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High Angle of Attack Handling Qualities Rating Scales

Chris A. Hadfield
University of Tennessee - Knoxville

To the Graduate Council:

I am submitting herewith a thesis written by Chris A. Hadfield entitled "High Angle of Attack Handling Qualities Rating Scales." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Aviation Systems.

R. Richards, Major Professor

We have read this thesis and recommend its acceptance:

Ralph Kimberlin, Peter Solics

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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HIGH ANGLE OF ATTACK
HANDLING QUALITIES RATING SCALES

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Chris A. Hadfield
May 1992

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The analysis and conclusions contained in this thesis are my own, and are not intended as those of the Naval Air Warfare Center or the United States Government.

ABSTRACT

Aircraft handling qualities rating scales have traditionally been developed for closed-loop handling tasks at moderate angles-of-attack (AOA). The latest fighter aircraft, using fly-by-wire flight controls and vectored thrust, are capable of sustained maneuvers at very high AOA. A pitch control margin test (Lackey, 1991) was performed using a specially developed rating scale, which evolved as an element of tests investigating controllability at high AOA, progressing through conceptualization, simulation, and eventual flight test. This pitch control margin test is analyzed in this thesis as a case study in the development of handling qualities rating scales to evaluate high AOA flying qualities.

It was found that choice of the most suitable measures of merit is important when evaluating a new flight regime. It was also found that rating scale design requires specific mission tasks, even for open loop scenarios, as well as a glossary of associated terms to minimize ambiguity.

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LIST OF ABBREVIATIONS

SYMBOL	DEFINITION	UNITS
AOA	Angle of Attack	deg
Bu No	Bureau Number (aircraft factory tail number)	-
CAF	Canadian Air Force	-
CAS	Computer Augmented Stability	-
CG	Center of Gravity	%MAC
CHR	Cooper-Harper Handling Qualities Rating	-
Cm	Coefficient of Pitching Moment	-
DDI	Digital Display Indicator	-
deg	Degree	-
DMS	Differential Maneuvering Simulator	-
FCS	Flight Control System	-
ft	Feet	-
hr	Hour	-
HARV	High AOA Research Vehicle	-
HUD	Heads Up Display	-
K	Thousand	-
KCAS	Knots Calibrated Airspeed	nm/hr
lb	Pounds	-
MAC	Mean Aerodynamic Chord	-
MAI	Moscow Aviation Institute	-
MFS	Manned Flight Simulator	-
MSL	Height Above Mean Sea Level	ft
NASA	National Aeronautics and Space Administration	-
NATC	Naval Air Test Center	-
nm	Nautical Miles	-
PCM	Pitch Control Margin	-

SYMBOL	DEFINITION	UNITS
PROM	Programmable Read-Only Memory	-
PRR	Pitch Recovery Rating	-
Q2sec	Pitch rate at two seconds from nose-down input (Q2sec)	deg/sec
Qav2sec	Average pitch rate within two seconds of nose-down input	deg/sec
Qdav1sec	Average Pitch Acceleration within 1 second of Nose-Down Input	deg/sec^2
Qd1sec	Pitch Acceleration at 1 second from Recovery Input	deg/sec^2
Qdmax1sec	Maximum Pitch Acceleration within 1 sec of Nose-Down Input	deg/sec^2
SEOE	Standard Error of Estimate	-
STEMS	Standard Evaluation Maneuver Set	-
TM	Telemetry	-
Trec	Time to Recover to Below 10° AOA	sec
USAF	United States Air Force	-
USN	United States Navy	-

CHAPTER 1

INTRODUCTION

When a pilot is asked how well an aircraft flies, his answer is his opinion. This opinion of handling qualities will vary based on a multitude of variables, such as the pilot's background, which maneuvers were performed, the pilot's expectations, etc. It will be subjective, and difficult to precisely quantify.

In the aircraft design process, however, predictions of handling qualities are critical. Designers require a measure of handling qualities that is reliable, repeatable, and directly linked to aircraft dynamics and performance characteristics. The accepted rating scale for expression of pilot opinion is the Cooper-Harper scale, developed in the late 1960's (Cooper and Harper, 1969).

A high AOA test was performed purely in the pitch axis, measuring the margin of pitch control required. Testing was conducted in simulation and in flight (Lackey, 1991). To quantify the results, a handling qualities rating scale was developed, similar to Cooper-Harper. Unfortunately, this scale provided only a vague mission scenario, with no clear reason given to the pilot for his control inputs. As a result, data varied significantly from pilot to pilot.

This thesis reviews handling qualities rating scales in general, investigates the rating scale used for this high AOA test, and suggests improvements to provide more useful results for future high AOA handling qualities research.

Thesis Statement

Handling qualities rating scales at high AOA require a clearly stated mission task, even for developmental simulation and open-loop tests, in order to obtain consistent and relevant results.

CHAPTER 2

BACKGROUND AND LITERATURE REVIEW

In preparation of this thesis, a literature review was conducted to gather information pertaining to previous studies of handling qualities rating scales and high angle of attack test.

General

New technology aircraft designs use vortex lift augmentation and relaxed static stability for improved performance and agility. Unfortunately, incorporation of these design concepts has occasionally led to insufficient nose-down pitch authority from very high AOA. Both the F-16 Falcon and the F/A-18 Hornet aircraft have experienced losses due to hang-up at high AOA. As newer designs demand increasingly more performance through a wider flight envelope, static stability has become relaxed further, compounding the risk of aircraft losses due to high AOA hang-up.

Pitch Control Military Specification

The Military Standard specification requirement for the amount of pitch control required, while lengthy, is quantitatively vague. It states that "aerodynamic control power ... shall be sufficient to assure safety throughout the combined range of all attainable angles of attack ... and to recover from any situation" (MIL STD 1797A, 1988).

This has led to a requirement for a quantitative definition of the amount of longitudinal control power required, especially at high AOA, and the purpose of this test program.

Angle of Attack

The AOA is a measure of the angle between the aircraft's wing chord line and the relative wind, as shown in figure 1. Early aircraft designs, without high lift devices or computer-driven flight control systems, typically stalled at 15 to 20 deg AOA. Current high performance fighter aircraft designs, using maneuvering flaps for variable camber, leading edge extensions for vortex lift augmentation, and vectored thrust for added control power can sustain flight at AOAs up to 50 deg and beyond (Loftin, 1985).

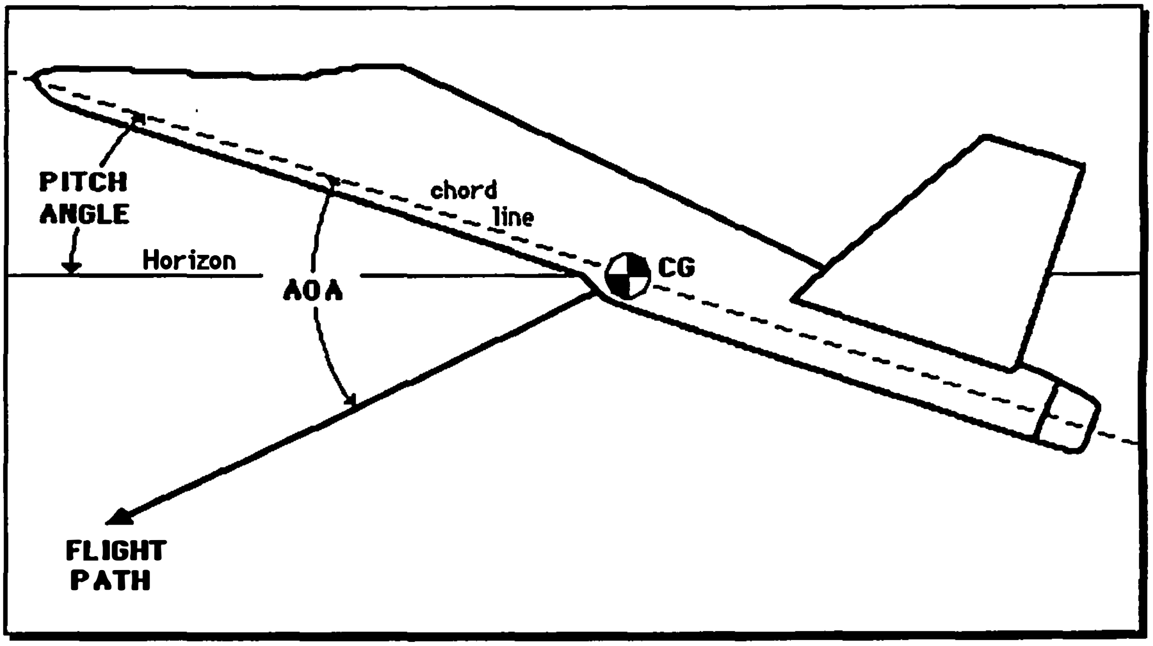

Figure 1. Angle-of-Attack

Coefficient of Lift

As AOA increases, the coefficient of lift also increases, until the angle to the relative airflow is so great that airflow over the wing separates, and lift is lost. This is shown in figure 2.

Traditional aircraft, such as transport or recreational, are not designed for controlled flight in the stall region, as it is not required for their design mission. Fighter aircraft, however, can gain tactical advantage by maneuvering into a region of the flight envelope unattainable to the adversary. This has driven designers to allow fighter pilots to fly beyond the stall, with sustained flight in the post-stall region.

The penalty for post-stall flight is a loss of control. At high AOA, airflow changes around the aircraft can cause a decrease in stability. Fighter aircraft, designed to have a minimum margin of stability for greater responsiveness and efficiency, can become unstable to the point of uncontrollability at very high AOA.

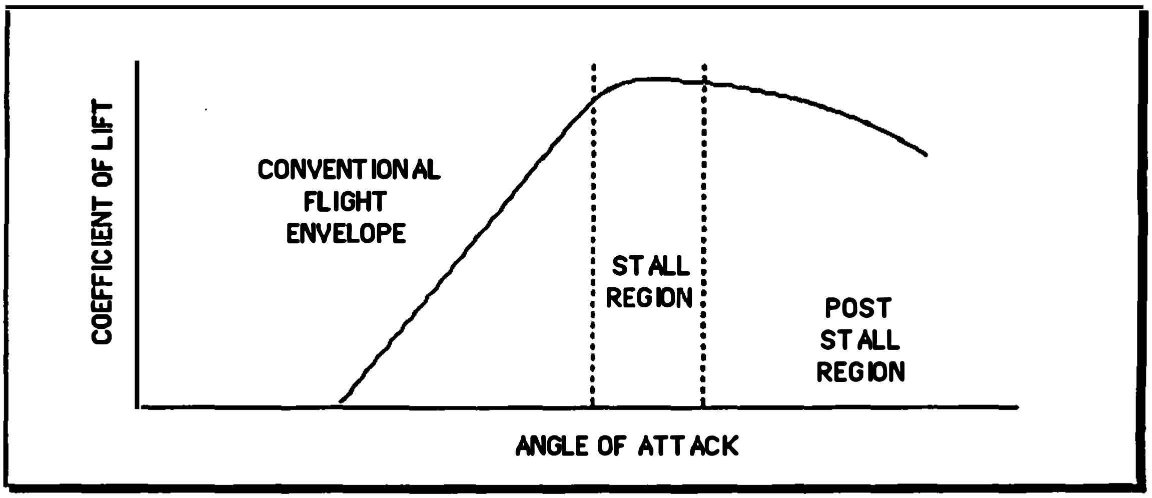

Figure 2. Coefficient of Lift vs Angle of Attack

Pitching Moment Coefficient

In the pitch axis, the total coefficient of pitching moment varies with AOA. A minimum margin of pitching moment exists, typically at a very high AOA, for each aircraft design. If this pitching moment reaches zero with full forward stick, then the aircraft will be unable to pitch back down, and an AOA hang-up will occur. If the moment goes beyond zero, the aircraft will uncontrollably pitch-up. A generic example of pitching moment coefficient variation versus AOA with the stick fixed full forward for two aircraft is shown in figure 3.

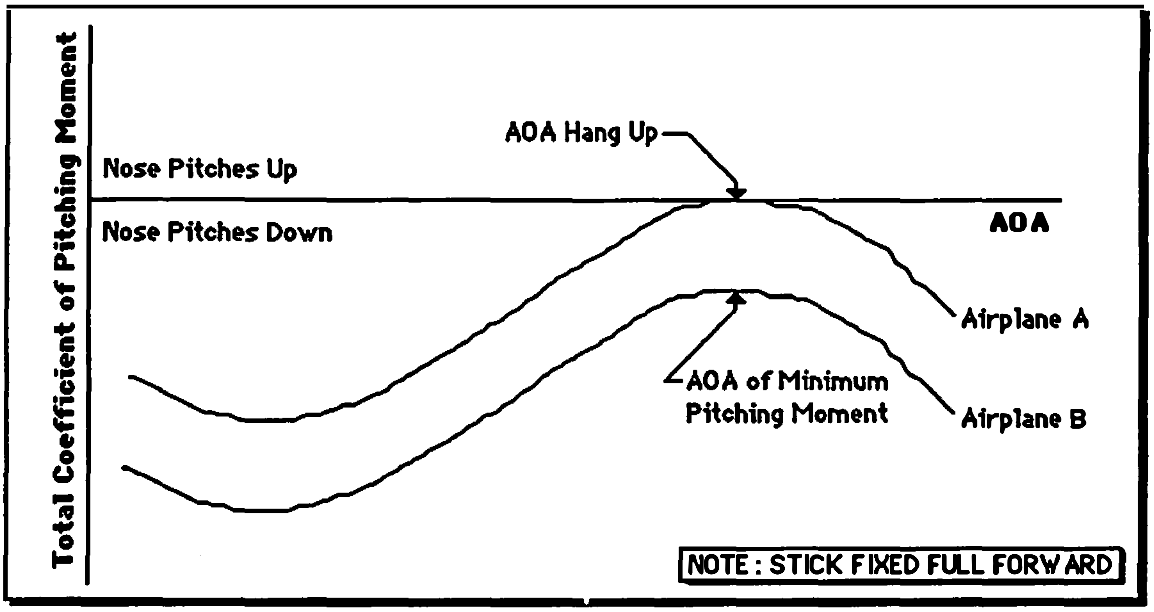

Figure 3. Coefficient of Pitching Moment vs Angle of Attack

Aircraft such as the X-31, NASA HARV and the F-22 are designed to fly precisely at very high AOA. This is accomplished through vectored thrust, and Computer Augmented Stability (CAS). CAS systems continually measure body rates and accelerations, compare the motions to pilot inputs, and then drive the flight control surfaces to comply with the pilot's requests. By limiting and controlling the flight control surface movements, and with the added control power of vectored thrust, sustained flight can be achieved at otherwise unstable conditions. The author has flown an X-29 simulator, and with the CAS system failed, loss of control occurs in less than one second. Yet with CAS functioning, this forward-swept aircraft has become a valuable high AOA research tool.

Since CAS systems and vectored thrust have allowed designers to shape and predict handling qualities at very high AOA, it has become necessary to define a standard of minimum control required for nose-down recovery. This basic amount of pitch control margin, developed and defined through use of a new Pitch Recovery Rating (PRR) Scale, was the reason for the test program that formed the basis of this thesis.

