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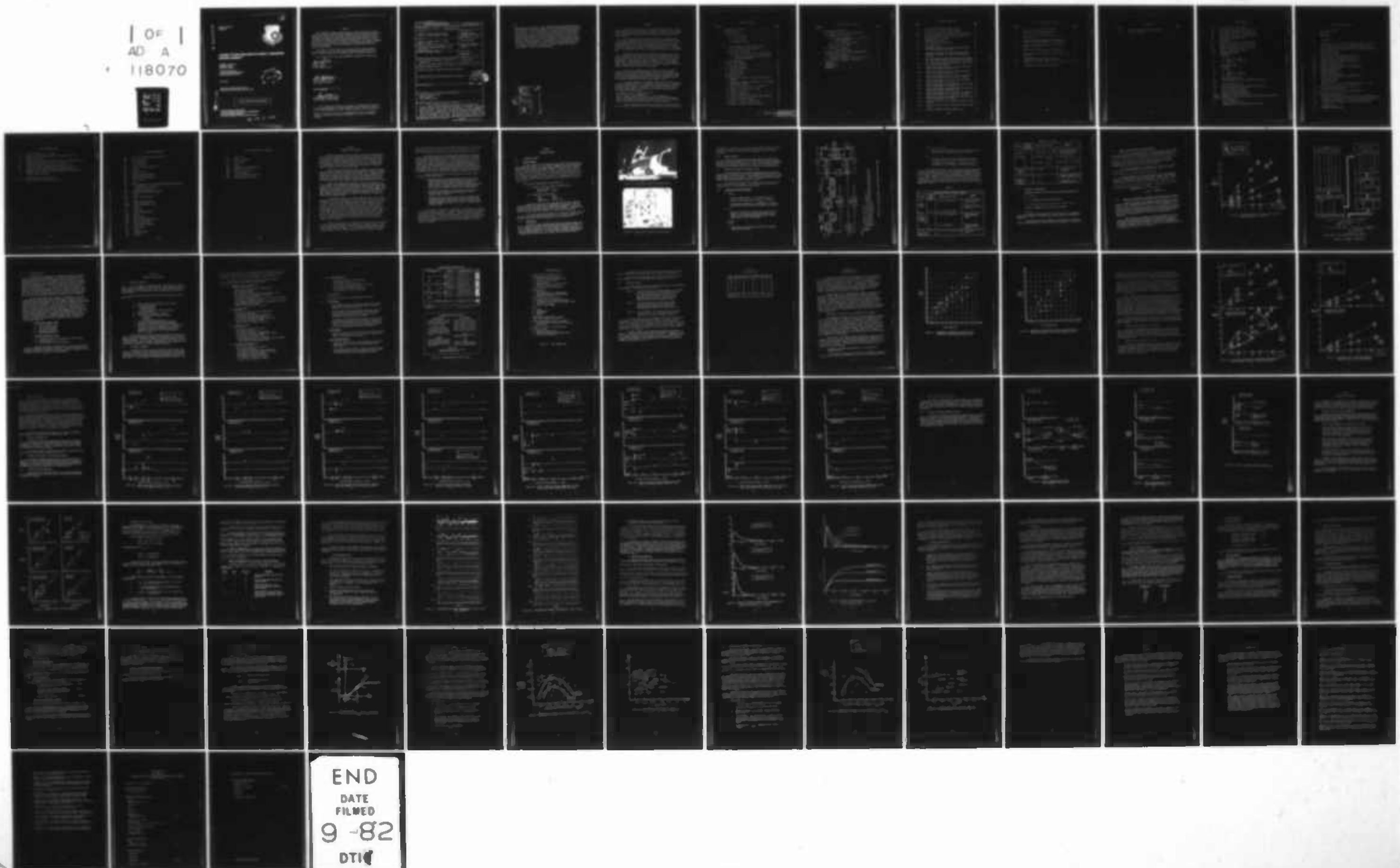

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AFWAL-TR-81-3171
VOLUME I

LATERAL FLYING QUALITIES OF HIGHLY AUGMENTED FIGHTER AIRCRAFT

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This technical report has been reviewed and is approved for publication.

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damping were also evaluated. Tasks included were actual target tracking, air refueling and precision landing as well as special Head-Up Display (HUD) tracking tasks. Results indicated that a properly designed HUD bank angle tracking task is a valid flying qualities evaluation task. Data show that lateral flying qualities are very sensitive to control system time delay and very short values of roll mode time constant typically result in poor lateral flying qualities. Excellent separation of the data into flying qualities levels is achieved for the Category A task data using time domain equivalent systems parameters. An optimum equivalent time constant value of 0.5 sec is indicated by the data; sensitivity to equivalent time delay is a minimum at this value. Volume I contains the body of the report, while Volume II consists of the Appendices.

FOREWORD

This report was prepared for the United States Air Force and Navy by Calspan Corporation, Buffalo, New York, in partial fulfillment of USAF Contract Number F33615-79-C-3613 and describes an in-flight investigation of the effects of high order control systems on the lateral-directional flying qualities of fighter aircraft.

The in-flight evaluation program reported herein was performed by the Flight Research Department of Calspan under the sponsorship of the AFWAL Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio and the Naval Air Development Center, Warminster, Pennsylvania working through a Calspan contact with AFWAL. This work was part of Project 6645-F, NT-33 Task 8 and utilized the USAF variable stability NT-33 operated by Calspan. Mr. Jack Barry was the program manager for AFWAL; his assistance deserves special acknowledgement.

Completion of this evaluation program was dependent on the contributions of many individuals from the Air Force, Navy, McDonnell-Douglas Corpration, and Calspan. Mr. Thomas Cord of AFWAL and Mr. David Bischoff of NADC served as the technical monitors for this program; their work is gratefully acknowledged. In addition, the support and interest of Mr. Ralph A'Harrah (NADC) and Mr. David Moorhouse (AFWAL) were appreciated. Mr. John Hodgkinson and Mr. William Moran of McDonnell-Douglas also deserve recognition for their technical guidance and assistance in this program.

The work of the evaluation pilots - Messrs John Ball and Michael Parrag of Calspan and LCdr Kenneth Grubbs of the Naval Air Test Center - warrants special recognition; their diligent efforts and professional manner were vital to the successful completion of the program. The support of NADC and the 107th Fighter Intercept Group of the New York Air National Guard was also gratefully appreciated for the supply of target aircraft.

This report represents the combined efforts of many individuals of the Flight Research Department. Mr. Stephen J. Monagan was the Project Engineer and served as Safety Pilot. Mr. Rogers E. Smith was the program's technical advisor and also served as a Safety Pilot. Mr. Randall E. Bailey was the Assistant Project Engineer. The contributions of the following individuals are also gratefully acknowledged:

Mr. Charles R. Chalk - Technical Consulting
Mr. James Lyons - Digital Computing
Messrs. Clarence Mesiah and Bernie Eulrich - DEFT Programming
Messrs. Ronald Huber and John Babala - Electronic Design and Maintenance
Messrs. Ray Miller, William Howell and Michael Sears - Aircraft Maintenance
Messrs. Alva Schwartz and Donald Dobmeier - Aircraft Inspection.

Finally, the excellent work of Mses. Miriam Ford, Dorothy Kantorski, and Chris Turpin in preparation of this report deserves very special recognition.

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LIST OF SYMBOLS

$e^{-\tau s}$	Time delay (sec), Laplace notation
F_{as}	Roll control stick force, positive right (lb)
F_{es}	Pitch control stick force, positive aft (lb)
F_{rp}	Rudder pedal control force, positive right (lb)
g	Acceleration of gravity (ft/sec^2)
h	Altitude (ft)
I_x	Moment of inertia about X axis (ft-lb sec^2)
I_y	Moment of inertia about Y axis (ft-lb sec^2)
I_z	Moment of inertia about Z axis (ft-lb sec^2)
I_{xz}	Product of inertia (ft-lb sec^2)
L	Rolling moment (ft-lb)
$L_{(\ )}$	$= \frac{1}{I_x} \frac{\partial L}{\partial (\ )}$
L_i'	$= \left(1 - \frac{I_{xz}^2}{I_x I_z}\right)^{-1} \left(L_i + \frac{I_{xz}}{I_x} N_i\right)$
N	Yawing moment (ft-lb)
$N_{(\ )}$	$= \frac{1}{I_z} \frac{\partial N}{\partial (\ )}$
N_i'	$= \left(1 - \frac{I_{xz}^2}{I_x I_z}\right)^{-1} \left(N_i + \frac{I_{xz}}{I_z} L_i\right)$
n_y	Side acceleration (g's)
$N_{Y_{EP}}$	Side acceleration at pilot's reference eye point (g's)
n_z	Normal acceleration (g's)
n_z/α	Normal acceleration per unit angle of attack (g's/rad)
p	Roll rate (deg/sec or rad/sec)
p_{ss}	Steady-state roll rate (deg/sec)
$\dot{p}_{max}$	Maximum roll acceleration (deg/sec^2)
$\dot{p}_{max}/F_{AS}$	Maximum roll acceleration per unit lateral stick force (deg/sec^2/lb)
r	Yaw rate (deg/sec)
s	Laplace operator (sec^{-1})
v	Incremental velocity along reference Y-axis (fps)

V	True velocity (ft/sec)
$\bar{x}$	Mean value
Y	Side force (lb)
$Y_{( )}$	$= \frac{1}{mV} \frac{\partial Y}{\partial ( )}$
x,y,z	Stability axes (i.e., a right hand orthogonal body axis system with origin at the c.g., the z axis in the plane of symmetry and the x-axis aligned with the relative wind at zero sideslip trimmed flight
α	Angle of attack (deg)
β	Angle of sideslip (deg)
$\delta_{a,e,r}$	Aileron, elevator, and rudder deflections (deg)
δ_{AS}	Aileron control stick deflection at grip (in)
δ_{ES}	Elevator control stick deflection at grip (in)
δ_{RP}	Rudder pedal deflection (in)
$\zeta_{a,e,r}$	Aileron, elevator and rudder actuator damping ratio
ζ_{DR}	Dutch-roll damping ratio
ζ_p	Phugoid damping ratio
ζ_{sp}	Short period damping ratio
ζ_ϕ	Damping ratio of numerator ϕ/F_{AS} transfer function
θ	Pitch attitude (deg)
σ	Standard deviation
τ	Additional roll control system transport time delay, $e^{-\tau s}$ (sec)
τ_E, τ_{Eff}	$e^{-\tau_E s}$, equivalent, effective time delay (sec)
τ_R	Roll mode time constant (sec)
τ_{R_E}, $\tau_{R_{Eff}}$	Equivalent, effective roll mode time constant (sec)
τ_s	Spiral mode time constant (sec)
τ_1	Numerator time constant of roll control system lead/lag prefilter (sec)
τ_2	Denominator time constant of roll control system lag prefilter (sec)
$\tau_{\theta_{1,2}}$	Airframe lead time constants in θ/F_{ES} transfer function (sec)
ϕ	Bank angle (deg)
ϕ_c	Commanded bank angle (deg)

LIST OF SYMBOLS (CONT'D)

ϕ_e	Bank angle error, $\phi_e = \phi_c - \phi$ (deg)
$\|\phi/\beta\|_{DR}$	Absolute value of controls-fixed roll to sideslip ratio at ω_{DR}
ψ	Heading angle (deg)
$\omega_{a,e,r}$	Undamped natural frequency of aileron, elevator, and rudder actuators
ω_{DR}	Undamped natural frequency of Dutch-roll (rad/sec)
ω_p	Longitudinal phugoid undamped natural frequency (rad/sec)
ω_{sp}	Longitudinal short period undamped natural frequency (rad/sec)
ω_ϕ	Undamped natural frequency of numerator quadratic in ϕ/F_{AS} transfer function numerator (rad/sec)
$(\ )_T$	Referenced to trim flight condition
$(\dot{\ })$	Rate of change of ( ) with time (( )/sec)

LIST OF ABBREVIATIONS

AFWAL	Air Force Wright Aeronautical Laboratories
AGL	Above Ground Level
AR	Air Refueling task
c.g.	center of gravity
DEFT	Display Evaluation Flight Test
deg	degrees
EP	Evaluation Pilot
ESP	Equivalent System Program
FFT	Fast Fourier Transformation
fps	feet per second
ft	feet
HUD	Head-Up-Display; also, Head-up-display-based Bank angle and Heading angle Tracking Tasks
ILS	Instrument Landing System
IMC	Instrument Meteorological Conditions
in	inches
KIAS	Knots, Indicated Airspeed
kts	knots
LA	Landing and Approach task
LATHOS	Lateral Higher Order System
lb	pounds
mil	milliradian
MOA	Military Operating Area
msec	millisec
MSL	Mean Sea Level
NADC	Naval Air Development Center
NATC	Naval Air Test Center
PIO	Pilot-induced Oscillation
PR	Pilot Rating
rad	radian
rms	root-mean-square
sec	seconds

LIST OF ABBREVIATIONS (CONCLUDED)

SP	Safety Pilot
SPR	Safety Pilot Rating
TAS	True Airspeed
Tgt	Target
TR	Formation and Gun Tracking Task
USAF	United States Air Force
VFR	Visual Flight Rules
VMC	Visual Meteorological Conditions
VSS	Variable Stability System

Section 1

INTRODUCTION AND PURPOSE

Modern fighter flight control systems use digital or analog computation techniques in combination with their advanced "fly-by-wire" technology to gain potential advantages such as improved mission performance and weight/cost reduction. Examples of modern fighter aircraft which incorporate such advanced flight control system designs are the F-16, YF-17, F-18 and Tornado. Unfortunately, the potential of this expanded flight control technology has not been realized. In fact, new flying qualities problems have often been created in the process of solving the old ones.

With the operational acceptance of full-authority electronic augmentation systems, the designer literally has the capability to tailor the flying qualities of the aircraft as desired for each mission task. Typically, these advanced design efforts have produced overly complex designs characterized by "higher order" responses to the pilot's inputs. The additional control system dynamics, or higher order effects, can potentially cause serious flying qualities problems for modern fighter aircraft while performing precision tasks.

These new flying qualities problems are most often related to the time delays which are introduced into the control system by the advanced flight control design. The source of these time delays, which can cause dramatic degradation in flying qualities for precision tasks, can be from the higher order complexity of the flight control system design or, in the case of digital systems, inherent time delays. Digital flight control systems tend to be the worse offenders since the power of the computer unfortunately encourages the design of very complex systems.

Criteria based on classical aircraft characteristics, such as those presented in MIL-F-8785B (Reference 1) are not sufficient alone for the design of modern aircraft with highly augmented flight control systems; they are also not adequate to evaluate the flying qualities of aircraft equipped with such systems. A series of research programs has been conducted using the USAF/Calspan NT-33A variable stability aircraft (References 3 to 10) to acquire a flying qualities data base which is applicable to aircraft with highly augmented flight control systems. From this research and data, criteria applicable to the highly augmented, high order fighter aircraft have evolved. The new military flying qualities specification (MIL-F-8785C, Reference 2) requires the use of equivalent systems to show compliance with criteria based on classical aircraft characteristics and also places limits on the allowable control system time delay.

Most of these previous flying qualities research efforts have centered on fighter aircraft longitudinal flying qualities. However, aircraft with modern, highly augmented flight control systems have exhibited equally serious lateral flying qualities problems. A suitable lateral flying qualities data base applicable to modern, complex fighter aircraft did not exist. Without such a data base the designer cannot avoid a potentially expensive trial and error development process with the real aircraft. The genesis of the research experiment described in this report comes from a clear need for a flying qualities data base for fighter aircraft with lateral higher order systems.

This report describes a research program intended to collect basic lateral-directional flying qualities data applicable to aircraft with higher order lateral flight control systems. The major portion of this experiment was devoted to the lateral axis because: 1) the directional axis is not yet a primary control axis, 2) experience to date with higher order flight control systems has not shown significant directional flying qualities problems, and 3) modern flight control systems allow the isolation of the lateral and directional axes. Future flight control systems may use the directional axis as a primary control axis (e.g. wings level turn, fire control-flight control coupling) and will require extensive directional flying qualities research.

The specific objectives of the flying qualities research program described in this report were to:

- Gather lateral-directional flying qualities data applicable to fighter aircraft with complex higher order lateral flight control systems in the context of precision maneuvering, tracking, and refueling tasks, and terminal approach and landing tasks (Class IV aircraft, Category A and C Flight Phases), as a function of important lateral control system parameters.

- Continue the development of suitable control system design and evaluation criteria which are applicable to highly augmented fighter aircraft.

- Compare various Flight Phase A and C lateral evaluation tasks with head-up display based evaluation tasks. Determine which evaluation tasks are most sensitive to lateral control system parameter changes and evaluate the validity of head-up display evaluation tasks.

This report is divided into two volumes. The main body of the report including the experiment design, its conduct, results, and preliminary analysis of the data are contained herein as Volume I. Detailed information concerning the experiment has, for the most part, been placed in a series of appendices presented in Volume II. Included in Volume II are also additional analyses and correlation of the data as well as the pilot comment summaries. Pertinent conclusions and recommendations based on this work are presented in the final sections of Volume I.

Section 2

EXPERIMENT DESIGN

2.1 EXPERIMENT SYSTEMS

2.1.1 NT-33A Aircraft

The test aircraft for this program was the USAF NT-33A research aircraft operated by Calspan. This aircraft is equipped with a Variable Stability System (VSS) which utilizes an analog response feedback technique to generate the desired augmented aircraft dynamic response. A variable feel system, suitable control system dynamics in the form of prefilters, and an adjustable time delay circuit allow simulation of various flight control parameters. For this program, a center stick was used. A detailed description of the NT-33A VSS is included in Appendix I and in Reference 11. Pertinent details of the lateral flight control system mechanization for this experiment are presented in Section 2.2.

The external configuration of the NT-33A was:

1) Formation, Tracking, Refueling and HUD Tasks -

Gear and Flaps	UP
Speed Brakes	CLOSED

2) Approach and Landing Tasks -

Gear	DOWN
Flaps	30 deg
Speed Brakes	OPEN on final

A potential limitation in the experiment was the NT-33A maximum achievable steady state roll rate of approximately 100 deg/sec at 280 KIAS. An examination of the flight records showed that the maximum roll rate commanded during the evaluation tasks was less than 100 deg/sec. Therefore, the NT-33A roll rate limit did not affect the results of this experiment.

For the refueling task evaluations, an air-to-air refueling boom was attached to the lower right forward portion of the NT-33A nose (Figure 2-1). The boom latched into the tanker drogue but did not transfer fuel.

2.1.2 DEFT System

The NT-33A is also equipped with a Display Evaluation Flight Test (DEFT) system which includes a fully programmable Head-Up Display (HUD) system. A complete description of the DEFT system is presented in Appendix J. For this program the HUD was used as the primary instrument reference by the evaluation pilot (Figure 2-2). A fixed HUD symbol, depressed approximately 1 degree below the horizon in level flight, was used as the air-to-air

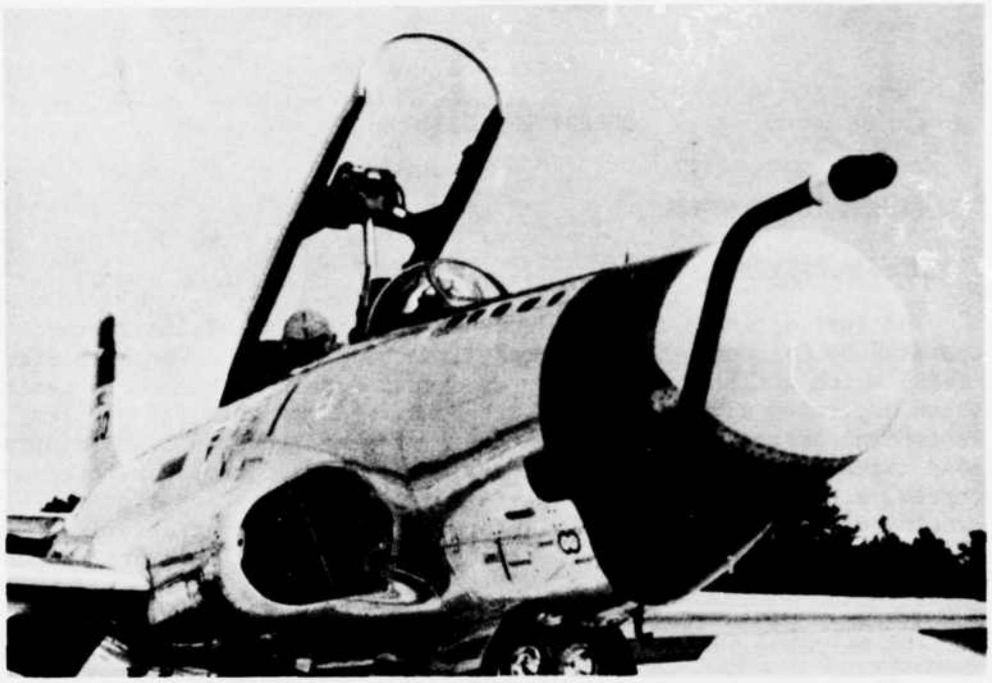


Figure 2-1 NT-33 Variable Stability Research Aircraft

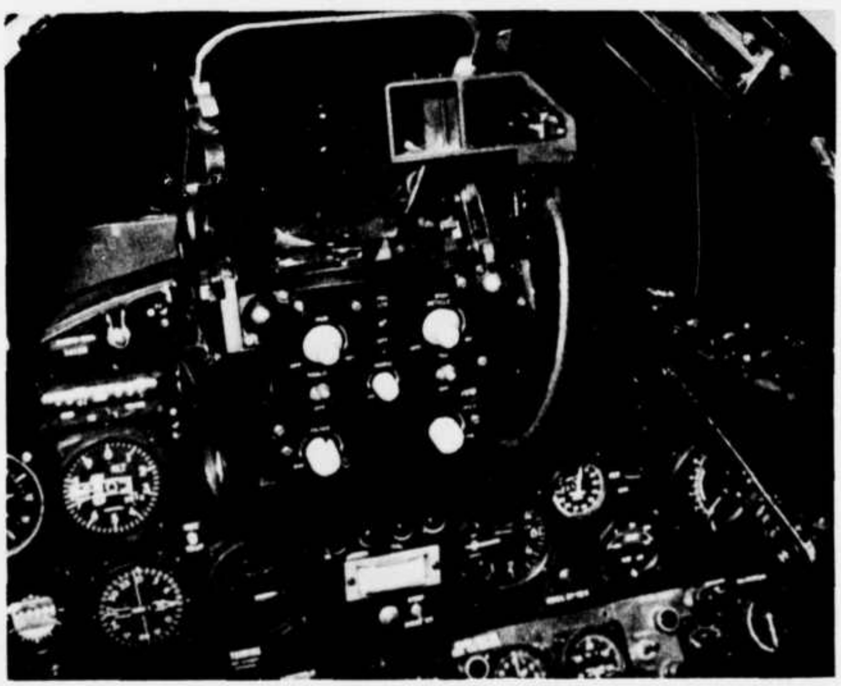


Figure 2-2 Evaluation Pilot Cockpit in NT-33 Aircraft

tracking index or "pipper." The HUD and associated digital computers were also programmed to produce a compensatory target tracking task for evaluations in this program. Details of these tasks are presented in Section 2.4 and Appendix D.

2.1.3 Support Aircraft

T-33 and F-101 aircraft from the 107th Fighter Interceptor Group (New York Air National Guard) and a T-2 aircraft from the Naval Air Development Center were used as targets for the air-to-air gun tracking and formation evaluation tasks discussed in Section 2.4. Naval Air Test Center A-3 and C-130 tanker aircraft were used during the air-to-air refueling evaluations.

