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FLIGHT INVESTIGATION OF FIGHTER SIDE-STICK FORCE-
DEFLECTION CHARACTERISTICS

G. Warren Hall, et al

Calspan Corporation

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FLIGHT INVESTIGATION OF FIGHTER SIDE-STICK FORCE-DEFLECTION CHARACTERISTICS

CALSPAN CORPORATION
P. O. BOX 235
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FINAL TECHNICAL REPORT AFFDL-TR-75-39

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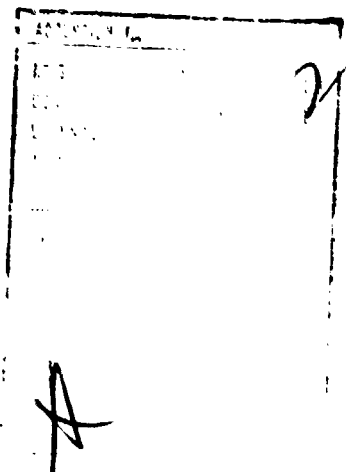
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This technic report has been reviewed and is approved for publication.

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FOR THE COMMANDER

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were evaluated by two pilots. Four values of nonlinear pitch and roll side-stick force-command gain resulting in different response per force ratios were evaluated with different side-stick force-deflection gradients, including a rigid side stick. For the particular airplane and control system dynamics simulated, the best configurations evaluated for both flight phases were those with high sensitivity of response to control force and a small amount of side-stick motion. The rigid side stick was considered satisfactory ($PR \leq 3.5$) for the landing approach but not for the up-and-away flight tasks. For the up-and-away tasks, a small amount of motion was beneficial in smoothing the initial response and improving the flying qualities of an overly sensitive airplane.

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FOREWORD

This report was prepared for the United States Air Force by Calspan Corporation, Buffalo, New York in partial fulfillment of Contract F33615-73-C-3051, Project No. 82190426, Task 7. Three prior technical reports have been published under this contract which are concerned with in-flight simulation investigations: AFFDL-TR-73-139, AFFDL-TR-74-9, and AFFDL-TR-74-110.

The program was performed by the Flight Research Department of Calspan under the sponsorship of the Air Force Flight Dynamics Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio. Captain Jerry B. Callahan (AFFDL/FGC) was the USAF project engineer and Captain Richard E. Ruffing was the project manager. The evaluation flying was performed at Edwards Air Force Base in October 1974.

The work reported in this document represents the efforts of a number of persons whom the authors wish to acknowledge: Major Fred Porter and Captain Charles Walls, USAF, the evaluation pilots; Mr. Robert P. Harper, Jr. who was the project safety pilot; and Mr. Ronald W. Huber who designed the variable stability system modifications and, along with Mr. Thomas J. Franclemont, performed the necessary calibrations and maintenance.

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GLOSSARY OF SYMBOLS

F_{As}	▪ Aileron side-stick force, positive to the right (lb)
F_{Es}	▪ Elevator side-stick force, positive for a pull (lb)
F_{RP}	▪ Rudder pedal force, positive for right rudder (lb)
g	▪ Acceleration of gravity (ft/sec ²)
h	▪ Altitude (ft)
K_{As}	▪ Nonlinear aileron force command gain (deg/lb)
K_{Es}	▪ Nonlinear elevator force command gain (deg/lb)
K_{Fs}	▪ Steady-state feel system gain (deg or in./lb)
K_p	▪ Nonlinear steady-state gain of ϕ/F_{As} transfer function ($\frac{\text{rad/sec}}{\text{lb}}$)
K_{n_3}	▪ Nonlinear steady-state gain of n_3/F_{Es} transfer function (g's/lb)
N_{FRP}	▪ Yawing acceleration per lb of rudder pedal force (rad/sec ² /lb)
n_3	▪ Normal acceleration at center of gravity, positive for a pull-up (g's)
n_3/α	▪ Steady-state normal acceleration change per unit angle of attack change, for constant speed maneuvering (g's/rad)
S	▪ Laplace operator (1/sec)
V	▪ Trimmed true airspeed (knots)
δ_{As}	▪ Aileron side-stick deflection at palm, positive to the right (deg or in.)
δ_a	▪ Aileron deflection, radians
δ_{Es}	▪ Elevator side-stick deflection at palm, positive aft (deg or in.)
δ_e	▪ Elevator deflection, radians
δ_{RP}	▪ Rudder pedal deflection, right pedal positive (in.)
ζ_d	▪ Dutch roll damping ratio
ζ_p	▪ Phugoid damping ratio
ζ_{sp}	▪ Short-period damping ratio
ζ_θ	▪ Damping ratio of second-order numerator term in ϕ/F_{As} transfer function
θ	▪ Pitch attitude (rad)
τ_R	▪ Roll mode time constant (sec)
τ_S	▪ Spiral mode time constant (sec)
τ_{θ_2}	▪ Airframe lead time constant in θ/F_{Es} constant speed transfer function (sec)

GLOSSARY OF SYMBOLS (cont.)

ϕ	▪ Roll attitude (rad)
$ \phi/\beta _d$	▪ Absolute value of control fixed roll-to-sideslip ratio evaluated at $\omega = \omega_d$
ω_d	▪ Dutch roll undamped natural frequency (rad/sec)
ω_p	▪ Phugoid undamped natural frequency (rad/sec)
ω_{sp}	▪ Short period undamped natural frequency (rad/sec)
ω_ϕ	▪ Undamped natural frequency of second-order numerator term in ρ/F_{A5} transfer function (rad/sec)
ILS	Instrument landing system
PIO	Pilot-induced oscillation
PR	Pilot rating (Cooper-Harper Scale)

Section I

INTRODUCTION

Acceptance of the idea of using electrical commands as the primary or sole means for a pilot to control his airplane makes feasible the use of small side-stick controllers in operational aircraft. The use of a side-stick with electrical commands, nonlinear gains, command prefilters, response feedbacks and signal shaping gives the designer a large number of parameters to manipulate to achieve good flying qualities. These options also present the research community with a vast number of combinations of system elements to consider, especially if there are significant interactions.

In such situations economic considerations force experimenters to limit the scope of any particular investigation by selecting what are hoped to be representative values of many of the system elements, which are then held constant while parameters of primary interest are varied in the experiment.

The primary area of interest in this in-flight investigation was side-stick force-deflection characteristics. The major question was whether it was necessary or desirable for a side stick controller to have motion for good flying qualities. A secondary question was: if motion was found desirable, how much motion is required and should the amount of motion be different for flight phases and piloting tasks?

A flight test program was designed using the USAF variable stability NT-33A airplane with its variable feel side-stick controller. A configuration representative of a modern high-performance fighter was used as the base for evaluating several values of side stick motion and aircraft control gain values. The up-and-away tasks (Flight Phase Category A) of formation, air-to-air tracking and acrobatic maneuvering and the landing approach tasks (Flight Phase Category C) were evaluated. Two experienced test pilots evaluated a total of thirty-nine configurations.

This report includes a description of the experiment, evaluation procedure, equipment used and the airplane and control system parameters varied. The experimental results are presented in the form of pilot comments and pilot ratings

Section II

TECHNICAL DISCUSSION

Several questions have arisen from current experience with fixed, force-command side-stick controllers. Most notable of these is whether a fixed side stick provides adequate cues to the pilot or if some displacement is required or desirable in certain flight tasks. Thus the primary purpose of this flight test program was to specifically evaluate force-deflection characteristics of a side stick controller. The economic constraints of the program, however, required that a number of airplane and control system parameters be held constant during the evaluation program. Many of these parameters can have a significant influence on the desired force-deflection characteristics.

Pitch-roll harmony is one aspect that is a complex result of the controller's force and deflection characteristics in the two axes together with the vehicle response magnitude and dynamics in both axes. Because of the large interactions involved, which complicate experimental definition and design specifications of control "harmony", many different combinations of pilot-force airplane-response characteristics in pitch and roll together with combinations of force-deflection characteristics would have had to be tested to define good and bad control harmony. Consequently, in this experiment the "control harmony" was selected from previously evaluated configurations for a fixed side stick. Two values of control stick deflection were selected for each axis from previously flown configurations: a small motion value, selected to provide a small but barely noticeable amount of motion, and a larger motion value selected to provide a noticeable but not objectionable or unrealistic amount of motion.

