For high Mach numbers engine intake performance and/or structural heating due to the high-speed compressibility effects can be considered as limits. Finally, the limitations due to maximum allowable structural as well as aero-elastic loads at the lower right side of the envelope mark another limit.

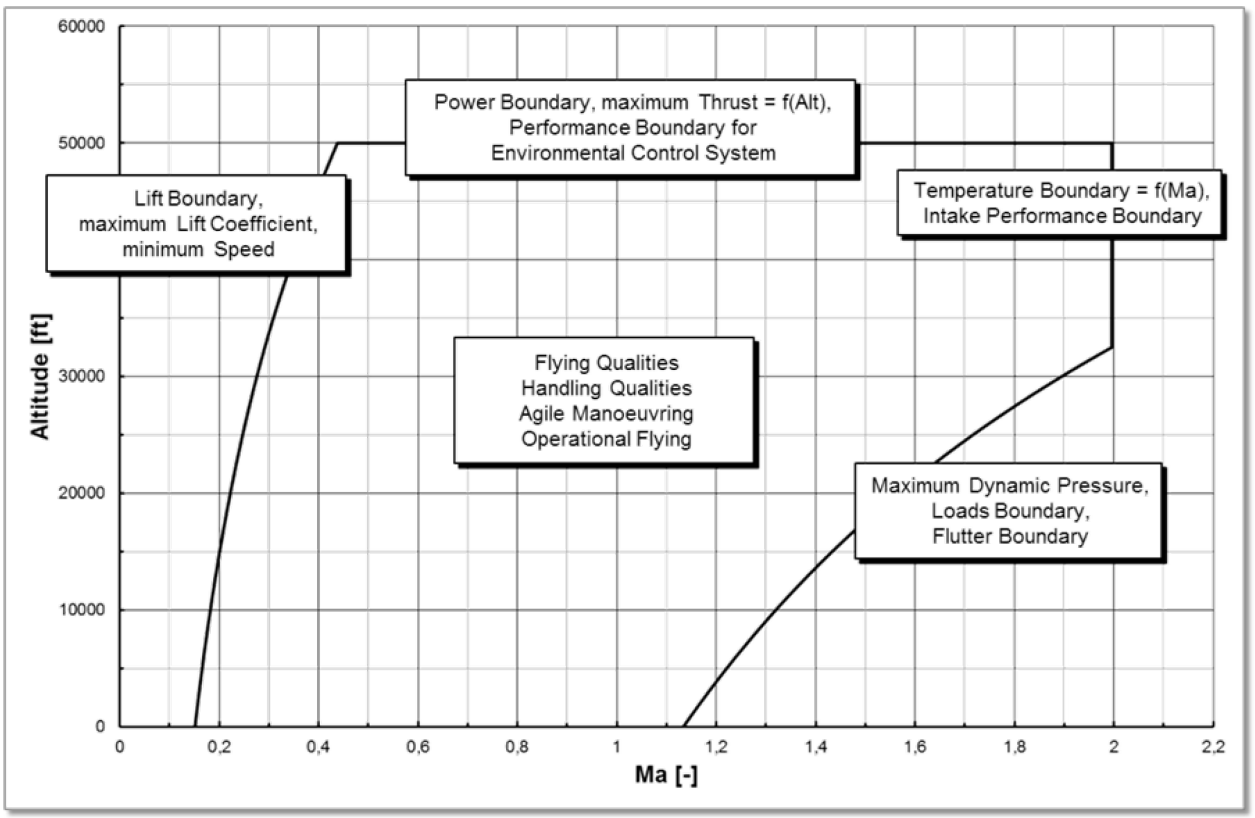


Figure 2-1: Schematics of Flight Envelope Boundaries.

At the beginning of flight testing (e.g., first flight of a new design) these boundaries are still very far away. The available envelope for initial flying is normally much smaller. The envelope expansion process starts at a "certain" point in the centre region of the envelope. From there on a cautious stepwise exploration into the requested envelope begins.

In preparation for first flight, contractors use the best available models to conduct a thorough evaluation of predicted aircraft characteristics, e.g., handling qualities. Based on these analyses a clearance for first flight is derived (to be explained further, in Section 3.7) During the envelope expansion process, a close "dialogue" between model analysis and flying is always maintained. This means each progressive step in the envelope is first predicted by analysis and then verified by flight test. In case discrepancies occur, a deeper analysis of model characteristics has to be made (see Section 3.7). A good reference for envelope expansion testing is the AGARD-AG-300 Vol. 21 [2].

Initially, the exploration process is cleared only to a relatively small flight envelope, as sketched in red dashed lines in **Figure 2-2**. The expansion process begins at a more or less arbitrarily chosen starting point. Variation in speed and Mach number, respectively, (depending on the task) at a constant altitude varies the

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

Angle of Attack (AoA). AoA becomes smaller when going at higher speeds or lower altitudes. It becomes larger when going at lower speeds or higher altitudes. At various speed break points a set of familiarisation manoeuvres (to be discussed later) is performed. This also includes a careful exploration of the given/allowable AoA envelope at this special test condition. For this wind-up-turns[3] are flown in steps up to a specified maximum cleared AoA value, as well as roller-coasters[4] which are flown down to a specified negative AoA value. Going to low speeds and, thus, the highest cleared AoA (at that time), means checking for acceptable characteristics when approaching stall. Going to higher speeds means checking with the aero-elastic disciplines whether the flutter behaviour is still acceptable. Going beyond the originally cleared flutter boundary (VCAS, Ma) requires specific flutter testing.

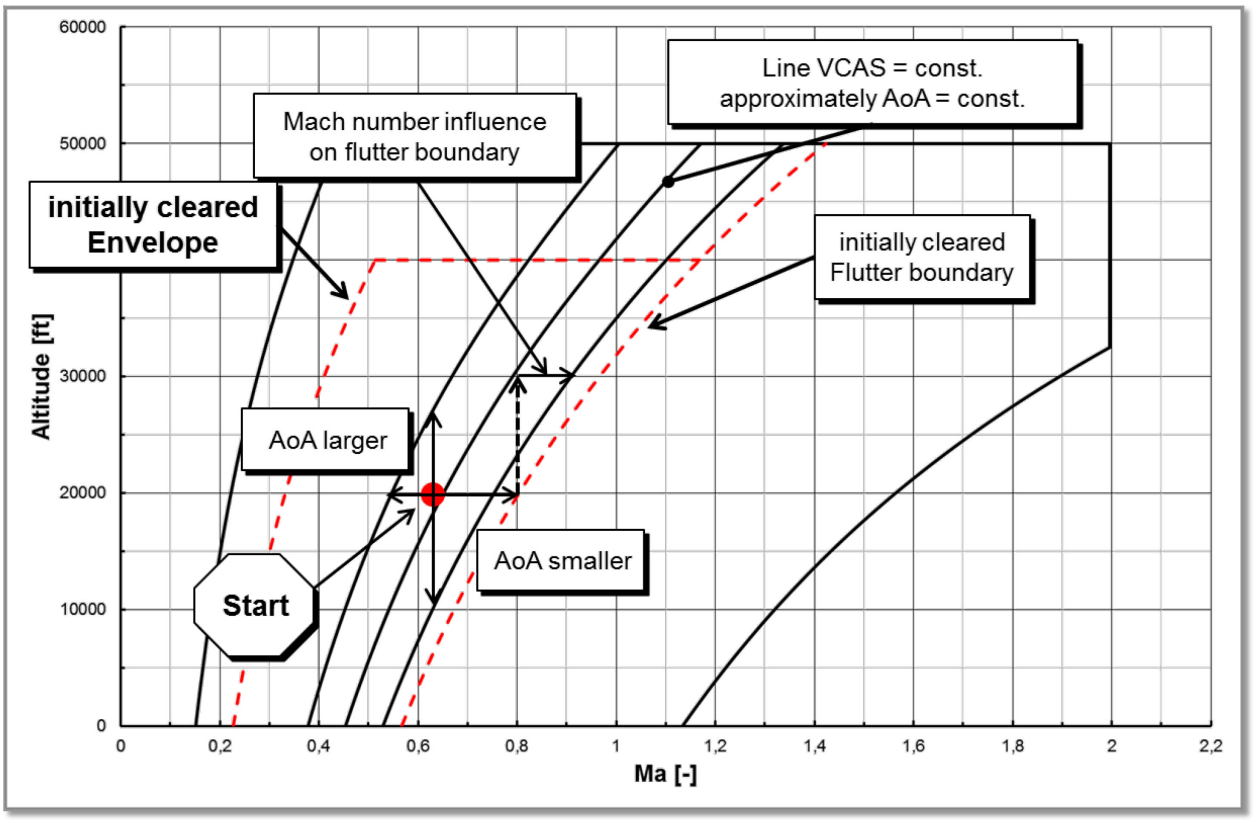


Figure 2-2: Schematics of Stepwise Envelope Expansion Process.

Going to higher altitudes, still in steady level flight, means for equal Mach number flying with a higher AoA at a smaller speed (VCAS). This in turn requires at this new altitude with respect to flutter a Mach number envelope expansion in order to "come back" to the originally cleared speed already achieved at a lower altitude and lower Mach number.

There is always an exchange between various disciplines in order to gain progress in expanding the boundaries. Aerodynamics and flight mechanics must be in close contact with aero-elastic loads (flutter) and system engineering (e.g., calibration of air data system). Only an efficient dialogue between all disciplines involved ensures a safe and rapid envelope expansion process.

[3] Spiralling turn with increasing AoA / normal load factor, to be explained in Chapter 4.

[4] Push-pull or pull push manoeuvre, to be explained in Chapter 4.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

Today this process is highly supported by various simulations and other model calculations. Already, prior to first flight, models are used to arrive at the initial flight clearance. The limiting factor for the initial flight envelope is the overall confidence in the reliability or accuracy of those models. Therefore, once the new aircraft is airborne, various model verification techniques (system identification) as well as model validation techniques (parameter estimation) are being used. For this, initial flying is tailored in a way that relevant analysis tools can be operated with the available flight data. Once the models have been validated and updated with results from various flight test analysis methods the next step for achieving an expanded cleared flight envelope can be started. There is a variety of literature on model validation and verification available, representative are the works of Jategaonkar [3]; Tischler and Remple [4]; and Klein and Morelli [5].

From this very brief description of the envelope expansion process, it is obvious that it is an iterative process. It can be put into the phrase “fly-analyse-fly”. Today, modern analysis capabilities (hardware and software tools) allow for a very rapid analysis process. In some cases, analysis is being done while the test article is still airborne and clearances to proceed to the next expansion step can be given “on-line” in real time. For this to occur, processes must be aligned in such a manner that possibly ambiguous analysis results do not hamper the decision for the next step. There must be clear and easily interpretable decision lines in order not to endanger flight safety. These decision lines must be agreed commonly prior to testing, e.g., as a set of clearly defined flight test continuation criteria.

One important part of the envelope expansion process is when the operational capabilities of the aircraft are under consideration. This is done in various stages of complexity. One more simple stage would be testing equipment in an operational environment, e.g., electronic self-protection systems under realistic threat scenarios. Store release testing can be very challenging as many aircraft disciplines are involved. Handling qualities testing is a discipline of the highest complexity as pilot or operator interaction with the entire aircraft system on Level 0 is under test.

As indicated in Figure 2-1 operational testing is necessary all over the entire flight envelope. During this testing physical flight boundaries can also be approached well inside the overall envelope limits given in Figure 2-1. One simple example is flying a tight turn with highest possible turn rate or smallest possible turn radius at a given flight condition. In this case the aircraft will manoeuvre either to the highest possible AoA or longitudinal load factor (depending on speed). These limits represent the physical boundaries for the aircraft, again. In older aircraft types, the pilot will have to monitor these limits from appropriate gauges: under stress this has the potential to be a very demanding task. Modern aircraft flight control systems provide pilots with so-called “carefree handling” characteristics where the implemented flight control laws ensure that physical limits are not exceeded. Now it is mainly a software issue, but the reliability of this software needs to be tested in flight. Reliability in this sense means proper protection against all relevant limits (e.g., AoA, normal load factor, and AoS).

Other operational tasks involve the pilot as a dynamic, unpredictable system element as part of the overall Pilot-Vehicle-System (PVS). In this regard, pilot dynamics and pilot performance influence the overall performance and it will also be an issue. Testing the pilot-vehicle-system comes at the very end of flight testing for operational performance. Normally several pilots are involved as overall flying techniques vary with pilots and different pilots can exhibit their own specific piloting technique in identical tasks. This may be different from the technique of other pilots. Thus, there is an influence on the outcome of the test.

Pilot-in-the-loop testing of operational tasks requires a very high degree of attention during the process, certainly by the pilot but also by the engineer monitoring the process. Aircraft system dynamics can easily be modelled and analysed in simulators of all kinds. Pilot behaviour in conjunction with a specific operational task in general cannot be modelled at all. Standard simulators do not provide feedback of motion cues to the pilot. Therefore, operational flight testing of the PVS can become critical for the special case when the overall PVS system dynamics become unstable (i.e., Pilot-in-the-Loop-Oscillations (PIO)).

As mentioned in the beginning, operational flight testing is closely connected to the customer, his requirements, and his expectations for the aircraft. Thus, test tasks in the operational phase must be defined in close co-operation between customer and contractor. Also, in many cases, customer personnel will be part of an integrated test team.

With all these considerations in mind, the necessity for a well-structured test approach becomes evident. During high AoA testing of the NASA F/A18 HARV programme, Wichmann and others [6] developed a methodology for structuring FQ and HQ testing. This methodology is given in **Figure 2-3**. They call it a manoeuvre pyramid [6]. It has been adopted for the purposes of this report.

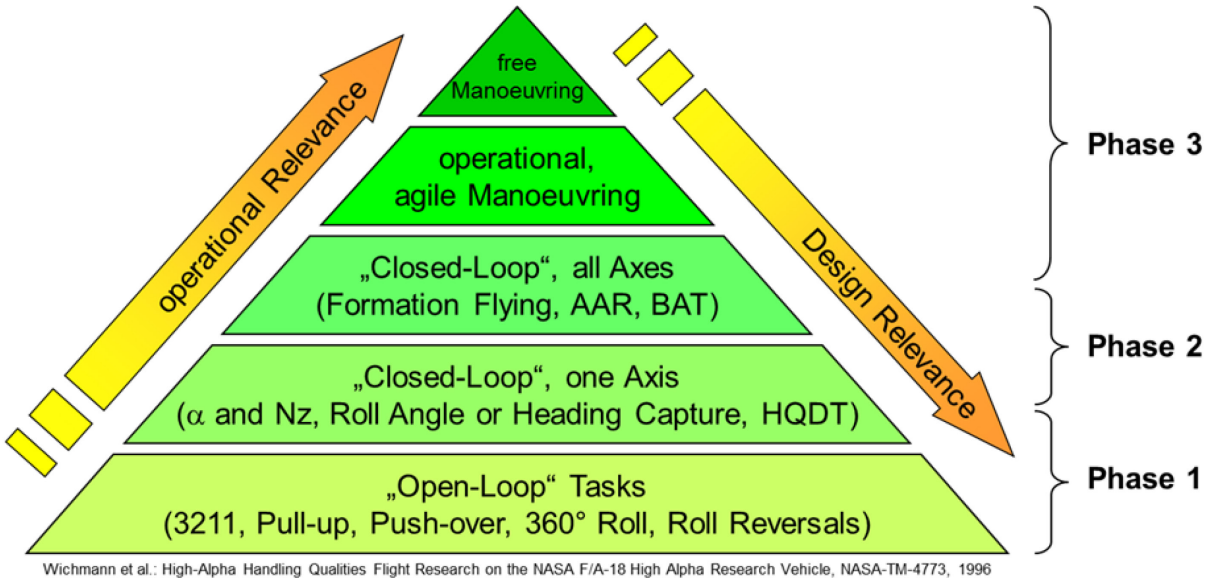


Figure 2-3: Structured Approach for Testing FQ and HQ.

This manoeuvre pyramid can be described by the following progression. Starting from the bottom, **Phase 1** mainly covers open loop manoeuvres. These are performed from the very beginning of the envelope expansion process. They mainly serve for identification of aircraft dynamics in all axes and to find out early about obvious snags. **Phase 2** is mainly dedicated to PIO resistance testing. This can be done with simple one-axis capture tasks as well as more complicated tasks challenging all axes, e.g., flying in close formation. Specific dedicated test techniques like Handling Qualities During Tracking (HQDT) or Boundary Avoidance Tracking (BAT) are also performed during this phase. Finally, **Phase 3** is dedicated to operational testing. It starts with more simple tasks as already performed, but continues with the evaluation of dedicated performance criteria. It is followed by typical operational tasks like Air-to-Air Tracking (AAT) or Basic Fighter Manoeuvres (BFM). At the top of the pyramid a small number of manoeuvres is performed which require agile manoeuvring up to the manoeuvring limits of the test aircraft, basic fighter manoeuvres as well as simulated air-combat encounters. It could also be designated “free-style” flying checking out what is possible and how well it can be done.

In the terminology also used later on, an **open loop manoeuvre** is a manoeuvre where the pilot excites aircraft dynamics and observes the reaction of the aircraft. In a **closed loop manoeuvre** the pilot interacts with aircraft dynamics in order to achieve a certain goal. In the context given here, trying to capture a pre-described attitude change, for example, can be considered open loop if the pilot is “only” tasked to change aircraft attitude for a certain amount and to observe resulting aircraft dynamics. It can also be considered to be closed loop when the pilot is tasked to closely capture a desired attitude change. For the first case he is more or less out of the loop, only observing, for the second case he is in the loop trying to control the aircraft and to achieve the given target.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

The purpose of this structured approach is to identify and uncover any snags or latent deficiencies for FQ and HQ as early as possible in the development process, e.g., already during the maiden flight. Results of open loop testing at the bottom of the pyramid can easily be related to simple design parameters of the aircraft. Thus, uncovering deficiencies in this area as early as possible helps in the rectification of deficiencies early on in the process when it can be achieved more easily than later.

Testing at the bottom of the pyramid is devoted to easy and quickly repeatable manoeuvres. In this sense the width of the pyramid indicates the amount of testing effort. When going up to more complicated test manoeuvres the testing effort becomes higher, and repeatability is not always given. Due to the nature of more complicated manoeuvres, analysis becomes more complicated as well. An easy connection to simple design parameters may not be given anymore. Possibly required design changes will be less easy.

Flying manoeuvres at the top the pyramid are always related to high gain pilot-in-the-loop flying. Rectification of deficiencies found when flying in this stage can be very difficult and expensive. Therefore Phase 1 and Phase 2 testing must be done as thoroughly as possible in order to find snags or deficiencies as early as possible. This report will focus on experiences gained.

With regard to the final verification of customer requirements as given in the contract between contractor and customer, the given pyramid describes a process of testing. It may be iterative during the course of introducing design updates, e.g., based on test results during the overall process. Testing with regard to verification of customer requirements, not only handling qualities, can only be done once a “design freeze” has been achieved.

The structure of the pyramid also supports flight safety and safety of testing. The given build-up approach starts with low risk level testing and only when confidence is achieved does it progress to higher levels of controlled risk testing.

This introductory section illustrates the possible complexity of FQ and HQ testing in flight test. Not mentioned so far is the interaction with other system disciplines. Very often the system clearances of one of the aircraft systems restrict the required envelope for FQ and HQ testing. This is illustrated by a simple example: Flight clearances for the gear box and the hydraulic system may not allow for normal load factors less than $n_z = 0$. This prohibits inverted flight. It certainly restricts flight trials for FQ and HQ. It becomes much more complex when system dynamics affect the overall aircraft handling qualities. This is the case when control display dynamics, e.g., in the Head-Up-Display (HUD), influence the control dynamics of the pilot. The pilot observes the flight path symbol to control the movement of the aircraft. Sometimes the flight path symbol may be displayed with a minor, hardly visible, but still very effective (in the negative sense) time delay. Thus, a dynamically unfavourable time delay is introduced, affecting the performance of the PVS.

Testing for FQ and HQ is highly interactive with other disciplines. The responsible flight test engineer must always consider effects by and on other systems when test flights are planned for FQ and HQ. Coming back to initial Step 1 testing, envelope expansion: this phase of testing is normally governed by Phase 1 (open loop) and partly by Phase 2 (closed loop) testing according to Figure 2-3. During testing, in order to go to a higher AoA or higher Ma number, the aerodynamic model must be valid in this portion of the envelope. Going to higher speeds increasingly involves the aero-elasticity discipline. It must be consulted whether the available flutter clearance is still valid or whether specific testing is needed for dynamic pressure extensions. Phase 3 testing according to Figure 2-3 is wholly operationally representative testing: a valid clearance for the entire envelope must be available. This report will focus on the overall envelope expansion process with special focus on FQ and HQ testing.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

2.2 FLYING QUALITIES VS. HANDLING QUALITIES

The differentiation between Flying Qualities (FQ) and Handling Qualities (HQ) is approached in the literature and during flight testing in various ways. It begins with individual definitions, which can be contradictory. This section provides the definitions that will be used in the remainder of this report.[5]

Cook [7] relates FQ and HQ to each other in a way that demonstrates how closely related they are. According to Cook, 'flying qualities' is considered to be a qualitative description of how well the airplane carries out the commanded task. 'Handling qualities' is considered to be the qualitative description of the adequacy of the short-term dynamic response to control inputs in the execution of the flight task.

We will see during the course of this report that a lot of effort is undertaken to expand the evaluation of FQ and HQ beyond qualitative measures. There are tools and methods for quantitative evaluation; furthermore, it will become very evident that pilot dynamics play an important role within this whole scenario. This means that an airplane can exhibit different handling qualities to different pilots because each pilot "feels" or "handles" the aircraft differently during execution of an identical task. Pilots have their own specific piloting techniques, each one exciting aircraft dynamics in a slightly different way. Pilots have different ways of perceiving cues from the outside (accelerations, vibrations, visual) which influence their individual reaction to these. Besides, different pilots react differently to the same cue.

Thus, going back to Cook's definitions, it is not the airplane that carries out the task, it is the pilot. And it is the pilot who perceives the short-term dynamic response to control inputs as one major influence on his controlling the aircraft to fulfil the task. Other influences are his techniques and his way of perceiving and reacting to outside cues during the fulfilment of the task. Short-term dynamic aircraft response, piloting techniques for the fulfilment of a task, and perception of environmental cues together make up how a pilot "feels" and "handles" an airplane. He experiences handling qualities.

This brings us to the second set of definitions for FQ and HQ. This is given by the US Air Force Test Pilot School (USAFTPS) [8]. Flying qualities are the characteristics, or dynamics, of the airplane. Thus, good flying qualities support the pilot in fulfilling the task given to him. Handling qualities are the characteristics of a pilot-vehicle-system that govern the ease and precision with which a pilot can perform the tasks required in support of a vehicle role. They basically represent the dynamics of the pilot plus the airplane. A schematic is given in **Figure 2-4**.

This is quite the opposite of Cook's definitions given above. The USAFTPS definitions include the pilot as a major contributor to handling qualities. Therefore, as reasoned above this report will adhere to the USAFTPS definitions:

Flying Qualities[6] **(FQ)**: Short-term dynamic behaviour of an airplane.

Handling Qualities (HQ): Dynamics of the Pilot-Vehicle-System (PVS) when fulfilling a task.

A review of FQ and HQ literature reveals the presence of both the Cook and USAFTPS definitions. For this reason, we have included this section to clarify the definitions used in this report.

With this in mind a second set of definitions can easily be given. Considering that modern aircraft are generally controlled by an electronic control system (either analogous or digital) we have to distinguish between control loop definitions. The inner loop(s) of the systems under consideration within this report

[5] Other languages e.g., the German language do not allow for this distinction. In German it is both "*Flugeigenschaften*".

[6] The term "Quality" is more or less related to a quantitative evaluation, which is done here by a pilot. Per definition, this is not exactly the case for "Flying Qualities". In this context and the definition given here, "Flying Qualities", should be rather called "Flying Characteristics". Nevertheless, the common denomination is "Flying Qualities", and it will be used within this report.

mean control loops used for the electronic (digital) control system, e.g., for stabilisation of the pitch axis. In the case of augmented aircraft, we consider the overall dynamics (unaugmented aircraft dynamics plus control law dynamics) as one, as they are visible to the pilot.

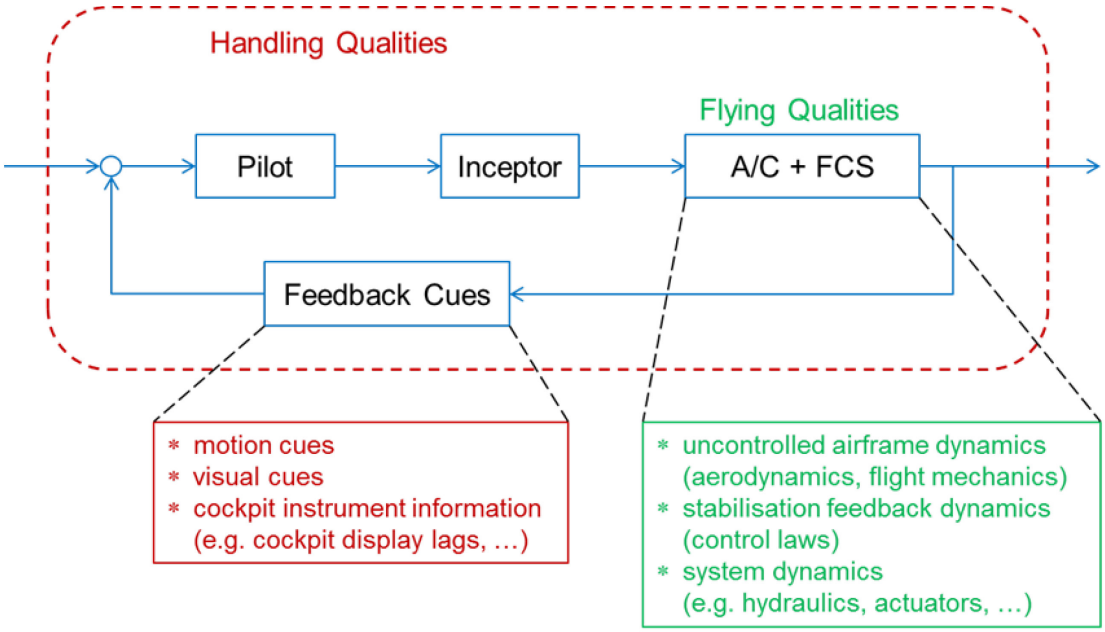


Figure 2-4: Schematic Distinction between Flying Qualities and Handling Qualities.

For the purposes of this report, we consider the outer loop closure as closed by the pilot. We do not consider an outer loop closure by an autopilot system. Therefore:

Open Loop Testing: Testing for airframe dynamics as they are exposed to the pilot. It is related to flying qualities testing. No pilot interaction to influence aircraft response shall take place.

This definition also includes aircraft with their inner loops already closed for stabilisation by the electronic control system. Important for the evaluation are those aircraft dynamics which are transparent to the pilot.

Closed Loop Testing: Testing of the pilot-vehicle-system. It is related to handling qualities testing when a pilot is performing a given task. Pilot interaction and pilot dynamics as a part of the overall dynamic system are vital in this instance.

The dynamics of a dynamic control system (inner loops) can have considerable influence on FQ and HQ. Modern control systems tailor aircraft dynamics, e.g., for a basic airframe which is unstable in the pitch axis. Thus, control law dynamics determine the magnitude of the short period frequency and the short period damping, the existence of the Phugoid may even be “controlled out” completely. The pilot will not “see” a Phugoid anymore. Tailored control law dynamics of this kind exhibit specific aircraft dynamics. Modern control law designs can make an aerodynamically unstable airframe flyable and they enhance FQ, enabling pilots to achieve better HQ. (Feedback loop for stabilising aircraft dynamics).

Other control law effects in design can affect HQ directly. This is done when pilot commands are tailored to specific design needs. For example, one field is enhancing the tracking capabilities of an aircraft by suppressing certain short-term aircraft dynamics (pitch axis drop back) for lower frequency pilot inputs. (Forward path or command path shaping for enhancing HQ).

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

To complete this section, a stricter and more academic set of definitions for FQ and HQ will be given:

Flying Qualities are described by the solution of the **homogenous system of differential equations** describing the aircraft motion. In the case of linear equations, solving the characteristic matrix (the "A" matrix or system matrix) for its Eigenvalues gives the characteristic modes, i.e., Eigen motion types (short period, Phugoid, roll mode, Dutch roll, and spiral) that make up aircraft dynamics.

Handling Qualities are given by the **in-homogenous solution of the system of differential equations** describing aircraft motion. Now the "non-zero" right side of the system of equations contains pilot control dynamics as the pilot 'closes the loop' when trying to fulfil a task. This is how (and where) pilot dynamics get into the system.

Another important issue must also be mentioned here. Up to now we have been discussing FQ and HQ on a pure flight mechanics basis only. The importance of pilot dynamics has also been pointed out. A third equally important area is aircraft system dynamics. For a conventional aircraft, it is the dynamics of the cable control system (friction, loose play in the system, back lash, hinge moments, etc.) that have an influence. For aircraft with hydraulic boosters at the control surfaces the dynamics of the hydraulic system and its capability to react to rapid transient inputs have a considerable influence on FQ and HQ. This plays an even more important role for modern flight dynamics-controlled aircraft where high dynamics generated by the control system may overstress the hydraulic system.

Airframe dynamics like structural elastic movements have an additional influence. In an elastic aircraft, the pilot may be positioned away from the centre of gravity. Due to dynamic elastic deformation in such a set-up, he may experience different accelerations than those acting at the centre of gravity. Thus, his perception of aircraft movement will be different than that experienced at the centre of gravity. Another important need is filtering structural dynamics in a way that they do not influence the flight control system. For this, structural notch filters are part of the control system. They are designed to cancel out any structural dynamic influences.

Discussion in this section shows how closely related FQ and HQ are. Cook [7] points out that the two qualities are very much interdependent and in practice are probably inseparable. We will see later on how strongly they depend on each other. One approach is to use common flying qualities characterised, e.g., by short period frequency together with pilot comments for a handling qualities criterion.

2.3 EXAMPLES FOR FLYING QUALITIES

In the following, some examples shall illustrate what is meant when speaking about flying qualities. As mentioned at the very beginning we will not discuss results of theoretical calculations, we will discuss flight test results. Typical examples have been taken to show basic dynamics effects on the characteristic longitudinal and lateral axes.

Longitudinal Axis

Modern highly augmented aircraft hardly ever display undamped aircraft Eigen motions. Thus, best available FQ can be achieved via appropriate control law tailoring. This is also the case for the following example, taken from flight tests of an augmented high-performance aircraft which would react as highly unstable when not augmented. Thus, stability augmentation with tailored control laws is essential for flying such an aircraft. **Figure 2-5** shows time responses for pilot's pitch excitation and corresponding pitch rate response. The dashed line shown also in the figure represents the pitch rate response calculated by a very simple Low Order Equivalent System (LOES) approximation[7] to the flight test result.

[7] Overall flight control characteristics of augmented aircraft are composed of high order system dynamics of the control law as well as high order actuation system dynamics. For analysis purposes very often a simpler low order equivalent model is chosen to approximate the real aircraft response.

Measured pitch rate response does not show any oscillations. The response is well damped. It exhibits a nearly dead-beat behaviour. Due to modelling approximations the LOES response shows some overshoots, but also here an undamped oscillation does not develop.

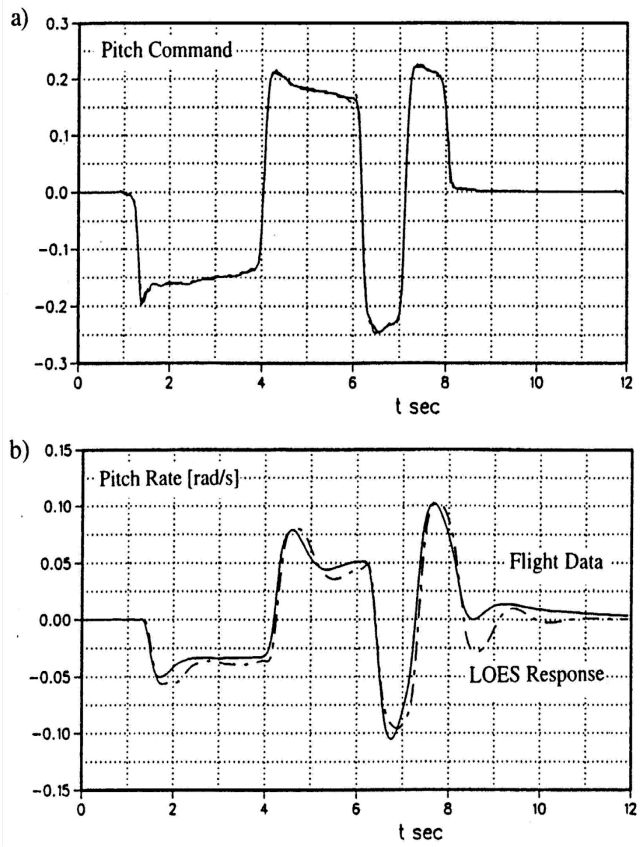


Figure 2-5: Short Period Excitation Together with Simple Model Response [9].

This result is very typical, and the nearly dead-beat system response is an indication of what is considered good flying qualities. With this type of response, it will be fairly easy for pilots to point the aircraft nose at different desired angles.

Lateral Axis

The example for the lateral axis basically is a similar one, it is given in **Figure 2-6**. It shows time histories for pilot inceptors for pitch (STP), roll (STR), and yaw (PED) in the first trace. The other traces show resulting pitch rate, angle of attack, angle of sideslip, roll rate, and yaw rate. The set-up is in a wind-up turn to the left. Once target AoA has been reached, the pilot initiates in quick succession a yaw and a roll doublet. The AoS response exhibits some rather small oscillations at the end of the time slice, responses for roll rate and yaw rate are dead-beat again.

Another remark on this diagram illustrating test conditions: target AoA for this yaw-roll-doublet in quick succession was (knowingly) at a condition where the pedal does not have much influence anymore, still, some very small AoS movement can be observed. There is hardly any yaw rate response. This shows that for specific testing, a method must be made available other than pilot excitation via stick or pedal. Modern control configured aircraft in many cases have a test signal generator incorporated into the controller allowing for single surface excitation even where the pilot signal does not get through anymore.

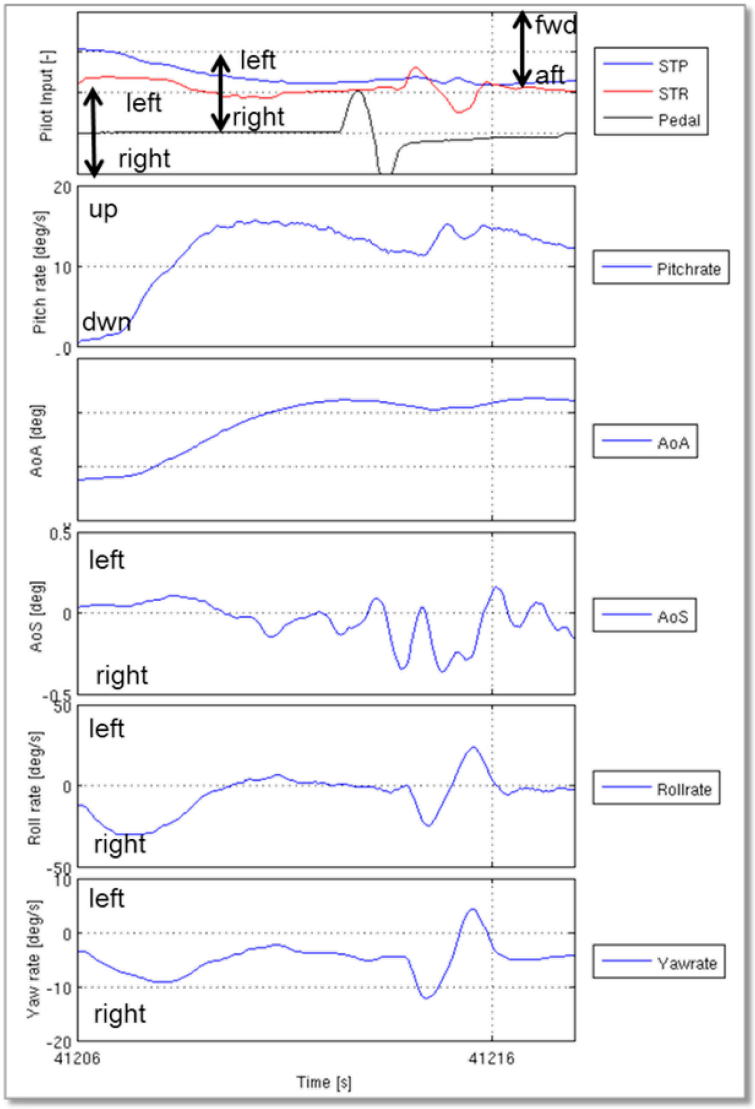


Figure 2-6: Lateral Axis Excitation for Aerodynamic Data Gathering [9].

Test manoeuvres of this kind are mainly used to gather data for aerodynamic parameter estimation methods and to determine system stability sufficient to continue envelope expansion. Already small excitations can be sufficient for certain analysis purposes. Larger inputs are better to show aircraft dynamics but may violate the requirement for linearity for analysis. It demonstrates the close interaction between different disciplines during the envelope expansion flight test process. Flying qualities test points are also good for another discipline. Moreover, progression in the envelope to e.g., larger angles of attack is normally dependent on the model validation results achieved with the outcome of these particular manoeuvres.

The first two examples illustrate aerodynamic and flight mechanic interaction, exhibiting good flying qualities. The following example now exhibits airframe pilot interaction. In an aircraft exhibiting a centre stick the pilot was tasked to perform a “half stick” roll. There was a new control law with higher roll authority installed and it was bound to be tested in flight. The request for a half stick roll was part of the usual cautious stepped approach. It is in a sense an open loop manoeuvre as there was no task connected to it. **Figure 2-7** shows the results of this exercise.

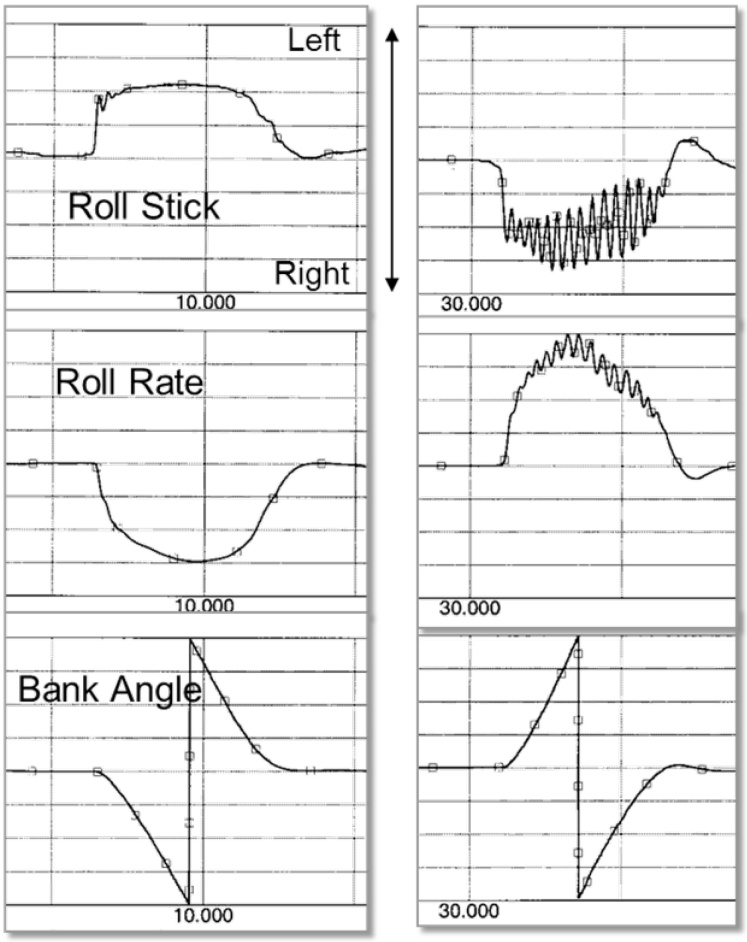


Figure 2-7: Unfavourable Airframe Pilot Interaction (Roll Ratcheting) [10].

In addition to the roll stick deflection also roll rate and bank angle are displayed. The roll response displayed in the left half of Figure 2-7 is a half stick roll to the left. On the first glimpse there is nothing really spectacular to see. For this task, the decision about the direction of roll was left to the pilot. He chooses his "best side" which was rolling to the left. In this case he (or she) has to push the roll stick to the left. Putting the stick into a "half stick" position to the left is fairly easy since the pilot has to exert a push force. This rather inconspicuous result tempted telemetry control to ask for a half stick roll to the right as well. The result is shown in the right half of Figure 2-7. For a half stick roll to the right the pilot has to pull the stick to the right. He now experiences other forces and tensions on the lower arm than for the push exercise with the roll to the left. Due to this it is much more difficult to hold the stick in the requested half stick position. Now, in addition, as shown in the case here, excessive roll accelerations act on the pilot's lower arm; he cannot keep the stick in the requested position as firm enough as required anymore. The result is the biomechanical ratcheting behaviour shown here. If one now goes back to the left roll one can see a very small hardly distinguishable ratcheting behaviour here already, when looking at the roll stick deflection at the very beginning of the manoeuvre. The lower arm pushing action for this case was strong enough to counteract the ratcheting tendency and it was not noticed in flight.

The examples presented for both axes are so-called Phase 1 manoeuvres as explained in Figure 2-3. In particular, the third example illustrates how important it is to find snags like the given ratcheting behaviour as early as possible in the testing process, Phase 1 testing. In this phase necessary corrections to the control law design, in this case for the roll axis, can be implemented much faster and more easily. If it had been discovered "only" in Phase 2 or 3 a lot more re-testing would have been necessary after rectification of this

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

snag. For the case given here the observed behaviour from flight could not be observed in simulation prior to the flight. A standard ground-based simulator does not exhibit motion cues to provoke such an interaction between pilot and airframe. A quick corrective solution into the control law was introduced (slight reduction of commanding of initial roll acceleration in the forward path of the controller) and the satisfactory fix was available for flight testing a couple of weeks after the event.

2.4 MISHAPS CAUSED BY ADVERSE PILOT-VEHICLE INTERACTIONS

As already pointed out in Section 2.2, the interaction of the pilot's dynamics with the dynamics of the air vehicle is of high importance. Pilot and aircraft interaction forms a closed loop feedback control system. The pilot's actions depend on his perception of the motions of the aircraft, which are in response to his commanded inputs. Unfavourable interaction behaviour happens when discrepancies in pilot dynamics and aircraft dynamics become dominant for the overall dynamics of the PVS.

Such a behaviour is frequently oscillatory and commonly called a **PIO**. Today this term stands for **pilot-in-the-loop-oscillations** or pilot-involved-oscillations. It describes adverse Aircraft-Pilot-Coupling (APC) phenomena. Historically, the abbreviation PIO meant pilot-induced-oscillations. This description of the phenomenon implies the presumption of blame on the pilot. Generally, it is not only the pilot who is to blame. It is the unfavourable interaction between pilot's and aircraft's dynamics which causes the incident. In other words: a disharmony between pilot's action and the aircraft's reaction, e.g., an excessive time lag between the input and the response. The cause for this lag does not always lie with the pilot. Both dynamic systems (pilot, aircraft) have an equally decisive impact. Therefore, the definition **pilot-in-the-loop-oscillations** is intended in the following discussion of PIO.

The PIO phenomenon has been discussed widely, very often from the design point of view, meaning how to avoid PIO in the design phase already. A very good overall summary is given by McRuer et al. in Ref. [11]. One of the best publicly documented PIO events is the YF-22 accident in 1992, which happened on the last scheduled flight of this aircraft. It is documented in Ref. [11], as well as by Harris and Black in Ref. [12].

The traces of the time histories of this event are reproduced in **Figure 2-8**, which is taken from Ref. [11]. The aircraft was at the end of a fly-by and the pilot was initiating a go-around when he retracted the gear and selected max reheat thrust. Besides the transition to the gear up configuration and selection of max reheat thrust two other configuration changes took place automatically at the same time. At first the authority of the pitch input changed, with the same stick force the pilot received more pitch authority, or, in other words, the pitch axis became more sensitive (in the gear up configuration). High pitch agility is a desired design feature. The second additional configuration change was the activation of thrust vectoring for better control of the pitch axis. This made the pitch axis even more sensitive because pitch authority was increased now with two effectors (horizontal tail, thrust vectoring) operating.

After the gear is raised (dashed line in Figure 2-8) an increase of amplitude in pitch state variables (pitch rate, pitch attitude, normal acceleration) can be observed. These were triggered by an increase of amplitude of stick pitch input at the moment when the gear was raised, indicated in the top trace. Very quickly resulting pitch rate starts lagging behind stick pitch input until they are approximately 180 deg out of phase at about 5 sec on the time axis; the pilot is pulling aft while the pitch rate goes nose down. This is an unstable situation and the pilot's stick input fans the pitch motion. At the same time, the traces of horizontal tail and thrust vectoring deflection show a characteristic triangular shape each. This is a very clear indication of rate limiting in the control loop.

Further interpretation can easily run into speculation since not all facts about this mishap are publicly available. But an experienced flight test engineer trying to understand what was going on is tempted

to “think onwards”. Two more thoughts will be given. The observed rate limiting of the pitch effectors can be considered most likely as the cause for the large negative phase shift of pitch rate with respect to pitch input. Plainly spoken, the actuation system cannot follow the rapid pitch demand. At about 6 sec the amplitude for the horizontal tail exhibits more than 30 deg, the amplitude for the thrust vectoring a little less than 30 deg. This surely represents a very high demand to the control system components affected.

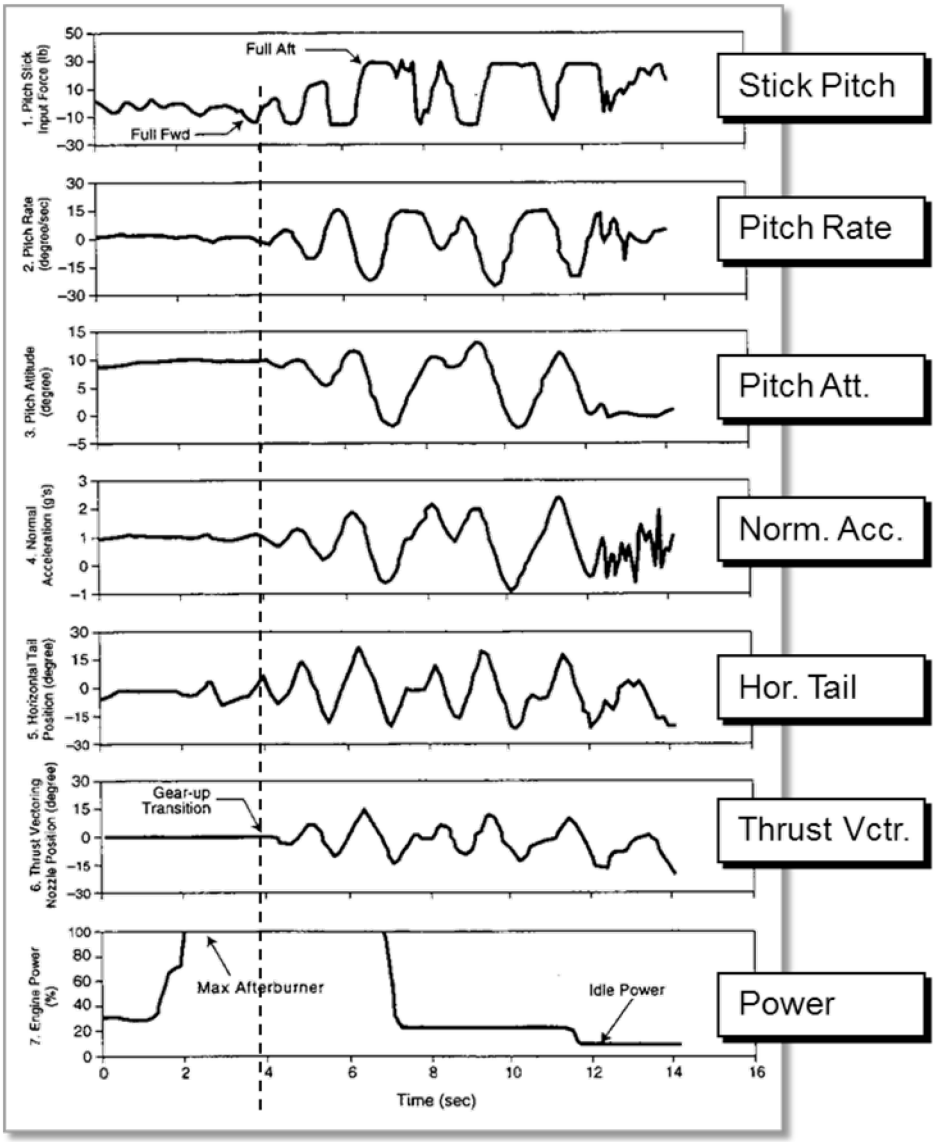


Figure 2-8: YF-22 PIO Event [11].

Secondly, only a (wild) guess can be given about the cause for the rate limiting. Non-optimal control law gains in combination with the change of stick sensitivity when raising the gear had an influence [11]. This, in combination with the available performance of the hydraulic system, could have caused the observed rate limitations in the horizontal tail and in the thrust vectoring. In addition, the trace for power most likely shows the position of the thrust lever, the demanded thrust level. Information about the actual engine status and the available hydraulic pressure in the actuation system is not available here. As it takes some time for the engine to spool up with rotational speed after a power request is given it also takes time to run up with hydraulic pressure, as the pressure generated by the hydraulic pumps is most likely dependent on engine

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

rotational speed. Also, it is unknown how well a possibly available hydraulic reservoir is charged. Thus, possibly, the available hydraulic oil flow was too low (the engine was almost at idle prior, due to the fly-by) and was not sufficient for the actuation system to follow the requested rapid pitch inputs properly. Thus, a lack of hydraulic energy in combination with not adequate control demands could have triggered the rate limiting effects observed.

These assumptions are only assumptions, nothing more. Still, this analysis shows, and this is the important thought, when going into FQ and HQ evaluations not only flight mechanics and control law characteristics are of importance. Performance of so-called “basic systems” can have a vital impact as well. FQ and HQ can be affected by the performance of the whole aircraft. Thus, performance of all systems involved must be considered and FQ and HQ characteristics can only be considered at system Level 0.

As different categories of PIO are to be discussed below, the example presented here is a CAT III PIO. It exhibits linear and non-linear relationships between state variables. In addition, the rate limiting fans the situation. But the transition from lower pitch sensitivity to higher pitch sensitivity in the gear up configuration seems to be the major trigger for the PVS to become unstable. Transition of system dynamics is a characteristic of CAT III PIO.

The PIO phenomenon is generally described as sustained, undesired, and unstable (diverging) oscillations of the pilot-vehicle-system. It stops when the pilot does not generate any further input; when he opens the pilot feedback loop within the overall PVS. The given example, though, shows that PIO can be much more complex. Non-linear effects like rate or position limiting play a role as well as time dependent more or less arbitrary changes of system characteristics.

Based on various research and summarised by McRuer et al. [11], the following categories are used to identify the character of a PIO event.

Category I PIO can be considered as linear PIO. The reactions of the PVS and its sub-systems involved in the event (e.g., pilot, flight control system) can be considered as system elements with linear behaviour.

From a design point of view CAT I PIO can be considered as mainly understood.

Category II PIO are considered quasi-linear as non-linear limiting effects present in the PVS have a severe effect on the observed overall system response. This can be rate limiters as shown above but also position limiters limiting the deflection of an effector to reach a required position.

From a design point of view CAT II PIO can be considered as partly understood.

Category III PIO are considered fully non-linear with non-linear transitions and changes of certain relevant system characteristics.

As these system changes are generally non-deterministic a conclusive design guideline is not available.

Finally, **Category IV PIO** involves all phenomena sketched above plus aero-elastic effects affecting pilot’s perception of the overall aircraft motion. These can be experienced when the pilot of a rather long aircraft with elastic fuselage deformations perceives up front in the cockpit another motion as the overall aircraft at the centre of gravity experiences.

With this paragraph the spectrum from pure flying qualities as discussed before has been expanded to complex pilot-vehicle interactions. With the definition for HQ given above the given example does not describe a classic handling qualities problem as there was no specific flying task given to the pilot. However, it illustrates how a coupling of specific vehicle dynamics and pilot dynamics can lead to a catastrophe.

A very good and comprehensive summary on the state-of-the-art on understanding and dealing with this subject was given at a NASA Dryden workshop at the turn of the millennium. Proceedings have been published in Ref. [13].

For handling qualities testing with high gain pilot tasks (pilot under stress) PVS resistance to PIO is important. Therefore, as pointed out in Figure 2-3 within the test pyramid, PIO resistance testing is a very important step to be completed before HQ testing with operational tasks can be commenced.

2.5 THE PILOT-VEHICLE-SYSTEM OF HIGHLY AUGMENTED AIRCRAFT

In the previous section the behaviour of the overall PVS depending on various system characteristics was observed. PIO was identified as a severe result of unfavourable aircraft-pilot interaction. In this section, an illustration will be given of how different pilot behaviour can influence the outcome of a test manoeuvre, in this case it is a closed loop operational one.

The traces given in **Figure 2-9** show the results of a tracking task. Pilots were tasked to track another aircraft in a 3 g turn. The task was flown as a "perch" set-up as initial condition with the fighter (the follower) approximately 1000 feet above the target. The follower had the target 30 deg offset at a distance of 3,000 to 4,000 feet.

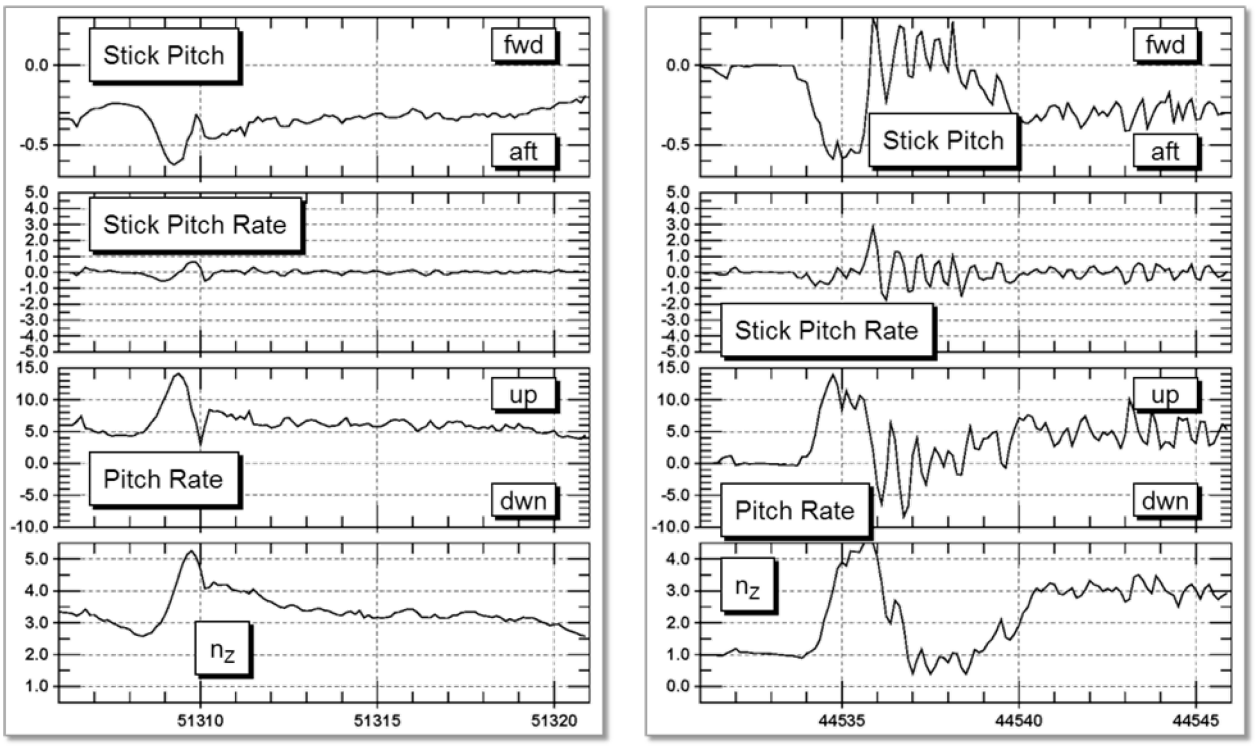


Figure 2-9: Influence of Different Pilot Behaviour on Dynamics of an Air-to-Air Tracking Manoeuvre [10].

The task started with a given flight condition in terms of altitude and speed as defined in the test matrix. When the follower pilot calls "go" the target pilot starts a 3 g turn and the fighter aggressively manoeuvres to put the fixed sight (symbol in HUD) on the target. The task ended after about 10 sec of tracking.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

The traces given in Figure 2-9 show relevant variables for the pitch axis. The traces on the left side show the results achieved with a so-called “low gain pilot” whereas the traces on the right half show the results achieved with a “high gain pilot”. Both start the tracking sequence with a rapid pull to approximately 4 g to 5 g which can be considered as the target gross acquisition phase. The following fine tracking phase shows for the low gain pilot in the left half hardly any stick pitch movement. On the contrary the high gain pilot shows clearly visible rather high amplitude stick pitch oscillations in order to stay on the target. His behaviour can also be considered as aggressive in this phase of the task.

This example illustrates inherent pilot behavioural characteristics designated as low gain and as high gain pilot behaviour. When testing HQ, one has to bear in mind that pilots can act or behave differently. Therefore, operational HQ testing must never be done with only one pilot. There must be always several pilots with different behavioural characteristics.

This example is also good for showing another feature which must be possibly considered when doing HQ testing. As already mentioned above, modern control augmented aircraft are normally “fitted” with command path shaping in the control system. This is done to tailor for excellent FQ in the first place. The control system of the aircraft under consideration in the example in Figure 2-9 provides the pilot with a so-called tracking filter.

The tracking filter suppresses the well-known drop back behaviour which every aircraft experiences in the pitch axis when changing pitch attitude. It is typical for dynamic systems of second order. The implementation of the tracking filter in this example is done in a way that for gross acquisition the filter is turned off and one accepts that the drop back is not a disturbing factor. It also retains the advantage of being more agile. For the fine tracking phase, though, the tracking filter is active, suppressing the drop back. One accepts a decrease in agility now, which in the fine tracking phase is not as important anymore.

In the given example, the low gain pilot (left half of Figure 2-9) follows this set-up perfectly. Once in the fine tracking phase the rate of the stick pitch is well below a certain threshold and the tracking filter is active aiding the pilot to stay on the target easily. The more or less aggressive inputs of the high gain pilot in the fine tracking phase (right half of Figure 2-9) exhibit a stick pitch rate well above the threshold for the tracking filter. The tracking filter is now not active in the fine tracking phase and the high gain pilot experiences unsatisfactory tracking behaviour due to the still present and disturbing drop back phenomenon.

Two conclusions for HQ testing:

- Different inherent behavioural characteristics of pilots can have significant influence on the outcome of HQ testing. Thus, testing must be always done several times and with different pilots (3 pilots are typically found to be sufficient), see next Section 2.6.
- Aircraft scheduled for HQ testing must be fully understood with all their features before a final conclusion on observed FQ or HQ behaviour can be made. With regard to HQ testing, especially, all control law features must be known and understood. Possibly specific testing of these features must also be considered.

The demonstrated possibilities of control law design underline that for modern augmented aircraft excellent FQ is a design task. In the example given here, excellent tracking capabilities are supported through the inclusion of a tracking filter. It supports the aim of achieving the best possible HQ in a closed loop task. The proof that excellent FQ are available in the real world and support excellent HQ can only be given by conducting dedicated HQ flight testing. Only flight test with a dedicated task delivers the full spectrum of HQ where all relevant cues to the pilot (especially motion cues) are present in the correct manner.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

2.6 PILOT GAIN OR HIGH GAIN AND LOW GAIN PILOTS

The term "pilot gain" has been and will be used frequently within this report. There are a variety of publications that address this topic. Only a few have it on their main focus. Rüdinger [14] examines pilot gain in connection with pilot workload. She gives characterisations of "low pilot gain" and "high pilot gain". She introduces the term "natural pilot gain". Mitchell and Klyde try to elaborate more deeply on pilot gain in Ref. [15], especially from the perspective of "high gain pilots" and "low gain pilots". They use the results of various flight investigations and conclude that pilot gain is a misnomer. To them the critical metric for pilot control is overall pilot-vehicle operating frequency (bandwidth) and not pilot gain alone. They do not give definitions for low gain and high gain pilot characteristics. In their examples a low gain pilot exhibits a smaller crossover frequency[8] than a high gain pilot.