General Literature Sources

General, less technical works contain some interesting insight, as they identify the basic precepts of handling qualities, and of high AOA flight, while referring to traditional aircraft designs. Heinemann et al, 1985, stated that "ideally, the designer should seek to combine good stability characteristics with a flight control system that produces reasonable responses to pilot inputs so that all desired maneuvers can be executed smoothly. Desired features of an aircraft control system include: ... prompt airplane response to control displacement without appreciable time lag. When the pilot actuates the controls the airplane should respond almost immediately." Mason, 1982, wrote that "being able to fly the airplane at a speed just above the stall is very important", and "with practice, it is possible to fly most airplanes within a full stall and not only keep the wings level but roll in and out of turns without spinning. It takes practice, but it can be done." Welch, 1981, said that "The ability of the fighter pilot to maneuver his aircraft for long periods of time ... at very high angles of attack is his stock in trade. It is immaterial whether he maneuvers his aircraft into an attacking position on an opponent or forces his opponent into uncontrolled flight. The end result is the same. In other fields of flying, except perhaps for crop dusting, high angle of attack maneuvering is generally confined to takeoff, approach, and landing, and during conditions of reduced thrust."

Technical Literature Sources

Fighter pilots will regularly fly tactical maneuvers at high AOA, and should be able to expect smooth, immediate response to nose-down inputs. The maneuverability and performance, or 'agility' of the fighter should provide good, predictable handling qualities, even at high AOA. Andrew Skow, 1992, defines aircraft agility as the ability to "minimize the time delays between target acquisition and target destruction". For agility in the pitch axis at high AOA, he says that "to minimize his vulnerability during the straight line acceleration, the pilot may only budget a short time segment to regain as much energy as possible". This gives pitch control margin tactical significance, requiring careful mission selection for handling qualities evaluations.

These high AOA handling qualities are, however, a qualitative judgement given by the pilot. In order to better design and compare aircraft, these qualities need to be defined and quantified. Several methods for rating aircraft handling qualities have been developed.

Cooper-Harper Rating Scale

The industry standard for handling qualities rating scales is the Cooper-Harper (CHR) Scale, 1969. A copy of this scale is presented in the appendix, figure 13.

The purpose of the CHR scale is to direct the pilot's evaluation processes through a decision tree, to standardize both method and terminology. A pilot enters the scale with a clearly defined standard of adequate and desired responses for a specific mission task. Using word choices and yes or no decisions, the pilot is led to a terse summation of how well the aircraft performed the task, and how hard it was to attain that task. From this, a number rating results, for ease of reference and comparison.

Unfortunately, the CHR scale has weaknesses. The choice of adjectives provided for the pilot in the decision tree was intended to equate to a linear scale, but McDonnell, 1968, showed that while the acceptable handling quality descriptors are fairly evenly spaced, the unacceptable descriptors are tightly grouped. A plot of these descriptors on a scale of psychological favorability is shown in figure 4.

This result is particularly relevant to this paper, since the handling qualities at high AOA are generally poor, near the control limits. It demonstrates that the CHR scale was optimized for heart-of-the-envelope testing, and becomes less useful as aircraft control becomes questionable.

Another weakness of the CHR scale is pilot variability. As Cooper and Harper noted in their report (1969), "the full decision tree should be traversed each time a rating is given, preferably aloud so the engineer can witness the decision process". If the pilot is not rigorous in using the scale as it was intended, or if his preconceptions of the mission task vary from the norm, his resulting ratings may be erroneous.

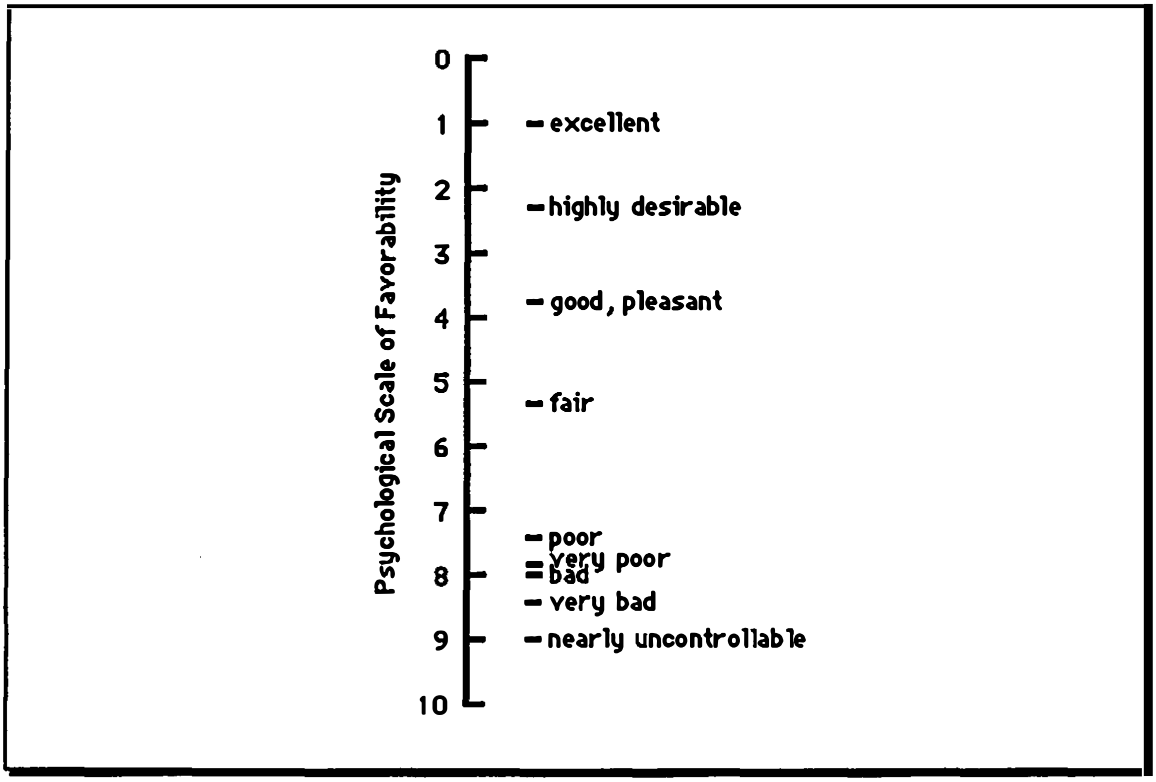

Figure 4. Cooper-Harper Adjective Distribution on a Psychological Scale

A third problem is the potential for pilot confusion caused by the ambiguous CHR scale phrases (Riley and Wilson, 1990). For example, if a pilot can attain desired performance criteria, but only with extensive compensation, the scale lets him down. A rating of four would indicate only moderate compensation was required, but a rating of five requires considerable compensation for adequate results. Thus pilots are forced to choose an inaccurate description, or use half ratings.

Another problem with the CHR scale is in the assigning of numeric ratings without rigorous use of the decision tree. It is very tempting for the pilot to merely give a number, and not go through all of the questions required. This leads to inaccurate and inconsistent rating results, especially amongst pilots not trained in correct use of the scale. Riley and Wilson (1990) have implemented a test method to minimize this effect. The decision tree questions have been mechanized to appear on the digital display indicator (DDI) screen in the cockpit. The pilot selects 'Cooper-Harper', and he is then presented with the yes or no questions, one at a time, as they appear in the CHR scale. Once he gets to the point where a description equating to a number is chosen, the screen resets. This serves the combined purpose of forcing the pilot to answer the questions in the order they were intended, and of removing the actual numbers from the pilot's decision process.

Moscow Aviation Institute Interval Scale

At the Moscow Aviation Institute, a pilot rating method called the "common rating scale" is used for handling qualities predictions and design (Efremov, 1991). It is a very simple scale, which uses common pilot word ratings and assigns them numerical values from one to nine, as shown in figure 5.

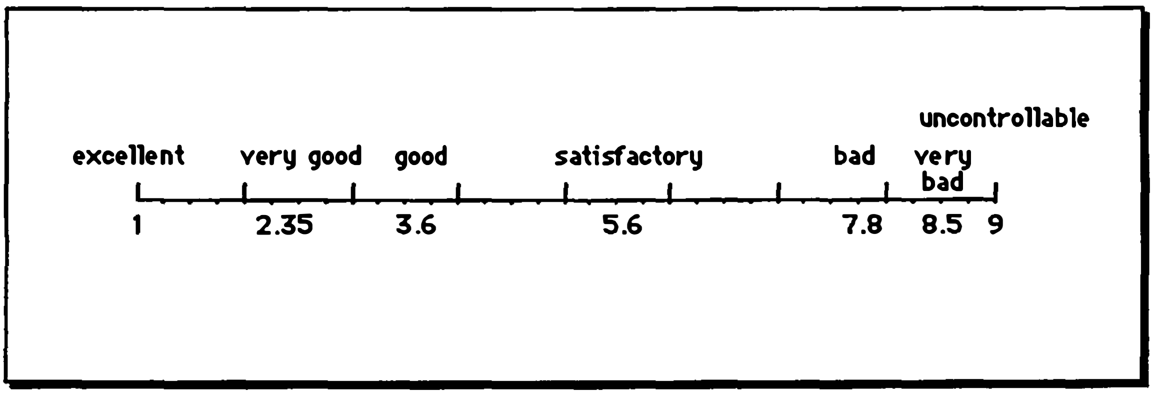

Figure 5. Moscow Aviation Institute Common Rating Scale

This scale is well adapted for use in mathematical modelling of the pilot-vehicle system. It allows simple transformation of pilot ratings into frequency domain calculations. Pilot workload is accounted for simply by addition of a time delay factor. Experimental results appear to match well with pilot rating predictions (Efremov, 1991).

The scale is not suited, however, for common pilot use. The simple assigning of one-word adjectives to a handling quality characteristic allows extensive leeway for pilot variability. Only pilots highly trained and disciplined in the use of this scale could generate consistent results. This would be particularly so for high AOA testing, where the handling quality ratings would invariably be towards the congested right end of the scale.

Word Surveys

Another method of evaluating handling qualities at high AOA is through use of word surveys. A variation of the decision tree method, word surveys force the pilot to respond to a list of questions after each maneuver. An example of a word survey was used in the Standard Evaluation Maneuver Set (STEMS) test (Wilson and Fogerty, 1991).

STEMS — Simulation Pilot Comment Card

Maneuver:

Date: Pilot:

	Rating	Comments
1. Does the maneuver capture the essence of operational use?	5 4 3 2 1 Closely □□□□□ Remotely	
2. Are the measures of merit tactically relevent/operationally useful?	5 4 3 2 1 Strong □□□□□ Weak	
3. Is the maneuver well defined, repeatable, and easy to fly?	5 4 3 2 1 Easy, Repeatable □□□□□ Difficult	
4. Would entry/exit conditions be difficult to establish during flight test?	5 4 3 2 1 Easy □□□□□ Impossible	
5. What information is required (e.g. airspeed, bank angle, target aircraft, etc.)?	5 4 3 2 1 Conventional Information □□□□□ Highly Specialized Displays	
6. Is the capture criteria representative of operational considerations (if it exists)?	5 4 3 2 1 Closely Tied to Operation □□□□□ Arbitrary	
7.* How well does the STEM represent the TEEM?	5 4 3 2 1 Very Closely □□□□□ Poorly	
8.* Did variations in design parameters result in operationally significant differences?	5 4 3 2 1 Very Significant □□□□□ Not Significantly Different	

Additional Comments:

* Questions only applicable to STEMs with corresponding TEEMs.

Figure 6. Word Survey - STEMS Project

This STEMS word survey is designed to be answered immediately following a specific maneuver. Each area of concern to the test engineer is contained in the eight questions, and the pilot has the straightforward task of rating each response on a scale from one to five. Additionally, a space for comments about each question is included, as well as general comments at the bottom.

This survey combines several desirable features for rating high AOA maneuvers. It is applied to a specific mission task or maneuver, minimizing ambiguity as to exactly what the pilot is evaluating. It has clearly stated questions, requiring a rating from the pilot. It also records comments which help describe the reasoning behind the rating, as well as general observations.

The main disadvantage of this type of handling qualities rating method is in its reliance on comments. The ratings from one to five help the pilot categorize his opinions, but the resulting ratings are not definitive on their own. Data analysis is difficult, and reduction of commentary to quantitative, easily comparable results requires extensive post-flight engineering work.

CHAPTER 3

TEST METHODOLOGY

General

NASA and the USN jointly conducted research to develop minimum pitch control margin guidelines. Simulation work was conducted from November 1989 to June 1990, during which a Pitch Recovery Rating (PRR) scale was developed to correlate pilot opinions quantitatively with aircraft pitch response. The simulation results and the PRR scale were then flight tested on an F/A-18 at the Naval Air Test Center from September 1991 to October 1991.

Test Concept

The problems of control margin compound themselves in all three aircraft axes, but this test was an attempt to isolate purely the longitudinal, or pitch axis. This was done for simplicity, with the intent that testing will eventually be conducted with all axes combined.

In order to separate only longitudinal inputs and response, the test maneuver selected was a full forward stick pushover from stable, high AOA conditions, conducted as follows:

1. Stabilize at constant heading, 35,000 ft MSL, 10° AOA, thrust for level flight, with CG set as desired.
2. Pull throttles to IDLE, and set 15° pitch attitude for deceleration.
3. Use lateral stick and rudder as required to negate roll and yaw motions.
4. Add thrust as required to stabilize trim airspeed at target AOA.

5. When on conditions, apply full forward stick until 10° AOA.
6. Recover, and comment using PRR scale.

The tolerances required to ensure stabilization at test conditions are listed in table 1. Actual test conditions are listed in the appendix, tables 4 and 5.

Test Parameter	Tolerance
Pitch Attitude during Deceleration	±5 deg
Stabilized Target AOA	±2 deg
Pitch Rate at Target AOA	±2 deg/sec
Roll Rate at Target AOA	±5 deg/sec
Yaw Rate at Target AOA	±2 deg/sec
Flight Path Rate at Target AOA	±5 deg/sec

Table 1. Test Tolerances

Simulation Facilities

A high fidelity, non-linear, six degree of freedom, modified F/A-18 simulation model was run in the fixed-base NASA Langley Differential Maneuvering Simulator (DMS). The pitching moment coefficient (Cm) characteristics (stick full forward) were modified for ease of variation, as shown in figure 7. The slopes of the two diagonal lines could be adjusted, as could the length of the flat spot, and the amount of minimum pitching moment. Freedom of movement of these variables is shown by the arrows in figure 7.