Nonlinear command-response relationships are quite common in the latest generation of fighter type airplanes. These nonlinear command gains have been tried in an attempt to avoid oversensitivity for small inputs while also making available maximum vehicle maneuver capability without excessive force requirements. Another way to alleviate the problem of high sensitivity is by using command prefilters which limit the bandwidth of pilot commands.

There may also be considerable interactions between the effects of nonlinear gains and command prefilters in terms of their effects on the control sensitivity characteristics. For this program, a linear spring gradient in combination with a set of nonlinear command gains and two different pitch command prefilters (one for up-and-away flight and another for the landing approach) were used. A description of the command nonlinearities and the characteristics of the two command prefilters is given in Section III. Still another nonlinearity that can have a strong influence on the acceptability of the force-deflection characteristics of a controller is the breakout force, and the slope or hysteresis in the system. Again, a representative breakout force in each axis was selected and remained fixed.

Force commands were used in this experiment even when the side controller had movement. This was purposely done to insure that the control command gains, i.e., airplane response per force input, remained constant. Since the side-stick mass and damping effects were small when the stick was allowed to move, i.e., the feel system dynamics were sufficiently "fast", the applied force and stick deflection are related essentially by the static spring gradient. In this case it makes little difference to the open-loop dynamics whether force or deflection is used as the command signal. Since the pilot is capable of sensing force and deflection independently, the type of command input could have an effect on the closed-loop dynamics. However, for the relatively small stick deflections evaluated, the feel system dynamics were not expected to have a major influence on this experiment.

The physical characteristics of the controller also can have an influence on the pilot's evaluation of the force-deflection characteristics. The pivot point about which the motion occurs has been found to be important, as well as the size and shape of the controller grip. The size and location of the arm rest can limit the motion capability of the wrist, especially for combined pitch and roll inputs. The acceptability of the force-deflection

characteristics can also be influenced by the need for trim and the type and location of the trim control mechanism. Several types of trim systems need to be evaluated: autotrim, rate or position trim and series or parallel action. In this experiment, the side-stick grip with an adjustable arm rest duplicated one in a current high performance fighter airplane. A four-position trim button provided rate trim. When the controller had motion, trim inputs were reflected in the controller position.

Controller-to-control-surface gearing, or control gain, can have a major influence on the acceptability of the stick force-deflection characteristics. Several values of control gain were evaluated; this was a major parameter in this experiment. These control gearings were based on configurations previously evaluated with a fixed side stick and were selected to provide both overly sensitive as well as heavy control forces.

Another set of parameters known to be important are the airplane dynamic characteristics. Of particular importance are the longitudinal short period frequency and damping ratio and the lateral roll mode time constant. In this experiment, the longitudinal short period and roll mode characteristics were held constant at values which should give good flying qualities according to MIL-F-8785B. One additional evaluation was performed with a reduced value of short period damping ratio and one with an increased value of roll mode time constant.

As evident by this technical discussion, a complete evaluation of all the parameters having an influence on the pilot's assessment of the flying qualities of a particular set of side controller/airplane characteristics would be a major undertaking. In order to design a manageable size experiment to produce valid results, it was necessary to select evaluation parameters and airplane-control system characteristics from past experiments or from known characteristics of operating airplanes.

Section III

DESCRIPTION OF THE EXPERIMENT

The variable stability NT-33A airplane with its variable feel side-stick controller was used to investigate the influence of side-stick motion and force-response gain on the pilot's assessment of the flying qualities of a high-performance fighter type airplane. The up-and-away tasks (Flight Phase Category A) were acrobatics, formation and air-to-air tracking while the landing approach tasks (Flight Phase Category C) consisted of an ILS approach and touch and go landings.

3.1 Configuration Definition

Dynamic characteristics representative of a good high-performance fighter airplane were implemented using the NT-33A variable system. The airplane dynamics are shown in Table 1 and the control system characteristics are discussed in the next sections. The characteristics of the variable feel side-stick controller were varied to allow evaluation of a fixed controller and two sets of stick motion characteristics for different values of control force command gain. Force commands were used in both the lateral and longitudinal axes. Therefore, force-response gains such as steady-state F_{Es}/n_z and F_{As}/p were unaffected by changes in feel system force/displacement gradient. The basic layout of the evaluation matrix is shown in Figure 1. Since the number of evaluations that could be performed was limited by available funding, it was decided to vary the longitudinal and lateral control force command gains simultaneously while attempting to maintain control harmony between the two axes. In addition to the basic airplane configuration defined in Table 1, two other up-and-away configurations were evaluated for the fixed and small-motion side controller at the medium control sensitivity. One configuration included a reduction in longitudinal short period damping ratio from $\zeta_{sp} = 0.6$ to 0.25 and the other looked at an increase in the lateral roll mode time constant from $\tau_R = 0.2$ to 1.0 seconds.

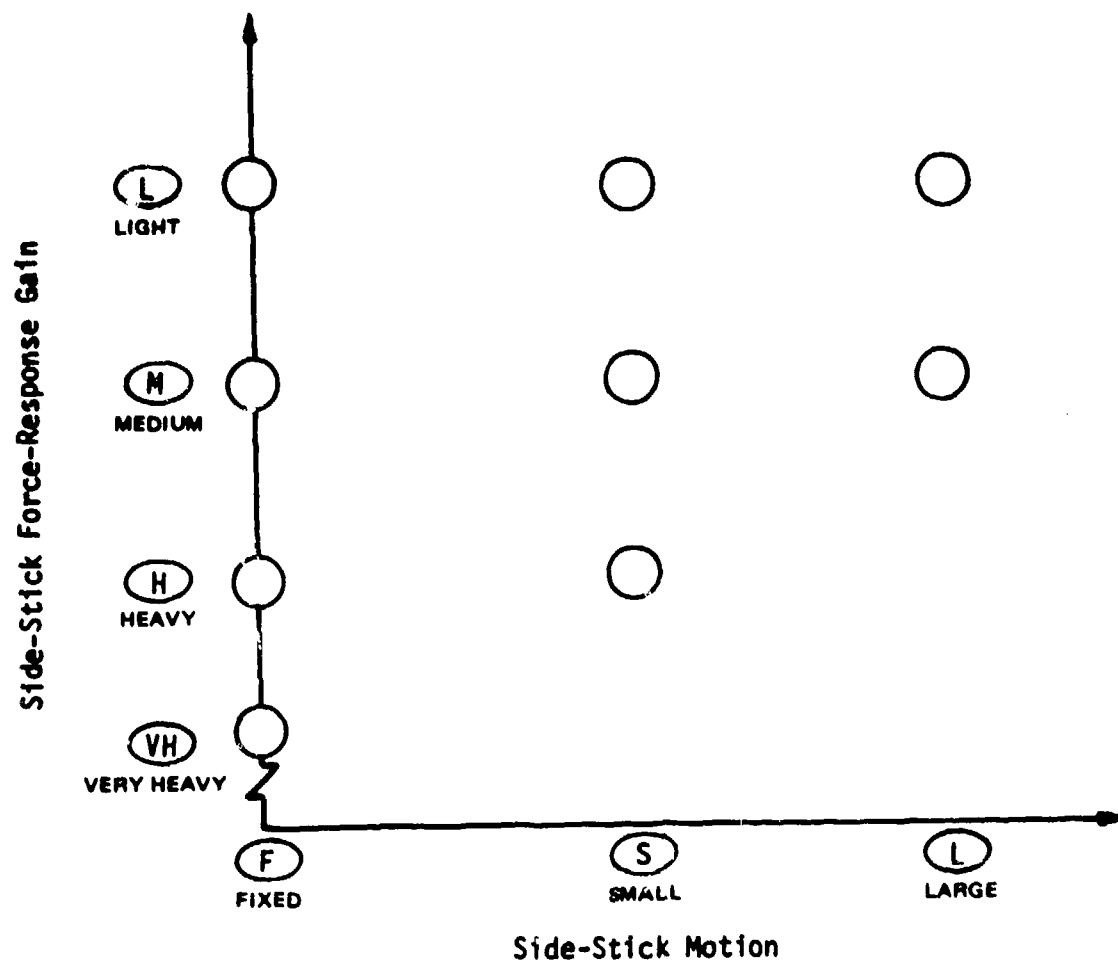
TABLE 1.
DYNAMIC CHARACTERISTICS OF SIMULATED AIRPLANE

	Up-and-Away Tasks (Flight Phase Category A)	Landing Approach Tasks (Flight Phase Category C)
V ft/sec	300	145
h ft	12000	4000
n_z/α g/rad	33	7
$1/\tau_{\theta_2}$	2.1	0.9
ω_{SP} rad/sec	5.0*	2.2
ζ_{SP}	0.6*	0.5
ω_p rad/sec	.09	.15
ζ_p	.05	.05
τ_R sec	.2**	0.5
τ_S sec	∞	∞
ω_d, ω_ϕ rad/sec	3.2	1.2
ζ_d, ζ_ϕ	0.4	0.25
$ \phi/B _d$	0.5	3

NOTE: * reduced to $\zeta_{SP} = 0.25$, $\omega_{SP} = 3.7$ rad/sec,
for additional configurations
(See Section 3.4)

** increased to 1.0 secs for additional
configurations (See Section 3.4)

*** The values of modal parameters are strictly
true only at the reference V and h . During
maneuvers the values vary with dynamic pressure.