Characterisations of different pilot behaviour are rare. Rüdinger [14] uses the term "natural pilot gain". She means a pilot's natural inherent disposition to fly an aircraft. One description of a **low gain pilot** is given by English in his blog [16]. He cites White [17] in describing X-15 pilot Joe Engle: "Engle was a low gain pilot. Like Charles Lindbergh or Chuck Yeager, he barely moved the stick, anticipating the need to do so and making small, necessary corrections in plenty of time. His inputs were smooth and progressive, never snatching the controls." On the contrary, a **high gain pilot** always stays "connected" to the aircraft he is flying. He is always giving small minute inputs in order to confirm that the aircraft is still there. This behaviour may result in high amplitude (high gain?) reactions when pursuing a given task.

This distinction does not mean at all that a low gain pilot is a "slow pilot". A low gain pilot is just as capable of being alert and reacting as rapidly as a high gain pilot. Still, he does it differently. A typical illustration is given in Figure 2-9. A deeper elaboration about low gain and high gain pilot characteristics goes beyond the scope of this report.

While experience with test pilots allows the flight test engineer to differentiate between pilot behaviour and identify one as "low gain" and the other one as "high gain", a general definition is not yet available. For this report, from a flight test point of view, the assumption is made that different pilots have different inherent piloting technique characteristics. This must be connected with their inherent way of treating or performing tasks given to them. And from a flight test point of view this must be taken as it is, and it must be taken into account when it comes to evaluations of the pilot-vehicle-system.

Therefore, HQ testing must always be performed with at least three different pilots. And, in order to drive a modern control configured aircraft in an orderly manner to its limits (e.g., rate limiting), a so-called high gain pilot must be part of the team.

2.7 FLYING QUALITIES AND HANDLING QUALITIES EVALUATION

As already indicated in Figure 2-3, operational relevance becomes more and more important when going to the top of the pyramid. Test tasks at the bottom are FQ tasks; on the way to the top of the pyramid they will become more and more HQ tasks. During all testing it must be taken as given (as a requirement for test) that the aircraft under consideration can be flown safely within the required envelope, especially for demanding HQ tasks which require high pilot gain. The only unknowns should be the pilot-vehicle-system dynamics during the execution of different operational manoeuvres.

However, the evaluation of flying qualities as described in the lower half of the pyramid must not be neglected. Evaluation starts from the beginning of the envelope expansion process, in order to understand the basic airframe dynamics. In that sense it is a safety issue as it gets the pilot into the right mind as early as possible.

[8] For crossover frequency see the introduction into McRuer's crossover pilot model given in Ref. [32] and briefly explained in Section 3.5.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

Required operational manoeuvring is heavily dependent on the specification applicable for the aircraft under test. For testing tasks in the lower portion of the pyramid, requirements can be taken from Military Standards or specially derived customer standards for a specific aircraft model. Operational testing goes into the application phase. Tasks must be defined specifically – they most likely are different from aircraft type to aircraft type. Almost always there is very intense customer involvement in this phase.

Once a specific task has been defined, relevant performance criteria have to be identified. For this a close dialogue with the customer and/or the project pilot is very helpful. For tasks with possibly measurable performance quantities like the offset on the runway during a landing approach, measurement data can be used for evaluation. For tasks like the one illustrated in Figure 2-9 (3 g turn tracking manoeuvre) the relative positioning of the target within the pipper in the Head-Up-Display (HUD) could be a method for evaluation of task performance.

When the specific test equipment is available the evaluation engineer can take the video documentation of the HUD display and do a quantitative evaluation. This can be time consuming and expensive. An easier way is asking the pilot. Positioning the target inside the pipper symbol would be satisfactory, positioning the target outside next to the pipper symbol would be adequate performance. The evaluation for this procedure works fast and, in most cases, this type of evaluation is accepted by all partners. Adequate pilot training on such an evaluation technique in a simulator normally provides reliable and repeatable results during flight testing.

In addition, the usage of a rating scale can be trained. This would provide much more refined results than only ‘desired’ or ‘adequate’. The most prominent rating scale for this endeavour is the well-known Cooper-Harper-Rating scale (to be discussed in the next chapter). Nevertheless, whichever method is being used its selection depends on customer requirements. And, as also pointed out later again, the last evaluation comment “doable” or “not-doable” is with the evaluation pilot.

2.8 OVERALL REMARK

This chapter concludes with some remarks about overall programme planning in general and HQ flight test planning in particular. Flight testing an aircraft comes at the end of the development chain. It is the last step of a (long) development program. Very often, due to sometimes very high complexity, these programs are behind schedule. This gives a lot of programme pressure on flight test management to reduce the delay as much as possible. A very easy way of reducing a delay is cutting the number of required test flights, which is always requested. “Why do you need so many flights, what for?” is the most asked question when it comes to flight test. The second most asked question is: “Why do you need so much time for analysis?”. In addition, it is commonly asked, “Why do you need more than one pilot for the same task?”

Within this context nowadays the term “virtual flight test” is stressed and promoted in order to save (development) time and cost. This does not mean rig and simulator testing prior to a test flight. It means substituting real world flight test with a simulator test. This may be possible within certain limitations only, namely the simulator model (all sub-models involved) must be a very good representation of the real world. For successful HQ testing very often visual cues and even more important motion cues are essential. If these are not present in the same way as in the real flight world a virtual flight test for HQ testing makes no sense at all.

Achievements like flight test safety and a secure return to base at the end of each test flight are mainly taken for granted. For many it is difficult to understand one has to work hard for this goal with transparent processes, high-quality analysis, high-quality reporting, and high-quality decision processes. A safe and stepped approach in flight test requires a certain number of flights and it serves the overall programme needs better than cutting the number of flights and taking unnecessary risks. This is especially true for HQ testing. Flights with identical test programs will have to be repeated several times, will consume test time and test budget, but they will give the assurance that different pilots with different inherent characteristic flying

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

techniques find out that the aircraft can be flown safely. No HQ snags were found. Coming from the other end: finding out about HQ deficiencies in an extensive test programme with trained test pilots is much better (cheaper) and much safer than finding out in regular day-to-day operational flying by an average not especially trained “fleet pilot”. This could, in the worst case, lead to a loss of lives and aircraft, and it gives bad publicity.

Thus, a sufficient amount of FQ and HQ flight test effort at the end of the development chain serves the overall programme goals!

The purpose of this chapter was “setting the scene”. We have sketched some basics about the envelope expansion process. We have defined Handling Qualities (including how they have to be treated during the envelope expansion process). The chapter has provided some explanatory examples of Flying Qualities and Handling Qualities, as well as an introduction to pilot-in-the-loop-oscillations and terms like “high gain” and “low gain” pilots. The following chapter will show how these effects may be quantified, for the purposes of analysis as well as for reporting purposes.

Chapter 3 – EVALUATION OF HANDLING QUALITIES

This section will give a background on HQ evaluation methods. Usually, a distinction is made between qualitative and quantitative evaluation methods. However, the outcome in most cases is that all methods result in a quantitative evaluation, as only the "evaluation figure" counts for the report. This is especially true when trying to "transport" a specific result to management who normally do not have a task-oriented specific background anymore.

There is a wide variety of books, reports and papers on flying qualities and handling qualities. Very often these are written from the point of view of the designer, trying to understand FQ and HQ from that end of the chain. The target is to have a final product exhibiting excellent FQ and HQ by design already – which is good, it makes flight-testing easier.

Some overarching literature shall be mentioned here, all coming from the design side of the process. We begin with an AGARD Advisory Report [18]. This 1991 report summarises all HQ criteria applicable at that time to highly augmented aircraft. It is a very concise and detailed report that gives examples and valuable application guidelines for each criterion. The second source is the well-known textbook by Hodgkinson [19]. This book provides much of the theoretical background necessary for a better understanding of the overall area. The book is related to practical experience as well. Another, shorter, overview is given by John Hodgkinson and Dave Mitchell in the book on Flight Control Systems by Pratt [20]. In brief, these are three exemplary sources, from the design side.

In the following various methods for quantifying handling qualities will be introduced and discussed. The main focus will be on using these methods in flight test trials; thus, the above-mentioned design aspect will not be stressed here.

3.1 QUALITATIVE EVALUATION OF HANDLING QUALITIES (QUALIFIED EVALUATION BY PILOTS)

"Qualitative" means an evaluation of pilot-vehicle-system dynamics according to the qualified opinion of a pilot, which eventually becomes a quantitative figure in accordance with a rating scale. It is the acquisition of reliable and desirably reproducible information on the ways an aircraft can be handled by pilots. This includes an overall rating which can be descriptive (written comment) or a discrete number in accordance with a rating scale which rates handling qualities, and or workload, and or PIO proneness of the PVS within the given task.

Cooper-Harper-Rating (CHR) Scale

The most prominent tool for the evaluation of handling qualities is the Cooper-Harper-Rating scale (CHR). The CHR scale and the reasoning behind it is summarised by Cooper and Harper [21]. This report gives an excellent overview of a longer period of research and an evaluation of various methods and tools that finally resulted in the rating scale which we know today as the Cooper-Harper-Rating scale. Contributing research is mentioned in Ref. [21]. The article also contains clear definitions of terminology, which will be used here, as necessary.

The beauty of the CHR scale is that it provides users with a structured guide that sets clear paths to the goal. It is set up in categories which are at first put in relation to each other in a flow chart [21]. This flow chart is given in **Figure 3-1**.

The diagram has four layers and four columns. Beginning from the entrance level 1, a tree of further possibilities is developed. The lowest level, 4, helps the user to make fine distinctions between various evaluations. The definitions for each of the terms of Figure 3-1 are given in Ref. [21] and are repeated here:

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

- **Satisfactory** – good enough without improvement, and, therefore, of the best category.
- **Unsatisfactory** but tolerable – just good enough and adequate for the purpose, improvement is desirable, and, therefore, of the next best category.
- **Unacceptable** to the pilot – not suitable for the purpose but still controllable, and in the third category.
- **Uncontrollable** – unacceptable for the purpose and of the poorest quality and in the fourth category.

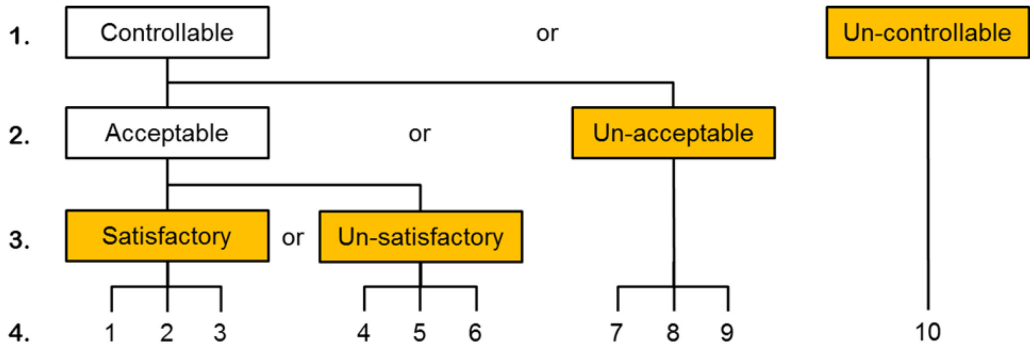


Figure 3-1: Sequence of Pilot Rating Decisions [21].

From this sequential tree of evaluation possibilities Cooper and Harper developed a decision tree based on explicit questions, to be given to an evaluation pilot. This is given in **Figure 3-2**. These questions give clear guidance to the pilot when going through it. The sequence of categories given above is now transformed into this tree giving the outcome of it. In other words, the tree of explicit questions guides the user to the characterising categories. From there on it is only a small step to arrive at the full (familiar) rating scale. As already indicated in Figure 3-1 three of the given evaluation categories are divided into sub-categories indicated by numbers. These numbers are used for a finer differentiation between quality differences. The result is the famous Cooper-Harper-Ratings.

Before we go into the final rating scale as it is being used world-wide today one other term shall be introduced and discussed in more detail. We take here the direct quote from the original Cooper-Harper report [21]:

> *"Pilot Compensation" as used in the scale is intended to indicate that the pilot must increase his workload to improve aircraft performance.[1] It relates the pilot's difficulty in completing a task with the precision required for the task. Stated another way, it is the measure of additional pilot effort and attention required to maintain a given level of performance in the face of less favourable or deficient characteristics. The total workload is then comprised of the workload due to compensation for aircraft deficiencies plus the workload due to the task.*

The final Cooper-Harper-Ratings Scale is given in **Figure 3-3**. It is a further development and extension of the decision tree already given in Figure 3-2. In addition, a description of aircraft behaviour in terms of various stages of deficiencies is given. The aim is to guide the pilot towards a decision. And, most importantly, a description of required pilot workload is given in detail. The major term in these descriptions is "compensation" as it is described above already. At this stage it must be stressed that pilot workload is comprised out of two components: a) The workload due to operation of a possibly deficient aircraft; and b) The workload due to the task given to the pilot. The latter most likely increases with more dominant deficiencies. But it should be a goal to keep both influences separated as much as possible. Only via this procedure can causes for aircraft deficiencies be clearly identified.

[1] Meant is improvement of the pilot-vehicle-system.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

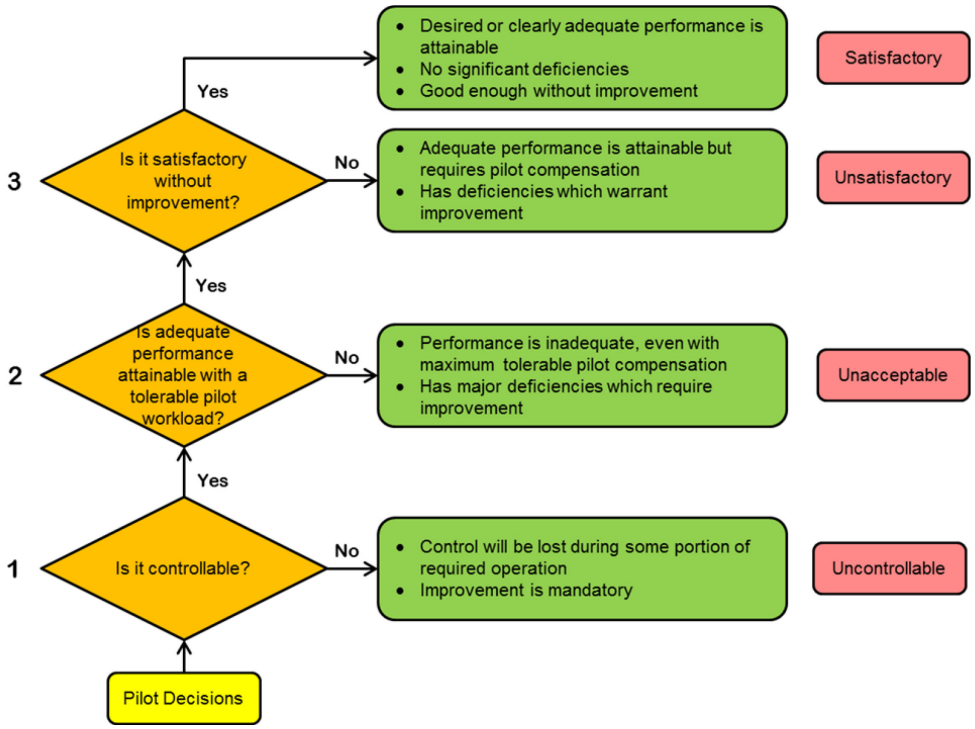


Figure 3-2: Major Category Selection and Definition [21].

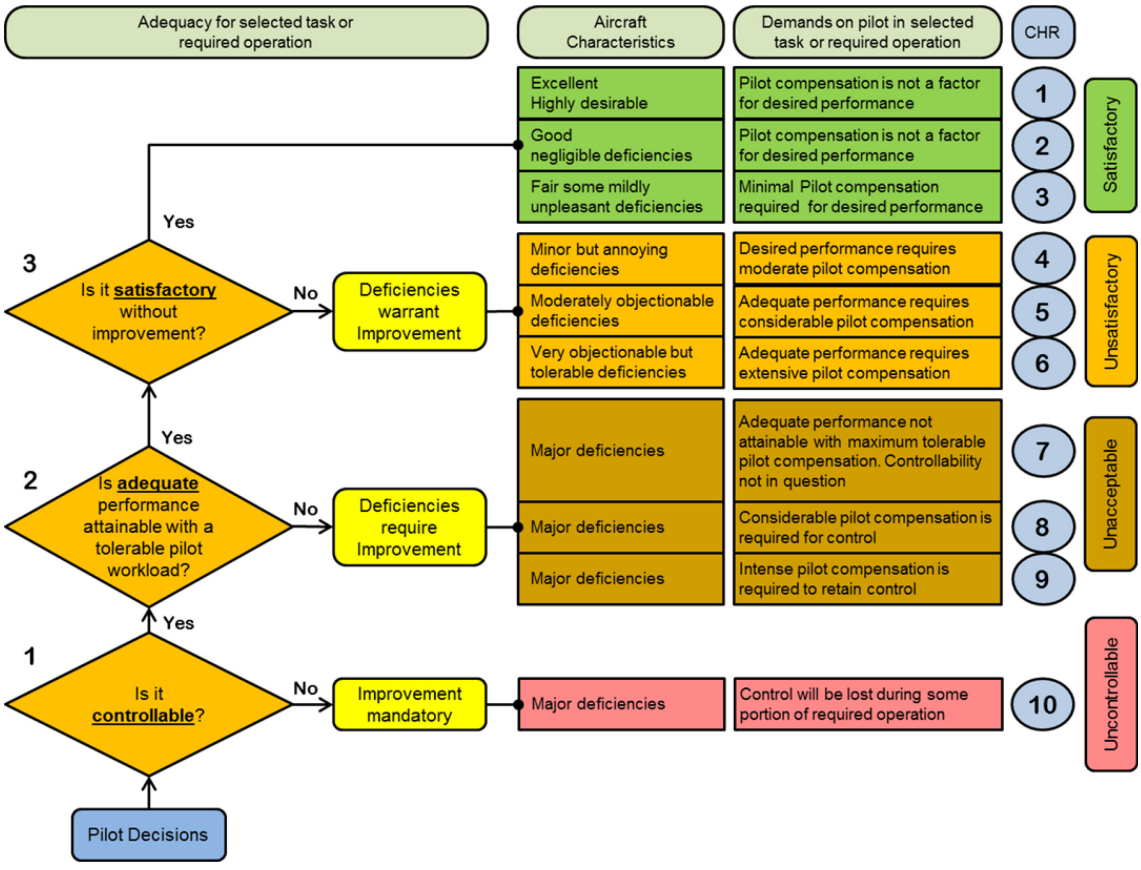


Figure 3-3: Cooper-Harper Pilot Rating Scale [21].

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

A card-sized printed version of the Cooper-Harper-Rating scale exists. Many test pilots have it. The purpose is to have the information readily available for a pilot in the cockpit in case he needs to look up certain meanings or the description of a specific rating. The reverse side of the card contains a collection and summary of definitions from the original Cooper-Harper report [21]. These are given in **Figure 3-4**. They will be used within the scope of this report as well.

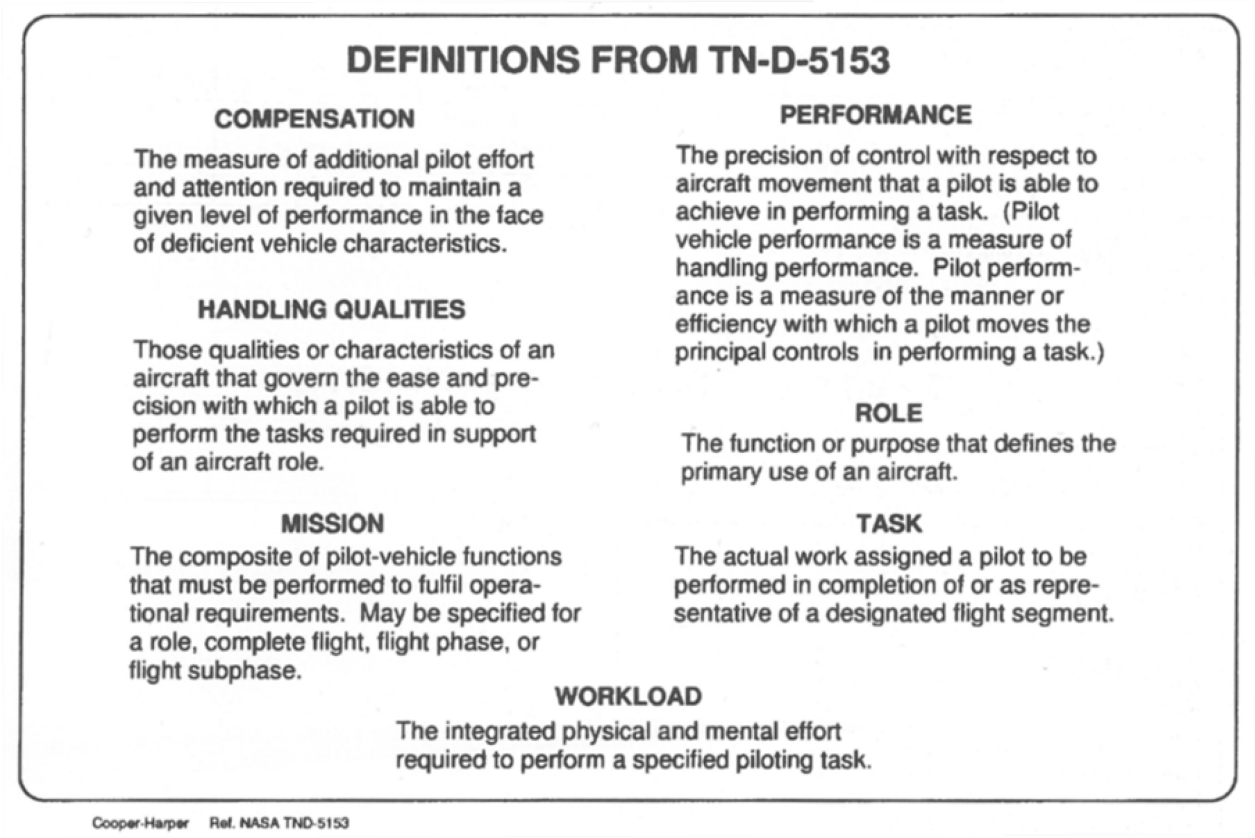


Figure 3-4: Summary of Definitions from the Original Cooper-Harper Report [21].

The Cooper-Harper-Rating scale may only be used in connection with a HQ task. Proper task definition comes from adequate operational requirements. Task descriptions define requirements for what can be considered as satisfactory (Level 1)[2] as opposed to unsatisfactory (Level 2 and Level 3). Levels must be clearly defined in the task definition. A proper task definition will be derived from the customer specification and requirements for safe flying within the operational envelope of the aircraft. Any HQ engineer defining such tasks will have close contact with the project pilot of the special project. Both engineer and pilot will review the given requirements in order to come up with fair and challenging task requirements. Only via this dialogue can a good way for testing be found.

It must be clearly understood that the right choice of requirements for “satisfactory” or “desired” is important. It is considered as “Level 1”. Any task fulfilment worse than that is considered “unsatisfactory”. Task fulfilment worse than desired but still in certain adequate limits (to be defined) is unsatisfactory but generally called “adequate” and it is designated “Level 2”. Any rating beyond Level 2 is considered “unacceptable” and it is “Level 3”. The worst classification then is “uncontrollable”.

[2] Levels 1 through 3 in connection with Cooper-Harper-Ratings must not be mixed up with overall aircraft system levels. Within this text it should be clear from the context which is meant.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

A set of "too loose" requirements can make any aircraft look excellent. A set of "too tight" requirements can make any aircraft look bad. Thus, setting up proper task requirements is most important. A typical example for a task description is given in **Figure 3-5** (it has been taken from Ref. [8]). Within this "approach and landing task" several sub-tasks have been defined together with the criteria for "desired" and "adequate" performance. For each one of these sub-tasks a separated pilot rating will be asked for.

Task		
Approach, land, and stop on a 2000×100 foot rough runway under the following conditions: maximum payload; night; 100 foot ceiling; one eighth mile visibility; 25 knot direct crosswind component; no external navigation aids; no runway lighting.		
Task Performance		
Goal	**Desired Performance**	**Adequate Performance**
autonomous approach path	±50 feet	±75 feet
touchdown speed	±5 knots	±10 knots
touchdown sink rate	≤ 6 feet/second	≤ 8 feet/second
touchdown box (100 feet from approach end)	50 feet wide × 200 feet long	100 feet wide × 400 feet long
roll-out track	±20 feet from centerline	±40 feet from centerline

Figure 3-5: Example of Typical Task Description [8].

Some peculiarities of the CHR scale shall be discussed now. The difference between the CHR3 and the CHR4 description is the change from "minimal pilot compensation" (CHR3) to "moderate pilot compensation" (CHR4). Both ratings, though, require desired performance. The necessity for higher pilot performance degrades still "desired" performance to "unsatisfactory" and Level 2.

Going now from CHR4 to CHR5 the description of CHR5 asks for "adequate performance" with "considerable pilot compensation". The step from CHR4 to CHR5 does not cover the possibilities of a) Where already "considerable pilot compensation" is required for still "desired" performance; or b) Where "moderate pilot compensation" is sufficient to achieve "adequate performance". Both combinations a) and b) may be considered as possible by an evaluation pilot and may bring him into a conflict when it comes to making a proper decision. This dilemma is known among pilots and it makes it difficult to come to a clear conclusion. It is a "grey zone", and it cannot be covered by a "CHR4 ½" as one might expect. The pilot must come to a full integer rating (Ref. [21] and see below). And it will be to his discretion what to value as more important: the degree of compensation or the fulfilment quality of the task.

A last point connected with the statements in the previous paragraphs: pilot skill is an important influence factor when evaluating HQ in general and in special with the CHR scale. It must be kept in mind that a well-trained pilot, especially for a given task with (extensive prior) simulator training, possibly experiences much less workload than a less trained pilot. Thus, this has an influence on the CHR given. Pilot training in a simulator in this context should be understood as an exercise for the evaluation pilot to better understand

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

the required test set up and possibly optimise his piloting technique according to operational aspects of the task. In the sense of training, it does not mean to practice the task. Each evaluation pilot will develop his own technique and will apply it during the test flight. Learning curves will be apparent and easily recognisable. They should be "filtered out" and not influence the rating he gives.

Therefore, evaluation of the task in terms of task performance should be done first. Interpretation of workload within the rating, which was experienced during the fulfilment of the task, should be of second order as the influence of level of training and skill cannot be valued with such a scale. Even a separate workload scale would give unreliable results, as training and skill cannot be measured. One must be aware that testing in a dedicated test environment with especially educated and trained test pilots leads to different results compared to evaluation of the same task by a normally trained operational fleet pilot.

When applying their scale Cooper and Harper clearly state [21]: "As a general rule, pilot ratings and comments are preferably **given on the spot** when the characteristics, performance, and workload are fresh in mind. If the pilot should later want to change his rating, the reasons for the change may be of interest." At another location in the text, they state: "Half ratings (e.g., rating 4 1/2) generally indicate the reluctance of the evaluation pilot to assign either of the adjacent ratings to describe the configuration". Basically, this indicates that "half ratings" are not normally helpful as they open a new "in-between" category which is **not defined**. Therefore, during HQ testing these "rules" given by Cooper and Harper should be observed strictly. It makes a concise evaluation of HQ over an entire (longer) test programme a lot easier.

On the event of the 50th anniversary of the publication of the original Cooper-Harper report [21], Mitchell presented a commemorative summary [22]. He gives an overview about the genesis of the CHR scale, reports various experiences, and includes a discussion on interpreting the scale. His final conclusion is: "The scale survives because it is effective".

PIO Rating Scales

A given task determines the use of an appropriate analysis method. When a pilot exercises a given operational task, he will most likely use the CHR scale as discussed above. Should the case happen in which he experiences a PIO-like response of the PVS he should still follow the specific task the CHR scale, as agreed, to an adequate and most likely not so favourable rating. That is to say, he must stay in the frame of the given task.

When going into dedicated Phase 2 testing (PIO resistance testing, see Figure 2-3) the task will be different and it will be to find out about, for example, undesirable oscillations. For this purpose, criteria other than performance criteria (see, e.g., Figure 3-5) are relevant; CHRs are not collected. Now terms like "undesirable motion", or "undesirable oscillations", or "controllability" are of importance.

At the same time as the Cooper-Harper-Rating (CHR) scale was being developed, other scales were under consideration in order to analyse PIO phenomena. Searching the literature, a variety of these can be found. Ref. [23] is one such early publication. There is also a GARTEUR report summarising test techniques for the experimental evaluation of PIO [24]. It summarises various PIO rating scales and discusses their applicability.

A very "early" and widely used PIO rating scale was given by the USAF Test Pilot School. First published in 1967, it is given in a revised version in **Figure 3-6** (see also Ref. [25]). It uses a decision tree with questions to the pilot just like the CHR scale.

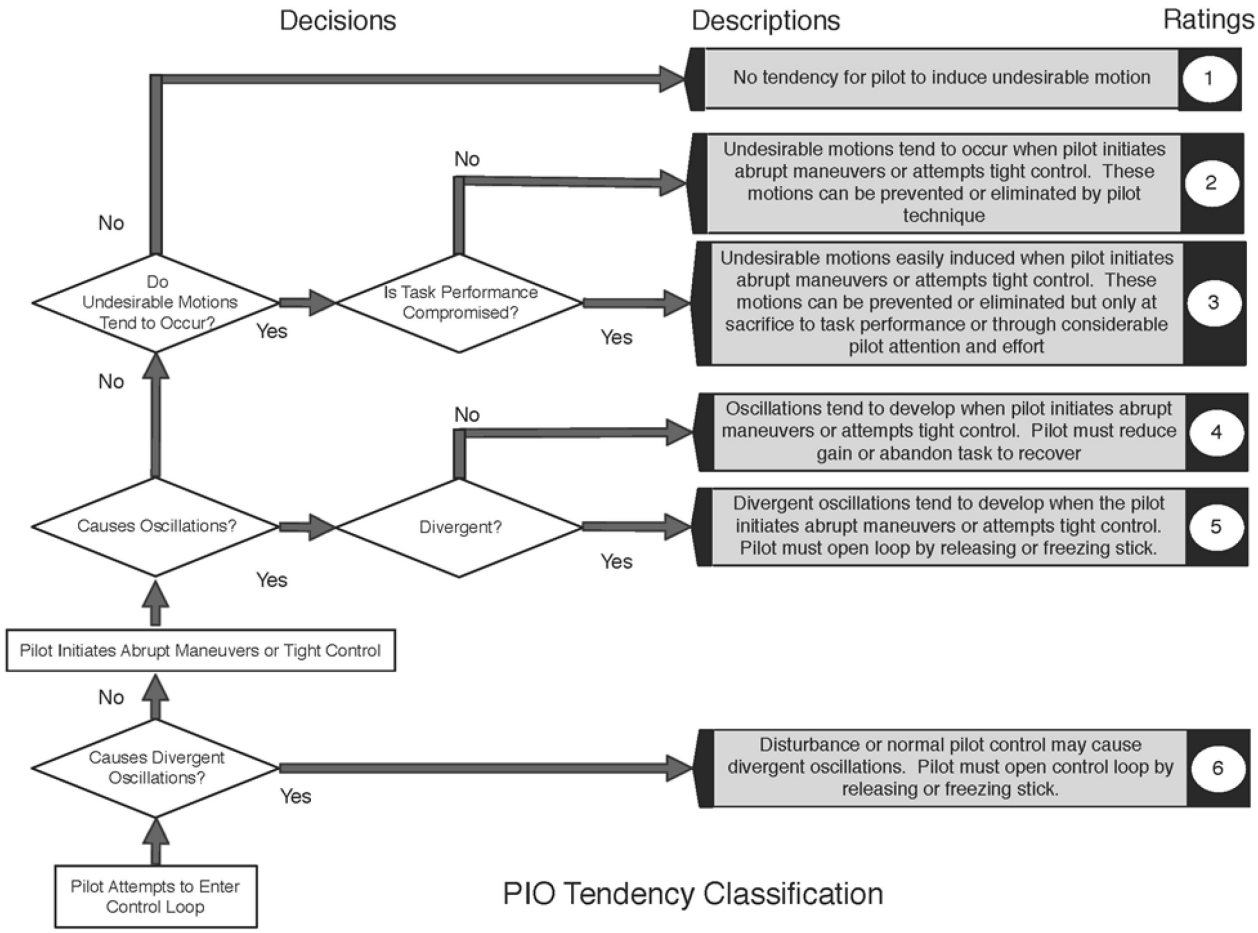


Figure 3-6: USAF Test Pilot School PIO Rating Scale [25].

The beauty of this scale is that it only focuses on undesirable motion and resulting oscillations. An undesirable motion is any aircraft motion that does not closely follow the pilot's control inputs. Unwanted overshoots, undershoots, or residual oscillations, or if the response is too rapid or too slow must therefore be characterised as undesirable. The setup of the scale also shows that it only focuses on aircraft motion, it does not consider fulfilling a task or task performance. This makes it easy to apply this scale in a wide area of applications.

Other scales use other decision trees with similar questions to those given above or even similar to the CHR scale. This, though, implies that a task similar to one given for HQ testing must be given to the PIO evaluation pilot. As some of the known PIO resistance testing tasks are pure open loop tasks (see below) the application of such a scale might become ambiguous.

Pilot Report and Evaluation Sheets

The two methods introduced above (CHR scale, PIO rating scale) must be considered as "digital" tools. They come up with one single number characterising the performance for a specific task. From the rating scale being used one can derive certain characteristics but, certainly, one does not get the "whole" picture. For this "analogue" pilot commenting serves to get the information "between the lines".

Two methods are used: The first one is listening to the pilot and questioning him about his observations. This can be done either via telemetry during the flight or in the debriefing immediately after the flight. The earlier

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

the better. This dialogue must be driven by the evaluation HQ flight test engineer. After the flight a pilot, normally, will write a (more or less detailed) report about the flight. This also gives useful analogue information and must always be considered!

A second method is using specific "Pilot Evaluation Sheets". These can be set up individually, e.g., depending on a task. There are no common formats. One is again from the USAF Test Pilot School given below for illustration in **Figure 3-7**.

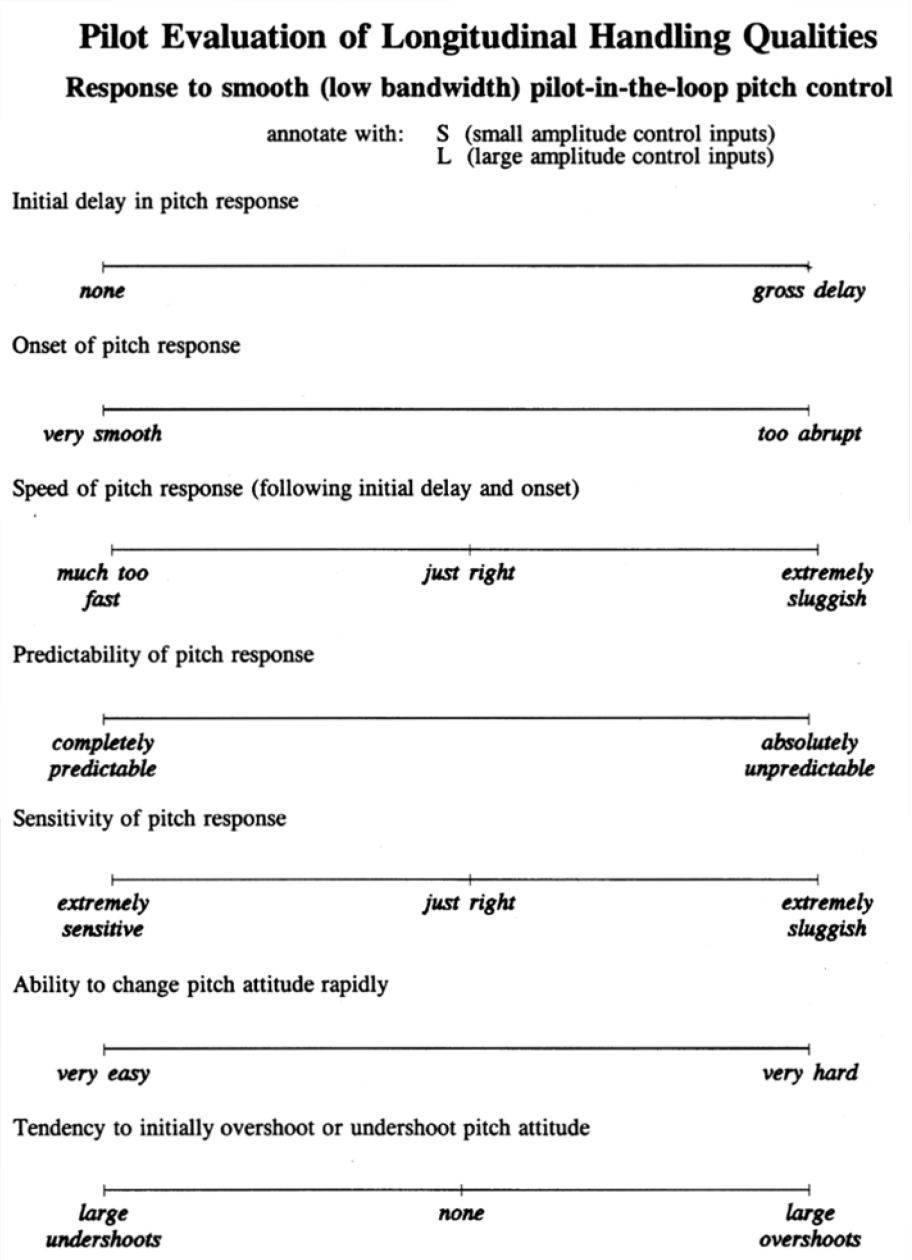


Figure 3-7: Exemplary Pilot Evaluation Sheet [8].

One has to keep in mind that using evaluation sheets spreads the overall evaluation range of one particular test point onto at least three layers: a) A pilot rating in accordance with a rating scale; b) Pilot evaluation sheet; and c) Pilot report. This approach delivers a large amount of information that has to be tailored

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

for a report. From the point of practicability, e.g., effort for analysis and reporting, most often only a CHR or a PIO rating is sufficient. Evaluation and proper interpretation of these figures within a test programme of several hundreds of test points already requires much evaluation effort. And, viewed from the practical point of view, management very often requests a rapid pace in the envelope expansion process. For this purpose, quick and precise evaluation methods (like CHR or PIO rating) can (must) be sufficient. A mandatory pilot report for each flight will also be available, and a thorough preparation of testing and evaluation with a CHR only is sufficient to not endanger flight safety.

This is not to abandon the usage of evaluation sheets. In an industry environment with a tightly scheduled envelope expansion test plan, the application of evaluation sheets can at some stages be too much of an effort. Their value is for more academic or scientific testing when, e.g., granular differences between control law standards must be interpreted.

Summarising Thoughts on "Qualitative" Methods

In the beginning of this chapter, it was stated that "qualitative" means an evaluation of pilot-vehicle-system dynamics according to the qualified opinion of a pilot. It was shown how these opinions can be channelled into (comparable) quantitative numbers via the proper usage of qualified rating scales. The tools have proven to be very powerful since the time they have been introduced. They deliver reproducible high-quality results as long as they are being applied properly (according to the rules, see above).[3]

It became clear that one way to achieve these high-quality results is adequate pilot training as well as thorough preparation of the test tasks. The other point is the pilot must be well trained in using the rating scales properly. Once these aspects of preparation are commonly understood, methods designated as qualitative can serve as powerful tools, ultimately providing valuable quantitative results in the form of easy numbers to be reported to upper management.

3.2 "OPEN LOOP" VERSUS "CLOSED LOOP" ANALYSIS METHODOLOGY

The above given rating scales are used for closed loop testing, pilot-in-the-loop, evaluation of fulfilment of a given task. On the modelling side, there is a variety of flying qualities and handling qualities criteria that primarily value certain characteristics derived from the flight mechanical model. In the first instance these characterise airframe dynamics or open loop dynamics. One of these parameters would be the frequency of the short period (to be discussed further down) or the frequency response due to a stick input in the pitch axis (also to be discussed in more detail further down).

These criteria are well documented, e.g., in Refs. [18], [19], and [20]. With a very brief and more general example, we shall illustrate the principal connection between those criteria and closed loop tasks. Ref. [26] gives the baseline on these criteria with extensive technical information aimed at setting up a MIL-STD. For the short period and the bandwidth criterion (to be discussed further down) very "simple" examples will be given on how to derive a criterion.

Figure 3-8 gives a very early criterion as reproduced in Ref. [19]. It shows a diagram of short period natural frequency as a function of short period damping. Indicated in this diagram are various areas where the pilot comments on an aircraft exhibiting various combinations of frequency and damping. These lines look very much alike a regular thumbprint, this is why it is often called the "thumbprint criterion". In Ref. [27] Shomber and Gertsen call these lines "iso-opinion boundaries" which gives this diagram already

[3] According to the rules given by Cooper and Harper [21] the CHR scale is an ordinal scale (no intermediate numbers). Praxis shows average and mean CHR are frequently used to "sum up" the results of a larger test campaign. This is "allowed" to the extent as long as it conveys useful information.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

a handling qualities flair. It indicates how characteristic open loop properties (here frequency and damping) can be put in relation with pilot commenting: together, they make up a criterion already.

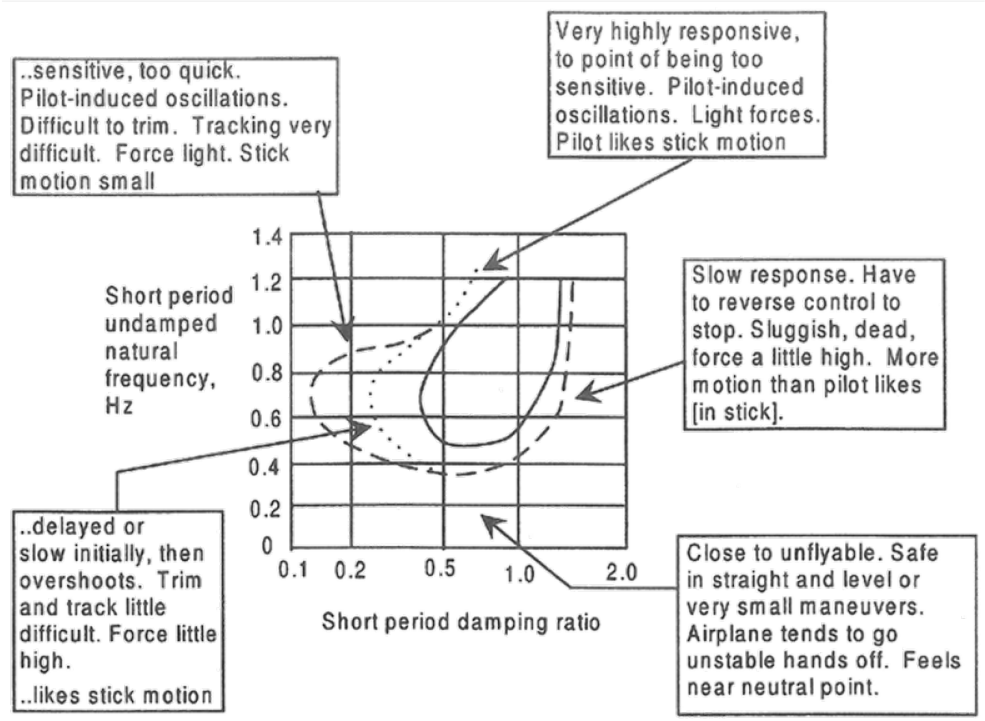


Figure 3-8: Thumbprint Criterion as Reproduced in Ref. [19].

Later on, this idea was developed. Based on a large variety of simulation results with a lot of variations of (open loop) system parameters, an even larger number of simulations was performed. In each of these simulations the pilot was given a common specific task and was asked for a CHR. He did not know what the specific variation of system parameters was. He just had to fly an aircraft for this task. e.g., landing task. The results of these large varieties of investigations are cited in Ref. [26].

The example given in **Figure 3-9** illustrates the principle of deriving a HQ criterion from open loop parameters. For one certain aircraft configuration system, parameters of the model were varied systematically in a way that the parameter bandwidth of the open loop pitch axis frequency response changed together with the equivalent time delay (both parameters will be discussed in more detail in the next section, here it is for the principle of deriving a criterion). Figure 3-9 gives a typical example from these investigations. Equivalent time delay is plotted versus bandwidth. Each one of the symbols marks, for the given aircraft model under consideration, one test with a specific variation of respective system parameters to "deliver" the shown combination of equivalent time delay and bandwidth. Since this can all be done via calculations, this diagram was generated via calculations in the first place. In a second step each one of these different configuration variations was tested with pilots in a simulator. Pilots were all given the same task, approach, and landing, and were asked for a CHR. The respective CHR is plotted right next to the respective symbol. Now boundaries between the region of satisfactory and unsatisfactory and the region of unsatisfactory and unacceptable can be drawn. In practise, these regions are often called Level 1 through 3. The area of CHR between 3 and 4 designates the boundary between Level 1 and Level 2. The area of CHR between 6 and 7 designates the boundary between Level 2 and Level 3. The boundaries shown had been consolidated with various other tests as well.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

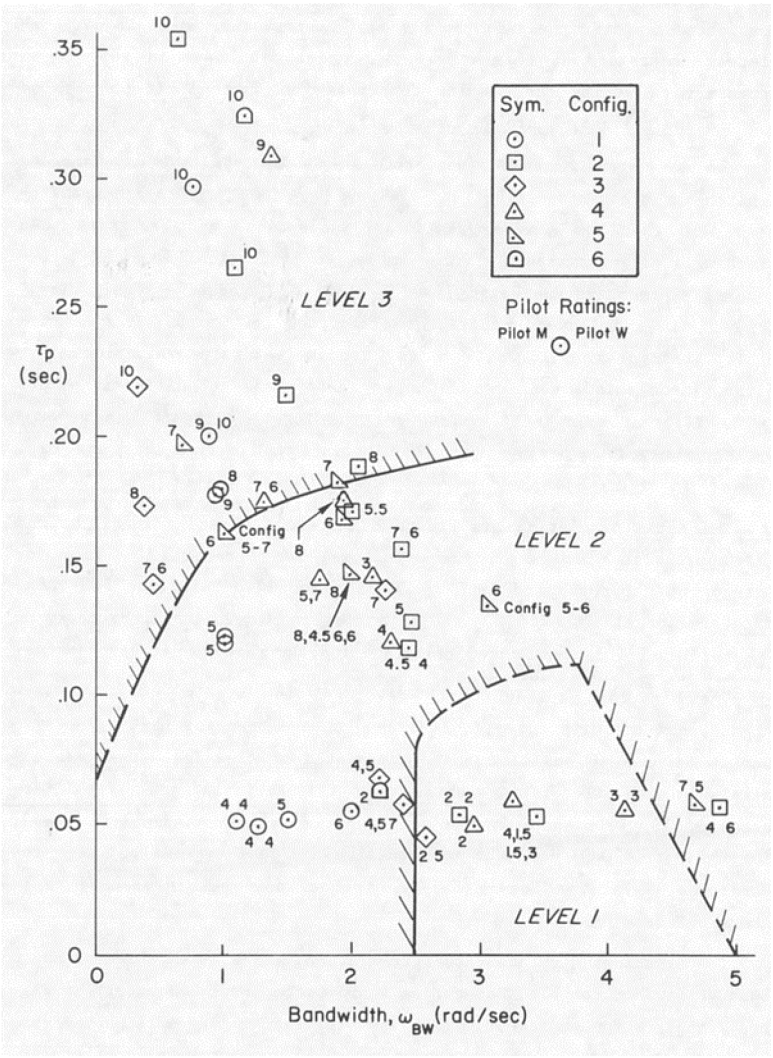


Figure 3-9: A Typical Result for Determination HQ Rating Boundaries (Here: Bandwidth Criterion) [26].

This example demonstrates how, in principle, a connection between open loop parameters (frequency and damping, or time delay and bandwidth frequency) can be correlated with a CHR from closed loop tasks exercised in a simulator. The derived boundaries now make up a criterion. Extensive investigations have shown that these boundaries for Level 1 through 3 vary with the kind of aircraft under test and the task. The following classifications for aircraft and tasks are in use, as given in Ref. [26]:

A. **Aircraft**

Class I:	Small light aircraft
Class II:	Medium weight, low to medium manoeuvrability
Class III:	Large heavy weight, low to medium manoeuvrability
Class IV:	High manoeuvrability aircraft

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

B. **Mission/Task/Flight Phases**

Non-terminal Flight Phases

Category A: Non-terminal flight phase that require rapid manoeuvring, precision tracking, or precise flight path control.

Category B: Non-terminal flight phases that are normally accomplished using gradual manoeuvres and without precision tracking, although, accurate flight path control may be required.

Terminal Flight Phases

Category C: Terminal flight phases are normally accomplished using gradual manoeuvres and usually require accurate flight path control.

Discussions in this section illustrate the benefit of connecting the open loop characteristics of an airframe with closed loop characteristics derived from a piloted task. As an outcome, criteria can be formulated to guide the design engineer. This connection is present in many areas of discussion about FQ and HQ. It will be vital to distinguish properly between open loop and closed loop characteristics, especially when problem areas are encountered.

3.3 QUANTITATIVE EVALUATION WITH LINEAR CRITERIA

Based on the principles given in the previous section, some representative examples for quantitative evaluations will be given here. They are normally called linear criteria as they basically deal with the linear transfer function behaviour of an aircraft and they are also aimed at predicting linear Category I PIO proneness.

For the pitch axis, results of many investigations and criteria are available. See, for example, Figure 3-8. A very simplistic approach is looking at the time response due to a step input. A schematic diagram illustrating this response is taken from Ref. [28] and is reproduced here as **Figure 3-10**. The linear mathematical model behind the diagram describes this result in the s-plane with the following transfer function:

$$\frac{\theta}{\eta}(s) = \frac{K_q\left(1+T_{\theta_2}s\right)}{s\left(1+\frac{2\zeta_{SP}}{\omega_{SP}}s+\frac{s^2}{\omega_{SP}^2}\right)}$$

This equation shows the transfer function of longitudinal attitude (θ) as a function of elevator deflection (η). The denominator is dominated by the characteristics of the short period motion (damping ζ_{SP}, undamped natural frequency ω_{SP}). Moving the single "s" from the denominator onto the other side one could reduce ($s*\theta$) into the pitch rate q, describing the fact that the differentiation of θ is q. In the numerator a gain factor, K_q, and the forward feed time constant, $T_{\theta 2}$, are of importance. The latter is a function of wing loading and lift slope.

Characteristic of the pitch axis is its behaviour when a step input is given on the elevator. This is schematically analysed in Figure 3-10. It shows traces for all relevant state variables of the pitch axis, starting from the bottom it shows flight path angle γ, longitudinal attitude θ, pitch rate q as well as pitch acceleration q dot, and finally angle of attack α, all as a function of time. The influence of variations of $T_{\theta 2}$ is visible, especially on the pitch rate drop back in the beginning or the drop back of longitudinal attitude once the command is removed. One can also easily imagine how θ is derived as integrated value from q, or the other way around, q is gained through differentiation of θ. It is also evident that $T_{\theta 2}$ more or less controls the initial reaction of the aircraft, so to speak the agility of the initial pitch up motion.

From this Gibson has developed a drop back criterion [28], which is in its nature a pure design criterion. He basically values the magnitude of the pitch rate drop back in relation to the steady state value of pitch rate.

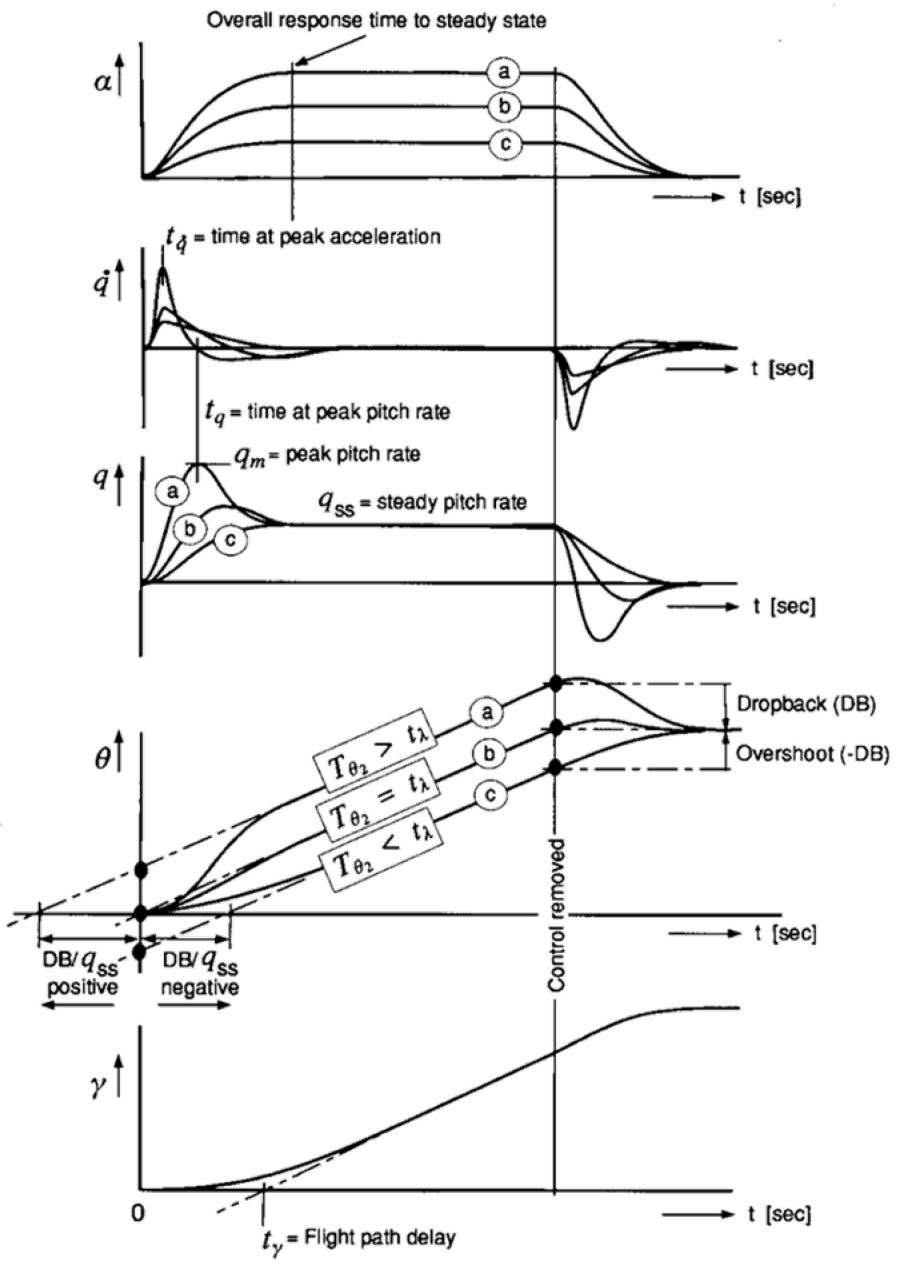


Figure 3-10: Generic Pitch Axis Time Response with Regard to a Step Input at t = 0 [28].

As the reaction on the initial pitch up motion is not reflected in the original thumbprint criterion (Figure 3-8), which reflects only frequency and damping, a criterion was developed which also takes initial pitch reaction into account [29]. This is called the Control Anticipation Parameter (CAP) criterion.

$$CAP \cong \frac{\omega_{SP}^2}{n_z / \alpha}$$

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

The numerator reflects overall agility (frequency of the short period) whereas the denominator reflects initial pitch acceleration, the increase of normal load factor as a function of AoA. As previously described with $T_{\theta 2}$ the denominator for the CAP is also proportional to the lift coefficient slope L_{α}. A typical graph for application of the CAP criterion is given in **Figure 3-11**. The diagram shows short period Eigen frequency as a function of pitch acceleration sensitivity. The given boundary lines represent lines of constant CAP (except for Level 1 below 3 rad/sec).

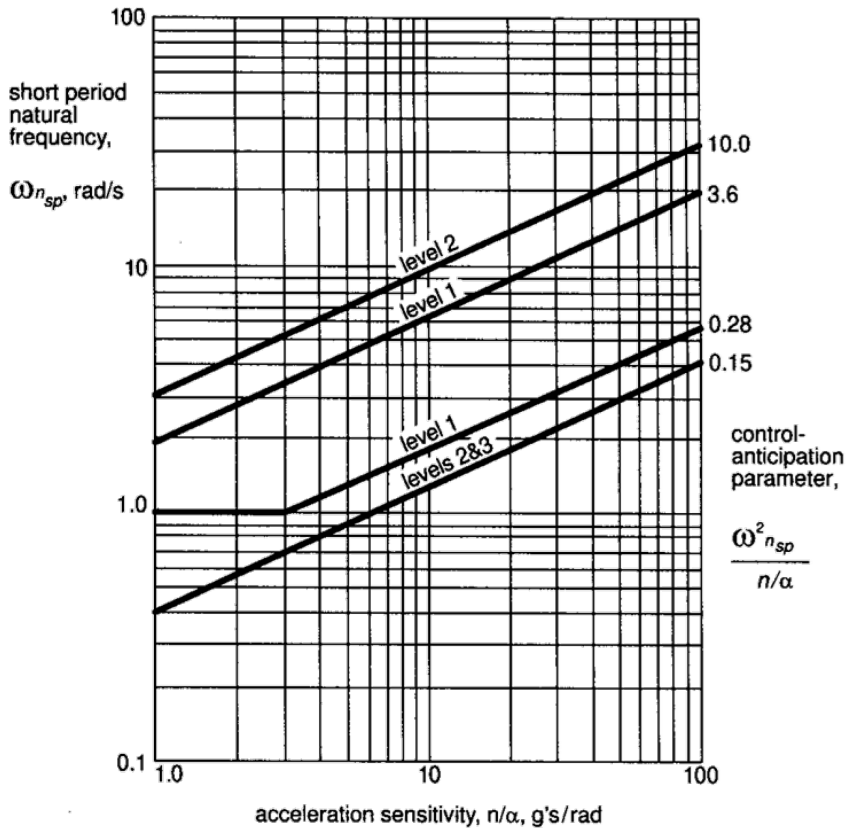


Figure 3-11: Typical Graph for Application of the CAP Criterion (CAT A Flight Phases).

Based on the previous description of initial acceleration behaviour, the CAP criterion transforms considerations taken in the time domain with time dependent aircraft behaviour (see Figure 3-10) into the frequency domain. The criterion graph displays short period frequency as a function of initial acceleration or acceleration sensitivity (Figure 3-11). In the given double logarithmic representation constant CAP values are given as straight lines. This is indicated through the notation on the right side of Figure 3-11. The CAP criterion is a design criterion, nevertheless, it can easily be assessed during flight-testing. The following example is taken from Ref. [9] and it shows flight test data. In the left half of **Figure 3-12** the same 3-2-1-1 manoeuvre is presented as in Figure 2-5. Flight test data of this type have been analysed during flight according to the Low Order Equivalent System (LOES) approach in which the overall non-linear behaviour pitch rate to pitch stick has been approximated with a simple linear model [9].

The LOES approach is chosen very often to analyse complex high order control configured aircraft. For the example given here the particular LOES analysis was used with a fourth order polynomial in numerator and denominator of the transfer function model. The parameters of the polynomials were calculated via the Z-Transform, see Ref. [9]. This technique can be easily applied for real-time evaluations and be used for in-flight analysis.

The result delivers complex conjugate poles, normally a high frequency pole pair and a low frequency pole pair (fourth order model). The high frequency pole pair is considered to be representative of all higher order aircraft system dynamics e.g., originating from the flight control system. The low frequency pole pair is representative of the Eigen value under consideration due to the given system excitation, here the short period, only. As the example stands for a highly augmented agile aircraft, specific control law dynamics do not allow for a Phugoid. There are also other analysis ways of applying the LOES approach, using other low order models than the one used here, see, e.g., Refs. [30] and [26].

The left half of Figure 3-12 indicates very good agreement between approximation and flight data for the pitch rate response. The curves lie almost exactly above each other indicating a very good match with respect to the frequency response. Slightly weaker agreement is achieved with respect to damping, which can be seen at the end of the manoeuvre. For application of the CAP criterion a good agreement frequency-wise is sufficient. The right half of Figure 3-12 shows resulting CAP values calculated on the basis of flight data. Simple LOES analysis as used here can already very easily be applied during a test flight in real-time. Nevertheless, there exists no criterion based on the analysis results shown here which could be used during the envelope expansion process as a sufficient in-flight "go" or "no-go" criterion.