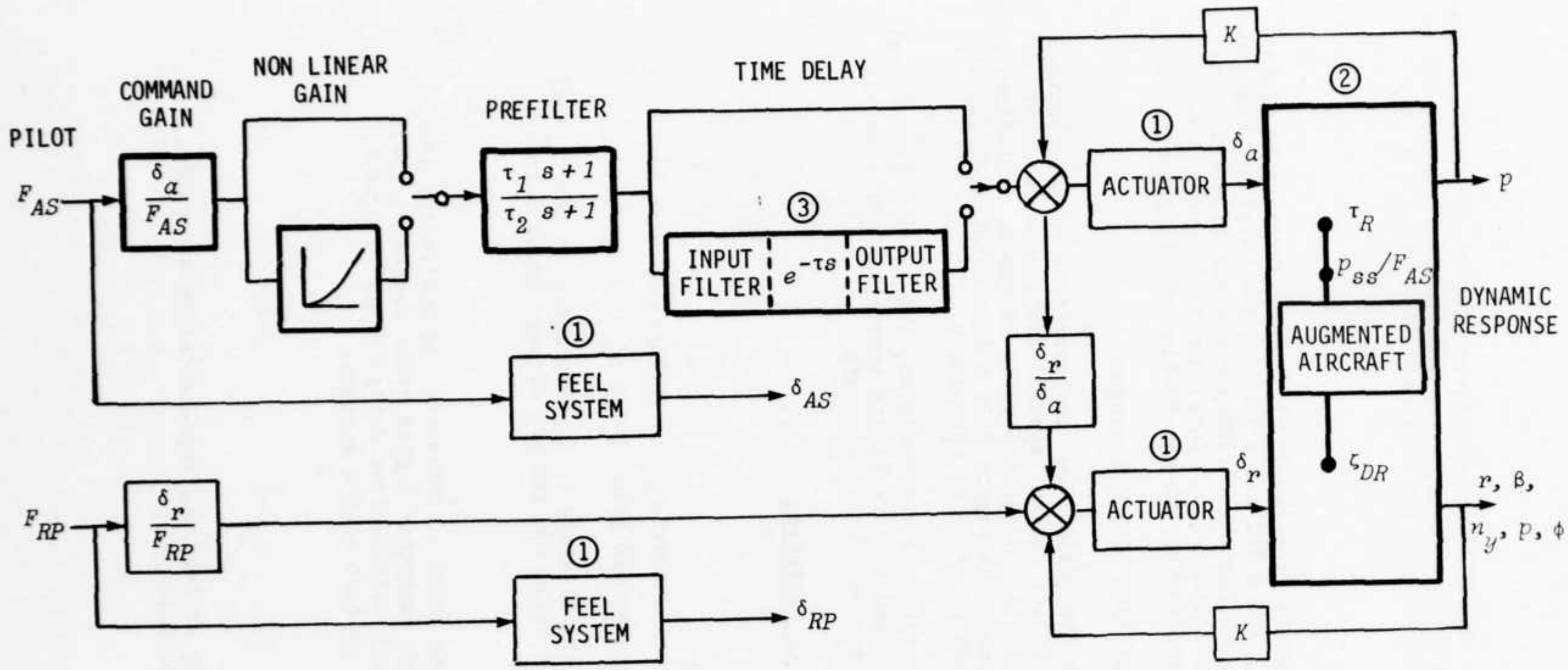
2.2 LATERAL-DIRECTIONAL FLIGHT CONTROL SYSTEM

For this experiment the evaluation configurations were mechanized using the NT-33A variable stability system, special electronic circuits, and a special digital time delay circuit. A block diagram of the lateral-directional flight control system is presented in Figure 2-3; a more detailed discussion of the simulation mechanization is given in Appendix I.

To satisfy the objectives of this program, the lateral-directional flight control system was designed to investigate several characteristics typically found in highly augmented fighter aircraft.

2.2.1 Experiment Controlled Variables

- τ_R, $L'_{F_{AS}}$
  - high roll damping (short τ_R) in combination with the necessary high command gains (high $L'_{F_{AS}}$) to achieve satisfactory steady-state roll performance is the typical modern fighter situation and was of particular interest.
- $e^{-\tau_E s}$
  - equivalent time delay to represent the equivalent delay effects of high frequency higher order control system elements or pure digital time delays found in typical modern flight control system designs.
- $\dfrac{\tau_1 s+1}{\tau_2 s+1}$
  - first order lag or lead/lag representative of typical command path prefilters.



NOTES:

① See Appendix G for details.

② Mechanization details given in Appendix I.

③ Added time delay varied by incremental values of pure transport delay; Total delay due to this circuit is approximated by equivalent time delay, $e^{-\tau_E s}$ (see Appendix G).

Figure 2-3: LATERAL-DIRECTIONAL FLIGHT CONTROL SYSTEM BLOCK DIAGRAM

- Nonlinear Command Gain
  - typically used in an attempt to satisfy conflicting initial ($\dot{p}_{max}$) and final response (p_{ss}/F_{AS}) requirements.

- ζ_{DR}
  - with the advent of full authority augmentation systems, much higher values of ζ_{DR} are achievable and, indeed, are typical of modern designs. A secondary goal of this experiment was to investigate the effects of high ζ_{DR}.

As discussed in Section 2.3, the selected evaluation configurations were specific combinations of these primary experiment parameters and the other fixed simulation characteristics. The experiment controlled variables and the range of values tested for each flight phase are summarized in Table 2-1. A complete summary of the configuration characteristics is contained in Appendix G. Values for the fixed characteristics and the ranges for the variable elements of the lateral-directional control system were selected as appropriate for modern high performance fighter aircraft engaged in Flight Phase A and C tasks.

TABLE 2-1

LATERAL-DIRECTIONAL EXPERIMENT VARIABLES

VARIABLE	FLIGHT PHASE CATEGORY	NOMINAL VALUES TESTED	COMMENTS
τ_R (Roll Damping)	A	• .15, .25, .45, .8 sec.	- Simulation minimum τ_R is .15 sec. - MIL-F-8785C Level 1 maximum τ_R is 1.0 sec.
	C	• .2, .25, .45, .8 sec.	
p_{ss}/F_{AS} (Related to Command Gain $L'_{F_{AS}}$)	A	• 10, 18, 25 deg/sec/lb	- Spans approximate MIL-8785C Level 1 limits.
	C	• 5, 10 deg/sec/lb	- Spans approximate MIL-8785C Level 1 limits.
$e^{-\tau_E s}$ (Equivalent Time Delay)	A,C	• 0, 55, 75, 105, 125, 225 ms	- See Appendix G for details.

TABLE 2-1 (concluded)

VARIABLE	FLIGHT PHASE CATEGORY	NOMINAL VALUES TESTED	COMMENTS
$\frac{\tau_1 s + 1}{\tau_2 s + 1}$ (Prefilter)	A,C	• Lag ($\tau_1 = 0$): $\tau_2 = .025$, .10, .17, .30, .5, 1.0 sec • Lead/Lag: $\tau_1 = .05$, $\tau_2 = .025$ • Lag/Lead: $\tau_1 = .15$, $\tau_2 = .4$	- Nominal configurations all included .025 sec. (40 rps) prefilter. - Used with $\tau_R = 0.45$ and $\tau_R = 0.80$ cases. - Used with $\tau_R = 0.15$ cases.
Nonlinear Command Gain	A,C	• 4 Types	- See Appendix G for description.
ζ_{DR} (Dutch Roll Damping Ratio)	A C	• .35, .8 • .35, .6	- Nominal configurations included lower ζ_{DR} value. - See Appendix I for mechanization details.

2.3 EXPERIMENT CONFIGURATIONS

Experiment configurations were formed by choosing combinations of:

- τ_R and $L'_{F_{AS}}$
- τ_1, τ_2 (lateral prefilter characteristics)
- τ_E (lateral equivalent time delay added to control system)
- Lateral command gain shape (linear or nonlinear)
- ζ_{DR}

The complete lateral-directional characteristics for an evaluation configuration consists of a combination of these elements as illustrated in Figure 2-3.

Other pertinent constant configuration characteristics including the complete lateral-directional transfer functions are summarized in Appendix G.

2.3.1 Baseline Lateral-Directional Configurations

The first step before the effects of the major control system elements of interest — time delay and prefilter lag — could be properly evaluated was to evaluate a baseline set of configurations with different combinations of τ_R and $L'_{F_{AS}}$. These baseline configurations were all flown with a 40 rad/sec lag prefilter because of VSS lateral noise considerations with force commands (see Appendix I for details). In effect, these configurations can be considered to be without significant control system dynamics.

The baseline configurations are presented in Figure 2-4 on a plot of τ_R versus $L'_{F_{AS}}$. Configurations were selected to lie along lines of constant p_{ss}/F_{AS}: 5, 10, 18 and 25 deg/sec/lb as shown.

Two digit numbers are used to identify each baseline configuration: first digit indicates level of roll damping (higher numbers: higher damping - smaller τ_R), second digit indicates level of p_{ss}/F_{AS} (higher numbers: higher steady-state roll rates per pound) and therefore lateral command gain $L'_{F_{AS}}$, for a given τ_R value. The prefix "L" designates configurations evaluated in the approach and landing task. For example,

Configuration 3-4: $\tau_R = 0.25$ sec

$p_{ss}/F_{AS} = 25$ deg/sec/lb

2.3.2 Other Lateral-Directional Configurations and Identification System

During the remainder of the experiment the effects of time delay, prefilter dynamics, nonlinear command gain and Dutch roll damping ratio on the baseline $\tau_R/L'_{F_{AS}}$ combinations were evaluated. The primary emphasis in the experiment was the investigation of the effects of time delay and prefilter lag for the various Flight Phase Category A and C tasks described in Section 3. First, the effects of the experiment variables were evaluated individually and then, to the extent possible in the context of this experiment, in combination.

Each configuration represents a particular combination of the experiment variables as previously discussed and illustrated in Figure 2-3. The creation of an experiment configuration in building block fashion is illustrated in Figure 2-5 which serves as the guide for the configuration identification system used in this report. The specific configurations tested are listed in Tables A-1 and A-2 in Appendix A.

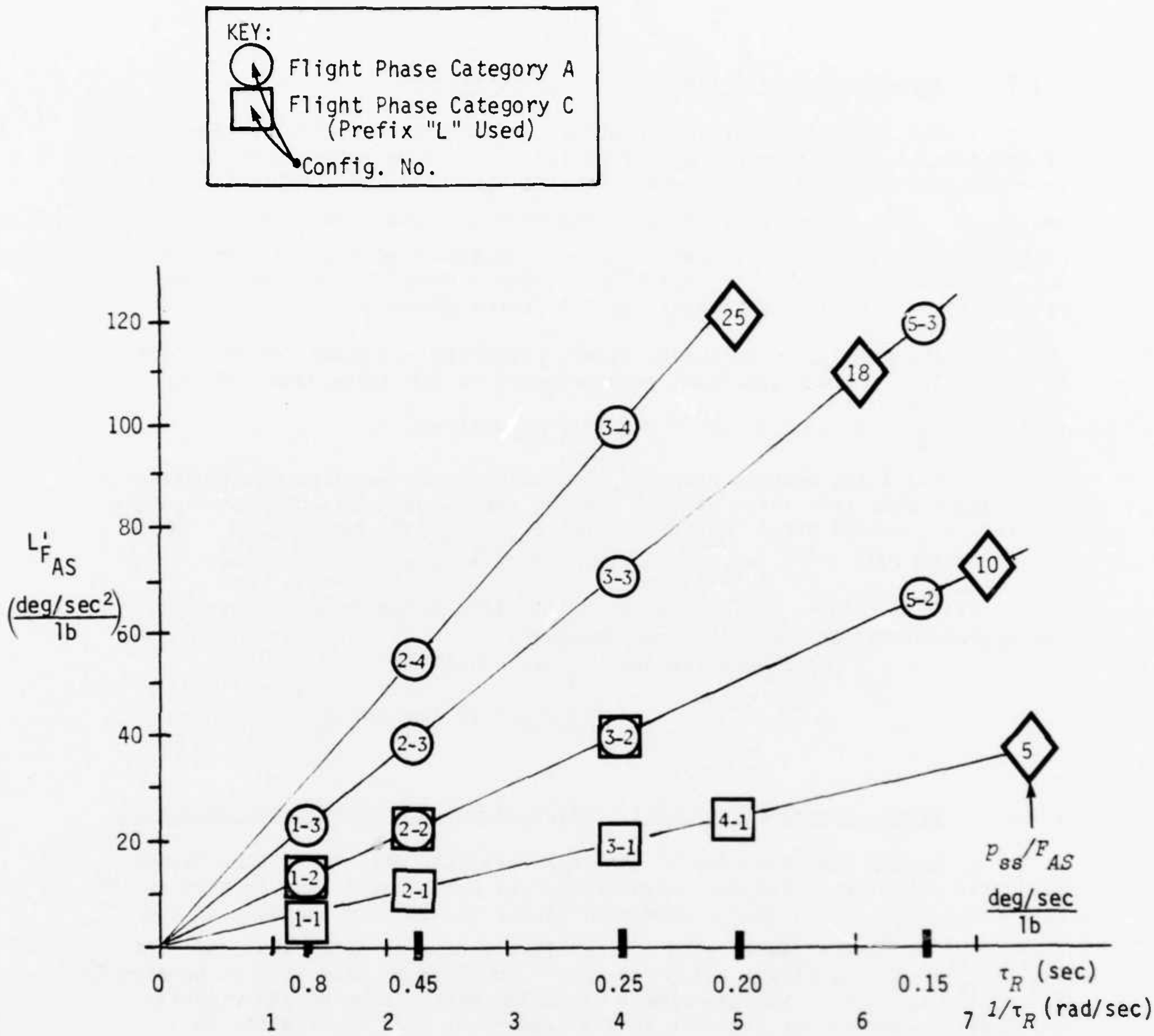


Figure 2-4: BASELINE CONFIGURATIONS (ALL INCLUDE AN ACTUATOR AND PREFILTER WITH τ_2 = .025 SEC)

BASELINE		
IDENT.	τ_R	p_{ss}/F_{AS}
(L)* 1-1	.8	5
2-1	.45	5
3-1	.25	5
4-1	.20	5
1-2	.8	10
2-2	.45	10
3-2	.25	10
5-2	.15	10
1-3	.8	18
2-3	.45	18
3-3	.25	18
5-3	.15	18
2-4	.45	25
3-4	.25	25

* Prefix for Category C task

EQUIVALENT TIME DELAY, τ_E (msec)*	
NOMINAL	0
T 0	55
T 1	75
T 2	105
T 3	125
T 4	225

* τ_E Added to Roll Control System

PREFILTER $\frac{\tau_1 s + 1}{\tau_2 s + 1}$		
	τ_1	τ_2
NOMINAL	0	.025
F 1	0	.10
F 2	0	.17
F 3	0	.30
F 4	0	.50
F 5	0	1.0
F 6	.15	.40
F 7	.05	.025

NONLINEAR GAIN	
NOMINAL	LINEAR
N 1	DIGITAC
N 2	2 BREAK POINT (25)
N 3	" (18)
N 4	" (10)

D.R. DAMPING RATIO (ζ_{DR})		
NOMINAL	∿	0.35
D 1	∿	0.6
D 2	∿	0.8

EXAMPLES

1.) 5-2 T1 F1: τ_R = .15 sec, p_{ss}/F_{AS} = 10 deg/sec/lb
τ_E = 75 ms, Prefilter τ_2 = .1 sec
Linear, $\zeta_{DR} \sim .35$

2.) L 1-2 F2: Landing Task, τ_R = .8 sec, p_{ss}/F_{AS} = 10 deg/sec/lb
τ_E = 0, Prefilter τ_2 = .17 sec
Linear, $\zeta_{DR} \sim .35$

NOTE: Nominal values assumed unless noted otherwise.

Figure 2-5: EXPERIMENT CONFIGURATIONS

2.4 EVALUATION TASKS

Flying qualities evaluations are dependent on configuration characteristics and the task being performed. It has been shown that evaluations of highly augmented aircraft with significant control system dynamics are particularly sensitive to task. For example, the flying qualities of aircraft with large time delays in the longitudinal flight control system can degrade dramatically during the last 50 ft prior to landing when a precision landing is the task (see Reference 8). This "flying qualities cliff" may not be exposed if the task constraints are relaxed; if, for example, no landing is required or the precision landing goal is removed. Also, if the visual environment cues are sufficiently inhibited (as in a ground-based simulation) such that the pilot is not properly stressed and his "gain" does not approach real task values, the serious flying qualities deficiencies may not be observed.

For this experiment, which is primarily concerned with the effects of representative higher order lateral control system elements on lateral-directional fighter flying qualities, it was therefore imperative that realistic tasks be used for the evaluations. Since the tests were performed in the NT-33A aircraft, the visual environment was the "perfect" real world and no compromises existed in that area. Within the constraints of flight safety, every effort was therefore made to make the tasks realistic. Tracking was done using a real target; refueling included all the ingredients of the real task except the actual transfer of fuel. Close formation maneuvers were on the wing of the target aircraft; finally, the approach and landing tasks included precision actual touchdowns. In addition, realistic HUD tracking tasks were included to evaluate the validity of HUD evaluation tasks. In every case, tasks were intended to direct the pilot's attention to the evaluation of lateral flying qualities.

1) <u>Flight Phase Category A Tasks</u>

- Close Formation Flying
- Air-to-Air Gun Tracking
- Air-to-Air Refueling
- HUD Bank Angle Tracking
- HUD Heading Tracking

2) <u>Flight Phase Category C Tasks</u>

- Instrument Landing System Approach and Visual Landing
- Visual Landing
- HUD Bank Angle and Heading Tracking

A detailed description of these evaluation tasks and the associated performance standards is presented in Appendix D. During the course of the experiment, modifications were made to some of the tasks in accordance with the evaluation results as discussed in the same appendix.

Section 3

CONDUCT OF THE EXPERIMENT

3.1 SIMULATION SITUATION

For this program, the simulated aircraft was defined as a typical modern, single-seat, fighter aircraft (Class IV). Where appropriate, such as during simulated instrument tasks, the pilot was required to extrapolate to this fighter aircraft environment which would include realistic additional cockpit duties.

The simulation guidelines given to the evaluation pilot are referenced below.

- Modern high performance fighter/attack aircraft
- Close formation flying
- Air combat maneuvering
  - Fine gun tracking
  - Initial acquisition of tracking solution
- Air-to-air refueling
- ILS approach in instrument conditions
- Visual approach and landing with/without
  - turbulence
  - crosswinds
  - offsets at decision height
- Evaluate lateral-directional flying qualities. Consider task performance and pilot compensation.
- Evaluation of lateral flying qualities is primary. Use of rudder is allowed if necessary, or if rudder significantly improves task performance/reduces pilot compensation. Otherwise, use of rudder should be kept to a minimum.

Since inclusion of wind and turbulence as controlled variables was beyond the scope of the program, flights were conducted in a wide range of wind and turbulence; conditions encountered are considered normal for typical fighter operations. The pilots were asked to evaluate the aircraft in the condition of the day, but to comment, if appropriate, on the projected effects of different representative wind and turbulence conditions.

3.2 EVALUATION PROCEDURES

In general, complete flights were devoted to either Flight Phase Category A or Category C tasks. Configurations were always flown in random order and the evaluation pilot had no prior knowledge of the configurations under evaluation. An average of approximately 5 evaluations were flown on each flight. A complete summary of the program evaluation sequence is given in Table B-1 in Appendix B. Air refueling evaluation missions were flown from Naval Air Station Patuxent River; the remainder of the flights originated from the Calspan Flight Research Facility in Buffalo. ILS and landing tasks were performed at Niagara Falls International Airport 20 miles from Buffalo.

The details of each evaluation task are presented in Appendix D; the evaluation sequence for each task was as follows:

- Formation and Gun Tracking (TR):

  Take off and climb to 10,000 ft MSL/280 KIAS
  Join on target aircraft
  Set up first evaluation
  E.P. (Evaluation Pilot) performs close formation task
  E.P. performs air-to-air gun tracking tasks
  NT-33A assumes formation lead
  E.P. and S.P. (Safety Pilot) record pilot comments and ratings
  Take necessary calibration records
  E.P. performs short HUD bank angle and heading tracking tasks
  Target assumes formation lead
  Repeat evaluation sequence as required.

- HUD Tracking (HUD):

  Take off and climb to 10,000 ft MSL/280 KIAS
  Set up first evaluation
  E.P. performs long bank angle tracking task
  E.P. performs long heading tracking task
  E.P. and S.P. record pilot comments and ratings
  Take necessary calibration records
  Repeat evaluation sequence as required.

- Air Refueling (AR):

  Take off and rendezvous with tanker
  Set up first evaluation
  E.P. performs air-to-air refueling task
  E.P. and S.P. record pilot comments and ratings
  Take necessary calibration records
  Repeat evaluation sequence as required.
  If circumstances allow, E.P. performs short HUD tracking tasks after each rating/comment phase.

- ILS Approach and Landing (LA):

  Take off and proceed to ILS pattern
  Set up first evaluation
  E.P. performs ILS approach/visual landing task
  E.P. and S.P. record pilot comments and ratings
  Take necessary calibration records
  E.P. performs short HUD tracking tasks
  E.P. returns to simulated IMC flight
  Repeat evaluation sequence as required.

- Visual Landing (LA):

  Take off and proceed to traffic pattern
  Set up first evaluation
  E.P. performs visual landing task
  E.P. and S.P. record pilot comments and ratings
  Take necessary calibration records
  E.P. performs short HUD tracking tasks
  Repeat evaluation sequence as required.

3.3 EXPERIMENT DATA

The primary data from the experiment take these forms:

- Pilot Ratings

  - At the completion of each evaluation, the pilot was asked to assign a pilot rating using the Cooper-Harper Rating Scale (Reference 12) as shown in Figure 3-1.

  - These ratings were assigned immediately after the completion of the evaluation tasks before making any detailed pilot comments; a review of the initial rating was a part of the comment card reproduced in this section.

  - In addition to the evaluation pilot rating, the safety pilot assigned a pilot rating before the evaluation pilot gave his rating. This additional rating can be used to increase the credibility of the evaluation pilot's rating and potentially as an aid to understanding any rating discrepancies.

- Pilot Comments

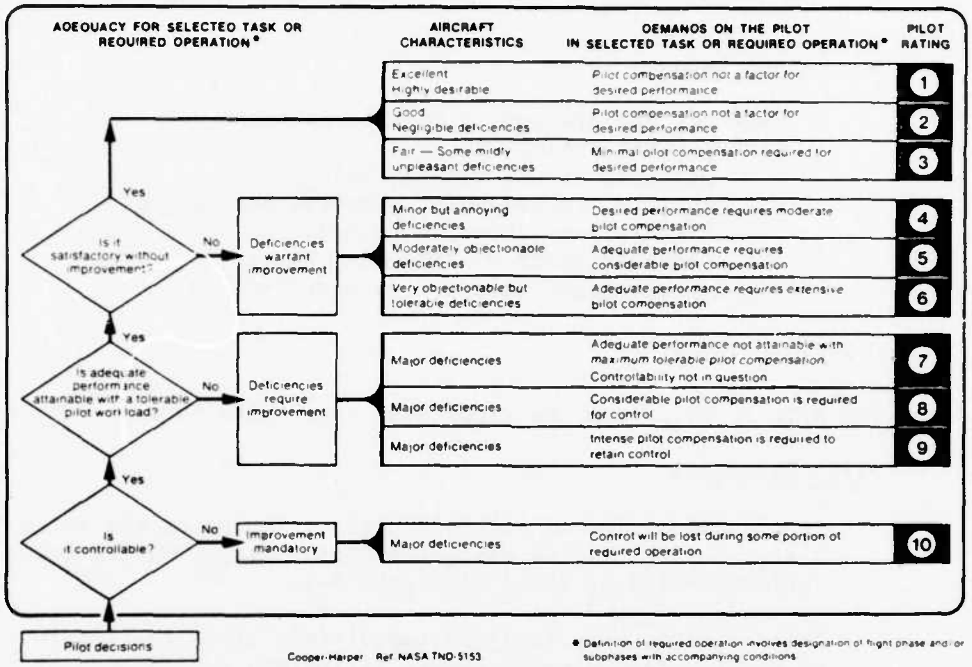
  - After the initial rating, the pilot was asked to make recorded comments on specific items listed on the Pilot Comment Card which is reproduced below as Figure 3-2.

- Task Performance Records

  - Complete records were taken of task performance during each evaluation using the NT-33A 28 channel digital magnetic tape recorder.

  - These records included complete records of the HUD tracking task performance; both the input commands to the pilot, the error signal created and his response were recorded.

HANDLING QUALITIES RATING SCALE



DEFINITIONS FROM TN-D-5153

COMPENSATION

The measure of additional pilot effort and attention required to maintain a given level of performance in the face of deficient vehicle characteristics.

HANDLING QUALITIES

Those qualities or characteristics of an aircraft that govern the ease and precision with which a pilot is able to perform the tasks required in support of an aircraft role.