Motion deg/lb			Force-Response Gain lb/g, lb/deg/sec	
Symbol	δ_{ES}/F_{ES}	δ_{AS}/F_{AS}	Symbol	$F_{ES}/n_z, F_{AS}/p$
F	0	0	L	see Figures 5, 6
S	.50	.77	M	
L	.91	1.43	H	
			VH	

Figure 1. Configuration Matrix for Both the Up-and Away and Landing Approach Tasks

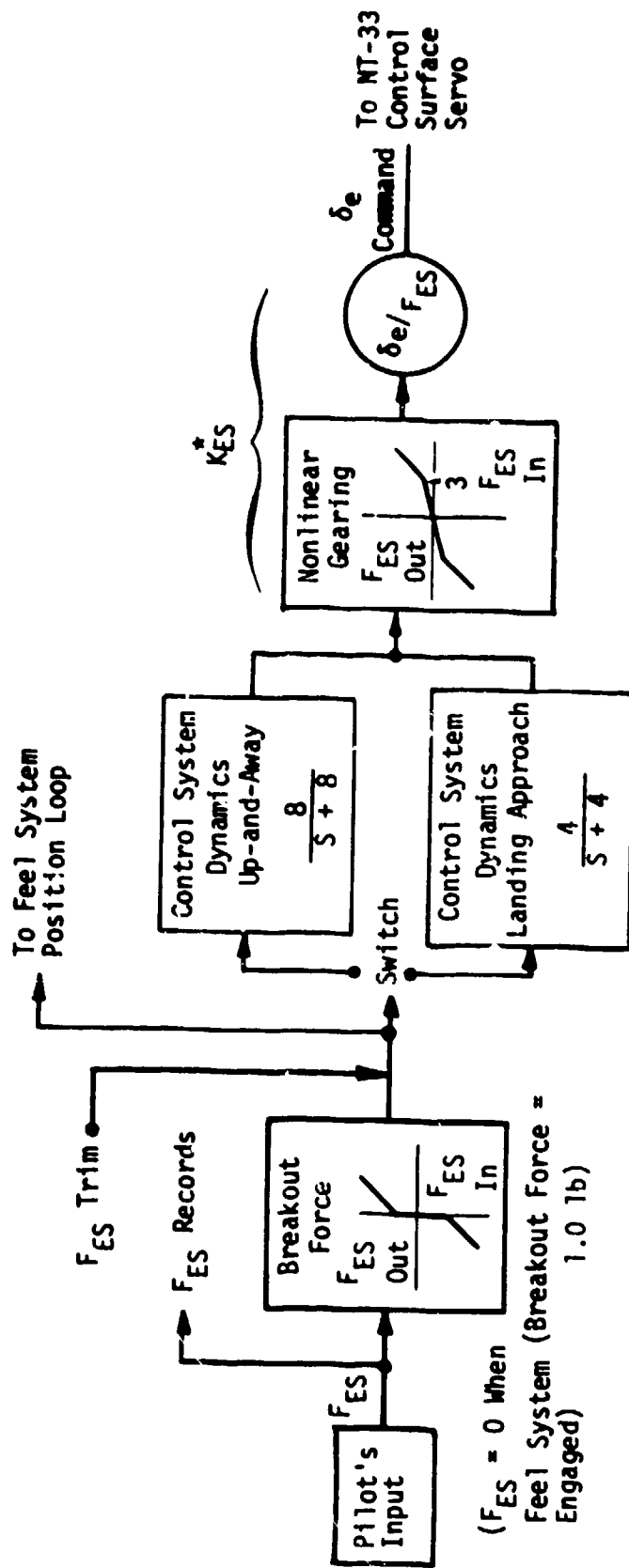
3.2 Control System Mechanization

The pitch and roll control systems for the simulated airplane were mechanized as shown in Figures 2 and 3. Force commands were used in both axes to command the appropriate control surface servo and surface deflection. For those configurations where side-stick motion was present, the feel system, which will be discussed in the next section, was in parallel with the force command channel. In other words, pilot-applied stick force commanded stick motion and also control surface motion. The stick force/deflection gradient and the control surface deflection per force input were therefore independently variable in this experiment.

Since the gearing or gain between stick force and control surface was nonlinear as shown in the schematic of the control system, the force-response gain was nonlinear. The details of the nonlinear stick force gain in pitch and roll are presented in Section 3.4 where the evaluation configuration characteristics are summarized.

Two first-order 20 rad/sec filters were included in the roll axis to suppress unwanted high-frequency "noise" in the roll force channel. These filter dynamics are felt to be far enough removed from the dominant roll dynamics so as not to be a significant factor in the lateral control response; however, they do attenuate high frequency force inputs and cause a small delay and high frequency phase shift. In the pitch channel two different first-order filters, one for each flight phase, were included as representative control system dynamics for a highly augmented fighter airplane. A breakout force of 1.0 lb was included in both the pitch and roll command channels.

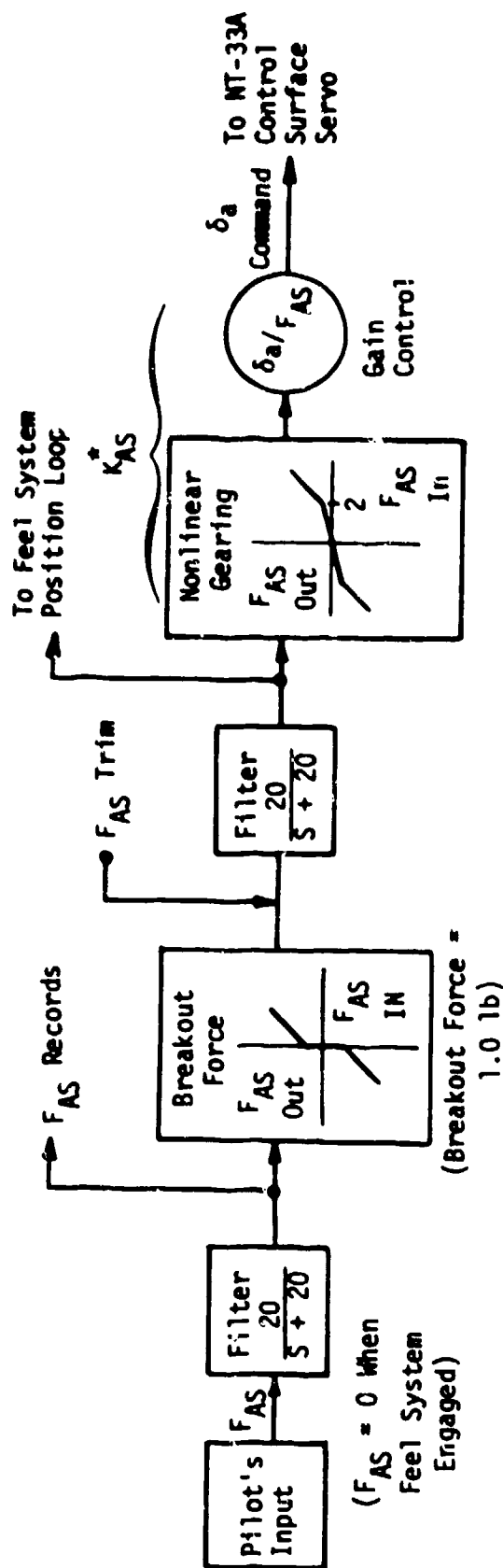
The rudder command channel was mechanized in a simple linear fashion using position commands with a very high force/displacement gearing to effectively simulate a force command system. No additional control system dynamics were introduced into the rudder command channel.