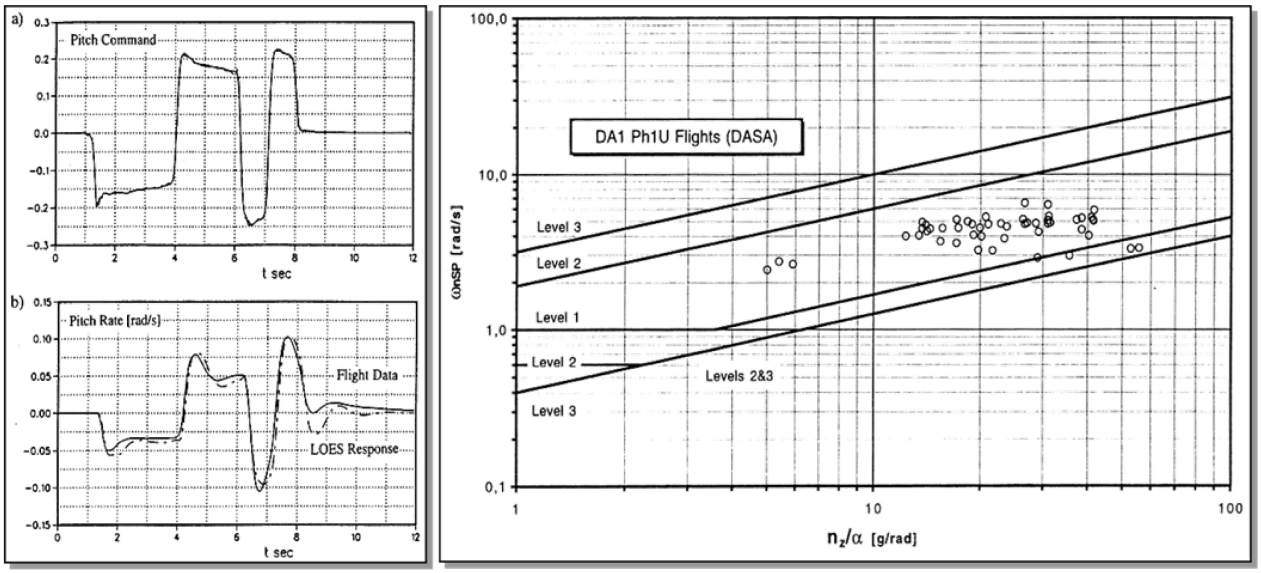


Figure 3-12: Flight Test Data for the CAP Criterion During Early Flying Period of Eurofighter [9].

Though the mathematics behind the CAP criterion are wholly linear, it is applicable for all sizes of pilot input. It gives reliable results in case of CAT I PIO. In case rate and/or position limiting play a role appropriate modelling via LOES analysis will reveal equivalent time delays. To that extent it has been used to predict CAT II PIO cases as well.

Other than discrete parameters (e.g., Eigen frequency) the following bandwidth criterion, as explained in **Figure 3-13**, uses the characteristics of the transfer function over the entire frequency range of pitch attitude as a function of stick pitch force. Thus, the whole frequency band characteristics of the pitch axis are under observation now[4]. Figure 3-13 shows the amplitude or gain (longitudinal attitude θ as a function of pitch stick force, F_e) as a function of frequency and in the lower half the corresponding phase angle. In the diagram only the short period response is shown, no Phugoid response. For an ideal fourth order

[4] Representations like the one given in Figure 3-13 are normally called "Bode Plot". They can be calculated from models via evaluation of the transfer function. They can also be generated from flight measurements by calculating the Fourier Transform of the measured data and generating the transfer function from these data.

system the dashed line in the lower half indicates that the phase lag will asymptotically approach the (-180 deg) line and will not cross it. These ideal systems cannot become unstable. The solid line shows for a regular n-th order system that the -180 deg line is crossed at some point where the system can become unstable when excited with that frequency.

The criterion is applied as follows: one takes the critical line at (-180 deg) phase lag. From this frequency ($\omega_{-180\ deg}$) in the gain diagram one goes back with 6 db gain margin and notes the frequency where this is. The same is done for the phase delay curve going back 45 deg phase margin. Again, the corresponding frequency is noted. The lower of the two noted frequencies is the bandwidth frequency. It is interpreted as that frequency up to which the pilot has sufficient control and stays away safely from the critical point.

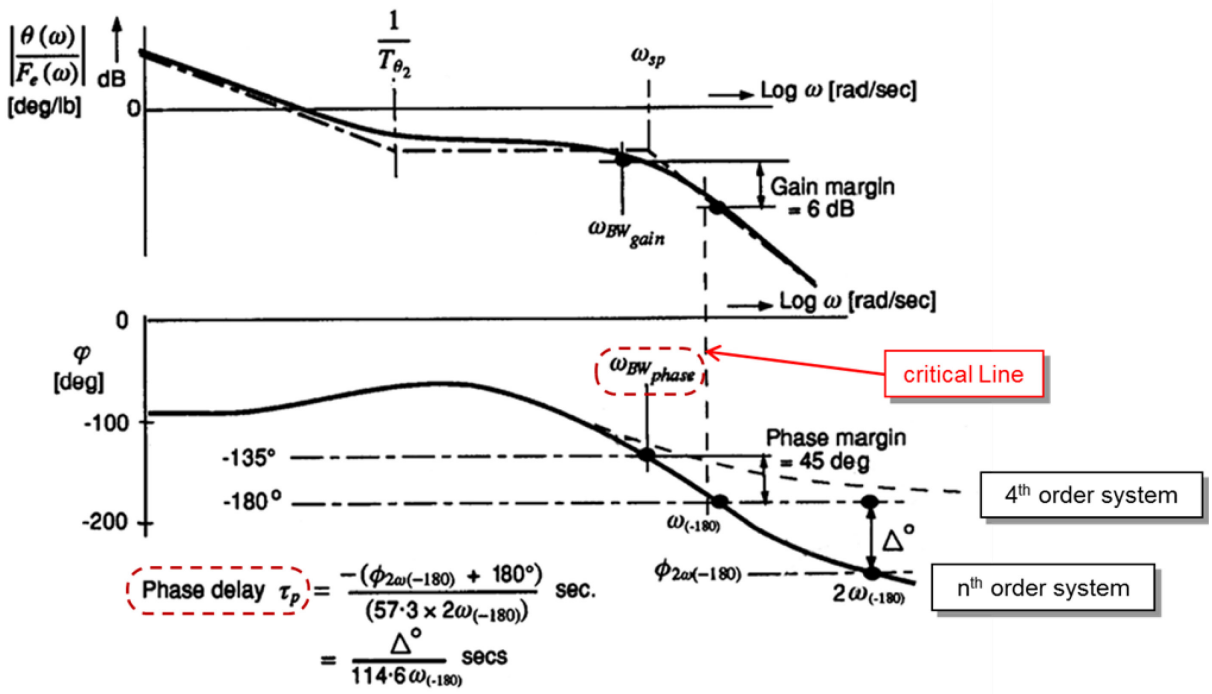


Figure 3-13: Schematic Diagram Explaining the Bandwidth Criterion [18].

The second parameter of the bandwidth criterion is the phase delay τ_P. The way it is calculated is given in Figure 3-13. Actually, this parameter is an approximation to equivalent time delay, and it describes the slope of the phase lag curve at (-180 deg). The steeper the curve goes through this point (τ_P large) the more critical it is since sudden phase lag changes can cause PIO proneness. The resulting criterion diagram (phase delay over bandwidth frequency) has already been given in Figure 3-9 when explaining how the boundaries for various HQ levels are being achieved. The bandwidth criterion is good for predicting linear Category I PIO proneness. With appropriate LOES analysis it can be extended to rate-limited data which will then exhibit larger phase delays.

Like the CAP criterion, the bandwidth criterion basically is a pure design criterion. It can be applied in flight test, but it will be time consuming, for one test point only. In order to get a good resolution, one must apply a frequency sweep from very low frequency (1/10 Hz) to sufficiently high frequency (2 Hz). Another factor is the length of the sweep because its length determines the fineness of the frequency resolution. Thus, ideally a sweep should be at least more than 20 sec long (i.e., 20 sec of measuring time result in a frequency resolution of $\Delta f = 1/20$ Hz in the frequency domain). This in turn is a challenge for flying. Keeping an aircraft straight and level for more than 20 sec and applying such a sweep is not difficult at all but doing the same for a required test

condition under g-load (e.g., 5 g) is not so easy. One way to circumvent these difficulties is using synthetically generated sweeps rather than pilot generated sweeps. Still the long test time per test point remains as well as the long stabilisation requirement in a turn. Further on also the bandwidth criterion does not support a stringent "go" or "no-go" criterion during envelope expansion flying.

3.4 QUANTITATIVE EVALUATION WITH NON-LINEAR CRITERIA

In the context of this chapter the system description "non-linear" comprises the entire pilot-vehicle-system. Basic airframe characteristics are still described with linear models, also all components like sensors, actuators, notch filters, etc. so the entire vehicle system set-up is considered nominally linear. Overall system dynamics (PVS), though, can lead to a non-linear system behaviour when certain elements suddenly change their behaviour. This can be the pilot changing his control strategy adaptation, e.g., due to an external trigger. Also, specific high performance control requirements possibly drive the actuation system into saturation, which in turn causes rate limitations in the actuation system.

Design criteria to cover such changing, non-linear dynamics are rare. One criterion was introduced by Duda in the late 1990s [31], [32]. The criterion integrates into the linear transfer function model describing aircraft dynamics, also a linear describing function for the rate limiter. The onset of rate limiting representing the non-linear behaviour.

With an iterative method, Duda verifies [32] that the overall aircraft dynamic system experiences a dramatic loss in phase once the rate limitation becomes active. A typical result from Ref. [32] is given in **Figure 3-14** in a Nichols diagram. The solid line represents the regular system behaviour without rate limiting. The dashed line neatly describes the jump in phase bringing the system into an unstable condition. Further details are found in Ref. [32].

The criterion is called the Open Loop Onset Point (OLOP) criterion. It is a pure design process criterion. Its application requires iterative model calculations. It is not suitable for a flight test application. It is mentioned here since it is the only known PIO criterion to cover these non-linear effects.

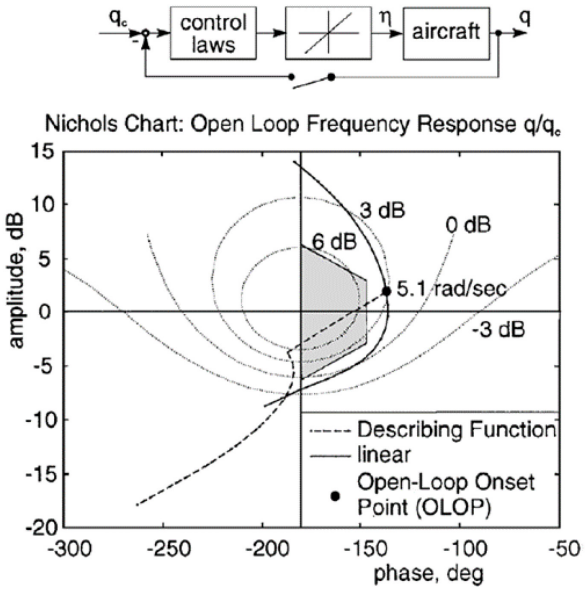


Figure 3-14: Jump Phenomenon Due to Rate Limiting in the Transfer Function of the Closed System [32].

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

3.5 CRITERIA REFLECTING PILOT MODELLING

The "sub-system" within the overall pilot-vehicle-system which can and normally reacts in a highly non-linear and unpredictable way is the pilot. This is especially true when the pilot changes his particular piloting technique due to, e.g., an external trigger like excessive stress. Pilot behaviour has been an item of research interest since the invention of manned flight.

McRuer and Krendel give a very comprehensive overview about pilot dynamics when acting within a pilot-vehicle-system [33]. They summarise the overall system as given in **Figure 3-15**. The complexity of all possible influences can easily be depicted. A much more detailed description must be taken from Ref. [33].

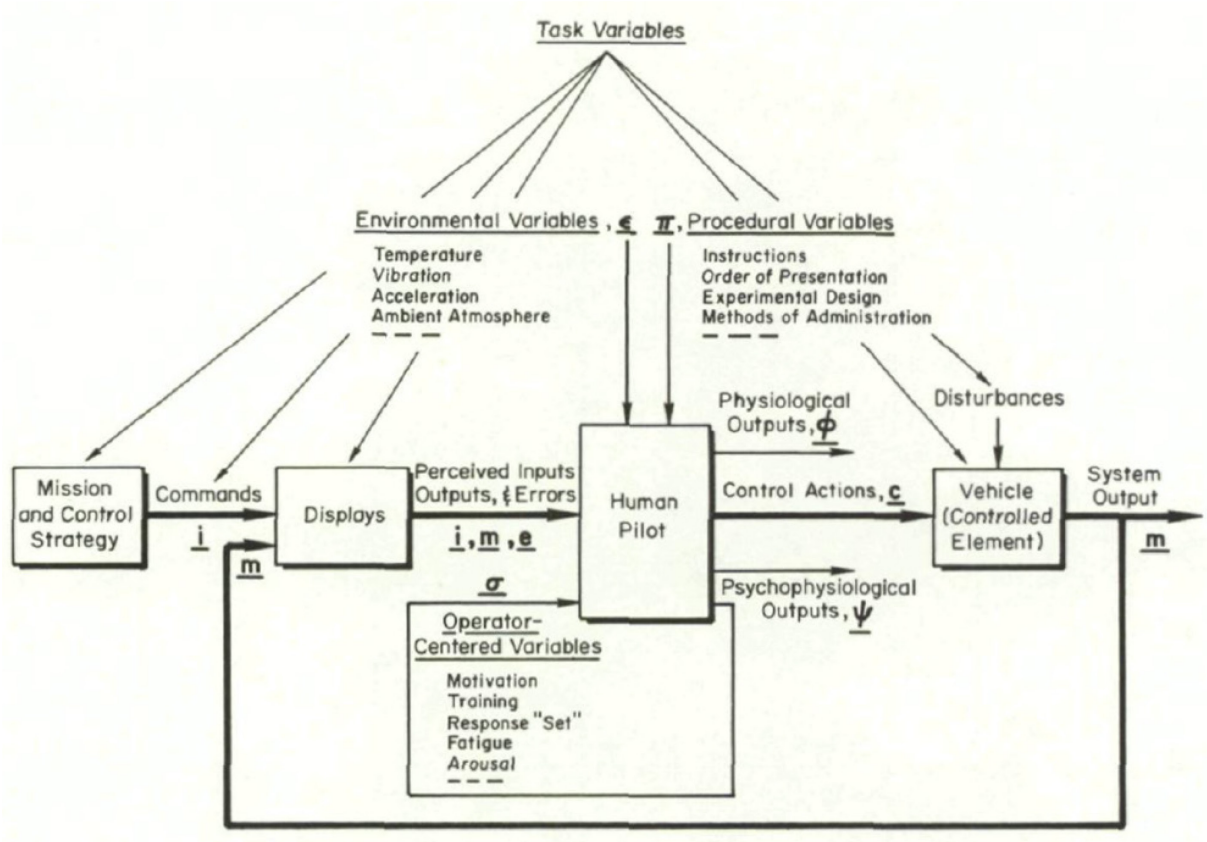


Figure 3-15: Variables Affecting the Pilot-Vehicle-System.

In a very intriguing set of examples, McRuer and Krendel show how just the "human-pilot-subsystem" as given above (Figure 3-15) can be interpreted. As shown in Ref. [33] the pilot adopts his dynamic behaviour according to the characteristics of the controlled vehicle. When comparing different pilot behaviour due to different system behaviour it became evident to them that the open loop dynamics of the overall PVS stay more or less the same. This is because of the variations of pilot dynamics as a function of the different aircraft model dynamics. Consequently, they came up with the following system model describing these combined system dynamics:

$$Y_P(j\omega)Y_C(j\omega) = \frac{\omega_C e^{(-j\omega\tau_e)}}{j\omega}$$

This is commonly known as McRuer's Crossover Pilot Model. It is the open loop transfer function of combined pilot and aircraft dynamics. Y_P and Y_C represent the respective describing functions for the pilot and the transfer function for airframe dynamics, which is the controlled system. ω_C is called the crossover frequency. For frequencies below ω_C good control is possible, and the gain is positive. The exponential function represents the effective time delay of pilot operation. A schematic of this model is given in **Figure 3-16**. The top half shows the gain, the graph crosses the 0 db line at the crossover frequency ω_C. The lower half shows the phase angle (dashed line). The second curve (the lower one, solid line) shows the phase lag for a pilot model with realistic pilot behaviour ($Y_{P,\ realistic}$). For lower frequencies, the coincidence between both curves is not so good but in the region of the crossover frequency it is rather good. Thus, the crossover model seems to be valid for the region of the crossover frequency. The coincidence in the upper gain diagram between the crossover model and the model with the realistic pilot function is so good that both curves cannot be distinguished. Phase margin must be positive, as indicated, thus, the crossover frequency must always be lower than that frequency when (-180 deg) phase lag is reached.

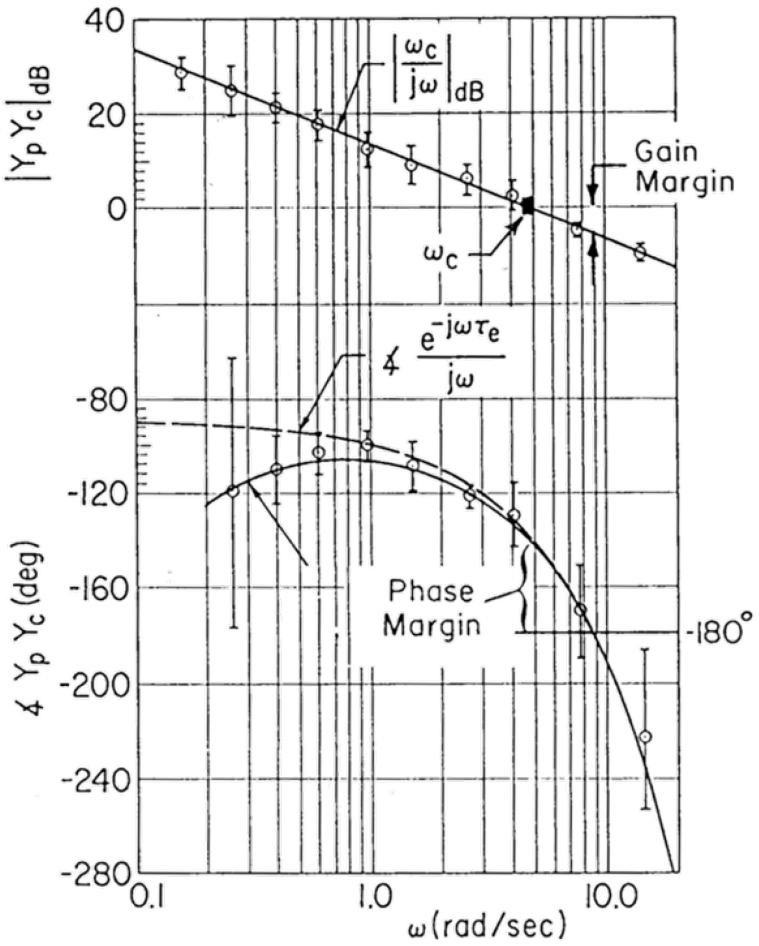


Figure 3-16: Schematic Representation of McRuer's Crossover Model [33].

The crossover model is very intriguing in describing pilot-aircraft dynamics. Basically, it shows that changing aircraft dynamics (Y_C) will change the reaction dynamics of the pilot (Y_P) as well, as $Y_C Y_P$ will follow the function given above. Consequences for HQ evaluations are such that, for example, control law changes during an aircraft development programme (changing Y_C) always require new and additional HQ flight-testing, as pilots (Y_P) will react differently.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

Neal and Smith [34] have made a proposal regarding quantitative evaluations of HQ in the presence of pilots. They introduce a rather simple pilot compensation model into their criterion, see **Figure 3-17**. The model consists out of a gain (K_P), a nominal time delay of 0.3 sec, and a lead-lag element with time constants T_{P1} (lead) and T_{P2} (lag). Longitudinal attitude θ is the overall system state variable for this example. For optimisation of a given task the pilot varies his gain and adaptation capability to lead or lag his command (F_S). For given (aircraft + FCS) dynamics these parameters are varied to optimise the parameters given in **Figure 3-18**, minimising droop and gain amplification at (-90 deg) phase. Gain amplification at bandwidth frequency is also called closed loop resonance. For calculation of these parameters an iterative method is required.

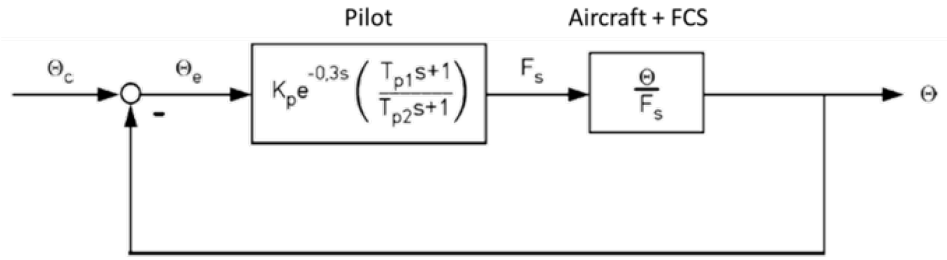


Figure 3-17: Neal-Smith-Criterion, Pilot Model as Part of Closed Loop System [34].

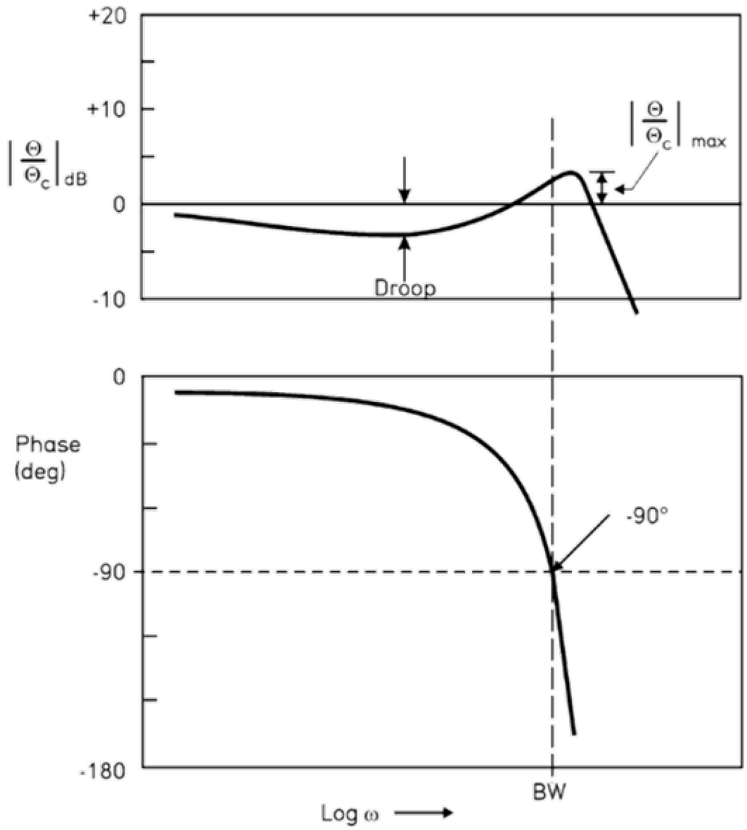


Figure 3-18: Neal-Smith-Criterion, Overall System Transfer Function with Optimisation Parameters [34].

Physical interpretation may be as follows: bandwidth is defined here as that frequency where a phase angle of -90 deg is reached. Pilots normally exhibit inherent integrating control characteristics. They feel least labour when having to integrate a control variable. In other words, when a pilot needs to follow a certain attitude task, he will mainly react to pitch rate cues. Integration of these pitch rate cues during the control task will give the attitude response. Integration of pitch rate gives pitch attitude which is (90 deg) behind pitch rate.

Bandwidth is a measure of how quickly the pilot can move the airplane's nose toward a target. Keeping the attitude gain (θ/θ_C) at bandwidth frequency as low as possible describes good attitude following properties of the overall system. Keeping the droop (as indicated in Figure 3-18) as small as possible is a measure of how fast the attitude change (pointing at a target) will come to rest or oscillations around the target will diminish.

The previously mentioned optimisation algorithm adopts the pilot model by variation of these three variables (droop, minimum gain at bandwidth frequency and bandwidth frequency at -90 deg phase lag) in the desired way. Outcomes are pilot parameters T_{P1} and T_{P2} and the achievable minimum gain at the bandwidth frequency. Neal and Smith proposed comparing these in the following evaluation diagram (**Figure 3-19**) with closed loop resonance as a function of required pilot compensation. The magnitudes of T_{P1} and T_{P2} are transposed into a lead-lag information, indicating when the pilot needs to apply lead compensation or lag compensation. This represents the phase angle of the pilot model as given in Figure 3-17. The boundaries for Level 1 through Level 3 according to the CHR transitions from 3 to 4 or from 6 to 7 are indicated in the diagram as well. They were derived in the manner previously described for Figure 3-9. The various test points are omitted here. Instead, pilot comments have been included in the diagram. They give an indication of how overall system characteristics are valued with variation of the Neal-Smith parameters from the optimisation process.

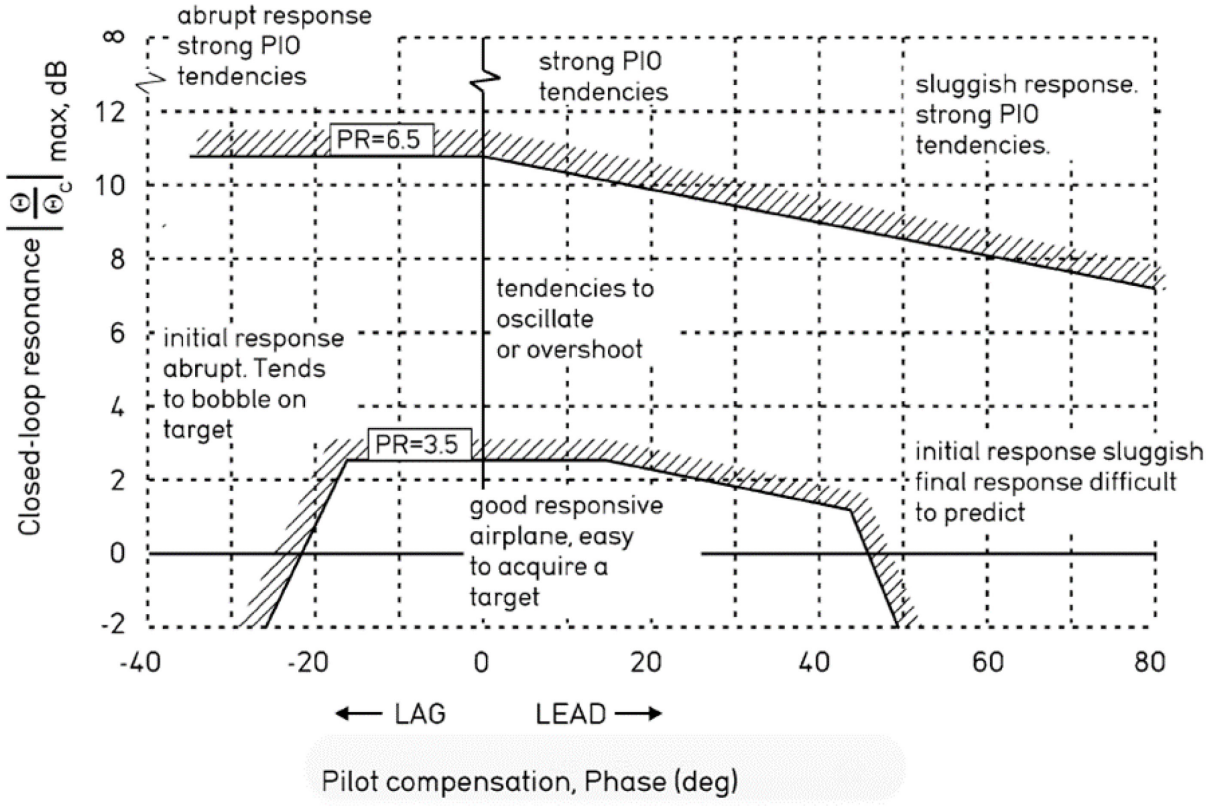


Figure 3-19: Neal-Smith-Criterion, Evaluation Diagram [34].

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

For linear PIO cases (CAT I) the Neal-Smith criterion gives reliable results. From a flight test point of view modern analysis tools are quick enough to deliver results in real-time while the aircraft is still up and flying. But, as mentioned elsewhere, the Neal-Smith criterion also does not give a clearly identifiable "go" or "no-go" criterion for envelope expansion flying.

3.6 DISCUSSION ON RATING SCALES AND CRITERIA

The previous sections of this chapter provide some specific examples of how handling qualities can be valued quantitatively (put into numbers). A quantitative evaluation depends on various stages. At the very beginning pilot comment and evaluation are of prime importance. This applies not only for Phase 1 testing when namely flying qualities are of interest.

Bringing a specific pilot task into the game now asks for task performance. This is what we build aircraft for, to fulfil a task requested by our customer. Task performance can be evaluated according to "satisfactory", "adequate", or "unacceptable". This involves the evaluation according to, e.g., the Cooper-Harper-Rating scale. This scale is based on stringent rules in order to gain comparable results for one task with different pilots. Such results will be fed back into the design process in order to improve the product where necessary. They also serve as proof of requirement fulfilment for the dialogue with the customer. Pilot evaluation of task performance within the scope of stringent rules also makes the Cooper-Harper-Rating scale a quantitative evaluation tool. The same is valid for PIO rating scales.

With the availability of CHR results, evaluations of flying qualities characteristics, e.g., short period frequency, can be put in relation to pilot comments quantitatively. Now these open loop characteristics (e.g., short period frequency) can be related to pilot evaluations based on closed loop HQ tasks, and such a HQ criterion (CAP or bandwidth, or others) can be applied in the design process to predict HQ for variations of various design parameters in different design stages. This normally assures a "flyable product" when entering flight test.

As this report is aimed at flight test techniques, the examples given above mainly serve to describe the overall FQ and HQ world. Quantitative criteria do not normally play a large role in testing. They serve to provide a better understanding. Flight test techniques will focus on safe flight operations, reliable pilot commenting, and reliable CHR or PIOR in order to arrive at a good and sound overall view on an aircraft.

A final remark within this section. Evaluation of FQ and HQ is an integrated process between design offices and flight test centres. Regardless of the evaluation result that proceeds from analyses made by the design office, the result that finally counts is the evaluation by the pilot in-flight. He or she has the famous "last word": satisfactory or unsatisfactory, flyable, or un-flyable.

3.7 FLIGHT CLEARANCE BASED ON HQ CRITERIA

Before entering a flight test sortie, a flight clearance must be available. It describes the allowed flying, and it brings up all limits (of all systems) that must be obeyed during the testing. Such a flight clearance is based on prior model knowledge and analysis. This has been the case ever since in manned aviation. Otto Lilienthal had his "prior investigations" before he was ready to go flying with his gliders. The Wright Brothers knew about Otto Lilienthal's experiences; they had their own wind tunnel and performed their own theoretical calculations prior to flying.

This process has not changed through today. Sometimes a vast number of simulations is performed prior to flying, in order to understand the (new) aircraft better. To describe the basic flying properties of an aircraft some models must be available, namely the aerodynamics model, the flight mechanics model, which is heavily dependent on the aerodynamics model, the flight control model, and finally the structural model.

These are the main basic models. For actual investigations, many more models are necessary than can be mentioned here. Neither will the issue of the "hardware in the loop" simulation be stressed here.

Early flight-testing is aimed at validation (and very often verification) of the aerodynamics model. The aerodynamics model drives the flight mechanics clearance; an improved flight mechanics model supports better understanding of the aircraft dynamics as viewed together with the flight controller. The following diagram describes the process for arriving at a flight mechanics clearance for flying.

A more general overview of the flight clearance process is given in **Figure 3-20**. Tools and methods required to successfully achieve a clearance for flight are discussed in this report. Essentially, the process requires accurate knowledge of key sub-system models of the aircraft such as actuator, aerodynamics, propulsion, structural dynamics, etc. These models feed into simulation tools that are used to predict the handling qualities of the pilot-vehicle system. Closed loop piloted simulation and open loop criteria, time and frequency based, are primary means to achieve the predicted evaluation.

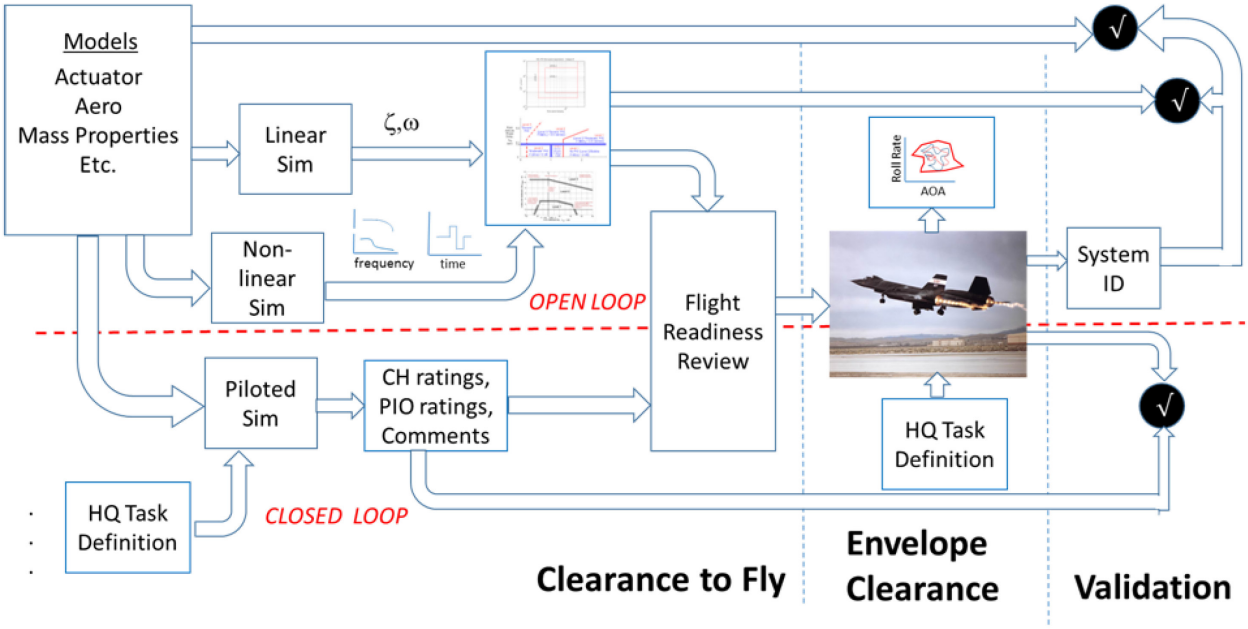


Figure 3-20: Schematic Overview of the General Flight Clearance Process (Courtesy NASA).

The envelope expansion process entails validation of the models and tools used in the predicted evaluation. This includes manoeuvres required for the application to the criteria and for validating the models for which the simulations are based. Additionally, closed loop piloted evaluations are conducted to validate simulation prediction as well as to ensure the criteria were adequate for the tasks involved.

Figure 3-21 gives a more specific schematic overview of the flight mechanics clearance process. It is a slightly modified version of a figure in Ref. [10]. The process is driven by requirements, namely HQ requirements. Adequate models (aerodynamics, flight mechanics, flight control) are analysed with regard to flight safety as well as requirement fulfilment in an extensive process. For an initial flight clearance, a variety of analyses of the available models needs to be performed. The most demanding model in this context is the aerodynamic model, as described via the aerodynamic data set. It brings with it a wide range of complexity: for example, already minor changes like a revised wind tunnel assessment may lead to changes in the control law design. Once the required model base is clear, linear analysis mainly checks the stability criterion (open loop Nichols' criterion for the controlled aircraft). Linear HQ criteria are applied

as well (e.g., CAP or Bandwidth). Further non-linear and off-line simulation analysis goes into assessing the time domain behaviour. The final step in this course of investigations is the manned simulation evaluation. All this assessment work contributes to the flight mechanics clearance, which in turn contributes together with the assessment work for all other systems to the final (initial) flight clearance. At this stage of the development process the flight clearance document comprises the most comprehensive understanding of the aircraft.

The next step before going to flying is flight preparation. Pilots assess the planned test schedules in various manned simulation sessions. Then, when all preparations are successfully made, the test flight commences. The next major step is analysis of test results, often already done during the flight, but mostly made after the flight. Understanding of these results comprises the most comprehensive understanding of the real aircraft at this stage. Analysis will show how well model analysis matches flight data, see Refs. [3], [4], [5].

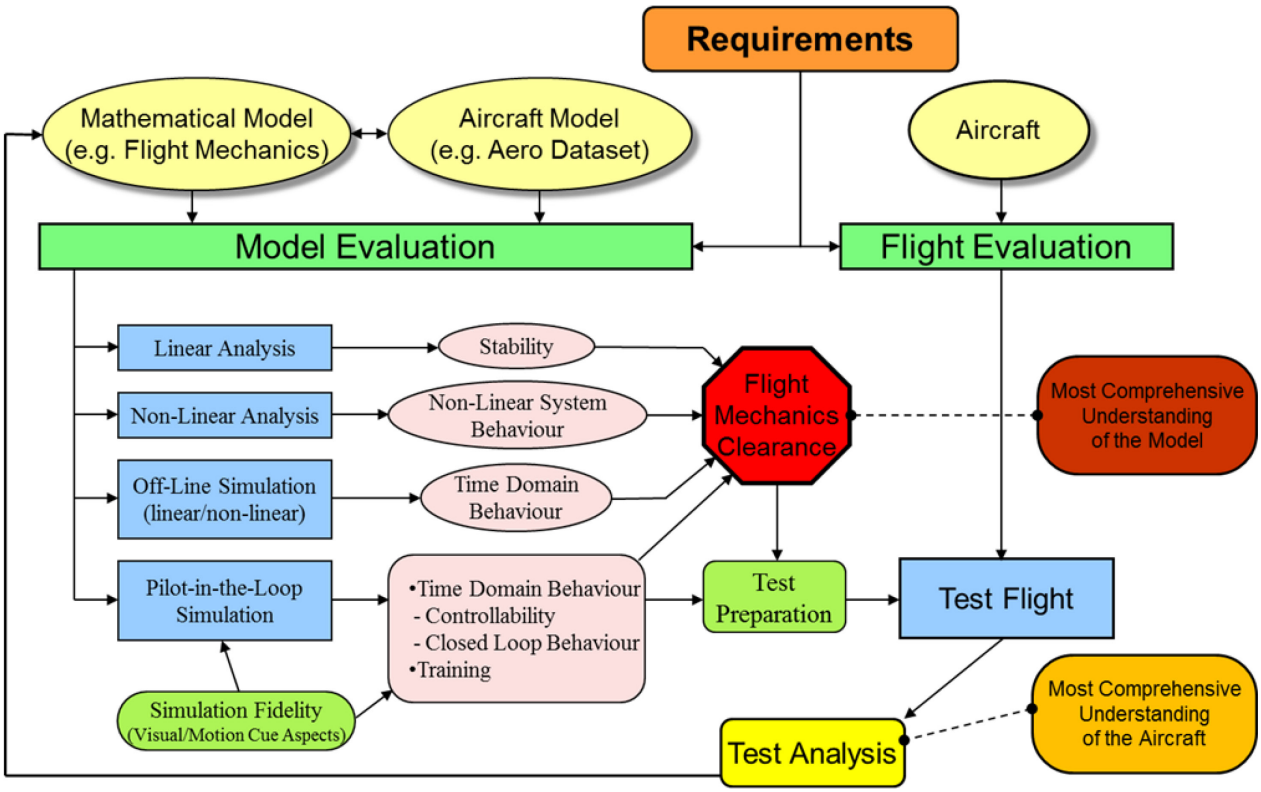


Figure 3-21: Schematic Overview of the Flight Mechanics Clearance Process [10].

Flight data analysis will show where the specification is met and where there are shortfalls. Most important in early flying phases is the check on model accuracy. For this analysis, model data are checked to see whether the flight test results lie within a certain tolerance band. This makes the overall process more robust against shortfalls. The flight mechanics clearance has been achieved with a data set with tolerances. When discrepancies between flight data and model data stay within the given tolerance band, no action will be required, as the flight clearance covers the whole tolerance band. If not, additional clearance work will be required before flying can commence again. Thus, flight test results are fed back into the development process upstream, and the next development cycle can start.

With respect to the flight mechanics clearance driven by criteria, the most sensitive feedback are changes to the aerodynamic dataset (see above). Other important feedback are pilot evaluations with regard to FQ and HQ. Resulting analysis will show whether the model needs to be updated. In any case, every update of any

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

model requires going through the flight clearance process in its entirety! This is why FQ and HQ testing is set up in a stepped process, see Figure 2-3, with increasing complexity. One of the aims of this method is to find snags as early as possible at a time when their rectification needs less effort than in later development stages.

When going onto more complex FQ and HQ testing, the flight clearance must be more specific and tailored for the planned testing. Phase 2 testing (Figure 2-3) requires, for PIO resistance testing, a well cleared envelope up to the physical limits (AoA_{max} and $n_{z,\,max}$). The same applies for all Phase 3 testing.

At this stage of the discussion the specific type of aircraft under test must be considered. When testing a more conventional aircraft with "fly-by-cable" flight controls, meaning a reversible flight control system, pilots will always have to monitor the given limits. This can increase workload considerably. It requires a certain character of flight clearance process.

Nowadays aircraft normally have a "fly-by-wire" flight control system. It has a sophisticated controller with many supportive functions to keep pilot workload for flying as low as possible. In these cases, such a flight control system provides the pilot with so called "carefree handling" functionality. It means when doing any sensible stick input, he will not have to observe any physical limits. These are observed by the flight control system and it ensures no limit exceedance. A system like this requires a much more complicated flight clearance process. The "carefree handling" system part must be wholly tested before commencing HQ testing.

Understanding the flight clearance process and, most importantly, understanding the aircraft's capabilities based on the available clearance is vital for flying qualities and handling qualities testing. Especially Phase 2 and Phase 3 testing require a more or less unlimited flight clearance. PIO resistance testing may lead the pilot into a situation where the aircraft goes towards its limits. Phase 3 closed loop testing requires the highest level of pilot attention to a given task. Here test point or manoeuvre dynamics can drive the aircraft into a very demanding situation. Restrictive flight envelope limitations will hamper a successful handling qualities test – one always has to expect the unexpected especially in highly demanding HQ testing.

3.8 OVERALL REMARK

This chapter has provided an introduction on how to evaluate HQ. For flight-testing the main tool is the Cooper-Harper-Rating scale, or in cases where applicable a designated PIO rating scale. The concept of the CHR scale requires the definition of a task. Performance of the pilot-vehicle-system when fulfilling such a task will be evaluated by a pilot when using the CHR scale.

Some evaluation criteria have been introduced, showing how open loop parameters like frequency can be used to guide the design engineer in connection with CHR evaluations. As said, these are supportive for the design process. Within a flight test environment, especially during envelope expansion, flying such criteria cannot be helpful as they do not provide a "go" or "no-go" criterion.

A flight clearance is mandatory before starting a test flight for HQ testing. The flight clearance depends on model evaluations as well as pilot evaluations in simulator testing (CHR).

A remark concerning caution when using simulator results: today's flight simulators are so compelling, with cockpit layouts identical to the actual airplane, and highly realistic displays, that we readily equate simulation already to actual flight experience. However, ground simulators can lack cues – obvious ones like motion as well as more subtle ones that we scarcely understand – that can strongly affect the pilot. For example, command gains optimised on the ground simulator are likely to be twice as high as preferred for flight. And the same high frequency phase lags (i.e., equivalent delays or similar measures) that are inconsequential in the simulator can surprise us with PIOs in-flight.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

With this cautious remark in mind: a flight clearance is not “a ticket” to do anything whatever in a test flight as long as it is not forbidden by the clearance document. The flight clearance gives a frame. Acting within this frame always must be cautious, especially when going beyond “known areas”.

The outcome of flight-testing feeds back into the clearance process and possibly has an effect on further testing. Only sound flight test analysis will prove the clearance to be valid. Overall HQ testing is highly dependent on the entire process leading to a flight clearance.

The following chapter will go into testing methods. This, at a first glance, is a catalogue of test manoeuvres. When setting up a test programme or a test matrix each test point of interest must be reflected against limits given by the available flight clearance.

Chapter 4 – FLIGHT TEST METHODS

In Chapter 2 it has been shown that flight testing for Flying Qualities (FQ) and Handling Qualities (HQ) must be structured and must be performed in a stepped approach with increasing complexity. In this chapter, various flight test techniques will be given accordingly, and their applicability will be discussed and explained.

The Manoeuvre Pyramid (Figure 2-3) separates testing in various phases. Test manoeuvres and test techniques in this chapter will be aligned accordingly.

The following sections of this chapter provide a sort of a catalogue of test manoeuvres or test techniques. This selection was made by the authors based on their individual own experiences. It is to be considered as a guideline. When using this catalogue for setting up an individual flight test programme it must not be used as a pure "copy and paste" source. The applicability of and the need for each task given here to the desired test programme must always be checked.

Phase 1 testing comprises open loop testing. This is the basic and initial testing when starting to fly a new aircraft or when starting to explore a modified aircraft behaviour due to a configuration change, be it external stores and/or a change of flight control laws. For the second issue it is also often called "Control Law Familiarisation" flying.

Phase 2 testing is an indispensable testing phase before actual HQ testing can commence. In this phase of testing, the overall pilot-aircraft dynamics are under consideration. The aim is to prove robustness against unwanted interactions or couplings between pilot and aircraft dynamics (PIO). In case of unexpected system dynamics, the aircraft can be brought to its physical limits (max. AoA, max. load factor). Therefore, an intermediate test step must be introduced prior to commencement of Phase 2 testing.

This **intermediate test step** (prior to Phase 2) is to explore aircraft behaviour at the physical limits of the flight envelope (namely max. AoA and max. normal load factor). This is normally done in a very special dedicated test programme with special precautionary measures like an anti-spin gantry. The outcome of this test programme is used to guide pilots at the limits when flying the aircraft manually. It is also used to test an automatic control and protection system with "Carefree Handling" features properly. Further testing for high manoeuvrability inside the envelope away from the outer limits is required to prove, e.g., reliability of such a "Carefree Handling". This is pure open loop testing, and it will be introduced here as it is a requirement prior to Phase 2 testing.

Phase 3 testing then is the final step in the testing pyramid. Here full pilot-in-the-loop dynamics are involved. A test catalogue with appropriate manoeuvres will be given. Finally at the very top of the test pyramid free style manoeuvring will challenge the highest complexity of the pilot-vehicle-system.

Synthetic Manoeuvre Excitation is a technique which can be part of modern control augmented aircraft. The control system of the test aircraft is amended with a specific test box which generates equivalent to a pilot synthetic commands for all three axes. It can either be "a piece of hardware" e.g., a separate signal generator or "a piece of software" as an integral part of the digital controller. Such a "box" can also generate single input signals for deflection of one specific control surface only. The benefit of such a synthetic command path signal is that the pilot controls the aircraft to remain at the desired test condition with stick and throttle as required whereas the signal generator overlays the test input over the pilot command. An example is a special roll yaw excitation at a flight condition at elevated g-load. The pilot's task is to maintain the test condition. The signal generator makes the special test signal at the pilot's command. The benefit of the synthetic control surface deflection is that sometimes, for aerodynamic model validation, there is the need to excite one specific control surface independently from others, which is done with the signal generator. Synthetic manoeuvre excitation if available is used during Phase 1 testing. Typically, it will utilise the manoeuvre types given here.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

As already stressed and will continue to be for the remainder of this chapter, HQ test tasks must be executed by “many more” than one pilot. The requirement is put in parentheses as it is sometimes very difficult to have the sufficient number of tests at all. This can be due to availability of different pilots or programme management requirements (“Why do you need so many tests in such a tight schedule?”). As pointed out in above chapters, PVS testing depends on pilot and aircraft dynamics. As different pilots execute different piloting techniques, or have different training or practice levels, or have different task perception, the dynamics of the PVS vary between pilots for one and the same task. In a practical or pragmatic sense “many more” means a minimum of three pilots is required for executing one test point in a HQ test programme. At least one of these (if available) must be a so-called high gain Pilot.

4.1 PHASE 1 TESTING (CONTROL LAW FAMILIARISATION)

4.1.1 Background of Control Law Familiarisation

Pilots need to be familiarised with the characteristics of a new aircraft or a known aircraft with configuration changes. This can be, for example, a set of new external stores. Such testing is applicable for conventional aircraft with a reversible flight control system and aircraft with a digital flight control system. The latter most likely will have a re-designed or adopted control law (e.g., according to a new store configuration). Thus, for testing a specific test schedule for familiarisation is required. To achieve this target a set of manoeuvres is given below. Each one tries to assist the pilot in understanding the open loop dynamics of the specific aircraft in a given new configuration. For a given specific configuration only a sub-set of these tests may be necessary.

Basically, these manoeuvres must be considered as open loop manoeuvres. In some cases, for precautionary measures a target is given, e.g., a maximum AoA in a Wind Up Turn or a maximum bank angle in a roll manoeuvre. For these limits pilot evaluation is only asked for whether it is achievable. Fidelity of the performance is not asked for; it is not a specific HQ task.

4.1.2 Control Law Familiarisation Manoeuvre Descriptions

Caution: Manoeuvres are given in alphabetical order. Recommendations about a possible test sequence will be given at the end of this section.

Altitude Capture

Task:

Stabilise straight-and-level flight at the initial altitude. Capture the target altitude as fast as possible and minimise the number of under- and overshoots.

Technique:

- When coming from higher altitude as target altitude capturing will generally be performed with a positive load factor manoeuvre.
- When coming from lower altitude capturing can be performed either:
  - With a negative load factor manoeuvre; or
  - Rolling inverted and capturing the target altitude with a positive load factor manoeuvre.

Depending on the overall testing purpose a clear definition must be given. In Phase 1 there will be no requirements for accuracy of altitude capturing.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

Reasoning:

Characteristic control ability when changing flight path.

Bank-to-Bank Roll

Task:

Gently roll from a banked turn to the opposite bank angle.

Technique:

The aircraft should be stabilised in a banked level turn at a specified normal load factor and then rolled with a view to capturing the opposite bank angle within a period of about 2 seconds. The opposite bank angle should be maintained for about 2 seconds, before the initial bank angle is recaptured and again maintained for about 2 seconds.

Caution:

During the control law familiarisation phase this manoeuvre must be performed in a gentle way only, with gentle stick inputs. Performing this manoeuvre with rapid roll stick inputs (half stick or even full roll stick) puts this manoeuvre into the agile manoeuvring class (Phase 3), roll inertia coupling must be expected.

Reasoning:

Characteristic control ability when manoeuvring under normal load factor.

Frequency Sweep

Task:

Perform a frequency sweep input (pitch axis, roll axis, or yaw axis) with increasing frequency as specified.

Technique:

- Stabilise at the specified flight condition for five seconds and trim control forces to zero, if possible.
- Input cyclic inceptor (stick or pedal) force commands using small amplitude square inputs (<¼ of max. command range).
    - Begin with input half-period of at least 2 seconds, at least sufficiently below the natural frequency of interest.
    - Dwell at low input frequency for at least three cycles.
    - Maintain constant input amplitude throughout manoeuvre.
        - Gradually increase input frequency maintaining square inputs as long as possible. Aim to capture at least 1 minute of data, see **Figure 4-1**.
        - Try to maintain initial zero bank angle as best as possible (not for roll sweeps).
        - Try to maintain altitude with small pitch stick inputs (average altitude only for pitch sweeps).
        - Use power as required.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

- When maximum input frequency is reached, check with telemetry control:
  - "Manoeuvre complete" indicating inceptor force can be returned to zero; or
  - "Continue" indicating that the pilot should build back down in frequency.
- Note: A flight test aid such as a cyclic tone played through a headset is permitted.

Reasoning:

Frequency sweeps are a useful test technique in order to measure in-flight transfer functions for model comparisons.

Experience:

From practical flight experience it may be easier to fly when the evaluation pilot starts with high frequencies and ends up with low frequencies. With a high frequency input in the beginning (pitch axis) the aircraft does not deviate much from the trim condition whereas with a low frequency input in the beginning due to the longer duration of the input signal into one direction a significant deviation from the trim condition is likely.

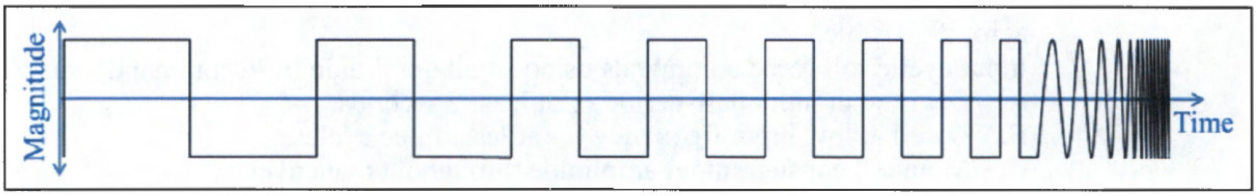


Figure 4-1: Frequency Sweep Schematics.

Gentle Course Changing Manoeuvres (GCCM)

Task:

Perform "Gentle Course Changing Manoeuvres" at test conditions according to the test matrix.

Technique:

Given load factor and/or bank angle limits must be observed. Normally bank angles up to 60 deg and longitudinal load factors in the range of 0 g up to 2 g are observed.

Reasoning:

Overall general manoeuvring characteristics.

Heading Capture

Task:

Perform a turn up to maximum cleared normal load factor to achieve a 90° heading change.

Technique:

Stabilise straight-and-level flight at the reference altitude. Thrust may be adjusted as required to assist in the performance of the manoeuvre. The manoeuvre is to be performed to the left and to the right. Attempt to minimise altitude and speed variations during the manoeuvre.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

Reasoning:

Overall general manoeuvring characteristics when performing a requested course change.

Inverted Flight

Task:

Fly the aircraft in steady-level inverted flight.

Technique:

From stabilised 1 g straight-and-level flight roll the aircraft through 180 deg angle of bank. Maintain inverted straight-and-level flight for approximately 10 seconds. Recover to 1 g straight-and-level flight.

Caution:

Maximum allowable duration of inverted flight depends on aircraft limitations.

Other limitations like minimum allowable AoA or minimum allowable load factor must be observed as well.

Reasoning:

Negative AoA characteristics.

Level Acceleration

Task:

Perform a level acceleration.

Technique:

Stabilise straight-and-level flight at a defined initial condition. Accelerate to the defined target speed/Mach number. Use throttle as required (gentle increase of throttle or slam, maximum dry power or reheat power). Maintain altitude.

Caution:

In case the target speed/Mach number is close to the given limit the acceleration must be stopped prior to reaching the limit in order to not violate the limit.

Reasoning:

Acceleration capability and trim characteristics during acceleration.

Level Deceleration

Task:

Perform a level deceleration.

Technique:

From a defined initial condition decelerate straight and level to the defined target, speed or AoA. Throttles are normally chopped to idle.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

- If the target speed or AoA is sufficiently away from max. AoA maintain altitude.
- If the target is close to (cleared) max. AoA altitude does not need to be maintained.

The initial condition requested for may also be in a turn with a specified normal load factor. For this the following measures should be taken:

- Reduce throttle(s) equivalent to a deceleration rate of approximately 5 kts/sec.
- Maintain altitude while using lateral stick and pedal to maintain bank angle.
- Recover before the specified maximum AoA is reached.

Reasoning:

Deceleration capability and trim characteristics during deceleration.

Loaded Roll

Task:

Perform a barrel roll with target normal load factor loading.

Technique:

Stabilise the aircraft at 1 g straight-and-level flight at the defined flight conditions. Enter roll while pulling to target AoA / load factor.

Reasoning:

Aircraft roll control under load.

Pitch Doublet

Task:

Perform a sinusoidal pitch input with frequency (equivalent to time base) and amplitude (equivalent to stick deflection) according to specific test requirements. Release the stick and allow stick-free response until the transient subsides. Observe aircraft reaction.

Technique:

Input frequency is normally set at the frequency of the short period. Thus, best excitation of aircraft dynamics can be expected.

Reasoning:

Pitch doublets are performed for the evaluation of dynamic longitudinal stability and acceleration sensitivity. Assess dynamic response characteristics (agility, damping).

Remark:

Doublets (pitch, roll, and yaw) may be replaced by 3-2-1-1 manoeuvres. They serve the same purpose and ideally have a better frequency content than a doublet, see Ref. [35]. Though, pilots prefer doublets. With regard to test economy reversing a 3-2-1-1 into a 1-1-2-3 manoeuvre hardly changes the test result. But with a 1-1-2-3 sequence the deviation of test aircraft state from the initial trim condition (test condition) during the manoeuvre is much less.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

Push, Push Over

Task:

Perform a gentle push manoeuvre.

Technique:

From a stabilised straight-and-level flight condition a push over to low normal load factors is performed using a progressive but non-aggressive application of pitch stick (<-1 g/s).

The minimum load factor or AoA to be achieved is according to test requirements. Mach number variation during the manoeuvre should be minimised (± M0.01 to M0.02) and, where possible, a constant throttle setting should be used. After reaching the target (load factor or AoA) gradually return to straight-and-level flight.

Reasoning:

Push overs serve for the evaluation of low angle of attack characteristics and to explore control feel and stability below 1g and low/negative AoA.

Roll 360

Task:

With rudder pedals free initiate a 360 deg roll using specified lateral stick deflection. Stop the roll with wings level and without significant bank angle overshoot.

Technique:

Stabilise aircraft at 1g straight-and-level flight before initiating the roll.

Depending on the basic characteristics of the test aircraft:

- Before initiation of roll raise nose slightly in order to minimise altitude loss during the roll manoeuvre.
- Initially observe roll stopping characteristics and anticipate roll stopping technique for later rolls.
- Do half stick and full stick rolls in both directions. Observe stick fixing characteristics (roll ratcheting).
- During the control law familiarisation phase this manoeuvre must be performed in a gentle way only, gentle stick inputs. Performing this manoeuvre with rapid roll stick inputs (half stick or full roll stick) puts this manoeuvre into the agile manoeuvring class (Phase 3), roll inertia coupling can be expected.

Reasoning:

Find out about rolling characteristics, onset and more important roll stopping behaviour.

Roll Doublet

Task:

Perform a sinusoidal roll input with frequency (equivalent to time base) and amplitude (equivalent to stick deflection) according to specific test requirements. Release the stick and allow stick-free response until the transient subsides. Observe aircraft reaction.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

Technique:

Input frequency is normally set at the frequency of the Dutch-Roll. Thus, best excitation of aircraft dynamics can be expected.

Reasoning:

Assess response characteristics of dynamic lateral stability and acceleration sensitivity (agility, damping).

Comment:

See also remark to Pitch Doublet.

Roll Reversals ("Scissors without target")

Task:

Conduct several (2 – 4) consecutive bank-to-bank rolls up to full back stick.

See 'Bank-to-Bank Roll'.

Reasoning:

Assess roll response characteristics when manoeuvring continuously.

Roller Coaster (RC or R/C)

Task:

Gently push to a negative load factor and return to straight-and-level flight by gently pulling.

Technique:

Stabilise straight-and-level flight at target condition before entering the manoeuvre. Target negative load factor as well as maximum positive load factor during recovery will be defined by the test programme.

Rate of stick deflection (nose down as well as nose up) should be kept at constant speed throughout the manoeuvre. Overall rate of stick deflection can vary according to specific test requirements.

Reasoning:

Assess aircraft behaviour over a large range of AoA below and around 0 deg AoA.

Steady Heading Sideslip (SHSS)

Task:

Apply constant rate rudder pedal input, increase angle of sideslip slowly, simultaneously apply roll stick input to the opposite direction in order to maintain steady heading (zero side force). Stabilise at target AoS for a couple of seconds. Slowly return to trim condition by reducing simultaneously rudder deflection and roll stick deflection. Apply rudder pedal deflection to the other side, keep heading steady with respective opposite roll stick deflection. Stabilise there at target AoS for a couple of seconds and slowly return to straight-and-level flight at original trim condition.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

Technique:

Stabilise straight-and-level flight at the desired test condition prior to entering the manoeuvre. As the manoeuvre goes into both AoS directions in one set-up decision on initial direction is left to the pilot.

Target AoS depends on the specific test requirements and available flight clearance. Rate of rudder input may be varied in accordance with flight clearance, test requirements, and available experience with aircraft type. In some cases, a special clearance for crossed control inputs may be necessary.

This type of testing may also be done with wings level. In this case it will be a wings level turn with a build-up of AoS respectively side force.

Reasoning:

Assess controllability of sideslip characteristics.

Wind Up Turn (WUT)

Task:

Initiate a turn while performing a progressive non-aggressive application of aft pitch stick (<1 g/s). Decrease turn radius gradually until the desired target normal AoA/load factor has been reached. Release stick and return to straight-and-level flight.

Technique:

Stabilise straight-and-level flight at the desired test condition prior to entering the manoeuvre. Target AoA or normal load factor will be given in the test programme.