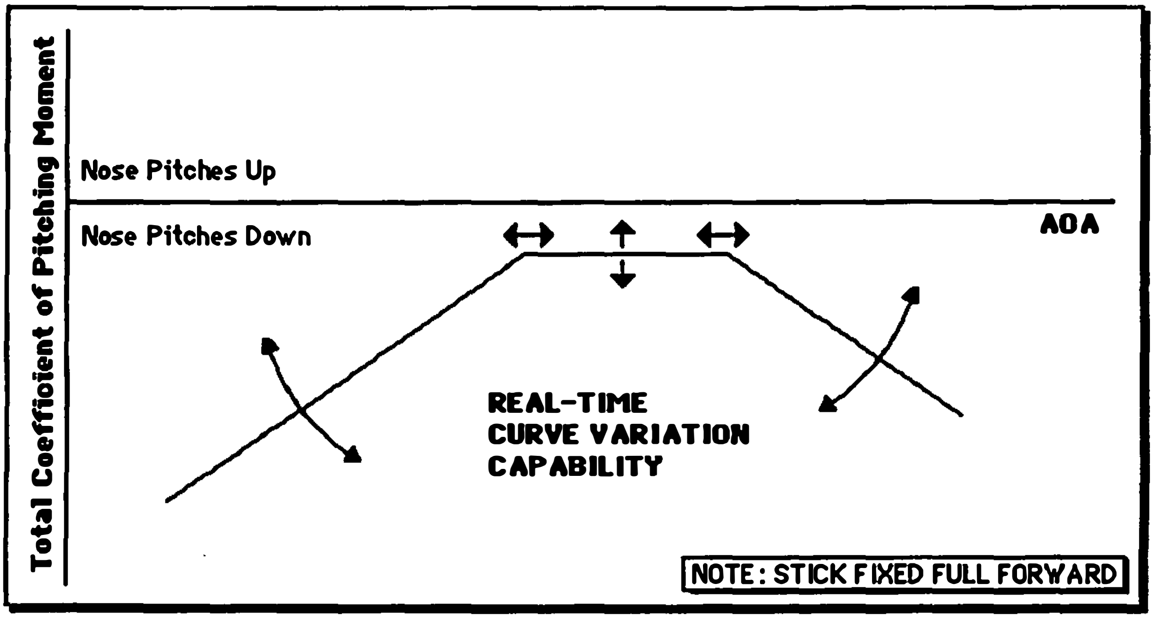

Figure 7. Simulation Pitching Moment Variation Characteristics

The simulation was designed to eliminate the effects of typical flight control system feedbacks and control surface actuator limits, to give a clearer picture of the response due to basic airframe characteristics. A generic example of Cm vs AOA during a full stick input, starting and ending at stabilized conditions, is shown in figure 8.

For the purposes of this test, piloted evaluations were flown in 19 simulation sessions for 55 test hours by 7 different aircrew. During this test the PRR scale was developed and refined, in conjunction with relevant measures of merit. Pitching moment coefficient variation was done in 'the blind', so that the pilot would not have preconceptions based on a known configuration. Each maneuver was repeated three times prior to assigning ratings.

The primary limitations of the simulation were its lack of motion and associated pilot cues required for high pitch-rate testing. The only indicator of pitch response was the movement of the pitch ladder and AOA symbology on the HUD. The projected image of the horizon and ground on the inside of the dome was invisible at the high pitch attitudes tested. In addition, the aircraft was pre-set at each test condition, in order to facilitate faster testing. This had the inherent drawback of a lack of real-world flight test technique problems such as thrust and energy management, and it added to the unreality of the simulation, and the removal from natural mission relation.

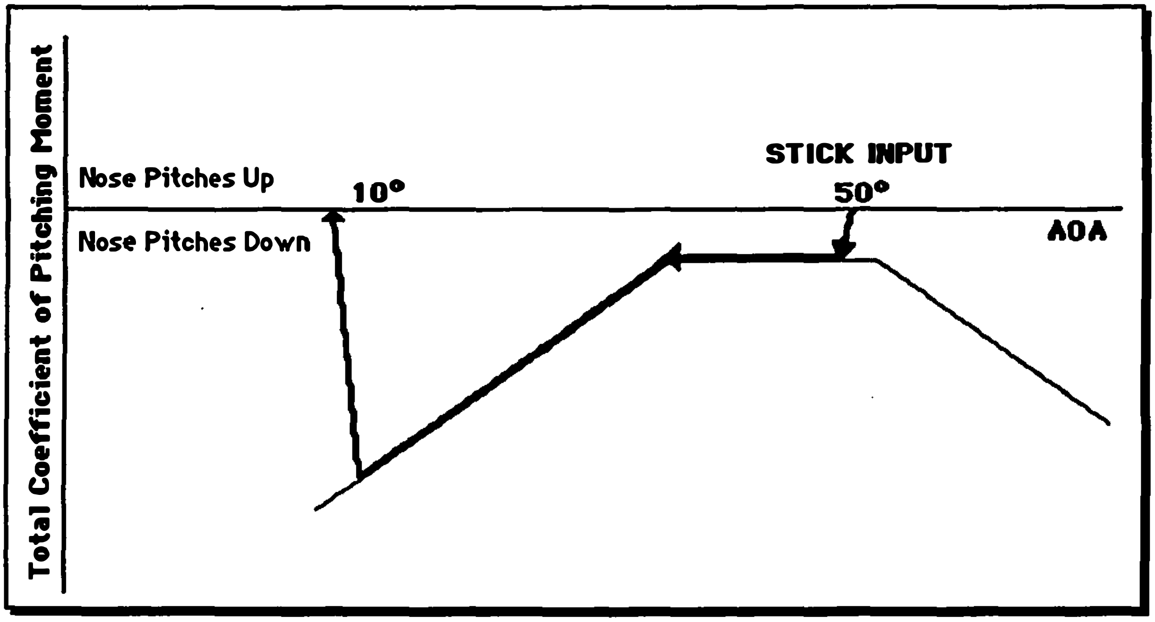

Figure 8. Simulation Pitching Moment Response to Stick Input

Measures of Merit

A primary objective of the test was to develop measures of merit relating aircraft dynamic response to pilot PRR scale rating. There are several parameters perceived by the pilot that influence his opinion of aircraft response to the full nose-down command. The measures of merit investigated for this test included:

1. Pitch acceleration (instantaneous, average, maximum)
2. Pitch rate (instantaneous, average)
3. Time to recover to 10° AOA (altitude loss, flight safety concerns)

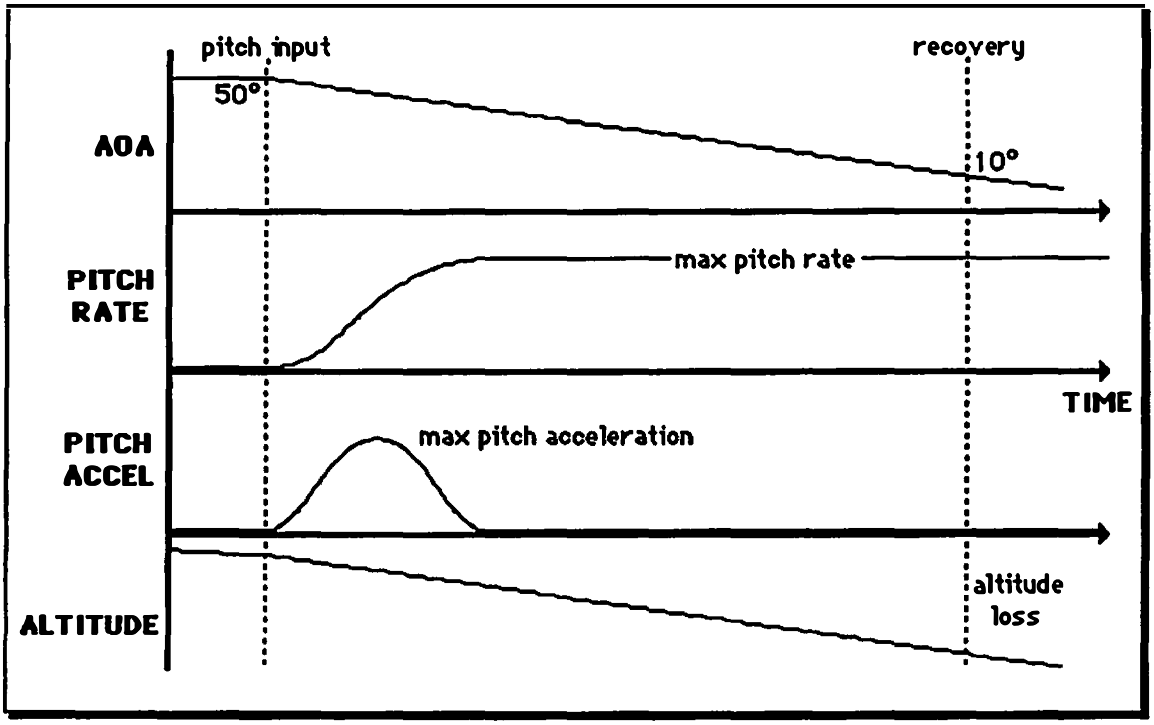

Figure 9. Measures of Merit

Flight Test

The test aircraft was an F/A-18, with a modified fuel transfer system to allow pilot-selectable CG control. A total of 6 flights for 9.8 flight hours were completed by two evaluation pilots, called Pilot A and Pilot B in this report. The PRR scale, as developed in the simulation phase, was used to evaluate relevant measures of merit.

In flight, the only way to easily change pitch recovery characteristics between runs was for the pilot to move the CG via fuel transfer. This physically limited the amount of parametric variation possible, and gave the pilot warning of how much pitch control response was likely to be available. Also, whereas simulation allowed any degree of control desired, flight test had to remain within conservative safety of flight limits. This restricted the spectrum of handling qualities changes presented to the pilot. No special recovery devices, such as a spin parachute, were included as part of the test, thus

CG had to be kept far enough forward to ensure recoverability. As soon as pilot ratings and comments indicating an impending loss of control (PRR scale rating of 4.5 or greater) were achieved, the aft CG movement was stopped. The amount of pitching moment variation possible with allowable CG movement is shown in figure 10.

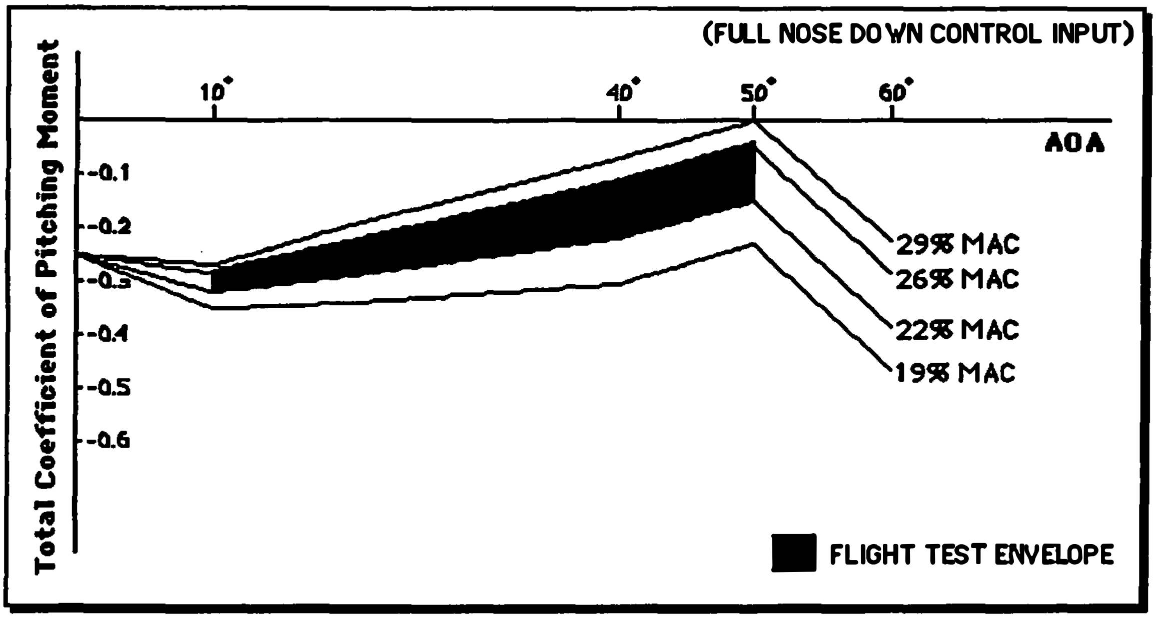

Figure 10. Flight Test Pitching Moment Variation with CG Movement

Instrumentation consisted of on-board tape recording of all aircraft parameters using a locally installed instrumentation pallet, HUD video and pilot voice recording, as well as TM link to a ground station for engineer monitoring and parameter recording.

The small number of pilots involved was a result of limited fiscal realities, but as both pilots had participated in the simulation and PRR scale development, it was felt that their results would be sufficient to achieve the purposes of the test. In order to prepare for the high AOA flight test, aircrew flew the Manned Fight Simulator (MFS) at NATC, and in-flight build-up points at lower AOAs.

Pitch Recovery Rating Scale

The PRR scale used during this test was developed during simulation to quantify pilot opinion, and relate it directly to aircraft design parameters via appropriate measures of merit. The test maneuver is essentially open-loop, as the pilot applies and holds one fixed control position throughout. This made the Cooper-Harper scale unsuitable, as it was designed for closed-loop tracking-style handling qualities tasks. The methodology of a Cooper-Harper style scale was desired, however, to step the pilot through a mission-relatable decision tree and give repeatable results. The PRR scale is presented in the appendix as figure 14.

Decision Factors

The Decision Factors box was intended as the decision tree entry point. By having the pilot first consider these six questions, he would be predisposed to call upon his training and experience to evaluate the pitch recovery maneuver.

The six questions were intended to be general, to get the pilot to evaluate the nose-down response impartially. Altitude loss during recovery was intentionally excluded, as it was felt to be an overall aircraft performance measure, separate from pitch recovery characteristics.

Category Definition

After the six decision factors, the PRR scale next requires the pilot to categorize the pitch recovery in one of four areas: unrecoverable, inadequate, satisfactory, or highly desirable. The resulting pilot ratings are divided into Level A, with 2.5 being the minimum tactically desirable rating, and Level B, with 4.5 as the minimum rating for safety.

Unrecoverable. If the aircraft became out-of-control during the maneuver, this was deemed unacceptable for mission and safety, and given a rating of six.

Inadequate. If there was sufficient control margin for recovery, but still not enough to meet the pilot's basic requirements, then the pitch response was labelled as inadequate. This led the pilot to next decide if the inadequacy was due to the recovery having been in doubt. If so, or if unnatural control inputs were required (such as pitch rocking), then the pitch response was rated as a five, significantly degrading the mission or flight safety. If the response only moderately degraded the mission or flight safety, then it was rated as a four. An intermediate rating of 4.5 was allowed for semantic ambiguity, or borderline cases.

Satisfactory. If there was sufficient control margin for adequate but not highly desirable recovery, then the pitch response was 'satisfactory'. The pilot had to decide if this recovery was merely adequate, or desirable. If it degraded the mission slightly, then the pitch response was rated as a three. If recovery was not a concern, and it was satisfactory for the mission, then it was rated as a two. An intermediate rating of 2.5 was again allowed for semantic ambiguity, or borderline cases.

Highly Desirable. If pitch response was excellent, and enhanced the mission, then it was rated as a one. It was accepted that some configurations would provide so much pitch response that full forward stick would exceed mission requirements, but the expected result was that the pilot would not use full control authority, and probably give a rating of one.

Rating Levels

For design guidelines, two threshold rating levels were established, as shown on the far right of the PRR scale, appendix figure 14. Level A was defined as tactically desirable, for any rating of 2.5 or better. Level B was for ratings of 3, 4 and 4.5, denoting pitch recovery that was acceptable for safety.

Level A Guidelines. In order for the nose-down recovery characteristics to qualify as Level A, they had to be suitable for the tactical mission. Ratings of 2 were given for recoveries that were satisfactory for the mission, while 3 ratings indicated a slightly degraded mission. This fixed the threshold at 2.5.

As the aircraft response becomes better, and more capable of achieving the specified mission task, the open loop response becomes taken for granted. The effects of the flight control system begin to predominate, as the pilot gets more and more critical of the finer points of the pitch response. Level A aircraft are expected to have good basic pitch control margin, and it is the minor deficiencies that decide the rating.

Level B Guidelines. For Level B response, it is the aircraft's basic ability to provide the minimum acceptable nose-down response that predominates. If the pilot was in doubt that recovery would occur in response to his pitch input, then the aircraft was deemed unsafe, and rated as a 5. If the recovery was not in doubt, but was marginal for the mission, then a 4 rating was given. This set the Level B threshold at 4.5.