Up-and-Away (Flight Phase Category A)	$\delta_e \text{ Command} = K_{ES}^* \left(\frac{8}{s+8} \right) F_{ES}$
Landing Approach (Flight Phase Category C)	$\delta_e \text{ Command} = K_{ES}^* \left(\frac{4}{s+4} \right) F_{ES}$

* Nonlinear Gain

Figure 2. Mechanization of Pitch Command Channel



$$\delta_a \text{ Command} = K_{AS}^* \left(\frac{20}{s+20} \right)^2 F_{AS}$$

* Nonlinear Gain

Figure 3. Mechanization of Roll Command Channel

3.3 Feel System Mechanization

As discussed in the previous section, the feel system was mechanized in parallel with the force command channels to the pitch and roll control surfaces. The simplified block diagram shown in Figure 4 illustrates this concept and documents the force/displacement transfer function for the feel systems. Section 3.7.2 discusses the features of the side-stick controller in more detail.

The gradients of force versus displacement, F/δ , used in this experiment, along with the identification symbols used through this report, are:

Symbol	$1/K_{FS}$	
	F_{ES}/δ_{ES}	F_{AS}/δ_{AS}
F	Fixed	Fixed
S	2.0 lb/deg (27 lb/in.)	1.3 lb/deg (17 lb/in.)
L	1.1 lb/deg (15 lb/in.)	0.7 lb/deg (9 lb/in.)

NOTE: Distance from side stick pivot to finger reference = 4.25 in.

For the Rudder: $F_{RP}/\delta_{RP} = 120$ lb/in. and δ_{RP} limits ± 0.5 in.

3.4 Summary of Configuration Characteristics

Since nonlinear gearings were used in pitch and roll, the steady-state airplane responses are nonlinear functions of the stick force. The command force per steady-state pitch and roll response are plotted in Figures 5 and 6, for the two flight phases, in the form of elevator stick force versus steady-state normal acceleration (F_{ES}/n_g) and aileron stick force versus steady-state roll rate (F_{AS}/p). The symbols shown, L, M, H and VH, will be used throughout the report to identify the levels of nonlinear command force-

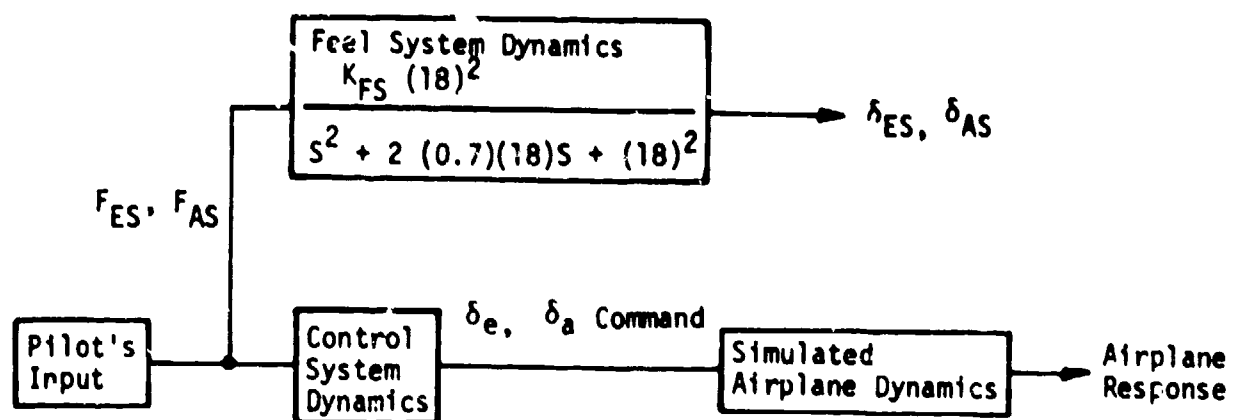


Figure 4. Feel System Mechanization

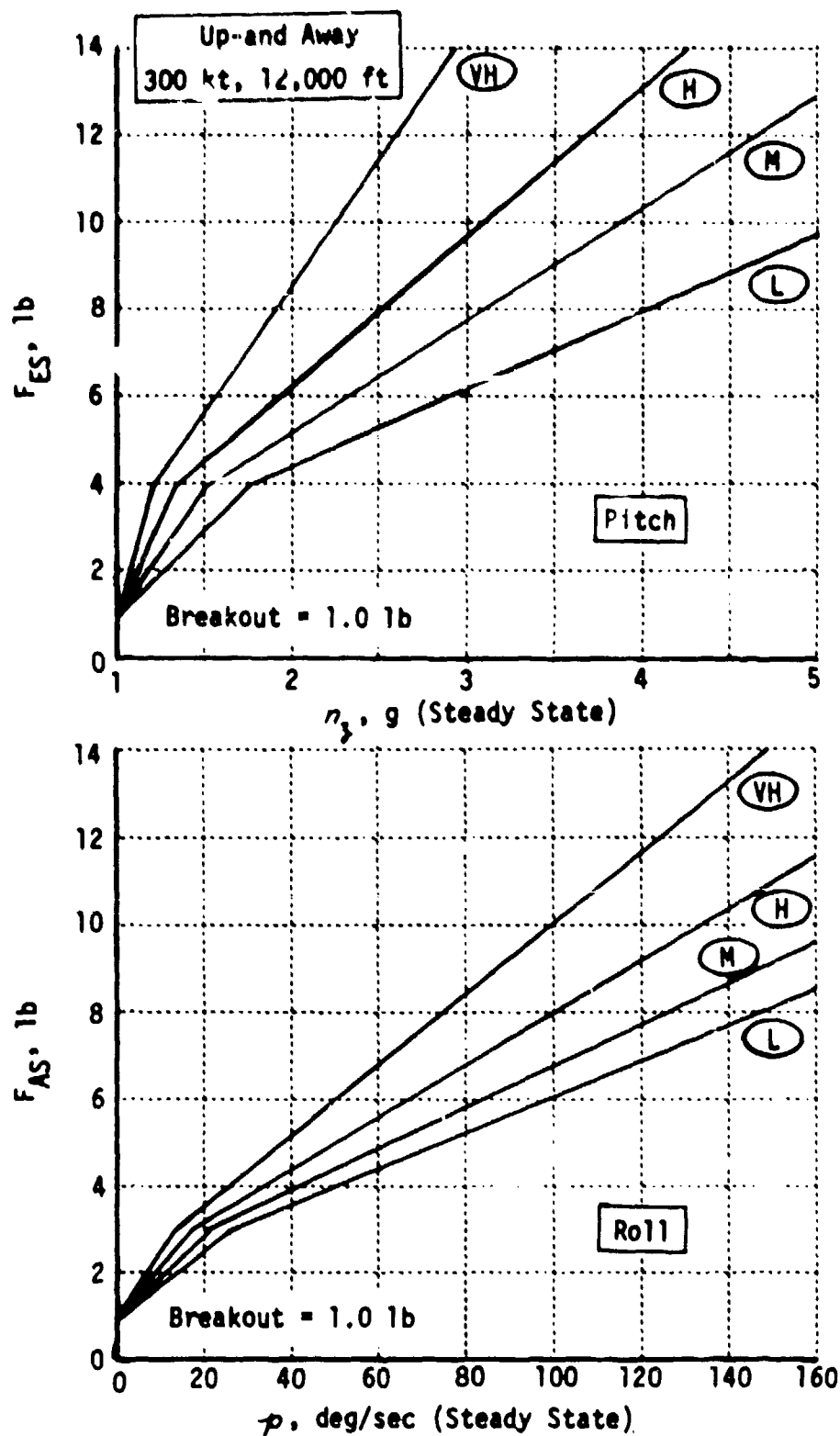


Figure 5. Control Force-Response Gains, Up-and-Away
(Flight Phase Category A)