During envelope expansion a stepped approach must be chosen. This can be to increase AoA in, e.g., 2 deg steps for consecutive WUTs, or increase of normal load factor in 1 g steps for consecutive WUTs. Going for an AoA target or for a load factor target depends on which side of the corner speed the initial test condition is.

For appropriate WUT performance specific test aircraft characteristics play an important role, mainly available energy. With increasing AoA induced drag increases quadratic and the thrust requirement to maintain a steady turn increases accordingly. In addition, desired target test conditions (speed, Mach number) must be kept constant at best ability.

Drag balance respectively speed/Mach number balance can be maintained while using the acceleration potential of decreasing altitude when performing a WUT. Special care must be taken by pilots:

- Not to lose excessive altitude. Flight planning must give a sufficiently high initial altitude.
- Not to exceed a given speed or Mach number limit while pilot's concentration is on observation of target AoA or load factor limit.

Note loss of altitude.

Thus, performing a WUT while giving up altitude must be trained by pilots prior in a simulator. They must know what to expect and which parameter (AoA, speed, or Mach number) to look for first. They must develop a special technique for a specific test requirement. And this can vary with different configurations (e.g., external stores).

Reasoning:

Wind up turns serve for the evaluation of high angle of attack / high normal load factor characteristics together with control feel and stability in manoeuvring flight.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

Yaw Doublet

Task:

Perform a sinusoidal pedal input with frequency (equiv. to time base) and amplitude (equiv. to pedal deflection) according to specific test requirements. Release the pedal and allow stick-free response until the transient subsides. Observe aircraft reaction.

Technique:

Input frequency is normally set at the frequency of the Dutch-Roll. Thus, best excitation of aircraft dynamics can be expected.

Reasoning:

Yaw doublets are performed for the evaluation of dynamic lateral stability and acceleration sensitivity (agility and damping).

Comment:

See also remark to Pitch Doublet.

4.1.3 Control Law Familiarisation Manoeuvre Execution

Selection and execution of manoeuvres given above in the previous section should be performed in a certain order with increasing complexity. One example of such an order is given below in **Table 4-1**. Test points should be scheduled in this order, it gives a certain build-up in complexity.

Table 4-1: Sequence of Test Manoeuvres for Control Law Familiarisation Phase 1.

	Control Law Familiarisation	Manoeuvre Specifics
1	Altitude Capture	
2	Gentle Course Changing Manoeuvring	Define bank angle limits
2	Heading Capture	e.g., 90 deg heading change
3	Pitch Doublet	Define time base (frequency) and amplitude
4	Roll Doublet	
5	Yaw Doublet	
6	Roller Coaster	Define min. g and max. g
7	Wind Up Turn	Up to FBS (stepped approach)
8	Push	Up to FFS (stepped approach)
9	Steady Heading Side Slip	Define target AoS
10	Bank-to-Bank Roll	Define target bank angle
11	Roll 360	define max. stick deflection
12	Loaded Roll	Repeat Roll 360 at higher AoA
13	Roll Reversal	Define max. bank angle (“scissors without target”)
14	Level Acceleration	
15	Level Deceleration	Stepped approach to max. AoA
16	Inverted Flight	

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

Phase 1 testing or control law familiarisation is at the initial stage of flight testing. It can comprise a large variety of different test conditions. Different manoeuvres to be executed at each test condition are given above. While single test points may be executed in a relatively short time, the cumulative number of test flights from Phase 1 can be large. Therefore, testing for a specific project may only require a sub-set. Nevertheless, it must be selected in a way that proper familiarisation and, thus, flight safety issues are not compromised.

4.2 CAREFREE HANDLING TRIALS (INTERMEDIATE TEST STEP)

Descriptions of this section are not directly related to FQ or HQ testing. As testing especially for HQ is at the very end of the overall testing chain and it is always considered at aircraft Level 0, testing for other disciplines must be completed before commencing HQ. One of these disciplines is (where applicable) “Carefree Handling” (CFH).

Phase 1 FQ/HQ testing is always under control of flyable limits. Thus, Phase 1 testing may be done as early as the first flight of an aircraft. Pure HQ testing, though, includes not only aircraft dynamics but also (sometimes unpredictable) pilot dynamics. Therefore, the aircraft must be cleared for such testing. This implies thorough knowledge about aircraft behaviour at the boundaries of the physical flight envelope as high gain HQ testing may bring the aircraft to these boundaries.

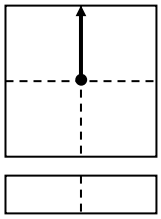
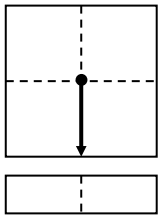
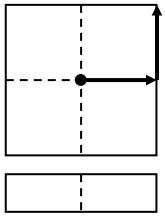
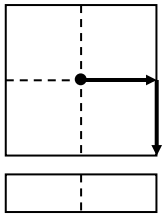
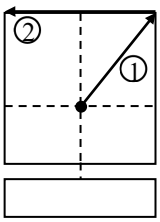
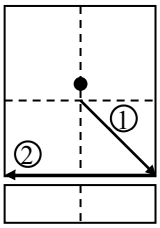
A special test programme outside regular FQ/HQ testing is required to explore aircraft behaviour at the physical envelope boundaries. This requires especially high AoA testing towards the AoA at stall or even beyond. For more conventional aircraft, the result will be an AoA/n_z envelope which will always have to be obeyed by the pilot manually by observation of the relevant gauges. Modern aircraft with digital fly-by-wire flight control systems normally have a feature which is called “Carefree Handling” properties. It means a pilot can make any meaningful control input at any position in the envelope and the carefree handling algorithm of the flight control system will protect the aircraft and him from crossing any physical flight envelope boundary. Corresponding tests to explore the physical boundaries and the protection algorithm of the control law can be very tedious. They must be performed very carefully in a stepped manner. Normally a test aircraft carries an anti-spin gantry.

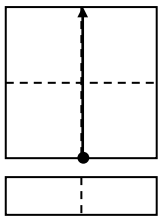
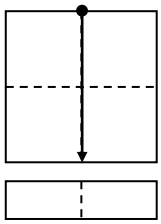
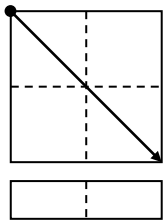
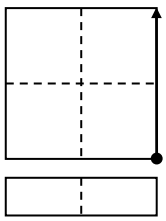
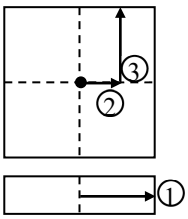
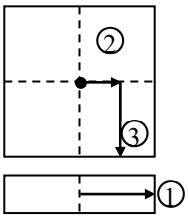
Once the step to explore the physical envelope boundaries has been successfully completed, a set of “control manoeuvres” will have to be executed to prove the reliability of the envelope protection algorithm inside the overall envelope, see Figure 2-1. This will have to be done at various test conditions inside the target flight envelope during high dynamic manoeuvring. These manoeuvres are pure open loop manoeuvres where the pilot only has to observe the aircraft reaction. This testing is very often placed in connection with HQ testing, which is why it is mentioned here. A typical sample of corresponding open loop manoeuvres is detailed in **Table 4-2**. These manoeuvres may vary when testing a given test aircraft.

Testing for Carefree Handling validates the “entire simulation chain”. This means, separate models (e.g., aero model, control law model, air data model, hydraulics model, …) having been validated on their own, are now being validated together in combination in one “run”.

Carefree Handling control testing must be successfully finished before PIO resistance testing and full closed loop HQ testing can commence.

Table 4-2: A Collection of Open Loop Carefree Handling Manoeuvres.

Manoeuvre	Description
	Rapid Push to FFS: Rapidly apply full fwd pitch stick and hold for approximately 4 seconds. Throughout the manoeuvre maintain the roll stick nominally central.
	Snatch to FBS: Rapidly apply full aft pitch stick and hold for approximately 4 seconds. Throughout the manoeuvre maintain the roll stick nominally central.
	FRS Rolling Push to FFS: Rapidly apply full roll stick. Once the roll rate has stabilised, rapidly apply full fwd pitch stick. Hold for approximately 360° bank angle change.
	FRS Rolling Break to FBS: Rapidly apply full roll stick. Once the roll rate has stabilised, rapidly apply full aft pitch stick. Hold for approximately 360° bank angle change.
	Diagonal Break to FFSFRS + FRS Reversal 1080°: Rapidly and simultaneously apply full fwd pitch and full roll stick. Once the AoA/n_z has stabilised, rapidly apply full opposite roll stick hold for approximately 1080° (3 x 360°) bank angle change or as long as possible.
	Diagonal Break to FBS/FRS + FRS Reversal 1080°: Rapidly and simultaneously apply full aft pitch and full roll stick. Once the AoA/n_z has stabilised, rapidly apply full opposite roll stick. Hold for approximately 1080° (3 x 360°) bank angle change or as long as possible.

Manoeuvre	Description
	Rapid Push to FFS from FBS: Apply full aft pitch stick. Once the AoA/n_z has stabilised, rapidly apply full fwd pitch stick. Hold for approximately 4 seconds.
	Snatch to FBS from FFS: Apply full fwd pitch stick. Once the AoA/n_z has stabilised, rapidly apply full aft pitch stick. Hold for approximately 4 seconds.
	Diagonal Break from FFS/FRS to FBS/FRS: Apply full fwd pitch and full roll stick. Once the AoA/n_z and roll rate stabilise, rapidly and simultaneously apply full aft pitch stick and full opposite roll stick. Hold for approximately 360° bank angle change.
	Rapid Push to FFS/FRS from FBS/FRS: Apply full aft pitch and full roll stick. Once the AoA/n_z and roll rate stabilise, rapidly apply full fwd pitch stick. Hold for approximately 360° bank angle change.
	Full Proverse Pedal + HRS Rolling Break to FFS: Apply full right rudder pedal. Once the sideslip has stabilised, apply half roll stick in the same direction as the rudder pedal. Once the roll rate has stabilised, rapidly apply full fwd stick. Hold for approximately 360° bank angle change. Full rudder pedal should be maintained throughout the manoeuvre.
	Full Proverse Pedal + HRS Rolling Break to FBS: Apply full right rudder pedal. Once the sideslip has stabilised, apply half roll stick in the same direction as the rudder pedal. Once the roll rate has stabilised, rapidly apply full aft stick. Hold for approximately 360° bank angle change. Full rudder pedal should be maintained throughout the manoeuvre.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

4.3 PHASE 2 TESTING (PIO RESISTANCE TESTING)

The proof of resistance of the Pilot-Vehicle-System (PVS) dynamics against Pilot-in-the-Loop-Oscillations (PIO) is a necessary and important test step prior commencing full pilot-in-the-loop tasks, HQ tasks. This is a precautionary measure in order to find out about "misaligned" PVS dynamics prior to HQ testing.

This section describes several techniques for applying this assessment. There are "simple" capture tasks as well as specially prescribed piloting techniques.

Test outcome will be rated according to the rating scale defined by the United States Air Force Test Pilot School (USAFTPS) as given in Section 3.1, see Figure 3-6. Furthermore, pilots will have to provide qualitative descriptions of possible PIO tendencies.

HQ testing during the development phase of an aircraft tends to bias pilot ratings toward the good end of the rating scale, since test pilots normally possess above average training and piloting skills. Moreover, test flights are generally conducted in fair weather conditions, and the flight test environment is most often a very controlled, safety-conscious environment to work in. Here pilots experience less stress that could trigger high bandwidth reactions. However, it is in the flight test environment where handling qualities deficiencies need to be detected, long before line pilots commence to operate the aircraft. The exposure of potentially hazardous characteristics in a safe, up-and-away test environment is the key objective of PIO resistance test methods. The aim is to deliberately drive the pilot into a high gain situation where unfavourable aircraft dynamics can be discovered.

4.3.1 Simple Pilot-in-the-Loop Manoeuvres

A very simple and easy to achieve test method is defining capture tasks. As aircraft agility is mainly evident in the pitch and the roll axis, these tasks will be attitude captures in these two axes. Generally, the task description will require a target attitude, maximum allowable stick deflection, and stick application speed (gently or rapidly).

At this stage, given capture manoeuvres do not require a "desired/adequate" HQ classification. At this stage investigation of "basic feel handling" is required: is the aircraft controllable and how easy is it to control? Nevertheless, the definition of tight capture targets can drive the PVS into unwanted oscillations.

Bank Angle Capture

Task:

Capture a desired bank angle, maintain it for 2 sec. Roll back to straight-and-level flight and maintain it for 2 sec. Capture the opposite bank angle, maintain it for 2 sec. Roll back and re-stabilise straight-and-level flight.

Technique:

Stabilise straight-and-level flight at test altitude. Target bank angle will be defined according to aircraft characteristics and testing purpose. Target bank angle may differ for different configurations. Appropriate values may be 30 to 60 degrees bank angle.

Maximum allowable stick deflection and stick input application speed must be defined. They can be benign in the beginning and more aggressive in following tests.

During attitude capturing try to minimise number of overshoots.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

Attitude reference should be the outside horizon and not any markings in the HUD. This eliminates possible adverse symbol dynamics within the HUD.

Reasoning:

Characteristic control ability when changing bank angle and trying to acquire a given value with varying aggressiveness.

Pitch Angle Capture

Task:

Capture a desired positive incremental pitch attitude (climb) and maintain for approximately 5 sec. Level off and recapture initial attitude and stabilise for 5 sec. Capture a desired negative decrement attitude (descent) and maintain for 5 sec. Level off and recapture initial attitude and maintain.

Technique:

Stabilise the aircraft at 1 g straight-and-level flight. Note pitch attitude (normally done with the aid of the HUD), this is the reference attitude.

Target pitch angle will be defined according to aircraft characteristics and testing purpose. Typical values are 5 deg to 10 deg attitude changes.

Maximum stick deflection and stick input application speed must be defined. They can be benign in the beginning and more aggressive later on.

During attitude capturing try to minimise number of overshoots.

Reasoning:

Assess pointing capability while trying to acquire a given value of attitude change with varying aggressiveness.

Comment (Pitch and Bank Angle Captures):

Testing for bank angle and pitch attitude captures solely relies on the pilot executing the manoeuvre. He decides about initiation and detection of target values. The purpose of this testing is to detect the pilot's ability to perform such tasks and his comfort in executing them with variable aggressiveness. In case the PVS dynamics show defects, these can be discovered here already easily, e.g., sluggish stick response or insufficient damping when making it difficult to execute such captures.

Loose Formation Flying

Task:

Follow loosely another aircraft, the target aircraft. The target aircraft performs gentle course changing manoeuvres up to given limits.

Technique:

The test aircraft follows in a 100 ft to 200 ft distance trying to replicate the manoeuvres of the target aircraft.

Reasoning:

Find out about PVS dynamics in a loose pilot-in-the-loop task.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

Aircraft Tracking

Task:

The pilot of the test aircraft tries to track a target aircraft in either a constant load factor turn (e.g., 3 g) or a wind up turn.

Technique:

Tracking distance should be about 300 ft to 500 ft. Depending on the test aircraft an appropriate target symbol or reference symbol should be chosen in the HUD.

Reasoning:

Find out about PVS dynamics in a lose pilot-in-the-loop "nose pointing" task with varying aggressiveness.

4.3.2 Pilot Technique Methods

As pointed out above the reasons for occurrences of a PIO can be various. In flight test PIO resistance should be tested as best as possible. More simple tasks are explained in Section 4.3.1. In this section more demanding tasks will be introduced which involve intense pilot action. Nevertheless, these tasks are "open loop", and high amplitude and high frequency inputs are requested for.

In addition to the collection given here attention is also drawn to Table 4.2 of the "McRuer-Report" given in Ref. [11], p. 100. This suggests a variety of tasks for APC evaluation.

4.3.2.1 KLONK Technique

During the development of the JAS-39 Gripen SAAB experienced two crashes with loss of the aircraft. Both can be attributed to rate limiting in connection with adverse aircraft pilot couplings. These are described in Ref. [11] by McRuer and in Ref. [36] by Kullberg and Elgcrona. In the aftermath, a lot of development work was undertaken at SAAB to find out ways and methods to avoid future accidents of this kind. One method developed for flight testing is called the KLONK method as given in Ref. [11]. It is a unique method. Its main purpose is to test an aircraft in flight with very high demands on control surface movements. This is to trigger maximum available deflection rates and to find out about any hidden rate limiting and time delay effects.

The KLONK is a formal procedure of stick movements to successfully reveal PIO susceptibilities. It is to detect disconnects between pilot and aircraft due to, for example, rate limiting. The method is described in Ref. [11], which outlines the steps to be executed as follows in a continuous pattern:

As it is not explained in Ref. [11] it is assumed here that positive stick deflection is nose down and negative stick deflection is nose up.

1) Move the control stick to maximum positive pitch deflection and hold for a selected time period. This is KLONK #1.
2) Move the stick to maximum negative pitch deflection and hold until the aircraft reaches maximum positive pitch angle (as a result of the command from the previous step). This is KLONK #2.
3) Move the stick to maximum positive pitch deflection and hold until the aircraft reaches maximum negative pitch angle (as a result of the command from the previous step). This is KLONK #3.
4) Repeat steps 2 and 3 for the desired number of KLONKS. For example, a 10-klonk test would cycle the pitch stick into the stops a total of 10 times.

5) Simultaneously with steps 1 through 4, move the stick to the maximum left roll position each time the stick is moved to maximum pitch position, and move the stick to the maximum right roll position each time the stick is moved to the minimum pitch position. Also, while the stick is being held in the pitch stops in steps 1 through 4, slowly reduce the roll command at a constant, selected rate.
6) Determine if the aircraft has remained stable and controllable for the specified number of KLONKS.
7) Repeat steps 1 through 6 using different values for the initial hold period in Step 1 and the roll command rate in Step 5.

According to Ref. [11], the KLONK method has been effective for assessing the effects of the kinds of delay build-up in connection with rate limiting.

4.3.2.2 Handling Qualities During Tracking (HQDT)

For PIO resistance testing the Handling Qualities During Tracking (HQDT) method is a special pilot test technique. It was developed by the US Air Force Test Pilot School and US Air Force Flight Test Centre [37]. Its aim is to artificially increase pilot bandwidth while performing tasks as described in the following. Although this method requires pilot feedback action it is considered here as an "open loop" task. It does not require any specific performance evaluation, as will be shown. A clear description of the method is also given in Ref. [8], descriptions given here are guided from Ref. [8].

The HQDT task is set up in a way in which pilots normally do not fly an aircraft. It needs special pilot training prior to commencing a test. This means getting acquainted with the specifics of the method as well as doing sufficient simulator training prior to testing to train the method.

Figure 4-2 illustrates schematically, in an amplitude/frequency relationship, possible pilot action during a tracking task. When tracking becomes necessary, i.e., when an error signal exceeds a certain threshold, pilots by nature adopt the lowest gain piloting technique that is consistent with reasonable task performance. This is schematically sketched in the lower left-hand corner of the diagram, low stick amplitude and slow frequency. Under certain conditions, when level of stress, excitement, anxiety, or fear exceeds a certain threshold, pilots may switch to a high gain piloting technique, high stick amplitude with rapid stick movements. This is equivalent to an amplitude/frequency relationship which is found in the upper right-hand corner of Figure 4-2. During such an event, it must be ensured that HQ do not deteriorate to a degree that compromises flight safety, possibly promoting PIO. Therefore, the potential to overlook hidden HQ deficiencies exists if evaluation tasks with their nature stay in the lower left-hand corner of Figure 4-2.

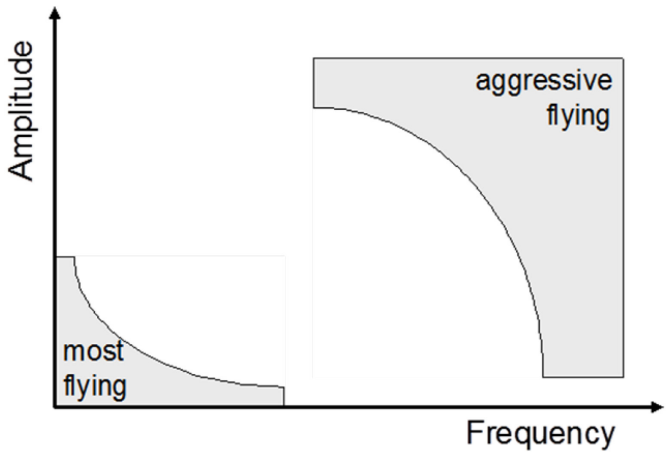


Figure 4-2: Schematics of Amplitude Frequency Relationship.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

The HQDT technique is set up in a way to identify deteriorating behaviour of the PVS as early as possible, early with respect to stick amplitude and/or frequency. For this special HQDT task the pilot is tasked to track a "precision aim/target" with varying stick amplitude and deflection frequency. Tasks will be defined further down.

The **build-up of the HQDT** piloting technique is broken down into three consecutive steps according to the behavioural analysis given. **Step 1** requires the pilot to track a given precision aim point with non-aggressive, small amplitude, low frequency control inputs (lower left-hand corner of Figure 4-2). For **Step 2**, tracking is "tightened-up" by gradually progressing to aggressive high frequency inputs with still low amplitude and, thus, shrinking the tracking threshold. With increasing frequency inputs, the pilot starts to react like a switching function. At the instant, the pipper or aiming index passes through the precision aim point, the pilot immediately reverses the control input (lower right-hand corner of Figure 4-2). Finally, for **Step 3**, the input amplitude is gradually increased until "bang-bang" control is achieved while stick inputs with high frequency and switching are maintained (upper right-hand corner of Figure 4-2). The applicable performance measure is minimum tracking error. Qualitative pilot comments are supported by PIO Ratings (PIOR).

As a **reference during HQDT** tracking tasks, fixed HUD indications can be used. Another possibility is using a fixed reference point in the cockpit field of view of the pilot. The choice of reference is at the pilot's discretion.

HQDT Tracking Technique

Each HQDT task is to be treated as a PIO assessment task and is not meant to reproduce normal operational pilot behaviour. Instead, the test aims to expose undesirable aircraft responses to extreme pilot inputs in case of surprise or danger.

Step 1: (Low frequency, non-aggressive, small amplitude)

Start tracking the precision aim point with non-aggressive, small amplitude, and low frequency control inputs.

Step 2: (High frequency, aggressive, small amplitude)

Slowly progress from low frequency to high frequency control using small inputs while tracking the precision aim point. Gradually "tighten up" the tracking by slowly progressing from non-aggressive, small amplitude, low frequency tracking inputs to aggressive, small amplitude, high frequency inputs.

The endpoint of this step is small amplitude control, in which the pilot behaves like a switching function: The pilot immediately reverses his control input at the instant the pipper or aiming index crosses through the precision aim point.

Step 3: (Large amplitude, high frequency).

For Step 3 inputs the pilot increases the amplitude of control inputs at high frequency. The endpoint of this step is "bang-bang" control. The pilot uses large amplitude control inputs as quickly and as aggressively as possible, reversing control input direction immediately at the instant the precision aim goes through the reference indication.

Overall Comment:

The pilot is not tasked to fulfil the HQDT task with prescribed control input deflections, e.g., maximum allowable stick deflection. The control input (rate and quantity of stick deflection) shall be applied to achieve an aircraft response that the pilot would expect in situations where quick

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

aircraft response is needed (e.g., a safety critical situation such as collision avoidance during formation flying). During successive, aggressive tracking the pilot shall track with high bandwidth (frequency) not necessarily with high gain (large stick deflection). The magnitude of stick deflection should be determined by the desired and the actual aircraft response.

HQDT-1 Horizon Tracking

Task:

From an offset attitude, defined in the test matrix, recapture, and track the horizon. Use Step 1 to Step 3 piloting technique.

Technique:

Briefly *s*tabilise descending or climbing flight path with wings level at prescribed pitch angles. Recapture the horizon and perform HQDT technique.

Possible initial offsets can be ±5 deg and ±10 deg with respect to the horizon. To be defined according to the relevant test needs in the test matrix.

HQDT-2 Bank Attitude Capture

Task:

From an offset bank angle, defined in the test matrix, recapture, and track the horizon. Use Step 1 to Step 3 piloting technique.

Technique:

Briefly stabilise the prescribed bank angle. Recapture the horizon and perform HQDT technique.

A possible initial starting bank angle can be 20 deg, 40 deg, and 60 deg. To be defined according to the relevant test needs in the test matrix.

HQDT-3 Aircraft Tracking (Constant Load Factor Turn)

Task:

Track target aircraft in a constant load factor turn.

Load factor and distance to target to be defined in the test matrix.

Technique:

- Evaluation pilot positions aircraft behind and below the target aircraft.
- Evaluation pilot calls out “Ready” when properly aligned.
- Target pilot rolls smoothly into level turn and slowly increases load factor until the test load factor is attained (use g onset rate of 2 sec/g or larger).
- The evaluation pilot positions the fixed reference indicator (HUD, cockpit) about 50mils from the target.
- When aligned the evaluation pilot calls “Tracking” and starts the evaluation.
- The evaluation pilot drives the fixed reference indicator (HUD, cockpit reference) toward the target. He continues to track with zero error using Step 1 through Step 3 pilot technique for about 30 sec.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

- After 30sec evaluation pilot calls “Reverse”. Target pilot performs a turn reversal with the same load factor/bank angle.
- Repeat set-up in the other direction.
- When done evaluation pilot calls out “End”.

HQDT-4 Aircraft Tracking (Wind Up Turn (WUT))

Task:

Track target aircraft in a windup turn with increasing load factor.

Final load factor and distance to target to be defined in the test matrix.

Technique:

- Evaluation pilot positions aircraft behind and below the target aircraft.
- Evaluation pilot calls out “Ready” when properly aligned.
- Target pilot rolls smoothly into level turn and slowly increases load factor until the test load factor is attained (use g onset rate of 6 sec/g or greater).
- The evaluation pilot drives the fixed reference indicator (HUD; cockpit reference) toward the target. He continuously tracks with zero error using Step 1 through Step 3 pilot technique.
- Target pilot calls out when target load factor is reached. Depending on load factor magnitude he maintains the target load factor for a couple of seconds.
- Target pilot calls out “End” and returns to initial condition.

HQDT-5 Aircraft Tracking – Formation Flying

Task:

Track target aircraft in a formation with gently moving target aircraft.

Maximum attainable load factor of target aircraft and distance to target aircraft to be defined in the test matrix.

Technique:

- The evaluation pilot positions his aircraft relative to the lead airplane in loose fingertip formation.
- The evaluation pilot selects a distinct target point on the formation partner which he intends to track.
- As fixed reference point a suitable marking in line of sight to the lead aircraft (e.g., sticker on the canopy) can be used.
- The evaluation pilot calls out “Ready” when properly aligned.
- The target pilot begins to manoeuvre gently in pitch and roll randomly.
- The evaluation pilot tries to maintain his position precisely with zero error and using Step 1 to Step 3 pilot technique for about 30 sec.
- When done the evaluation pilot calls out “End”.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

Caution:

While in all other tasks defined for this HQDT PIO assessment the pilot is asked to control an attitude of the aircraft, during the task of formation flying the focus is on closed loop control not only on attitude but also on relative altitude to the target aircraft. Since changes of altitude are an integration of changes in pitch attitude, the phase shift resulted from that integration might turn altitude tracking with the HQDT method to become unstable.

Another issue during this type of testing may be the selected set-up for tracking. If the evaluation pilot selects a reference inside the cockpit other than the pipper in the HUD to track an external target point on the formation partner, most likely a distinct reference on or at the canopy, relative movement of pilot's head with respect to the canopy during the task plays a role too. This way the line of sight from the pilot via the cockpit reference point to the outside target point changes due to the head movement and additional dynamics are introduced, possibly provoking a PIO.

HQDT-6 Air-to-Air-Refuelling Basket Tracking

Air-to-Air-Refuelling (AAR) is one of the operational tasks that normally requires a high pilot-in-the-loop engagement. For PIO resistance evaluation the HQDT technique may be applied behind the AAR basket of a tanker as well. This may additionally be necessary as the receiver aircraft flight dynamics (change in control law) may be modified for AAR operation.

Task:

Perform HQDT task about 30 ft behind trailing AAR basket with tip of AAR refuelling probe (receiver aircraft) aligned with centre of AAR basket (tanker).

Technique:

The evaluation pilot (receiver) starts and ends the manoeuvre on his own discretion starting with Step 1 HQDT inputs for a couple seconds, afterwards he will continue with Step 2 inputs.

Caution:

As precautionary measure in close vicinity of the tanker aircraft Step 3 inputs should not be performed!

HQDT Execution Comment

HQDT is designed unquestionably counter the way aircraft are normally flown and may be perceived as unnatural. Its purpose is to serve as a handling qualities "safe gate", being able to expose handling qualities deficiencies in a safe, controlled environment. For this testing with the HQDT technique requires thorough preparation and training prior to commencing the flight tests.

Preparations and trainings should be done in a simulator with a high-fidelity visual system in order to keep the time lag for the build-up of the visual information as small as possible. Such a simulator training is indispensable for all pilots involved in the testing.

Properly executed, HQDT is expected to highlight high bandwidth HQ characteristics of an aircraft in certain axes, depending on the task. Additionally, formation HQDT is expected to highlight vertical and lateral translational dynamics of the test aircraft in one "shot".

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

4.3.3 Specific Synthetic Target Techniques

A specific test technique may be generated with “outside cues” triggering the evaluation pilot with dedicated tasks. These would occur unexpectedly, denying to him the possibility of task anticipation. Such a technique includes a certain “surprise factor”, challenging the pilot in a way, like a sudden task change or problem arousal in real environment. This is a desirable effect for PIO resistance testing. Thus, these methods are considered “closed loop”. This can be done, for example, with specifically generated symbols projected into the HUD display. These represent an artificially animated target to be followed by the pilot. Another method is building an external target pattern on ground. It resembles a set of lamps whose lighting is artificially and arbitrarily animated and it generates a certain pilot load when flying towards this ground target.

Artificial targets also have an advantage in that identical tasks can be given to different pilots, thus creating the possibility of identical task repetitions with different pilots. Subsequent analysis can be made using comparisons of variations of pilot behaviour/techniques for this task.

Artificial target methods generate high gain, precise, well defined, and repeatable tasks.

4.3.3.1 GRATE/ATLAS Technique

A very simple test set-up can be achieved with varying ground targets (variably lit lamps). This method has distinct advantages. Such a test set-up does not need a flight clearance as there is no flying test equipment, and there are no modifications necessary to the test aircraft. The need is for a large enough test range where the targets can be arranged properly and where there is sufficient air space for a controlled descent/attack on the targets. Such a test task emulates a ground attack task.

The Ground Attack Test Equipment (GRATE) has been developed by DFVLR in Germany (today DLR) in the early 1980s, see Refs. [38] and [39]. A functionally equivalent system Adaptable Target Lighting Array System (ATLAS) has been developed by NASA a few years later, see Ref. [40]. The main part of both systems is an array of lamps arranged on ground.

Test Set-Up:

Figure 4-3 gives an impression of the location of the lamps and the overall size of the total arrangement on ground. When looking at the arrangement from a distance at some altitude and approaching it with a given glide path angle (approximately 15 deg) the pattern looks like a diamond as indicated in the upper left half.

The system has been realised differently by DFVLR and NASA. This is not an issue here. It is important that the lamps of both systems can be lit in individual patterns which the approaching pilot has to follow as closely as possible. With DFVLR realisation the lighting pattern is triggered from ground equipment only. Whereas with the NASA realisation the initiation of the lighting pattern can be done via radio of the evaluation aircraft.

Task:

At 5,000 ft AGL approach test area in the indicated overflight direction. Speed as required by the test matrix. At 5 NM distance initiate a 15 deg descent towards the lighting pattern. All lamps will be lit. Once acquired give a call to the ground station. Lights will be turned off and the random lighting sequence for the test will be started. Always point aircraft nose at the currently lit lamp with high gain and high precision. Give qualitative comments. The test is finished when reaching 1,000 ft AGL or the lighting sequence is over.

Technique:

Depending on test purpose and test aircraft initial altitude and approach speed may be varied. Speed and approximate altitude variation during the descent approach give the duration of the lighting sequence. For piloting reasons at the beginning of the sequence the front lights (closer to the approaching aircraft) will be lit individually whereas towards the end of the sequence/manoeuvre it is easier and better to follow the rear lights lit (further away from approaching aircraft). The lighting sequence can be any sequence which serves to excite the PVS dynamics in the desired way.

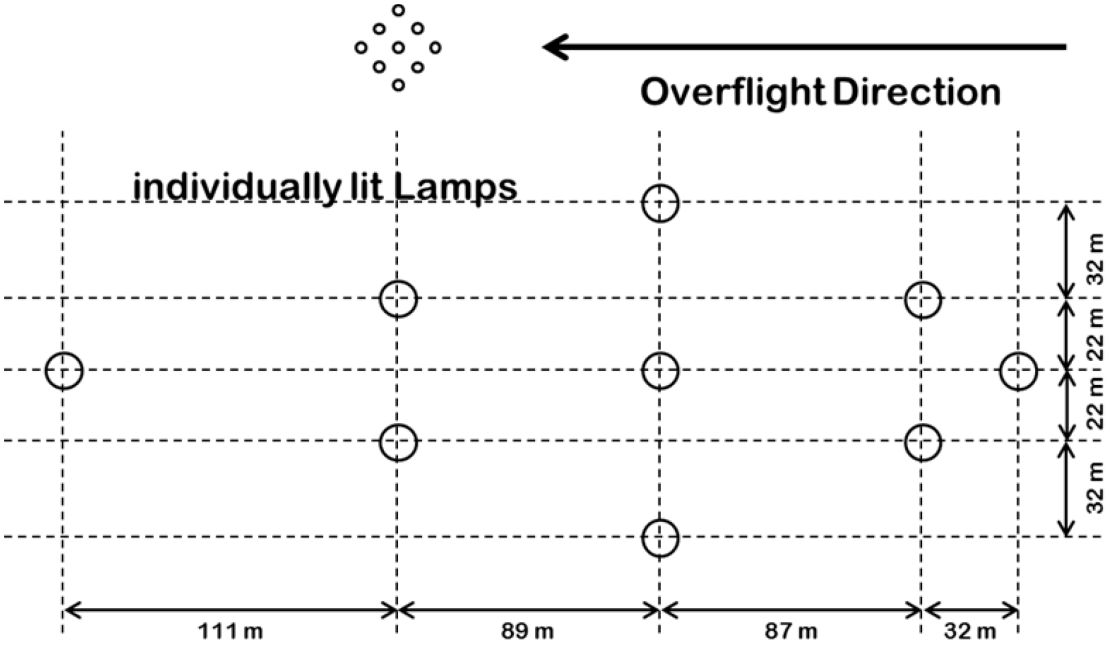


Figure 4-3: On-Ground Lamp Pattern for GRATE and ATLAS Technique.

4.3.3.2 Boundary Avoidance Tracking

In the early 2000s, HQDT was the primary PIO susceptibility test method in use at the USAF TPS. A new test technique was developed based on a new explanation of pilot perception of some flight tasks. In 2004, William Gray III theorized that a major contributor to PIO was not so much the effort of tracking a desired outcome, as it was avoiding a boundary of some sort (common boundaries would include the ground or other aircraft but could also include aircraft limits or envelopes). Mr. Gray developed a Flight Test Technique (FTT) whereby pilots would attempt to track a target, while simultaneously avoiding boundaries. The target tracking as a goal, whereas the boundary avoidance was required (the pilots were instructed to treat them as true "cliffs"). The boundaries were moved closer and closer to the tracking target as a function of time, thus increasing the workload of the pilot. This took on the term of "Workload Build-up" (WLB), although most literature refers to Boundary Avoidance Tracking (BAT). The philosophy of this test technique is explained and discussed by Gray in Ref. [41].

Much of the early research focused on the possibility that BAT performance could quantitatively determine task performance as the point at which the pilot switched from target tracking to boundary avoidance. This switch would decrease the point tracking performance and define the best achievable performance [42]. **Figure 4-4** shows the concept of maximum attainable tracking performance and shows how changing boundaries (given through the lines 1 through 6, with 6 being the tightest boundary) can drive the pilot to determine that performance.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

Test Set-Up:

Either a target aircraft or a programmable flight test display (commonly a HUD) is required to depict artificial boundaries for the pilot. **Figure 4-5** and **Figure 4-6** show two techniques used in the past, one using physical markings on a target aircraft, the other using virtual boundaries shown in the test-unique HUD. In both cases, the pilot must step through the boundaries to tighter and tighter tolerances, all while tracking the specified point (the wingtip-insignia line for the T-38, and the "pitch target line" in the HUD).

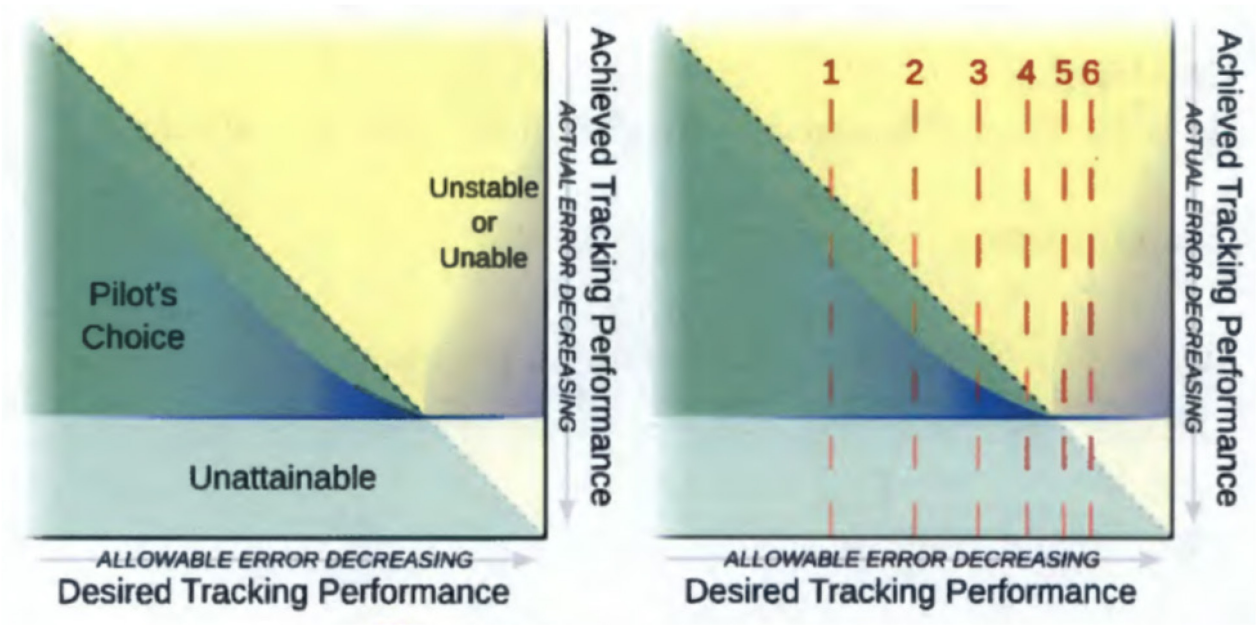


Figure 4-4: 34 Maximum Attainable Performance (Left), Decreasing Boundaries (1 to 6) Driving Performance to Find the Maximum Attainable Performance (Right) [41], [42].

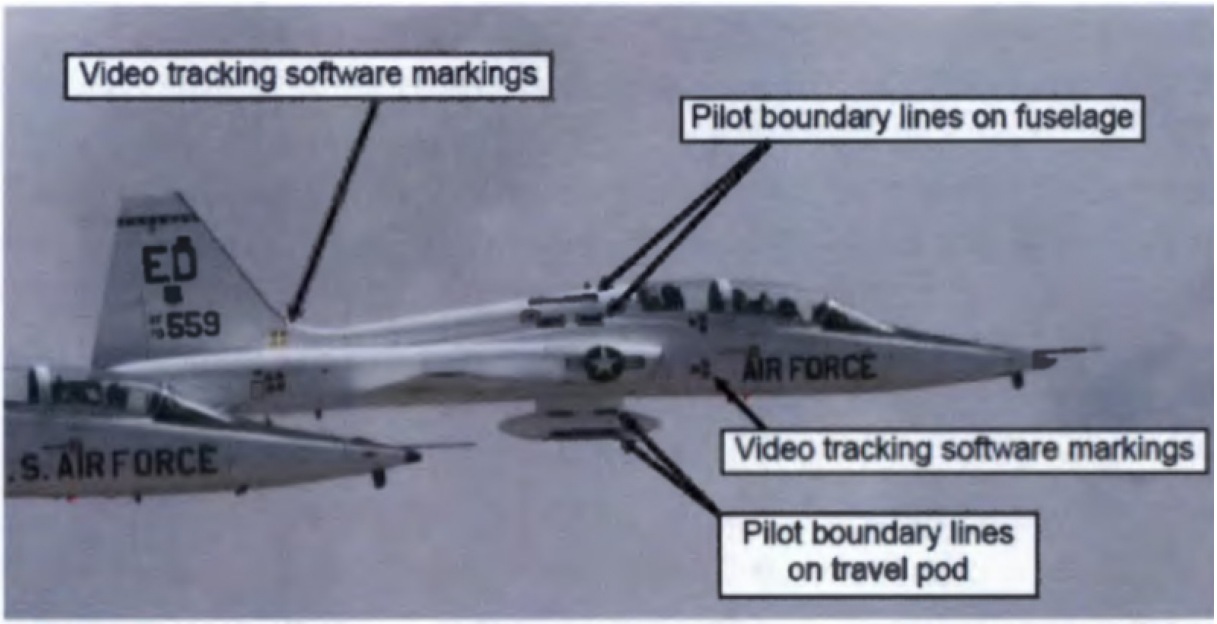


Figure 4-5: T-38 Target Aircraft Markings for Pilot and Camera Used in HAVE BAT [43].

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

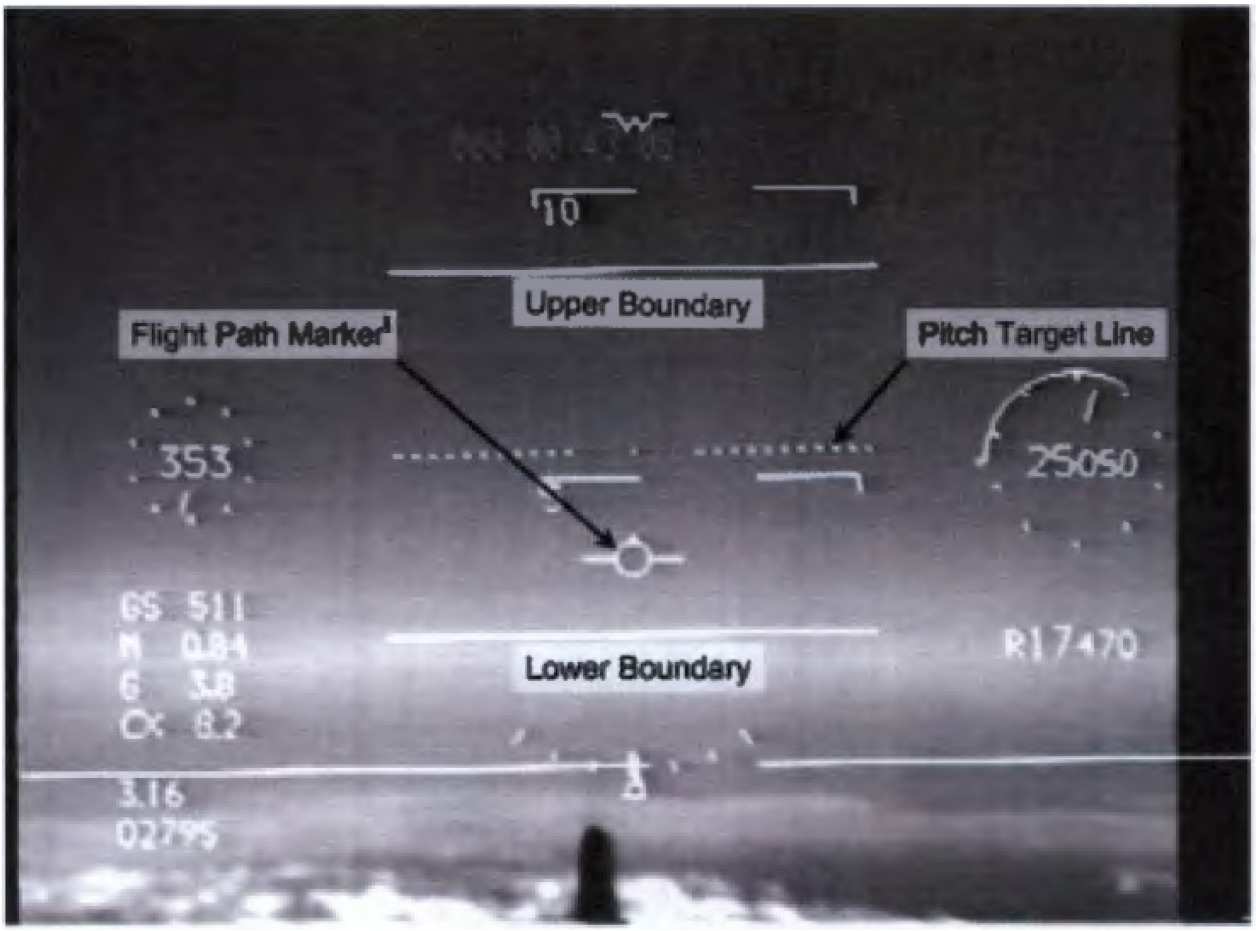


Figure 4-6: NF-16D HUD Task Used in BAT DART [41].

Task:

Using a target aircraft: The test and target aircraft set up in fingertip formation at the specified altitude and airspeed, such that a point of reference is formed on the target aircraft from the eye point of the test pilot (i.e., line up the wingtip with the centre of the USAF insignia). Upon initiation, the target aircraft begins manoeuvring (approximately +/- 0.5g) while the test pilot attempts to track the point of reference.

Using a flight test display: The test aircraft sets up at the specified altitude and airspeed. A pre-programmed target signal is displayed to the pilot, such that he has to manoeuvre to track the target.

Technique:

As the tracking task is occurring, the test pilot must also be cognizant of the pre-marked boundaries either on the target aircraft or in the flight test display, and systematically abiding by the tighter and tighter boundaries. At any point, if the boundaries are touched, the task is abandoned. It is critical that the pilot treat the artificial boundaries as though they were real.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

4.4 PHASE 3 TESTING (OPERATIONAL HANDLING QUALITIES ASSESSMENT)

Phase 3 testing goes into operational testing. Therefore, depending on the specific development contract, also customer pilots may be part of this programme and may have the contractual right to participate.

In the following a set of performance-based operational manoeuvres is given. The authors do not claim that this set is a complete set of manoeuvres. Nevertheless, in the past this set has proven to be practical. Tests gave a valuable overall insight into HQ of a test aircraft.

Where applicable, for each manoeuvre a performance criterion in terms of "desired" and "adequate" is given. Given values come from experience from the past. For a specific test campaign these criteria must be reviewed and adapted to given test requirements. The responsible HQ engineer will lead this endeavour together with the industry project pilot and possibly with a representative customer pilot as well.

The given set of manoeuvres comes from various experiences in industrial HQ envelope expansion campaigns. It has proven to give good and satisfactory results. Depending on the given specific tasks or possibilities possibly only a sub-set may be applicable.

The following list of Manoeuvre Groups is organized in *alphabetical order*.

4.4.1 Air-to-Air-Refuelling (AAR)

Aerial refuelling is one of the most challenging tasks when operating aircraft. At first, two aircraft most likely of different size and different manoeuvring capabilities are operating in very close vicinity together. Secondly, they have a fixed somehow flexible connection during most of the time of the operation. This needs special care on the part of all involved and operational regulations. A detailed description of aerial refuelling procedures is given in ATP-3.3.4.2 [44], which is a NATO standard. Another very helpful document is the ARSAG AAR Test Guide [45]. In the following specific HQ aspects will be introduced.

Aerial refuelling can be achieved with two different techniques: a) With a hose-drogue system; and b) With a refuelling boom system. From a Handling Qualities point of view the hose-drogue technique bears much higher demands on the receiver pilot as on the tanker pilot. For the refuelling boom technique, the higher demand is on the boom operator situated in the tanker aircraft whereas the receiver pilot "only" has to manoeuvre into and stay in the proper position behind the tanker. Nevertheless, this task can be as challenging especially when a large aircraft is to be positioned behind a tanker aircraft (equally sized or even smaller than the receiver). **Figure 4-7** and **Figure 4-8** illustrate both AAR methods.

Formation control during AAR is always with the tanker. The receiver aircraft joins the tanker from below on its left side. The receiver pilot manoeuvres his aircraft into an observation position at the left-wing tip of the tanker, so that he can be identified by the tanker. On clearance from the tanker the refuelling manoeuvre is started from this position.

Testing of and performing AAR in operational flight poses various challenges. Essential is a sufficient overlap of AAR operational envelopes of the tanker and of the receiver aircraft. A tanker will have a special operational envelope while flying in refuelling configuration. The same applies for a receiver aircraft. It is now important that both envelopes overlap in speed and altitude. And this overlap must provide a margin to both aircraft for manoeuvring during the AAR operation within their envelope without forcing the partner to leave its envelope. If the relationship between both envelopes for example is such that the tanker must fly at the "high speed" end of his envelope and the receiver aircraft flies at the "low speed" end of its envelope precautionary procedural measures have to be taken that both aircraft can fly safely.

Figure 4-7: Example of "Hose-Drogue" Air-to-Air-Refuelling.

Figure 4-8: Example of "Boom" Air-to-Air-Refuelling.

AAR manoeuvres can be assessed in two different ways. A more academic set-up assesses HQR for the various phases of the AAR sequence and to better understand receiver aircraft system dynamics in a refuelling situation. Subsequently an operational hook-up performed in a steady and constant manner from the observation position into the contact position serves to assess operational AAR characteristics.

Detailed procedures are dependent on the refuelling technique in use as well as on specific tanker and receiver characteristics. They will be assessed for operational suitability by evaluating the ability to precisely control azimuth, altitude, and fore/aft position relative to the tanker aircraft. Also, the ability to precisely control closure rate and attitude during hook-up and refuelling will be evaluated.

The following **Figure 4-9** schematically explains the situation for AAR from a HQ point of view. On one side of the figure the special cues and influences on the pilot are mentioned. These are visual cues

for orientation due to the receiver position in the tanker specific refuelling position. Not under consideration here are receiver influences on a tanker which must be considered as well, for example, when a rather large aircraft like the C-5 Galaxy refuels from a smaller KC-135.

Relative distances to wing wakes and engine wakes of the tanker play a role, as well as dynamic characteristics of the hose-drogue system or the boom system. On the other side the specific tanker aircraft wake influences the flow towards the receiver. This will be sensed by the receiver flight control system and has an influence on the flight mechanics state feedback and, thus, on receiver aircraft dynamics. These altered dynamics influence pilot reactions as well. This basically illustrates the tanker-aircraft, receiver-aircraft, receiver-pilot dynamic system. Where applicable boom operator dynamics must also be considered. It also clearly indicates that from a receiver aircraft point of view HQ evaluations for AAR must be done for all tankers to be used/cleared. There is a tanker specific clearance for a receiver aircraft for each tanker to be operated with.

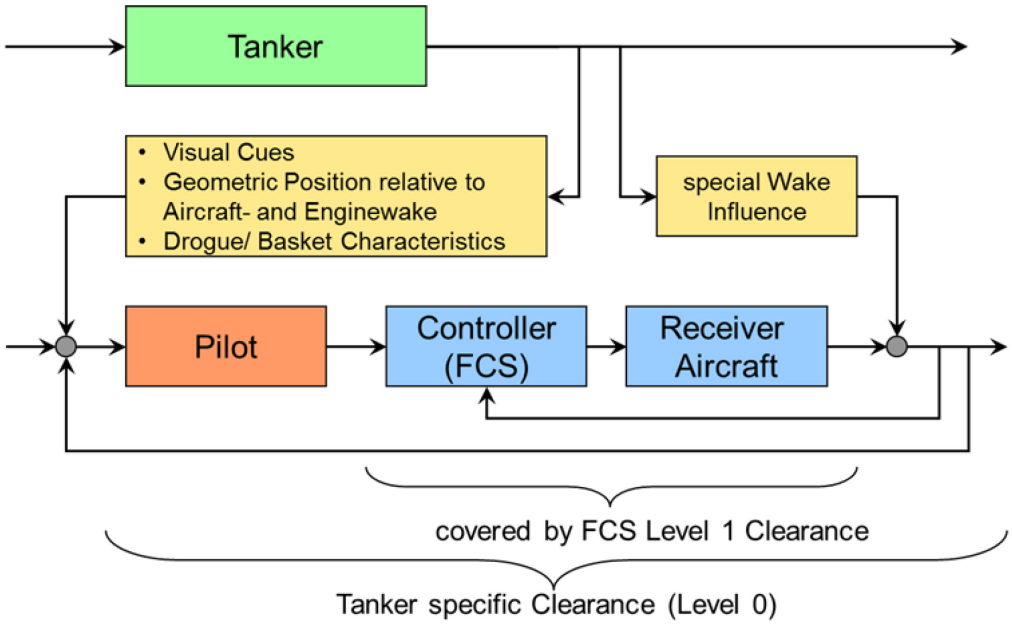


Figure 4-9: Schematic System Diagram Tanker-Receiver-Pilot-Receiver-Aircraft.

4.4.1.1 Hose-Drogue AAR

In the following the aerial refuelling task will be introduced at first for the hose-drogue (hose-basket) system.

AAR-1 Observation Position

Task:

On clearance from tanker re-join tanker aircraft from below and assume observation position at left wing tip position of tanker aircraft.

Performance:

Desired:

Maintain tanker observation position laterally, vertically, and longitudinally within ±5 ft or ±1.5 m of tanker right wing tip.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

Adequate:

Maintain tanker observation position laterally, vertically, and longitudinally within ±10 ft or ±3 m of tanker right wing tip.

AAR-2.0 Refuelling Box Exploration

Task:

On clearance from tanker position receiver aircraft behind basket so that the tip of the receiver aircraft is sufficiently free of the basket, distance 6 ft to 8 ft or 1.5 m to 2 m behind basket.

Move receiver aircraft laterally behind basket (up and down, left, and right) to explore available refuelling box. Note when tanker aircraft wake turbulences or tanker induced vibrations occur.

Technique:

This test set-up is aligned with the most common situation that a tanker aircraft carries refuelling pods under the outer surfaces of its wings. Testing needs to be adapted for a situation with the hose-drogue system aligned with the centre line of the tanker aircraft.

The evaluation pilot will move the receiver aircraft laterally behind the basket.

- Upward movement is to find out about the location of the wing trailing vortex sheet.
- Outward motion is to find out about the location about the wing tip vortex.
- Inboard motion is to find out about the location of possible tanker propulsive wakes (propeller wake, jet engine exhaust stream).

The procedure has been outlined in Ref. [45]. Mentioned boundaries will be evaluated post flight with a pilot sketch. This serves as a guideline for all subsequent AAR tests. A schematic example is given in **Figure 4-10**. The introduction of Levels 1 through 3 indicates where low (almost none) aerodynamic disturbances can be felt (Level 1) and where high and intolerable disturbances can be felt (Level 3).

Depending on the location of the refuelling probe on the receiver aircraft (right or left side of cockpit) the refuelling situation changes considerably with the position behind the tanker (left or right wing). This is due to the fact that the lateral position of the receiver with respect to the tanker cannot be mirror imaged from one side to the other. Therefore, this test must be performed at all tanking positions for one tanker.

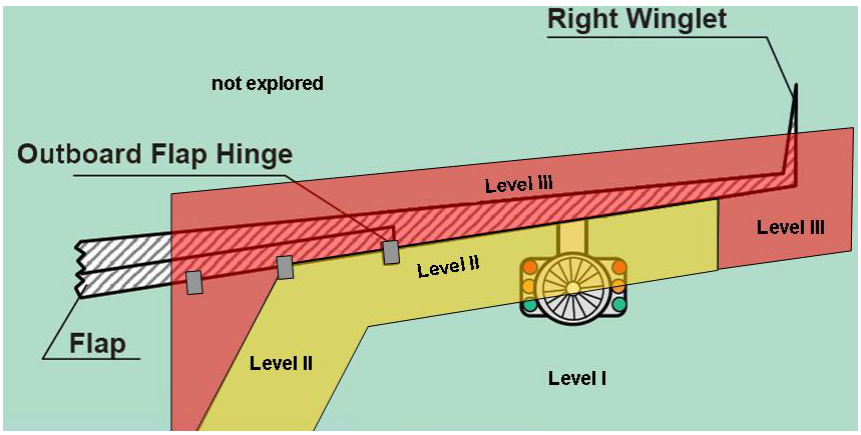


Figure 4-10: Schematics of Result of an AAR Refuelling Box Exploration.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

Reasoning:

Different tankers exhibit different wake characteristics at the refuelling station. In this initial test step, the allowable refuelling area behind the basket of a specific tanker must be identified.

AAR-2.1 Pre-Contact Position

Task:

On clearance from tanker start from observation position and expeditiously assume pre-contact position at about 5 ft or 1.5 m behind drogue. Maintain aircraft position for about 1 min.

Technique:

For adequate position maintenance the pilot will align the receiver aircraft on a line from pilot's viewpoint via tip of refuelling probe to the centre of the basket.

The evaluation pilot reports on environmental anomalies, e.g., turbulent outside air flow, or large to excessive basket movements.

Performance:

Desired:

- Laterally and vertically within half a basket radius or ±1 ft or ±0.3 m.
- Longitudinally within ±2 ft or ±0.6 m.

Adequate:

- Laterally and vertically within one basket radius or ±2 ft or ±0.6 m.
- Longitudinally within ±5 ft or ±1.5 m.

AAR-2.2 Assume Contact Position

Task:

On clearance from tanker start from pre-contact position and perform hook-up with about 2 - 3 KCAS overtake. Make contact.

Assess situation (turbulence, basket movement, receiver aircraft dynamics) when achieving contact and note number of unsuccessful contacts before final contact is made.

Technique:

For adequate contact alignment the pilot will align the receiver aircraft on a line from pilot's viewpoint via tip of refuelling probe to the centre of the basket.

Engine/thrust adjustment technique will be made according to pilot's discretion.

For HQ evaluation purposes a "dry contact" is sufficient. "Dry" means no fuel take over from the tanker. This can be controlled in two ways, no fuel pumping from the tanker or no opening of the receiving valves on the receiver.

Depending on specific tanker environment the test requirement may be to have the hose pressurised (primed). This may be necessary due to differences in hose-drogue dynamics with primed and non-primed systems.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

Performance:

Desired:

- Laterally and vertically within half a basket radius or ±1 ft or ±0.3 m.
- Longitudinally within ±5 ft / ±1.5 m of the nominal hose refuelling range mid-position.

Adequate:

- Laterally and vertically within one basket radius or ±2 ft or ±0.6 m.
- Longitudinally within ±10 ft or ±3 m of the nominal hose refuelling range mid-position.

AAR-2.3 Maintain Contact Position

Task:

Maintain contact position relative to the nominal hose position in straight-and-level flight as well as in turns.

Performance:

Desired:

- Laterally and vertically within ±2 ft or ±0.6 m.
- Longitudinally within ±5 ft / ±1.5 m of the nominal hose refuelling range mid-position.

Adequate:

- Laterally and vertically within ±5 ft or ±1.5 m.
- Longitudinally within ±10 ft or ±3 m of the nominal hose refuelling range mid-position.

AAR-3 Disconnect

Task:

Perform normal and emergency disconnect.

Performance:

Assess HQ qualitatively and give recommendation for emergency disconnect procedure.

AAR-4 Operational Hook-up Procedure

Task:

On clearance from tanker start from the observation position. Continuously move the aircraft into the contact position and perform contact.

Assess handling qualities qualitatively when achieving contact and note number of unsuccessful contacts before final contact is made.

Performance:

Desired:

90 sec time to achieve successful contact.

Adequate:

120 sec time to achieve successful contact.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

4.4.1.2 Boom AAR

The following describes specific Handling Qualities manoeuvres which are applicable for boom AAR.

AAR-5 Uncoupled HQ Characteristics

Task:

Establish FQ characteristics behind moving AAR-boom.

Technique:

- Close-in behind tanker at about 100 ft distance.
- Direct boom operator to fly box pattern (see **Figure 4-11**) at slow rate (1 deg/sec to 2 deg/sec).
- Track boom with defined reference in HUD.
- Repeat box pattern at fast rate (3 deg/sec to 4 deg/sec).
- Close-in to pre-contact position.
- Practice emergency separation from pre-contact position.
- Re-join tanker close to pre-contact position.
- Repeat box pattern as described above (slow and fast).
- Close-in to contact position with boom at mid-length. No coupling.
- Practice emergency separation from uncoupled position.
- Re-join uncoupled contact position.
- Direct boom operator to fly Bow Tie pattern (see **Figure 4-12**).
- Follow boom positioning instructions and boom tracked receiver receptacle. a) Mid-length boom; b) Short boom; and c) Long boom.
- Repeat with reverse Bow Tie pattern.
- Perform station keeping in contact with boom at mid-boom length (30 deg elevation, 0 deg azimuth).