The Level B guidelines are of primary interest to the aircraft designer, as they set the minimum standard of nose-down response required.

Post-Maneuver Word Survey

A questionnaire was used following each maneuver to aid in soliciting pilot comments, as shown in figure 11. After using the PRR scale, the pilot would step through this questionnaire, to help verbalize the reasons for the given rating.

1. Describe response to stick input.
   a. Pitch response
   b. Accompanying roll / yaw motions
   c. Disorienting motion

2. Compare this response to other aircraft you have flown.
   a. Aircraft
   b. Conditions
   c. Similar, better, or worse

3. Give your opinion on the appliaction of this maneuver to combat.
   a. Characteristics that enhance or degrade combat effectiveness
   b. Describe what you would most like to improve on this response

4. Determine impact of other influence on your opinion.
   a. Did recovery time affect your opinion?
   b. Did altitude loss affect your opinion of the recovery?
   c. Were you most concerned about mission safety or mission accomplishment during this maneuver?
   d. Did pilot technique affect results?
   e. What pilot compensation was required to complete this maneuver?

Figure 11. Post-Maneuver Word Survey

CHAPTER 4

RESULTS AND DISCUSSION

General

Test results for both the simulator and flight test were analyzed by correlating the proposed measures of merit with PRR scale ratings. The PRR scale itself was also examined, for flight test utility and consistency.

Measures of Merit

Pilot Decision Time Line

During the simulation phase, one of the pilots analyzed his decision process during the pitch-down recovery, and broke it up into specific events and decision points. This pilot rating time line is presented in figure 12.

The first indication of aircraft response to the pilot occurs during the forward stick input. The timeline shows that if the desired nose-down response occurs prior to full stick, then the PRR scale rating would be 1.

The first decisive thought by the pilot occurs within the first second following input, and he reaches the first decision point: if the nose-down acceleration is as desired, a rating of 2 is given. If not, the pilot waits.

After 1.5 to 2.0 sec, the pilot makes his second decisive thought: if the pitch rate is adequate, he rates the recovery a 3. If a pitch rate is established, but is inadequate, then the rating is 4.

If the pilot is forced to wait much longer for a nose-down rate, then the recovery becomes doubtful, and after 5 to 10 sec the pilot checks AOA to ensure it is decreasing. If it is, he rates the recovery a 5, and if AOA is hung up, then the recovery is deemed out of control, and the worst rating of 6 is given. All project pilots agreed that this decision tree time line was an accurate approximation of typical thought processes.

Time From Full Forward Stick	Decision Point	Pilot's Observation	Rating
During full forward stick input	DP0	Desired nose down acceleration (Qd) prior to full forward stick	1
0.5 to 1.0 sec (pilot's first thought)	DP1	Immediate desired nose down Qd with full forward stick	2
1.5 to 2.0 sec (pilot's 2nd thought)	DP2	Adequate nose down rate (Q) established	3
		Rate (Q) established, but less than adequate	4
5 to 10 sec	DP1	Decreasing AOA	5
		No AOA decrease	6

Figure 12. Pitch Control Margin - Pilot Rating Time Line

Pitch Acceleration

Pilot comments stressed pitch acceleration as the most important factor in determining the adequacy of the initial stages of a recovery. In the period of time immediately following forward stick, the pilots expected a quick, predictable nose-down acceleration, without reversals. Pitch acceleration was evaluated using three methods:

1. Maximum pitch acceleration within one second of nose-down input (Qdmax1sec)
2. Pitch acceleration at one second from recovery input (Qd1sec)
3. Average pitch acceleration within one second of nose-down input (Qdav1sec)

Maximum Pitch Acceleration within One Second of Nose-Down Input. The variation of Qdmax1sec with PRR scale ratings is shown in the appendix, figures 16 and 17. Flight test data for each of the two project pilots is plotted along with that pilot's simulation results, as well as the simulation database, averaged for all simulation pilots.

Flight test results for Qdmax1sec showed poor correlation with simulation results. Pilot ratings were generally worse, and showed less variation with changes in Qdmax1sec. As an example, for an average acceleration of -14 deg/sec, Pilot A's simulation rating was 3, indicating adequate pitch control margin. Flight test rating for the same maximum acceleration was 4.5, denoting inadequate pitch control margin, and the poorest rating possible short of the recovery itself being in doubt.

These large differences were due to the characteristics of the pitch acceleration response. In simulation, pitch acceleration was designed to stay constant during the first second after the nose-down input. In flight, however, flight control system feedback effects caused pitch acceleration to rapidly increase to a peak and then reverse. As the Qdmax1sec measure of merit only measured the maximum acceleration, it made no allowance for this effect. Qdmax1sec should not be used to define high AOA pitch control margin specification requirements.

Figure 16 also shows the difference between the simulation database average for all pilots versus pilot A. For Qdmax1sec of -15 deg/sec, the database average simulation rating was 2.5, indicating adequate to desirable recovery. Pilot A's simulation rating for the same maximum acceleration was 3.0. For this and all other measures of merit, Pilot A tended to give poorer ratings than the average. This is due to interpretation of the PRR scale, and is discussed later.

Pitch acceleration at one second from recovery input. The variation of Qd1sec with PRR scale ratings is shown in the appendix, figures 18 and 19. Flight test results for Qd1sec showed much better correlation with simulation results than did Qdmax1sec. This was again due to the characteristics of the pitch acceleration response. The peak and reversal in acceleration experienced in flight test occurred during the first second, and by the one second mark had become essentially constant at a similar value to that seen in simulation.

Unfortunately the amount of data scatter was large, both for simulation and flight test. A Standard Error of Estimate (SEOE) was calculated to evaluate the goodness of curve fit for all three pitch acceleration measures of merit. Discussion of the SEOE is shown in the appendix, figure 27. Results of this calculation, listed in table 2, showed that data scatter for Qd1sec was roughly the same as that for Qdmax1sec, and almost twice that of Qdav1sec. This result shows that Qdmax1sec is a weak measure of merit due to data inconsistency, and should not be used to define high AOA pitch control margin specification requirements.

Average pitch acceleration within one second of nose-down input. The variation of Qdav1sec with PRR scale ratings is shown in the appendix, figures 20 and 21. Flight test results for Qd1sec showed much better correlation with simulation results than either Qdmax1sec or Qd1sec, especially for better pilot rating values. Degradation of correlation for higher ratings was due to the flight test characteristics of the pitch acceleration response. As the test aircraft CG moved aft, the peak and reversal in acceleration was accentuated, due to control law and feedback effects. This gave the pilot the initial impression that he was going to achieve a rapid, desirable acceleration, but it rapidly decreased and the final pitch acceleration was slower than desired, forcing the pilot to give poorer ratings. For the more forward CG case, however, the response was more similar to simulation, and the ratings matched well.

The SEOE for Qdav1sec showed the least data scatter of the three acceleration measures of merit, as shown in table 2. This result, combined with the overall good match of flight test and simulation results indicates that Qdav1sec is the best acceleration measure of merit to define high AOA pitch control margin specification requirements.

Measure of Merit	SEOE (simulation)	SEOE (flight test)
Qdmax1sec	3.0	2.0
Qd1sec	3.0	2.9
Qdav1sec	1.7	1.4

Table 2. Standard Error of Estimate for Pitch Acceleration Measures of Merit

Pitch Rate

Once the initial pitch acceleration was established, the subsequent factor important in pilot comments was pitch rate. As it tended to be considered later in the pilot's rating process, pitch rate was evaluated using the following two methods:

1. Pitch rate at two seconds from nose-down input (Q2sec)
2. Average pitch rate within two seconds of nose-down input (Qav2sec)

Pitch rate at two seconds from nose-down input. The variation of Q2sec with PRR scale ratings is shown in the appendix, figures 22 and 23. Flight test results for Q2sec showed considerable data scatter, and little correlation between pitch rate at 2 sec and pilot rating. The SEOE for Q2sec was 3.7, quantifying the excessive degree of curve fit uncertainty. Although simulation had predicted 2 sec as a significant time to measure the pitch rate, flight test results did not agree. Simulation and decision point time line predictions were not validated for Q2sec, indicating that other cues during flight test overrode pitch rate at 2 sec. This result shows that Q2sec is a poor measure of merit to define high AOA pitch control margin specification requirements.

Average pitch rate within two seconds of nose-down input. The variation of Qav2sec with PRR scale ratings is shown in the appendix, figure 24. This measure of merit was not investigated in the simulator, thus the results are only shown comparing

Pilots A and B to each other. Flight test results for Qav2sec showed reasonable correlation between the pilots, and showed a definite increase in PRR scale rating numbers as Qav2sec decreased. The reason for Qav2sec giving more worthwhile results than Q2sec is that the effect of the flight test acceleration irregularities tended to be minimized when only the average rate was considered.

The SEOE for Qav2sec of 3.3 was still high, but was better than Q2sec. This advantage, combined with the apparent utility of this criterion, indicates that Qav2sec is the better rate measure of merit to define high AOA pitch control margin specification requirements. Qav2sec should be investigated in the simulator to verify its utility under a wide range of pitch control margin conditions.

Measure of Merit	SEOE (simulation)	SEOE (flight test)
Q2sec	unavailable	3.7
Qav2sec	unavailable	3.0

Table 3. Standard Error of Estimate for Pitch Rate Measures of Merit

Time to Recover

In the pilot rating time line, after the pilot analysis and thought processes had determined that the rate was insufficient, the next decision was made after 5 to 10 sec. Simulation results indicated that a correlation existed, at least for the worse cases, between pilot ratings and the time required to reduce to below 10° AOA (Trec). The variation of Trec with PRR scale ratings is shown in the appendix, figures 25 and 26.

The simulation results showed a definite cliff in pilot ratings as Trec increased past 4 sec. This is where the pilots ceased thinking about the tactical reason for the nose-down control input, and began worrying about being out of control.

In flight test, safety considerations made out of control flight unacceptable, especially as the amount of pitch control margin was being controlled by CG movement. The test plan had been to cease moving the CG aft as soon as a PRR scale rating of 4.5 was given. This caused a skewing of the flight test results, as recovery was never in doubt, and the third time line decision point was never reached. Test results showed Trec to be fairly constant as pilot ratings increased to 4.5, making it a poor measure of merit to define high AOA pitch control margin specification requirements when the aircraft recovery is not in doubt.

Pitch Recovery Rating Scale

General

In using the PRR scale, the pilots first stepped through the six decision factors, asking about adequacy of pitch response and mission suitability. This forced the pilots to draw upon their experience to determine what constituted adequate, and what mission the response might be suitable for. Unfortunately, no standardized mission task was chosen. The varying backgrounds of the pilots and their perception of the reason for the nose-down pitch input had a significant effect on their resulting ratings.

Mission Relation

As shown in appendix figures 16 through 26, a consistent difference existed between Pilot A, Pilot B, and the average simulation database, both in simulation and in flight test. This was due to their differing approaches to mission relation in the PRR scale. When Pilot A was asked, via the decision factors, to visualize a mission, he wrote down six possible scenarios which could require a full nose-down input from high AOA. These six scenarios are listed in the appendix, figure 15. Pilot B also chose a specific mission, shown in the same figure. All other simulation pilots used an undefined composite mission task.

The result of precisely specifying the mission was a worsening of PRR scale ratings for a given measure of merit. This is predictable, as a pilot with no clear-cut scenario in mind would not be as demanding of the aircraft as a pilot who felt himself to be in an air combat situation.

For Pilot A, mission tasks 1, 2, 3, 4 and 6 gave basically the same sense of urgency, and resulted in a consistent approach to the PRR scale. Scenario 5, however, made the Pilot A feel a heightened requirement for immediate pitch acceleration response, with little regard for anything beyond 2 seconds, and thus tended to yield worse ratings. As a result, task 5 was only used initially in the simulator, and task 2 was used exclusively during flight test.

Pilot B's mission task was very similar to Pilot A's task 6, thus both pilots used a common rating scale interpretation for simulation and flight test. Other project pilots did not, however. NASA HARV research pilots gave consistently better pilot ratings than the average, as their concern was not in air combat mission relation, but rather in flight safety, and positive recovery from high AOA. Their results are not any less valid than those of Pilots A and B, but data interpretation becomes difficult when the rating scale allows too large a spectrum of interpretation. The author recommends that specific mission scenarios be defined for PRR scale use, and that pilot rating results be compared only in regard to that scenario.

Semantic Ambiguity

Another indicator of the immaturity of the PRR scale was pilot use of personal alternative decision trees to aid in scale usage. Ambiguities in the PRR scale words caused Pilot A to make up a simplified decision tree, shown in appendix figure 28. When using this simplified method in parallel with the PRR scale, Pilot A gave the same ratings, despite the apparent differences. Although this scale required extensive user familiarity for consistent use, and would not be suitable for general usage without extensive briefing and training, its simplicity shows the pilot's desire for a straightforward, uncluttered approach, and clear choices with unambiguous words.

Pilot B was also dissatisfied with the wording of the PRR scale, and made up his own evaluation vocabulary to arrive at the same ratings. This scale is shown as the appendix figure 29. Noteworthy in this scale is the small number of words required to convey a 1, 2 or 6 rating, and the greater number needed for a 4 or 4.5. This shows the necessity for scale expansion in that region.

All project pilots expressed dissatisfaction with the following words and phrases:

Unnatural control inputs: Without clear definition, this was too imprecise. What may be unnatural for one pilot may be just what another expects. If a maneuver required an odd control input, but recovery was not a concern, the pilot had to decide if the input was odd enough for a 5 rating.

Desirable recovery (recovery was not a concern): The comment in parentheses was confusing. If recovery had been a concern, then the pilot would have been choosing between a 4 and 5 rating, yet 'desirable' meant a rating of 2.

Recoverable: Some pilots gave a 6 rating if the simulator didn't recover within some personal maximum amount of time, or if a control input other than pitch was required for recovery, while others gave a 6 only if the simulator crashed.

Adequate, Desirable: These two words require mission relation to have meaning, yet the vagueness of overall mission relation caused pilots to be unsure when choosing between these words.

The author recommends that a glossary be included with the PRR scale to minimize ambiguity of the words used during the pilot decision and rating process.

Minimum Safety Level Variation

If the nose-down response characteristics were not adequate for the mission, but recovery was not in doubt, then the pilot could only choose between a 4 and a 4.5 rating. This gave very little room for rating differentiation in an area of significant interest, as noted in Chapter 3. In the early stages of an aircraft design, concern is for the bare airframe's ability to meet basic aerodynamic requirements such as pitch control margin. The designer needs clear guidelines in the area of minimum control required, where the PRR scale provides minimal differentiation.

The wide range of ratings available to the pilot for an adequately recovering aircraft also tended to influence the scenario chosen. Since the pilot has four possible ratings to give an adequate or better aircraft (1, 2, 2.5, 3), and only two for inadequate aircraft (4, 4.5), the scale is better suited to tactical mission scenarios. The author recommends that the section of the PRR scale for aircraft with safe but inadequate pitch response be expanded to allow more variety in pilot ratings.

Closed versus Open Loop Tasks

The pilot technique used during this test was intended to be purely open loop; the stick was to be moved from neutral to the forward stop, and held there until AOA had decreased below 10 deg. The tactical slant of the PRR scale, however, forced pilots to choose a specific mission scenario, which created a more closed loop-type situation; the pilot had the stick full forward for a reason, and was waiting for a certain response or imaginary sight picture to then move the stick aft. Closed loop tasks such as this require a rating scale with specific tolerance levels, and allowances for workload required, such as Cooper-Harper.