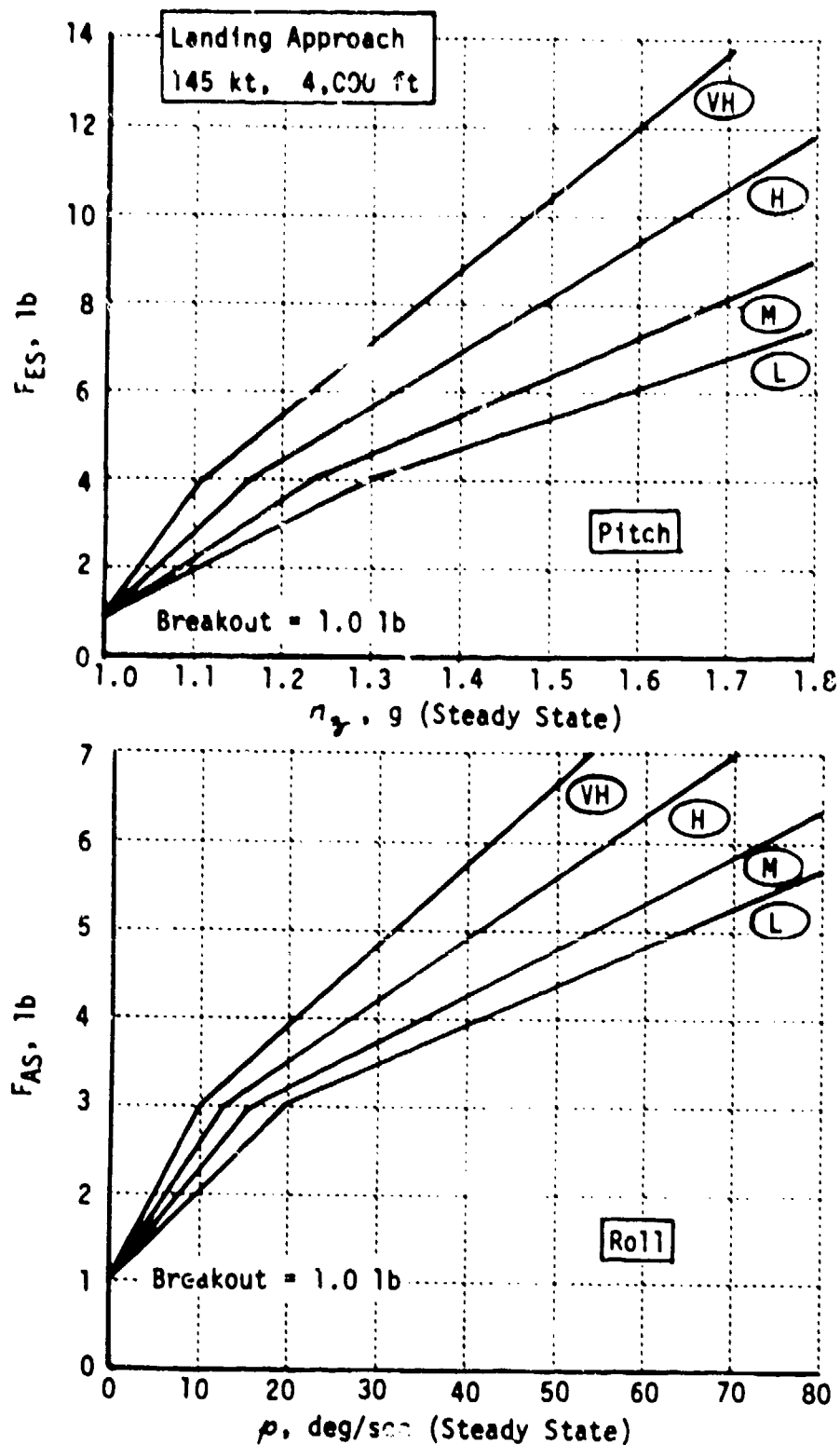


Figure 6. Control Force Response Gains, Landing Approach
(Flight Phase Category C)

response gains. These symbols refer to light, medium or nominal, heavy, and very heavy side-stick forces. The levels are for identification purposes within this experiment and should not be considered as absolute indicators of control force-response gain levels. For example, the configurations identified as H had low values of control force gain and therefore the stick force required to achieve a given steady-state response was heavy.

The rudder control sensitivity used was approximately:

<u>Up-and-Away</u>	<u>Landing Approach</u>
$N_{FRP} \sim .019 \frac{\text{rad/sec}^2}{\text{lb}}$	$.004 \frac{\text{rad/sec}^2}{\text{lb}}$

Each configuration consisted of a set of simulated airplane dynamics, a selected pair of nonlinear pitch/roll command force-response gains (L, M, H or VH) and a level of side-stick controller motion (fixed, F; small, S; large, L). Nine configurations were evaluated at each flight condition, plus four additional up-and-away configurations with changes in longitudinal short period damping ratio, ζ_{sp} , or lateral roll mode time constant, τ_R .

Summarizing the information in Sections 3.1, 3.2 and 3.3, the approximate constant-speed normal acceleration and roll rate transfer functions for side-stick force inputs are listed below:

Up-and-Away (Flight Phase Category A):

$$\frac{n_z}{F_{ES}} = \frac{K_{n_z}^*}{\underbrace{\left(\frac{s}{8} + 1\right)}_{\text{CONTROL SYSTEM}} \underbrace{\left(\frac{s^2}{5} + \frac{2(0.6)s}{5} + 1\right)}_{\text{SHORT PERIOD}} \underbrace{\left(\frac{s^2}{60^2} + \frac{2(0.7)s}{60} + 1\right)}_{\text{CONTROL SURFACE SERVO DYNAMICS}}}$$

$$\frac{p}{F_{AS}} = \frac{K_p^*}{\underbrace{\left(\frac{s}{20} + 1\right)^2}_{\text{STICK FORCE FILTER}} \underbrace{(.2s + 1)}_{\text{ROLL MODE}} \underbrace{\left(\frac{s^2}{60^2} + \frac{2(0.7)s}{60} + 1\right)}_{\text{CONTROL SURFACE SERVO DYNAMICS}}}$$

Two configurations with the nominal force-response gain (M), one with a fixed stick (F) and the other with small stick motion (S), were evaluated with ζ_s , reduced to 0.25 (from 0.6). In addition, the same two nominal configurations were evaluated with τ_R increased to 1.0 secs (from 0.2 secs). In each case, the command channel gains were adjusted to retain approximately the nominal (M) steady-state control force-response gains shown in Figure 5.

Landing Approach (Flight Phase Category C):

$$\frac{n_z}{F_{ES}} = \frac{K_{n_z}^*}{\left(\frac{s}{4} + 1\right) \left(\frac{s^2}{2.2^2} + \frac{2(0.5)s}{2.2} + 1\right) \left(\frac{s^2}{60^2} + \frac{2(0.7)s}{60} + 1\right)}$$

$$\frac{P}{F_{AS}} = \frac{K_P^*}{\left(\frac{s}{20} + 1\right)^2 (.5s + 1) \left(\frac{s^2}{60^2} + \frac{2(0.7)s}{60} + 1\right)}$$

* steady-state nonlinear gain shown in Figures 5 and 6.

3.5 Evaluation Pilots

The two evaluation pilots used in the program were both members of the U.S. Air Force Test Pilot School staff and have extensive flight and test pilot experience. Pilot A had over 4000 hours total flight time with 550 hours considered flight test experience. Pilot B had over 3800 hours with 800 hours of flight test experience.

To ensure that the configurations were evaluated against a common criterion, the pilots were briefed collectively on the evaluation tasks, maneuvers, rating scale (Figure 7) and comment cards. Although the general experimental design was discussed during the pre-evaluation briefing, the

pilots were not given prior knowledge about the specific configurations to be evaluated.

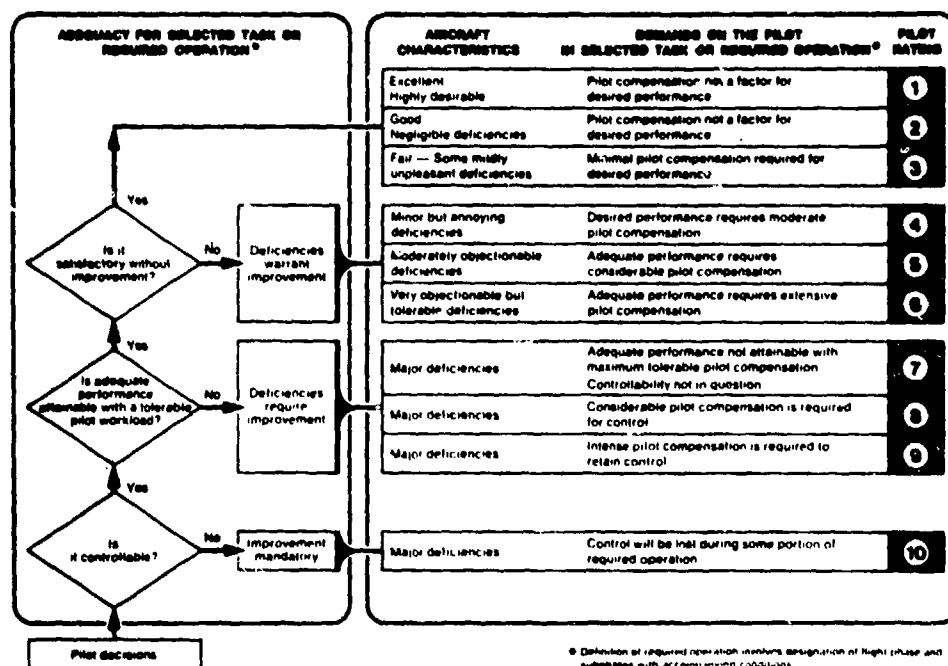


Figure 7. Cooper-Harper Pilot Rating Scale

Pilot comment data was the major source for determining why a pilot liked or disliked a particular configuration and therefore the reasons for his pilot rating. The pilots were instructed to make pilot comments at any time they wished but were required to make specific comments about the items listed on the comment cards. The complete pilot comment card is reproduced below:

UP-AND-AWAY PILOT COMMENT CARD

- A. Make any general comments pertinent to evaluation (task performance)
- B. Make specific comments about:
 - 1) Ability to trim (did you trim?)
 - 2) Stick forces
 - 3) Stick motion
 - 4) Control harmony
 - 5) Predictability of airplane response to pilot inputs
 - 6) General airplane control (longitudinal and lateral-directional)
 - a) During close formation, pilot rating
 - b) During air-to-air tracking, pilot rating
 - c) During maneuvering flight, pilot rating
 - 7) Effects of turbulence
- C. Summary comments:
 - 1) Good features
 - 2) Objectionable features
 - 3) Special piloting techniques
 - 4) Pilot rating based on mission task
 - 5) Give primary reasons for ratings

LANDING APPROACH PILOT COMMENT CARD

- A. Make any general comments pertinent to evaluation (task performance)

- B. Make specific comments about:
 - 1) Ability to trim (did you trim?)
 - 2) Stick forces
 - 3) Stick motion
 - 4) Control harmony
 - 5) Predictability of airplane response to pilot inputs
 - 6) General airplane control (longitudinal and lateral-directional)
 - a) During approach to runway
 - b) During flare and touchdown
 - c) On closed pattern
 - 7) Effects of turbulence/crosswinds

- C. Summary comments:
 - 1) Good features
 - 2) Objectionable features
 - 3) Special piloting techniques
 - 4) Pilot rating based on mission task
 - 5) Give primary reasons for ratings

Pilot A evaluated all of the configurations and Pilot B evaluated 14 of the 22 configurations. Sufficient repeat evaluations were provided for both pilots to determine pilot repeatability.

3.6 Evaluation Procedures

The evaluation mission was defined in the context of a high performance fighter including up-and-away tasks (Flight Phase Category A) of formation flying, air-to-air tracking and acrobatics, and landing approach tasks (Flight Phase Category C) consisting of an ILS approach and closed pattern touch-and-go landings.

The up-and-away evaluations were performed about a nominal speed and altitude of 300 kts and 12,000 feet with a target airplane. Evaluation instructions were as follows:

- (1) Check ability to trim.
- (2) Perform small maneuvers about level flight or other maneuvers to obtain familiarization with the configuration and to investigate the acceptability of the control system sensitivities.
- (3) Join on the target airplane and fly loose parade formation. Tighten up the formation compatible with the airplane handling qualities and safety considerations. Drop back and fly in trail formation during larger target airplane maneuvers.
- (4) Assume a "perch" position above, behind and laterally displaced from the target airplane. Close and track the target airplane, at ranges between 1000 and 1500 ft, to obtain steady tracking information. Assume an offensive role while the target airplane performs defensive maneuvers.

- (5) Assume a defensive role as the target airplane assumes a perch position and attempts to close and track the NT-33A.
- (6) Independent of the target airplane, perform sufficient rolling and overhead acrobatic maneuvers to assess the gross maneuvering capability of the configuration.
- (7) Relinquish control of the airplane to the safety pilot, complete the pilot comment card and provide separate Cooper-Harper ratings for the formation, air-to-air tracking, and acrobatics tasks as well as for the overall configuration.

The landing approach evaluations were performed at a nominal approach speed of 145 kts. The evaluation instructions were as follows:

- (1) Perform small maneuvers about level flight or other maneuvers to obtain familiarization with the configuration and to investigate the acceptability of the control system sensitivities.
- (2) Perform an ILS approach to a touch-and-go landing.
- (3) Operating in a closed pattern, perform sufficient touch-and-go landings to evaluate the configuration in the landing approach phase.
- (4) Relinquish control of the airplane to the safety pilot, complete the pilot comment card and provide a Cooper-Harper rating for the configuration.

3.7 Equipment

3.7.1 NT-33A Aircraft

The aircraft used for the flight evaluations was the USAF variable stability NT-33A, shown in Figure 8 and described in detail in Reference 1. Briefly, the NT-33A airplane is an in-flight simulator capable of reproducing with a high degree of fidelity the dynamic response and control system characteristics of an entirely different airplane. The response feedback variable stability system modifies the static and dynamic responses of the basic NT-33A by commanding control surface positions through full authority electrohydraulic servos. The front cockpit controls are disconnected from the NT-33A control system, and the evaluation configurations are flown from the front cockpit through a fly-by-wire control system. A programmable analog computer, associated aircraft response sensors, control surface servos, and an electrohydraulic force-feel system provide the total simulation capability. The safety pilot can vary the computer gains through controls located in the rear cockpit and thus change the airplane dynamics and control system characteristics in flight.

3.7.2 Variable Feel Side-Stick Controller

The electrohydraulic variable feel side-stick controller is shown in Figures 9 and 10 and described in Reference 2. This side stick is capable of operating as a rigid stick with force commands to the aircraft surface servos or it can be operated as a moving control in both pitch and roll with independently variable spring gradients in each axis. When stick motion is permitted, the control surfaces can be commanded with either control force or control motion. The characteristics of the side-stick controller can be varied by the safety pilot in flight.

-
1. Hall, G.W. and R.W. Huber: "System Description and Performance Data for the USAF/CAL Variable Stability NT-33A Airplane," AFFDL-TR-70-71, June 1970.
 2. Hall, G.W., R.W. Huber and W. Close: "Development of an Airplane Electrohydraulic Variable Feel Side-Stick Flight Controller," Calspan Report No. AK-5280-F-3, September 1974.



Figure 8. NT-33A Variable Stability Aircraft

FORWARD



Figure 9. Variable Feel Side-Stick Controller Installed in Variable Stability NT-33