  Contact for this test point is desired, uncoupled contact acceptable, to be chosen on discretion of test team.

  - Roll to 15 deg bank angle, max. roll rate 1 deg/sec.
  - From this position roll to 30 deg bank angle, max. roll rate 3 deg/sec.
  - Accomplish at least 90 deg heading change.
  - Roll to wings level, max. roll rate 3 deg/sec.

Reasoning:

Explore basic receiver aircraft characteristics while preparing for the boom AAR task.

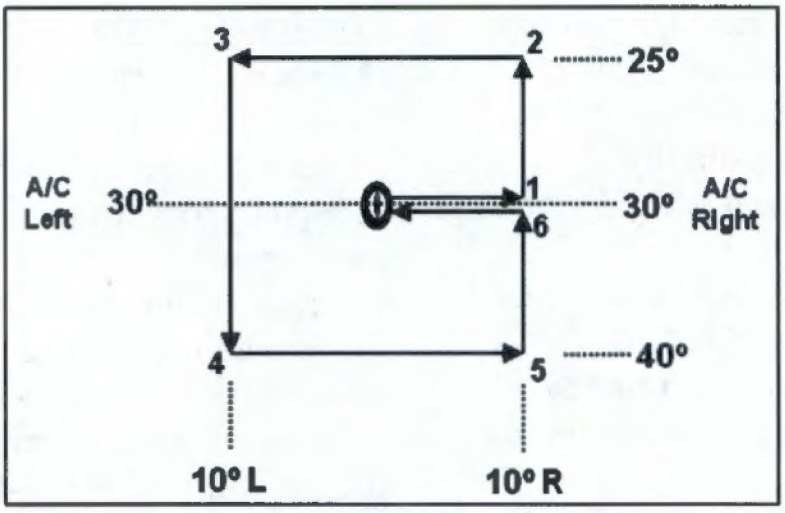


Figure 4-11: Boom AAR, Box Pattern of Boom Tip.

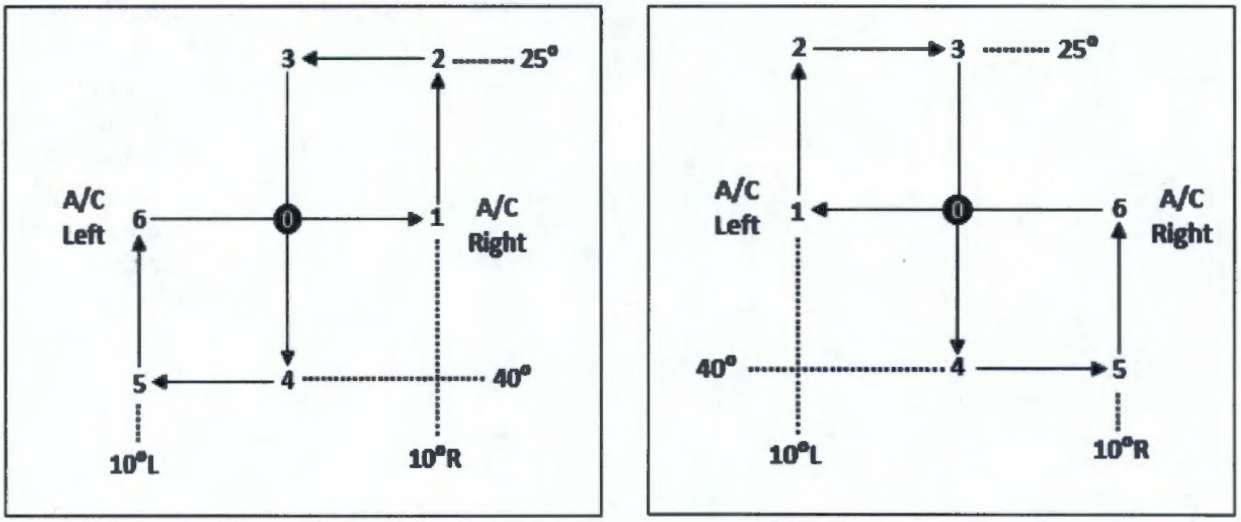


Figure 4-12: Boom AAR, Bow Tie Pattern of Boom Tip; (Left) Regular, (Right) Reverse Pattern.

AAR-6 Coupled HQ Characteristics

Task:

Establish HQ characteristics while in contact with AAR-boom.

Technique:

- Establish contact with 30 deg elevation and 0 deg azimuth.
- Perform compatibility disconnects and normal contacts.
- Assess HQ during multiple two-minute periods during the fuel transfer. (Give only one CHR).

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

Performance:

Desired:

- ±4 deg elevation for maintaining up-down position.
- Boom extension length within solid green band (depending on type of tanker).
- ±5 deg azimuth for maintaining centre line position.

Occasionally momentary excursions are acceptable.

Adequate:

- ±7 deg elevation for maintaining up-down position.
- Boom extension length within solid yellow band (depending on type of tanker).
- ±10 deg azimuth for maintaining centre line position.

Occasionally momentary excursions are acceptable.

4.4.2 Air-to-Air Tracking (AAT)

Tasks of this kind will be conducted to evaluate the suitability of the aircraft handling characteristics for required highly agile manoeuvres and the ease with which the pilot can achieve the desired tasks within the operating limitations of the aircraft. They are also to evaluate the pilot's workload necessary to achieve the best weapons aiming and tracking accuracy.

As these manoeuvres require the most out of pilot and aircraft only a failure free aircraft can be used. Adequate clear and safe "knock-it-off-criteria" must be defined by participating pilots and briefed prior to the flight.

AAT-1 Gun Tracking During 3 g Turn

Task:

Track target aircraft as expeditiously as possible.

Technique:

The fighter aircraft (evaluation aircraft) is positioned about 1,000 ft above the target aircraft at a distance of about 3,000 ft to 4,000 ft. The fighter will have the target at about 30 deg off set at either side.

The task starts with the flight conditions in terms of altitude and speed as defined in the test matrix. When the fighter pilot calls "go" the target starts a 3 g turn and the fighter aggressively manoeuvres to put the fixed sight on the target.

The manoeuvre is over once the evaluation pilot is satisfied with the tracking solution.

Performance:

Gross Acquisition:

- Desired: Pointing error ±15 mils.
- Adequate: Pointing error ±25 mils.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

Fine Tracking:

- Desired: Pointing error ±4 mils.
- Adequate: Pointing error ±6 mils.

AAT-2 Heat to Gun Manoeuvre

Task:

Aggressively acquire the target aircraft.

Technique:

Evaluation and target aircraft set up 1 NM line abreast at co-altitude. On an agreed start signal the target aircraft starts to manoeuvre with constant g and power setting according to the requested test condition (manoeuvring only in the horizontal plane).

In the first part of the manoeuvre the evaluation pilot uses a certain attack mode provided by his aircraft, e.g., missile tone to acquire the target aircraft as close as possible.

After successful acquisition, the evaluation pilot selects a different acquisition mode, e.g., gun mode, and calls “FOX 2”. The target reverses the turn, and the fighter again acquires the target. This time the evaluation pilot uses the new acquisition method, e.g., gun symbol in HUD.

The evaluation pilot calls for termination of the manoeuvre once he has acquired the target again.

Performance:

Gross Acquisition

- Desired: Pointing error ±15 mils.
- Adequate: Pointing error ±25 mils.

Fine Tracking Phase

- Desired: Pointing error ±4 mils.
- Adequate: Pointing error ±6 mils.

AAT-3 Scissors

Task:

Find a gun tracking solution against target aircraft at common altitude.

Technique:

Both aircraft (fighter and target) fly at common altitude about 3,000 ft apart line abreast. Both aircraft try to establish a gun solution by using scissors manoeuvring technique.

The manoeuvre is over once one of the two has acquired a gun tracking solution.

AAT-4 Butterfly Manoeuvre

Task:

Track an aerial target with out of plane manoeuvring.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

Technique:

Task set-up is with fighter and target aircraft 1 mile line abreast. Both aircraft break away from each other and afterwards turn into each other again. After 3/9-line passage flying towards each other the target turns 360 deg with 5 g in the plane of manoeuvring. The fighter is free to manoeuvre to find a gun tracking solution, including out of plane manoeuvring.

The manoeuvre is over once the fighter has acquired a gun tracking solution.

4.4.3 Basic Fighter Manoeuvres (BFM), Gross Manoeuvring

BFM-1 F-Pole Manoeuvre

Task:

- Simulate firing of beyond-visual-range missile.
- Perform a level break turn with 50 deg heading change.
- Simultaneously decelerate the aircraft as quick as possible (airbrake out, throttles at idle).
- After 20sec continue turn (max. dry) and rapidly assume heading 180 deg out of start heading.

Performance:

Qualitatively assess:

- Precision in roll control.
- Available roll rate and predictability.
- Available load factor and predictability.

Reasoning:

The F-pole manoeuvre is a tactical manoeuvre as it is applicable in a beyond-visual-range active radar missile fight.

BFM-2 Full Stick Break Turn

Task:

- Stabilise the aircraft at 1g straight-and-level flight and the heading noted.
- Aggressively apply full aft, full lateral control inputs to achieve 90° bank angle, setting thrust as required.
- Maintain full aft stick until a 180° heading change has been achieved.
- Roll out on a heading 180° from the initial heading.
- Capture “wings level”.

Performance:

Desired:

- Capture ±5 deg angle of bank.
- 1 overshoot.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

Adequate:

- Capture ± 10 deg angle of bank.
- Maximum 2 overshoots.

BFM-3 Immelmann

Task:

- Stabilise the aircraft at 1g straight-and-level flight and the heading noted.
- Apply full back stick and set thrust as required.
- After a half loop, level out in inverted flight on a heading 180° from the initial heading.
- Roll to wings level and stabilise at 1g straight-and-level flight.

Performance:

Qualitatively assess:

Available longitudinal load factor and its predictability during the pull.

Desired**:**

- Capture bank angle ±10 deg.
- 1 Overshoot.

Adequate:

- Capture bank angle ±15 deg.
- 2 Overshoots.

BFM-4 Loaded Roll

Task:

Stabilise the aircraft at 1g straight-and-level flight at the defined flight conditions. Perform a high g barrel roll with maximum n_z loading.

Performance:

Qualitatively assess:

- Precision in roll control.
- Available roll rate and predictability.
- Available load factor and predictability.

BFM-5 Looping

Task:

Stabilise the aircraft at 1g straight-and-level flight. Perform a looping with scheduled AoA and up to FBS with power setting as required.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

Performance:

Qualitatively assess:

- Ability to control n_z and AoA.
- Ability to perform vertical manoeuvres while managing energy (e.g., min. energy loss).
- Check for lateral/directional effects, e.g., wing rock, bank changes.
- Check for undesired interaction between axes and control harmony.

BFM-6 Max. Longitudinal Load Factor Reversals

Task:

- Stabilise the aircraft at 1g straight-and-level flight.
- Perform a full aft stick level turn adjust thrust to maintain speed and altitude.
- Reverse the turn using a full roll stick input (roll over the top or underneath) while maintaining FBS.
- As soon as the aircraft achieves the equivalent opposite bank angle return to wings level.

Performance:

Qualitatively assess:

- Precision in roll control.
- Available roll rate and predictability.
- Available load factor and predictability.

BFM-7 Negative Longitudinal Load Factor Reversals (Jink Out)

Task:

- Stabilise the aircraft at 1g straight-and-level flight.
- Perform a level 60 deg turn and adjusted thrust to maintain speed and altitude.
- Apply full forward stick and full lateral stick in the opposite sense.

Performance:

Qualitatively assess:

- Precision in roll control.
- Available roll rate and predictability.
- Available load factor and predictability.

BFM-8 Split-S

Task:

- Stabilise the aircraft at 1g straight-and-level flight and the heading noted.
- Roll the aircraft inverted and capture 180° bank angle.
- Apply full back stick and set thrust as required.
- Level the aircraft on a heading 180° from the initial heading.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

Technique:

As the Split-S manoeuvre generates a rapid aircraft movement towards the ground the manoeuvre must be assessed first at a safe altitude. Only when approximate loss of altitude during this manoeuvre is known the initial altitude can be reduced.

Performance:

Qualitatively assess:

Available longitudinal load factor and its predictability during the pull. Note altitude loss.

Desired:

- Capture bank angle ±10 deg.
- 1 Overshoot.

Adequate:

- Capture bank angle ±15 deg.
- Maximum 2 Overshoots.

4.4.4 Descent, Approach, and Landing (DAL)

Handling qualities during descent, approach, and landing need to be assessed in order to demonstrate that the aircraft can be adequately controlled about all three axes during these critical flight phases. Different techniques need to be flown to demonstrate the ability to precisely control horizontal and vertical flight path and airspeed. Different configurations need to be flown as well (weight, CG). Configuration airbrake in and out (if applicable) influences aircraft characteristics as well as landing gear up and down, whereas (most certainly) the gear up configuration can be chosen for all tests except for the final landing.

DAL-1 Descent

Task:

Perform aircraft descent according to given test requirements.

Technique:

A variety of test requirements/schedules may be given, e.g., IFR descent, range descent, rapid descent. Additional configuration measures like extension of (possibly available) airbrake may be given in test schedule.

Performance:

Maintain given speed/Mach schedule within the following limits:

Desired Performance:

Mach: ±0.02, KCAS ±10 kts.

Adequate Performance:

Mach: ±0.05, KCAS ±20 kts.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

Reasoning:

Procedures for given descent schedules need to be assessed in order to demonstrate their suitability.

For agile, rapid descents, according to pilot comments, the respective schedule may need to be refined in order to reduce risk of disorientation.

DAL-2 Approach

Various approach techniques can be tested.

APPR-1 Flight Path Stability

Task:

Assess flight path stability while in an approach pattern.

Technique:

Initiate the approach with reference flight path and nominal approach speed. Use normal approach configuration with landing gear down. Change speed according to test requirements via pitch stick input with constant throttle setting.

Assess flight path behaviour.

Reasoning:

Aircraft behaviour changes when flying on “the backside of the power curve”, low speed, high AoA. Thus, speed stability behaviour needs to be tested.

APPR-2 Normal Visual Approach

Task:

Carry out a normal visual approach.

Technique:

- Initiate the approach approximately one mile out on final, nominal approach conditions with landing gear up.
- On final approach lower the landing gear.
- The task will be performed in any wind or turbulence condition as allowed by the operational limits of the aircraft.
- If applicable: The manoeuvre will be performed with airbrake in and out, and if applicable, from front and rear cockpit.

Performance:

Desired:

Maintain approach AoA within ±1 deg.

Adequate:

Maintain approach AoA within ±2 deg.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

Appr-3 Longitudinal Offset Approach

Task:

Perform a longitudinal offset approach by aligning the aircraft with the runway centreline but initially aiming for touchdown 500 ft short of the normal aim point.

Technique:

- Established approach conditions according to test matrix.
- Correct back to the normal touch down aim point at 200 ft AGL (or any other value as given in the test matrix).
- Capture the runway and revert to a normal landing or a touch and go.

Performance:

Desired:

- Touch down laterally ±10 ft from centreline and longitudinally ±100 ft from desired touch down point.
- Capture and maintain centreline within ± 3 ft.

Adequate:

- Touch down laterally ±25 ft from centreline and longitudinally ±200 ft from desired touch down point.
- Capture and maintain centreline within ± 10 ft.

Reasoning:

Aircraft behaviour changes when flying on “the backside of the power curve”, low speed, high AoA. Thus, speed stability behaviour influences pitch pointing characteristics in the final before touch down.

Appr-4 Lateral Offset Approach

Task:

Perform a lateral offset approach by aligning the aircraft with approx. 200 ft offset from the runway centreline.

Technique:

- Establish approach conditions according to test matrix with 200 ft lateral offset.
- Correct back to runway centreline at initially 500 ft AGL.

  (With a stepped procedure according to the test matrix in follow-on tests the correction altitude can be reduced down to 200 ft AGL.)
- Capture runway centreline within predefined lateral tolerances and revert to normal landing procedure or a touch and go.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

Performance:

Desired:

- Touch down laterally ±10 ft from centreline and longitudinally ±100 ft from desired touch down point.
- Capture and maintain centreline within ± 3ft.

Adequate:

- Touch down laterally ±25ft from centreline and longitudinally ±200 ft from desired touch down point.
- Capture and maintain centreline within ± 10 ft.

Reasoning:

Lateral dynamics of the PVS shall be challenged with this type of manoeuvre. When going down with the decision altitude and coming closer to the ground pilot stress may play a role as well. Also, a heavy aircraft may give higher challenges than a light one.

Appr-5 GCA Approach

Task:

Perform an approach under Ground Control Assistance.

Technique:

In a regular approach follow Ground Control instructions.

Performance:

Desired:

- Maintain requested approach speed within ±3 kts.
- Maintain requested glide path angle within ±1 deg.
- Maintain requested heading within ±1 deg.

Adequate:

- Maintain requested approach speed within ±5 deg.
- Maintain requested glide path angle within ±3 deg.
- Maintain requested heading within ±2 deg.

Reasoning:

This type of test point is selected for investigation of PVS interaction with an “outside” control input.

Appr-6 Overshoot

Task:

From a nominal stabilised approach, initiate a sudden go-around at approximately landing gear height above runway, or at least below 50 ft AGL.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

Technique:

Pitch up rapidly to attain fly away flight path and apply power as appropriate. End manoeuvre when a positive rate of climb is attained. If contact with the runway is unavoidable, such contact is acceptable, provided the aircraft is safely controllable and there is no danger of tail strike.

Repeat manoeuvre with simulated single engine failure (1 throttle to idle, one throttle as required).

Performance:

Desired:

±1 deg deviation from reference flight path.

Adequate:

±2 deg deviation from reference flight path.

Reasoning:

Even after a sudden manoeuvre like an overshoot the aircraft must be controllable with certain precision.

Appr-7 Formation Approach and Go-Around

Task:

From a nominal stabilised approach in close formation with wingman positioned upwind initiate break away and a go-around at approximately landing gear height above runway, or at least below 50 ft AGL.

Technique:

- Configure for power approach. If applicable extend airbrake as required.
- Maintain fingertip formation during final approach.
- Transition to 10 ft wing tip clearance prior to approaching minimum descent altitude.
- At minimum descent altitude initiate go-around.
- Pitch up rapidly and break away from wingman.
- Attain fly away flight path and apply power as appropriate. End manoeuvre when a positive rate of climb is attained.
- If contact with the runway is unavoidable, such contact is acceptable, provided the aircraft is safely controllable and there is no danger of tail strike.

Performance:

Desired:

±2 ft longitudinal, lateral, vertical position from wingman during approach

Occasional momentary excursions are acceptable.

Adequate:

±5 ft longitudinal, lateral, vertical position from wingman during approach.

Occasional momentary excursions are acceptable.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

Reasoning:

The aircraft must be controllable during formation approach, after a sudden manoeuvre like an overshoot the aircraft must be controllable with certain precision.

DAL-3 Landing

As the terminal flight phase, landing is a critical manoeuvre. Handling qualities evaluations need to be conducted in order to provide qualitative evaluations of proper landing techniques (light aircraft, heavy aircraft, where applicable with and without airbrake). Landing in adverse environmental conditions are important as well (cross wind, slippery runway).

Procedures and pilot techniques for normal landing and performance landing will be conducted up to the allowable cross wind limits in order to demonstrate that the aircraft can be adequately controlled about all three axes during the landing with the provided techniques at low speeds. It is also a check for adequate control for aggressive corrections in the final landing phase.

Another important issue is the evaluation of the possibilities/ease with which directional control on ground can be achieved with and without the use of nose wheel steering.

Final variation of test conditions depends on the given tasks, available clearances, and weather conditions.

Ldg-1 Normal Landing

Task:

Perform a normal full stop landing according to given procedural rules.

Technique:

For a normal landing after touchdown the aircraft will be decelerated on the runway until a full stop is achieved. It can be conducted with airbrake in and out (if applicable), also with usage of a possibly available brake chute.

In case of a performance landing the aircraft is brought to a most efficient stand still, obeying appropriate braking techniques in order to not overstress the brakes.

The aero braking technique may be used as well. For this technique after touchdown of the main landing gear the nose landing gear is kept off the ground for as long as possible. Through this method significant aerodynamic drag generated by the inclined aircraft can be used for braking as well.

Performance:

Desired:

- Touch down laterally ±10 ft from centreline and longitudinally ±100 ft from desired touch down point.
- Capture and maintain centreline within ± 3 ft.

Adequate:

- Touch down laterally ±25 ft from centreline and longitudinally ±200 ft from desired touch down point.
- Capture and maintain centreline within ± 10 ft.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

Reasoning:

Landing is the most critical flight phase. Proper aircraft handling must be proven. The purpose is to evaluate control sensitivity and harmony in landing.

Landings (airbrake in and out) will evaluate the ability to control horizontal and vertical flight path and airspeed for landing as well as the ability to control sink rate and attitude in a flare.

Ldg-2 Touch and Go

Task:

Perform a Touch and Go

Technique:

After touch down of main landing gear re-accelerate the aircraft for a take-off while maintaining nose landing gear in the up position on the runway.

Performance:

Desired:

- Touch down laterally ±10 ft from centreline and longitudinally ±100 ft from desired touch down point.
- Capture and maintain centreline within ± 3 ft.

Adequate:

- Touch down laterally ±25 ft from centreline and longitudinally ±200 ft from desired touch down point.
- Capture and maintain centreline within ± 10 ft.

Ldg-3 Roller Landing

Task:

Perform a Roller Landing.

Technique:

After touch down (main landing gear) and de-rotation of the nose landing gear on the runway the aircraft will be accelerated for a subsequent take-off.

Performance:

Desired:

- Touch down laterally ±10 ft from centreline and longitudinally ±100 ft from desired touch down point.
- Capture and maintain centreline within ± 3 ft.

Adequate:

- Touch down laterally ±25 ft from centreline and longitudinally ±200 ft from desired touch down point.
- Capture and maintain centreline within ± 10 ft.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

4.4.5 Formation Flying (FF)

FF-1 Close Formation

Formation Flight, Formation Take-Off, Formation Climb, Formation Descent, Formation Approach, Formation Overshoot, and Formation Landing.

Task:

Perform close formation flight in fingertip and close trail position with a lead aircraft.

Technique:

Lead aircraft:

Perform gentle turns e.g., lazy 8 manoeuvres up to ±40 deg angle of bank combined with modest accelerations and decelerations. Steadily increase angle of bank up to ±90° and normal load factor up to 4g during manoeuvring in formation.

Evaluation aircraft:

Achieve and maintain agreed ideal reference lines. Correct for deviations in all three axes. Perform Echelon turns up to 60° bank angle.

Performance:

Desired:

- Gentle target manoeuvring: Maintain relative position of a reference point on the lead aircraft within ±2 ft in all directions.
- More extreme target manoeuvres: Maintain relative position of a reference point on the lead aircraft within ±4 ft in all directions.

Adequate:

- Gentle target manoeuvring: Maintain relative position of a reference point on the airplane within ±4 ft in all directions.
- More extreme target manoeuvres: Maintain relative position of a reference point on the airplane within ±8 ft in all directions.

FF-2 Formation Re-Join

Task:

From a position approx. 1NM in trail, expeditiously assume close formation fingertip position:

a) With lead aircraft flying straight ahead.

b) With the lead aircraft in a level turn (30° – 45° bank angle).

Technique:

Selection of re-join side of lead aircraft to pilot's discretion. In a turn upper and lower side should be tested as reference cues may be different.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

Performance:

Desired:

- Re-join formation and achieve relative position of a reference point on the airplane within ±5 ft in all directions.

Adequate:

- Re-join formation and achieve relative position of a reference point on the airplane within ±10 ft in all directions.

TOC-3 Formation Take-Off

See Section 4.4.7 “Take-Off and Climb-Out”.

Appr-7 Formation Approach and Go-Around

See Section 4.4.4 “Descent, Approach, and Landing (DAL)”.

4.4.6 Ground Attack Manoeuvring (GAM)

Operational ground attack manoeuvres will be given in the following. The specific task will be to evaluate the PVS in various available ground attack modes.

It will not be the task to perform these manoeuvres according to the selected weapon sub-system. The task will be to evaluate PVS dynamics with the given guidance methodology (e.g., HUD symbols). There will be no weapon release.

GAM-1 Loft Attack

Task:

- Select a target (own discretion) and stabilise the required flight condition (test matrix).
- Select the appropriate weapon system mode and follow the “pull-up director” as displayed in the HUD.

Performance:

Desired:

Maintain aircraft symbol in the HUD within one diameter of the size of the aircraft symbol of the pull-up director symbol.

Adequate:

Maintain aircraft symbol in the HUD within two diameters of the size of the aircraft symbol of the pull-up director symbol.

GAM-2 Dive Attack

Task:

- Select a target (own discretion) and stabilise the required flight condition (test matrix).
- Select the appropriate weapon system mode and follow the appropriate directions given in the HUD.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

- Establish a dive angle not steeper than 20 deg and consequently capture with the aircraft symbol the steering symbol as indicated in the HUD.

Performance:

Desired:

Maintain the aircraft symbol within one diameter of the aircraft symbol size of the steering symbol.

Adequate:

Maintain the aircraft symbol within two diameters of the aircraft symbol size of the steering symbol.

GAM-3 Dive Toss Attack

Task:

- Select a target (own discretion) and stabilise the required flight condition (test matrix).
- Select the appropriate weapon system mode and follow the appropriate directions given in the HUD.
- Establish a dive angle not steeper than 20 deg and consequently capture with the aircraft symbol the steering line as indicated in the HUD and keep the aircraft symbol on the pull-up director symbol.

Performance:

Desired Performance:

Maintain the aircraft symbol within one diameter of the aircraft symbol size of the pull-up director symbol.

Adequate:

Maintain the aircraft symbol within two diameters of the aircraft symbol size of the pull-up director symbol.

GAM-4 Strafe Pass

Task:

- Select a target (own discretion) and stabilise the required flight condition (test matrix).
- Select A/S gun attack mode.
- Start the manoeuvre at approximately at 4,000 ft altitude.
- The manoeuvre is finished when reaching minimum allowable altitude.

Performance:

Qualitatively assess the HQ of the aircraft, e.g., pointing capability.

4.4.7 Take-Off and Climb-Out (TOC)

Take-off is a critical flight phase and aircraft handling qualities play an important role for this phase. Handling qualities evaluations need to be conducted in order to provide qualitative evaluations of proper ground roll techniques (light aircraft, heavy aircraft). Take-offs in adverse environmental conditions are important as well (cross wind, slippery runway).

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

TOC-1 Take-Off

Task:

Perform aircraft take-off.

Technique:

- Apply thrust setting (dry, reheat, single engine) according to test matrix.
- Perform brake release according to given procedural rules, e.g., at requested engine condition in terms of engine rotational speed.
- Keep pitch stick in neutral position.
- At calculated rotation speed, smoothly and progressively apply aft stick and control the rotation rate to meet the calculated take-off speed.
- Control the desired climb-out attitude with given HUD symbols.
- Once a sufficient positive rate of climb has been established, raise the landing gear.

Performance:

Desired:

- ±3 ft deviation from runway centreline throughout take-off roll.
- ±1 deg from reference AoA.
- ±1 deg from reference flight path.
- ±5 deg deviation from desired bank angle.

Adequate:

- ±10 ft deviation from runway centreline throughout take-off roll.
- ±2 deg from reference AoA.
- ±2 deg deviation from reference flight path.
- ±10 deg deviation from desired bank angle.

Reasoning:

HQ during max. dry and max. reheat take-offs up to the allowable cross wind limits will be evaluated in order to assess:

- Recommended piloting techniques.
- HQ during rotation.
- Assess capabilities to attain reference attitude and airspeed following take-off.

Directional control characteristics of the aircraft during take-off roll will be assessed in order to evaluate the:

- Ease with which directional control can be achieved.
- Ability to perform take-off ground roll in gusty and cross wind conditions (adequacy and ease of directional control).

This requires a variety of take-off runs with various engine settings, various runway conditions, and various cross wind conditions. Depending on operational necessity it may be required to test various combinations of these conditions.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

TOC-2 Climb-Out

Task:

Perform aircraft climb-out according to given test requirements.

Technique:

Initiate the climb from level flight (performance climbs will be conducted straight from the runway). The following schedules may be possible: normal, single engine climb-out, performance climb, minimum fuel consumption climb.

- Follow the given climb schedule and level off at target altitude (will be defined by the pilot during climb according on ATC discretion).
- Single engine climbs will be conducted with one engine at idle throttle setting.

Performance:

Desired:

- Normal climb / single engine climb / minimum fuel consumption climb:
  - Maintain speed / Mach number within ± 10 KCAS or ± 0,02 Mach.
  - Level off within ± 100 ft (normal climb only).
- Performance climb:

  Maintain speed / Mach number within ± 20 KCAS or ± 0,03 Mach.

Adequate:

- Normal climb / single engine climb / minimum fuel consumption climb:
  - Maintain speed / Mach number within ± 20 KCAS or ± 0,03 Mach.
  - Level off within ± 100 ft (normal climb only).
- Performance climb:
  - Maintain speed / Mach number within ± 40 KCAS or ± 0,05 Mach.

Reasoning:

Procedures for given climb schedules need to be assessed in order to demonstrate their operational suitability.

For agile performance climbs, according to pilot comments, the respective flight test recommended schedules will reduce the risk of a spatial disorientation.

TOC-3 Formation Take-Off

Task:

Perform aircraft take-off in formation with another aircraft.

Technique:

- Line up with wingman upwind and with at least 10 ft lateral separation.
- Signal when ready.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

- Apply thrust setting according to test matrix.
- Perform brake release once wingman starts rolling.
- Apply given procedural rules, e.g., at requested engine condition in terms of engine rotational speed.
- Retard by lead to allow wing man adequate power control.
- Keep pitch stick in neutral position.
- At calculated rotation speed, smoothly and progressively apply aft stick and control the rotation rate to meet the calculated take-off speed.
- Maintain wing tip clearance throughout take-off roll and rotation.
- Control the desired climb-out attitude following the wingman and with given HUD symbols.
- Once a sufficient positive rate of climb has been established, raise the landing gear.
- Transition to fingertip formation.

Performance:

Desired:

- ±5 ft maintain longitudinal position during take-off roll.
- ±3 ft maintain vertical position.

Adequate:

- ±10 ft maintain longitudinal position during take-off roll.
- ±5 ft maintain vertical position.

Reasoning:

HQ during formation take-offs will be evaluated in order to assess:

- Recommended piloting techniques.
- HQ during rotation.
- Assess capabilities to attain close formation position following take-off.

Directional control characteristics of the aircraft during take-off roll will be assessed in order to evaluate the:

- Ease with which directional control can be achieved.
- Ability to perform take-off ground roll in case of gusty and cross wind conditions (adequacy and ease of directional control).

4.5 STANDARD EVALUATION MANOEUVRES (STEM)

In the early 1990s a US Air Force initiative was started to design a set of flight manoeuvres which are well suited for testing HQ of modern high-performance aircraft. The process of manoeuvre design and evaluation is well documented in Refs. [46], [47], [48], and [49]. There have been extensive simulation sessions as well as flight test campaigns for selected aircraft. A set of 20 manoeuvres has been developed, commonly known as STEM-manoeuvres.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

These manoeuvres are given in the referenced catalogue and are explained in detail in these documents, namely Ref. [47]. Because of this excellent documentation only a very brief overview will be given here. Some of the STEMS have been given in the previous sections already, in a similar set-up as here.

The given manoeuvres are more of academic nature than the ones given in the previous section. Nevertheless, they are valuable for identifying or isolating FQ/HQ deficiencies. The given generic form allows for manoeuvre adaptation according to specific test needs. The full description of these manoeuvres is given in Ref. [47].

STEM-1 Tracking During High AoA Sweep

This manoeuvre is initiated with the evaluation pilot in trail of a cooperative target aircraft. The target enters a turn with decreasing turn radius and the evaluation pilot evaluates his ability to track the target. The manoeuvre is designed such that the evaluation pilot must gradually increase AoA until tracking can no longer be conducted.

STEM-2 High AoA Tracking

Other than the STEM-1 manoeuvre this manoeuvre is set up in a way that the evaluation pilot can do the required tracking at a more or less constant AoA. It is a follow-on manoeuvre for STEM-1 for cases where possibly problems had occurred during sweeping tracking.

STEM-3 High AoA Lateral Gross Acquisition

This manoeuvre is set up such that the evaluation pilot can pull to a desired AoA, stabilise, and then roll to acquire a target aircraft. It was developed to help isolate the lateral axis for flying qualities evaluations at high AoA.

STEM-4 Dual Attack

This manoeuvre consists of the evaluation aircraft and two target aircraft. The targets fly straight-and-level with a 90 deg heading difference and the evaluation aircraft manoeuvres in-between them to alternately acquire each target.

This is to evaluate loaded roll capabilities as well as the ability to unload, roll, and pull to transition between the targets. Good longitudinal as well as lateral dynamics and roll performance can be demonstrated at high AoA.

STEM-5 Rolling Defence

The pilot establishes a turn at a desired AoA or load factor condition, rolls over the top to the opposite bank angle and starts pushing while maintaining lateral stick.

Primary intention is to verify full flight control system control capability while moving in such a manoeuvre.

STEM-6 Maximum Pitch Pull

Stabilise condition and apply full aft stick until the pitch rate stops. It is a simple and easy repeatable manoeuvre to isolate pitch axis peculiarities.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

STEM-7 Nose Up Pitch Angle Capture

Set-up as STEM-6 but with capturing maximum possible pitch attitude. A target aircraft as reference is positioned above the evaluation aircraft.

STEM-8 Crossing Target Acquisition and Tracking

This manoeuvre is conducted by setting up a target aircraft above the evaluation aircraft with a 90 deg heading offset, and the target immediately enters a turn toward the evaluation aircraft. The evaluation pilot tries to acquire rapidly and then continue tracking the target as it crosses in front. This manoeuvre allows the acquisition and tracking capabilities of an aircraft to be exercised through the multiple-axis acquisition of a target aircraft.

STEM-9 Pitch Rate Reserve

Establish a level turn at given conditions. Pull full aft stick and maintain until the nose rate drops below its initial value. It is to demonstrate available pitch authority from a loaded condition.

STEM-10 High AoA Longitudinal Gross Acquisition

While in a turn behind a target aircraft the evaluation pilot performs a series of longitudinal acquisitions of the target aircraft. The intention is to isolate any adverse HQ characteristics during longitudinal capture tasks.

STEM-11 Sharkenhausen

This task is initiated with a head-on target aircraft that is downrange, offset, and higher than the evaluation aircraft. The evaluation pilot attempts to capture the target as rapidly as possible and then track the target. This manoeuvre allows to evaluate the acquisition capabilities of an aircraft to be exercised through a multiple-axis acquisition of a target aircraft.

STEM-12 High AoA Roll Reversal

Starting from a Split-S at test AoA a full roll input is applied. After desired heading change the roll input is reversed until the returning to the initial heading. With this manoeuvre high AoA roll performance is investigated.

STEM-13 High AoA Roll and Capture

Other than for STEM-12 a lateral capture has to be performed.

STEM-14 Minimum Speed Full Stick Loop

A special test technique to identify the minimum entry speed for a full stick loop.

STEM-15 Minimum Time 180 deg Heading Change

Systematic evaluation of possible options to obtain a 180 deg heading change.

STEM-16 1g Stabilised Push Over

From a stabilised high AoA condition (wings level) aggressively apply full forward stick. Evaluate nose down pitch authority at high AoA.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

STEM-17 J-Turn

Apply full stick and roll input simultaneously. Whenever the aircraft has achieved a 180 deg heading change or wings level inverted (whichever comes first) remove roll input and continue to move back up to the horizon. This manoeuvre serves to demonstrate high AoA manoeuvrability.

STEM-18 Tanker Boom Tracking

Try to track the tanker probe, be it steady or being moved by the boom operator. This manoeuvre is to evaluate high gain tracking techniques.

STEM-19 Tracking in PA

Track a target aircraft in 1500 ft range in power approach mode. If possible, the target can perform a sequence of heading changes making the manoeuvre more demanding.

STEM-20 Offset Approach Landing

Correct an established offset from runway centre line and perform a precision landing. This manoeuvre is to correct flight path, speed, and roll performance while configured for approach.

4.6 PRINCIPAL TEST MATRIX (HOW TO USE THIS CATALOGUE?)

The catalogue given in this chapter is a large collection of test manoeuvres applicable for FQ and HQ evaluations. The following discussion shall give some advice in how to use it. As all test programs are specific and different from each other only a rather high-level discussion can be given.

In the very beginning of this report, flight testing was distinguished between Step 1 and Step 2 testing. Step 1 testing is the system integration part where it is proven that an aircraft is safe to fly. Step 2 is the requirements part where it is proven whether the test article complies with given customer operational requirements, whether it is fit for purpose. The given catalogue, with regard to FQ and HQ, covers both steps. Nevertheless, it does not claim to give a complete collection of test manoeuvres.

When a new aircraft needs to be tested from maiden flight onwards a special envelope expansion test programme will be executed. As has been pointed out in Chapter 2, this “Step 1 Programme” will be very much a discipline interactive programme. It will have to be aligned between disciplines of aerodynamics, flight mechanics, air data calibration, loads, flutter boundary evaluation, and integration of various mechanical system disciplines. Some of the test manoeuvres given in this chapter (Phase 1 manoeuvres) may also be used to support this initial testing.

The given structure of this chapter separates the test manoeuvres catalogue into three parts in another sense, Phase 1 testing basically covers open loop testing, Phase 2 testing is devoted to PIO resistance testing, and Phase 3 testing to operational testing, see also Figure 2-3. This separation is orientated at various levels of test complexity, and it reflects the various stages of FQ and HQ testing.

With regard to separation of FQ and HQ testing Phase 1 through Phase 3 testing is applicable to Step 1 testing (safe to fly). Step 2 testing (fit for purpose) from its nature will mainly be required for Phase 2 testing (depending on customer requirements) and for Phase 3 testing. Its contents will depend on the specification as well as special additional customer test requirements.

In the following some basic thoughts will be given on what an application of the given catalogue can look like.

4.6.1 Initial Flight Envelope Expansion

Flying capabilities for a maiden flight depend on many factors. The major allowing or limiting element is the flight clearance. With regard to flying experience, once the aircraft is airborne the pilot will make himself familiar with basic controllability. Afterwards aircraft dynamics in approach configuration should be of interest. This is done normally in a safe altitude, e.g., 5,000 ft AGL with several "practice approaches". Depending on technical capabilities or clearance issues the landing gear may be raised or not. The second part of a first flight will be to get acquainted with aircraft controllability and dynamics in a wider range than the landing configuration. A typical altitude (depending on the clearance) will be at 20,000 ft, see **Figure 4-13**.

Normally Phase 1 test manoeuvres as given above will be used with increasing complexity. Table 4-1 given in Section 4.1.3 gives the proper order, test points 1 through 10 and 13 and 14 are applicable. Doublets, Roller Coaster, Wind Up Turn, and Steady Heading Sideslip (test points 3 to 9) are also well suited for different aerodynamic parameter estimation methods.

Once the first flight has been successfully completed, results of flight data analysis will indicate how the next flights can be planned. Post flight analysis of these specially mentioned aero data gathering manoeuvres serves the validation of the aerodynamic model. Depending on the outcome of these analyses and the special analysis and clearance process for the specific project this may have an impact on the next flights, see discussion to Figure 3-21.

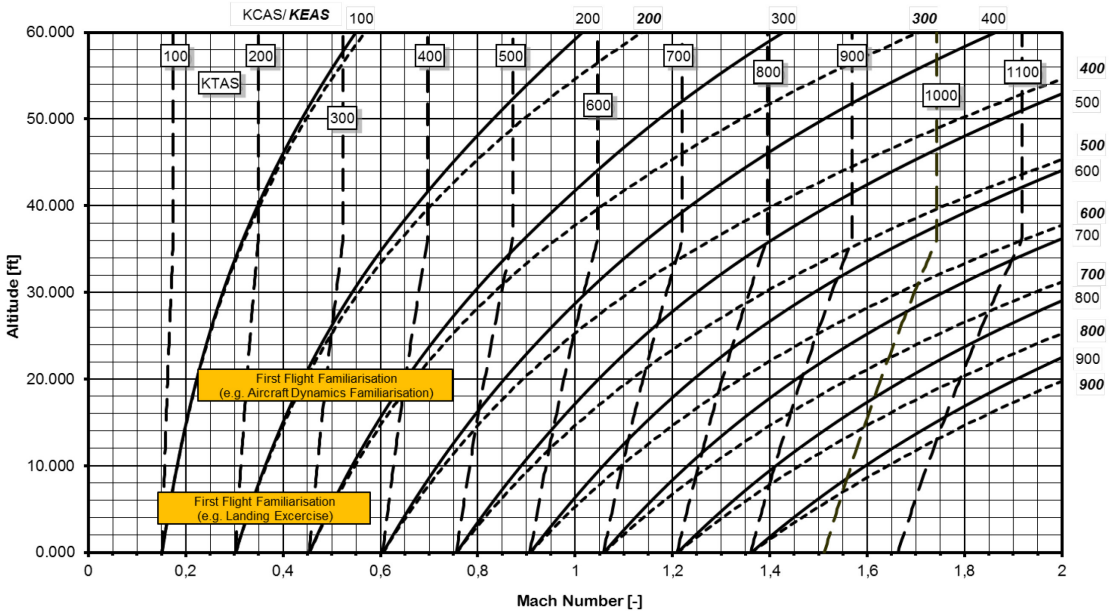


Figure 4-13: Typical First Flight Test Regimes.

4.6.2 Control Law Familiarisation (Phase 1)

As already indicated by its name, FQ Phase 1 testing serves familiarisation purposes. This can be for various reasons. The special case for a maiden flight has been discussed in the previous section. Nevertheless, there can be something like a familiarisation need also during an already existing project respectively test programme. This is the case when a new and heavy store (e.g., 2,000 lbs) is integrated into a 12 ton aircraft, for example. Such a test endeavour needs just as much attention than a maiden flight.

In such a case and with less critical stores, the familiarisation test programme will also be used for aerodynamic data gathering as well. And thoughts as indicated above will be necessary as well.

In the case of a control law familiarisation test period to get to know a modified controller software version the manoeuvre set-up as given in Table 4-1 (see Section 4.1.3) will be applied. Test points should be flown in the given order of sequence. This gives a certain build-up of complexity. In addition, some climbs and descents will be scheduled according to the needs of the programme.

Figure 4-14 shows a generic test set-up for envelope expansion flying in Phase 1. Considerations due to test needs of other disciplines (e.g., Loads or Flutter) are not anymore reflected here. Nevertheless, they still have to be taken into account.

For fast jets, testing in the supersonic region will also have to be considered as flying in this regime will be required for operational tasks. The example here is given for a case where supersonic flight is only possible well above 30,000 ft altitude. There may be situations where this is necessary and allowed at lower altitudes as well.

The overall fineness of test points depends on the operational requirements or programme needs. Thus, this determines the overall number of test points and, thus, the number of flights needed. And recalling, Phase 1 testing should also be flown with at least three pilots (see above).

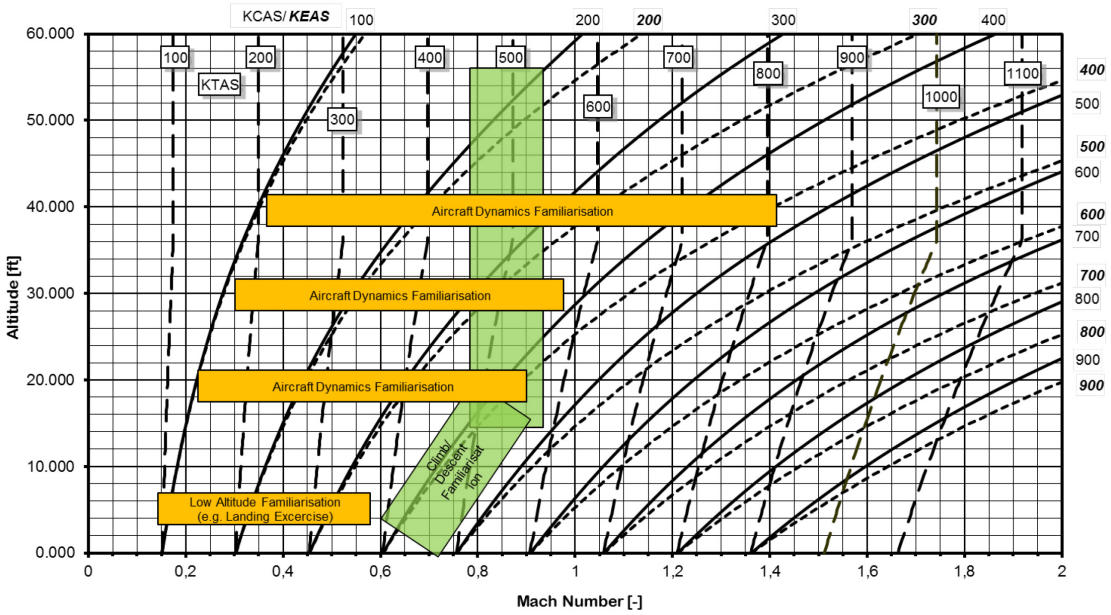


Figure 4-14: Generic Test Matrix for Phase 1 Flight Tests.

4.6.3 PIO Resistance Testing (Phase 2)

PIO resistance testing is highly applicable for any (larger) modifications of highly augmented aircraft, be it the integration of a large store or a modification of the control laws. Section 4.3 gives a collection of possible techniques to test for PIO resistance. The selection of a method depends on various conditions. These can be of technical nature (e.g., availability of synthetic HUD target), test facility availability, or even programme or customer needs. Still, it is mandatory to do this type of testing as best as possible.

The areas of PIO resistance testing within the flight envelope must be put into relation to the operational needs, to the region where most likely the most demanding manoeuvring will take place. **Figure 4-15** gives a test band at 8,000 ft and at 20,000 ft altitude. Both are in the subsonic range. The density and the type of test points depends on operational needs.

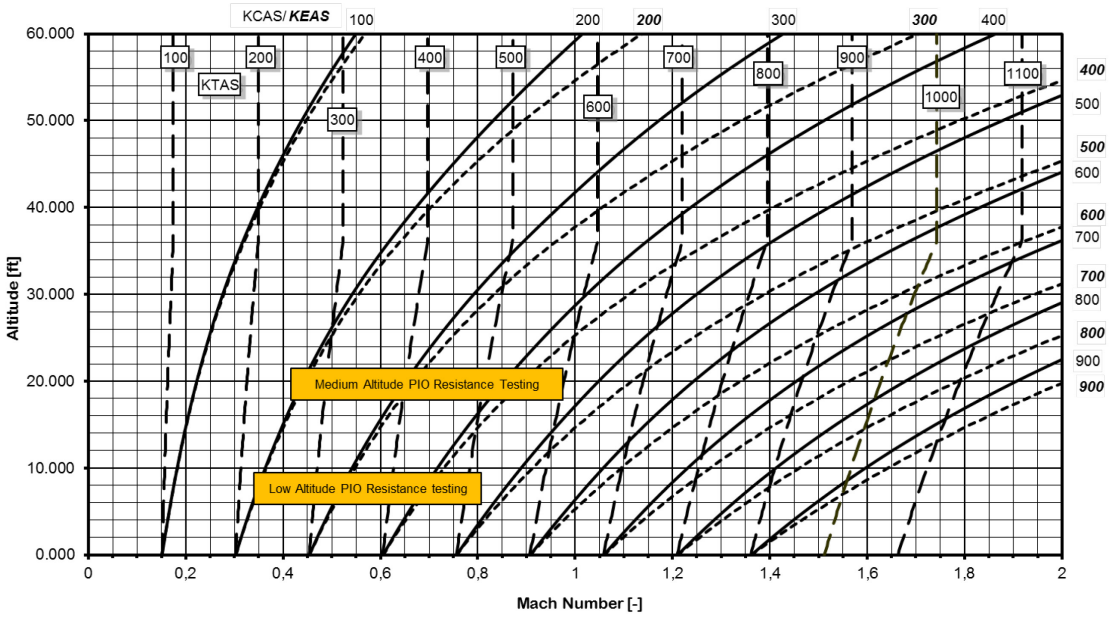


Figure 4-15: Generic Test Matrix for PIO Resistance Testing.

4.6.4 Operational Testing (Phase 3)

As the title of this test phase already indicates, operational testing is dependent on the operational needs of the specific aircraft programme. Thus, a general guideline cannot be given. Some points, though, shall be pointed out.

Aerial Refuelling:

In cases where aerial refuelling is possible and required, PIO resistance testing and operational testing must be considered. The available test envelope is the overlap of two envelopes, the AAR envelope of the tanker and the AAR envelope of the receiver. These may only overlap for a small altitude and speed regime. This governs the possible range of test points. Besides, each pair of tanker and receiver must be tested.

AAR refuelling evaluations should be made as early as possible in the test programme. Once an AAR refuelling clearance is available AAR can be used as test enabler. This means test flights may be prolonged (where possible) via aerial refuelling.

Terminal Flight Phases:

Take-off and landing (still) are the most critical phases of a flight. Thus, operational testing for these phases must be done as early as possible. Critical issues here can be aircraft weight (centre of gravity) and crosswind situations. For take-off additionally (where applicable) single engine and max. dry versus reheat situations are of importance. For landing additionally (where applicable) airbrake in and out, drag chute in and out, and special landing techniques (aero braking) are of importance. This list of parameter variations alone already spans a wide range of test possibilities to be considered.

Only when all these points have been completed satisfactorily one can continue on to do high gain pilot-in-the-loop manoeuvres. The most prominent but also fairly easy to achieve (in terms of test set-up) are offset landings. A stepwise decrease in altitude to achieve the runway re-alignment is mandatory.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

Formation Flying:

This type of manoeuvring is always required when more than one aircraft is flying en route to the same destination. Testing can be scheduled easily, often on a ride along basis, as long as a cooperative aircraft is available. At first the lead aircraft will fly benign course changes. Once confidence is gained more aggressive or agile manoeuvres will follow.

Basic Fighter Manoeuvres, Gross Manoeuvring:

Manoeuvres of this group are all agile manoeuvres for a single aircraft. There is no cooperative or target aircraft required. They can be flown in less aggressive and more aggressive manners. This spans already a wide range of possibilities to be scheduled. Actual selection of a manoeuvre out of this test catalogue depends on the specific test aircraft and its operational requirements.

Air-to-Air Tracking:

This category always requires a target or cooperative aircraft. Actual selection depends on the specific operational requirements.

Ground Attack Manoeuvring:

This category of manoeuvres is important for aircraft which have to fulfil an air-to-ground role. Testing here is only aimed at understanding the weapon system information feedback to the pilot when he tries to deploy, e.g., a bomb. In other words, the PVS dynamics when pursuing a ground attack task. Again, actual amount of testing is dependent on the operational requirements and the possible different ways of information feedback to the pilot.

4.6.5 Some General Test Matrix Considerations

When setting up a test point matrix for a specific test task, various aspects are of interest. The most important and overarching aspect is flight safety. The other equally important issue is testing for the desired purpose of satisfying the customer, the final goal.

Flight safety requires a stepped approach. This means a test point matrix should be set up with increasing complexity. This can be as simple as prescribing AoA increments, or normal load factor increments for Phase 1 manoeuvres. Delta AoA increments can be as small as 1 deg, depending on the test task. When going towards max. AoA WUTs this may be reasonable. For tasks well below max. AoA, increments of 1 deg or 2 deg may be sufficient. This all depends on how practical it is for the pilot to fly with such a requirement. When the specific aircraft and its display systems do not allow 0.5 deg increments to be clearly identified, it makes no sense to task a pilot to fly such increments. This also applies for other tasks.

Given boundaries or available clearances must be taken into account when setting up a test matrix. The process of boundary extension must be considered. The test matrix must not only show the necessary sequence of test points, but it must also show halting points that can only be passed once sufficient and satisfactory analysis is available. In some case these are called safety gates.

The need for special facilities must be clearly stated in a test matrix. This means cooperative aircraft, specific ground observation methods (e.g., kinetheodolites for observation of landing accuracy), or special test ranges. This all must be indicated so that it can be ordered and/or scheduled in time for the tests.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

4.7 FLIGHT SAFETY TEST CONSIDERATIONS

As already mentioned several times, flight test safety is an overarching requirement. One way of following this requirement is categorising all testing into risk levels. Flight test centres have their individual procedural rules for a resilient flight safety process resulting in the proper classification of tests. With regard to FQ and HQ testing, several flight safety critical issues need to be considered. Flying a known aircraft with a new large store (e.g., 2,000 lbs bomb) for the first time is a safety critical issue. The same applies for testing flight control law software updates which incorporate significant changes to the overall aircraft dynamics, e.g., changes to the control law forward path. For all of these, every flight test centre will follow its own rules to come up with a flight safety satisfying review process. Reviews or gates must be passed before continuation of the flight test programme, e.g., “flight test programme review”, “flight test readiness review” prior to commencement of flying, proper pre-flight “briefing culture”, and proper “reporting culture”.

This is another reason why FQ and HQ testing is set up in Phases 1 through 3 with increasing complexity.

As a more technical requirement, telemetry coverage of testing must be defined. Safety critical tests will have to be covered via telemetry and monitored on ground. For less safety critical tests, telemetry coverage may not be a requirement. In all cases, a special “hot mike” audio connection between the test aircraft and ground control is mandatory.

One issue not to be underestimated is pilot training. Modern test facilities provide high fidelity simulators which allow literally every flight to be pre-tested in a simulator. Depending on confidence in the test aircraft type this may not be necessary for all tests. Testing which goes towards the boundaries of the cleared flight envelope does require simulator sessions prior testing. This is necessary for pilots to get acquainted with the special test technique and aircraft behaviour and it helps to prevent breaking the given limit. Special HQ test techniques may require prior simulator training in order to get accustomed to the test technique, e.g., for HQDT trials. Simulator sessions also serve as training for analysis engineers, to better understand the test sequence and display of online monitoring data.

Another issue in pilot training is staying current. HQ testing pilots in particular must be up to date. Thus, it may be necessary for pilots to have special “practice flight” prior to commencing dedicated HQ testing, e.g., AAR.

For all formation flights, air-to-air-refuelling tasks, or tracking against an airborne target, a face-to-face briefing prior to the flight with all other personnel participating in this flight is mandatory. The briefing must detail all test specific issues, including all safety and mid-air potential aspects. For all tests involving a target aircraft, minimum ranges, de-confliction responsibility, target manoeuvring grades and “knock-it-off” criteria have to be clearly defined and included in the briefing.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

Chapter 5 – PRACTICAL EXPERIENCES

Following the more theoretical introduction of the preceding chapters this chapter shall illustrate the given methodology with practical results. It is as well organised along the classification of the three phases given in Figure 2-3.

5.1 PHASE 1 TESTING (THE VALUE OF OPEN LOOP TESTING)

The benefit of open loop familiarisation manoeuvres has already been illustrated in Section 2.3, see Figure 2-5, Figure 2-6, and Figure 2-7. In the following some examples will be given which can be considered “open loop”.

Open loop testing serves many purposes which include providing an initial look at aircraft Stability and Control (S&C) characteristics for safe envelope expansion; clearing an envelope for the execution of aircraft handling qualities manoeuvres; and collecting data for updating models or model validation. Open loop testing directly supports the updating as described in Figure 3-21 of Section 3.7. LOES or aerodynamic model extraction test results from open loop testing may be used to predict or validate handling qualities flight test results.

From C-17

The example of roll ratcheting given in Figure 2-7 was experienced on an agile high-performance aircraft. This phenomenon may also be observed on large by far less agile aircraft. Norton [50] reports on aero-elastic pilot in the loop oscillations while testing the C-17 aircraft. The corresponding figure showing these oscillations is given in **Figure 5-1**. Like a fighter aircraft the C-17 has a centre stick as pilot inceptor.

As described in Ref. [50]:

> *An aeroelastic pilot-augmented oscillation was found to exist on the McDonnell Douglas C-17A [see Figure 5-1] during a roll with an abrupt application of lateral stick. The coupling produced a pronounced 2.2 hertz roll “ratcheting” oscillation superimposed on the steady-state roll. The sharp aileron and spoiler input excited the wing fundamental antisymmetric bending mode, with heavy outboard engine nacelle pitching motion. which produced an oscillatory lateral acceleration at the pilot station, shaking the pilot-stick limb bob weight system. This caused the pilot to inadvertently command lateral stick inputs which had the effect of sustaining the wing bending and lateral accelerations, especially when the stick was held out of the center detent in the region of high forward path gains.*
>
> *The roll ratcheting was a very undesirable characteristic which had the potential for causing additional dynamics and controls difficulties during development testing, and produced wing loads in excess of design limits. Later FCS software versions reduced gains in the forward stick path for the lateral axis and this eliminated the potential for pilot augmented oscillations.*
>
> *A recovery procedure was briefed for flights intended to investigate the roll ratcheting response or for tests in which there was a high potential for exciting the oscillation. The procedure involved centering the stick after achieving a safe attitude and decelerating.*

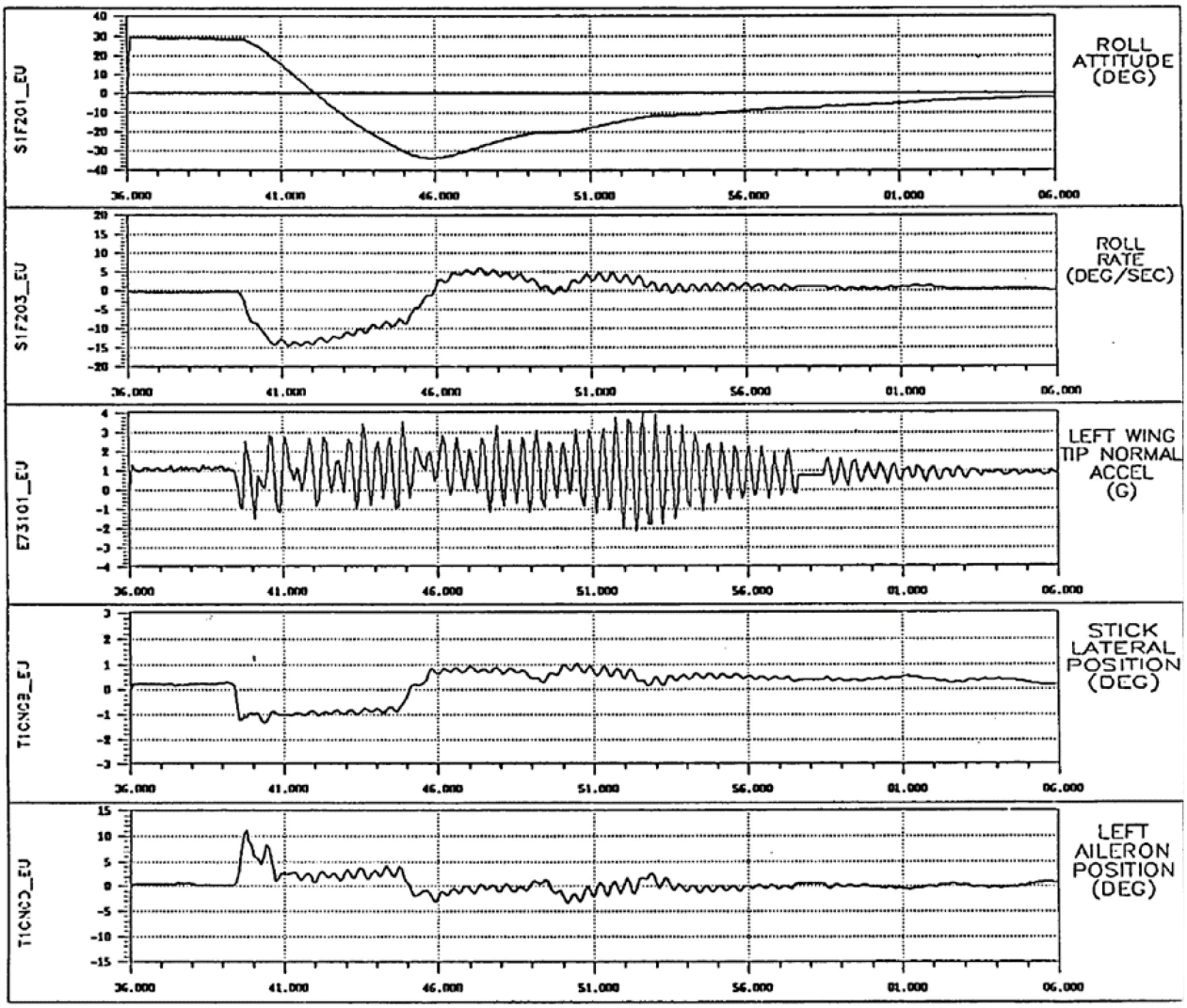


Figure 5-1: Example of Roll Ratcheting in C-17 Aircraft Flight Test [50].