MISSION

The composite of pilot-vehicle functions that must be performed to fulfill operational requirements. May be specified for a role, complete flight, flight phase, or flight subphase.

PERFORMANCE

The precision of control with respect to aircraft movement that a pilot is able to achieve in performing a task. (Pilot-vehicle performance is a measure of handling performance. Pilot performance is a measure of the manner or efficiency with which a pilot moves the principal controls in performing a task.)

ROLE

The function or purpose that defines the primary use of an aircraft.

TASK

The actual work assigned a pilot to be performed in completion of or as representative of a designated flight segment.

WORKLOAD

The integrated physical and mental effort required to perform a specified piloting task.

Figure 3-1: COOPER-HARPER PILOT RATING SCALE

PILOT COMMENT CARD

1. Assign overall Cooper-Harper Rating.
2. Attitude Control (as applicable)
   a. Undesirable Motions (PIO/Ratcheting)
   b. Initial vs. Final Response
   c. Predictability
   d. Precision/Accuracy vs. Aggressiveness
   e. Tracking - Fine vs. Gross
   f. Compensation Techniques (Rudder?)
3. Position Control
   a. Overshoots
   b. Precision/Accuracy vs. Aggressiveness
   c. Maneuvering Target vs. Nonmaneuvering
   d. Compensation Techniques
4. Flight Path Control (if applicable)
   a. Trimmability (Velocity Control Problem?)
   b. Precision/Accuracy (Heading, Bank Angle, Track)
   c. Instrument vs. Visual
   d. Small vs. Large Changes
5. Feel
   a. Forces
   b. Displacements
   c. Sensitivity
   d. Harmony
6. Turbulence/Crosswind Effect on Rating
   (None, Minor, Moderate or Severe)
7. Review Cooper-Harper Rating - Any Change?
   a. Rate Any Subtask if Significantly Different From Overall
8. Summary of Features Not Already Covered
9. HUD Tracking Task
   a. Similar to Primary Task?
   b. Rating (If Different From Primary Tasks)
   c. Deficiencies of HUD Task

Figure 3-2: PILOT COMMENT CARD

In addition to these data, HUD movies were taken during the various tasks, including the HUD tracking tasks, to illustrate pilot performance.

The results of the experiment are discussed in the next major sections; examples of the task performance data are given in Appendix E.

3.4 EVALUATION SUMMARY

Three qualified evaluation pilots participated in this flying qualities investigation; their backgrounds are as follows:

Pilot B - Calspan Research Pilot, limited experience as a flying qualities evaluation pilot but extensive experience as a flying qualities instructor pilot at the military Test Pilot Schools. Extensive military fighter experience including air refueling; has approximately 2500 hours in fighter aircraft.

Pilot G - U.S. Naval Test Pilot, current F-18 test pilot during evaluation period. Extensive military fighter experience including air refueling; has approximately 3500 hours in fighter aircraft.

Pilot P - Calspan Research Pilot, experienced flying qualities evaluation pilot. His 4500 flight hours include experience in a variety of fighter aircraft.

The three evaluation pilots performed a total of 214 evaluations of 118 different configurations during the program; 42 evaluation flights of approximately 1.3 hours each were flown. A summary of the flights for each pilot on the different tasks is presented below. Evaluations were distributed by pilot in approximately the same proportions as for the flights. There was approximately 20% overlap in configurations and each pilot repeated approximately 20% of his evaluations.

A complete summary of the evaluations performed is presented in Appendix B. The pilot rating results for the evaluations considered to represent valid flying qualities data are given in Appendix A. Approximately 10% of the original evaluations were rejected from the experiment data base as discussed in the appendix. Pilot comment data for all the evaluations performed are contained in Appendix C.

TABLE 3-1

EVALUATION FLIGHTS

Task	Pilot B	Pilot G	Pilot P	Total
TR	15	2	4	21
AR	3	4	-	7
HUD	2	-	2	4
LA	3	-	7	10
TOTAL	23	6	13	42

Section 4

EXPERIMENT RESULTS

The purpose of this section is to present the pilot rating results of the experiment which, along with the pilot comment data, form the data base for the more detailed discussion and analysis of the results presented in Sections 5 and 6. A summary of all the data discussed in this section is presented in Appendix A, Tables A-1 and A-2. As explained in Appendix A not all the evaluations performed are included in the data base. The evaluation sequence given in Appendix B and the pilot comment summaries contained in Appendix C include all the evaluations performed; the rationale for the exclusion of particular configurations is also presented.

The major thrust of this experiment was to gather a lateral flying qualities data base applicable to highly augmented fighter aircraft with significant control system dynamics in the form of time delays and lags. Secondary, sub-experiments of an exploratory nature were also performed to investigate the effects of special filtering (lead/lag, lag/lead), nonlinear command gain shaping and high Dutch roll damping. The presentation of the results of this multi-dimensional experiment in an orderly fashion is not easy. To assist in this effort the results of the gun tracking (TR) and air refueling tasks (AR) are combined and the HUD only evaluations are not included directly in the data base. The justification for this step is given in the next two subsections.

4.1 COMPARISON OF TRACKING (TR) AND AIR REFUELING (AR) RESULTS

The averaged pilot ratings for the two tasks are compared in Figure 4-1. Use of averaged pilot ratings is the method by which trends of the data can be seen most clearly. In addition, the fact that the evaluation pilots were fortuitously representative of a wide, but realistic, range of pilot task aggressiveness makes the averaging process more credible. In the context of the typical inter and intra pilot ratings scatter in the experiment (see Section 5 for details), the results for the two tasks are similar. The TR and AR pilot rating results are therefore considered together in this report for convenience in presenting the results. In analyzing the data, however, the pilot comments and ratings cannot be viewed separately nor can the task differences (Appendix D) be disregarded.

The majority of the large deviations from perfect correlation are ratings involving Pilot G who tended to be considerably more aggressive in the refueling tasks and tended to give significantly higher pilot ratings than Pilot B. Pilot B could be viewed as the most representative pilot in terms of his approach to the tasks. In addition, his use of the rating scale and comment card was more thorough.

4.2 COMPARISON OF TRACKING AND REFUELING (TR + AR) RESULTS WITH HUD-ONLY RESULTS

The averaged pilot ratings for these tasks are compared in Figure 4-2. HUD-only results are for the evaluations in which only HUD tracking tasks were

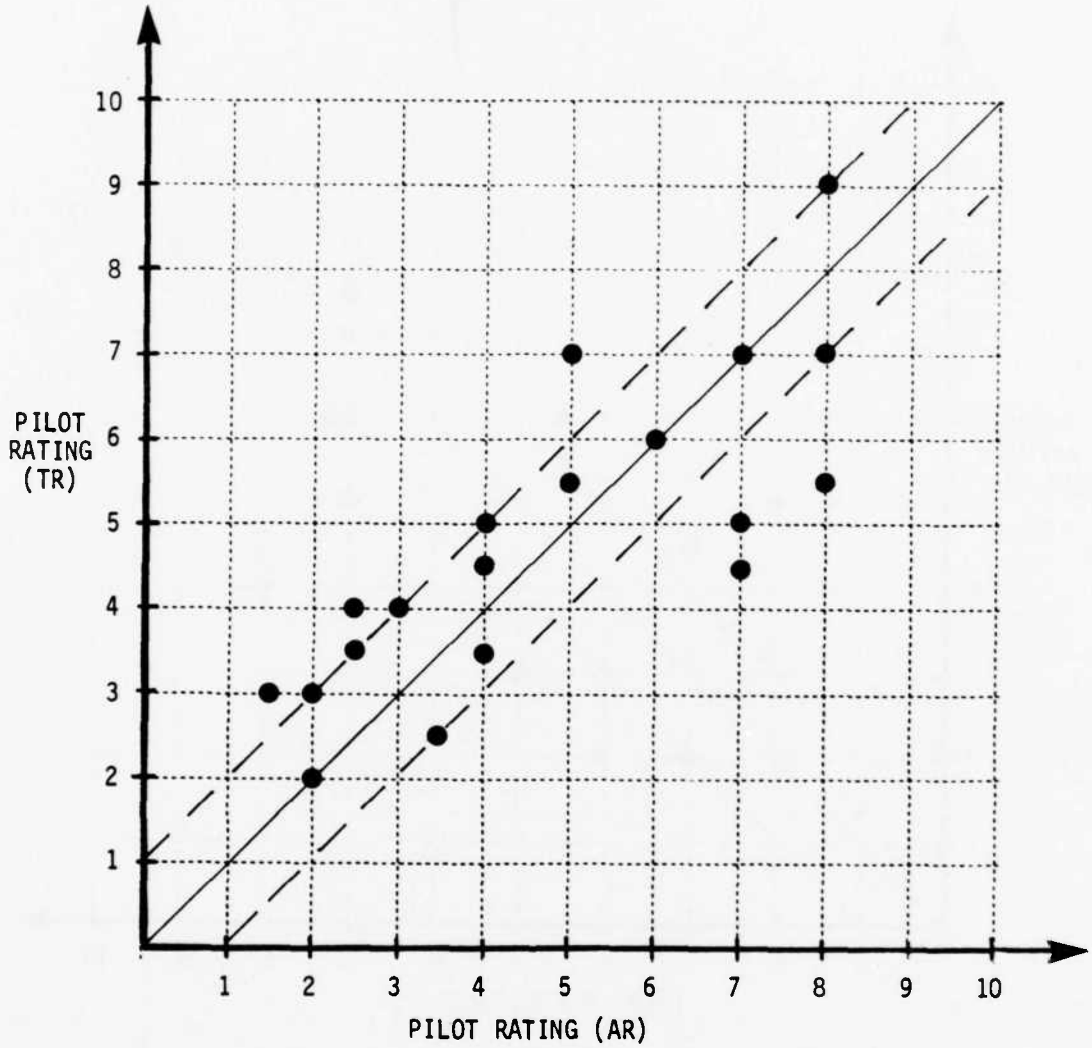


Figure 4-1: COMPARISON OF AVERAGED PILOT RATINGS FOR GUN TRACKING (TR) AND AIR REFUELING (AR) TASKS

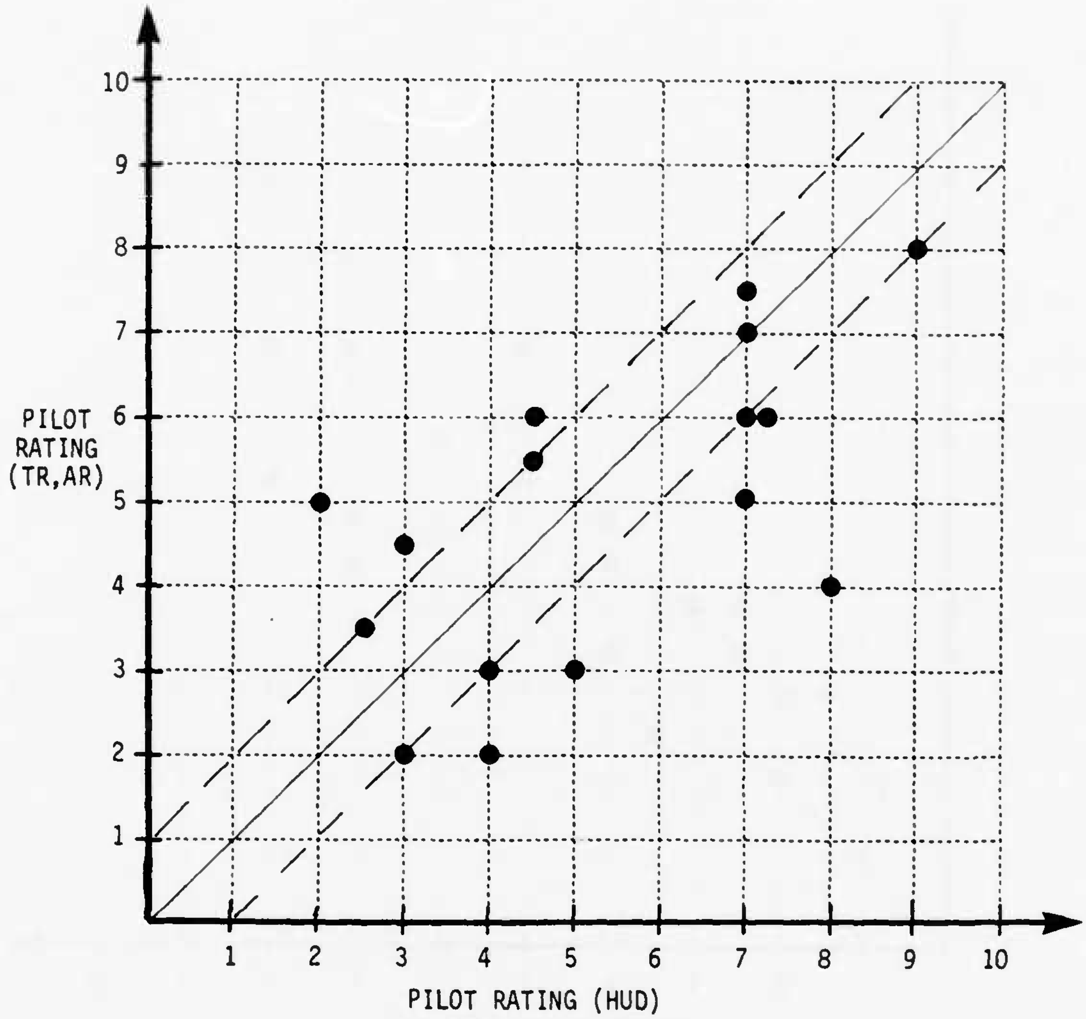


Figure 4-2: COMPARISON OF AVERAGED PILOT RATINGS FOR GUN TRACKING (TR) AND AIR REFUELING (AR) TASKS WITH HUD TRACKING TASK DATA

evaluated. Abbreviated lengths of the HUD tracking tasks were generally performed after the tracking (TR) evaluations, but separate ratings were not part of the evaluation scenario. Special comments were given where appropriate and in some cases estimated ratings (see comment summaries in Appendix C).

Although the scatter in the data is larger than for the other task comparisons, in the context of the inter and intra pilot rating variability shown in this experiment, the results for the HUD-only evaluations are representative of those given for the actual tasks. Further support for this generalization can be found in the pilot comments for the actual tracking task when HUD tasks were also included. In the majority of cases the pilots indicated that the observations from the HUD task were similar to those for the real tracking task.

These findings support the premise that HUD-displayed tasks can evoke the same flying qualities "answers" as evaluation tasks with target aircraft. This equivalence is, however, subject to the contraints that the pilot's "sense" of the task is properly calibrated and the displayed tasks are correctly designed. Specifically, the HUD-only evaluations were interspersed among the target evaluations tasks; the pilots were tuned to the task and fully aware of the task performance and aggressiveness levels that are realistic for the actual, target tasks. Also, the displayed tasks were adjusted, although not fine tuned, initially so the dynamics of the displayed task were compatable to the targeted task in terms of the magnitudes and frequencies that the attitude commands changed. Showing the equivalence of the HUD tasks and the targeted tasks for flying qualities evaluation achieves a sub-objective of this program.

These HUD-only data are not, however, used as part of the experiment data base except for guidance when no other data exists. The multitude of data from the targeted evaluations permits the convenience of omitting the HUD-only data for clarity.

4.3 BASELINE PILOT RATING DATA, TR + AR TASKS

The baseline configuration pilot rating data for the tracking and refueling tasks for all the evaluation pilots are given in Figure 4-3. Note that all baseline configurations include a prefilter (with $\tau_2 = .025$) and actuator as explained in Section 2. Also presented are the averaged pilot ratings for these tasks. Estimated $PR = 3.5$ and 6.5 boundaries are included on the averaged data plot.

4.4 BASELINE PILOT RATING DATA, LA TASKS

The baseline configuration pilot rating data for the approach and landing tasks for all the evaluation pilots are given in Figure 4-4. Note that all baseline configurations include a prefilter (with $\tau_2 = .025\ sec$) and actuator as explained in Section 2. Also presented are the averaged pilot rating for this task. No pilot rating boundaries could realistically be estimated with the limited data set.

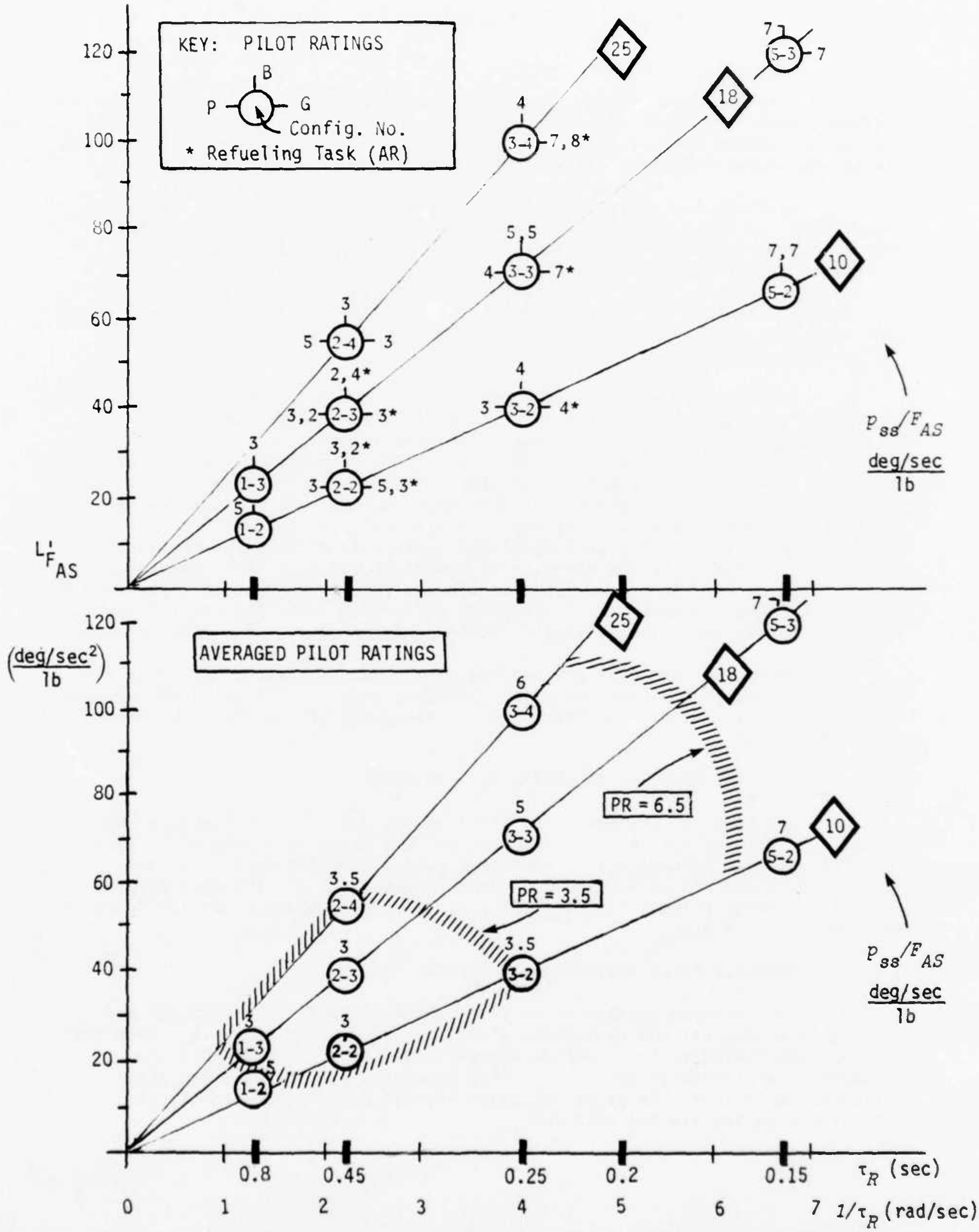


Figure 4-3: PILOT RATING DATA, BASELINE CONFIGURATIONS, GUN TRACKING (TR) AND AIR REFUELING TASKS (AR), FLIGHT PHASE CATEGORY A

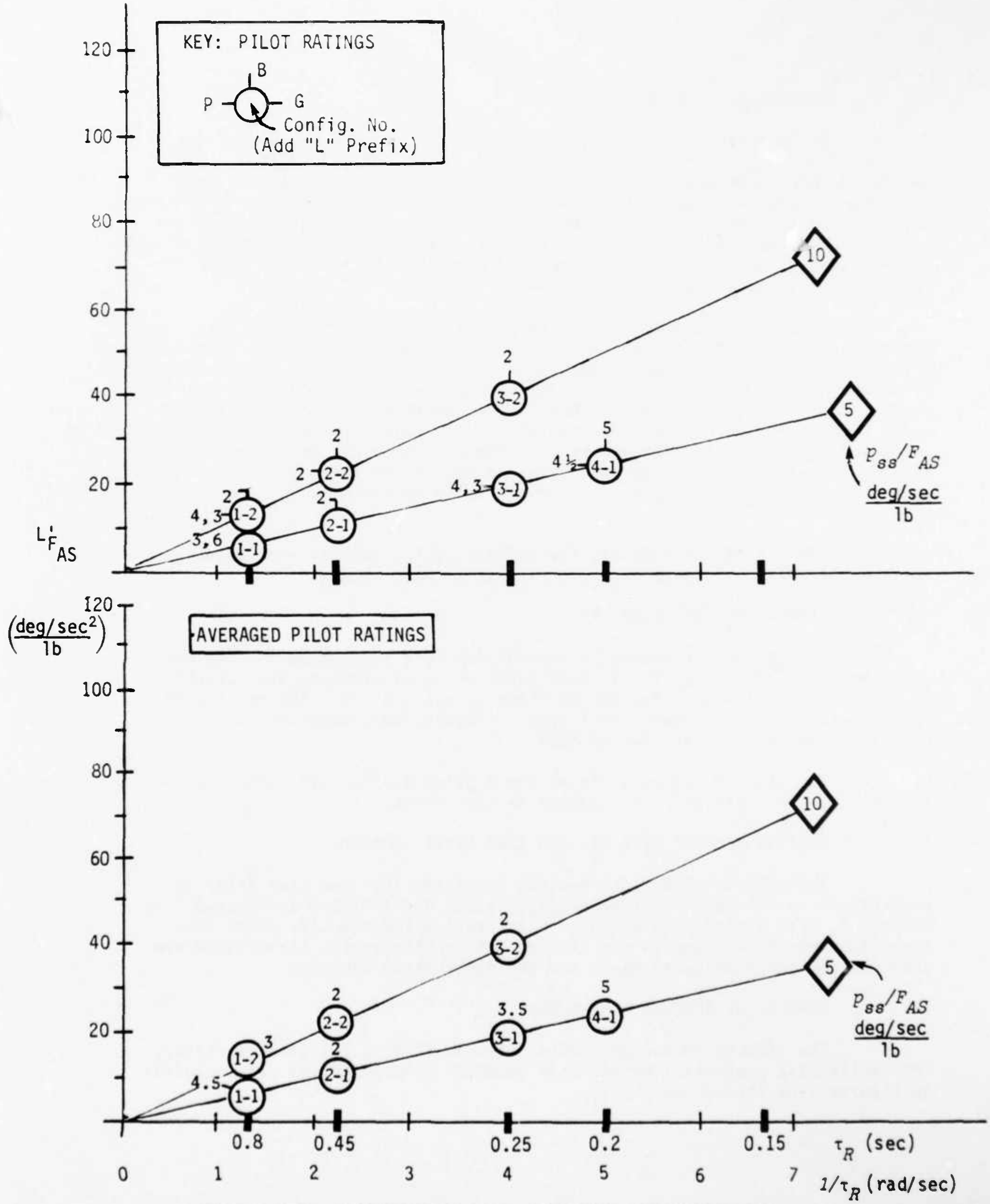


Figure 4-4: PILOT RATING DATA, BASELINE CONFIGURATIONS, LANDING TASK (LA), FLIGHT PHASE CATEGORY C

4.5 EFFECTS OF TIME DELAY

The effects of adding equivalent time delay (see Appendix G for details of delay characteristics) to selected baseline configurations are presented in Figures 4-5a through d for Flight Phase Category A (TR + AR) and Flight Phase Category C (LA) tasks. Time delay configuration identifiers are shown on the bottom axis of each set of plots. Additional analyses are required to determine the total equivalent time delay of the experiment flight control system including the prefilter and actuator and also, the resulting equivalent roll mode time constant.