This dichotomy of a tendency towards closed loop evaluation of an open loop pilot technique was again caused by vague mission relation. Pilots were taking the scenario beyond the intended scope of the PRR scale. Once the nose-down recovery is complete, then the CHR scale is required to evaluate the ensuing capture and tracking task. The author recommends that mission scenarios be chosen to accentuate the open loop, nose-down pitch recovery response, and not a follow-on closed loop task.

Number Rating Fixation

The limited number of aircrew involved in this test, and the carefully monitored use of the PRR scale limited the pilot tendency to fixate on assigning numerical pilot ratings without first going through the intended question and answer decision process. As has been experienced with the CHR scale, however, human nature will eventually tend to cause pilots to misuse the PRR scale in this way. This effect can be minimized by use of kneeboard sequential flipcharts, or DDI implementation. The author recommends that scale usage be carefully monitored to ensure numeric pilot ratings are not given prematurely.

Post Maneuver Word Survey

Further comments for each recovery were generated using the questionnaire shown in Chapter 3, figure 11. These comments were helpful in further clarifying why each particular PRR scale rating was given, but as was noted in Chapter 3, the qualitative nature of these type of comments made them difficult to use for data comparison purposes.

Revised Pitch Recovery Rating Scale

In order to eliminate or minimize the limitations and ambiguities of the PRR scale, the author developed a revised version, shown in the appendix, figure 30. A glossary of terms and guidelines for use of the revised scale is included as appendix figure 31. This new scale incorporates the following improvements:

1. The first step is mission scenario definition. This establishes at the outset a clear picture in the pilot's mind of the reason for the nose-down input. The glossary lists potential mission scenarios for fighter aircraft.
2. In the decision tree, the first question is "did the aircraft recover?". This removes the ambiguity of the original scale, which challenged the pilot by asking if the aircraft were recoverable.
3. Control margin adequacy has been specified as mandatory, required and adequate. This clarifies the differences between the three categories of control, and eliminates the ambiguity of the original scale which allowed 'satisfactory' control margin to give an 'adequate' recovery.
4. The worst pilot rating has been tied to 'loss of aircraft', to avoid the confusion regarding personal time limits on recovery.
5. An extra category was added in the Level B area. This rating was for recoveries that may have been momentarily in doubt, but overall judged as safe. This gives the pilot more choices in rating a marginal aircraft, and provides five Level B categories, as opposed to the original three. It expands the area of the scale that is of greatest interest to aircraft designers, to ensure more accurate rating of the minimum threshold.
6. "Unnatural control inputs" was removed from the scale, as it was not part of the defined open loop input, and as it added confusion.
7. The unsafe threshold was defined as "recovery in doubt for an excessive period", and where the mission task became secondary to safety concerns.
8. "Marginal" was removed from the scale.
9. "Adequate" was removed as a pitch response characteristic.

10. "(recovery was not a concern)" was removed from the 2 pilot rating description.

These changes, in conjunction with the glossary, make the PRR scale simpler to use, and provide the user with more accuracy in the prime area of interest. The author recommends adoption of the revised Pitch Recovery Rating Scale for future pitch control margin simulation and flight test.

CHAPTER 5

CONCLUSION

The purpose of this thesis was to review and analyse handling qualities rating scales at high AOA, specifically as they related to the pitch control margin simulation and flight test. A background literature search revealed several methods for evaluating handling qualities, but none that were suited to high AOA open-loop pitch recovery rating.

The Pitch Recovery Rating Scale was developed and used during simulation and flight test, as a rating method to evaluate several measures of merit for pitch response. The most suitable measures of merit were found to be:

1. Average pitch acceleration during the first second, and
2. Average pitch rate during the first two seconds.

The PRR scale was found to have several weaknesses:

1. Mission task definition was too vague to allow repeatable pilot to pilot comparison,
2. Semantic ambiguity in the scale decision process contributed to pilot confusion and variability in ratings, and
3. Requirement for carefully controlled, rigorous use to avoid inappropriate tasks and premature rating number fixation.

A revised version of the PRR scale was developed and is included as appendix figure 30, along with a user's Glossary. These revisions make the PRR scale simpler to use, and provide the user with more accuracy in the prime area of interest.

The use of handling qualities rating scales at high AOA was found to require specific mission tasks, even for open loop scenarios. In addition, design of the scale must allow it to focus the most flexibility for pilot ratings in the area of prime interest to the user of the data. Also, choice of the most suitable measures of merit is important when evaluating a new flight regime.

CHAPTER 6

RECOMMENDATIONS

A summary of the recommendations contained in this thesis is listed as follows:

1. Qdmax1sec should not be used to define high AOA pitch control margin specification requirements.
2. Qdmax1sec is a weak measure of merit due to data inconsistency, and should not be used to define high AOA pitch control margin specification requirements.
3. Qdav1sec is the best acceleration measure of merit to define high AOA pitch control margin specification requirements.
4. Q2sec is a poor measure of merit to define high AOA pitch control margin specification requirements.
5. Qav2sec should be investigated in the simulator to verify its utility under a wide range of pitch control margin conditions.
6. Trec to be fairly constant as pilot ratings increased to 4.5, making it a poor measure of merit to define high AOA pitch control margin specification requirements when the aircraft recovery is not in doubt.
7. Specific mission scenarios should be defined for PRR scale use, and that pilot rating results be compared only in regard to that scenario.
8. A glossary should be included with the PRR scale to minimize ambiguity of the words used during the pilot decision and rating process.
9. The section of the PRR scale for aircraft with safe but inadequate pitch response should be expanded to allow more variety in pilot ratings.
10. Mission scenarios should be chosen to accentuate the open loop, nose-down pitch recovery response, and not a follow-on closed loop task.
11. Scale usage should be carefully monitored to ensure numeric pilot ratings are not given prematurely.

12. The revised Pitch Recovery Rating Scale should be adopted for future pitch control margin simulation and flight test.

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APPENDIX

Altitude (x1000 ftMSL)	Airspeed (KCAS)	AOA (deg)	Gross Wt. (lb)	CG (%MAC)	Flight	Zulu Time (hr:min:sec)	Date (m/d/y)
37.5	130	30	32,900	22.0	1	15:58:25	9/30/91
36.0	115	40	32,400	22.0	1	16:04:10	9/30/91
33.0	100	50	31,650	22.0	1	16:12:42	9/30/91
39.5	115	35	31,200	22.5	1	16:19:01	9/30/91
36.0	105	40	30,600	22.5	1	16:25:27	9/30/91
33.5	105	50	30,200	22.5	1	16:32:23	9/30/91
40.0	115	35	29,600	23.5	1	16:39:22	9/30/91
34.5	110	40	29,100	23.5	1	16:46:28	9/30/91
35.0	80	50	28,650	23.5	1	16:53:03	9/30/91
34.0	85	50	32,655	23.0	1	18:19:18	9/30/91
35.0	90	50	32,000	24.0	1	18:26:29	9/30/91
33.5	80	50	31,500	24.5	1	18:33:44	9/30/91
35.0	75	50	30,800	25.0	1	18:40:57	9/30/91
34.5	90	50	30,200	25.5	1	18:47:54	9/30/91
33.0	85	50	31,800	24.0	3	17:43:40	10/2/91
32.0	55	50	31,000	25.0	3	17:53:13	10/2/91
30.5	95	50	31,800	25.0	4	13:29:00	10/4/91
33.0	95	50	31,000	25.5	4	13:36:05	10/4/91
30.0	110	50	30,500	26.0	4	13:43:33	10/4/91
30.2	102	50	29,900	26.5	4	13:51:31	10/4/91
35.0	95	50	29,300	26.5	4	13:58:23	10/4/91
33.5	110	40	33,200	23.0	4	14:55:55	10/4/91
33.0	100	50	33,000	23.0	4	15:02:29	10/4/91
35.5	110	40	32,400	22.5	4	15:08:36	10/4/91
31.0	100	50	32,000	22.5	4	15:14:43	10/4/91
32.5	110	40	31,200	24.0	4	15:21:40	10/4/91
34.0	85	50	30,800	24.0	4	15:27:55	10/4/91
30.0	95	50	30,300	23.5	4	15:34:01	10/4/91
36.0	95	40	29,700	23.5	4	15:40:17	10/4/91

Table 4. Flight Test Conditions - Pilot A

Altitude (x1000 ftMSL)	Airspeed (KCAS)	AOA (deg)	Gross Wt. (lb)	CG (%MAC)	Flight	Zulu Time (hr:min:sec)	Date (m/d/y)
35.5	120	30	33,200	22.50	5	16:19:31	10/7/91
34.5	95	40	32,600	22.50	5	16:26:53	10/7/91
33.0	70	50	32,100	22.50	5	16:34:17	10/7/91
36.0	110	30	31,400	23.50	5	16:40:57	10/7/91
35.0	100	40	30,900	23.50	5	16:47:32	10/7/91
32.0	75	50	30,300	23.50	5	16:56:07	10/7/91
34.0	70	50	29,650	24.00	5	17:04:01	10/7/91
33.5	90	50	33,200	24.00	6	15:47:32	10/8/91
33.5	80	50	32,400	24.50	6	15:59:50	10/8/91
32.0	75	50	31,800	25.00	6	16:06:01	10/8/91
34.0	90	50	31,300	25.00	6	16:11:59	10/8/91
34.5	75	50	30,800	25.50	6	16:17:39	10/8/91
35.0	80	50	30,400	26.00	6	16:23:30	10/8/91
34.5	70	50	29,900	26.50	6	16:29:17	10/8/91

Table 5. Flight Test Conditions - Pilot B

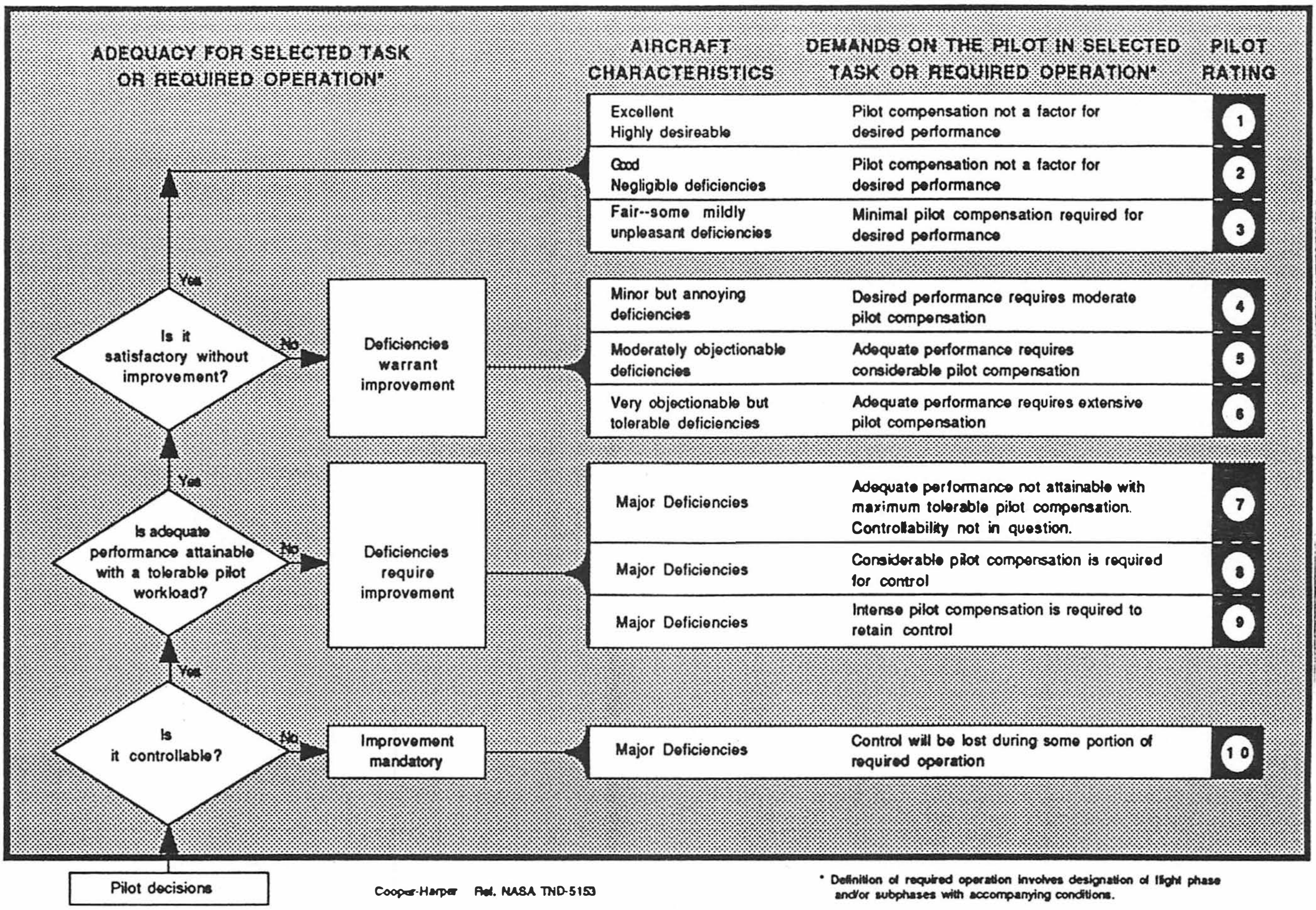

Figure 13. Cooper-Harper Handling Qualities Rating Scale

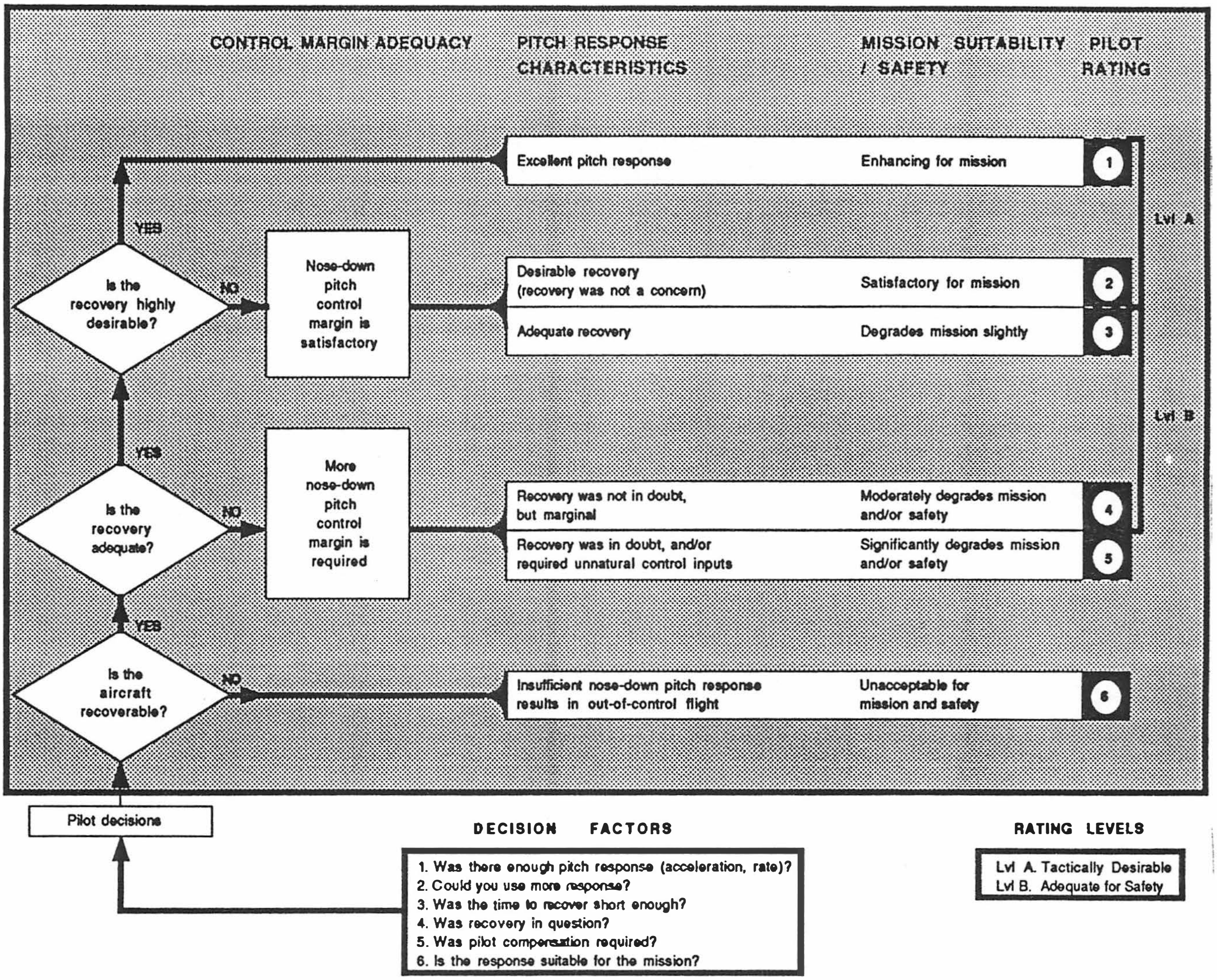

Figure 14. Pitch Recovery Rating Scale

PILOT A MISSION TASKS

1. Offensive in a vertical fight (recovering to low AOA after a successful tracking gun shot).

2. Defensive in a vertical fight (recovering/unloading to low AOA with a known threat above and behind).

3. Defensive during guns tracking (using high AOA to force an overshoot, and unloading to track).

4. Guns jink (have pulled to max AOA, and now unload prior to rolling and pulling out of plane).

5. Collision avoidance (to miss another high AOA aircraft with a converging flight path).

6. Vertical extension (have pulled to high AOA to flush out a less capable bogey, and now push over to get target in the HUD).