From Quiet Spike

The following gives an example from the NASA F-15 Quiet Spike flight test programme for achieving flight clearances based on open loop tests. A view of the test article is given in **Figure 5-2**. Results have been taken from Refs. [51] and [52].

The Quiet Spike test programme was designed to investigate the effects of a long boom, attached to the front end of an F-15, on the sonic boom signature of the airplane. CFD based modelling of the spike provides aerodynamic perturbation models for simulation. Prior to flight aerodynamic and mass property models are updated and analysed for stability and handling qualities. Variations of aerodynamic cases are run and compared against criteria, for example in **Figure 5-3** for the CAP criterion. Questionable cases are evaluated in piloted simulation. Based on this analysis, regions of cleared aerodynamic variations are identified prior to flight and incorporated into flight clearance envelopes.

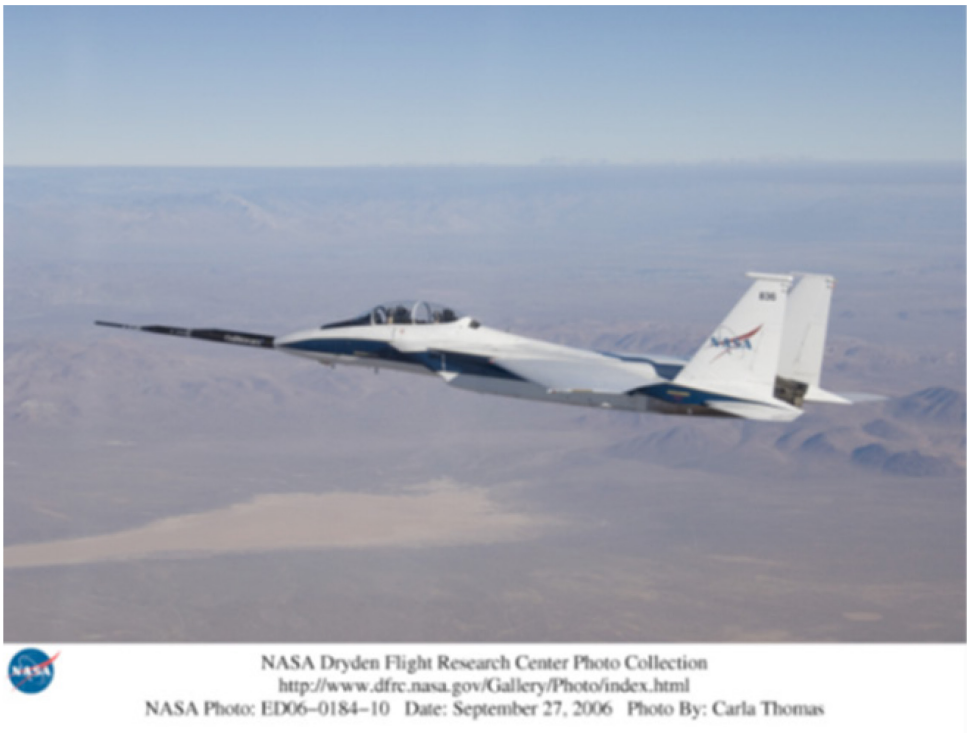


Figure 5-2: NASA F-15B in Flight with Quiet Spike Attached.

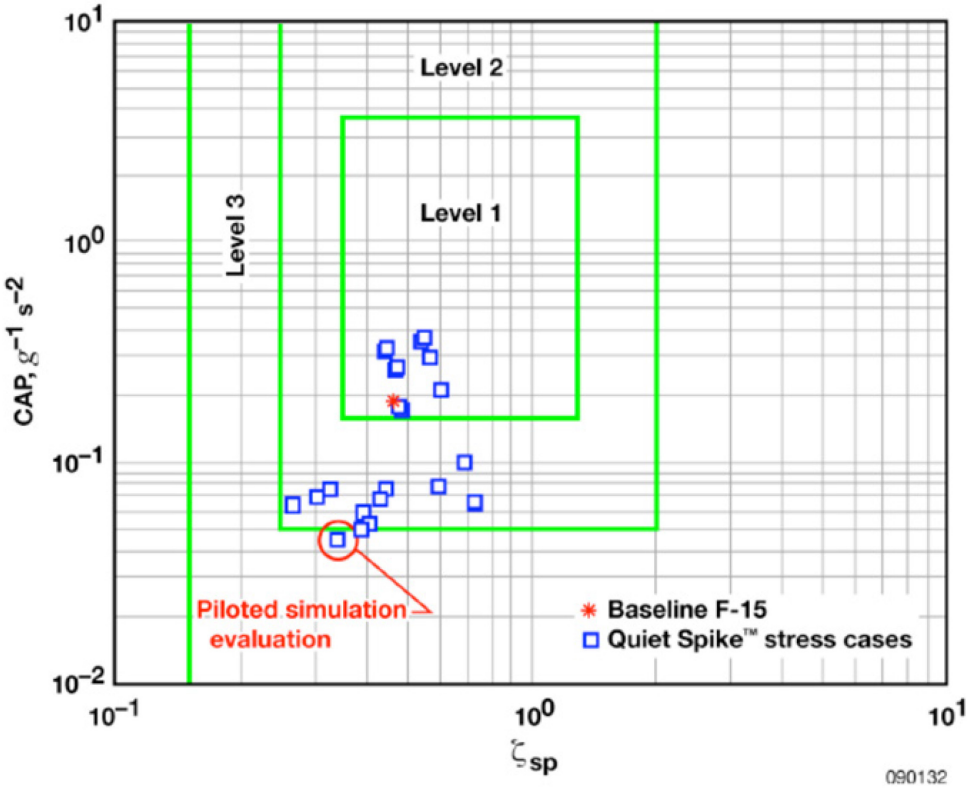


Figure 5-3: Evaluation of CAP Criterion for NASA F-15B Quiet Spike Aircraft (15.000 ft, Ma = 0.8, CAS Off).

Parameter estimation performed on doublets in flight and their results are over-plotted on the envelopes to check operation in cleared regions (see **Figure 5-4** for $c_{n\beta}$ evaluations). Adjustment of flight test conditions during envelope expansion are based on aerodynamic trends, per trend identified at Mach 1.3 in Figure 5-4. The original test plan called for a point at 1.4 Mach. Data at 1.35 Mach was added, and the change of trend noted. Parameter estimation could be done in the control room to make a more efficient flight test process.

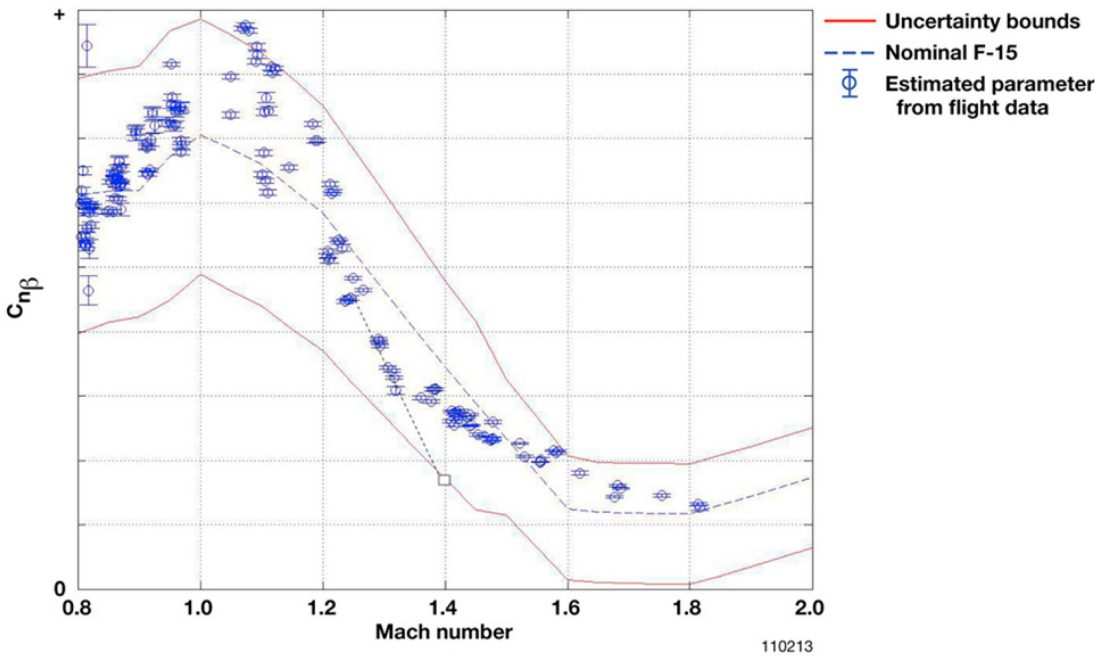


Figure 5-4: NASA F-15B Quiet Spike, Analysis of Supersonic Yaw Stability Derivative $c_{n\beta}$.

From X-29

An example from the X-29 programme (see **Figure 5-5**) shows how open loop flight testing can validate linear models used to predict pre-flight stability and handling qualities, see Refs. [53], [54]. Requirements for handling qualities are based on CAP, Dutch roll frequency and damping, and roll mode criteria.[1] In addition to handling qualities requirements, stability margins of 22.5 deg / 3 dB were used as stability design requirements and were validated during the envelope expansion phase.

Envelope clearance in the control room consisted of pseudo real-time flight data comparison of open loop frequency response and time history doublets to predicted models to determine if they were tracking according to prediction. This technique significantly enhanced the efficiency of the test programme. It is described in **Figure 5-6** (right).

Pilot induced frequency sweeps were generated in flight, see Figure 5-6, (right). The feedback and error signal from the control laws was telemetered to the ground where a FFT algorithm transformed the data to the frequency domain. As seen in Figure 5-6 (right) this technique allowed stability margins to be estimated in pseudo real-time during flight envelope expansion and compared to linear predictions. Additionally, stick inputs from pilot induced test doublets were fed into the linear models to generate state outputs for comparison with flight data (see schematic sketch in top half of right half of **Figure 5-7**). Over-plotting linear prediction and flight data provided insight to the flight control system personnel monitoring the applicability of the pre-flight predictions that were used to obtain clearance for a given test point during the flight.

[1] A detailed explanation of these criteria is best found in Ref. [25].

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

Figure 5-5: X-29 Test Aircraft.

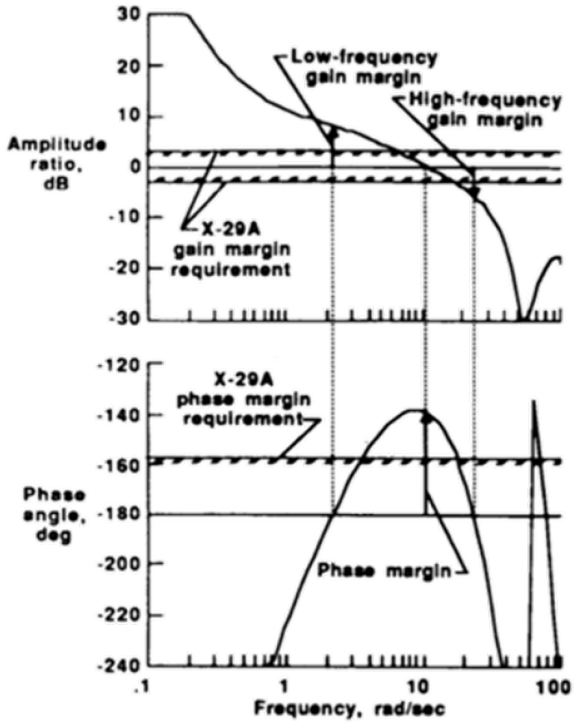


Fig. 2 Stability margin requirements for the X-29A envelope expansion program.

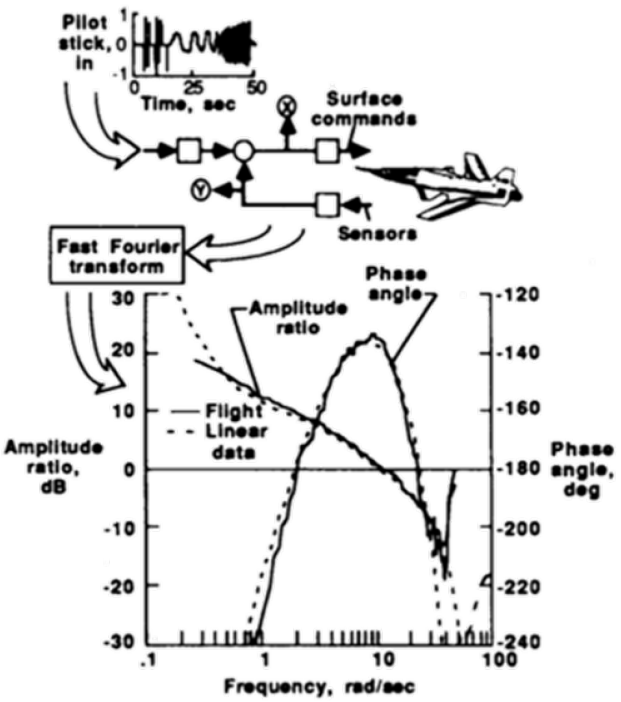


Fig. 3 Real-time frequency response analysis procedure.

Figure 5-6: In-Flight Envelope Expansion Methodology for X-29 [53].

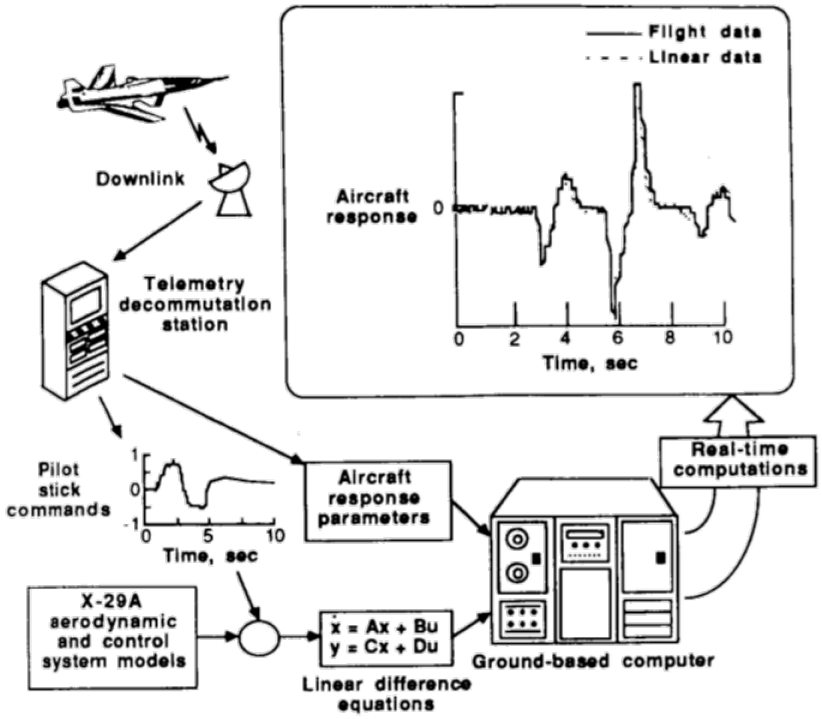


Figure 5-7: Schematics of Real-Time Comparisons between Linear Predictions and Flight Data [53].

From X-38

The real-time stability margin concept from X-29 was extended to X-38, see **Figure 5-8**, by a technique to allow continuous measurement of stability as documented in Ref. [55]. Here the system excitation is a sum of cosine waves at carefully selected frequencies according to predicted crossover frequencies. The excitation signal waves are further phase shifted to reduce the peak magnitude of the excitation signal while maintaining frequency content. Sliding time window segments are picked to provide frequency resolution at the lowest desired frequencies while maintaining test conditions and minimising processing time. This technique provides an estimate of stability updated each frame.

Figure 5-8: X-38 Test Aircraft.

Figure 5-9 shows the technique applied to X-38 simulation data with 20 sets of uncertainty cases. Within 10 s the technique converges on margin estimates which can be shown to be consistent with more traditional techniques for estimating stability.

Figure 5-9 data show how stability margin changes with flight condition (and corresponding control system gain changes) and with varying uncertainties. The worst-case flight condition and uncertainty set can be quickly determined. For example, the uncertainty sets show two groupings with respect to gain margin. A look at the uncertainties shows that the group with the lower gain margins is associated with instances where pitching moment was increased by 66.7% [55].

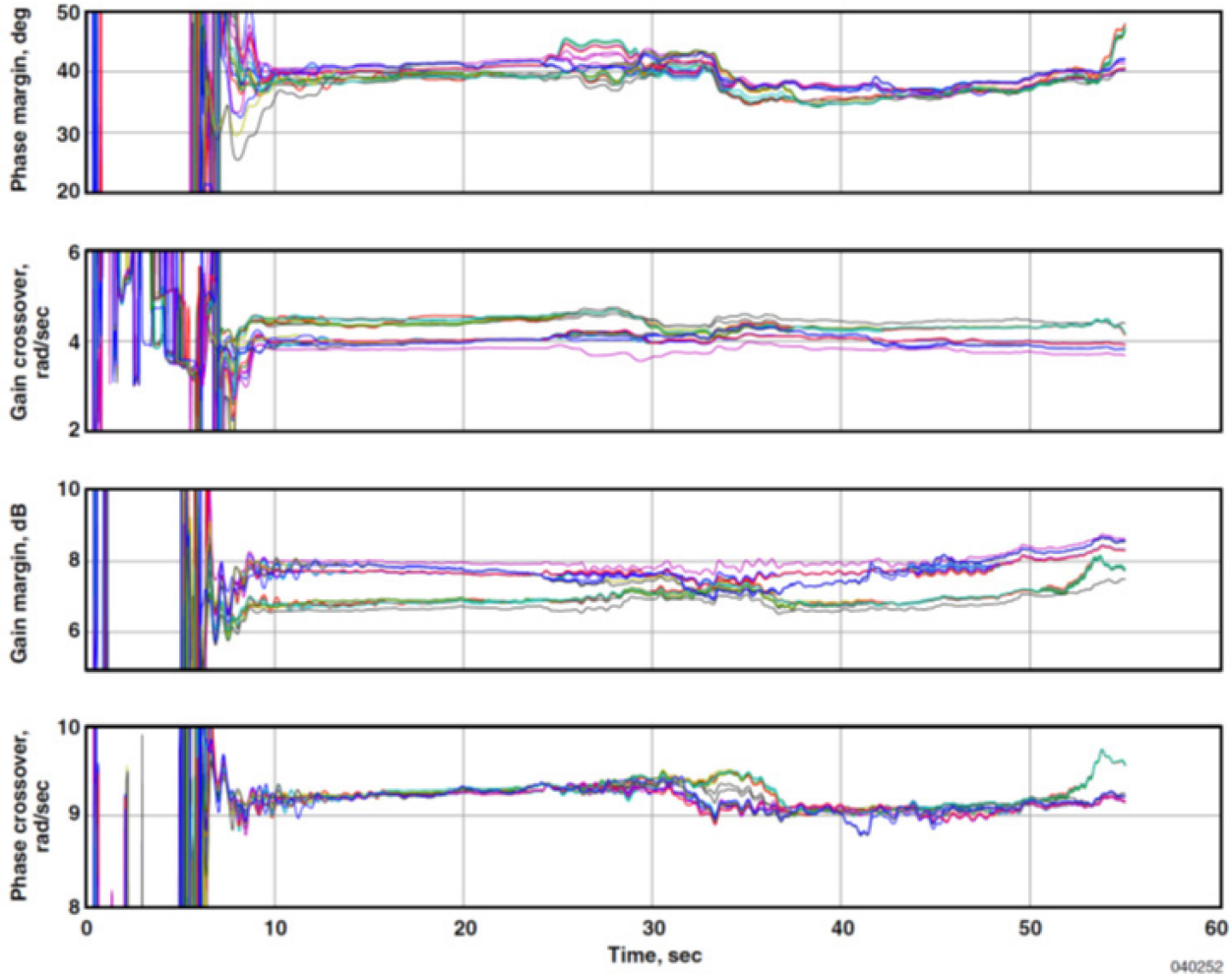


Figure 5-9: X-38 Real-Time Stability Margin Calculation for Elevator Loop [55].

5.2 SOME ASPECTS OF CAREFREE HANDLING TESTING

This section provides a brief special analysis of the methodology of Carefree Handling manoeuvres. **Figure 5-10** gives a printout from telemetry monitoring during an envelope expansion flight. It shows various aircraft state variables as a function of AoA (dotted green lines). In extensive pre-flight simulation trials limit lines have been calculated. The orange lines are those calculated in simulation with the nominal aerodynamic data set. The red lines are those calculated with an aerodynamic data set with tolerances on which the clearance is based. Both sets of lines have been achieved and calculated after a series of non-linear

simulations of the manoeuvre (rapid roll reversal after a 360 deg full stick roll). They give the maximum permissible values of the state variables during this manoeuvre. During the test, this diagram is on the screen and the analysis engineer observes the development of the actual variables, the green lines. The “go” or “no-go” criterion is simple. Exceedance of the green line across the nominal line (orange) is permissible. Exceedance across the red line (tolerance case) is not permissible. Thus, a very simple quick and easy criterion to apply during flight is available.

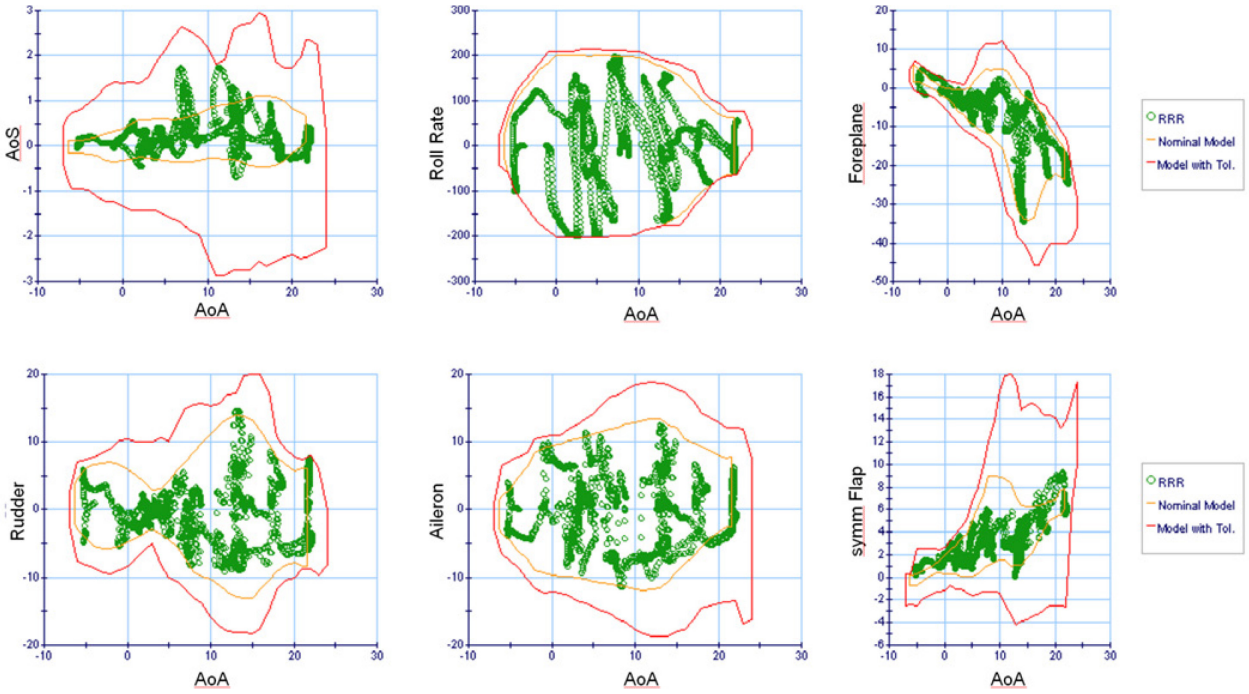


Figure 5-10: Carefree Handling Envelope Expansion (Rapid Roll Reversal after 360 deg Roll).

5.3 PHASE 2 TESTING (THE CHALLENGES OF PIO RESISTANCE TESTING)

5.3.1 Some Aspects about the Usage of Tools

From this section onwards, we will describe testing which in general uses tools such as the CHR scale. We begin with some practical experiences with the CHR scale.

Sometimes in literature but very often in briefings and debriefings, discussions start about the proper usage of the Cooper-Harper rules given in Ref. [21] and explained in Section 3.1. This section summarises some experiences.

Cooper-Harper-Ratings

In Ref. [21] Cooper and Harper establish clear rules on how to apply the scale. They clearly vote against so called “half CHR” like a 4½. This goes into a grey area of criteria since “half ratings” are not defined. Another “no-go” is when the pilot says in the debriefing “I have to think about the CHR, whether it is a ‘half’ or not. I will sleep about it and tell you tomorrow”. This has actually happened to the author. The final rating was delivered a couple days later together with the written pilot report.

Note that critical to the use of the Cooper-Harper scale is the establishment of desired and adequate performance criteria. The definition of these criteria will heavily influence the pilot ratings that result. While selection of performance criteria should be based on realistic requirements for the category of airplane being

tested, they should also present enough of a challenge to the piloting task so that inherent deficiencies in the pilot-vehicle-system will become evident. Definition of the performance requires careful selection of relevant parameters and relevant criteria together with pilots, and it typically requires simulation validation.

Pilot Comment Sheets

From HARV, see also Ref. [6]: critical to the piloted evaluation of handling qualities is documenting pilot comments and opinions. They are essential to be able to interpret numerical ratings and identify deficient pilot-vehicle characteristics. Pilot evaluation sheets or questionnaires designed for the particular aircraft and the role for which it is being used are valuable tools for collecting pilot comments. Use of these tools facilitates comments on relevant characteristics across multiple pilots and flight test conditions. **Figure 5-11** gives an example pilot sheet from Ref. [6] used in the F-18 High Alpha Research Vehicle programme. Transcribing and documenting pilot comments, while undoubtedly tedious, is an essential part of the data collection required to adequately interpret handling qualities data.

5.3.2 Experiences with the KLONK Technique

A report or a paper related directly to the KLONK technique does not seem to be available publicly. The description of this technique is given in Ref. [11] by McRuer and it is repeated here in Section 4.3.2.1. Kullberg and Elgcrona [36] describe very openly SAAB's experience with PIO testing. It can be interpreted from their presentation that they are referring to testing with the KLONK method. As also discussed in Ref. [36], the application of HQDT played an important part in the investigations. This will be addressed in the next section.

The KLONK method is considered important in the context of PIO resistance testing for various reasons. It is mainly aimed at finding regions in operating an aircraft where rate limiting occurs. A systematic approach gives information not only when rate limiting occurs, it provides insight into system dynamics with respect to time delays and phase lags encountered once the aircraft operation comes close to a "rate limiting case".

Some quotes from Ref. [36] illustrate experiences:

- *"However, as development progressed as planned through the flight test programme, there was a desire to boost agility at lower speeds and modifications were introduced. Assessment showed that under extreme conditions, using full roll and pitch stick, rate saturation and departure from stabilised flight could be reached. It was understood that it was vital not to reach rate saturation for any length of time as the effects of the reduced gain and additional phase lag would cause the aircraft to become unstable. The possibility of the "cliff edge" was found …"*
- *"Analysis has shown that the effective time delay between pitch stick and pitch acceleration response increased from less than 100 milliseconds to around 800 milliseconds. The subsequent response and pitch up caused the pilot to eject …"*
- *"PIO is a result of 'disharmony' between the pilot's action and the aircraft's reaction, i.e., there is an excessive time delay between the input and subsequent response."*

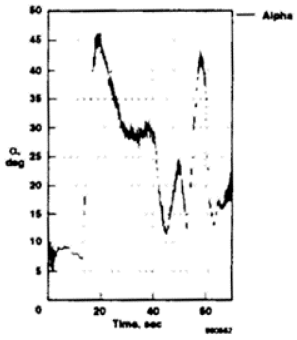
Analysis and evaluation of the testing described in the first quote led to the development of a special criterion. Nevertheless, the explanation of it in Ref. [36] is rather brief.

It is evident from the findings reported in Ref. [36] that it is important to have an excellent understanding of the system under test with respect to any possible rate limiting occurrences. Resulting response delays can have a detrimental influence. Testing in this area must be carefully planned, system and flight safety issues must guide to a safe testing strategy.

For the sake of completeness, it shall be mentioned here that a final satisfactory solution was accomplished by SAAB through the introduction of phase compensating rate limiters, as pointed out in Ref. [36].

HARV HQ Comment Card

HARV flight 319 card 12A
.45 Mach Longitudinal/Lateral Tracking TV



File=flt319.12a; Signal Suffix=[none]; Date=[none]

Flight: 319
Card #: 12A
CLAW: 151.1
Mode: TV
Gain Set: Medium
Pilot: Schneider
Target A/C: 850/Smolka
Mach No: 0.45
Altitude: 25000.
Target AOA: varies
Maneuver: .45M Tracking
Actual AOA: 11-46 (30 avg.)
Reticle/Depression: 12.5/80mil
Desired: within 5mil 50% time and within 25mil remainder
Adequate: within 5mil 10% time and within 25mil remainder
Date: 07Sept95

Pilot Comments: Maneuver,... Burner,... ok, on him... a little longitudinal bobble, 32 alpha... nose... right wing... left wing. Kind of a hellico- [Controller] Reverse. [Pilot] nose... reverse, good... see the pitch bobble? [Controller] Reverse. [Pilot] here comes the reverse... [Controller] Reverse. ... and recover, altitude. [Pilot] OK, knock it off. [Target] Knocking it off. [Pilot] Very good.
(snip to post-maneuver comments)

Attitude Control:

Undesirable Motion: OK, comments; undesirable motions; the only one that I really did not like was the longitudinal pitch bobble that we've seen before on other tracking tasks. And it's still there, probably due to the major dumbbell effect that we have with the airplane.
Predictability: Predictability was pretty good, except in the long axis. You could sometimes over-control pretty easily there and get the pipper off from where you wanted it.
Initial Response: Initial response was good in both axes.
Aggressiveness Effects H/Q: Aggressiveness had a major effect on the longitudinal pitch bobble. If you really got on it it wasn't... wasn't gonna settle down. And you had to compensate with... being a little more open hand, little bit less aggressive with the controls in that axis. And... trying to... separate out the lateral control movements from the longitudinal. That's a little bit aggravating too when you go from wingtip to wingtip.
Compensation Techniques:
Roll Performance: Roll performance, I thought was quite good.
RPC:

Feel System:

Forces: And ... forces were light, satisfactory.
Control Motion: Control motions; small.
Harmony: Harmony was good.
Nonlinearily: It was linear.

Cooper Harper Rating:

Longitudinal HQR: [4] Longitudinal first. Controllable? Yes. Adequate performance? Yes. Satisfactory without improvement? No. Desired performance required moderate compensations. I'd give it a 4. I think I had desired performance there, but I definitely did not like the longitudinal bobble, and you can ask Keith to think about that for a minute and see if he agrees.
Lateral/Dir. HQR: [3] And for the lateral axis... Controllable? Yes. Adequate performance? Uh, yes. Satisfactory without improvement? I would say "yes". And I would say... minimal compensation in the lateral axis. HQR 3.
Confidence Rating: [1] And... confidence rating: I'd give it a 1 on that one.

PIO Rating:
Other Comments:

Times:

Target Maneuver:	11:11:18 (right turn)
Maneuver:	11:11:21
Acquisition:	11:11:28 (42° AOA)
Knock It Off:	11:12:10
Comments Begin:	11:12:31
Comments End:	11:14:29

Figure 5-11: Sample of Completed Pilot Information Sheet.

5.3.3 Experiences with the HQDT Technique

Swedish Experience (SAAB and FMV)

As already discussed above in connection with the KLONK manoeuvre [36], experience with a HQDT technique was also gained during the PIO investigations, although not necessarily with the same setup as explained by Twisdale [37] (although it is called HQDT). These tests were mentioned in Ref. [36]. An additional description is given on the SAAB web site [56], and additional investigations were performed by the Swedish Defence Materials Administration (FMV) [57]. For the setup of specific HUD tracking methodologies, a synthetic target was implemented in the HUD and the pilot was tasked to track it as assiduously as possible [56]. A typical tracking pattern is given in **Figure 5-12**. The excitation is given as the angle (with respect to infinity) with which the HUD symbol is moving as a function of time.

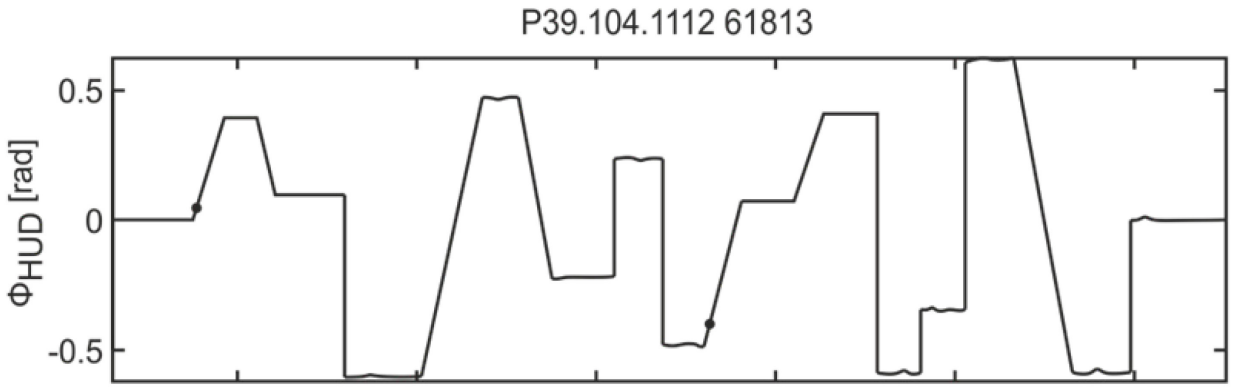


Figure 5-12: Typical HUD Tracking Pattern [56].

A second setup is given with two aircraft flying in formation where the wingman is the evaluation aircraft. The schematic setup is given in **Figure 5-13**. The target aircraft, number 1, has a distinct and easily visible marking on the left side of the fuselage. It is two concentric circles, see Figure 5-13. It is the task of the pilot of the evaluation aircraft, number 2, to track the target aircraft as precisely and as assiduously as possible while the target aircraft is manoeuvring within certain limits, to be defined by the specific test setup. For this the evaluation pilot of the wingman aircraft has to bring the tip of the wing tip missile in line with the centre of the circles (see sketched line in Figure 5-13). Keeping the missile tip within the inner circle would be “desired”, keeping it within the outer circle would be “adequate”.

The method was used by SAAB [36] and FMV [57] for the JAS-39 Gripen. The results given in Ref. [57] were achieved with the AJS / JA-37 Viggen. For the test flights the target aircraft stabilised for a couple of seconds in order to give the wingman sufficient chance to align his aircraft as indicated in Figure 5-13. After this the target would start manoeuvring according to a given test plan, e.g., only pitch axis, only roll axis, or combined axes, with varying dynamics. The evaluation pilot in the trailing aircraft had to evaluate his aircraft according to initial response, predictability, sluggishness, PIO tendencies, and workload. The method is considered beneficial for a quantitative comparison between different aircraft configurations, e.g., different control law versions. The method requires special flight safety considerations and planning for failure cases as two aircraft are flying in close formation and manoeuvring rapidly.

In Ref. [36] the conclusion states: “Detail assessment enabled the establishment of a ‘footprint’, from parametric variation of stick inputs in both pitch and roll, taking into account the effects of atmospheric disturbances such as gusts and turbulence, where rate limiting effects could be encountered …”

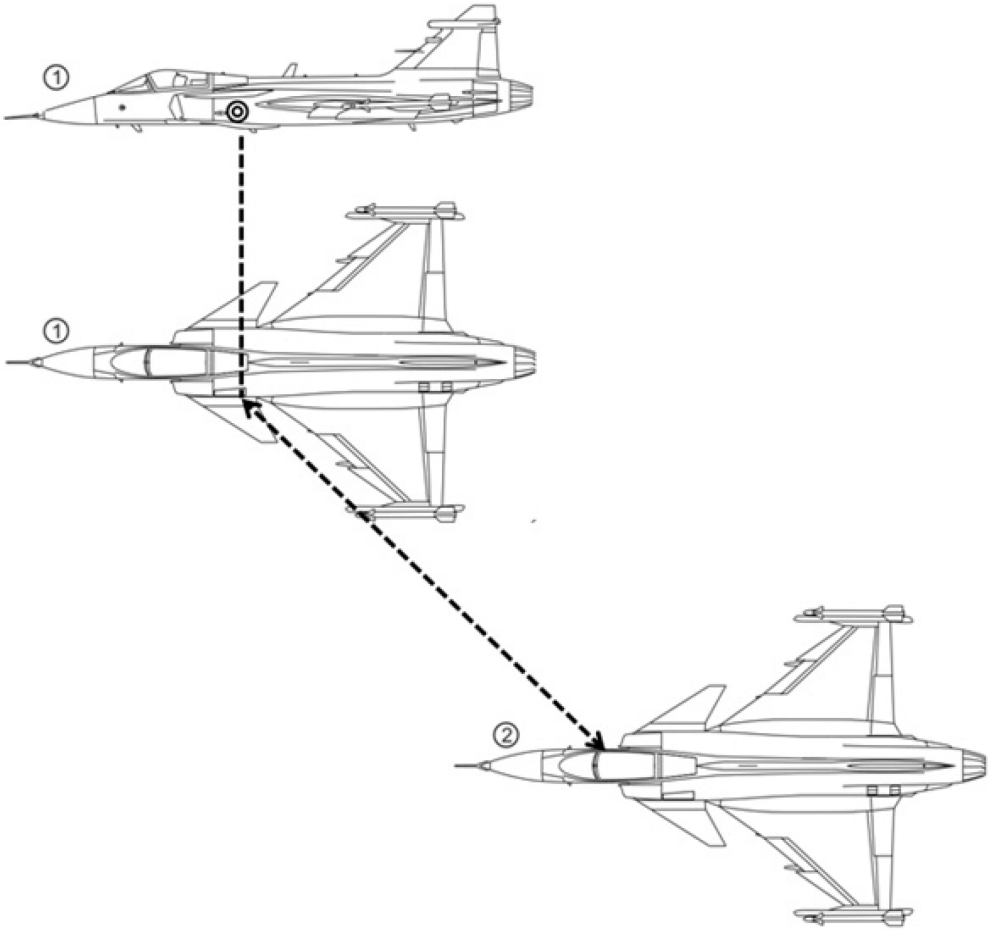


Figure 5-13: HQDT Set-Up at SAAB and FMV [56].

Airbus Defence and Space (Former DASA and EADS) Experience

An extensive test campaign on PIO resistance testing with the aid of the HQDT technique has been reported in Ref. [58]. Test setup and manoeuvre selection was according to the procedures defined in Section 4.3.2.1. In the following, a typical example for 1 g horizon tracking (attitude tracking) will be presented. Pilots involved in the trials had received extensive prior training in simulator sessions. One pilot was a graduate of the USAFTPS and had been taught the HQDT technique there already.

Time history results for the example, designated here 1g low-speed attitude HQDT (Ma = 0.4), are given in **Figure 5-14**. The top trace shows the pitch stick STP deflection in non-dimensional units and the second trace depicts the resulting system response in form of pitch attitude. The pilot started with Step 1 HQDT and over time he gradually increased amplitude to Step 3 HQDT as indicated in the figure. It can be observed that with increasing amplitude frequency decreases, up to about 25 sec into the sweep. Even with maximum input amplitude in connection with the required “bang-bang” switching technique for Step 3 HQDT response frequency remained “low”. Aircraft response was such that the pilot was not able to decrease attitude amplitude (tracking error) as required. During testing, however, this particular pilot realised that if he allowed for a little anticipation, although this is against the “rules” given in Section 4.3.2.1, [37], he could now decrease pitch amplitude considerably, as can be seen in Figure 5-14 for times greater than 28 sec. Consequently, frequency increased as well because the aircraft did not need as much time anymore to “travel” through the horizon.

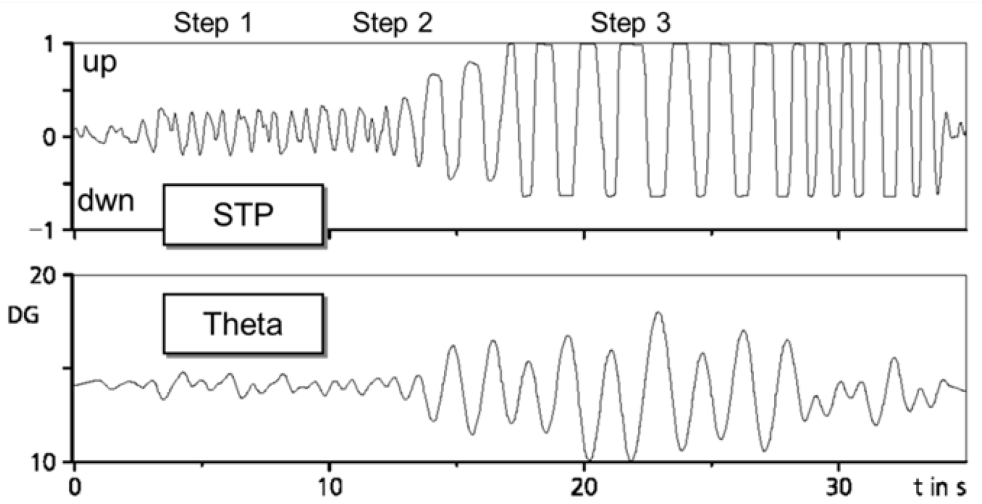


Figure 5-14: Time Histories of 1g Low-Speed Attitude HQDT Case.

A frequency domain analysis of this time slice regarding only the pure "bang-bang" switching portion up to 28 sec is given in **Figure 5-15**. The first trace gives the already known STP signal, cut at 28 sec, the second trace the spectral density X_K as a function of frequency omega, the third trace the power spectral density S_{XX}, and finally the fourth trace the accumulated power spectral density E_{XX} over frequency, where 100% represents the total power achieved at ½ of the sampling frequency (Nyquist criterion). The power spectral density shows a distinct peak at app. 4 rad/sec. 90% of energy in this signal is accumulated at app. 7 rad/sec. Bandwidth (pilot injected frequency spectrum) can therefore be considered to be less than that value. In other words, less than 1 Hz.

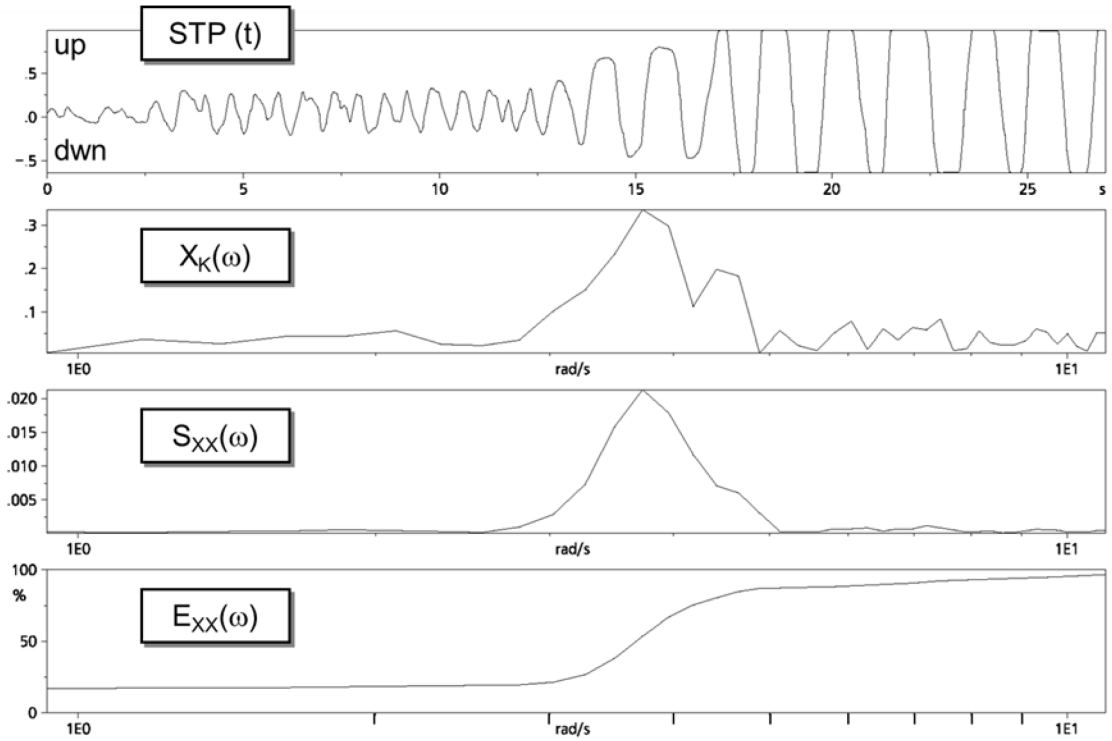


Figure 5-15: Frequency Domain Analysis for the 1g Low-Speed Attitude HQDT Case.

Further analysis of this time slice now including the signal portion with pilot compensation is given in **Figure 5-16**. Now a second peak can be observed for the spectral density as well as for the power spectral density at app. 6 rad/sec. This second peak reflects the higher frequency achieved when the pilot started compensating. Accordingly, 90% energy level is achieved at app. 8 rad/sec. This means that this pilot increased bandwidth by about 2 rad/sec only by deviating from the original prescribed technique.

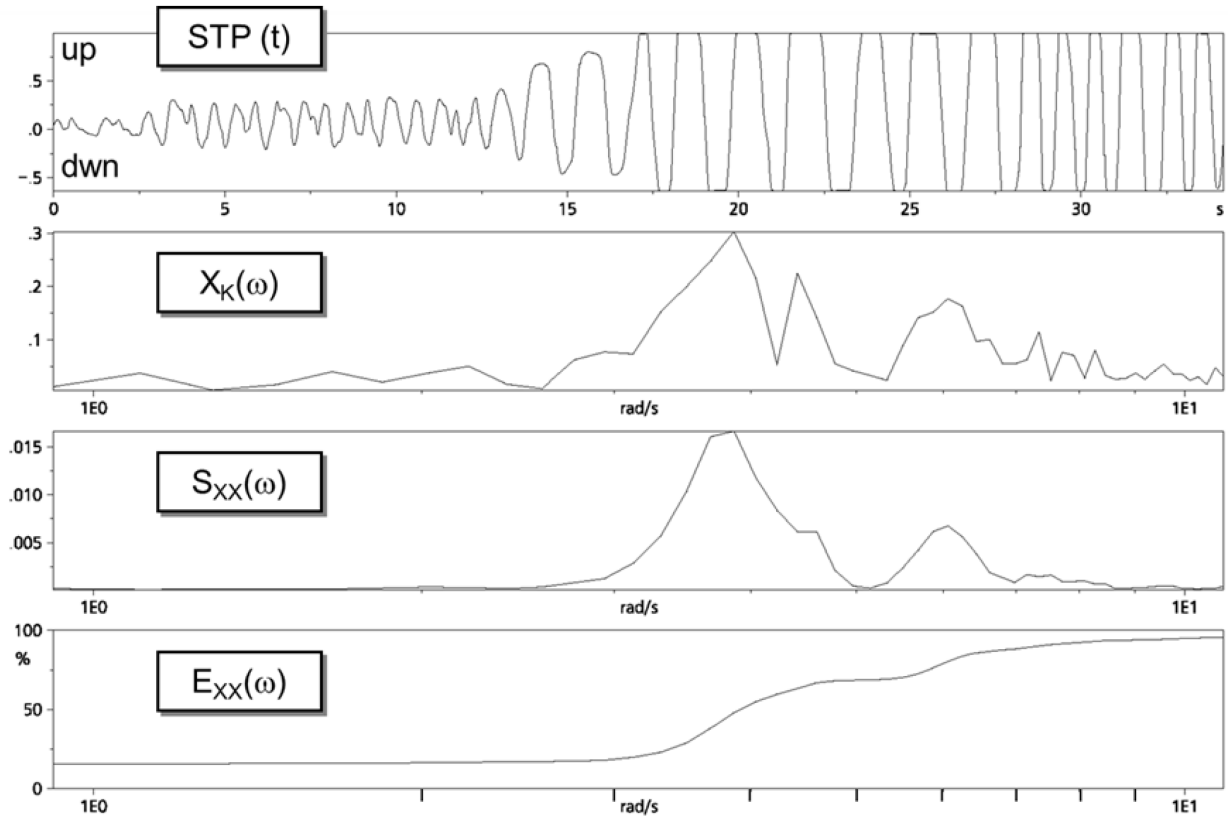


Figure 5-16: Frequency Domain Analysis for the 1g Low-Speed Attitude HQDT Case with Pilot Compensation.

PIOR ratings given for this case were PIOR1 for steps 1 and 2 and PIOR2 for step 3. This pilot did not distinguish between the non-compensating and compensating phase as a PIOR2 allows for a pilot technique to prevent/eliminate undesired motions, see Figure 3-6.

Overall testing experience from Ref. [58] has proven that the HQDT technique in formation tasks as prescribed in Section 4.3.2.1 (HQDT-5 task) is the most difficult one. One reason for this finding is based on physical coherences. During formation flying, flight path angle becomes the predominant control variable, which is subsequently derived into a vertical, translational motion by the pilot. Flight path delay is primarily influenced by the numerator time constant $T_{\theta 2}$, introducing phase lag into the system. Hence, it is not surprising that for Step 3 inputs system bandwidth decreases, requiring the pilots to maintain full forward or full back stick for a notable time, before the heaving motion induced any vertical deviation from the precision aim point. Overall, this behaviour led to some uncomfortable aircraft reactions which were commented on by pilots accordingly. One distinct pilot comment to the formation HQDT task is repeated here:

> *When applying the first high amplitude stick input aircraft attitude response was crisp and quick, as previously reported for the horizon/guns tracking. After stick reversal the pitch attitude motion reversed and so did the flight path motion, but obviously the relative vertical position to the lead aircraft continued to change in the original direction until the flight path angle decreased to zero*

– as it would be the case for any other aircraft around the world. Subjectively this could be perceived by the pilot as an apparent lag between stick input and aircraft response, but this was assessed to be factually a normal behaviour for the given task …

There is a high risk that the perceived discomfort during this formation task might lead pilots to the impression of encountering a PIO problem. This pilot would not support such a conclusion at all because the observed aircraft response was believed to be absolutely normal for the given task and stick inputs. ***Which aircraft response do people seriously expect from an agile aircraft which gets mishandled by up to full pitch stick deflections in close formation??***

The main course of the latter part of this quote echoes Twisdale [37] when explaining possible problems with this technique (see also Section 4.3.2.1). Following this experience, not only this particular pilot but the whole test team commonly agreed not to provide any PIOR for this task.

C-17 Experience

Experiences with HQDT when testing the (large) C-17 military transport aircraft have been reported by Kendall in Ref. [59]:

During HQDT test on the C-17 in which pilots aggressively tracked close behind the tanker's boom which was being suddenly moved by the test boom controller, oscillations could be excited, but were easily terminated at will by the pilot. However, the structural excitation of the aircraft was a factor in these tests.

HQDT tests in the power/approach configuration were specified by AFFTC as a prerequisite to performing specification compliance crosswind landing tests. The intention was to minimize the risk of a pilot-induced oscillation (PIO) close to the ground where abandoning the task might not be possible. These tests were performed by the C-17 tracking the A-37 airplane at low speed as it made sudden lateral and vertical flight path displacements. The crosswind landing envelope was eventually expanded to 30 knots without incident and with no related control law change.

Résumé of HQDT:

The application of dedicated PIO resistance testing with the HQDT method in Phase 2 and further HQ evaluations with high gain pilot in the loop operational tasks during Phase 3 still gives consistent results. This is an indication that the HQDT method supports or possibly complements findings generated with other techniques. Much more detailed comments and interpretations on HQDT are given in Ref. [58]. They relate in particular to the described test campaign.

To summarise, HQDT is difficult to apply. It needs cautious application requiring extensive simulator training. With these measures the outcome of a test campaign serves the purpose sufficiently [58].

5.3.4 Experiences with the Boundary Avoidance Tracking (BAT) Technique

Two Test Management Programs (TMPs) were completed at the USAF TPS, HAVE BAT, and BAT DART. The HAVE BAT TMP had three primary objectives:

1) Determine the system open loop characteristics;
2) Determine the values of selected parameters that characterise the boundary avoidance tracking; and
3) Determine the degree of correlation between the system open loop characteristics and the boundary avoidance tracking parameters.[43].

This was accomplished using both simulators and T-38 aircraft. The airborne testing consisted of formation tasks in which the target aircraft manoeuvred in specified vertical motions while the test pilot attempted to maintain position relative to the target. Boundaries were specified with markings on the target (discussed later). The tracking task was abandoned once the boundaries appeared to become a threat [43]:

The test team observed first-hand that:

1) *Pilots adapt their control inputs based on the handling qualities of the aircraft and the level of threat posed by a boundary; and*
2) *That the imposition of boundaries can lead to divergent oscillations. Further examination could reveal much about how pilots react to stimuli and how the system characteristics impact the final outcome* [43].

BAT DART was a separate TMP with the objective to: "determine if a bounded tracking task could be used to produce numerical aircraft handling qualities data" [42]. Again, simulators were used to determine task bounds and timing, as well as to gather significantly more data than could be done in flight. The flight portion of the project was completed in the VISTA NF-16D in-flight simulator. Instead of a formation location, the parameter to be tracked was flight path, with bounds decreasing as a function of time as shown in **Figure 5-17**.

Correlations between boundary value (shown in terms of time) and Cooper-Harper-Rating of a tracking task were found from the in-flight portion of the research, as shown in **Figure 5-18**. While this data shows the usefulness of BAT in gathering quantitative HQ data, the effect of changing the task or the boundaries has yet to be shown [42].

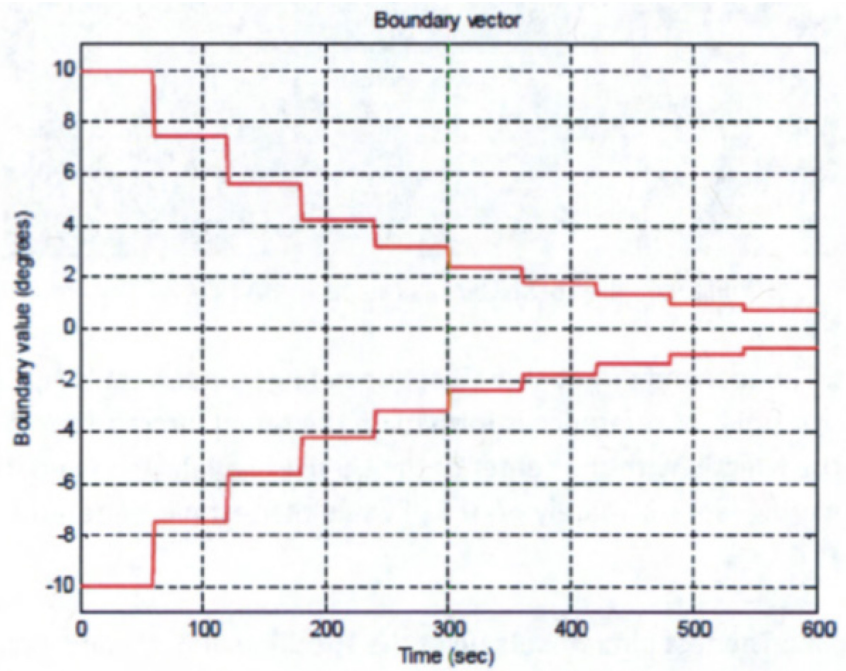


Figure 5-17: Flight Path Boundary Profile [42].

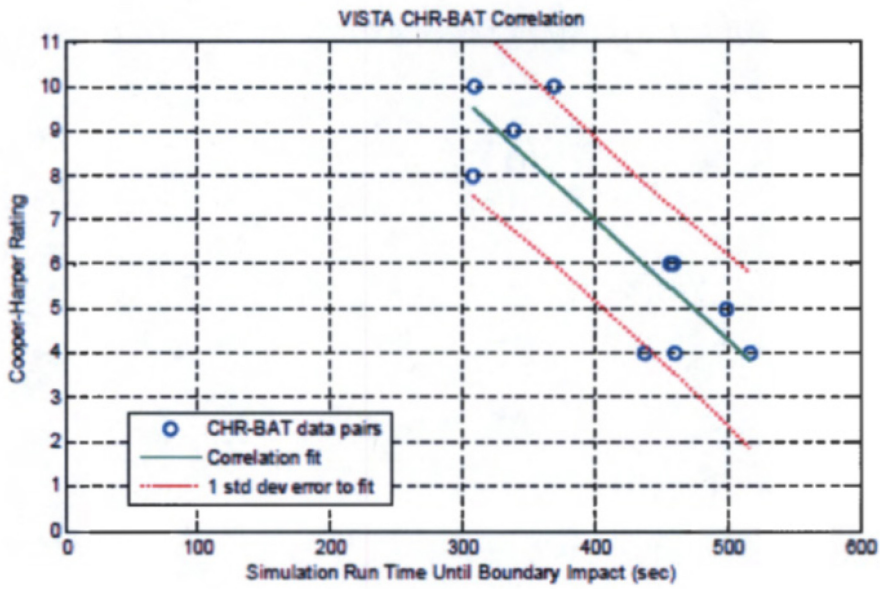


Figure 5-18: Correlation between Boundary Value and CHR.

BAT Implementation and Issues

In order to implement the BAT technique, a set of variable boundaries is required. This is a technical problem as much as it is a psychological one. Samples of these boundaries are shown in Section 4.3.3.2. If a virtual boundary is used (such as the HUD example), care must be taken that the time delay associated with the display is minimal, as it will impact the overall dynamics of the pilot-plus-aircraft (plus-display) system.

Both Refs. [41] and [42] note the psychological difficulties of this method: "it is difficult to get student test pilots to 'role-play' as if the artificial boundaries are real" [41]; "One of the difficulties in using boundaries in simulators or actual flight test is simulating a real-world boundary, like the ground" [42]. This potential issue has been noted for other techniques as well (such as HQDT) and is solvable via coaching of the test pilot. The methods are easily understood, but the criticality of boundary avoidance must be conveyed.

As mentioned earlier in Section 3.8 at the very end of Chapter 3, simulators often do not actually do their job in critical piloting situations, and it is not completely understood why. And this must be in the mind of testers when preparing for BAT testing in a simulator. One way of describing the situation invokes a new definition of FOD as 'Fear of Death'. Simulators by their intended nature do not generate this FOD.

5.3.5 Other Techniques

From F-15 IFCS

An F-15 aircraft, see **Figure 5-19**, was used to research the utility of adaptive flight control systems in the presence of failures [60]. Specifically, a neural network based direct adaptive flight control system was implemented to investigate adapting flying qualities to an acceptable level in the presence of a simulated stabilator failure. The stabilator surfaces provide the majority of the control power for both pitch and roll control. Disabling one of the stabilators was expected to introduce significant changes in pitch dynamics which couples into significant roll dynamics as the pilot performs a task.

Figure 5-19: NASA NF-15B Research Aircraft, Tail Number 837.

Handling quality complications can result when a pilot interacts with an adaptive flight control system. The pilot, flying a formation flying task with the simulated stabilator failed and the adaptive control system active, rated the lateral fine tracking as a CHR of 7 and a PIOR of 4. Pilot comments indicated a PIO was triggered during the run. The time history, **Figure 5-20**, shows the results from the task where the bottom plot in the figure is a compilation of the adaptive gains in the controller. In the time history the pilot starts with moderately aggressive tracking at approximately 30 s. As he increases aggressiveness at approximately 50 s some further adjustment of the neural network weights is observed, and PIO is triggered. By approximately 60 s the weights have settled to fairly constant values.