Equivalent time delay derived by the frequency domain matching technique advocated by the McDonnell-Douglas Corporation ("McFit") has been used to measure the added time delay because the time delay circuit of the NT-33 consists of a pure digital delay plus two analog filters which contribute "equivalent" delay. Equivalent time delay is therefore a convenient approximation of the added initial response delay. Nearly identical values of time delay are measured for the time delay network by time domain equivalent techniques such as that used in Section 6 ("effective" time delay) in the context of this experiment. The time delay circuit is described fully in Appendix G.

For all of the figures, the averaged pilot ratings are presented; where applicable, the range of pilot ratings is also shown.

4.6 EFFECTS OF PREFILTER LAG

The effects of adding increased prefilter lag, above the nominal .025 sec first order lag, to selected baseline configurations are presented in Figures 4-6a through d for Flight Phase Category A (TR + AR) and Flight Phase Category C (LA) tasks. Prefilter configuration identifiers are shown on the bottom axis of each set of plots.

For all the figures, the averaged pilot ratings are presented; where applicable, the range of pilot ratings is also shown.

4.7 EFFECTS OF PREFILTER LAG AND TIME DELAY COMBINED

The effects of adding specific prefilter lags and time delay in combination to selected baseline configurations are included in Figures 4-6a through c. For clarity the averaged pilot rating for the time delay alone evaluation has been added to the figure; full configuration identifiers are included for the time delay alone and the combination ratings.

4.8 EFFECTS OF SPECIAL PREFILTERS

The effects of adding special filters ("F6" a lag/lead prefilter, "F7" a lead/lag prefilter) to selected baseline configurations are included in Figures 4-5a through c.

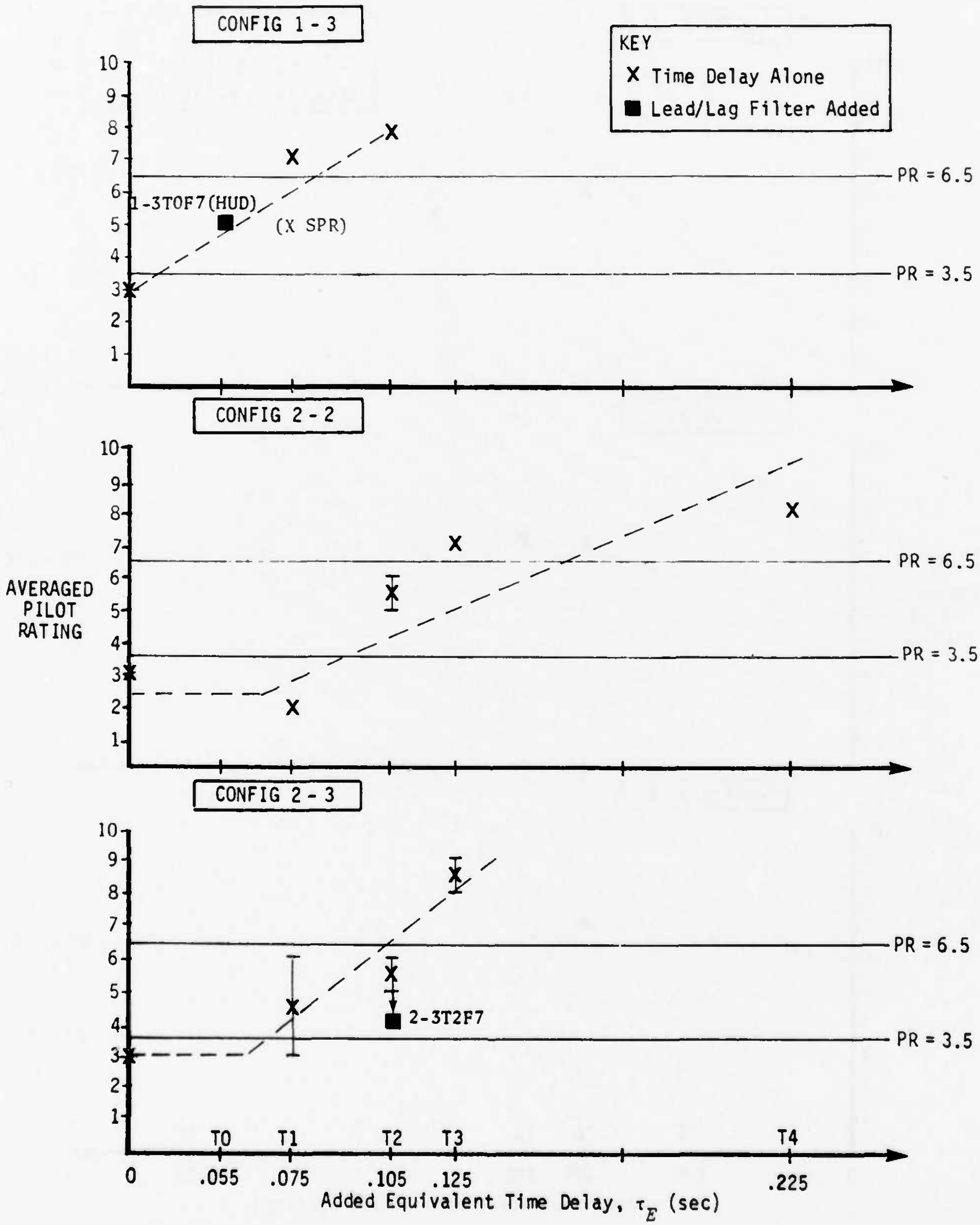


Figure 4-5a: EFFECT OF EQUIVALENT TIME DELAY AND SPECIAL PREFILTER, FLIGHT PHASE CATEGORY A TASKS (TR + AR)

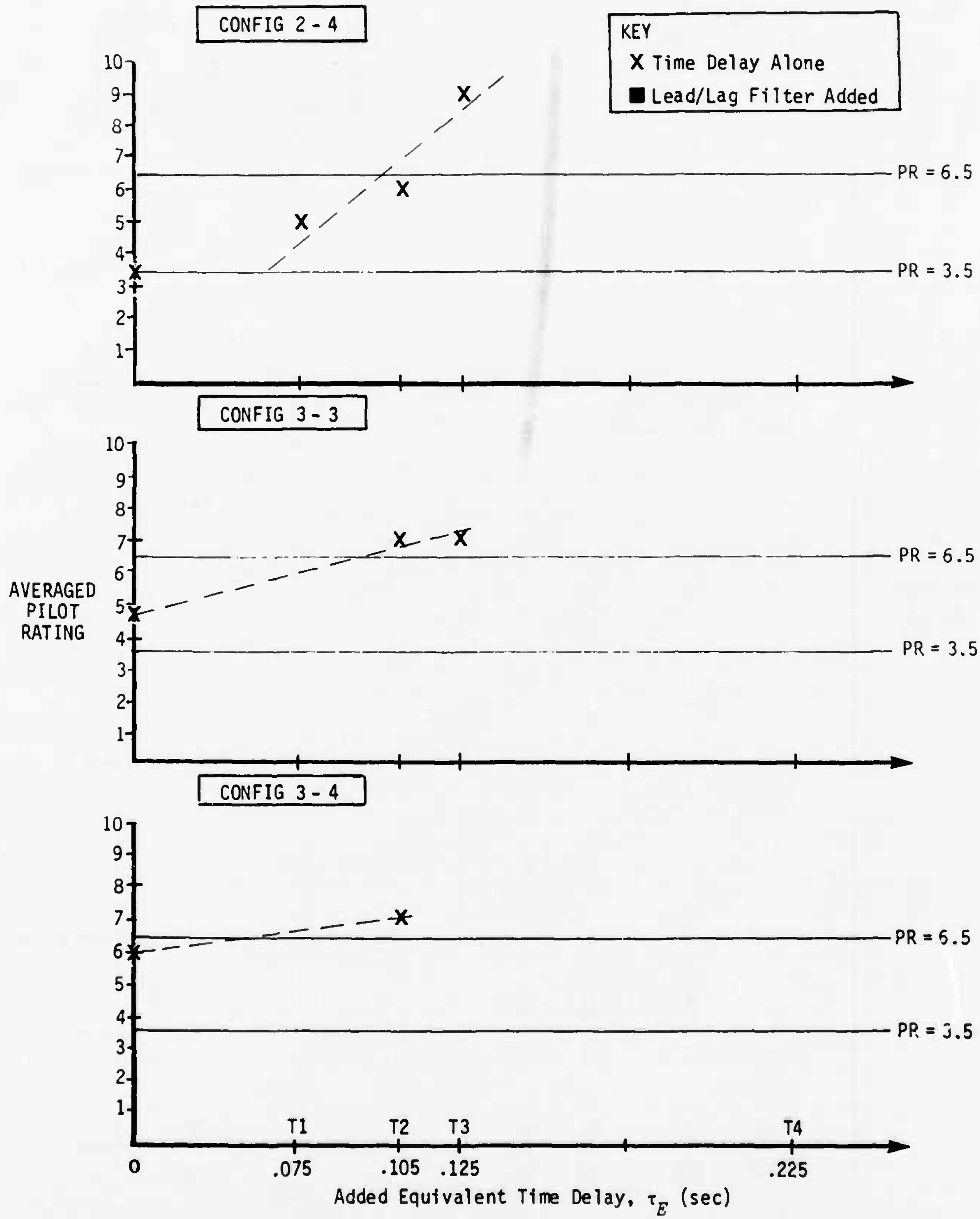


Figure 4-5b: EFFECT OF EQUIVALENT TIME DELAY AND SPECIAL PREFILTER, FLIGHT PHASE CATEGORY A TASKS (TR + AR)

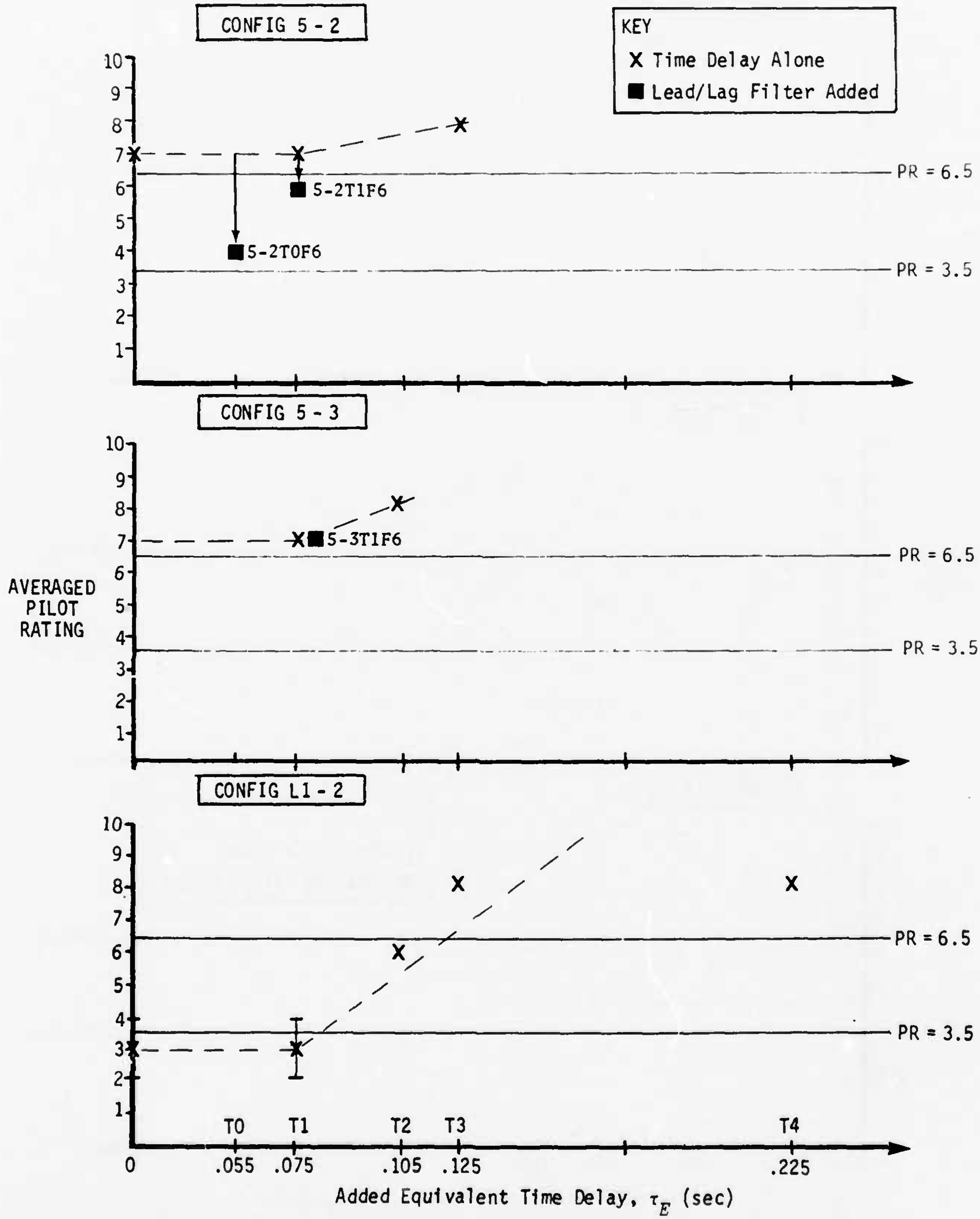


Figure 4-5c: EFFECT OF EQUIVALENT TIME DELAY AND SPECIAL PREFILTER, FLIGHT PHASE CATEGORY A (TR + AR) AND C (LA) TASKS

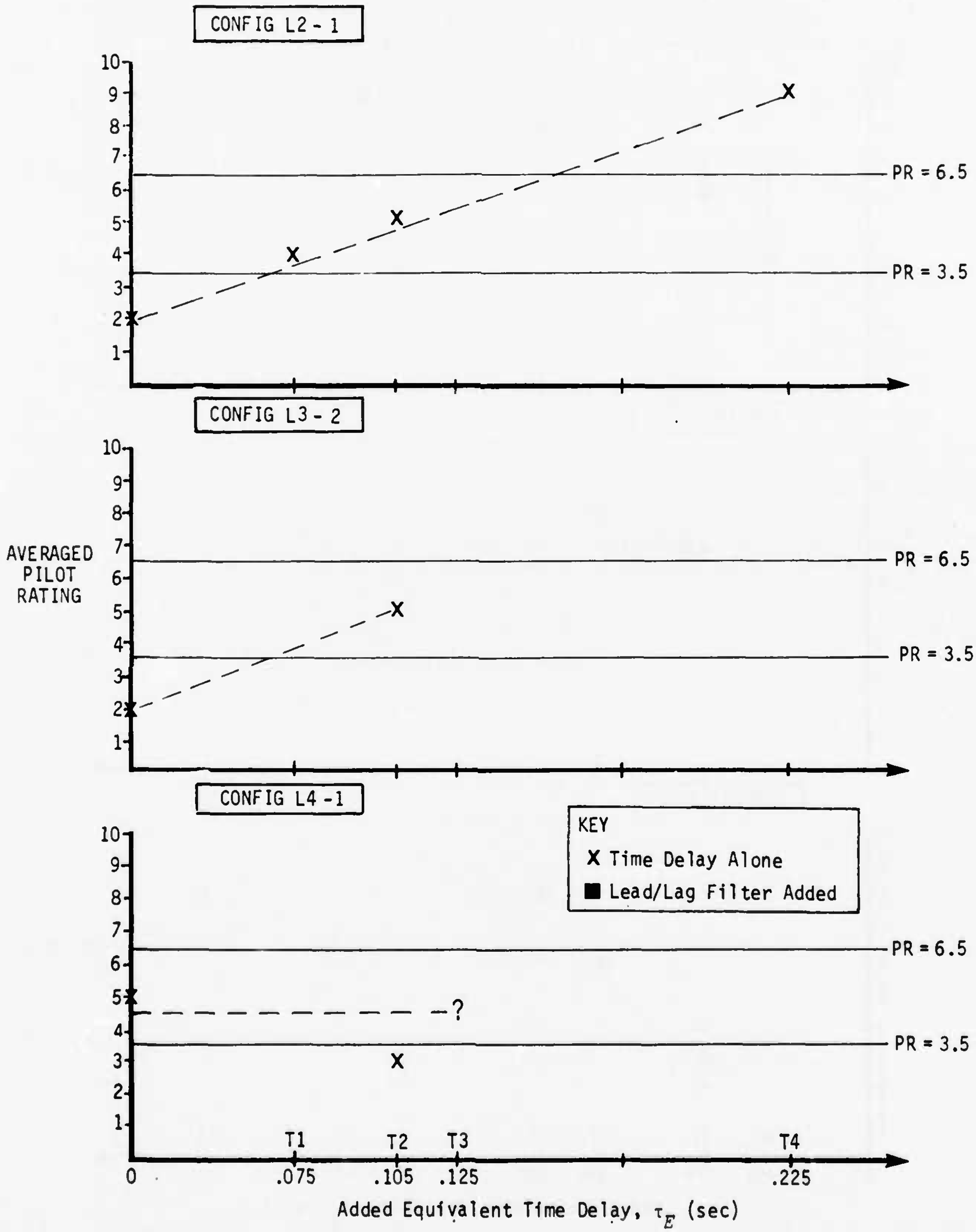


Figure 4-5d: EFFECT OF EQUIVALENT TIME DELAY AND SPECIAL PREFILTER, FLIGHT PHASE CATEGORY C (LA) TASKS

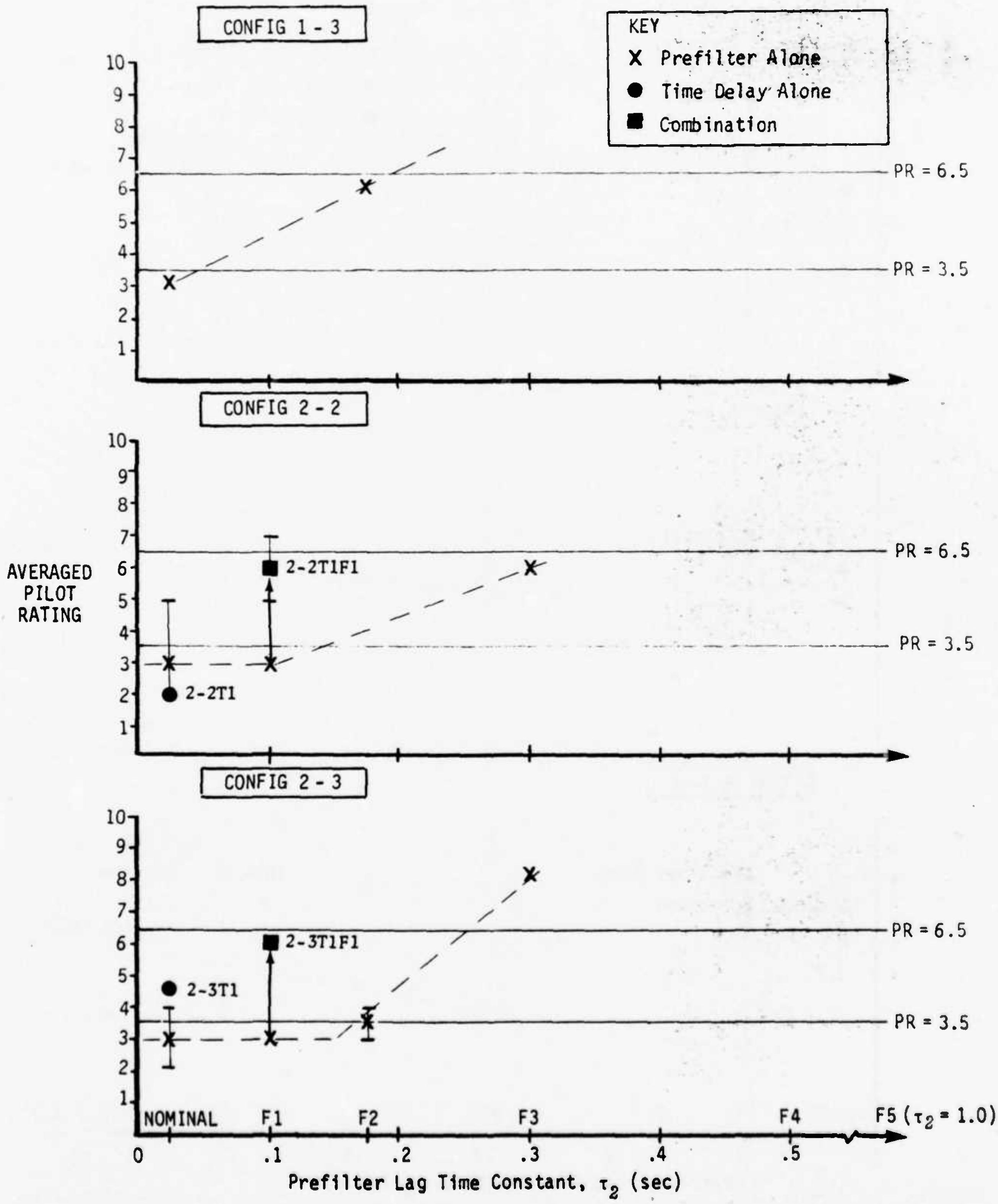


Figure 4-6a: EFFECT OF PREFILTER LAG AND COMBINATIONS WITH TIME DELAY, FLIGHT PHASE CATEGORY A TASKS (TR + AR)

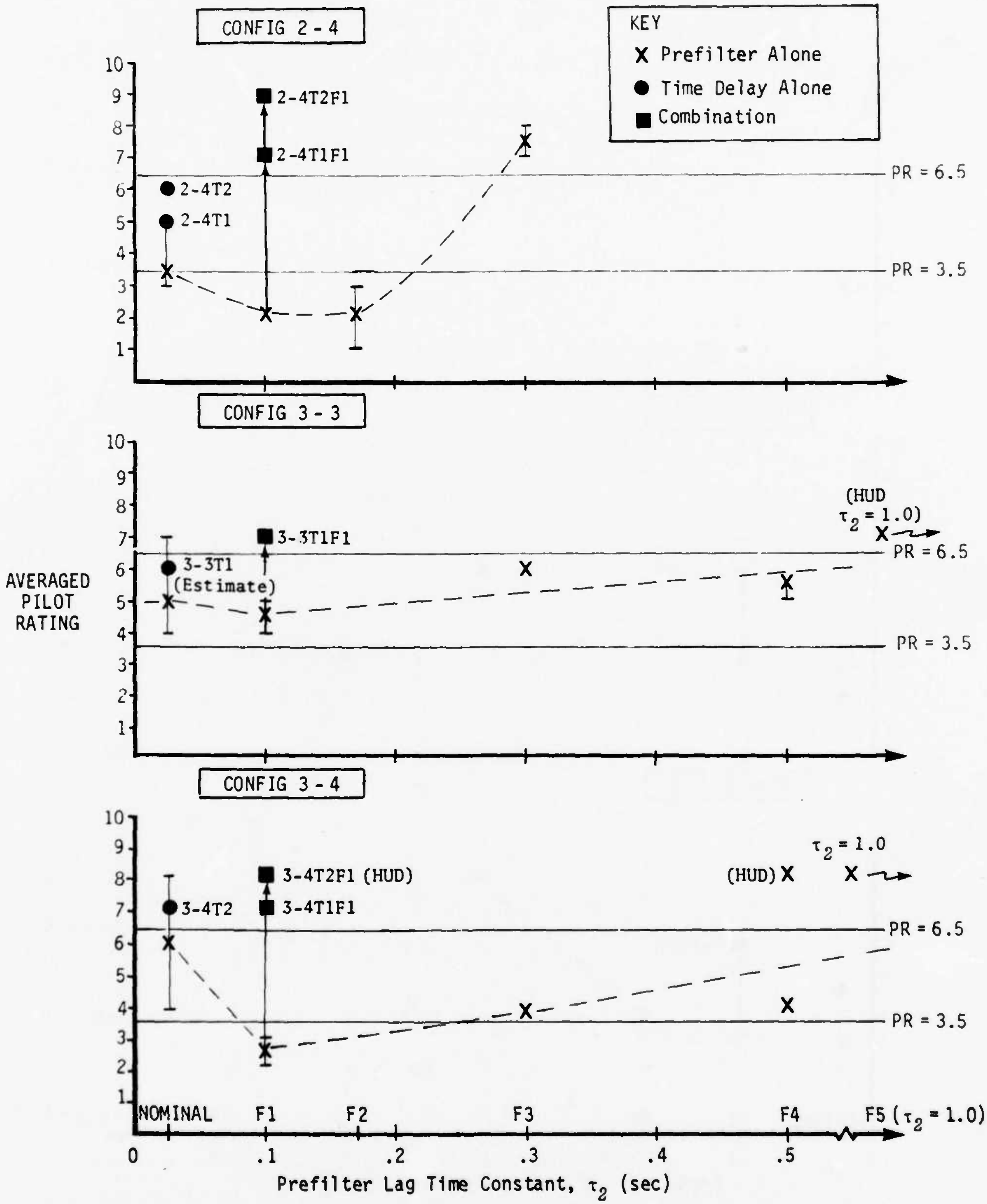


Figure 4-6b: EFFECT OF PREFILTER LAG AND COMBINATIONS WITH TIME DELAY, FLIGHT PHASE CATEGORY A TASKS (TR + AR)