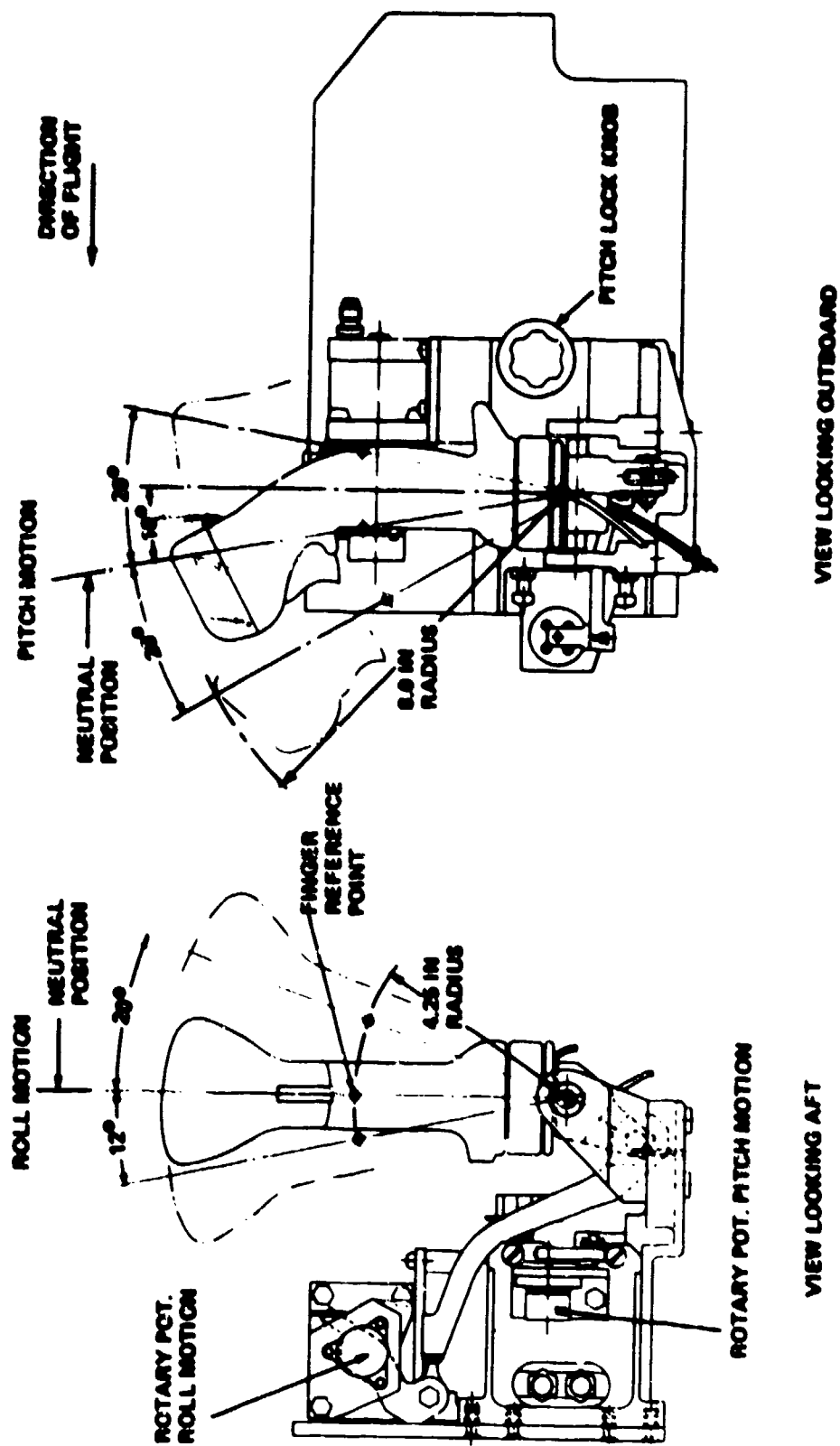


Figure 10. Side-Stick Motion Limits

Section IV

DISCUSSION OF EXPERIMENTAL RESULTS

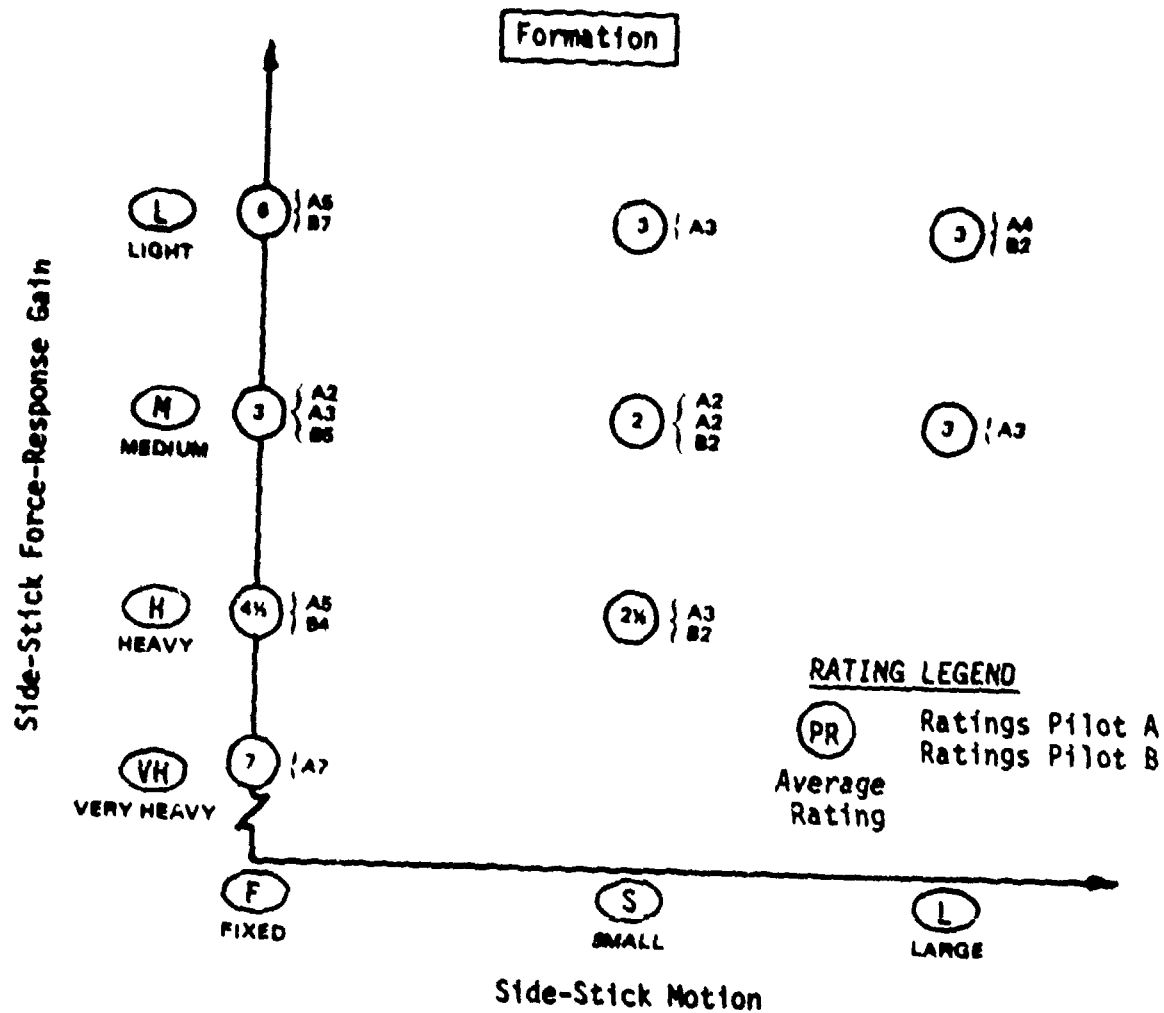
This section summarizes and discusses the effects of variations in side-stick force-command gain and stick motion on the flying qualities of an advanced fighter aircraft. The results of the experiment which was described in the preceding sections are in the form of pilot ratings and pilot comments. A complete summary of the pilot ratings and pilot comment summaries for all the tasks evaluated in both the up-and-away and landing approach flight phases, is presented in Appendix A.

For clarity in ascertaining trends, the results are presented in the following sections in the form of "averaged" pilot ratings. The individual pilot ratings are also shown on each figure. These "averaged" pilot ratings represent the average of all the evaluations for a given configuration and are therefore simple averages. The first sections discuss the results for the up-and-away tasks (Flight Phase Category A) followed by a discussion of the landing approach evaluations (Flight Phase Category C). Two general observations are worth making at this point: at no time did the evaluation pilots notice the non-linearity in their control force responses, and the results which follow were all obtained in essentially smooth conditions with no crosswinds present. Insufficient data were obtained in crosswinds and significant turbulence to warrant inclusion in this report, however, it can be stated that crosswinds did tend to degrade pilot performance and pilot rating.

4.1 Close Formation Task

As discussed in Section 3.6, the evaluation pilots were asked to give separate pilot ratings (PR) for each of the up-and-away tasks as well as an overall rating for the mission. The averaged pilot ratings for the close formation task are presented in Figure 11 for each of the configurations evaluated.

For the configurations evaluated with a fixed side stick (F), there is a sharp gradient in PR with variations in control force gain with the nominal configuration (M) receiving the best rating. In each case, the introduction of



Motion deg/lb			Force-Response Gain lb/g, lb/deg/sec	
Symbol	δ_{ES}/F_{ES}	δ_{AS}/F_{AS}	Symbol	$F_{ES}/n_z, F_{AS}/p$
F	0	0	L	see Figures 5, 6
S	.50	.77	M	
L	.91	1.43	VH	

Figure 11. Pilot Rating Data for Formation Task

some stick motion (S) improves the rating, particularly for the case with the lightest force-response gain (L). As previously explained, the force-response gain and motion variations were made simultaneously in both the pitch and roll axes of the side stick. Although not specifically optimized, these variations were designed to retain good control harmony. The results further indicate that for the formation task the pilot is insensitive to the amount of motion present after the initial improvement shown with the smallest motion studied (S).