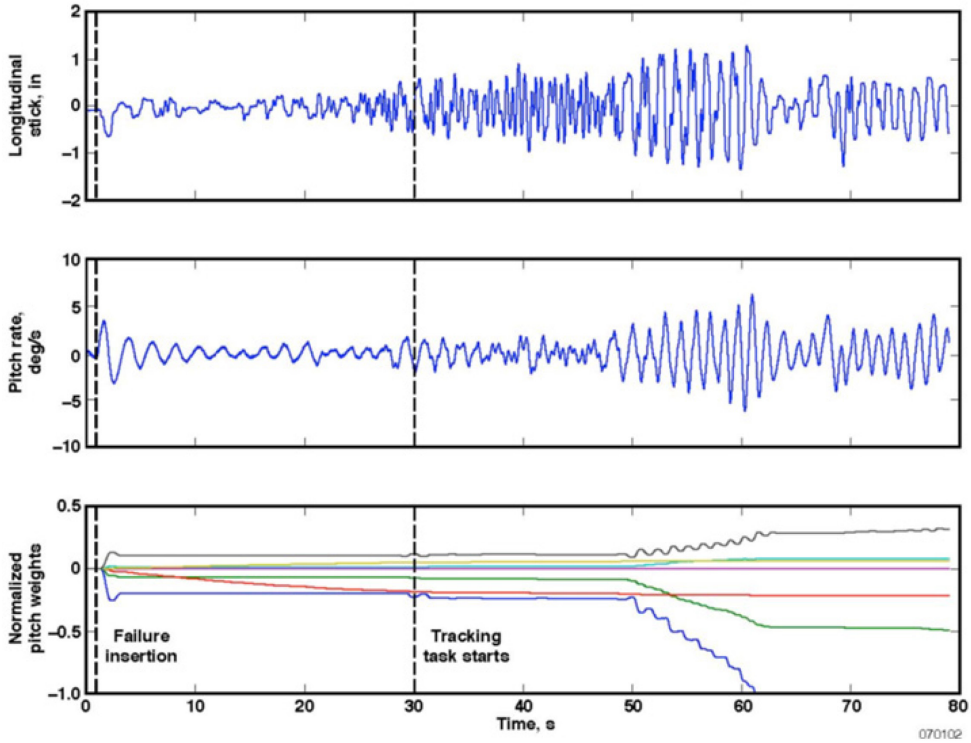


Figure 5-20: Typical Formation Flight Time History.

Subsequent analysis of the manoeuvre indicates that the PIO was caused from the nature of the gain adaptation during the task. While improvement had also been noted with the adaptive controller, this particular run highlighted the potentially adverse handling quality characteristics that can result from adaptive elements in the control system.

From F-18 Model Reference Adaptive Controller

In support of the F-15 IFCS programme, a quantitative measure of pilot workload was used on flight data to delineate characteristics between adaptive controllers being evaluated in flight. The technique, as applied in Ref. [61], utilises measures of duty cycles and pilot aggressiveness to provide insight into pilot workload during a given manoeuvre. Pilot aggressiveness is determined by evaluating the commanded stick positions relative to their maximum ranges, per the equation below where δ_{ap} and δ_{ep} are the lateral and pitch stick deflections respectively:

$$J_A = \frac{100\%}{t_f - t_0} \sum_{\tau=t_0}^{t_f} \left(\frac{\left|\delta_{ap}(\tau) - \bar{\delta}_{ap}(\tau)\right|}{\delta_{ap}^{max} - \delta_{ap}^{min}} + \frac{\left|\delta_{ep}(\tau) - \bar{\delta}_{ep}(\tau)\right|}{\delta_{ep}^{max} - \delta_{ep}^{min}} \right) \Delta\tau$$

Duty cycle measures how frequently the pilot makes significant reversals in the commanded stick position as illustrated by the example below during 2 g air-to-air tracking manoeuvre, **Figure 5-21**.

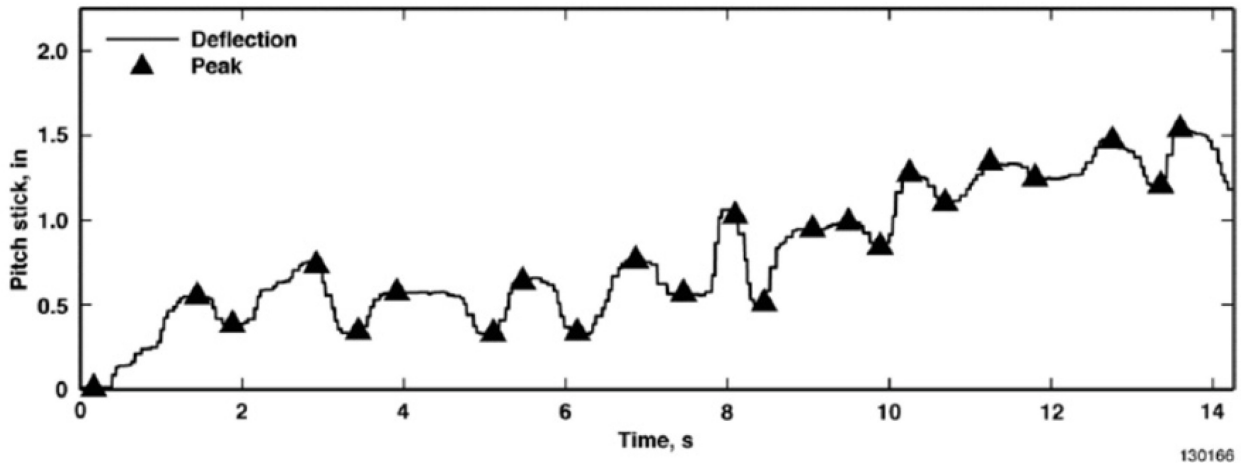


Figure 5-21: Duty Cycle Measurements for Pitch Stick.

The two parameters were then cross-plotted to provide insight on pilot workload levels for the un-failed state baseline controller ('Un-failed NDI'), the baseline controller with a failure that results in reduced pitch damping (NDI), and 3 adaptive controllers coupled with the same failure, **Figure 5-22**.

While the effect of the adaptive controllers has reduced the workload for pilot B in the task, his workload still remains elevated compared to the un-failed controller configuration. This illustrates one technique for quantifying pilot workload which, as applied in this programme, provided a measure for potential benefits of adaptive controllers. Applying such techniques also provides further insight into pilot comments, and pilot ratings, such as the Cooper-Harper-Ratings, which relies on a qualitative pilot self-assessment of the compensation applied to complete a task.

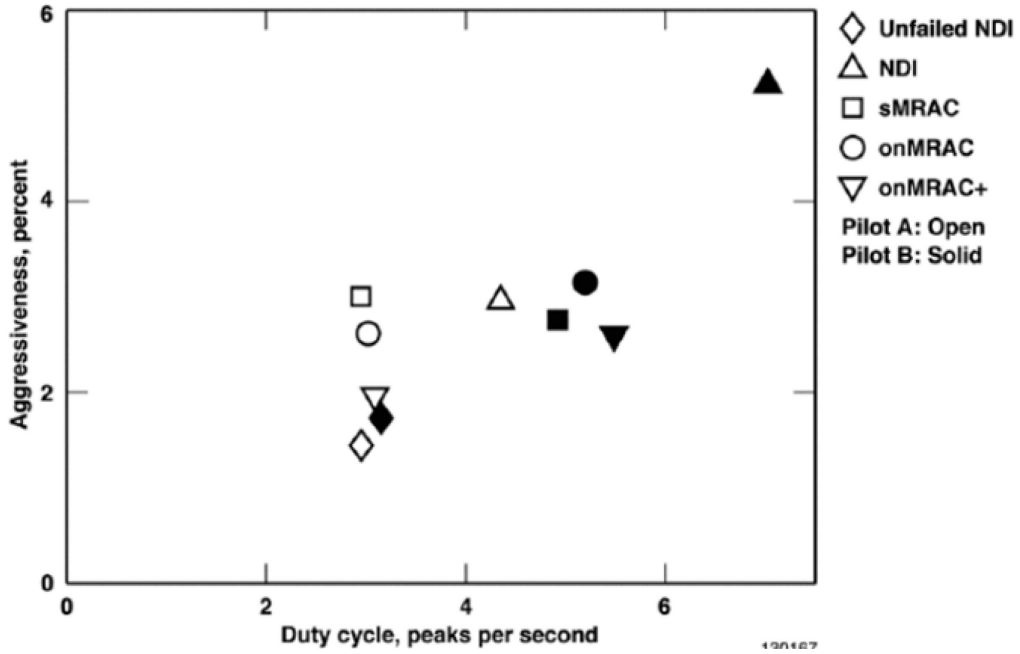


Figure 5-22: Analysis of Duty Cycle Measurements During Air-to-Air Tracking.

PIO Detection with ROVER

A technique developed at Hoh Aeronautics has been shown to be effective at identifying PIOs. The technique, identified as Real-time Oscillation Verifier (ROVER), is applied in Ref. [62]. The premise of ROVER assumes that for PIOs to occur the following conditions exist:

1) The aircraft response is oscillatory.
2) The oscillation is out of phase with the pilot input.
3) The frequency of the oscillation is in a range where PIOs occur.
4) The amplitude of the aircraft responses and the pilot input are large enough to be of concern.

ROVER monitors the four conditions above and sets a flag when each condition is observed. The method as applied in Ref. [62] is shown in **Figure 5-23**.

The ROVER technique can be applied post flight to time history data, or it can be applied in real-time flight test as a method for determining when PIO is occurring. **Figure 5-24** shows an example of post flight processing of a PIO event from a fighter type aircraft.

The time history of the PIO event is indicated in the top trace of the figure. ROVER estimates of frequency and phase difference make up the 3rd and 4th trace from the top. The bottom trace indicates the number of conditions identified by ROVER as necessary for PIO. At approximately 7 sec the PIO event begins. At approximately 9.5 sec, one half cycle into the PIO oscillation, ROVER correctly identifies all 4 PIO conditions as true. ROVER does require calibration of threshold values used in identifying conditions of significant aircraft responses and pilot inputs, but once calibrated does provide a useful tool for rapid detection of PIO conditions.

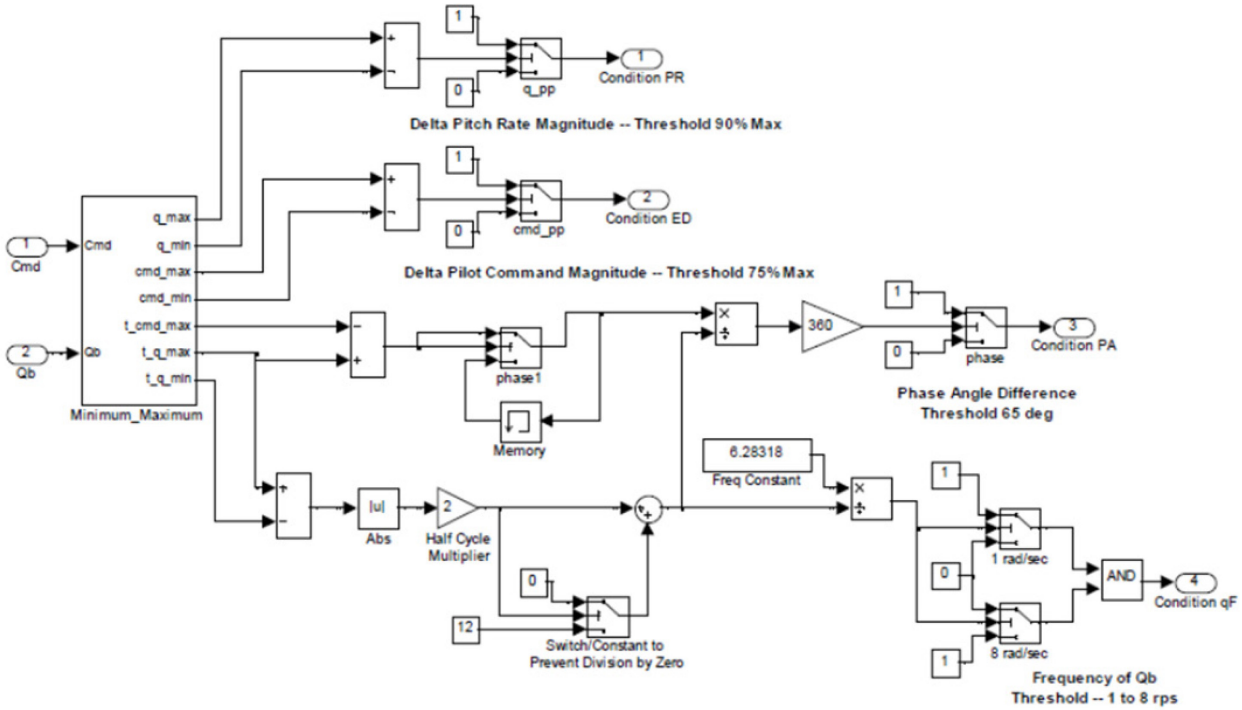


Figure 5-23: ROVER Model Conditions Block for Flag Computation.

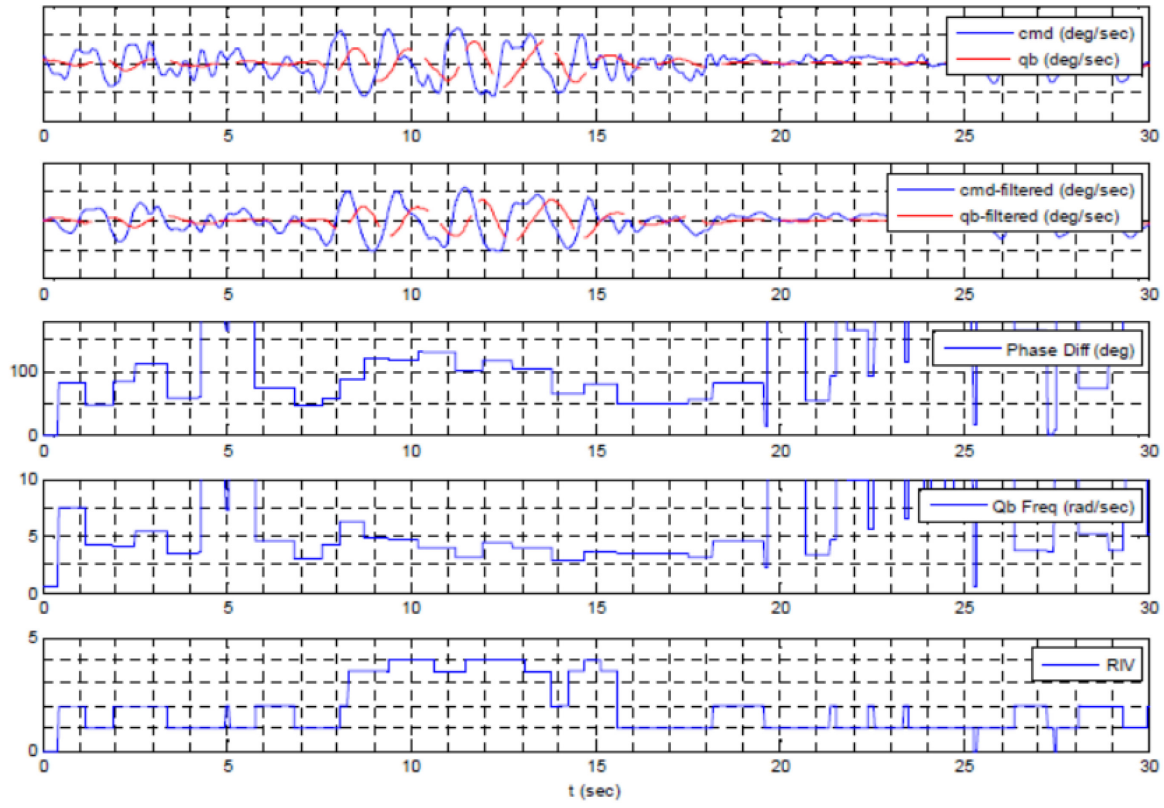


Figure 5-24: ROVER Evaluation of Modern-Day Fighter.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

PIO Investigations with Large Aircraft

In the "End of the Century" summary given in Ref. [13], contributions from Airbus and Boeing summarise their experience with PIO resistance testing for large aircraft. Some remarks made in those contributions will be repeated here.

Data were collected in high as well as in low altitude cruise and approach and landing conditions. Testing was performed in formation flight with the evaluation aircraft trailing a companion aircraft in a similar position as for boom AAR. Consequently, similar tracking manoeuvres as those performed during boom AAR were assessed, e.g., as presented in Section 4.4.1 with test manoeuvre AAR-5-uncoupled-HQ-characteristics (Figure 4-11). A similar manoeuvre had been flown in the wing tip formation position. As reported, altitude changes as well lateral deviations had been tasked for evaluation, in both cases ±10 to 20 ft. The instruction on how and which reference points had to be taken is not given in Ref. [13].

Tasks in ground proximity were a constant altitude fly-by over a runway. Target altitude would have been 50 ft AGL ±10 ft while maintaining runway centre line. The challenging part of this test manoeuvre was adjusting the thrust properly. Pilot comments for the entire manoeuvre were: achievable. Complexity was increased with lateral S-turns within the boundary of the runway sides or vertical S-manoeuvres with quasi sinusoidal altitude changes of ±20 ft. For both types of manoeuvres rapid acquisition of the limitations was asked for. Other manoeuvres flown were offset manoeuvres as described herein.

The pilots' experience was that no single manoeuvre had been effective for exposing potential PIO. The most effective design strategy appeared to be careful diligence during normal test flying. Within the test philosophies given here, only the combined evaluation and interpretation of all test points flown gives the most comprehensive understanding.

Some remarks made on pilot gain within the presentations:

- Pilot gain is most important in closed loop performance and stability.
- Pilot gain is not easily controlled. Pilots do not (cannot) change gain at will.
- Evaluation tasks require a consistent level of pilot aggressiveness.
- Any proposed evaluation technique must give consistent results across a given pilot population.

  → Results must not depend on individual pilot performance.

5.3.6 Experiences with PIO Resistance Testing More Generally

Instantaneous Centre of Rotation (ICR)

Since pilot perception acts as the loop-closure for the outer loop control discussed earlier, any aircraft motions that affect the perception of the true motion have the ability to alter HQ. Structural dynamics can be sensed as inaccurate aircraft motion. Unusual locations of the Instantaneous Centre of Rotation (ICR) can drive these sensations as well.

As the pitch effectors of an aircraft have more influence on the overall aerodynamic lift while generating pitching moment, the point about which the aircraft rotates tends to move forwards (on conventional-tailed or flying wing aircraft). When this point moves ahead of the pilot station, a non-minimum phase zero is added to the n_z transfer function as sensed by the pilot. This results in a "sinking" sensation when pulling back on the stick in an effort to increase load. The decrease in pilot station n_z is due to the decreased lift of the deflected surface prior to an increase in AoA.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

The effect of unusual ICR placement (i.e., ahead of the pilot station) has been shown to increase the likelihood of adverse pilot coupling. This has been studied in depth in Ref. [63], although the most well-known scenario was the space shuttle PIO encountered on landing approach of free flight #5 in 1977 [64].

Future designs may necessitate unusual ICR locations (due to structural, low observability, etc. drivers). The HQ effects of such a design choice may not overcome the priority given to these design decisions, it can guide testers where to investigate the flight envelope for the possibility of PIO.

PIO Susceptibility Testing

In addition to performing testing in which the pilot is attempting to achieve the best performance of the system, evaluation of the PIO susceptibility of the pilot-plus-aircraft system is essential. PIO testing is designed to keep the pilot fully in the loop, even at the expense of performance of the task. This can be done by a large number of techniques, including HQDT, Boundary Avoidance, and others. The endpoint, though, of all these techniques is to reach a state where no error at all is tolerated, and the pilot assiduously attempts to eliminate any error. If the pilot is continuously in the loop, the overall system stability can be determined. This is accomplished via the PIO rating scale, and it is only a measure of stability. One can consider this a determination of whether there is a pole in the right half plane the pilot-plus-aircraft system.

Determination that there is an instability in the system does not inherently mean that the HQ is unsatisfactory, only that more investigation needs to be accomplished. PIO susceptibility testing does not determine how easily recognisable the PIO is, how dangerous it is, or how easy it is for the pilot to get out of the loop. This critical information must come from other, operational tasks, as well as pilot comments.

All this is to say that a high PIO rating during PIO susceptibility testing does not immediately indicate that a flight controls fix is warranted, only that further investigation is necessary.

5.4 PHASE 3 TESTING (THE CHALLENGES OF OPERATIONAL TESTING)

5.4.1 Practical Aspects from Various Projects

From SR71 (1)

A useful flight test technique [65] for increasing pilot gain to wring out deficiencies in flight dynamics is shown in the SR-71 flight test in **Figure 5-25**. The example in the figure is a Bank Angle Capture and Hold (BACH) manoeuvre. A requirement to hold and acquire bank angle within a specified heading change is defined. The specified heading change can be reduced to increase the urgency in completing the manoeuvre, thereby increasing the pilot gain in the task.

The pilot in this manoeuvre was not able to acquire a bank within the specified regions within the 4 deg heading change requirement. While this data was being used to develop manoeuvre concepts for supersonic aircraft, the concept of increasing the urgency while maintaining a level of precision in a realistic task is a useful technique for the evaluation of the pilot-vehicle-system.

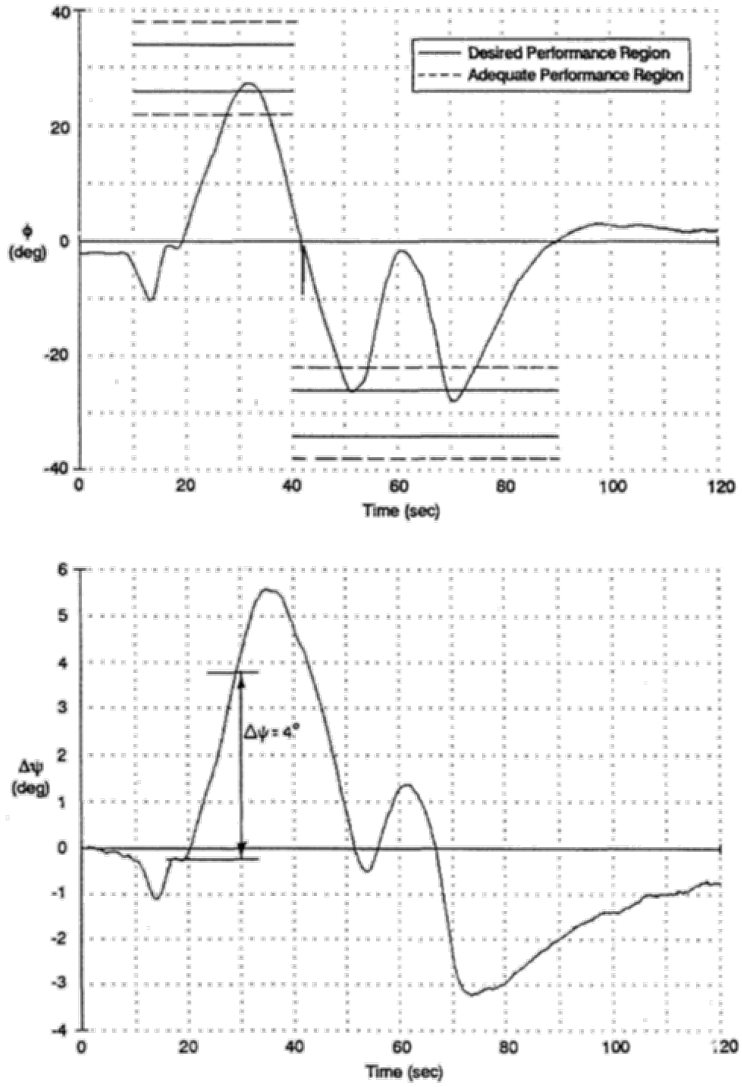


Figure 5-25: SR-71 Bank Angle and Heading Change Requirements [65].

From SR71 (2)

The following example from SR-71 flight research [66] on supersonic handling qualities illustrates the impact displays and lags can have on the handling qualities. A vertical plane altitude change manoeuvre was developed to evaluate the flightpath response handling qualities at Ma = 3.0. The manoeuvre required the pilot to pull up and capture a targeted altitude change at a climb rate of 1,000 ft/min while maintaining constant Knots Equivalent Airspeed (KEAS). Desired performance was defined as maintaining the target altitude with less than 100 ft deviation and maintaining less than 5 kn deviation in KEAS. Adequate performance was defined as maintaining the target altitude within 300 ft while maintaining less than 10 kn deviation in KEAS. The manoeuvre was flown using an inertial derived vertical speed, and an Instantaneous Vertical Speed Indicator (IVSI). Despite the naming convention, the IVSI was shown to add approximately 6 sec of lag at the altitudes the SR-71 was flying at. Cooper-Harper-Ratings are significantly degraded from level 1 to level 2 when using the IVSI as feedback for the manoeuvre, see **Figure 5-26**.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

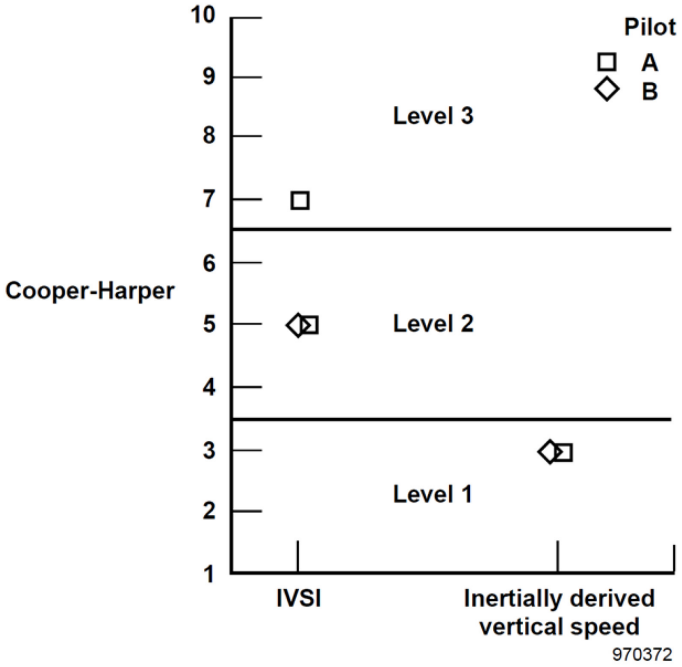


Figure 5-26: SR-71 CHR for the Vertical Plane Altitude Manoeuvre [66].

A time history of the manoeuvre (see **Figure 5-27**) illustrates the difficulty experienced by the pilot in maintaining the desired rate of climb when using the IVSI. The pilot commented that he could not keep the rate of climb anywhere near where he wanted it.

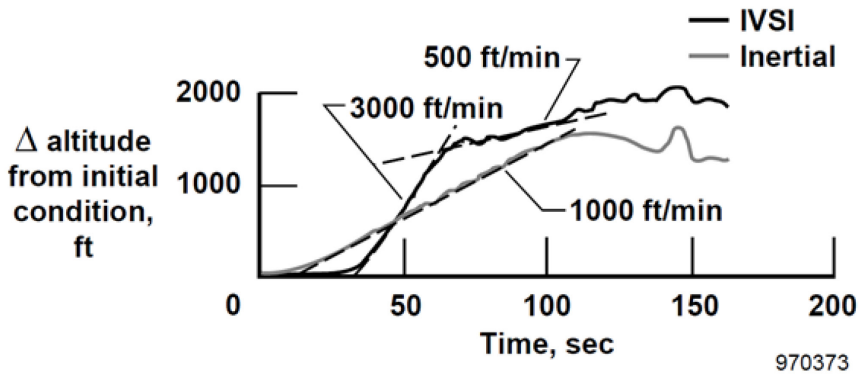


Figure 5-27: SR-71 Comparison of Time Histories [66].

From HARV

While not formally relevant to a flight envelope clearance process, the application and extension of handling qualities criteria was investigated for high angle of attack, post stall manoeuvring in the F-18 High Alpha Research Vehicle programme [6]. An F-18 was modified for multi-axis thrust vectoring to enhance manoeuvring characteristics up to 70 degrees angle of attack. The aircraft is shown in **Figure 5-28**.

Figure 5-28: NASA F-18 HARV During High AoA Testing.

Evaluation manoeuvres were developed in simulation to investigate handling qualities in the 30 deg to 60 deg alpha range. Manoeuvres ranged from open loop performance metric identification, to closed loop pitch attitude captures, normal acceleration captures, bank angle captures, gross acquisition, and fine acquisition tracking tasks (for an example see **Figure 5-29**), and combat manoeuvring. This range of manoeuvres proved insightful for evaluating high alpha criteria. Pilot comments and ratings were obtained and compared to high alpha design guidelines established by simulation and conventional criteria.

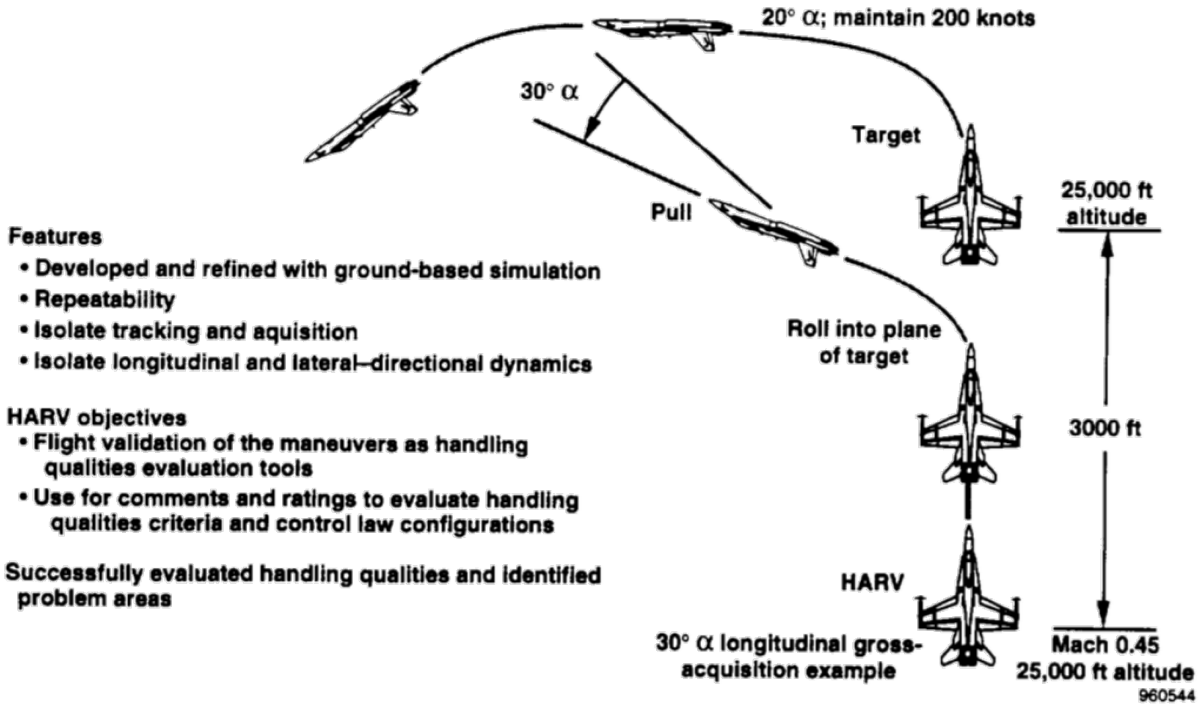


Figure 5-29: NASA F-18 HARV High AoA Manoeuvres.

An example comparing data to roll axis design guidelines is shown in **Figure 5-30**. The guidelines identify desirable bank angle capture overshoots to be less than 30%. Pilot comments and data validated the 30% overshoot, indicating that weighting overshoot over initial roll rates was beneficial.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

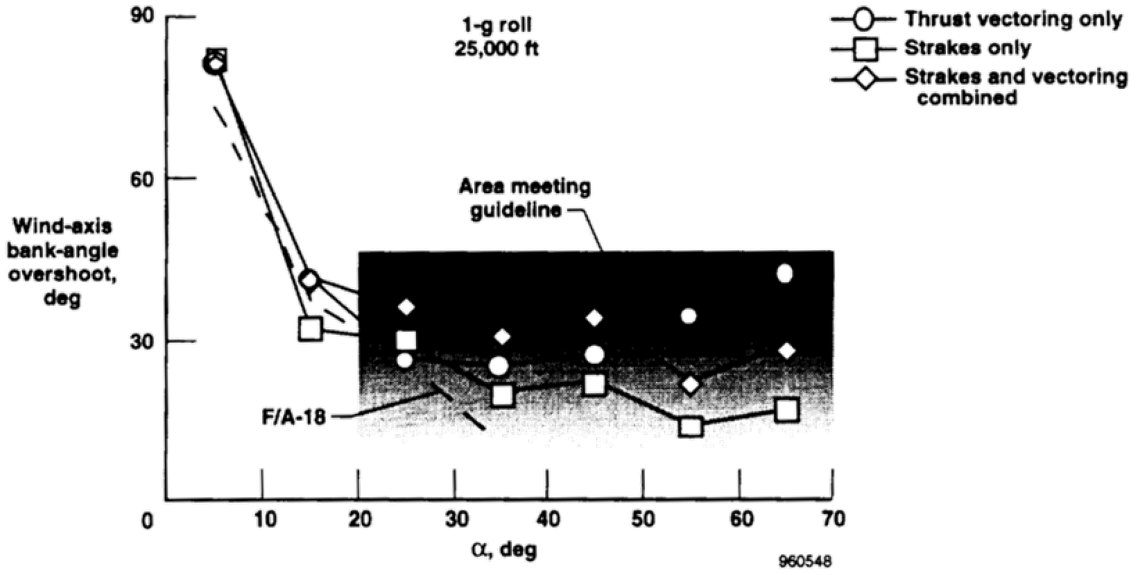


Figure 5-30: NASA F-18 HARV Wind Axis Bank Angle Overshoots after 90 deg Wind Axis Bank Angle Change.

Conventional criteria were also examined for applicability to the high alpha regime. An example is given below in **Figure 5-31** for 3 different control laws applied to the bandwidth criterion at 30 deg AoA. Overall handling qualities were predicted by pilots to be level 1 for control law version 26, level 2 for version 27, and level 1 for version 28. However, version 28 was considered an improvement over both version 26 and 27. The conclusion of the authors [6] was that the trends observed in the criterion were reasonably predicted, but that boundaries for level 1 and level 2 may require adaptation to improve applicability to the high alpha region.

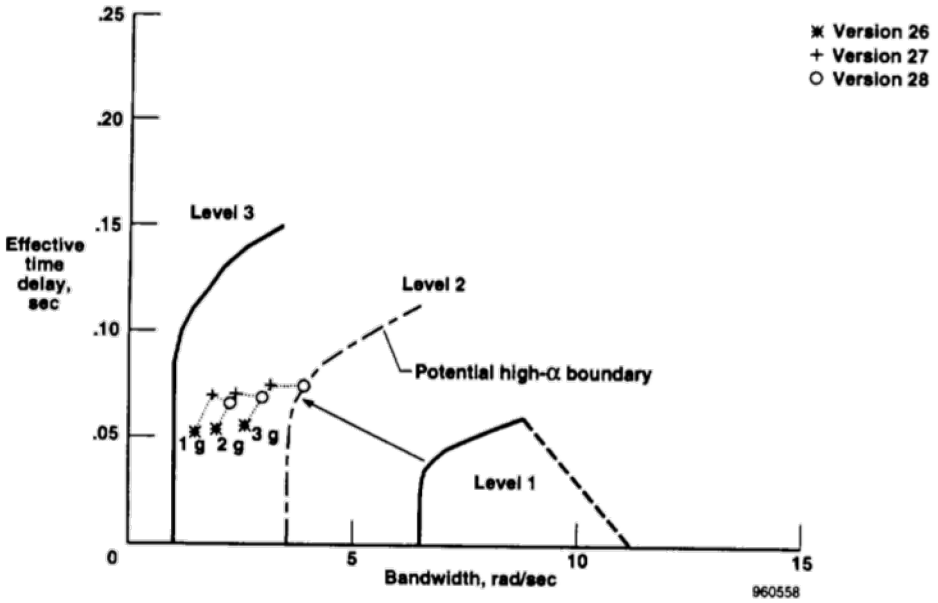


Figure 5-31: NASA F-18 HARV Bandwidth Criterion Application.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

5.4.2 Experiences from Aerial Refuelling

General Considerations:

As already mentioned in Section 4.4.1 aerial refuelling is one of the most challenging tasks in HQ testing. It therefore requires extensive preparations across various disciplines and partners. Considerations given below are essential for good and thorough planning for AAR HQ testing. Also, proper consideration of the effects described below will help for better interpretation of any HQR given by the evaluation pilot.

- **Various systems are involved and the interaction with them needs to be considered:**
  - Fuel system

    The fuel system is a system on its own and the system responsible will determine all testing within the scope of AAR. Generally, a combination of all fuel system modes for aerial refuelling operable on the tanker must be tested in combination with all possible system modes for aerial refuelling of the receiver.

    It needs to be coordinated with the HQ discipline as both systems are normally tested together.

  - Air Data System (ADS)

    The ADS generally is affected in two ways: a) ADS characteristics when flying in the wake of another aircraft must be known. This may have an influence on stability augmentation within the receiver FCS; and b) For the hose-drogue AAR a conflict may arise between ADS sensor locations, AAR probe location, and close vicinity of the drogue especially during contact approach, e.g., under turbulent atmospheric conditions.

    Special considerations for test planning are required.

  - Lighting System

    Both aircraft, tanker, and receiver, have a special lighting system for approaches and guidance for the task and especially during dark. They must be clearly visible and must not disturb the other aircraft.

    Inside receiver cockpit lighting must not cause any reflections, e.g., on the glass of the canopy, irritating the pilot during the AAR operation.

  - Electromagnetic Compatibility

    Electromagnetic emissions of both tanker and receiver in close vicinity of each other must be considered. Most likely the receiver will have turned off his radar, communication antennas located in the rear of the tanker may not be operated during the AAR manoeuvre. Possibly a special flight clearance for, e.g., the receiver is required with resulting operational constraints for electronic equipment.

  - There may be additional system interactions not further considered here.
- **Flight test safety** is always important. In AAR operational testing in the close vicinity of two (or more) aircraft, special operational procedures must be developed in order to not endanger any aircraft and the outcome of the tests.
- Prior to the commencement of testing for AAR a special **wake survey** of the receiver aircraft in trailing position to the tanker must be performed, see Section 4.4.1. From an operational point of view various trailing distances must be investigated.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

In all this testing special care must be taken to not to come too close to, for example, the empennage of the tanker. Too close proximity to the empennage must be a criterion just as aerodynamic disturbances are, as outlined in Section 4.4.1

- **Approaching dynamics** to the drogue and developing the specific technique for the hook-up is part of the more academic test programme as defined in Section 4.4.1.

  Another aspect is when a large receiver aircraft approaches a possibly small tanker, e.g., a C-5 Galaxy approaches a KC-135. An approach like this may be challenging for the tanker as well. The "bow wave" of the receiver influences the flow around the horizontal stabiliser; thus, trimming of the tanker[2].

  Considerations of this effect must be accounted for.

  Another aspect of approach dynamic is engine responsiveness. This may as well be a determining factor.

- For hose-drogue AAR **hook-up dynamics** a technique may be considered which has an influence on contact success rate. When flying in calm air hose and drogue will trail the tanker calmly making a successful hook-up "easy". When flying in more turbulent air hose and drogue may show some adverse dynamics making a successful hook-up more difficult.

  In this case it may be helpful for a "dry contact test point" to have the hose primed. This means the tanker starts pumping fuel into the hose. It makes the hose heavier than in the non-primed condition and influences hose-drogue dynamics favourably. After the hook-up, the receiver will not start the refuelling process (dry contact).

- **Visual cues** play an important part in AAR. They support the pilot of the receiver aircraft the most during the entire operation.

  Supportive lighting from the tanker indicating the proper refuelling position to the receiver must be equally and clearly visible during day and night, during cloudy days and sunny days. The lighting must never dazzle or blind the receiver aircraft pilot.

  For hose-drogue AAR behind a large tanker three refuelling positions are commonly possible: left wing, right wing, and centre fuselage position. All three positions must be evaluated as the visual cues in all are very different.

  A location of the refuelling probe on the left side of the cockpit will give the receiver pilot very good visual cues when refuelling behind the right wing of the tanker as the pilot will always see the tanker as a reference. When refuelling behind the left wing of the tanker visual cues are scarce as the pilot now has to look away from the tanker. This makes refuelling on this side much more difficult, especially in the dark.

  During night-time AAR it may be difficult for the pilot of the receiver aircraft to see the drogue when approaching the hook-up position. This may become worse when refuelling takes place at that station where the pilot has to look outbound of the wing of the tanker. Proper lighting is essential, but it varies with tanker and receiver aircraft.

- As for all HQ testing, **crew proficiency** is an important factor for reliable HQR during AAR testing. The test pilot must be trained and proficient for the task.

[2] The term "bow wave" is used in many publications, e.g., Refs. [41] and [42], and everybody understands what is meant. But aerodynamically spoken it is not a wave emanating from the receiver, it is the flow field induction as described by potential theory of the large fuselage which influences the tanker, mainly its tail. The lift generating wing flow field ahead of a large and heavy receiver aircraft also has an influence on the tanker.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

It may be mentioned here from test experience that for a specific test an evaluation pilot doing an AAR manoeuvre commented with rather unfavourable HQR after the test. This was unusual since the aircraft under consideration normally exposes Level 1 HQ in AAR operations. Only in the debriefing did this specific evaluation pilot (a well-trained test pilot) reveal that this test was his very first hose-drogue AAR manoeuvre. Crew proficiency is important.

- Crew endurance

  The nature of flight testing for AAR implies that many test points for this specific task will be scheduled and can be executed during one test flight. When planned and performed properly enough fuel for a long-lasting test flight will be available.

  On the other hand, sound HQ evaluations of the AAR refuelling task require a lot of concentration by the evaluation pilot. This requirement can be very tiring in a long-lasting flight with many scheduled hook-ups, not only for the evaluation pilot but also for the test crew in telemetry. Experience indicates that a sortie with more than 20 hook-ups makes not much sense. The capacity of the evaluation pilot to concentrate beyond this point will be reliable enough for a successful hook-up but no longer reliable enough for a sound HQR.

- Large receiver aircraft

  Modern large receiver aircraft will most likely have a state-of-the-art fly by wire FCS. Some of these are operated via a side stick – for the captain on the left side the side stick will be left as well, for the co-pilot on the right side it will be on the right. This may pose a problem in a specific tense or stress test situation for a test pilot who comes from the fighter community. There the stick is always in the right hand and the throttle is in the left. Now sitting in the left pilot seat this may lead to confusions since the intrinsic behaviour may be different.

- Receiver aircraft configuration

  Also, for test planning different receiver aircraft configurations must be considered. A heavy and “draggy” receiver with various outboard stores will act differently compared to a light, clean, and more agile configuration. Different receiver aircraft configurations must be tested and cleared for AAR operations.

  In this context again engine responsiveness is mentioned. It may be easier for a draggy configuration to control speed as the required thrust changes become larger than for a less draggy configuration. On the other hand, a heavy aircraft may react a lot more sluggish than a light and agile aircraft.

This extensive excursion on some general aspects illustrates how thoroughly integrated with other systems and influences HQ testing for AAR can be. A thorough evaluation of these aspects determines the amount of overall testing for AAR.

SAAB Experience

The SAAB JAS-39 Gripen aircraft was originally developed and produced without any intention of offering AAR capability. Only later AAR capability was requested for this aircraft. Aircraft modifications (HW and SW) without changing the appearance of the aircraft and flight testing of the new system have been reported in Ref. [67]. Some selected results and experiences shall be repeated here.

Figure 5-32 shows AAR refuelling envelopes of the two different tanker aircraft under consideration in Ref. [67]. The left side shows the envelope of a tanker capable of flying high and relatively fast. On the right side one can see the envelope of a “slow” tanker not able to fly as high as the one on the left side. Symbols

show scheduled test points, numbered according to the sequence of testing. Flight testing was started with the fast tanker approximately right in the middle of its envelope. At that altitude (FL200) all selected operational speeds had been tested before going to a higher and a lower altitude; only at the end of testing had speeds at the envelope limits (test points 10 and 11) also been tested. Testing with the slow tanker was more difficult due to the reduced AAR refuelling envelope as compared to the fast tanker.

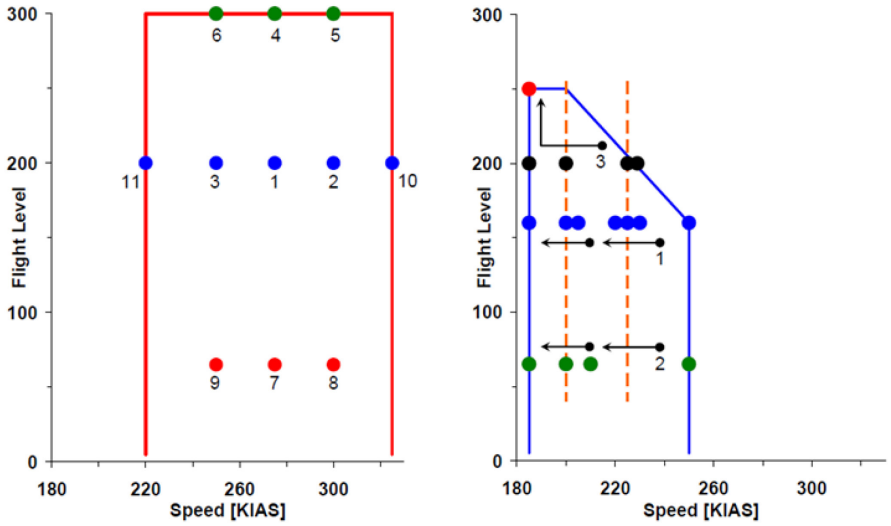


Figure 5-32: AAR Refuelling Envelopes of Two Different Tanker Aircraft [67].

From an operational and a HQ point of view, testing in a spread over the entire envelope is necessary. Higher altitudes and lower speeds require testing at higher AoA and consequently higher drag, whereas testing at lower altitudes and higher speeds will be done at smaller AoA. Thus, a wide spread of different receiver aircraft capabilities is to be investigated. This affects receiver aircraft HQ as well as engine response dynamics when controlling speed as precisely as possible.

Also, in Ref. [67], one can find a comprehensive catalogue of test manoeuvres performed. Finally, an extensive discussion about refuelling probe location on the Gripen aircraft is given. Due to the fact that the probe was integrated into the aircraft only very late in the process, compromises had to be taken. This means with respect to the location of the pilot's head in the single seat aircraft the probe has a more astern position in the twin seat aircraft. Thus, in the twin seat aircraft, performing AAR from the front seat is much more difficult than in the single seat aircraft because the probe tip is further aft with respect to the front seat pilot's head position. Ref. [67] reports that good aural communication between rear seat and front seat pilot was beneficial.

Ref. [67] also mentions how a proper disconnecting technique can be essential. When disconnecting "improperly" at the end of the AAR manoeuvre it could occur that a bouncing drogue would "touch" the receiver aircraft. Thus, disconnecting needs to be initiated in a way that the receiver separates along the trail of the drogue, making drogue movement minimal when disconnecting.

Fused Reality

One flight test technique explored under a NASA Small Business Innovative Research proposal was the blending of virtual images with real-world scenes in flight to produce handling qualities closed loop tasks. The concept proposed by Systems Technology Inc. (STI); designated as fused reality, involved a flight test evaluation of 3 tasks: offset landing, air-to-air drogue refuelling, and formation flight [68]. The proposed benefits of such a system are:

1) Tasks can be repeated more consistently.
2) Tasks like the formation flight and refuelling do not require additional aircraft to fly, thereby reducing costs.
3) Tasks, like the offset landing, can done with a runway image that is projected above the actual runway, providing a safety margin of error.

Figure 5-33 compares the real-world scene with the fused reality scene for the drogue refuelling task.

Additional cues to aid in evaluating the task, such as drawing boxes for adequate and desired performance criteria could have a benefit not available in the real-world scenario. **Figure 5-34** from Ref. [69] highlights how the virtual scene can be enhanced to provide the pilot discernment on the tracking performance and tracking position called out for in the task description.

Figure 5-33: Comparison of Real-World and Fused Reality Scene.

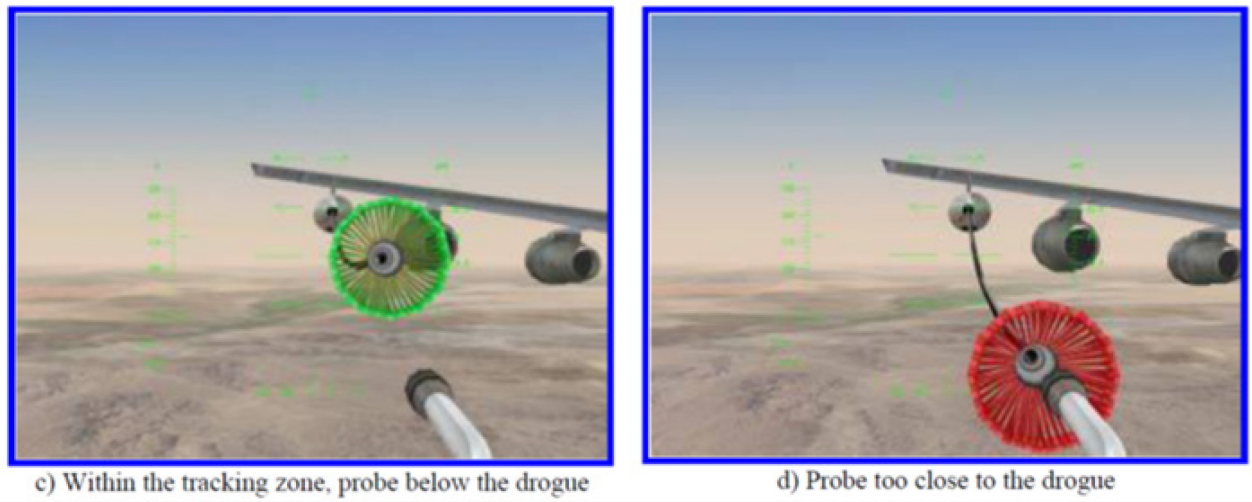


Figure 5-34: Enhancement of Visual Cues.

When the pilot is maintaining the desired tracking distance in the task the basket turns green. When the probe enters into a too close proximity to the basket it turns red. This provides the pilot feedback during the manoeuvre which promotes consistency across the manoeuvre.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

While still in development, pilot evaluations were favourable of the fused reality concept. Data from in-flight simulation indicated that the fused reality scene was sufficient to delineate differences between handling qualities configurations tested.

Simulation Considerations to Evaluate HQ During AAR:

For the sake of completeness, a simulator result considering the evaluation of HQ in AAR is mentioned here. In accordance with the Neal-Smith HQ criterion as presented in Figure 3-18 and Figure 3-19 a more theoretical investigation in Russia is given in Ref. [70]. This research proposes slightly adopted boundaries for HQR for the AAR task (see Figure 10 in Ref. [70]).

From SR-71 (3)

In an internet forum (www.theaviationgeekclub.com [71]) an interesting report is given on AAR operations with the SR-71 aircraft, see Figure 4-8. Due to the special design of the SR-71 and the common USAF tanker both were flying at approximately 300 KCAS at the edge of their respective refuelling envelopes. The tanker at the "high speed" end, the receiver at the low-speed end with the J58 engine not "really liking" subsonic operation. For this, both engines of the SR-71 had to be operated at approximately max dry power. During a typical AAR operation, the aircraft took about 35,000 kg of fuel. At the end of the AAR sequence the challenge became to keep the now heavy aircraft steady behind the tanker in AAR contact. Higher weight means higher AoA and, thus, higher induced drag. This would mean max dry power would not be sufficient anymore to follow the tanker properly. Therefore, one engine of the SR-71 had to be put into minimum reheat power in order not to fall behind. Speed control was performed with the other engine still operating in the dry range. This posed several difficulties. It must not have been easy to modulate thrust and control speed with the still in maximum dry operating J58 engine in that condition. The aircraft was flying due to the asymmetric thrust now with a yaw angle in trail of the tanker which caused additional coordination effort by the pilot. The significant change in position of centre of gravity also had to be managed by the pilot – not to mention the stress and workload it would have meant to unintentionally disconnect and have to re-connect in order to pick up the necessary amount of fuel for fulfilment of the required mission.

These examples illustrate specific operational experiences in AAR. Connected HQ difficulties could only be touched upon briefly. With some imagination for the SR-71, the differences in AoA of tanker and receiver can be drawn from Figure 4-8.

5.4.3 Experiences from External Stores Integration

5.4.3.1 Overview

External stores are indispensable to fulfil operational or mission requirements of military aircraft. Fuel tanks, bombs, smart weapons, electronic warfare pods, targeting and navigation pods are the most common stores that are carried by aircraft to enhance the mission capability. Store integration flight test starts after the baseline configuration of the aircraft is established and proceeds through the entire life cycle of the aircraft with changing operational requirements.

The aircraft's HQ characteristics are affected by the store carried during flight. As it needs to perform its mission effectively, store integration test campaigns must include HQ testing. The limiting factor is that the certification programmes usually aim to minimise the cost as much as possible. Thus, flight hours for HQ testing are usually quite restricted. Within the scope of this report overall HQ testing methods have been described in Chapter 4. These methods are just as relevant for external stores integration testing. The amount of testing depends on how large of an effect the "new" store has on the baseline configuration.

Studies on the effect of external stores on the stability characteristics of fighter airplanes have been conducted by NASA for many years. A brief overview about stores' effects is given by Spearman in Ref. [72] (1972) for a number of external stores and aircraft. He illustrates the effects of external stores on the stability of several fighter airplanes with different tail and wing configurations based on wind tunnel test results.

Samples of lateral and longitudinal stability changes with added stores from Ref. [72] are presented in the following. In **Figure 5-35** the directional stability changes with the addition of relatively big, winged missiles on a delta-wing fighter with aft-tail can be observed. A significant change on the directional stability coefficient $c_{n\beta}$ with increasing AoA is visible resulting in a substantial increase in directional stability with the added missiles.

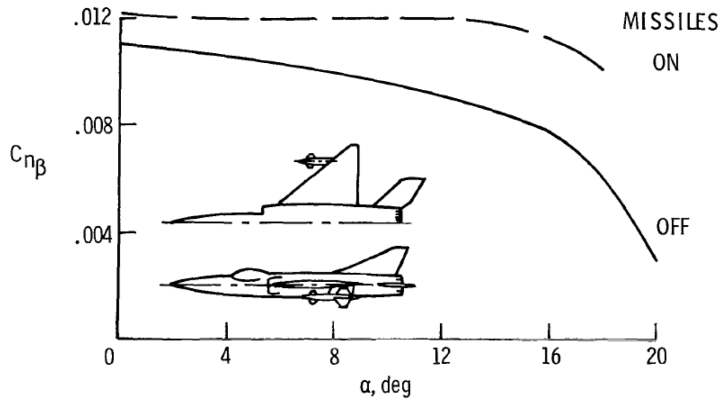


Figure 5-35: A Sample of Change of Directional Stability with External Store at M = 1.6 [72].

Figure 5-36 shows the longitudinal stability changes with the addition of inboard and outboard stores on a 45 deg swept wing fighter airplane at Mach 1.6. The change of the pitching moment coefficient c_m with angle of attack is noticeable with the added inboard stores that caused a measurable reduction in longitudinal stability.

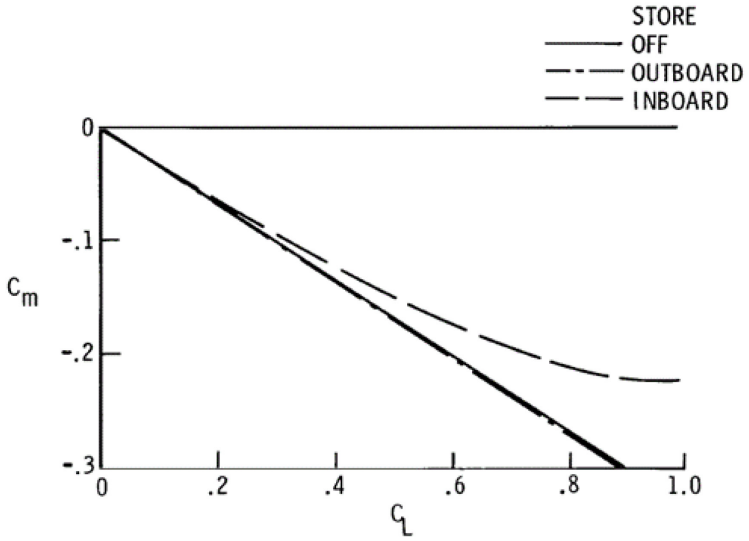


Figure 5-36: A Sample of Change of Longitudinal Stability with External Store at M = 1.6 [72].

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

One important conclusion in Ref. [72] is that even similar stores may produce different effects on different types of aircraft. Furthermore, the effect of stores on aircraft stability and consequently its handling qualities may have a significant influence.

External store integration into a given aircraft can be divided into three phases. **Stage 1** integration includes all air vehicle integration tasks such as aerodynamics, structures, loads, flutter, environmental compatibility (noise and vibrations, both on the platform aircraft as well as on the new store), Handling Qualities, and finally safe separation. **Stage 2** is dedicated to all software integration tasks, store communication with the platform aircraft as well as testing of cockpit display changes. Finally, **Stage 3** completes the integration process with the verification of the operational deployment of the store, e.g., live fires.

This text will only focus on HQ issues that are part of Stage 1 testing. Other equally important subjects for testing in Stage 1, e.g., flutter, structural coupling, environmental data gathering, or other disciplines, will not be touched upon here. But it should be kept in mind that testing for these disciplines is just as important as HQ testing and it can require much more test effort than HQ testing.

HQ testing is a very important part of Stage 1 store certification. However, certification programmes, which are conducted during the life cycle of an aircraft, usually aim to minimise the cost and time schedule as much as possible. As a result, flight hours are usually quite restricted for HQ testing for a store integration programme. Therefore, a challenge surfaces for the test crew to optimise the number of test points while safely covering all necessary aspects of HQ testing.

5.4.3.2 Approach for HQ Testing for External Store Integration

The content of possible handling qualities testing for store integration is outlined in MIL-HDBK-1763 [73]. It aims to determine the extent of compatibility between military aircraft and aircraft stores. It is for guidance only and cannot be cited as a requirement. However, it is in wide use for store certification work. Another guideline is given in an AGARDograph (AGARD-AG-300-Vol-29) [74]. Both provide uniform guidance requirements for establishing the extent of compatibility between an aircraft, specific stores, and suspension equipment and guidance to justify the airworthiness of stores for use on an aircraft.

The **type of external store** greatly influences the requirements for integration tests in general. Overall requirements are mission-oriented and are determined by the new store carried. An aircraft that carries multiple general-purpose bombs with external fuel tanks and an aircraft with only air-to-air missiles have different mission requirements and consequently, different HQ requirements and, thus, limitations during flight. Moreover, carriage of the stores can be external or internal. In general platform aircraft HQ are affected twofold. Firstly, overall aircraft HQ while carrying the store are affected. Secondly, HQ during operational use of the store, e.g., during deployment, are of importance.

Testing for **internally carried stores** can be relatively simple. The CG position change of aircraft while loaded is the main point of interest for aircraft with internally carried stores, since the external aerodynamics of the aircraft remain unchanged. The change in handling qualities with open bay doors is still an issue. However, the effect of the store shape is minor compared to the effect of creating a cavity on the aircraft body. These factors reduce the need for handling qualities testing for internally carried stores due to fact that the aircraft handling qualities are already tested at different CG positions during the development phase. Consequently, the required testing for handling qualities is quite limited or none for internally carried stores.

Externally carried stores on the other hand, have an effect on the aerodynamic characteristics of an aircraft as well as the changing of the CG position. An illustration of effects on aerodynamics is given in Figure 5-35 and Figure 5-36. The effect of change on the aerodynamics is evident in the performance, flying and handling qualities of the aircraft. Different store types drive the shape of the store and consequently the effect of the store on aircraft aerodynamics. Stores like fuel tanks are designed to reduce

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

the effect on the aircraft aerodynamics, namely drag, as much as possible. Stores such as weapons or electronic hardware pods have mission-oriented shapes that can have a considerable impact, see e.g., Figure 5-35. Cruise missiles, which have stealthy and lift generating bodies, and target towing stores are other examples.

Change in the aircraft's aerodynamics is not an issue to be neglected since the behaviour of the aircraft changes with it. A major change to the aircraft aerodynamics with an additional store can cause serious handling qualities issues such as loss of control, PIO tendencies etc. Therefore, it is preferable to design new external stores to be similar to previously already integrated and certified stores as far as possible, to reduce risk and testing.

The MIL handbook suggests testing the aircraft under consideration without and with the new store in order to detect differences in HQ characteristics, e.g., for ground attack manoeuvring. Tests should be performed according to the methods given in Chapter 4. The proper selection of the tests given there depends on the specifics of the new store to be integrated.

Usually, the approach for HQ testing in store integration consists of a comparison of the baseline aircraft and the test article with the new loaded aircraft characteristics. The difference of handling qualities between two loading configurations is investigated. Results with any previously integrated similar stores are utilised to reduce the risk and size of the test campaign. Similarities highlight dynamically and aerodynamically (inertia, stiffness, shape, dimensions) similar stores. As a summary, there are two main options:

Case 1:

No similar store and loading configurations are available for the test aircraft. This case requires consideration of a "fully blown" envelope expansion test campaign, as explained briefly in Section 2.1. Prior to flight testing, the influence of the store on the aerodynamic characteristics of the aircraft is tested in the wind tunnel or analysed by CFD for all necessary aircraft loading configurations. Stability and control characteristics of an aircraft with carriage of external stores are examined to reduce the risk of testing using the results of this endeavour. Considerations for flight envelope restrictions due to changes on aircraft's flight control system are made at this stage to ensure safety of flight testing.