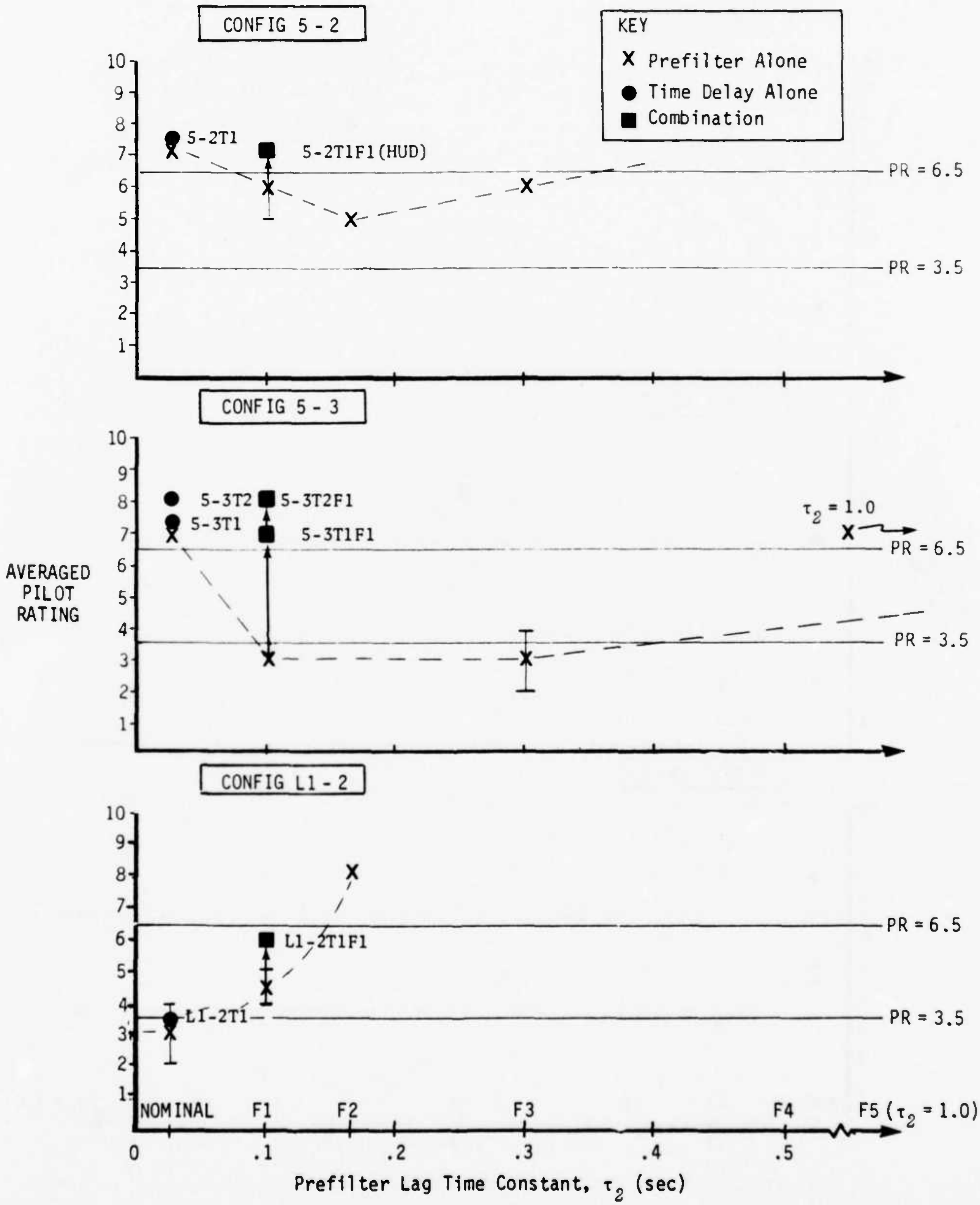


Figure 4-6c: EFFECT OF PREFILTER LAG AND COMBINATIONS WITH TIME DELAY, FLIGHT PHASE CATEGORY A (TR + AR) AND C (LA) TASKS

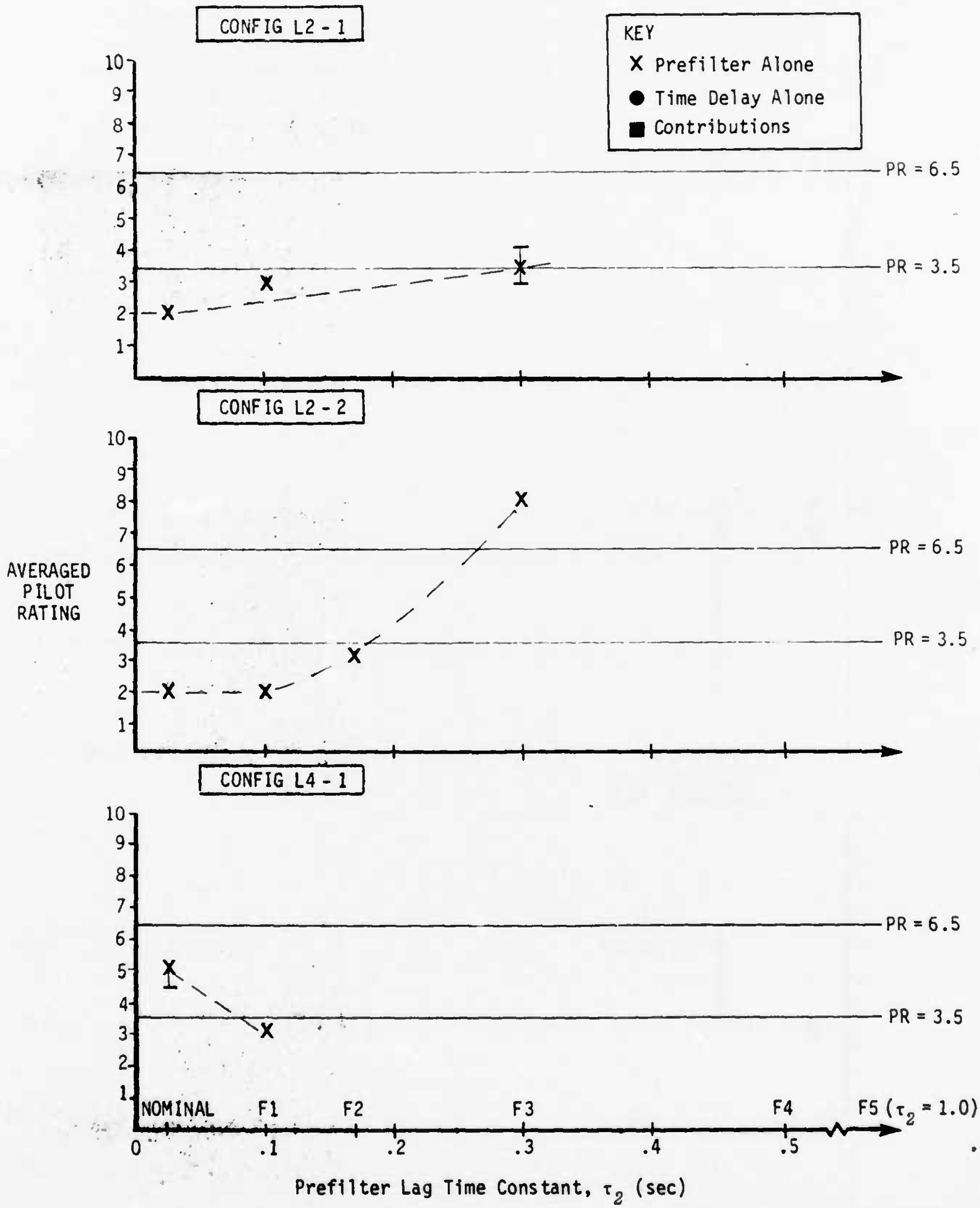


Figure 4-6d: EFFECT OF PREFILTER LAG AND COMBINATIONS WITH TIME DELAY, FLIGHT PHASE CATEGORY C (LA) TASKS

4.9 EFFECTS OF NONLINEAR COMMAND GAIN

The effects of using special non-linear command gain implementations (see Appendix G for full descriptions) in place of the baseline linear gain schedule for selected baseline configurations are illustrated in Figures 4-7a and b. In some instances HUD-only ratings were used for comparison because the desired real task data was not valid or not obtained because of schedule constraints.

4.10 EFFECTS OF INCREASED DUTCH ROLL DAMPING

The effects of increasing the Dutch roll damping ratio (ζ_{DR}) from the nominal 0.35 value on selected baseline configurations for Flight Phase Category A (TR + AR) and C (LA) tasks are shown in Figure 4-8. Again, where necessary HUD-only ratings are used for comparison. Note that Configuration 3-4T1F1 is used for comparison with 3-4T1F4D2 since 3-4T1F4 was not evaluated; since the presence of the time delay dominates the ratings,3-4T1F4 would not be rated better than 3-4T1F1.

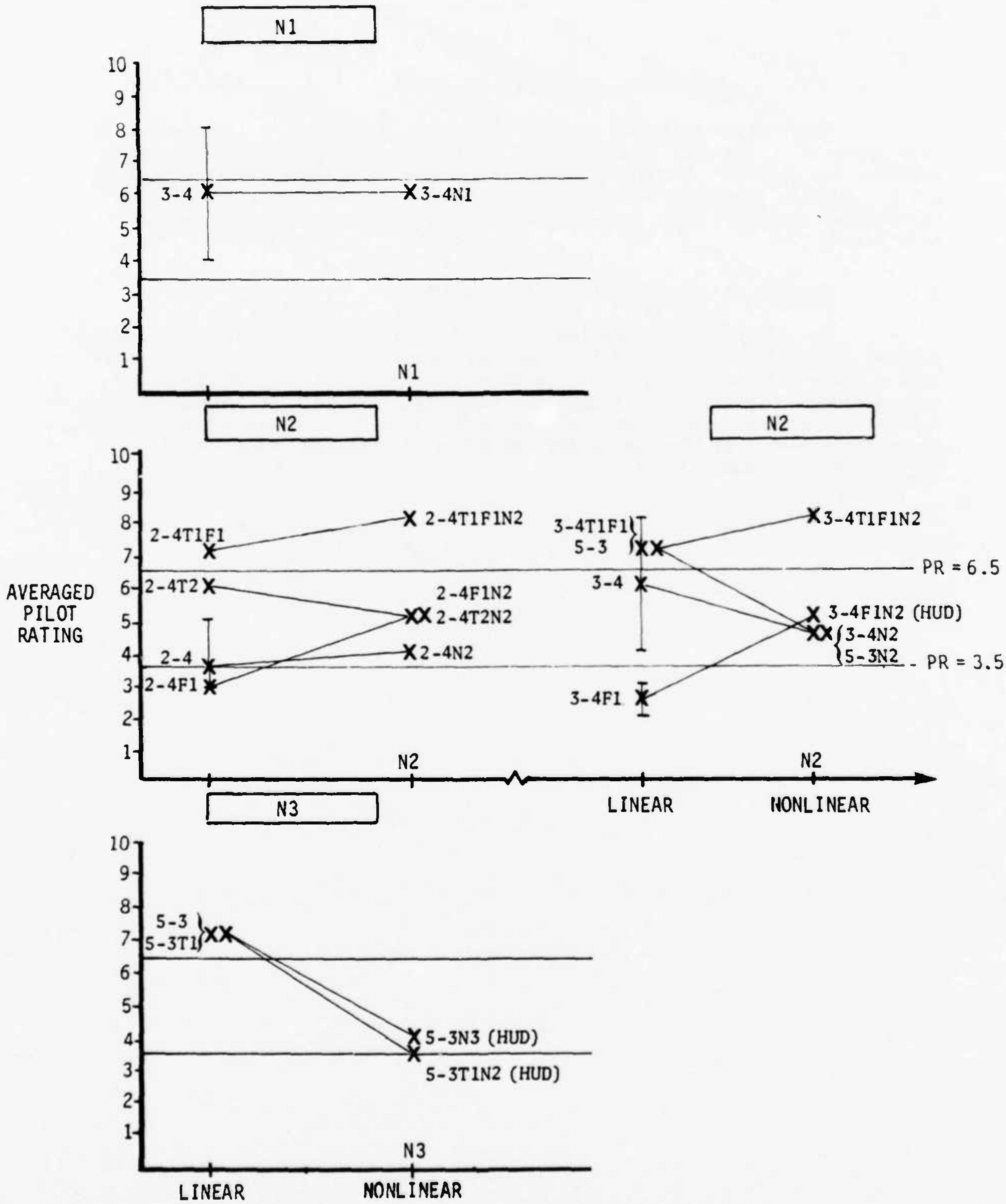


Figure 4-7a: EFFECT OF NONLINEAR GAIN, FLIGHT PHASE CATEGORY A TASKS (TR + AR)

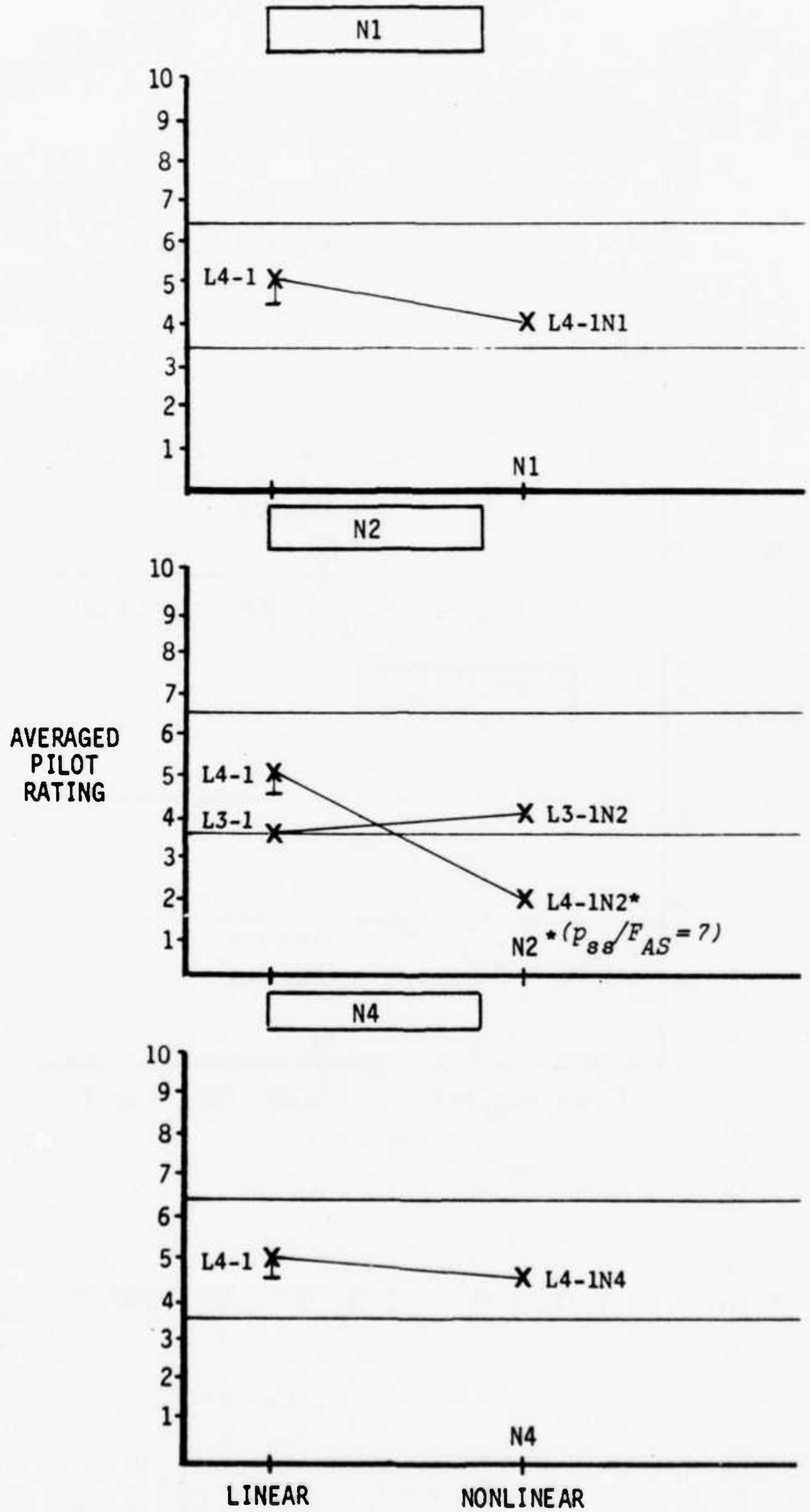


Figure 4-7b: EFFECT OF NONLINEAR GAIN, FLIGHT PHASE CATEGORY C TASKS (LA)

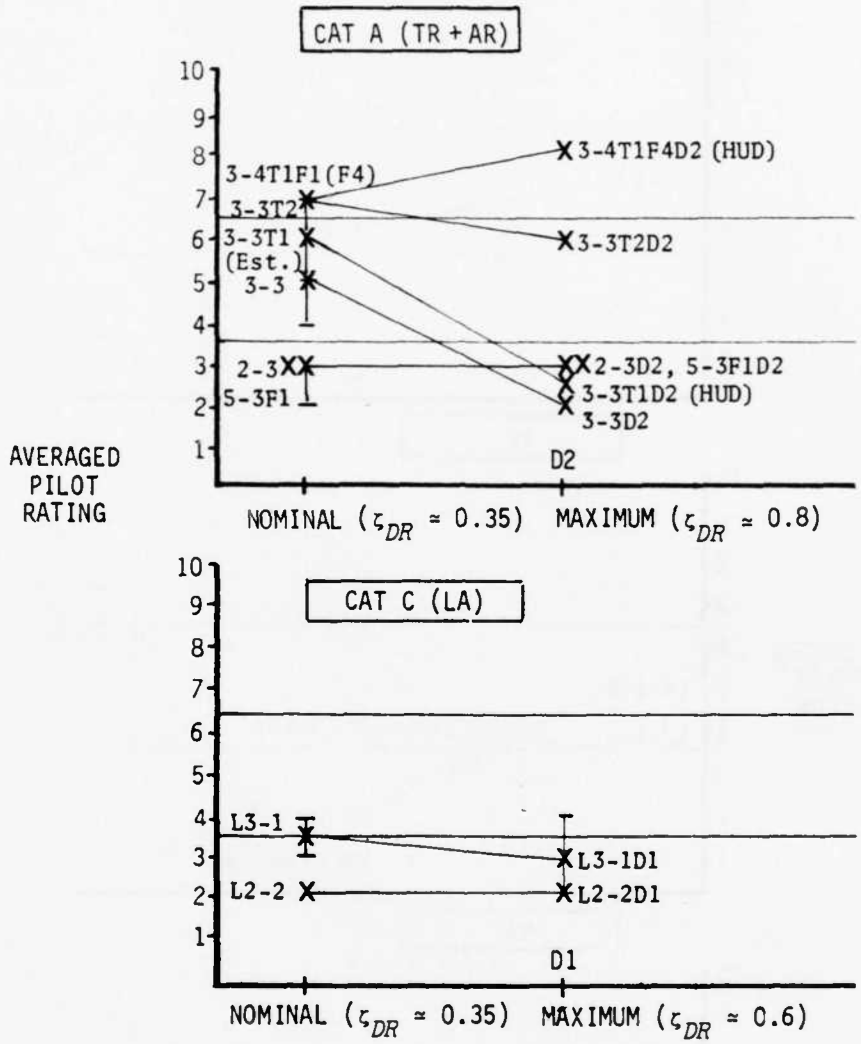


Figure 4-8: EFFECTS OF INCREASED DUTCH ROLL DAMPING (ζ_{DR})

Section 5

DISCUSSION OF THE RESULTS

The purpose of this section is to present a discussion of the results outlined in Section 4. Preliminary analysis of the results including correlation of the results with existing criteria and data is summarized in Section 6. A necessary foundation for this discussion is a review of the performance of the evaluation pilots in terms of their inter and intra pilot variability.

5.1 INTER AND INTRA PILOT RATING COMPARISONS

Two aspects of the evaluation pilot rating performance are of interest: comparison of ratings by the different pilots of the same configuration (inter pilot ratings), and comparison of repeat ratings by the same pilot of a configuration (intra pilot ratings). The inter and intra pilot rating comparison data are presented in Figure 5-1.

The following comments on the comparisons can be made:

- All of the pilot ratings were reasonably consistent in that the majority of their repeat ratings fell within a 1 rating point variation. Pilot B, who has the most repeat evaluations, was particularly consistent. He was thorough in the use of the rating scale and his results substantiate the merit of the rating scale when used as designed.

- Pilot G tended to give higher ratings than Pilot B particularly for the sensitive configurations. There are two reasons for this trend. Pilot G was clearly more aggressive than the other pilots and therefore often observed stronger degradations in performance; in addition, he tended to be less thorough in using the rating scale.

- The data indicates that Pilot P had a tendency to give higher ratings than Pilot B. However, three of the high deviation points are from one high rating by Pilot P for Configuration 2-3T1 which was rated three times by Pilot B.

In summary, the evaluation pilots performed their evaluation role very well. The three pilots represented a realistic cross section of piloting aggressiveness with Pilot G being clearly the most aggressive in his approach to the tasks. Pilots B and P approached the tasks with similar degrees of aggressiveness.

Since the pilots were representative of a realistic cross section of fighter pilots, averaging their ratings to determine the trends in the pilot rating data is reasonable.