PILOT B MISSION TASK

1. Pushover from a nose-high attitude to point towards a bogey below and slightly forward of the test aircraft.

Figure 15. Pitch Recovery Rating Scale - Pilot Mission Tasks

Model F/A-18A Airplane

Bu No 162445

Configuration: Cruise
Loading: Clean
FCS PROM: 8.3.3
Method: Stabilized Pushover

Pressure Altitude: 30-40 Kft MSL
Airspeed: 55 to 130 KCAS
Gross Weight: 28.6 to 33.2 Klb
CG Position: 22.5 to 26.5%MAC

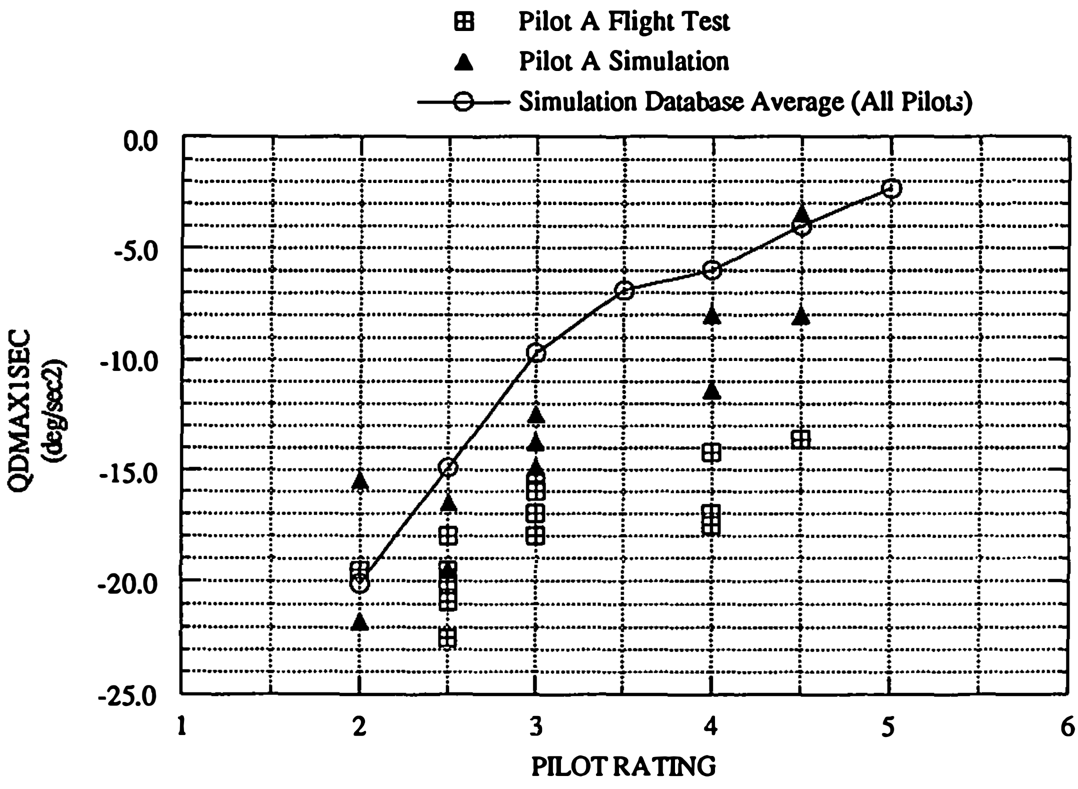

Figure 16. Qdmax1sec Variation with Pilot Rating for Pilot A

Model F/A-18A Airplane

Bu No 162445

Configuration: Cruise
Loading: Clean
FCS PROM: 8.3.3
Method: Stabilized Pushover

Pressure Altitude: 32-36 Kft MSL
Airspeed: 70 to 120 KCAS
Gross Weight: 29.6 to 33.2 Klb
CG Position: 22.5 to 26.5%MAC

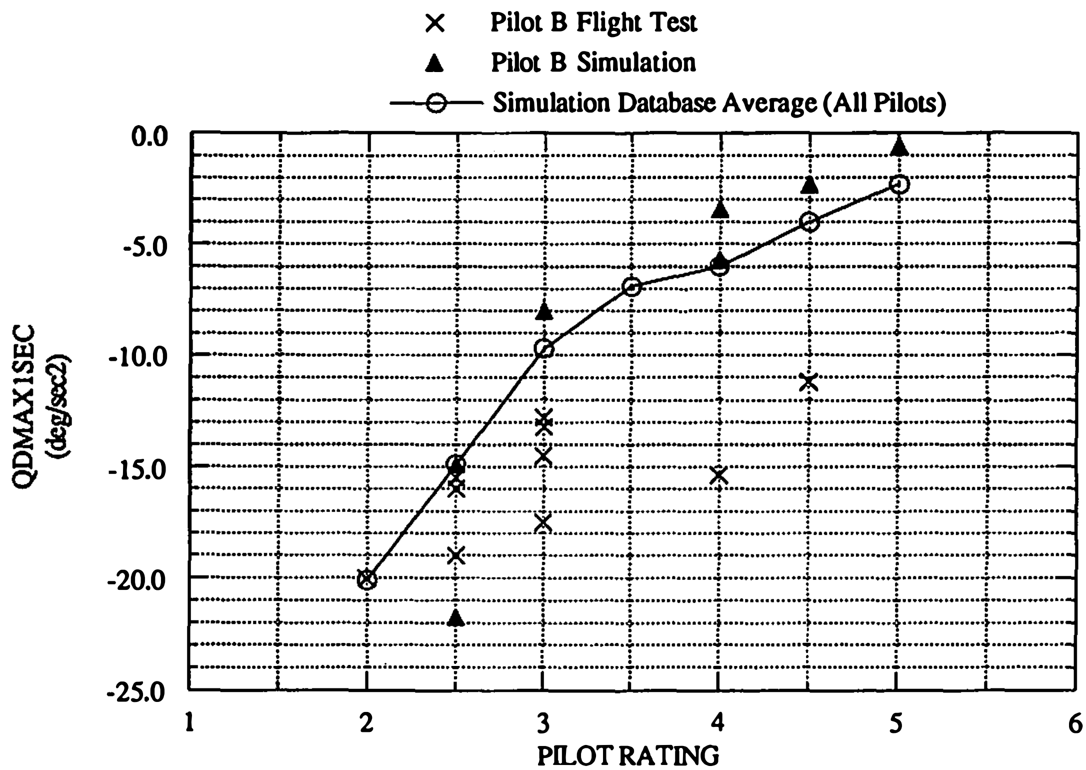

Figure 17. Qdmax1sec Variation with Pilot Rating for Pilot B

Model F/A-18A Airplane

Bu No 162445

Configuration: Cruise
Loading: Clean
FCS PROM: 8.3.3
Method: Stabilized Pushover

Pressure Altitude: 30-40 Kft MSL
Airspeed: 55 to 130 KCAS
Gross Weight: 28.6 to 33.2 Klb
CG Position: 22.5 to 26.5%MAC

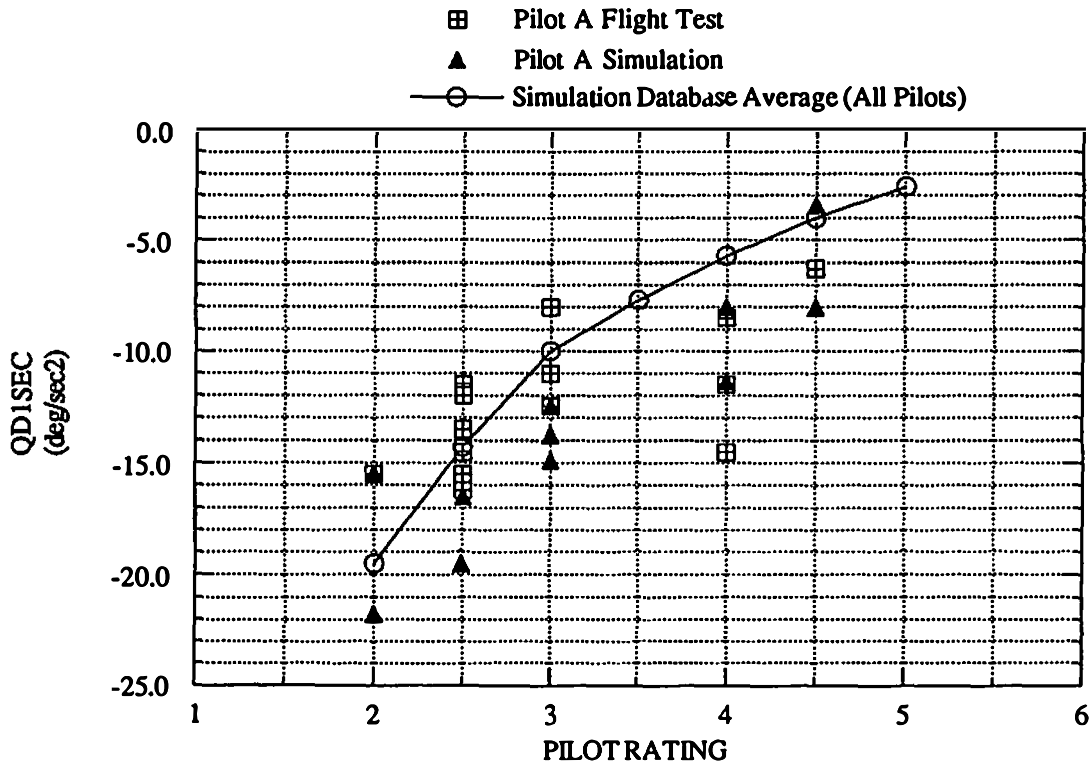

Figure 18. Qd1sec Variation with Pilot Rating for Pilot A

Model F/A-18A Airplane

Bu No 162445

Configuration: Cruise
Loading: Clean
FCS PROM: 8.3.3
Method: Stabilized Pushover

Pressure Altitude: 32-36 Kft MSL
Airspeed: 70 to 120 KCAS
Gross Weight: 29.6 to 33.2 Klb
CG Position: 22.5 to 26.5%MAC

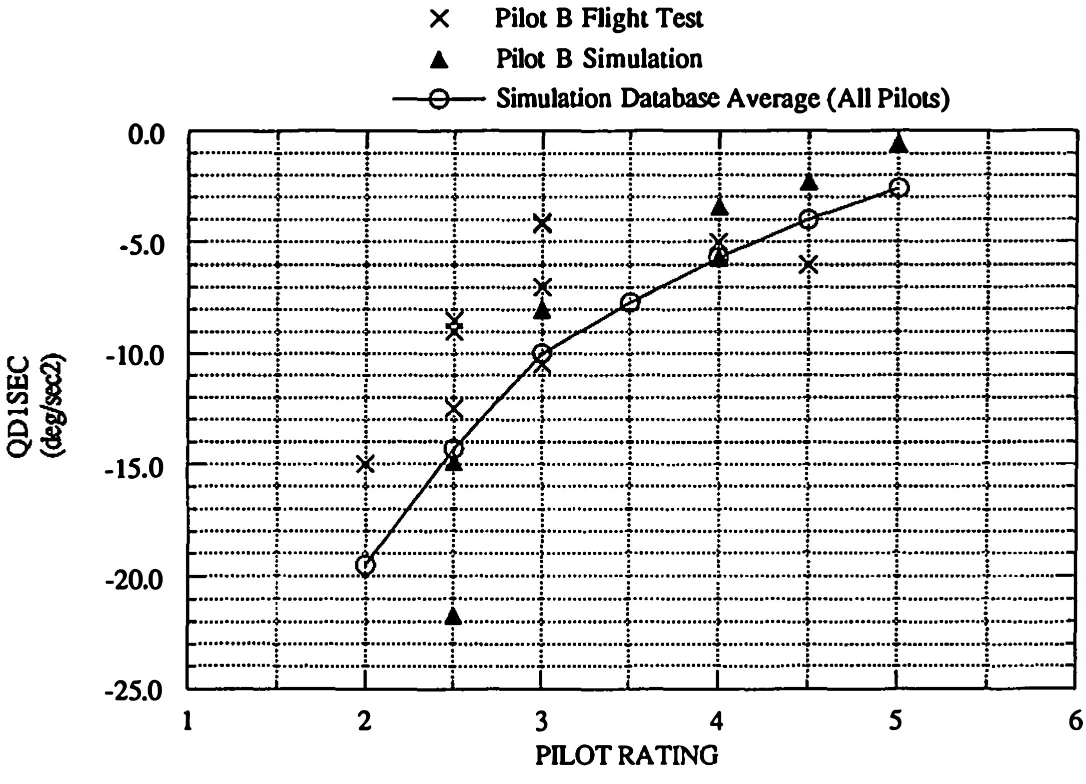

Figure 19. Qd1sec Variation with Pilot Rating for Pilot B

Model F/A-18A Airplane

Bu No 162445

Configuration: Cruise
Loading: Clean
FCS PROM: 8.3.3
Method: Stabilized Pushover

Pressure Altitude: 30-40 Kft MSL
Airspeed: 55 to 130 KCAS
Gross Weight: 28.6 to 33.2 Klb
CG Position: 22.5 to 26.5%MAC