Case 2:

A similar store and loading configuration is available from the inventory of the aircraft. In this case, the risks of testing can be mitigated since the aircraft's characteristics can be predicted with acceptable accuracy. The number of HQ test points can be reduced by decreasing the number of incremental test points that are defined for case 1 based on the confidence attained from previous store flight test data.

In either case, the HQ test should be performed without jeopardizing flight test safety and with good engineering judgment.

5.4.3.3 HQ Flight Test Techniques for Store Integration

The flight test technique for FQ and HQ is based on the approach presented in Section 2.1 and Chapter 4. Testing according to the manoeuvre pyramid [6] presented in Figure 2-3 is utilised from bottom to the top. Possible test point or manoeuvre definitions are given in Chapter 4.

At the planning stage, the flight control system features, known and expected aircraft characteristics and flight envelope limitations need to be taken into consideration (e.g., based on wind tunnel investigations or experiences with similar stores in flight already). Store separation and asymmetrical loading configuration effects on the aircraft characteristics must also be considered.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

The flight test stage starts with the selection of most critical loading configurations. The riskiest loading configurations are generally unsymmetrical loading configurations and configurations that demand and allow for high manoeuvrability. Once a platform aircraft has delivered a store it will have to fly asymmetrically, thus, testing with unsymmetrical loading is just as important. For HQ testing it is often sufficient to consider the case of the most unfavourable asymmetry only. The configurations are tested against the limits of controllability within the flight envelope. The flying qualities tests are utilised to investigate the flight envelope for unexpected behaviour from the aircraft. The handling qualities testing, however, is tailored based on the mission requirements.

Most commonly used testing phases for handling qualities are as follows:

- Taxi and ground handling;
- Take-off characteristics, including crosswind;
- Climb, cruise, manoeuvring descent characteristics, including effectiveness of speed brakes, power, and configuration changes at variable speeds in the flight envelope;
- Subsonic, transonic, supersonic characteristics;
- Buffet onset and intensity, vibration, and stall/high angle of attack characteristics;
- Low-speed flying characteristics (with and without high lift devices) including stalls, wave-offs, and crosswind landings;
- Formation flight characteristics;
- Air-to-air refuelling characteristics;
- Approach characteristics; and
- Landing characteristics, including offset landings.

In addition to these the following phases are also considered based on the mission:

- Basic Fighter manoeuvres (only where applicable, as a large external store affects aircraft manoeuvrability, e.g., AoA limitations, no carefree handling characteristics anymore, …);
- Air-to-Air Tracking (only where applicable);
- Low Level Flight;
- Terrain Following; and finally
- Air-to-Ground Weapon Delivery.

Safe separation must be considered separately from this “basic” HQ testing. It must be considered initially as a flight safety critical test item. It must therefore be conducted with all necessary precautionary measures. Depending on the operational characteristics of the store, safe separation must be possibly proven under various conditions. For HQ, the immediate transitional phase when the store leaves the platform aircraft is important. Possible adverse effects on the platform’s controllability and stability as well as PIO tendencies need to be expected.

5.4.3.4 Experiences

The main objective of store integration is enhancing the aircraft’s capability to perform and achieve a mission objective. The workload of the pilot while performing such a mission can be separated into the workload due to operation of an aircraft and the workload due to the task given. Operation of some stores does add extra pilot workload during their employment. Characteristics of the Human-Machine-Interface

(HMI) in aircraft avionics and cockpit design play an important role. Only operational HQ testing will reveal whether the HMI can be operated properly without any unnecessary workload to the pilot. This additional task workload should not be mixed with the workload caused by the aircraft's HQ. An example can be given from an IR missile deployment during a turning engagement. Undue pilot workload due to inefficient cockpit and avionic design as well as algorithms used to employ the missile (i.e., selection of missile, uncaging the seeker, multiple switch manipulations, unclear display symbols, etc.) naturally increases the task workload of the pilot. This workload must be separated from overall aircraft's HQ evaluation. Nevertheless, it affects operational efficiency.

HQ evaluations of lifting body stores carry some particularities. For example, during integration testing of a lifting body store in an aircraft with irreversible augmented controls, at open loop manoeuvres, the aircraft showed a neutral stability response in pitch axis while closing in to the stall speed. The CG was calculated at forward position in cruise configuration with symmetrical loading configuration. It has been indicated that the lift generated with the store was able to change the aerodynamic centre of the aircraft to reduce the stability margin significantly below a certain speed and between a certain fuel state. The results showed significant effect of lifting body stores on aircraft dynamics.

As an example, the response during an attempt for a pitch doublet is presented in **Figure 5-37** (blue line). The diagram shows pitch rate as a function of time. The aircraft behaved unexpectedly with increasing angle of attack and near constant pitch rate after pilot removed the positive elevator input which cut the doublet manoeuvre short. The expected aircraft response is also presented in Figure 5-37 for comparison with the complete doublet input from the pilot.

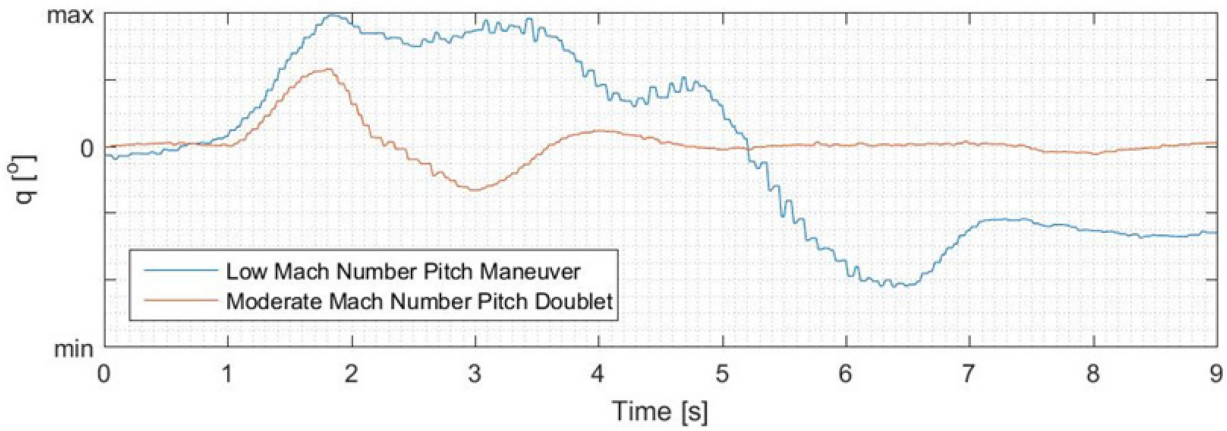


Figure 5-37: External Store Loading Configuration, Open Loop Pitch Excitation Test Pitch Rate Time History.

Since a condition like this is considered only to be a low possibility flight condition, only warnings were provided within the pilot handbooks. However, the results show significant effect of lifting body stores on aircraft dynamics.

Another example for lifting body stores can be given from a cruise missile integration to an aircraft with fly-by wire control system. During take-off testing with asymmetrical loading configuration the aircraft showed a tendency to turn its nose into the crosswind as soon as the aircraft reached the speed at which a meaningful aerodynamic load is achieved. The result was not unexpected from the test preparation standpoint. However, it showed the lifting body store had a significant effect over the take-off HQ characteristics of the aircraft.

Figure 5-38 presents the time histories from two tests for a particular store. The figure shows traces for speed, yaw rate, and heading as a function of time. In the first flight, the response of the aircraft is unexpected to the pilot, as a result a large yaw rate developed caused by the pilot's reaction to asymmetrical loading configuration. On the second flight, knowing what was to come, the pilot was able to reduce the yaw rate using moderate compensation.

Yaw rate data gathered from the first test flight is further examined to understand the response of the aircraft during take-off, see **Figure 5-39**. The rate produced by the aircraft was countered by rudder input which resulted in a diminishing oscillation. This oscillation resulted on the change of heading of the aircraft on the runway and after the aircraft left the runway surface. On the second flight the expected behaviour of the aircraft is compensated for much faster compared to the first one, based on pilot's experience from the first flight and the oscillation gain reduced significantly.

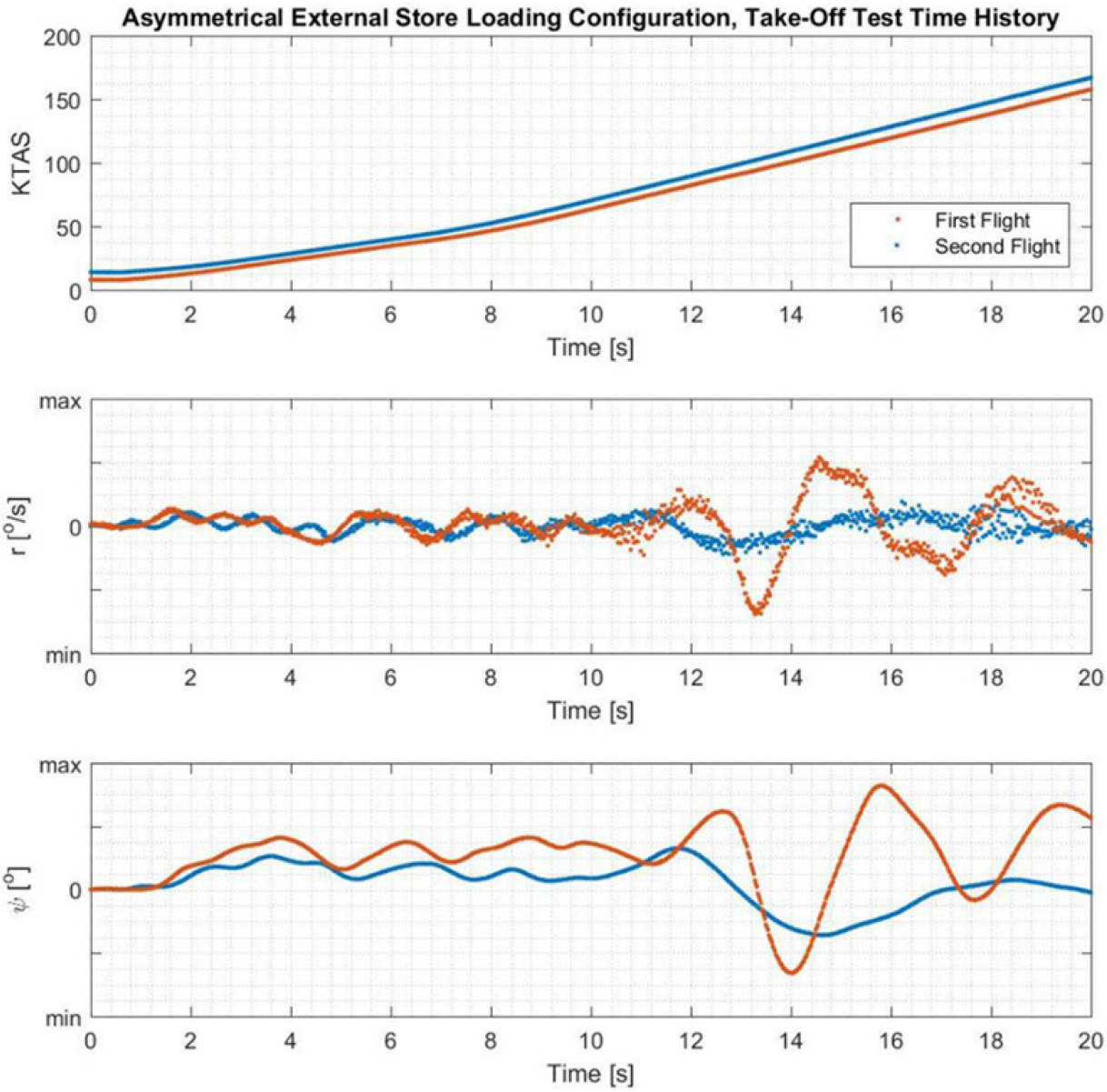


Figure 5-38: Asymmetrical External Store Loading Configuration, Take-Off Test-Time History.

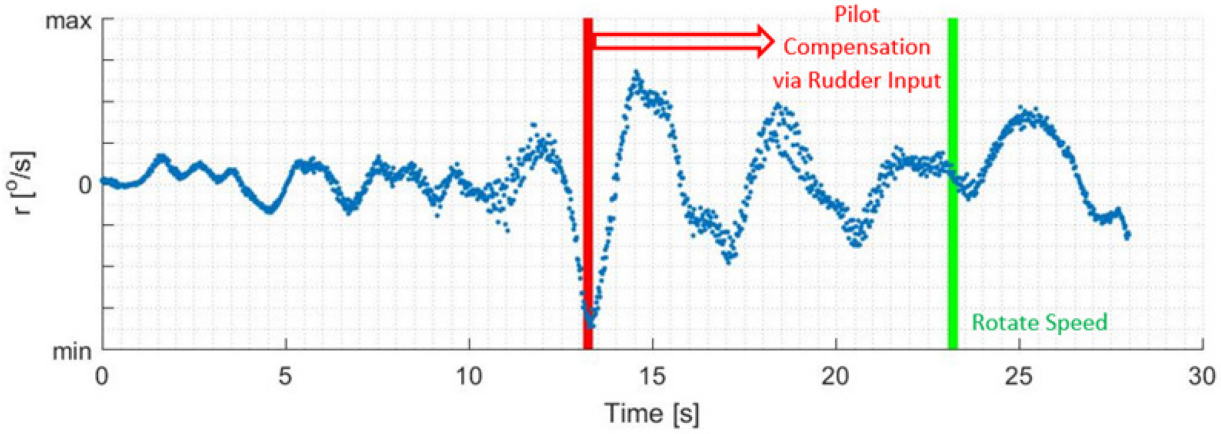


Figure 5-39: Asymmetrical External Store Loading Configuration, Take-Off Test Yaw Rate Time History.

As a precaution, the expected behaviour of the aircraft is put in as a warning in the flight manual for this case, indicating the necessary response required from the pilot. A surprising fact was that the store had a significantly lower weight compared to stores already certified to the aircraft, which have shapes of aerodynamically neutral geometries and no tendency of showing similar behaviour at asymmetrical loading configurations. In addition, it was observed that the lack of feedback from the stick significantly decreased the situational awareness and response time of the pilot (irreversible FCS).

For release of stores where a pilot action is required after release (pilot in the loop stores), the recovery time from separation effects on the platform aircraft may become a factor to be evaluated. This kind of task requires the aircraft to reach a state (attitude, load factor, etc.) which needs to occur within a desired time frame after separation to initiate, e.g., target tracking. The defined manoeuvre requirement is solely dependent on the effect of store separation and the response of the aircraft to pilot's commands. The test plan should cover the required time to recover from the effects of separation on aircraft's HQ based on the desired and adequate performance requirements. Laser guided air-to-ground store integration with self lasing operation or pilot in the loop EO/IR guided missile launches against a moving target from a single seat aircraft can be examples for this case.

In general, typical desired performance for the recovery from separation effects is around 5 s while the adequate performance is up to 8 s. However, the values are greatly dependent on the fly out time of the employed store.

5.4.4 Experiences with Operational HQ Testing More Generally

Motion Control

As indicated in Section 5.3.3, when reporting about HQDT experiences one aspect requires further elaboration. In regular air-to-air tracking tasks, the pilot controls the flight path mainly by using the attitude feedback information. And this is what the pilot controls: attitude.

When following a target aircraft in close formation, depending on the task, not only attitude is important. The pilot also needs to control relative positioning, which can be reduced to controlling attitude and heave.

As already mentioned, when discussing pilot modelling in connection with the Neal-Smith criterion, (see Section 3.5), a well-liked control habit is controlling attitude while it has a 90 deg phase lag with respect to pitch angle velocity. Pitch rate is the prime cue that the pilot senses. Now, having to control attitude plus

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

relative position, the pilot has to control a 90 deg phase shift variable (attitude), which he likes to control, and a 180 deg phase shift variable (relative position). Keeping this second variable under control makes the task difficult, especially when the target is more agile in its manoeuvring. Its large phase shift may lead to unwanted oscillations, which may be interpreted as PIO already.

Care must be undertaken when scheduling HQ tasks with the desire to control attitude and heave at the same time: care not to make the manoeuvre too agile so that the evaluation pilot cannot follow properly anymore and care not to run into unwanted system dynamics (target with follower), which may become unstable when these two aircraft fly in close vicinity.

Visual Cues

Given that HQ tasks generally require definite desired/adequate performance criteria in order to apply the ubiquitous Cooper-Harper scale, a method by which these criteria can be quantified for the pilot is necessary. For attitude tracking tasks, these criteria are easily definable and presentable to the pilot (i.e., ±1 degree pitch during a capture task). Additionally, for object tracking tasks such as air-to-air and air-to-ground tracking, metrics readily available to the pilot can be used (i.e., 5 mil relative to the HUD pipper). These are particularly useful measurements since they directly relate to the operational implementation after which these tasks were designed.

Flight path tracking tasks, however, do not readily present such straightforward performance metrics. For instance, it is simple enough for an engineer to specify a formation position to be maintained within ±3 ft vertically and ±5 ft laterally. The pilot, lacking any cues to determine a relative location from the specified point cannot accurately rate performance, and thus, cannot follow the CHR tree.

When the target aircraft is directly in front of the test aircraft, the HUD is a good source for a position reference, since it is parallax free. Another common method is to use two reference points on the target itself, such as the wingtip and the front of the canopy to determine position during a fingertip formation type task. Of course, all these methods only define a line along which the test aircraft is situated, rather than an actual relative position, but it has been found that the apparent size of the target aircraft is usually enough to gauge distance along the positional reference line defined earlier.

For lateral tracking tasks, it is usually sufficient to have the pilot visualise a vertical plane below the target aircraft and focus on positioning relative to this plane. In this manner, lateral offset and capture tasks can be performed with a target aircraft to simulate a tanker rendezvous. This can serve to build confidence in the handling qualities of a receiver prior to being in close proximity to the tanker aircraft.

The method commonly used at the US Air Force Flight Test Centre (AFTC) is to determine visual cues, based on the target aircraft, to be used as reference points for establishing planes and offsets that enable a pilot to accurately assess his/her position relative to the specified point. Examples of these points are shown in **Figure 5-40** [41]. Clever use of tape allows for tailorable tasks where relational position is critical.

A method that has been used in the past, but poses fairly significant problems, is the use of markings or tape on the inside of the canopy or windscreen. While this seems to provide a good reference point relative to a target aircraft, these markings can introduce additional dynamics through the physiological coupling with the pilot. Cases have been seen in the past where high PIO ratings were collected on tasks conducted in this manner, even though all other forms of tracking at the same flight condition resulted in good ratings. It is suspected that the vertical acceleration response of the test aircraft was subtly changing the position of the pilot's head within the cockpit, meaning the eye-point reference to the mark on the canopy changed. Additionally, it is possible for the pilot to subconsciously move his/her head in an attempt to align the canopy mark with the prescribed point on the target aircraft, negating some of the fine tracking aspects of the task.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

Close proximity handling qualities tasks such as formation and simulated aerial refuelling are an important aspect of testing new aircraft. In designing these tasks, effort should be taken wherever possible to ensure that visual references outside the cockpit can be used for aircraft positioning. For these purposes, the HUD can be considered a target outside the cockpit since it is collimated to represent a point at infinity.

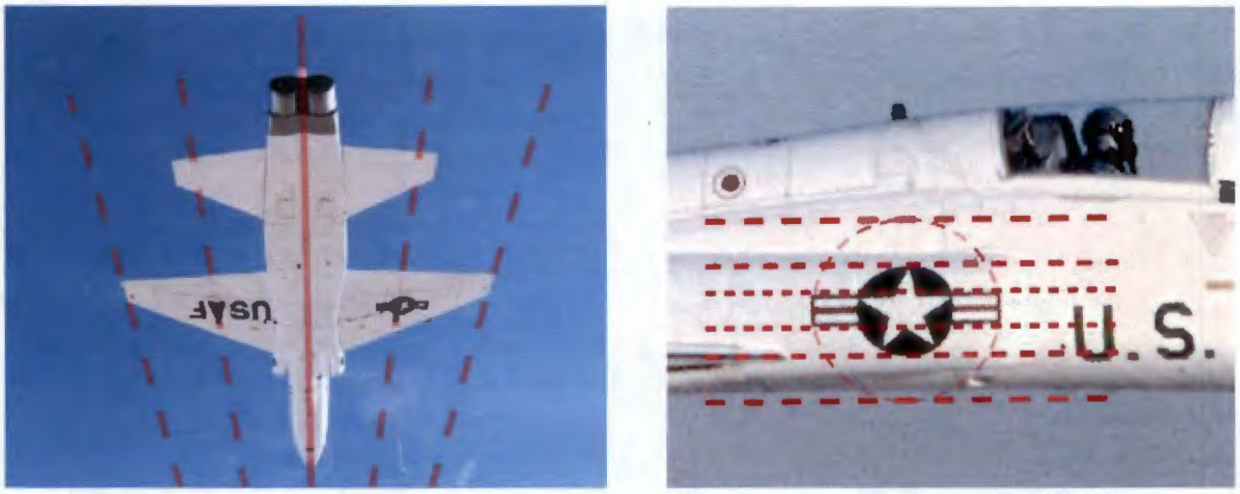


Figure 5-40: Illustration of Visual Cues Definitions, Lateral Displacement Target (Left), Formation Target (Right).

Engineers Going for the "Gold Plated" Solution

It must be noted here that the natural engineer's tendency is to further try to measure the performance attainable for each task, e.g., by quantifying the positional relationship between aircraft in formation, or by quantifying the accuracy with which a pilot lands his aircraft in a prescribed landing box on the runway. While it is tempting to try to use highly accurate INS or GPS solutions to numerically determine these relative positions, this really does not meet the intent of defining a task to the pilot and evaluating his performance. The point of the task is to define a challenging, yet doable task that applies to operational tasks in which pilots may find themselves. The desired/adequate performance is a proxy to ask, "can you perform this task as accurately as is necessary?" The pilot opinion and evaluation of their performance is the real data the testers are after.

Therefore, for the HQ evaluation engineer / flight test analysis engineer who sets up the test programme it is, as mentioned above in previous sections, indispensable to set up a test point and its performance criteria in a close relationship with relevant requirements or specifications and in a mutual dialogue with the project pilot!

Chapter 6 – SUMMARY

Flight testing and evaluation of Flying Qualities and Handling Qualities plays a major part in the development of any aircraft. It is the final stage in bringing the proof of operational maturity, operational safety, and verification of the fulfilment of contractual customer requirements. As this is aimed at operational testing, verification of all other aircraft systems play a role as well. Their operational capabilities must be proven within their individual specifications prior to HQ testing. Their individual performance can have a major impact on HQ testing and resulting HQ performance.

FQ and HQ testing stand at the end of a highly integrated process. The process must be well structured to catch in a safe manner all possible imponderables which might arise. An effective and safe process is required. The focus of this report is on flight test relevant techniques to evaluating Flying Qualities and Handling Qualities as part of this process. Interfaces to other disciplines are touched on, of which the most important and indispensable is flight clearance. This report provides background and a guideline on how to set up tests for Flying Qualities and Handling Qualities for flight testing. A structured approach is described, basically with a Step 1 for open loop testing (no pilot interaction); a Step 2 for PIO resistance testing; and finally, a Step 3 for closed loop (pilot interaction fully in the loop) and operational testing.

The report is organised into major sections. **Chapter 2** begins with the evaluation of Flying Qualities. Handling Qualities is introduced as part of the overall flight envelope expansion task for a new or a modified already existing aircraft. This chapter focuses on how FQ and HQ evaluation is embedded into the overall process and what its impact can be on the overall characteristics of an aircraft. Important to the discussion is the clear distinction drawn between Flying Qualities and Handling Qualities. The first describes the dynamic behaviour of an aircraft, which is dominated by the inherent characteristics of aerodynamics and flight mechanics, the Eigen values (e.g., Short period or Dutch roll). Flying Qualities is a denomination for the open loop characteristics of an aircraft (no pilot interaction). Handling Qualities describes the dynamic behaviour of the pilot-vehicle-system. It is always connected to a specific (operational) task labelled with a distinct performance criterion. Handling Qualities is the denomination of dynamic pilot-vehicle-characteristics for a given task.

Distinctive examples show how systematic testing for FQ and HQ can reveal system shortcomings or how those can be revealed even on a “ride along” basis. Another aspect in pilot-vehicle-system testing is the occurrence of Pilot-in-the-Loop-Oscillations (PIO). These occur unexpected and normally endanger the aircraft and the lives of the crew. Thorough analysis must be applied to reveal the causes. A systematic testing approach must be applied during regular HQ testing in order to address this phenomenon properly. Testing must drive different pilots to act in a manner that is as “high gain”, and “aggressive” as possible during specially defined tasks.

The distinction between “high gain” and “low gain” pilots is made frequently during HQ testing. On one hand, pilot gain is connected to a specific task challenging a pilot’s skills with deliberate workload and stress, provoking high gain reactions by the pilot. On the other hand, it is commonly understood that pilots exhibit different piloting skills and techniques depending on their experience. Thus, pilot reactions to a specific task depend on specific pilot performance and may be different for different pilots. Finally, the terms “high gain” and “low gain” pilot refer to inherent piloting characteristics that characterise an individual pilot to be in one of the two categories.

For HQ testing it is important to be aware of these facts and to tailor a dedicated HQ test programme in a way that “high gain” and “low gain” piloting techniques are covered. This implies that it is imperative to involve more than one pilot in HQ testing programmes, including low gain, and high gain pilots. An absolute minimum requirement would be to involve at least three pilots and at least one from each category.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

This report also stresses that HQ test programmes are the last in line of a long lasting and highly complex development and test programme for an aircraft. Incurred schedule delays which can be considered as normal in such programmes must not be used to put HQ testing under such pressure that eventually flight test safety and operational safety are endangered by potential requests for reductions in Handling Qualities testing and more important a reduction in the number of pilots involved, each one repeating equal test points with his or her own individual piloting technique. The number of pilots involved is an important measure to safeguard the quality of results and the quality of the product. Deficiencies in HQ must not be discovered in operational service.

Chapter 3 reviews the process of evaluating FQ and HQ. Qualitative evaluation of HQ by trained pilots in connection with the well-known Cooper-Harper-Rating (CHR) scale will lead to a resilient quantitative test result. PIO rating scales also support this approach. After a thorough introduction to these scales, further examples explain how the evaluation process of HQ works from the design aspect. Some typical HQ criteria, their physical meaning, and their connection to the CHR scale are introduced here.

Pilot modelling plays an important role in these criteria. Some criteria use dedicated simple pilot models to arrive at a reliable HQ rating. McRuer's crossover model gives good and simple insight into pilot behaviour. It tells intriguingly how pilots adapt their dynamic behaviour when the dynamics of an aircraft change, and it gives a simple theoretically derived argument of why only minor changes to a flight control law and aircraft dynamics require (extensive) HQ flight testing for verification of the change.

Finally, the derivation process for a flight clearance is sketched. Within this pre-flight HQ evaluations via various criteria and extensive unmanned and manned simulations play an extensive role prior to flying.

Chapter 4 mainly contains an extensive catalogue of various test methods to be applied for FQ and HQ testing. It is organised according to the described steps of testing. It contains a large variety of test manoeuvres, their description, and the reasoning for such a manoeuvre. More importantly, a guideline on how to use the catalogue is given at the end of the chapter. The guideline is aimed at supporting the user in the proper selection of tasks within the various phases of HQ testing. It also includes necessary flight test safety considerations for and during testing.

Finally, **Chapter 5** contains an extensive selection of various practical applications for FQ and HQ testing. The chapter is again structured according to the different phases of testing so as to illustrate for the reader how FQ and HQ testing is experienced in "real life". It is "only" a set of selected results, easily accessible in the literature. The results of HQ flight testing very likely contain confidential information not to be disclosed to the public. Still, it gives an overview of available experience and supports the reader together with the information given in the other chapters for the set-up of a required test programme.

Chapter 7 – REFERENCES

[1] MIL-STD-1797 A, Flying Qualities of Piloted Aircraft, US Department of Defence, (December 1997).

[2] F. Webster, T.D. Smith, Flying Qualities Flight Testing of Digital Flight Control Systems, AGARDograph, AGARD-AG-300, Vol. 21, (2001).

[3] R.V. Jategaonkar, Flight Vehicle System Identification, A Time-Domain Methodology, Second Edition, AIAA, (2015).

[4] M.B. Tischler, R.K. Remple, Aircraft and Rotorcraft System Identification, Second Edition, AIAA, (2012).

[5] V. Klein, E.A. Morelli, Aircraft System Identification – Theory and Practice, Second Edition, Sunflyte Enterprises, (2016).

[6] K.D. Wichman, J.W. Pahle, C. Bahm, J.B. Davidson, B.J. Bacon, P.C. Murphy, A.J. Ostroff, and K.D. Hoffler, High-Alpha Handling Qualities Flight Research on the NASA F/A-18 High Alpha Research Vehicle, NASA-TM-4773, (1996).

[7] M.V. Cook, Flight Dynamics Principles, 3rd Edition, Butterworth-Heinemann of Elsevier, Oxford, (2013).

[8] Flying Qualities Testing, Course Handbook, US Air Force Flight Test Centre, Edwards AFB, (2002).

[9] H.-Chr. Oelker, E.W. Muthsam, Investigations on Handling Qualities and Aerodynamic Characteristics of Eurofighter 2000 at Daimler-Benz Aerospace Flight Test Centre, AGARD CP-593, pp. 25-1 to 25-12, (1996).

[10] H.-Chr. Oelker, R. Osterhuber, M. Hanel, Experiences with Eurofighter Handling Qualities Testing, AIAA Atmospheric Flight Mechanics Conference, Chicago, AIAA-2009-6321, (2009).

[11] D.T. McRuer et al., Aviation Safety and Pilot Control, National Research Council, National Academy Press, Washington, D.C., (1997).

[12] J.J. Harris, G.T. Black, F-22 Control Law Development and Flying Qualities, AIAA Atmospheric Flight Mechanics Conference, San Diego, AIAA-1996-3379, (1996).

[13] M.E. Shafer, P. Steinmetz, Pilot-Induced Oscillation Research: Status at the End of the Century, NASA-CP-2001-210389/ Vol. 1 and Vol. 2, (2001).

[14] I. Rüdinger, Pilot Gain and the Workload Build-up Flight Test Technique, Dissertation TU Braunschweig, DLR-FB-2014-40, (2014).

[15] D.G. Mitchell, D.H. Klyde, This is Pilot Gain, AIAA SciTech Forum, AIAA-2019-0562, (January 2019).

[16] D. English, Are You a Low-Gain Pilot? https://www.innerairmanship.com/blog/2016/07/01/are-you-a-low-gain-pilot/, https://www.innerairmanship.com/blog/author/hikoudo/ (Retrieved on 27 May 2021).

REFERENCES

[17] R. White, Into the Black, Bantam Press, London, (2016).

[18] AGARD-AR-279, Handling Qualities of Unstable Highly Augmented Aircraft, AGARD Advisory Report, (1991).

[19] J. Hodgkinson, Handling Qualities, AIAA, (1998).

[20] J. Hodgkinson, D. Mitchell, Handling Qualities, in R.W. Pratt (Editor): Flight Control Systems, Progress in Astronautics and Aeronautics, AIAA (2000).

[21] G.E. Cooper, R.P. Harper, The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities, NASA-TN-D-5153, (1969).

[22] D.G. Mitchell, Fifty Years of the Cooper-Harper Scale, AIAA-2019-0563, (2019).

[23] D.A. DiFranco, Flight Investigation of Longitudinal Short Period Frequency Requirements and PIO Tendencies, Air Force Flight Dynamics Laboratory, AFFDL-TR-66-163, (June 1967).

[24] GARTEUR FM/ AG12, Test Techniques for Experimental Detection of PIO, GARTEUR/ TP-120-03, (2000).

[25] D.T. McRuer, Pilot-Induced Oscillations and Human Dynamic Behaviour, NASA-CR-4683, (July 1995).

[26] R.H. Hoh, D.G. Mitchell, J. Hodgkinson, Proposed MIL Standard and Handbook – Flying Qualities of Air Vehicles, Vol. II, Proposed MIL Handbook, AFWAL-TR-82-3081, Vol. II, (1982).

[27] H.A. Shomber, W.M. Gertsen, Longitudinal Handling Qualities Criteria: An Evaluation, Journal of Aircraft, Vol. 4, p. 371, (1967).

[28] J.C. Gibson, Development of a Methodology for Excellence in Handling Qualities Design for Fly By Wire Aircraft, Dissertation, Technical University of Delft, Netherlands, (1999).

[29] W. Bihrle, A Handling Qualities Theory for Precise Flight Path Control, Air Force Flight Dynamics Laboratory, Technical Report AFFDL-TR-65-198, (1966).

[30] R. Clarke, M. Allen, R. Dibley, J. Gera, J. Hodgkinson, Flight Test of the F/A-18 Active Aeroelastic Wing Airplane, NASA-TM-2005-213664, (2005).

[31] H. Duda, Effects of Rate Limiting Elements in Flight Control Systems – A New PIO Criterion, Paper AIAA Guidance Navigation and Control Conference, Boston, AIAA-1995-3204, (1995).

[32] H. Duda, Prediction of Pilot-in-the-Loop Oscillations Due to Rate Saturation, Journal of Guidance, Control, and Dynamics, Vol. 20, p. 581, (1997).

[33] D.T. McRuer, E.S. Krendel, Mathematical Models of Human Pilot Behaviour, AGARD-AG-188, (1974).

[34] T.P. Neal, R.E. Smith, An In-Flight Investigation to Develop Control System Design Criteria for Fighter Airplanes, AFFDL-TR-70-74, Vol. I, (1970). See also: T.P. Neal, R.E. Smith, A Flying Qualities Criterion for the Design of Fighter Flight-Control-Systems, Journal of Aircraft, Vol. 8, p. 803, (1971).

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

[35] R. Koehler, Design and Implementation of Input Signals for Identification of Pilot/Aircraft Models, DFVLR-FB 84-08, ESA-TT-880, (1984).

[36] E. Kullberg, P.-O. Elgcrona, SAAB Experience with PIO, AGARD-AR-335, Paper 9, (1995).

[37] T. Twisdale, T.A. Ashurst, System Identification from Tracking (SIFT), a new Technique for Handling Qualities Test and Evaluation, AFFTC-TR-77-27, (November 1977).

[38] R. Koehler, E. Buchacker, A Flight Test Method for Pilot/Aircraft Analysis, NASA-CP-2428, Paper 35, (1986).

[39] R. Koehler, E. Buchacker, D.J. Biezad, GRATE – A New Flight Test Tool for Flying Qualities Evaluations, AGARD-CP-452, Paper 8, (1988).

[40] M.F. Shafer, R. Koehler, E.M. Wilson, D.R. Levy, Initial Flight Test of a Ground Deployed System for Flying Qualities Assessment, NASA-TM-101700, (1989).

[41] W. Gray, Handling Qualities Evaluation at the USAF Test Pilot School, AIAA 2009-6317, (August 2009).

[42] J. Dottor, An Analysis of Aircraft Handling Qualities Data Obtained from Boundary Avoidance Tracking Flight Test Techniques, AFIT/GAE/ENY/07-M24, (March 2007).

[43] R. Warren, B. Abell, S. Heritsch, K. Kolsti, B. Miller, Limited Investigation and Characterization of Boundary Avoidance Tracking, AFFTCTIM-06-04 (June 2006).

[44] ATP-3.3.4.2, Air to Air Refuelling, NATO Allied Tactical Publication, (April 2019).

[45] Aerial Refueling Systems Advisory Group (ARSAG), Guidance Document Aerial Refueling Test Methods, Document 41-09-15, (13 April 2015).

[46] D.J. Wilson, Aircraft Maneuvers for the Evaluation of Flying Qualities and Agility-Maneuver Development Process and Initial Maneuver Set, WL-TR-93-3081, (August 1993).

[47] D.J. Wilson, Aircraft Maneuvers for the Evaluation of Flying Qualities and Agility-Maneuver Descriptions and Selection Guide, WL-TR-93-3082, (August 1993).

[48] D.J. Wilson, Aircraft Maneuvers for the Evaluation of Flying Qualities and Agility-Simulation Data, WL-TR-93-3083, (August 1993).

[49] D.J. Wilson, Aircraft Maneuvers for the Evaluation of Flying Qualities and Agility-Flight Test Plan, WL-TR-93-3084, (August 1993).

[50] W.J. Norton, Aeroelastic Pilot-in-the-Loop Oscillations, AGARD-AR-335, Paper 10, (1995).

[51] C.M. Moa, S.C. McWherter, T. Cox, Flight Test Results on the Stability and Control of the F-15 Quiet Spike Aircraft, NASA-TM-2012-215978, (February 2012).

[52] S.C. McWherter, C.M. Moa, Stability and Control Analysis of the F-15B Quiet Spike Aircraft, NASA-TM-2009-214651, (August 2009).

REFERENCES

[53] J. Gera, J.T. Bosworth, Dynamic Stability and Handling Qualities Tests on a Highly Augmented, Statically Unstable Airplane, NASA-TM-88297, (August 1987).

[54] J.T. Bosworth, T.H. Cox, A Design Procedure for the Handling Qualities Optimization of the X-29A Aircraft, NASA TM 4142, Unclassified, (September 1989).

[55] J.T. Bosworth, S.J. Stachowiak, Real-Time Stability Margin Measurements for X-38 Robustness Analysis, NASA-TP-2005-212856, (February 2005).

[56] SAAB, A Journey of Change in the Aircraft Industry - Keeping Unique Development Skills , SAAB Web Publication, https://saabaircraftindustry.com/en/roads-to-new-capability/development-skills/designing-the-world-s-best-control-system/, (Retrieved on April 2020).

[57] B. Kullberg, HQDT. A Method for Predicting Handling Qualities in High Performance Aircraft, Society of Flight Test Engineers, SFTE-1995-26-18, (1995).

[58] H.-Chr. Oelker, O. Brieger, Flight Test Experiences with Eurofighter Typhoon During High Bandwidth PIO Resistance Testing, AIAA Atmospheric Flight Mechanics Conference, Keystone, AIAA-2006-6496, (2006).

[59] E.R. Kendall, The Design and Development of Flying Qualities for the C-17 Military Transport Airplane, in M.B. Tischler, Advances in Aircraft Flight Control, Taylor and Francis, (1996).

[60] J.T. Bosworth, P.S. Hayes, Flight Test Results from the NF-15B Intelligent Flight Control System (IFCS) Project with Adaptation to a Simulated Stabilator Failure", DFRC-772, (January 2010).

[61] C. Hanson, J. Schaefer, J.J. Burken, D. Larson, M. Johnson, Complexity and Pilot Workload Metrics for the Evaluation of Adaptive Flight Controls on a Full Scale Piloted Aircraft, NASA TM 2014-216640, (February 2014).

[62] C.M. Elliot, Evaluating the Ability of Real Time Detection with Two Recent Pilot-Induced Oscillations, AIAA Atmospheric Flight Mechanics Conference. Hilton Head, AIAA-2007-6388, (2007).

[63] E.J. Field, J.B. Armor, K.F. Rossitto, D.G. Mitchell, Effects of Pitch Instantaneous Center of Rotation Location on Flying Qualities, AIAA-2002-4799, (2002).

[64] G.L. Teper, R.J. DiMareo, I.L. Ashkenas, R.H. Hoh, Analyses of Shuttle Orbiter Approach and Landing Conditions, NASA-CR-163108, (1981).

[65] D. Klyde, D.G. Mitchell, Development of Supersonic Demonstration Maneuvers with the SR-71 Aircraft and Simulator, 36th Aerospace Sciences Meeting and Exhibit. Reno, AIAA-1998-0493, (1998).

[66] T.H. Cox, D. Jackson, Supersonic Flying Qualities Experience Using the SR-71, NASA-TM-4800, (August 1997).

[67] J. Kaliff, L. Dahlström, J. Sjöstrand, Verification of AAR Functionality – JAS39 Gripen, Society of Flight Test Engineers, SFTE-2006-37-15, (2006).

[68] R.T. Olson, D.H. Klyde, B.R. Cogan, Flight Testing of Fused Reality Visual Simulation System, Society of Flight Test Engineers, (2015).

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

[69] E. Bachelder, D.H. Klyde, N. Brickman, S. Apreleva, B. Cogan, Fused Reality for Enhanced Flight Test Capabilities, AIAA Atmospheric Flight Mechanics Conference, Boston, AIAA-2013-5162, (August 2013).

[70] A. Efremov, E. Efremov, M. Tiaglik, Advancements in Predictions of Flying Qualities, Pilot-Induced Oscillation Tendencies, and Flight Safety, Journal of Guidance, Control, and Dynamics, Vol. 43, p. 4, (2020).

[71] The Aviation Geek Club, Former SR-71 Pilot Explains Why the Blackbird had to Light One Afterburner During Aerial Refueling, https://theaviationgeekclub.com/former-sr-71-pilot-explains-why-the-blackbird-had-to-light-one-afterburner-during-aerial-refueling/, (Retrieved on February 2020).

[72] M.L. Spearman, Some Effects of External Stores on the Static Stability of Fighter Airplanes, NASA-TN-D-6775, (April 1972).

[73] MIL-HDBK-1763, Aircraft/Stores Compatibility: Systems Engineering Data Requirements and Test Procedures, Department of Defense Handbook, (June 1998).

[74] AGARD-AG-300-Vol-29, Aircraft/Stores Compatibility, Integration and Separation Testing, (September 2014).

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

Annex A – AGARD AND STO FLIGHT TEST INSTRUMENTATION AND FLIGHT TEST TECHNIQUES SERIES

1. Volumes in the AGARD, RTO and STO Flight Test Instrumentation Series, AGARDograph 160

Volume Number	Title	Publication Date
1.	Basic Principles of Flight Test Instrumentation Engineering (Issue 2) Issue 1: Edited by A. Pool and D. Bosman	1974
	Issue 2: Edited by R. Borek and A. Pool	1994
2.	In-Flight Temperature Measurements by F. Trenkle and M. Reinhardt	1973
3.	The Measurements of Fuel Flow by J.T. France	1972
4.	The Measurements of Engine Rotation Speed by M. Vedrunes	1973
5.	Magnetic Recording of Flight Test Data by G.E. Bennett	1974
6.	Open and Closed Loop Accelerometers by I. McLaren	1974
7.	Strain Gauge Measurements on Aircraft by E. Kottkamp, H. Wilhelm, and D. Kohl	1976
8.	Linear and Angular Position Measurement of Aircraft Components by J.C. van der Linden and H.A. Mensink	1977
9.	Aeroelastic Flight Test Techniques and Instrumentation by J.W.G. van Nunen and G. Piazzoli	1979
10.	Helicopter Flight Test Instrumentation by K.R. Ferrell	1980
11.	Pressure and Flow Measurement by W. Wuest	1980
12.	Aircraft Flight Test Data Processing – A Review of the State of the Art by L.J. Smith and N.O. Matthews	1980
13.	Practical Aspects of Instrumentation System Installation by R.W. Borek	1981
14.	The Analysis of Random Data by D.A. Williams	1981
15.	Gyroscopic Instruments and Their Application to Flight Testing by B. Stieler and H. Winter	1982
16.	Trajectory Measurements for Take-off and Landing Test and Other Short-Range Applications by P. de Benque D'Agut, H. Riebeek and A. Pool	1985

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

Volume Number	Title	Publication Date
17.	Analogue Signal Conditioning for Flight Test Instrumentation by D.W. Veatch and R.K. Bogue	1986
18.	Microprocessor Applications in Airborne Flight Test Instrumentation by M.J. Prickett	1987
19.	Digital Signal Conditioning for Flight Test by G.A. Bever	1991
20.	Optical Air Flow Measurements in Flight by R.K. Bogue and H.W. Jentink	2003
21.	Differential Global Positioning System (DGPS) for Flight Testing by R. Sabatini and G.B. Palmerini	2008
22.	Application of Fiber Optic Instrumentation by L. Richards, A.R. Parker Jr., W.L. Ko, A. Piazza and P. Chan	2012
23.	Application of IRIG 106 Digital Data Recorder Standards for Flight Test by J.M. Klijn and B.A. Lipe	2020

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

2. Volumes in the AGARD, RTO and STO Flight Test Techniques Series, AGARDograph 300

Volume Number	Title	Publication Date
AG237	Guide to In-Flight Thrust Measurement of Turbojets and Fan Engines by the MIDAP Study Group (UK)	1979

The remaining volumes are published as a sequence of Volume Numbers of AGARDograph 300.

1.	Calibration of Air-Data Systems and Flow Direction Sensors by J.A. Lawford and K.R. Nippress	1988
2.	Identification of Dynamic Systems by R.E. Maine and K.W. Iliff	1988
3.	Identification of Dynamic Systems – Applications to Aircraft Part 1: The Output Error Approach by R.E. Maine and K.W. Iliff	1986
	Part 2: Nonlinear Analysis and Manoeuvre Design by J.A. Mulder, J.K. Sridhar and J.H. Breeman	1994
4.	Determination of Antenna Patterns and Radar Reflection Characteristics of Aircraft by H. Bothe and D. McDonald	1986
5.	Store Separation Flight Testing by R.J. Arnold and C.S. Epstein	1986
6.	Developmental Airdrop Testing Techniques and Devices by H.J. Hunter	1987
7.	Air-to-Air Radar Flight Testing by R.E. Scott	1992
8.	Flight Testing under Extreme Environmental Conditions by C.L. Henrickson	1988
9.	Aircraft Exterior Noise Measurement and Analysis Techniques by H. Heller	1991
10.	Weapon Delivery Analysis and Ballistic Flight Testing by R.J. Arnold and J.B. Knight	1992
11.	The Testing of Fixed Wing Tanker & Receiver Aircraft to Establish Their Air-to-Air Refuelling Capabilities by J. Bradley and K. Emerson	1992
12.	The Principles of Flight Test Assessment of Flight-Safety-Critical Systems in Helicopters by J.D.L. Gregory	1994
13.	Reliability and Maintainability Flight Test Techniques by J.M. Howell	1994
14.	Introduction to Flight Test Engineering Issue 1: Edited by F. Stoliker	1995
	Issue 2: Edited by F. Stoliker and G. Bever	2005

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

Volume Number	Title	Publication Date
15.	Introduction to Avionics Flight Test by J.M. Clifton	1996
16.	Introduction to Airborne Early Warning Radar Flight Test by J.M. Clifton and F.W. Lee	1999
17.	Electronic Warfare Test and Evaluation‡ by H. Banks and R. McQuillan	2000
18.	Flight Testing of Radio Navigation Systems by H. Bothe and H.J. Hotop	2000
19.	Simulation in Support of Flight Testing by D. Hines	2000
20.	Logistics Test and Evaluation in Flight Testing by M. Bourcier	2001
21.	Flying Qualities Flight Testing of Digital Flight Control Systems by F. Webster and T.D. Smith	2001
22.	Helicopter/Ship Qualification Testing by D. Carico, R. Fang, R.S. Finch, W.P. Geyer Jr., Cdr. (Ret.) H.W. Krijns and K. Long	2002
23.	Flight Test Measurement Techniques for Laminar Flow by D. Fisher, K.H. Horstmann and H. Riedel	2003
24.	Precision Airdrop by M.R. Wuest and R.J. Benney	2005
25.	Flight Testing of Night Vision Systems in Rotorcraft by G. Craig, T. Macuda, S. Jennings, G. Ramphal and A. Stewart	2007†
26.	Airborne Laser Systems Testing and Analysis by R. Sabatini and M.A. Richardson	2010
27.	Unique Aspects of Flight Testing Unmanned Aircraft Systems by A.E. Pontzer, M.D. Lower and J.R. Miller	2010
28.	Electronic Warfare Test and Evaluation by M. Welch and M. Pywell	2012
29.	Aircraft/Stores Compatibility, Integration and Separation Testing by O. Nadar	2014
30.	High Altitude Rotary Wing Flight Testing – Considerations in Planning Rotary Wing Performance Testing for High Altitude Operations by J. O'Connor, J. McCue, J. Holder and B. Carrothers	2018
31.	Reduced Friction Runway Surface Flight Testing – Wet Runway Taxi Test Procedures at Edwards AFB by T.E. Lundberg	2018

‡ Superseded by Volume 28.

† Volume 25 has been published as RTO AGARDograph AG-SCI-089.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

Volume Number	Title	Publication Date
32.	Flight Test Safety and Risk Management by D. Morley, J. Newsome, D. Moore, P. Comeau, B. A. Neal, P. C. Stoliker, A. Karwal, C. Buck, Ö. Kirli, C. B. Rice, F. P. Henderson, J. R. Stevenson and J. A. Mortensen	2020
33.	Flight Test Techniques for the Assessment of Fixed-Wing Aircraft Handling Qualities by H.-C. Oelker, T. Cox, J. Duncan, M. Fırat and E. Topbaş	2021

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

REPORT DOCUMENTATION PAGE

1. Recipient's Reference	2. Originator's References	3. Further Reference	4. Security Classification of Document
	STO-AG-300-V33 AC/323(SCI-303)TP/1018	ISBN 978-92-837-2337-0	PUBLIC RELEASE

5. Originator Science and Technology Organization
North Atlantic Treaty Organization
BP 25, F-92201 Neuilly-sur-Seine Cedex, France

6. Title

Flight Test Techniques for the Assessment of Fixed-Wing Aircraft Handling Qualities

7. Presented at/Sponsored by

This AGARDograph has been sponsored by the SCI Flight Test Technical Team (FT3) of the Systems Concepts and Integration Panel (SCI) of STO.

8. Author(s)/Editor(s)

Hans-Christoph Oelker, Timothy Cox, Joseph Duncan, Muharrem Fırat, Eren Topbaş

9. Date

July 2021

10. Author's/Editor's Address

Multiple

11. Pages

190

12. Distribution Statement There are no restrictions on the distribution of this document. Information about the availability of this and other RTO unclassified publications is given on the back cover.

13. Keywords/Descriptors

Aircraft Coupling (APC); Boundary Avoidance Tracing (BAT); Cooper-Harper-Rating Scale (CHR); Flight testing; Flying Qualities (FQ); Ground Attack Test Equipment (GRATE); Handling Qualities (HQ); Handling Qualities During Tracking (HQDT); Pilot-In-the-Loop Oscillations (PIO)

14. Abstract

This AGARDograph gives a guideline for flight testing of Handling Qualities for fixed wing aircraft. After a more theoretical part on what are Handling Qualities and how they can be evaluated, a detailed catalogue of dedicated flight test techniques is given. At the end various examples illustrate how Handling Qualities can be flight tested.

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

NORTH ATLANTIC TREATY ORGANIZATION

BP 25
F-92201 NEUILLY-SUR-SEINE CEDEX • FRANCE
Télécopie 0(1)55.61.22.99 • E-mail mailbox@cso.nato.int

SCIENCE AND TECHNOLOGY ORGANIZATION

DIFFUSION DES PUBLICATIONS

STO NON CLASSIFIEES

Les publications de l'AGARD, de la RTO et de la STO peuvent parfois être obtenues auprès des centres nationaux de distribution indiqués ci-dessous. Si vous souhaitez recevoir toutes les publications de la STO, ou simplement celles qui concernent certains Panels, vous pouvez demander d'être inclus soit à titre personnel, soit au nom de votre organisation, sur la liste d'envoi.

Les publications de la STO, de la RTO et de l'AGARD sont également en vente auprès des agences de vente indiquées ci-dessous.

Les demandes de documents STO, RTO ou AGARD doivent comporter la dénomination « STO », « RTO » ou « AGARD » selon le cas, suivi du numéro de série. Des informations analogues, telles que le titre est la date de publication sont souhaitables.

Si vous souhaitez recevoir une notification électronique de la disponibilité des rapports de la STO au fur et à mesure de leur publication, vous pouvez consulter notre site Web (http://www.sto.nato.int/) et vous abonner à ce service.

CENTRES DE DIFFUSION NATIONAUX

ALLEMAGNE
Streitkräfteamt / Abteilung III
Fachinformationszentrum der Bundeswehr (FIZBw)
Gorch-Fock-Straße 7, D-53229 Bonn

BELGIQUE
Royal High Institute for Defence – KHID/IRSD/RHID
Management of Scientific & Technological Research
for Defence, National STO Coordinator
Royal Military Academy – Campus Renaissance
Renaissancelaan 30, 1000 Bruxelles

BULGARIE
Ministry of Defence
Defence Institute "Prof. Tsvetan Lazarov"
"Tsvetan Lazarov" bul no.2
1592 Sofia

CANADA
DGSIST 2
Recherche et développement pour la défense Canada
60 Moodie Drive (7N-1-F20)
Ottawa, Ontario K1A 0K2

DANEMARK
Danish Acquisition and Logistics Organization
(DALO)
Lautrupbjerg 1-5
2750 Ballerup

ESPAGNE
Área de Cooperación Internacional en I+D
SDGPLATIN (DGAM)
C/ Arturo Soria 289
28033 Madrid

ESTONIE
Estonian National Defence College
Centre for Applied Research
Riia str 12
Tartu 51013

ETATS-UNIS
Defense Technical Information Center
8725 John J. Kingman Road
Fort Belvoir, VA 22060-6218

FRANCE
O.N.E.R.A. (ISP)
29, Avenue de la Division Leclerc
BP 72
92322 Châtillon Cedex

GRECE (Correspondant)
Defence Industry & Research General
Directorate, Research Directorate
Fakinos Base Camp, S.T.G. 1020
Holargos, Athens

HONGRIE
Hungarian Ministry of Defence
Development and Logistics Agency
P.O.B. 25
H-1885 Budapest

ITALIE
Centro Gestione Conoscenza
Secretariat General of Defence
National Armaments Directorate
Via XX Settembre 123/A
00187 Roma

LUXEMBOURG
Voir Belgique

NORVEGE
Norwegian Defence Research
Establishment
Attn: Biblioteket
P.O. Box 25
NO-2007 Kjeller

PAYS-BAS
Royal Netherlands Military
Academy Library
P.O. Box 90.002
4800 PA Breda

POLOGNE
Centralna Biblioteka Wojskowa
ul. Ostrobramska 109
04-041 Warszawa

PORTUGAL
Estado Maior da Força Aérea
SDFA – Centro de Documentação
Alfragide
P-2720 Amadora

REPUBLIQUE TCHEQUE
Vojenský technický ústav s.p.
CZ Distribution Information Centre
Mladoboleslavská 944
PO Box 18
197 06 Praha 9

ROUMANIE
Romanian National Distribution
Centre
Armaments Department
9-11, Drumul Taberei Street
Sector 6
061353 Bucharest

ROYAUME-UNI
Dstl Records Centre
Rm G02, ISAT F, Building 5
Dstl Porton Down
Salisbury SP4 0JQ

SLOVAQUIE
Akadémia ozbrojených síl gen.
M.R. Štefánika, Distribučné a
informačné stredisko STO
Demänová 393
031 06 Liptovský Mikuláš 6

SLOVENIE
Ministry of Defence
Central Registry for EU & NATO
Vojkova 55
1000 Ljubljana

TURQUIE
Milli Savunma Bakanlığı (MSB)
ARGE ve Teknoloji Dairesi
Başkanlığı
06650 Bakanliklar – Ankara

AGENCES DE VENTE

The British Library Document Supply Centre
Boston Spa, Wetherby
West Yorkshire LS23 7BQ
ROYAUME-UNI

Canada Institute for Scientific and Technical Information (CISTI)
National Research Council Acquisitions
Montreal Road, Building M-55
Ottawa, Ontario K1A 0S2
CANADA

Les demandes de documents STO, RTO ou AGARD doivent comporter la dénomination « STO », « RTO » ou « AGARD » selon le cas, suivie du numéro de série (par exemple AGARD-AG-315). Des informations analogues, telles que le titre et la date de publication sont souhaitables. Des références bibliographiques complètes ainsi que des résumés des publications STO, RTO et AGARD figurent dans le « NTIS Publications Database » (http://www.ntis.gov).

DISTRIBUTION STATEMENT A. Approved for public release: distriution unlimited.

NORTH ATLANTIC TREATY ORGANIZATION

BP 25
F-92201 NEUILLY-SUR-SEINE CEDEX • FRANCE
Télécopie 0(1)55.61.22.99 • E-mail mailbox@cso.nato.int

SCIENCE AND TECHNOLOGY ORGANIZATION

DISTRIBUTION OF UNCLASSIFIED STO PUBLICATIONS

AGARD, RTO & STO publications are sometimes available from the National Distribution Centres listed below. If you wish to receive all STO reports, or just those relating to one or more specific STO Panels, they may be willing to include you (or your Organisation) in their distribution.

STO, RTO and AGARD reports may also be purchased from the Sales Agencies listed below.

Requests for STO, RTO or AGARD documents should include the word 'STO', 'RTO' or 'AGARD', as appropriate, followed by the serial number. Collateral information such as title and publication date is desirable.

If you wish to receive electronic notification of STO reports as they are published, please visit our website (http://www.sto.nato.int/) from where you can register for this service.

NATIONAL DISTRIBUTION CENTRES

BELGIUM
Royal High Institute for Defence – KHID/IRSD/RHID
Management of Scientific & Technological Research for Defence, National STO Coordinator
Royal Military Academy – Campus Renaissance
Renaissancelaan 30
1000 Brussels

BULGARIA
Ministry of Defence
Defence Institute "Prof. Tsvetan Lazarov"
"Tsvetan Lazarov" bul no.2
1592 Sofia

CANADA
DSTKIM 2
Defence Research and Development Canada
60 Moodie Drive (7N-1-F20)
Ottawa, Ontario K1A 0K2

CZECH REPUBLIC
Vojenský technický ústav s.p.
CZ Distribution Information Centre
Mladoboleslavská 944
PO Box 18
197 06 Praha 9

DENMARK
Danish Acquisition and Logistics Organization (DALO)
Lautrupbjerg 1-5
2750 Ballerup

ESTONIA
Estonian National Defence College
Centre for Applied Research
Riia str 12
Tartu 51013

FRANCE
O.N.E.R.A. (ISP)
29, Avenue de la Division Leclerc – BP 72
92322 Châtillon Cedex

GERMANY
Streitkräfteamt / Abteilung III
Fachinformationszentrum der Bundeswehr (FIZBw)
Gorch-Fock-Straße 7
D-53229 Bonn

GREECE (Point of Contact)
Defence Industry & Research General Directorate, Research Directorate
Fakinos Base Camp, S.T.G. 1020
Holargos, Athens

HUNGARY
Hungarian Ministry of Defence
Development and Logistics Agency
P.O.B. 25
H-1885 Budapest

ITALY
Centro Gestione Conoscenza
Secretariat General of Defence
National Armaments Directorate
Via XX Settembre 123/A
00187 Roma

LUXEMBOURG
See Belgium

NETHERLANDS
Royal Netherlands Military Academy Library
P.O. Box 90.002
4800 PA Breda

NORWAY
Norwegian Defence Research Establishment, Attn: Biblioteket
P.O. Box 25
NO-2007 Kjeller

POLAND
Centralna Biblioteka Wojskowa
ul. Ostrobramska 109
04-041 Warszawa

PORTUGAL
Estado Maior da Força Aérea
SDFA – Centro de Documentação
Alfragide
P-2720 Amadora

ROMANIA
Romanian National Distribution Centre
Armaments Department
9-11, Drumul Taberei Street
Sector 6
061353 Bucharest

SLOVAKIA
Akadémia ozbrojených síl gen M.R. Štefánika, Distribučné a informačné stredisko STO
Demänová 393
031 06 Liptovský Mikuláš 6

SLOVENIA
Ministry of Defence
Central Registry for EU & NATO
Vojkova 55
1000 Ljubljana

SPAIN
Área de Cooperación Internacional en I+D
SDGPLATIN (DGAM)
C/ Arturo Soria 289
28033 Madrid

TURKEY
Milli Savunma Bakanlığı (MSB)
ARGE ve Teknoloji Dairesi Başkanlığı
06650 Bakanliklar – Ankara

UNITED KINGDOM
Dstl Records Centre
Rm G02, ISAT F, Building 5
Dstl Porton Down, Salisbury SP4 0JQ

UNITED STATES
Defense Technical Information Center
8725 John J. Kingman Road
Fort Belvoir, VA 22060-6218

SALES AGENCIES

The British Library Document Supply Centre
Boston Spa, Wetherby
West Yorkshire LS23 7BQ
UNITED KINGDOM

Canada Institute for Scientific and Technical Information (CISTI)
National Research Council Acquisitions
Montreal Road, Building M-55
Ottawa, Ontario K1A 0S2
CANADA

Requests for STO, RTO or AGARD documents should include the word 'STO', 'RTO' or 'AGARD', as appropriate, followed by the serial number (for example AGARD-AG-315). Collateral information such as title and publication date is desirable. Full bibliographical references and abstracts of STO, RTO and AGARD publications are given in "NTIS Publications Database" (http://www.ntis.gov).

ISBN 978-92-837-2337-0