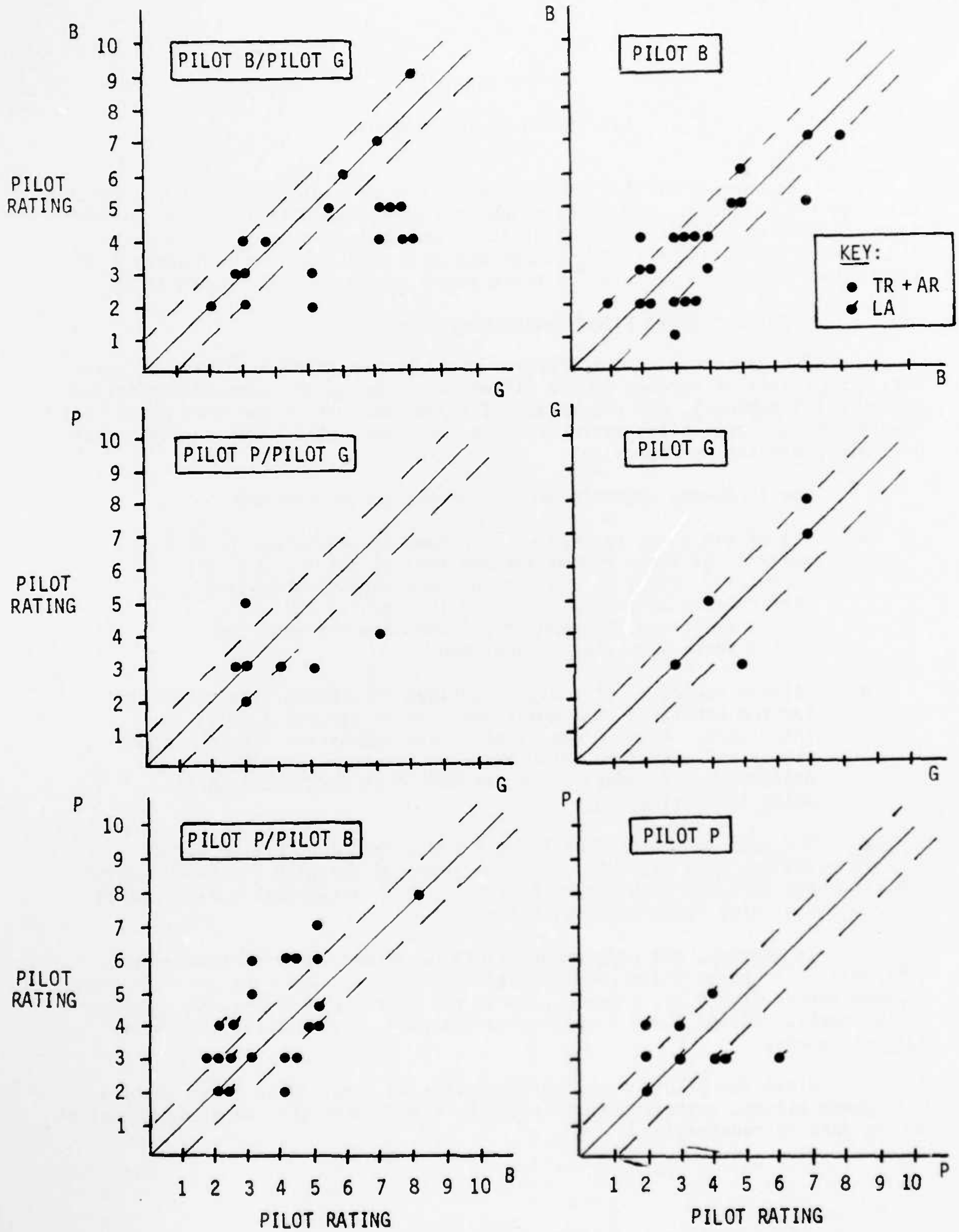


Figure 5-1: INTER AND INTRA PILOT RATING CORRELATION

5.2 CATEGORY A (TR + AR) TASKS

The approximate PR = 3.5 (Level 1) and the PR = 6.5 (Level 2) boundaries drawn on Figure 4-3 show that the data from this experiment indicates limits on roll damping (τ_R) and command gain ($L'_{F_{AS}}$). The values of steady-state performance, p_{ss}/F_{AS} used in this experiment appear to be satisfactory provided satisfactory values of τ_R and $L'_{F_{AS}}$ are selected.

The data suggests minimum values of τ_R of:

Level 1 (PR $\leq$ 3.5) $\approx$ 0.3 secs

Level 2 (PR $\leq$ 6.5) $\approx$ 0.17 secs

and maximum values of $L'_{F_{AS}}$ of:

Level 1 $\approx$ 55 deg/sec^2/lb

Level 2 $\approx$ 110 deg/sec^2/lb

Assuming that the Dutch roll mode is effectively cancelled, and that the spiral mode is neutral, (both valid assumptions for this experiment; see Appendix G for exact transfer functions), then:

$$\frac{\phi}{F_{AS}} = \frac{L'_{F_{AS}}}{s(s + 1/\tau_R)} \; ; \quad \frac{p_{ss}}{F_{AS}} = L'_{F_{AS}} \tau_R$$

Without significant control system dynamics, as in the baseline configurations,

- $L'_{F_{AS}}$ is a measure of the initial roll acceleration per unit stick force
- τ_R is the dominant factor in the predictability of the final response
- p_{ss}/F_{AS} is a measure of the roll control sensitivity to pilot inputs

p_{ss}/F_{AS} is related to the gross roll maneuvering performance and is of course, a function of $L'_{F_{AS}}$ and τ_R. $L'_{F_{AS}}$ and τ_R are of direct importance to the fine tracking performance of the aircraft. All of these parameters are interrelated and the discussion of the data can therefore be made from several different viewpoints. From the pilot's viewpoint, for a given task he desires good initial response ($\dot{p}_{MAX}/F_{AS}$ or $L'_{F_{AS}}$ for the baseline configurations), predictable final response (good value of τ_R) and satisfactory roll performance (p_{ss}/F_{AS}) for acceptable stick force levels.

Correlation of all the Category A data including the baseline configurations and those with added time delay and prefilter lag is discussed in Section 6.

Of primary interest is the observed trend from the pilot rating data which indicates a degradation in pilot rating as τ_R is decreased at essentially constant $L'_{F_{AS}}$ and satisfactory values of p_{ss}/F_{AS}. The data suggests that there are lower (τ_R *too short*) limits as well as the well-documented upper (τ_R *too large*) limits on roll mode time constant. Since modern aircraft are typically highly damped in roll the experiment concentrated on the short time constant flying qualities boundaries.

Baseline configurations 2-4, 3-3 and 5-2 are obvious candidates for discussion; they are configurations with approximately constant initial acceleration to a pilot input ($L'_{F_{AS}}$) yet the averaged pilot ratings degrade from 3.5 to 7 as τ_R decreases from 0.45 to 0.15 sec for otherwise satisfactory values of p_{ss}/F_{AS} (25 to 10 deg/sec/lb).

5.2.1 Baseline Configurations 2-4, 3-3 and 5-2 ("Roll Ratcheting")

As shown on Figure 4-3, the pilot ratings degrade as τ_R is decreased in moving from 2-4 (PR = 3.5) to 3-3 (PR = 5) to 5-2 (PR = 7). Typical pilot comments were:

Config.	Pilot	Eval. No.	Comments
2-4	B	124	"Precision/accuracy good even when aggressive"
3-3	P	119	"Desired performance obtained but jumpy response"
	B	44	"Definite ratcheting - small corrections during fine tracking were a problem"
5-2	B	12	"Wing rocking, roll oscillations, quick, sharp, ratcheting - certainly did bother fine tracking (rudders didn't help)"

The pilot comments and ratings indicate that a lower limit of roll mode time constant was defined by degraded lateral flying qualities due to "roll ratcheting". Roll ratcheting was a term commonly used by the evaluation pilots to describe a configuration's roll response which was objectionably abrupt, resulting in a very high frequency, pilot-induced oscillation ("wing rocking"). This roll response was also characterized as having "square corners" or being very "jerky".

The puzzle presented by this data is centered on the fact that as τ_R is decreased the ϕ/F_{AS} transfer function becomes more *"K/s like"*. Since the general assumption is that pilots prefer *K/s* type systems, the pilot ratings should improve with increased roll damping (τ_R *decreasing)*, not degrade. The data, both pilot ratings and comments, however do not appear to support this position.

Although the scope of this present effort precludes a very extensive exploration into this apparent contradiction, it is logical to look into the experiment data more carefully and to review outside data sources for suitable information.

1. HUD Tracking Task Data

Sample HUD tracking task data for baseline Configurations 2-4, 3-3 and 5-2 are contained in Appendix E. Specifically, the same set of configurations listed in the above table are of interest. HUD tracking task data for configurations 5-2 and 2-4 are also shown in Figures 5-2 and 5-3.

The following observations from these records can be made:

- **The tracking performance in terms of the ϕ_{ERROR} is essentially the same for each configuration in that no overshoots or oscillations are present. Tracking movies for each configuration indicate equally good performance.**
- Small amplitude oscillations are evident in roll rate and roll acceleration for Configuration 3-3 (Pilot B) and strongly present for Configuration 5-2. Frequency of the "ratcheting" is ≈ 16 rad/sec.
- **These oscillations are pilot-induced.**
- **Nulling of the tracking error is done less crisply for Configurations 3-3 and 5-2 in that a long "tail" exists on the ϕ_{ERROR} trace.**
- **The roll rate and lateral stick force traces for 5-2 are less sharp than for 2-4 indicating that the pilot is perhaps intentionally flying smoothly (applying lag compensation) or backing out of the closed loop in the presence of the ratcheting potential of the configuration.**

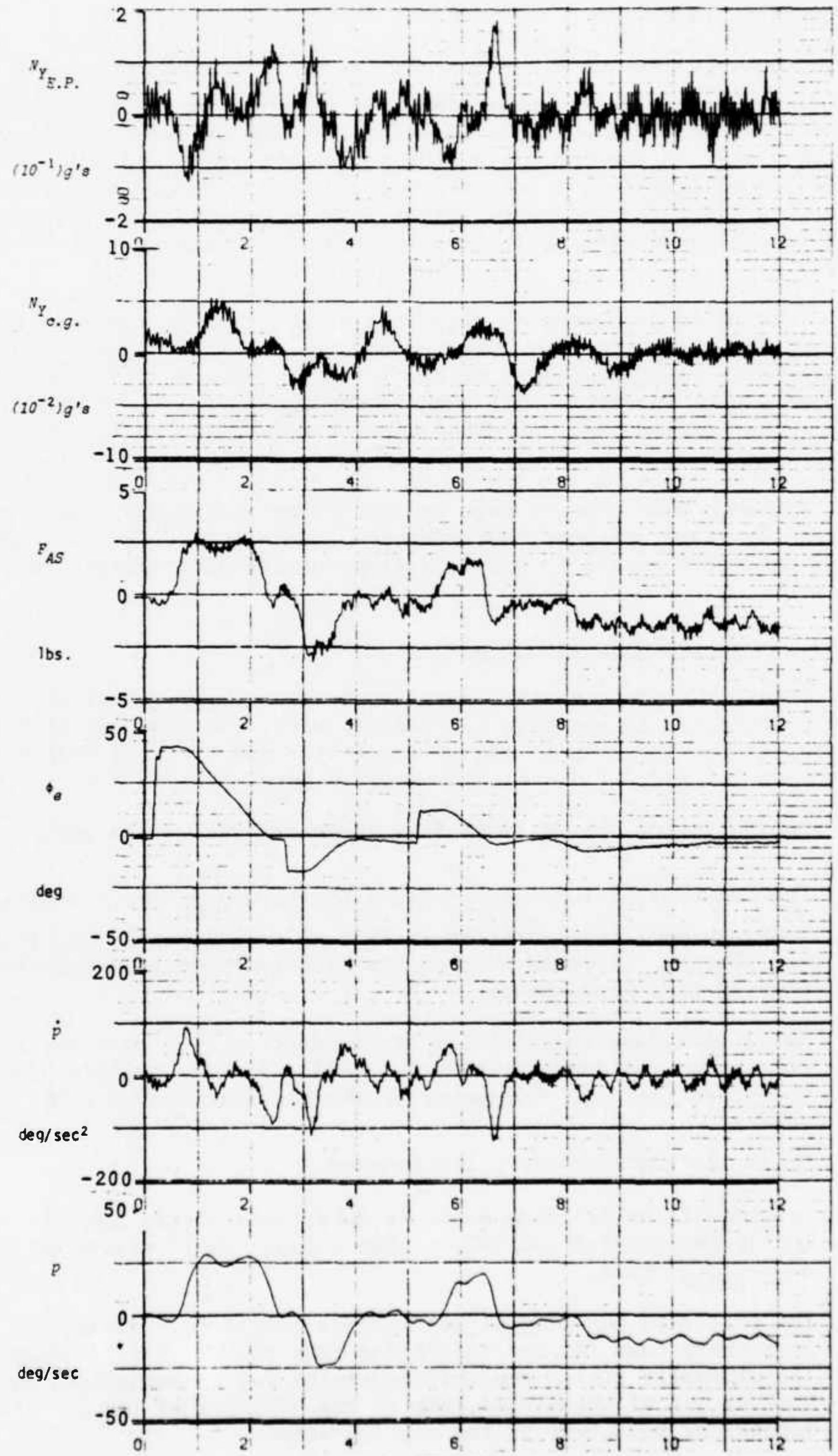


Figure 5-2 : HUD TRACKING TASK RECORD, CONFIGURATION 5-2 (EVAL. NO. 12) "ROLL RATCHETING"

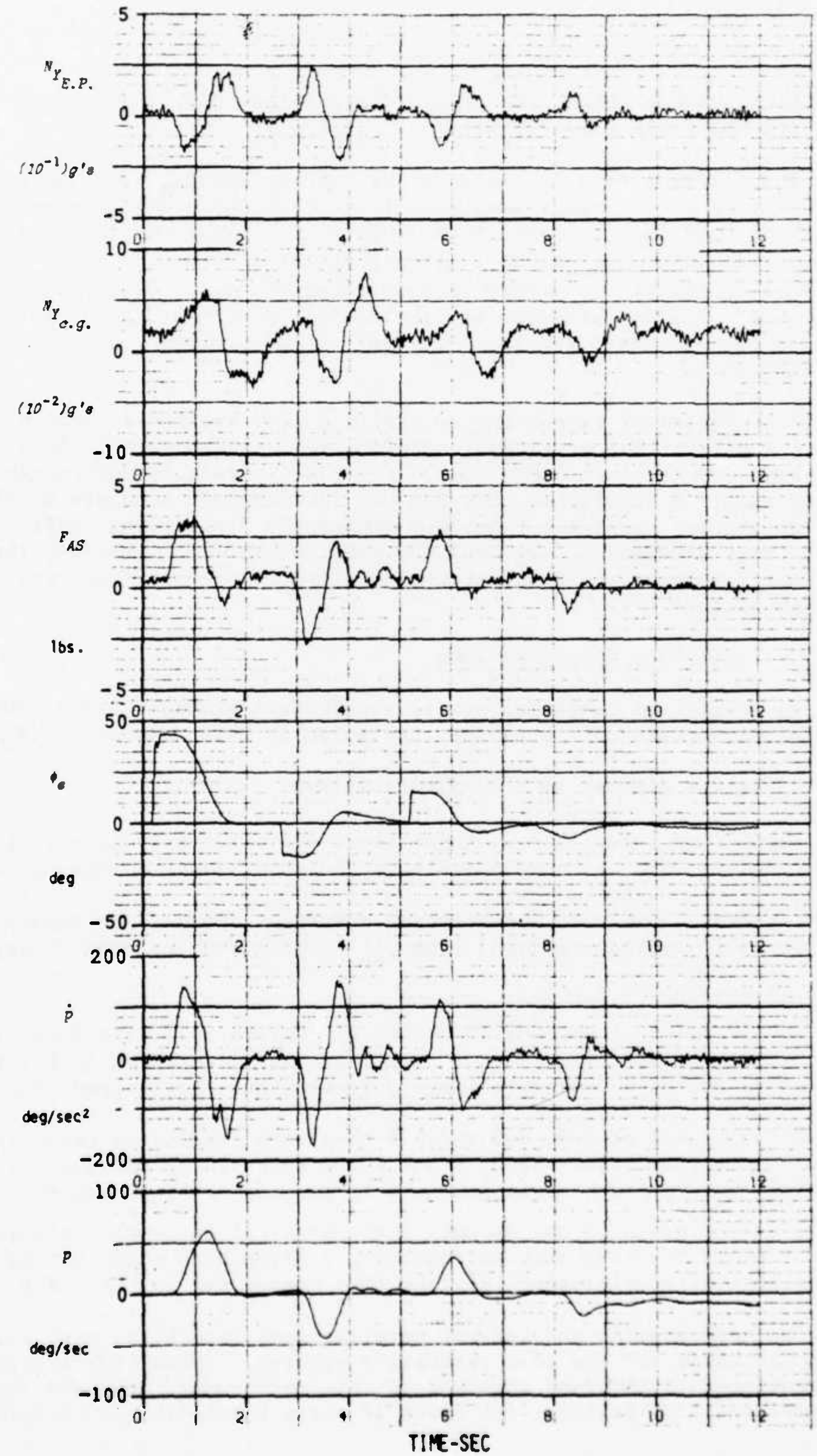


Figure 5-3: HUD TRACKING TASK RECORD, CONFIGURATION 2-4 (EVAL. NO. 124)

- Although not shown, the sideslip excursions during the task are about the same for all configurations.

The tracking records indicate that the ratcheting problems certainly were real. It is interesting to note that little deterioration in performance as measured by bank angle errors in the HUD task or pipper motion in the gun tracking task is apparent; in fact, desired performance can often be achieved yet the overall aircraft is judged to require improvement, i.e. "ratcheting is not acceptable". These characteristics resulted in a PR = 7 for Configuration 5-2. This situation often led to a "rating/comment anomaly" as discussed in the next subsection.

The problem of ratcheting is almost a ride qualities concern in that the angular accelerations or lateral accelerations at the pilot's head are the major problem; the aircraft doesn't move far but the ride is unacceptable in the fighter task. A simulation that did not include very accurate accelerations at the pilot station would not therefore expose the "ratcheting" difficulties observed in this experiment. Perhaps the experiments which verified the "goodness" of K/s systems did not properly reflect these attendant real-life acceleration factors.

2. <u>Open-Loop Considerations</u>

As previously mentioned, there are several vantage points from which to view the interaction of the primary variables in this discussion (τ_R, $L'_{F_{AS}}$ and p_{ss}/F_{AS}) in the context of the pilot's lateral task.

For a step input, the configurations exhibit nearly identical maximum values of $\dot{p}$ because $L'_{F_{AS}}$ is nearly constant, but the shapes of the responses are very different. The roll acceleration responses approach an impulse function in the limit as τ_R approaches zero. The p_{ss} achieved varies from 25 deg/sec/lb for 2-4 to 10 deg/sec/lb for 5-2.

If the pilot is assumed to desire a specific roll rate then his input must be 2.5 times greater for 5-2 than for 2-4. As illustrated in Figure 5-4 the attendent $\dot{p}$ maxima are proportionately greater for the assumed step inputs.

The response of 2-4, 3-3 and 5-2 to a unit impulse is shown in Figure 5-5. Here the maximum values of p, $\dot{p}$ and $\ddot{p}$ are essentially the same for all the configurations but the bank angle achieved is reduced as τ_R decreases (going from 2-4 to 5-2). Again if one assumes that the pilot has some standard of performance during tracking such as requiring a given bank angle therefore the angular and lateral accelerations will be much higher for 5-2 than for 2-4.

The high angular and lateral accelerations associated with 5-2 are apparently the basis for the roll ratcheting problem. These high accelerations would be generated if the same standard of roll performance achieved for 2-4 was attempted in 5-2. Further, the onset of these accelerations to pilot inputs

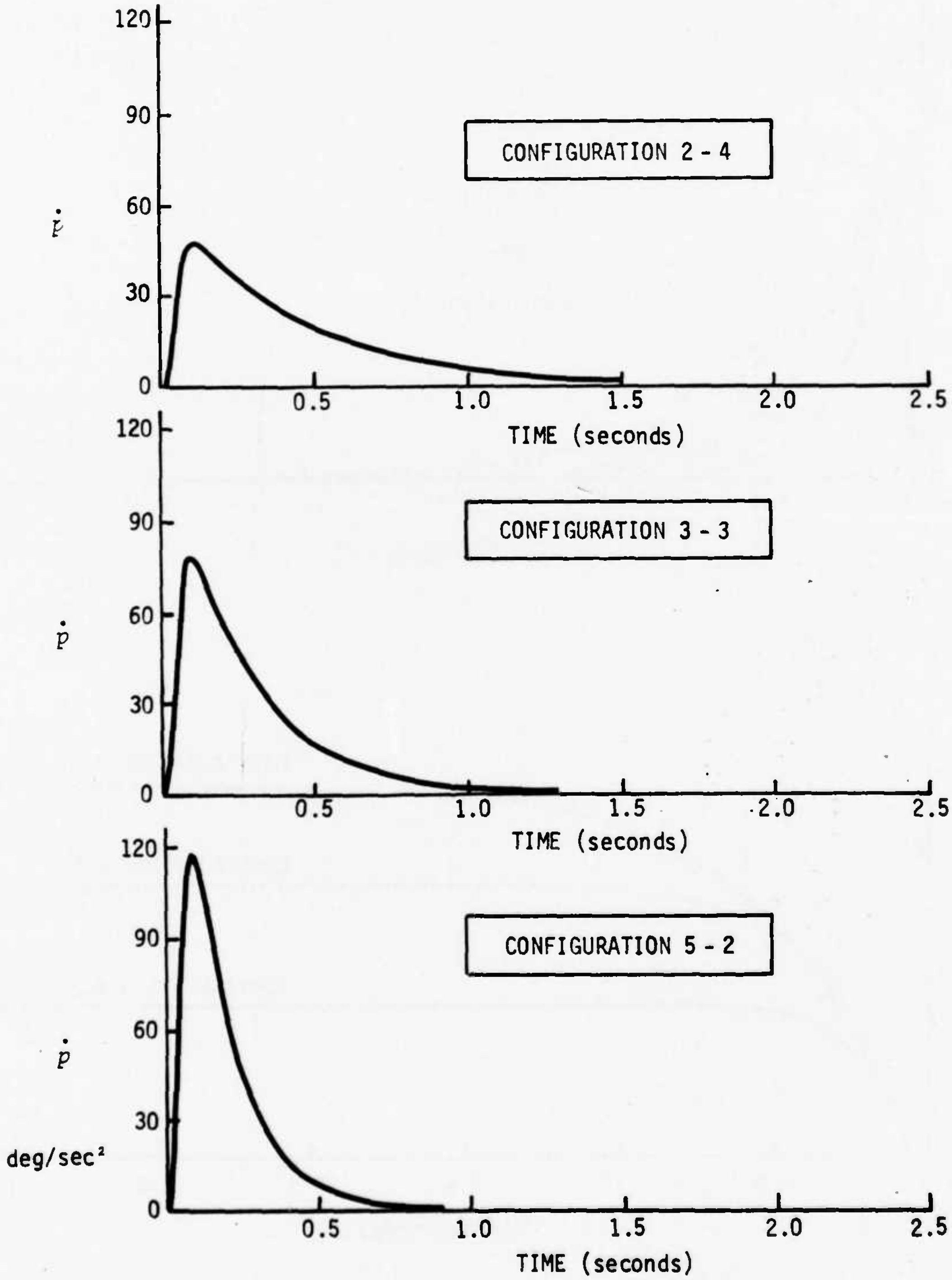
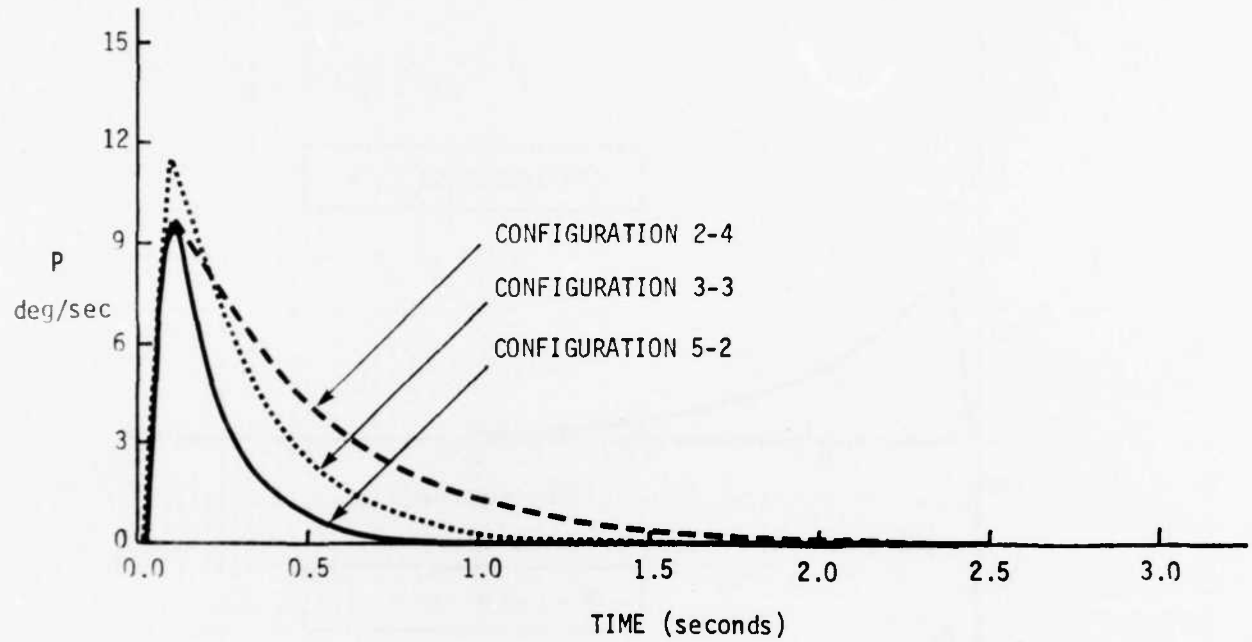


Figure 5-4: ANGULAR ACCELERATION REQUIRED FOR CONFIGURATIONS 2-4, 3-3 AND 5-2 TO ACHIEVE P_{ss} = 25 DEG/SEC



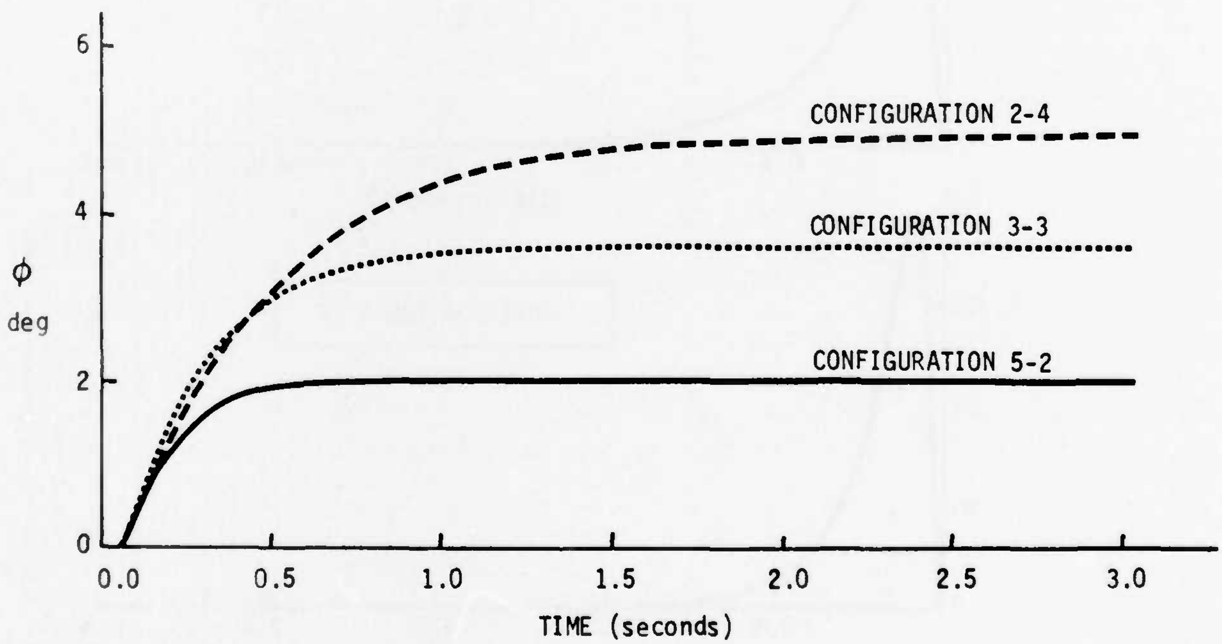


Figure 5-5: RESPONSE OF CONFIGURATIONS 2-4, 3-3 and 5-2 TO 10 LB IMPULSE F_{AS} INPUT

is clearly sharper and more abrupt for Configuration 5-2 as shown by both the actual task performance records (Figure 5-2) and the step time history responses (Figure 5-4). In any event the catalyst for the phenomenon would appear to be excessive roll damping (τ_R too short).