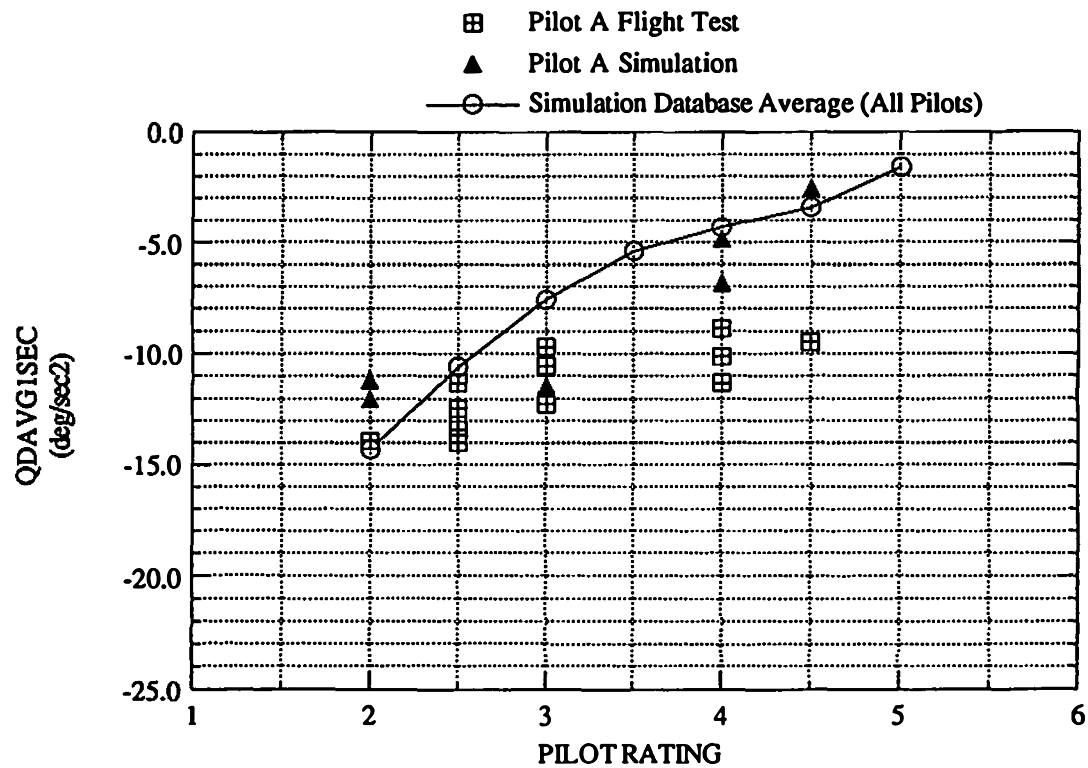

Figure 20. Qdav1sec Variation with Pilot Rating for Pilot A

Model F/A-18A Airplane

Bu No 162445

Configuration: Cruise
Loading: Clean
FCS PROM: 8.3.3
Method: Stabilized Pushover

Pressure Altitude: 32-36 Kft MSL
Airspeed: 70 to 120 KCAS
Gross Weight: 29.6 to 33.2 Klb
CG Position: 22.5 to 26.5%MAC

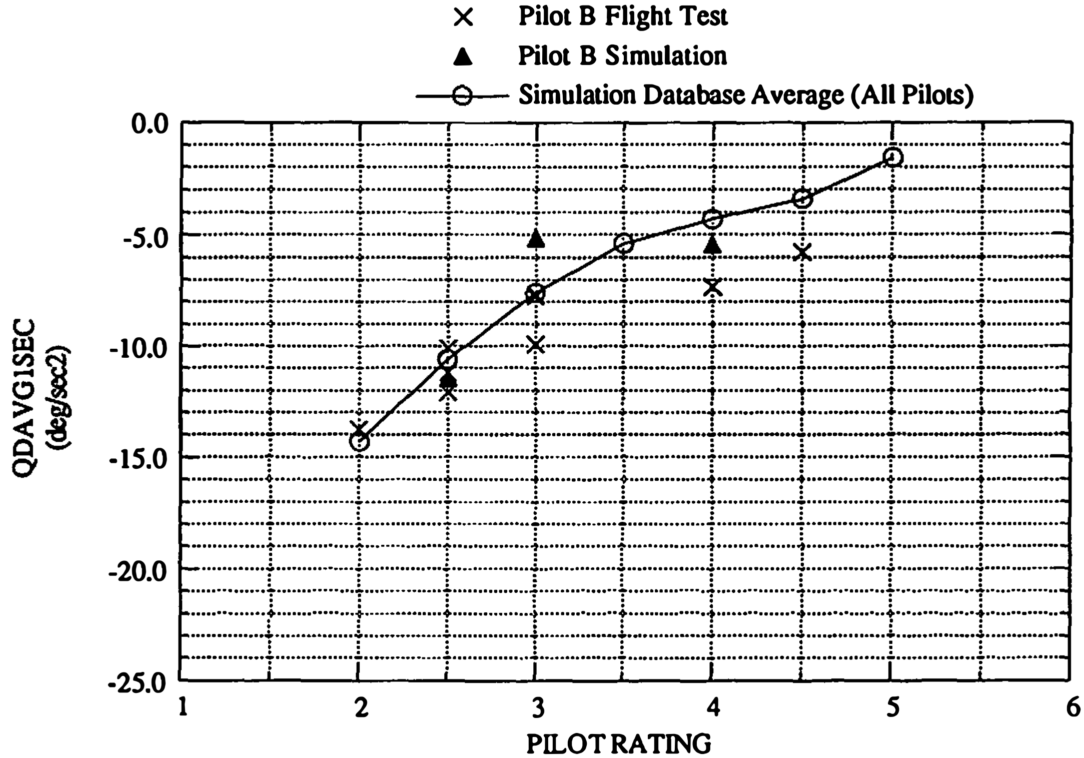

Figure 21. Qdav1sec Variation with Pilot Rating for Pilot B

Model F/A-18A Airplane

Bu No 162445

Configuration: Cruise
Loading: Clean
FCS PROM: 8.3.3
Method: Stabilized Pushover

Pressure Altitude: 30-40 Kft MSL
Airspeed: 55 to 130 KCAS
Gross Weight: 28.6 to 33.2 Klb
CG Position: 22.5 to 26.5%MAC

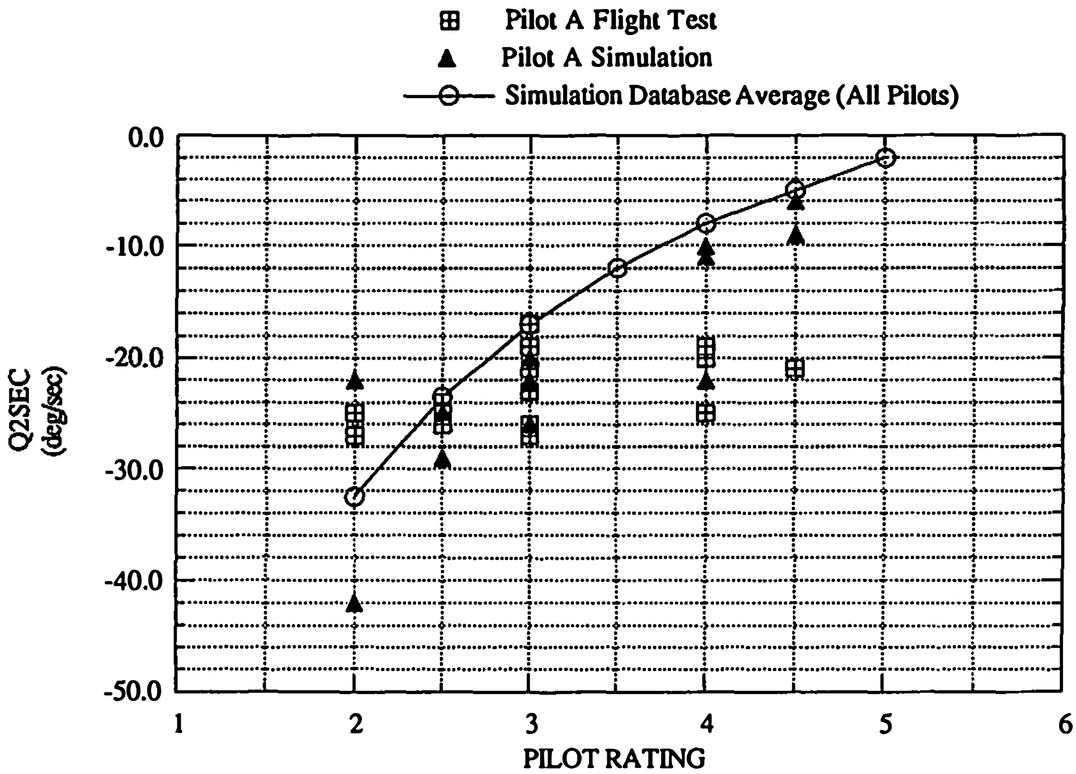

Figure 22. Q2sec Variation with Pilot Rating for Pilot A

Model F/A-18A Airplane

Bu No 162445

Configuration: Cruise
Loading: Clean
FCS PROM: 8.3.3
Method: Stabilized Pushover

Pressure Altitude: 32-36 Kft MSL
Airspeed: 70 to 120 KCAS
Gross Weight: 29.6 to 33.2 Klb
CG Position: 22.5 to 26.5%MAC

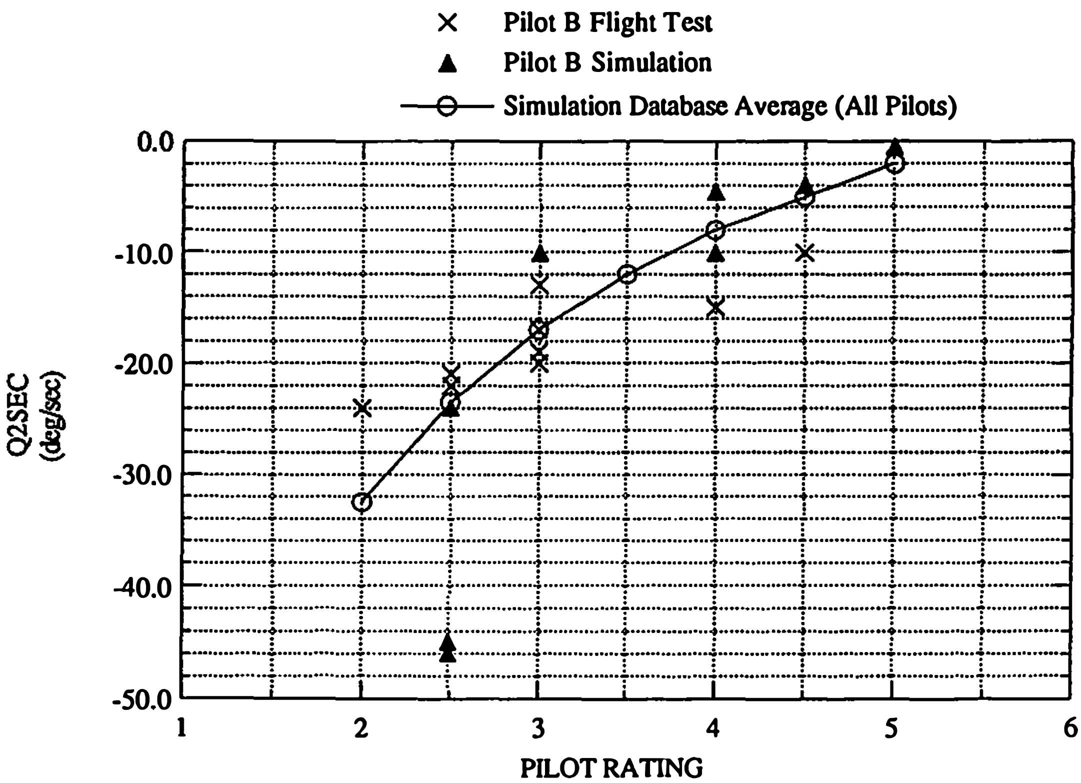

Figure 23. Q2sec Variation with Pilot Rating for Pilot B

Model F/A-18A Airplane

Bu No 162445

Configuration: Cruise
Loading: Clean
FCS PROM: 8.3.3
Method: Stabilized Pushover

Pressure Altitude: 30-40 Kft MSL
Airspeed: 55 to 130 KCAS
Gross Weight: 28.6 to 33.2 Klb
CG Position: 22.5 to 26.5%MAC

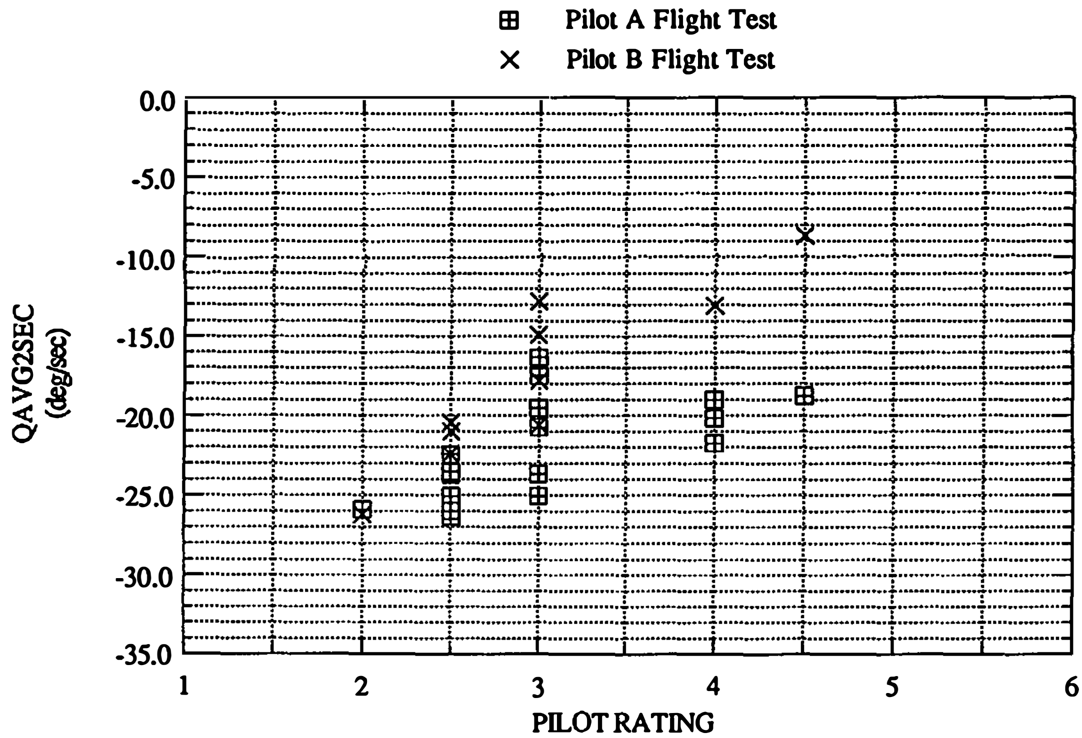

Figure 24. Qav2sec Variation with Pilot Rating for Pilots A and B

Model F/A-18A Airplane

Bu No 162445

Configuration: Cruise
Loading: Clean
FCS PROM: 8.3.3
Method: Stabilized Pushover

Pressure Altitude: 30-40 Kft MSL
Airspeed: 55 to 130 KCAS
Gross Weight: 28.6 to 33.2 Klb
CG Position: 22.5 to 26.5%MAC