It appears from the HUD tracking performance records in Appendix E and Figures 5-2 and 5-3 that with Configuration 5-2 the pilot attempts to compensate by using similar sized inputs as in 2-4 but holds the pulse for a longer time to achieve the desired bank angle change. He, in effect, attempts to slow down his inputs; however, he typically reverts inadvertently to abrupt commands which lead to the small amplitude "ratcheting" oscillation.

3. Closed-Loop Considerations

A recent study centered on analytically investigating the roll ratcheting question (Reference 13) indicates that the ingredients of the observed ratcheting problem can be reproduced in a reasonable fashion if the following scenario is followed.

- A simple pilot model consisting of a gain, a first-order lag compensator of 0.3 sec transport delay is adjusted to achieve a satisfactory closed-loop bank angle tracking bandwidth (using the Neal-Smith definitions in Reference 5) of approximately 2 rad/sec for a K/s-like aircraft (very short roll mode time constant).

- This compensation and bandwidth would allow satisfactory bank angle control and avoid abrupt inputs which produce unwanted high accelerations.

- Suppose the pilot reverts to an abrupt input technique to demand the desired response more rapidly, creates high angular accelerations and then switches his closure to angular acceleration error instead of bank angle error. Then, with sufficient pilot gain, a ratcheting-type oscillation of $\approx$ 16 rad/sec results.

- Roll ratchet is therefore best explained by a model that assumed the pilot is closing the aileron loop on angular acceleration response cues.

- The study concludes the roll angular acceleration and the lateral linear accelerations at the pilot station are important considerations in flying qualities. The angular and linear accelerations can become objectionably high when the roll damping ($\tau_R < .15$ sec), the height above the roll axis, or the product of these factors becomes very large.

Clearly, more analysis is required in this area; fortunately, the HUD tracking task performance data which contains all the necessary input and output data presents a unique opportunity for pilot modelling studies.

4. Other Data

Recent modern fighter aircraft have exhibited roll ratcheting problems similar to the problems noted for Configuration 5-2. In each case the aircraft were highly augmented with particularly high levels of roll damping. Caution must be used however, with regard to the context that the term "ratcheting" is taken since this description has been used frequently to describe many similar yet different pilot/aircraft motions. Examples of roll ratcheting, analogous to that shown in this experiment are cited to add further substance to the credibility of this data set.

- A previous NT-33 experiment (Reference 14) conducted to investigate lateral-directional flying qualities of lifting body entry vehicles noted similar ratcheting problems when τ_R became small (around 0.1 secs).

- Similar problems were evaluated during the Surviable Flight Control System (SFCS) program implemented on an F-4 aircraft. As reported in Reference 23, the roll control system was tailored to yield very short roll time constants. Pilot evaluations, however, indicated an "oversensitive roll response which was universally objectionable to the pilots". The roll response exhibited "high roll accelerations... and roll ratcheting or jerkiness around neutral, particularly during tasks involving precise control."

- Roll ratcheting was also experienced during the prototype YF-16 evaluations. A pilot-induced oscillation with a frequency of approximately 12.5 rad/sec was experienced (Reference 24). Interestingly, the pilot repeated the same roll maneuver a short time later without incidence of roll ratchet. Comparison of the two time histories suggests that the pilot, when performing the second maneuver, slowed his input (adopted lag compensation) to avoid inducing the roll oscillation. This observation agrees well with the closed-loop roll ratchet scenario presented herein, although this analysis is by no means exhaustive. Important differences between our experiment and the YF-16 controller geometries and characteristics (i.e., sidestick versus centerstick) certainly pertain. The example is, however, relevant to this experiment and its results.

- As another example, several configurations flown during the variable stability NT-33 simulation of the F-18A (Reference 10) were evaluated as exhibiting roll ratcheting; lateral flying qualities were consequently downrated. The evaluated configurations were early flight control system designs for the F-18 first flight with a simulation error that effectively doubled the desired roll command gain ($L'_{F_{AS}}$) and roll damping (L'_p). Decreasing the roll command gain and roll damping eased the roll ratchet tendencies.

• Finally, the V/STOL flying qualities specification background data (Reference 15) contains examples from hovering experiments which substantiate the trends shown in the data from this experiment. The hover data indicates a degradation in pilot rating, for constant control sensitivity (L_δ or M_δ), as the damping (L_p or M_q) is increased.

These data represent further evidence that there is a real-world upper limit to the levels of roll damping (lower limit on τ_p) for each level of flying qualities. The K/s criterion for good flying qualities does not apparently directly apply to real aircraft in high gain tasks. It is interesting to note that the in-flight examination of K/s-like aircraft (using the variable stability NT-33, Reference 25) actually only approximated K/s dynamics by using τ_p = .35. Excellent flying qualities were evaluated for this configuration. This result agrees favorably with the data presented herein.

Again, further analysis of the data is required to ensure that other factors are not influencing the data.

5.2.2. Pilot Rating/Comment Anomaly

The roll ratcheting type configuration (for example 5-2 and 5-3) presented a special problem to the evaluation pilots which led to a "pilot rating/comment" anomaly on several occasions.

For these configurations the performance in terms of tracking accuracy was typically good - desired performance was generally obtained (PR = 4 on performance alone)- but the aircraft was often judged to be unacceptable (PR = 7) because the deficiencies (ratcheting, jerkiness) required improvement in the view of the pilots. In some cases the pilot rating was either a 4 or a 7 depending on the opinion of the pilot on that particular flight.

For example, Configuration 5-3 was given a 7 by Pilot C and a 4 by Pilot B with similar comments; for the HUD-alone tracking evaluation Pilot B gave a 7 and 4. In three of the evaluations the rating dilemma was directly discussed. Subsequent discussions with the evaluation pilots and the safety pilot indicated agreement that the deficiencies exhibited should require improvement despite the external performance achieved; a pilot rating of 7 was therefore used in the data base for this configuration.

Configurations for which the rating/comment anomaly might be a factor are noted in the pilot comments in Appendix C. The configurations where the pilot discussed rating/comment anomaly problems are:

Configuration	Evaluation No.
5-2	12
5-3	36
3-3T3	73
3-4T2	101
3-3T2	115
5-3N2	168
5-3	184
5-3	190
5-3	210

5.2.3 General Observations

- Time Delay Effects

The effects of adding equivalent time delay to the baseline configurations are summarized in Figures 4-5a through d. Although the data are hardly sufficient to define the rating trends with time delay completely the following estimates are made. Configurations 2-2, 2-3 and 2-4 are the basis for these estimates which are clearly "best guesses".

- Additional Equivalent Time Delay Threshold: (No effect on PR) $\approx$ *70 ms*
- Total Equivalent Time Delay Threshold: (Includes actuator and nominal prefilter effects $\approx$ *50 ms*) $\approx$ *120 ms*
- Slope After Threshold: $\approx$ *1 PR/30 ms*

All of the time delay data is included in the application of the time history criterion discussed in Section 6.

- Prefilter Effects

The effects of increasing the prefilter time constant, τ_2, for the baseline configurations are summarized in Figures 4-6a through d. For a good basic configuration such as the "2-" series the effect of the prefilter is not apparant until values of τ_2 of about .17 sec (6 rad/sec prefilter). For the more sensitive configurations, 3-4 and 5-3, the prefilter lag is clearly beneficial and lags of $\tau_2 = 0.3$ can be tolerated before degradation due to lag begins.

All of the prefilter lag data is included in the application of the time history criterion discussed in Section 6.

- Combination Effects

The effects of combining a time delay and prefilter lag on the baseline configurations are presented in Figures 4-6a through d. In each case, the rating with the time delay added to a given prefilter configuration is worse than the rating with the prefilter alone; in most instances the rating for the combined is worse than the time delay alone case.

The beneficial effects of the prefilter lag are totally eliminated when even small time delays are included in combination; Configurations 3-4T1F1 and 5-3T1F1 are examples of this effect and clearly illustrate improperly designed augmented aircraft with degraded flying qualities due to excessive lag prefiltering and cascaded, high order dynamics (equivalent time delay).

All of the combination time delay and prefilter configurations are included in the application of the time history criterion discussed in Section 6.

- Special Filter Effects

The data for the few cases where special lead/lag (F7) and lag/lead (F6) filters were added to selected baseline configurations are included in Figures 4-5a through c. The special lag/lead filters were designed to investigate the merit of canceling a short roll mode time constant and effectively replacing it with a longer roll time constant in response to pilot inputs. This filtering scheme would therefore retain the desirable gust rejection characteristics of a highly damped aircraft in roll, yet decrease the roll sensitivity to pilot inputs by forward loop compensation. Conversely, the lead/lag filters were implemented to examine the utility of quickening the roll response to pilot control inputs.

Unfortunately, the special filters (F6 and F7) could not be properly evaluated without the addition of the time delay network because of aileron buzz (Appendix G). This procedure may have compromised the evaluation of these filters by the resulting high order system due to cascading the time delay and special filters.

Insufficient data were obtained in this secondary experiment to allow definitive conclusions. The data are included in the correlation study using the time history criterion presented in Section 6.

- Nonlinear Gain Effects

The effects of using nonlinear command gain schedules are summarized in Figure 4-7a. Implementation details are presented in Appendix G.

A general observation is that this phase of the experiment is inconclusive. The data indicate improved pilot ratings when nonlinear gain N3 was used but only two data points were gathered and then the evaluations were on the HUD alone. Close regard to the pilot comments and ratings together must be made to interpret these results properly. Several evaluations had pilot comments which were very different due to the nonlinear gearings although the pilot ratings were essentially unchanged. Detail analyses of these data were beyond the scope of this report.

Further research is clearly in order.

- Effects of Increased Dutch Roll Damping

The effects of increasing the baseline value of ζ_{DR} from 0.35 to approximately 0.8 are presented in Figure 4-8.

The results indicate that in general the effect of increasing ζ_{DR} is not significant. In two cases an improvement in the pilot rating was evident but the data are sparse and therefore not totally credible. A general conclusion would appear to be that Dutch roll damping ratio values on the order of 0.4 are sufficient. However, more research would be required to substantiate this conclusion.

5.3 CATEGORY C (LA) TASKS

The data base gathered for the approach and landing tasks are presented in Figures 4-4, 4-5c and d, 4-6c and d. For the baseline data that are available, many of the comments made in Section 5.2 for the Category A tasks also apply to the approach and landing task data. A brief review of some general comments on the Category C data fol' ws; all the data is included in the application of the time history criterion discussed in Section 6.

5.3.1 General Observations

- **Baseline Configurations**

The data, although limited in coverage, suggests a minimum value of τ_R of 0.25 sec for Level 1 (PR < 3.5) flying qualities. As in the Category A data, when τ_R is reduced at a constant value of $L'_{F_{AS}}$ flying qualities finally begin to deteriorate for small τ_R ($\approx$ 0.2 sec) when the roll ratcheting problem surfaces (Configuration L4-1).

- **Time Delay Effects**

Estimates which qualify as "best guesses" can be made using the better configurations (L1-2 and L2-1) for guidance:

- Additional Equivalent Time Delay Threshold (No effect on PR)	$\approx$ 70 ms
- Total Equivalent Time Delay Threshold (Includes actuator and normal prefilter effects $\approx$ + 50 ms)	$\approx$ 120 ms
- Slope After Threshold:	$\approx$ 1 PR/30 ms

- **Prefilter and Combination Effects**

Again the trends are similar to those shown in Category A data.

For a good Configuration (L2-2), a .17 sec prefilter lag (6 rad/sec prefilter) can be tolerated before significant degradation in pilot rating occurs. Prefilter lag is beneficial to "sensitive" configurations like L4-1 which exhibits the beginnings of roll ratcheting.

In the one evaluation with a combination of time delay and prefilter present (L1-2T1F1) the pilot rating is worse than when either element alone is present.

- Nonlinear Gain Effects

The effects of using nonlinear command gain schedules are summarized in Figure 4-7b. Implementation details are contained in Appendix G.

The results indicate that the nonlinear gain schedules employed did affect flying qualities. Clearly, more data are required before any conclusions can be made but the pilot ratings and comments for nonlinear gearings with Configuration L4-1 do indicate variations in apparent flying qualities. Improved flying qualities were noted in one instance (Configuration L4-1N2 with P_{ss}/F_{AS} increased to 7 deg/sec/lb).

- Effects of Increased Dutch Roll Damping

The effects of increasing the baseline value of ζ_{DR} from 0.35 to approximately 0.6 are presented in Figure 4-8.

The results from this very limited data set indicate that Dutch roll damping values on the order of 0.4 are sufficient.

Section 6

CORRELATION OF DATA USING TIME HISTORY PARAMETERS

6.1 EFFECTIVE PARAMETERS

The search for a suitable criterion with which to correlate all of the data finally centered on a time history criterion analogous to that used by Chalk for pitch axis correlations in Reference 16. This approach is similar in concept but different in some details to that used by Van Gool in Reference 17 to correlate large aircraft lateral flying qualities.

The criterion is in effect an equivalent system approach in the time domain. As shown in Figure 6-1, the time history of the p response to a step force input is utilized to make the necessary measurements of the parameters:

τ_{Eff} - Effective Time Delay (sec)

$\tau_{R_{Eff}}$ - Effective Roll Mode Time Constant (sec)

"Effective" rather than "equivalent" is used to distinguish the parameters by the method (time versus frequency domain) the equivalent systems were obtained.

The τ_{Eff} is not included in the measurement of $\tau_{R_{Eff}}$ and is measured as shown by projecting the maximum slope of the response to the axis.

The effective paramters τ_{Eff} and $\tau_{R_{Eff}}$ were calculated using a computer program and each configuration's nominal dynamics (Appendix A, Table A-3).

Also given in Table A-3 are the calculated $\dot{p}_{MAX}/F_{AS}$ values. $\dot{p}_{MAX}/F_{AS}$ is a measure of the initial acceleration for a pilot input (after any time delay) and reflects the effects of any filtering. Filters can significantly affect the high frequency gain which is reflected by $\dot{p}_{MAX}/F_{AS}$. For the essentially unaugmented baseline configurations, $L'_{F_{AS}}$ is an appropriate measure of the initial acceleration. In either case the initial acceleration is a function of the lateral command gain.

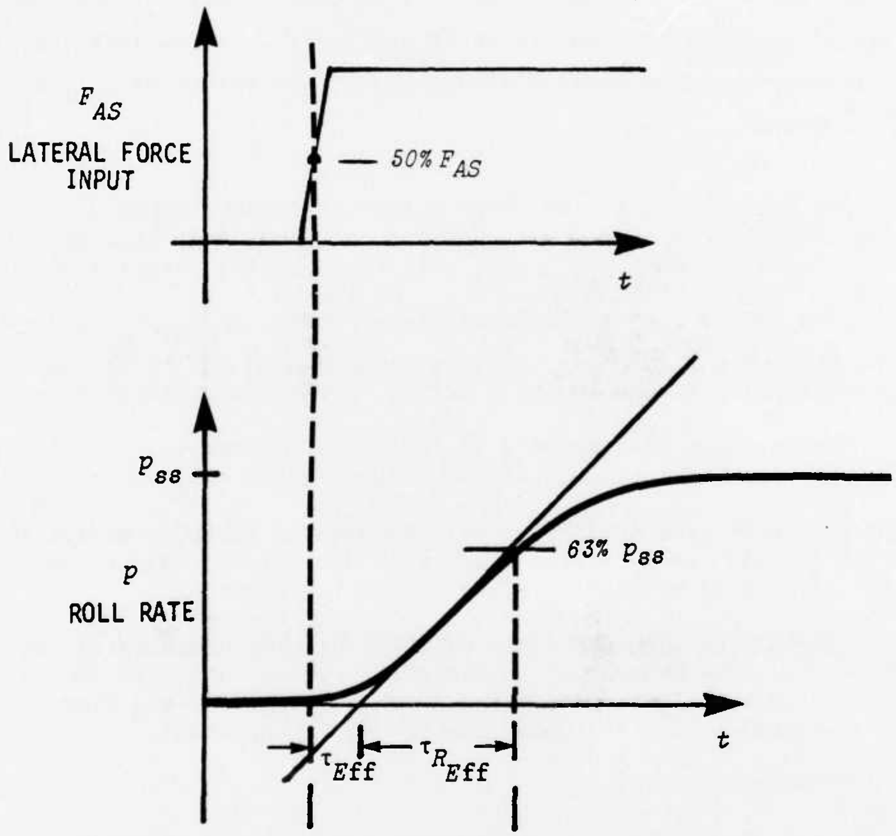


Figure 6-1: TIME HISTORY CRITERIA $\tau_{R_{Eff}}$ AND τ_{Eff} CALCULATION

6.2 APPLICATION TO CATEGORY A TASK DATA (TR + AR)

For a given value of $\tau_{R_{Eff}}$ the command gain determines the value of $\dot{p}_{MAX}/F_{AS}$ and the p_{ss}/F_{AS} values. The data in this experiment suggests that the values of p_{ss}/F_{AS} selected (10 to 25 deg/sec/lb) are satisfactory if τ_R is satisfactory; or, from another viewpoint, if the values of $\dot{p}_{MAX}/F_{AS}$ required are satisfactory.

For each configuration there exists an optimum range of command gains; for example, consider Configurations 3-2, 3-3, 3-4 which all have the same $\tau_{R_{Eff}}$ = .26 sec and τ_{Eff} = .045 sec. Pilot rating varies from 3.5 to 6 as the command gain increases (which in turn increases $\dot{p}_{MAX}/F_{AS}$ and p_{ss}/F_{AS}). Making the realistic assumption that the command gain can be optimized, the representative pilot rating for this series of configuration is PR = 3.5.

This process was employed in reviewing the Category A pilot rating data which are plotted in Figure 6-2 as a function of τ_{Eff} and $\tau_{R_{Eff}}$, effective time delay and roll time constant. All the data is included except the non-linear gradient and the increased Dutch roll damping configurations. Data points are identified by configuration number in Figure 6-3.

Considering the wide range of configuration characteristics included in the data base, the separation of the pilot rating data into flying qualities levels is really excellent. Anomalies in the correlation are minor and in each case a rationale for the deviation is readily apparent.

Observations are:

- A value of $\tau_{R_{Eff}}$ of approximately 0.5 sec is optimum; sensitivity to τ_{Eff} is at a minimum at this value.
- Maximum tolerable τ_{Eff} for Level 1 flying qualities is 0.11 sec.
- The increment in τ_{Eff} between Level 1 and Level 2 pilot rating boundaries is approximately .04 sec; lateral fighter flying qualities are apparently very sensitive to time delay.
- Lower limits on $\tau_{R_{Eff}}$ are evident.

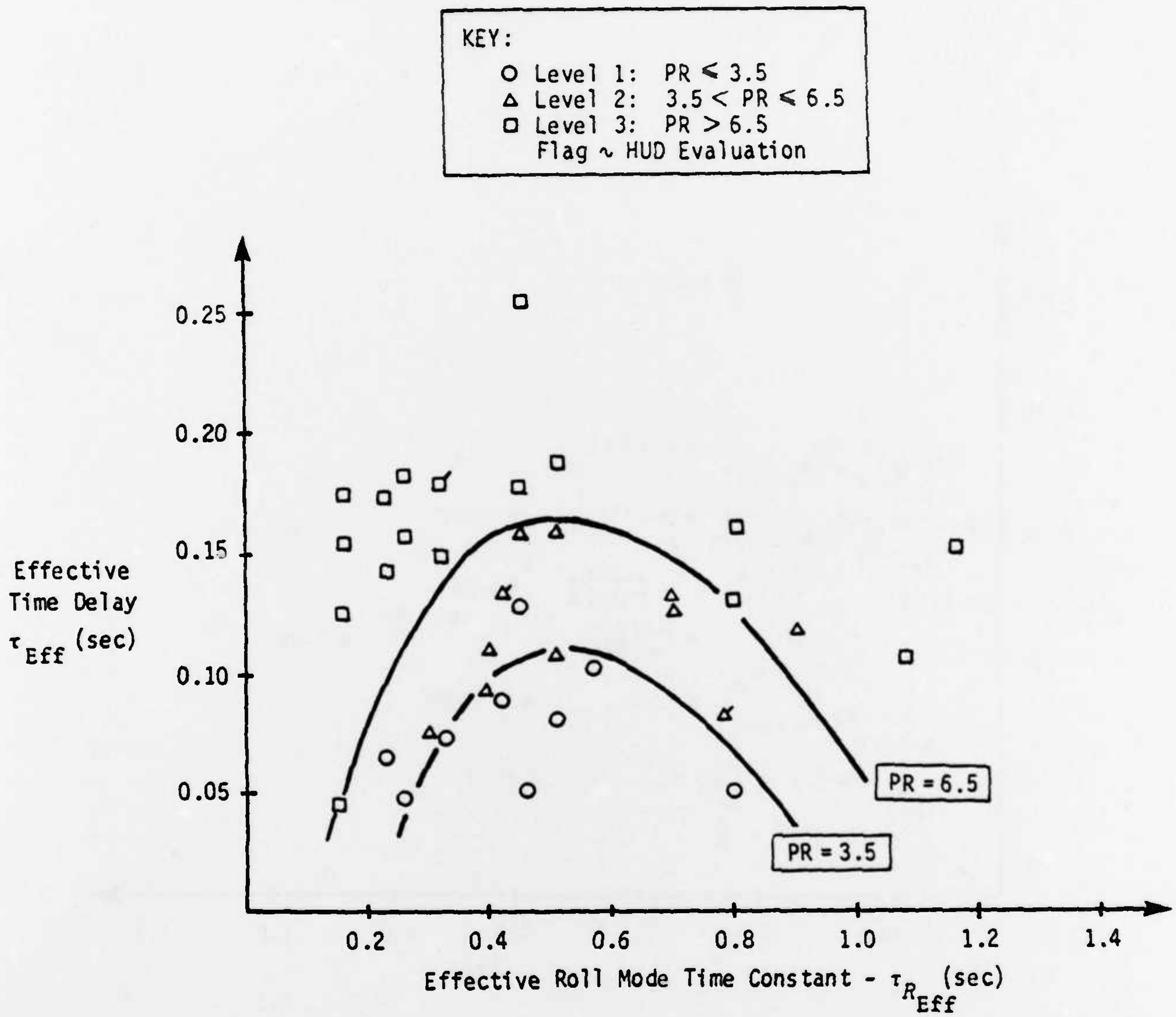


Figure 6-2: CORRELATION OF CATEGORY A TASK (TR + AR) DATA WITH τ_{Eff} AND $\tau_{R_{Eff}}$

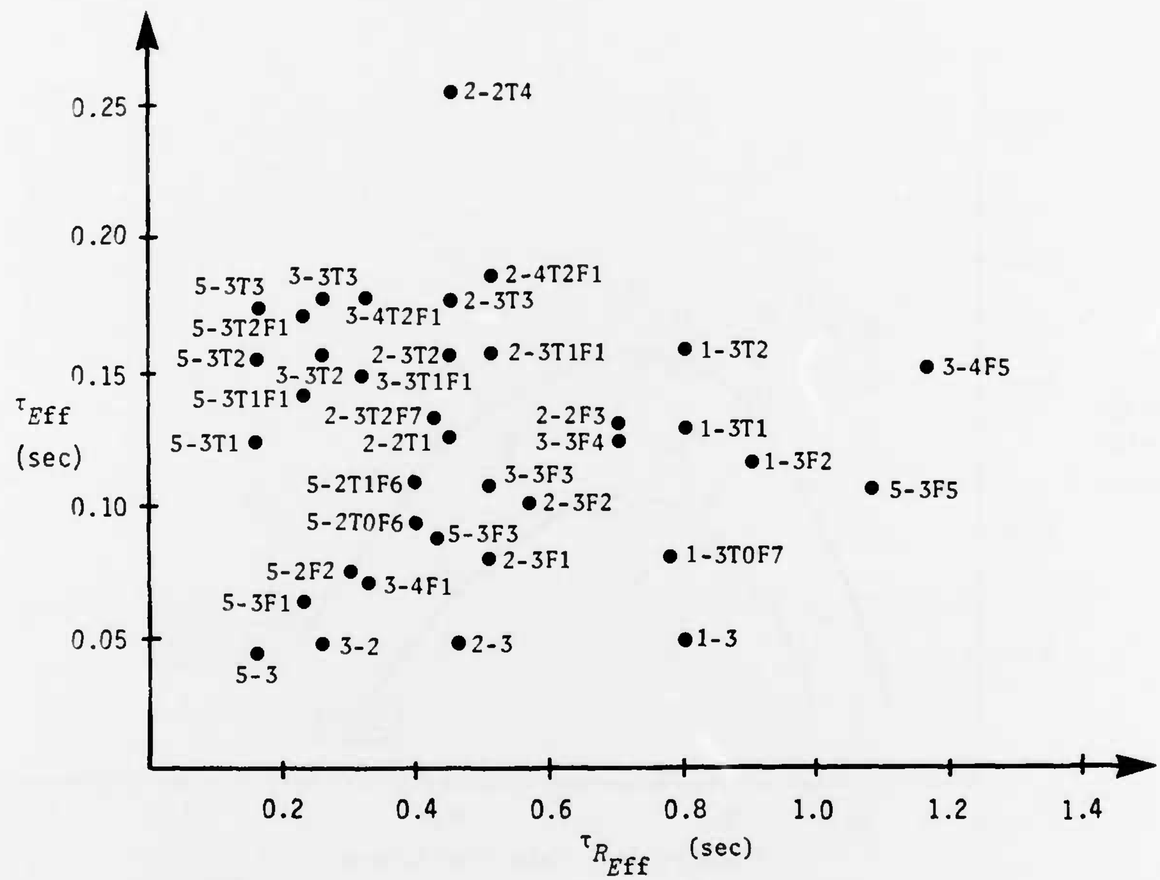


Figure 6-3: IDENTIFICATION OF DATA POINTS IN FIGURE 6-2

6.3 APPLICATION TO CATEGORY C TASK DATA (LA)

The equivalent parameter correlation process described in Subsection 6.2 was employed for the Category C approach and landing data. Equivalent parameters for the LA task configurations are summarized in Appendix A , Table II-3 along with the $\dot{p}_{MAX}/F_{AS}$ values.

The data base for this portion of the experiment is considerably smaller than for the Category A tasks and the variation in pilot ratings is somewhat higher.

All Category C data except the nonlinear and high Dutch-roll damping configurations are plotted on the effective parameter (τ_{Eff} versus $\tau_{R_{Eff}}$) plane in Figure 6-4. Data points are identified by configuration numbers in Figure 6-5.

The separation of the data from configurations with a wide variety of characteristics into flying qualities levels is reasonable and similar to the results for the Category A tasks data. The Level 1 boundary is similar to that estimated for the Category A data with a slightly greater tolerance to the effective parameter values suggested. A Level 2 boundary cannot be completely defined but the data indicates greater tolerance to larger τ_{Eff} values than for the Category A task. This increased tolerance to larger delays would seem to be reasonable for the less demanding roll control requirements during landing.

Separation of the data into well defined flying qualities regions is clearly not as good as shown for the Category A task data. In most cases the anomalies are the result of somewhat inconsistent pilot ratings; with the limited data set these anomalies cannot be clarified properly.

Observations are:

- A value of $\tau_{R_{Eff}}$ of approximately 0.5 sec is optimum; sensitivity to τ_{Eff} is at a minimum at this value.
- Maximum tolerable τ_{Eff} for Level 1 flying qualities is 0.14 sec.
- The increment in τ_{Eff} between Level 1 and Level 2 pilot rating boundaries cannot be accurately defined but is significantly larger than shown for the Category A task data.
- A lower limit on $\tau_{R_{Eff}}$ is suggested but not clearly defined.

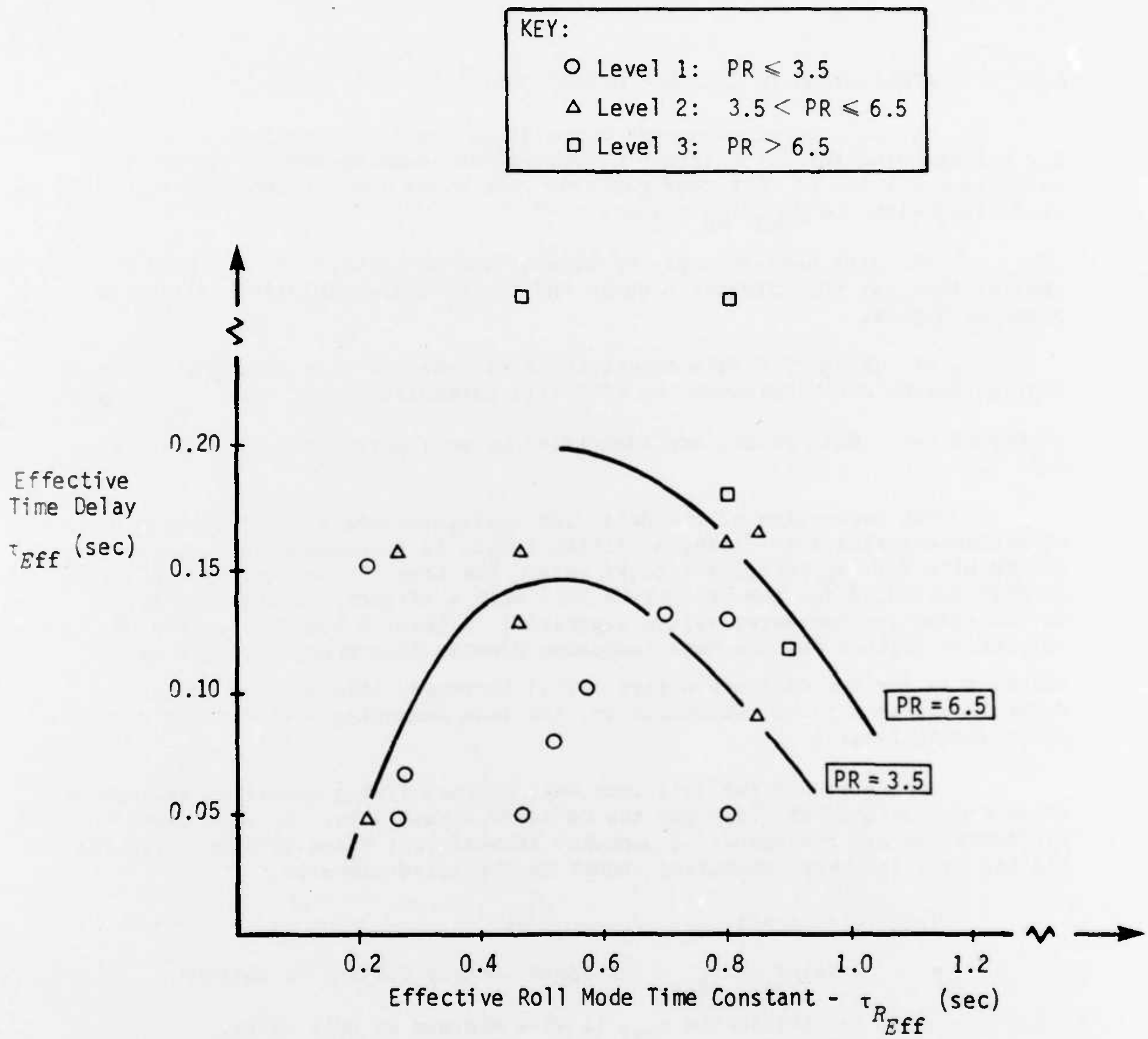


Figure 6-4: CORRELATION OF CATEGORY C TASK (LA) DATA WITH τ_{Eff} AND $\tau_{R_{Eff}}$

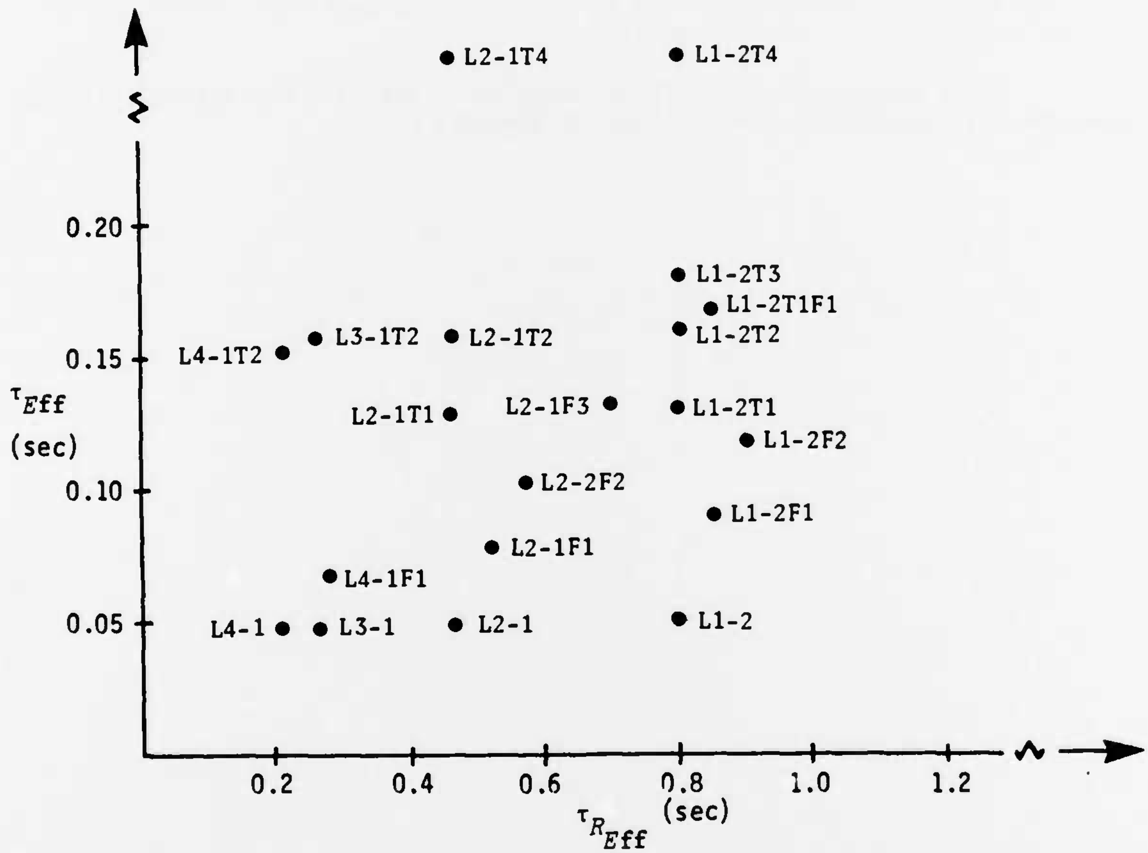


Figure 6-5: IDENTIFICATION OF DATA POINTS IN FIGURE 6-4

The results of the correlation of the data using equivalent lateral time history parameters are, in general, encouraging. A significant advantage of this equivalent system approach is that the necessary measurements can be made directly from flight test records. Similar results would be expected using a frequency domain equivalent systems technique. However, differences pertain between the two equivalent systems methods; hence, the parameter values measured by the two methods and the resulting flying qualities "answers" are neither identical nor interchangeable.

Correlations of the results using other data and the existing flying qualities specifications are reviewed in Appendix F.

Section 7

CONCLUSIONS

This experiment was directed at the lateral-directional flying qualities of advanced fighter aircraft. In particular, the effects on fighter lateral flying qualities of control system elements such as time delay and prefilter lag were of interest. Although further analysis of the experiment data is required, the following conclusions may be drawn.

1. Air-to-air gun tracking and air refueling (probe and drogue style) are equally demanding lateral flying qualities tasks; formation flying by comparison was not a critical task.

2. A properly designed HUD bank angle tracking task, flown by trained pilots, is a valid lateral flying qualities evaluation task.

3. Short roll mode time constant (high roll damping) can lead to serious lateral flying qualities problems in the form of "roll ratcheting" during precision tasks.

4. There is a lower limit on roll mode time constant for satisfactory flying qualities for aircraft without significant flight control system dynamics. Concurrently, there is a lower limit on equivalent roll mode time constant for satisfactory flying qualities for aircraft with significant control system dynamics.

5. Fighter lateral flying qualities are very sensitive to time delay in the lateral control system; the allowable time delay is a function of the equivalent roll mode time constant.

6. For aircraft with essentially first-order roll rate response to lateral inputs, a Dutch roll damping ratio of 0.4 is sufficient for satisfactory lateral flying qualities during precision tasks; high values did not significantly improve lateral flying qualities within the context of this experiment.

7. Equivalent time history parameters in the form of effective time delay and effective roll mode time constant can be used to evaluate the lateral flying qualities of highly augmented fighter aircraft.

Section 8

RECOMMENDATIONS

This in-flight evaluation program to study the effects of typical advanced control system elements on fighter lateral flying qualities has produced a significant foundation of useful data. The data base is informative but far from complete. Specifically, the following recommendations are presented:

1. The data base for the approach and landing task is incomplete; more evaluation data are needed.

2. The effects of nonlinear command gain shaping were not extensively explored in this experiment; a dedicated study of the effects of this important modern flight control system design feature is required.

3. The HUD bank angle tracking data from this experiment represents a unique data set for pilot modeling investigations; all the necessary task data ingredients are in digital form. Analysis of this data should be undertaken.

4. Additional analysis should be done to continue the development of suitable lateral flying qualities criteria applicable to highly augmented fighter aircraft. This effort should include refinement of the equivalent time history parameters method and application of other criteria such as the frequency response equivalent system method and the Neal-Smith criterion.

5. An experiment should be undertaken using an advanced ground-based simulator which effectively replicates a portion of this experiment including the HUD tracking task. This work would potentially answer questions concerning the applicability of ground simulation evaluations for precision tasks. In addition, adaption of the HUD task to produce the same flying qualities evaluations on the ground as achieved in flight could potentially be a useful "calibration" method for extending the role of the ground simulator.

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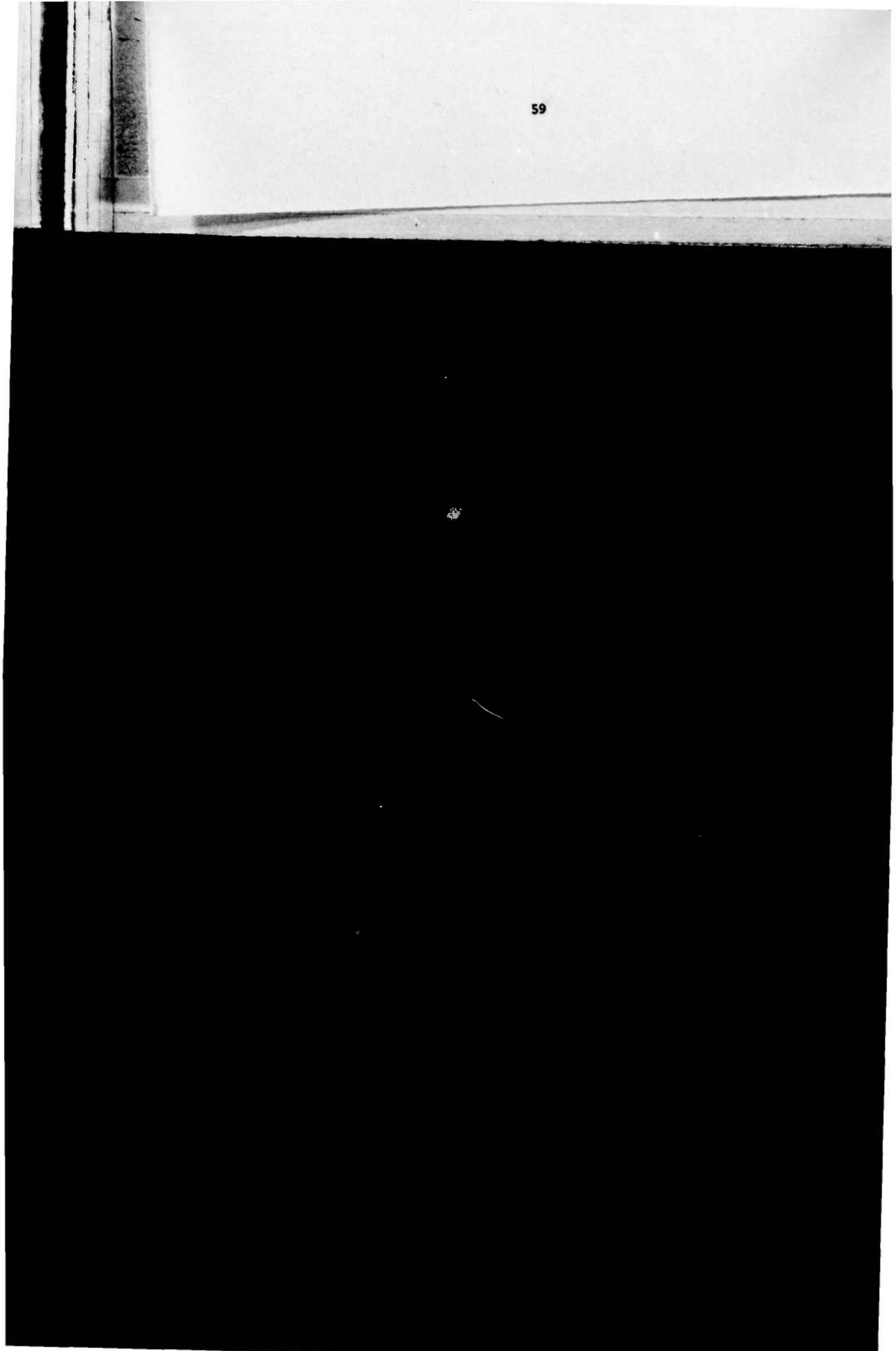
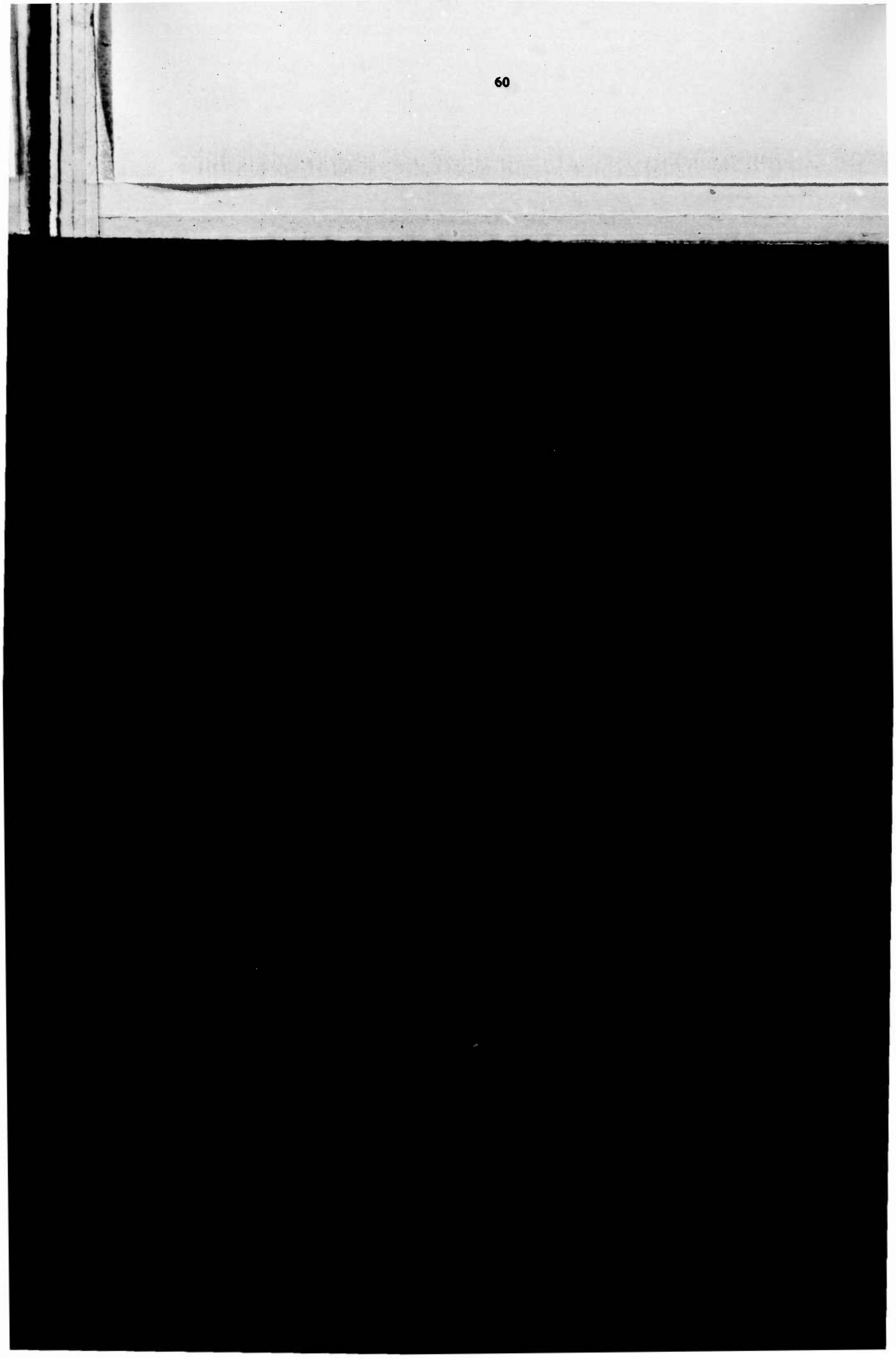
- Lower limits on $\tau_{R_{Eff}}$ are evident.





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