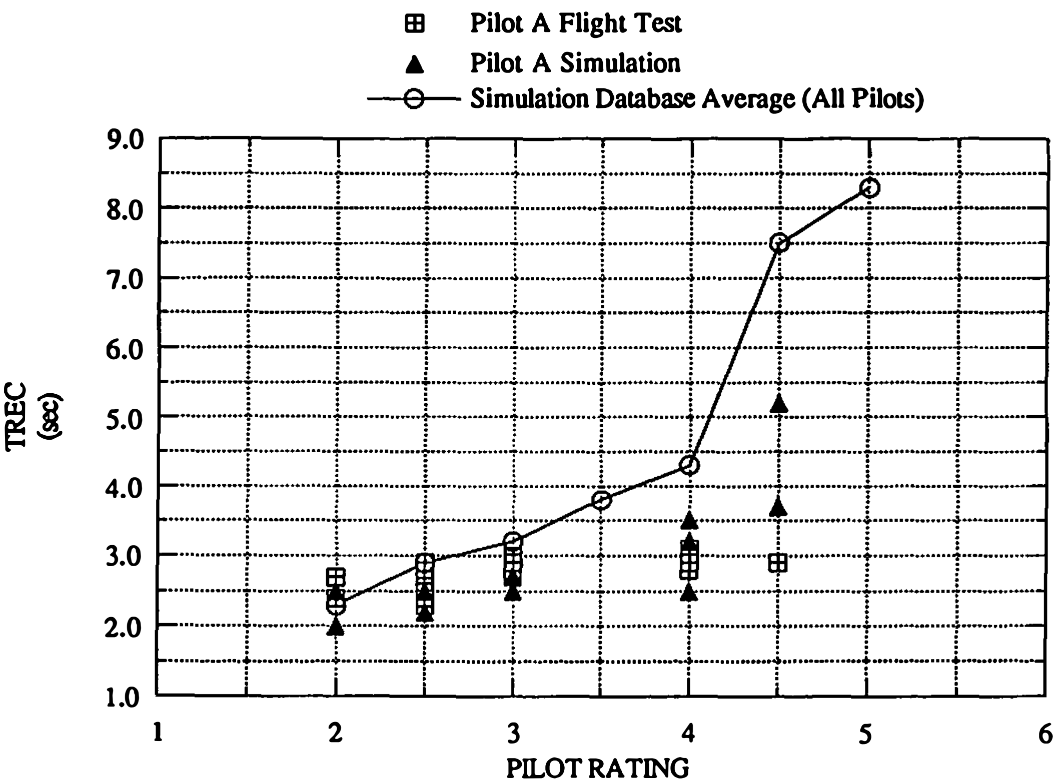

Figure 25. Trec Variation with Pilot Rating for Pilot A

Model F/A-18A Airplane

Bu No 162445

Configuration: Cruise
Loading: Clean
FCS PROM: 8.3.3
Method: Stabilized Pushover

Pressure Altitude: 32-36 Kft MSL
Airspeed: 70 to 120 KCAS
Gross Weight: 29.6 to 33.2 Klb
CG Position: 22.5 to 26.5%MAC

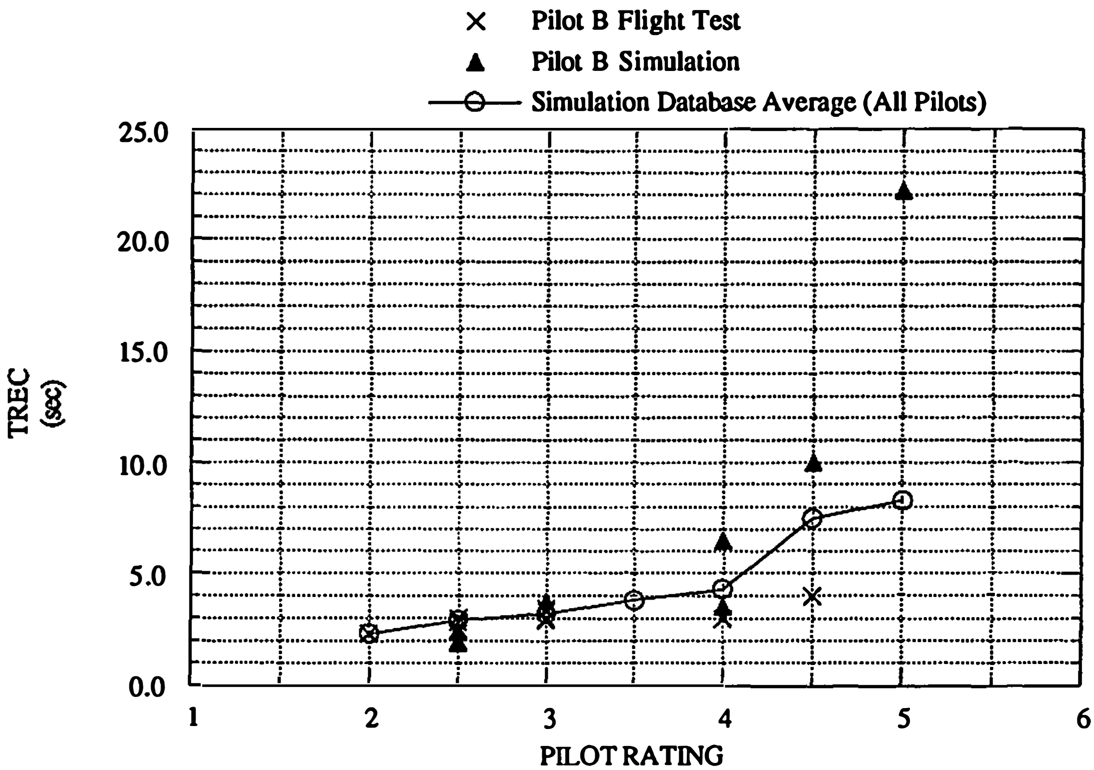

Figure 26. Trec Variation with Pilot Rating for Pilot B

The Standard of Error Estimate (SEOE is a common statistical tool, used to quantify goodness of fit, using a base-10 logarithmic fitted curve. The equation and its associated variable definitions are as follows:

$$SEOE = [(\Sigma(y - y_{est})^2)/n]^{1/2}$$

y = current measure of merit value

$y_{est} = a_0 + a_1(\log(x))$

a_0 and a_1 are constants

x = current pilot rating value

n = total number of data points

Figure 27. Standard Error of Estimate Calculation

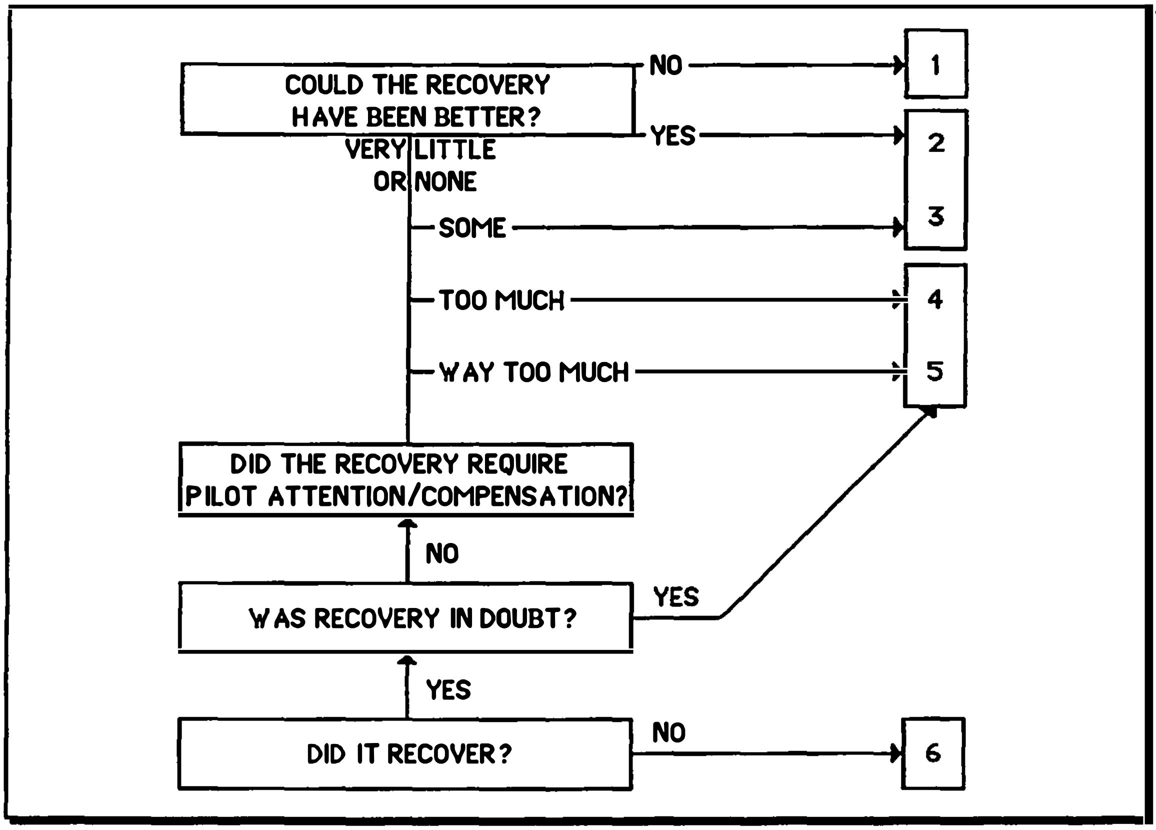

Figure 28. Pilot A Simplified Alternate Decision Tree

PILOT COMMENT	RATING
Perfect response; best that could be	1
Maybe not perfect but I'll take this in my jet as is	2
Pretty good, but needs a slight change to make it right	2.5
OK, but needs a moderate change or multiple changes to fix it	3
No safety problem; I was sure the nose was coming down, but much too slow to be useful. Must have a change	4
No safety problem, but some safety concern. The nose moved and kept moving at a constant or increasing rate but so slow it was uncomfortable. Must have a change	4.5
Hang up in nose down pitch rate or so slow the pilot would certainly roll off	5
Uncontrollable	6

Figure 29. Pilot B Alternate Decision Tree

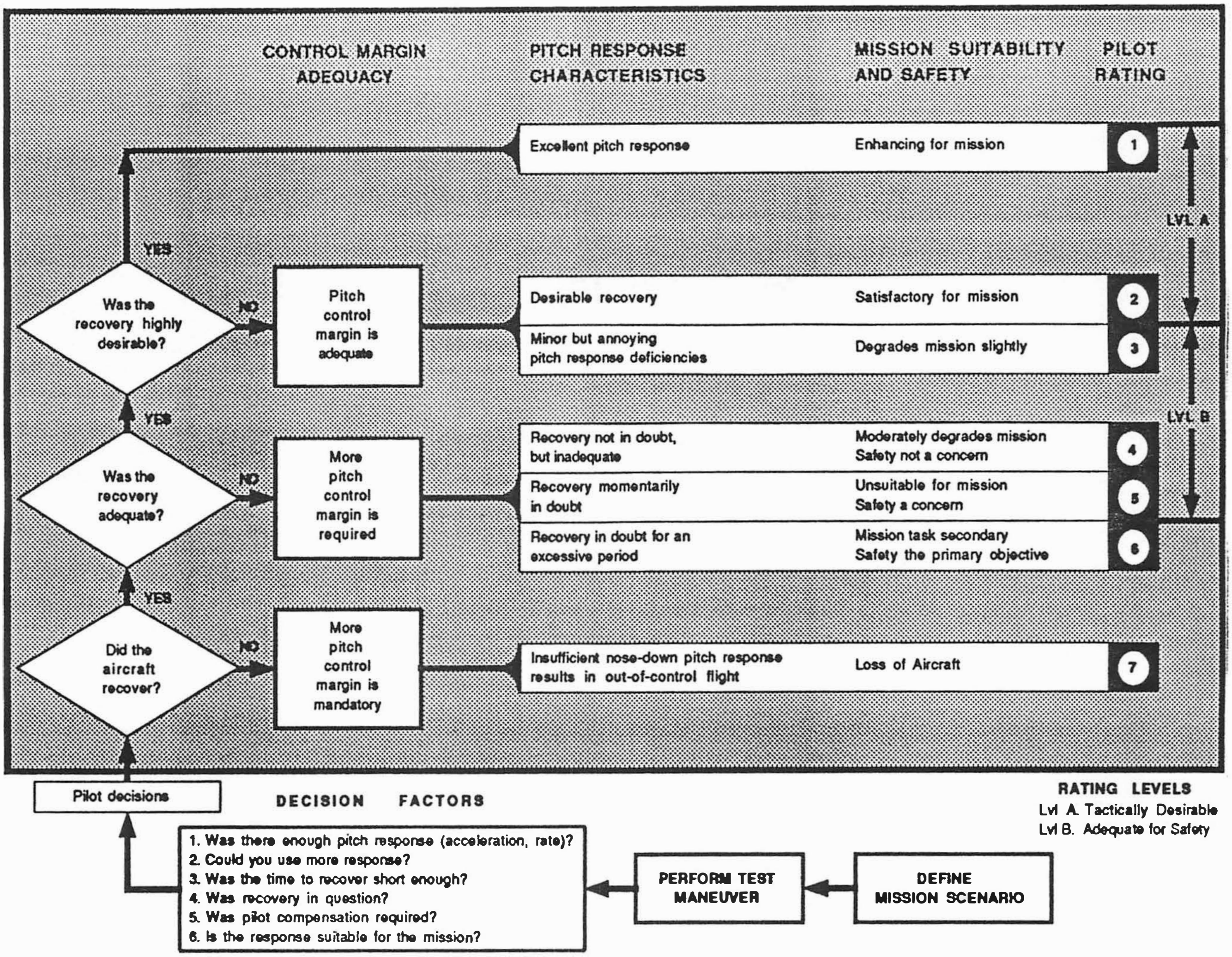

Figure 30. Modified Pitch Recovery Rating Scale

REVISED PITCH RECOVERY RATING SCALE GLOSSARY

Mission Scenario: Mission tasks should be chosen to ensure the following:

1. Open loop, single axis control inputs only.
2. Representative mission relation, to provide a realistic sense of urgency and threat response requirements to the pilot.

An example for a fighter aircraft would be: defensive in a vertical fight (recovering / unloading to low AOA with a known threat above and behind).

Adequate: Suitable for the mission. Deficiencies are minor. Would only need slight changes make it desirable.

Excessive: The recovery was in doubt for so long that safety became the overriding concern. Pilots would probably attempt a roll-off or alternate recovery method rather than wait.

Momentarily: The pilot was briefly worried about the safety of the recovery, but the period of worry was short enough that the overall recovery was judged as safe.

Unsuitable: The pitch response was so poor that mission task achievement was lost.

Moderately: The pitch response was poor enough that mission task achievement was in doubt.

Highly Desirable: The recovery could not have been better.

Figure 31. Modified Pitch Recovery Rating Scale Glossary

VITA

Chris Austin Hadfield was born in Sarnia, Ontario, Canada on August 29, 1959. He attended elementary schools in Sarnia, Milton, and Oakville, and graduated from Milton District High School in June, 1977. The following May he entered the Canadian Armed Forces, attending Royal Roads Military College until May 1980. He graduated from the Royal Military College, Kingston, Ontario, in May 1982, with an honours degree in Mechanical Engineering. In December, 1988, he was the outstanding graduate of the USAF Test Pilot School.

He has amassed over 2000 hours flying over 50 aircraft types, and is currently employed as a Test Pilot and Project Officer on exchange to the USN at the Naval Air Warfare Center, Aircraft Division, in Patuxent River, Maryland.