4.2 Air-to-Air Tracking Task

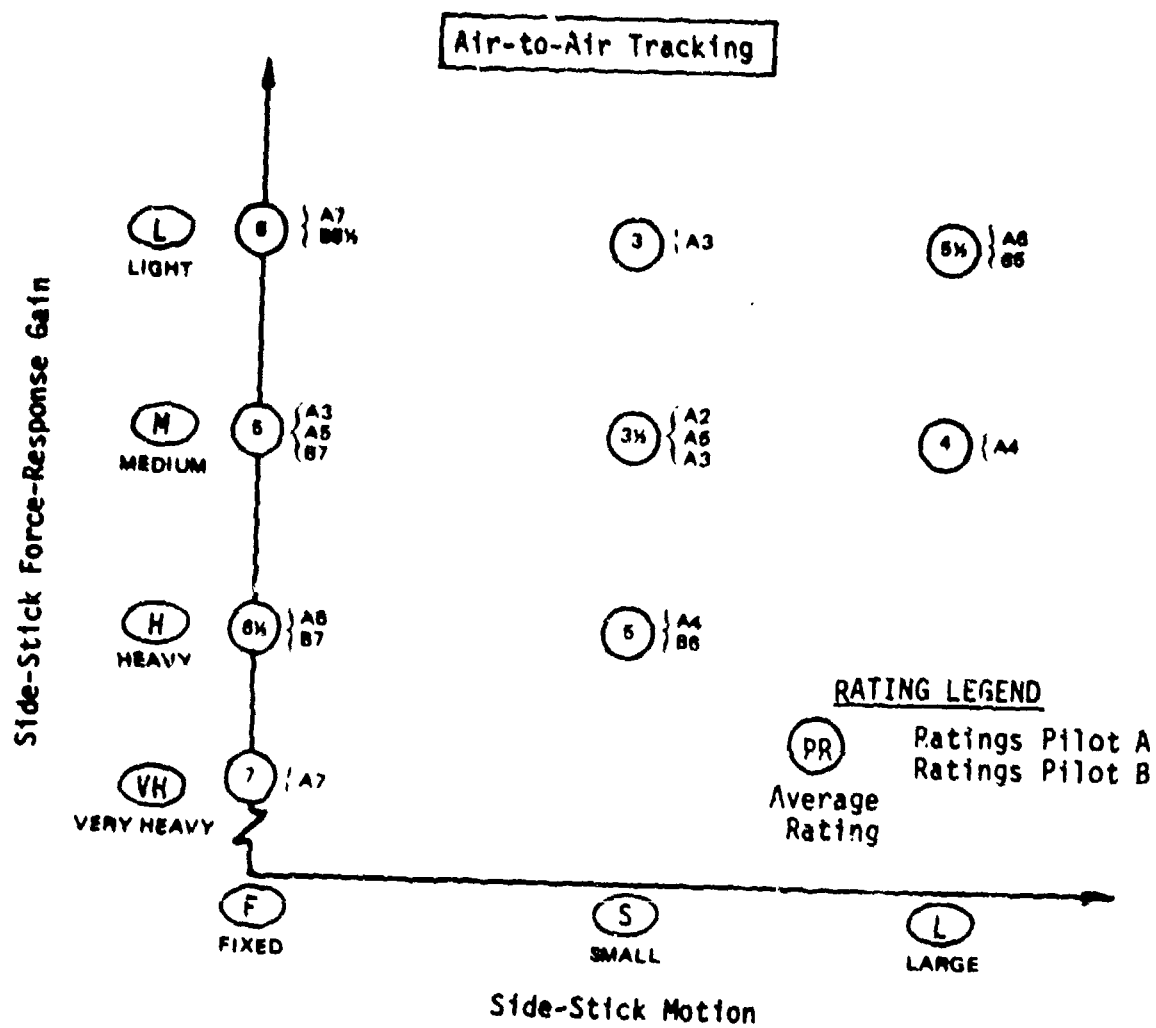
The pilot rating results for the air-to-air tracking task evaluations are shown in Figure 12. This task was more demanding in terms of the aircraft flying qualities than the formation task. Again, the ratings for the fixed stick (F) show a sharp gradient in rating with the nominal configuration (M) receiving the best rating. For this task the introduction of stick motion is clearly beneficial for the medium (M) and lightest (L) force-response gain configurations, while further increases in motion result in a degradation in pilot rating.

4.3 Gross Maneuvering Task

For the acrobatic or gross maneuvering task, the results are very similar to those presented for the formation task and are shown in Figure 13.

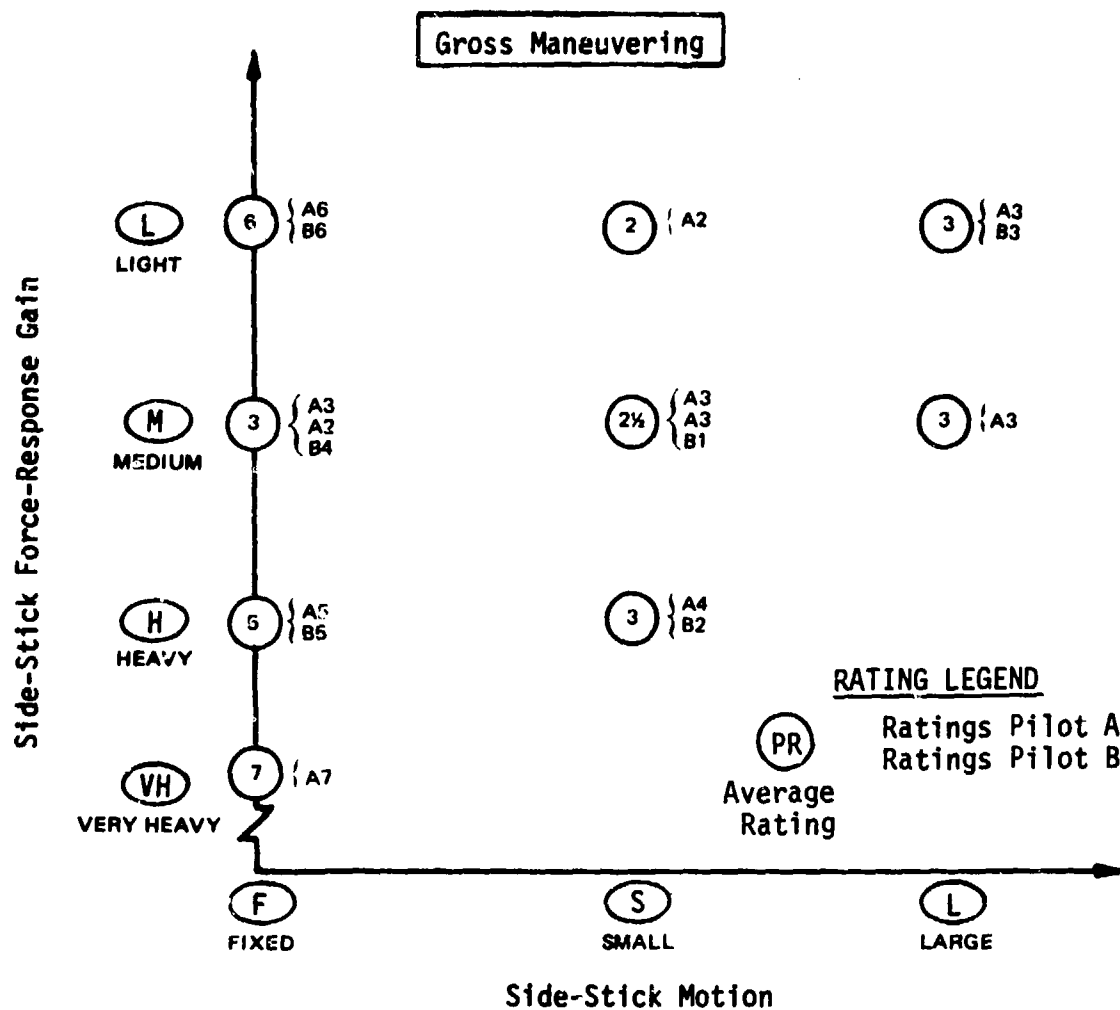
4.4 Overall Up-and-Away Fighter Mission (Flight Phase Category A)

Each up-and-away evaluation was summarized in the form of an overall pilot rating for the mission which consisted of the three tasks previously presented: formation, air-to-air tracking and gross maneuvering. These averaged overall ratings are presented in Figure 14 for each configuration.



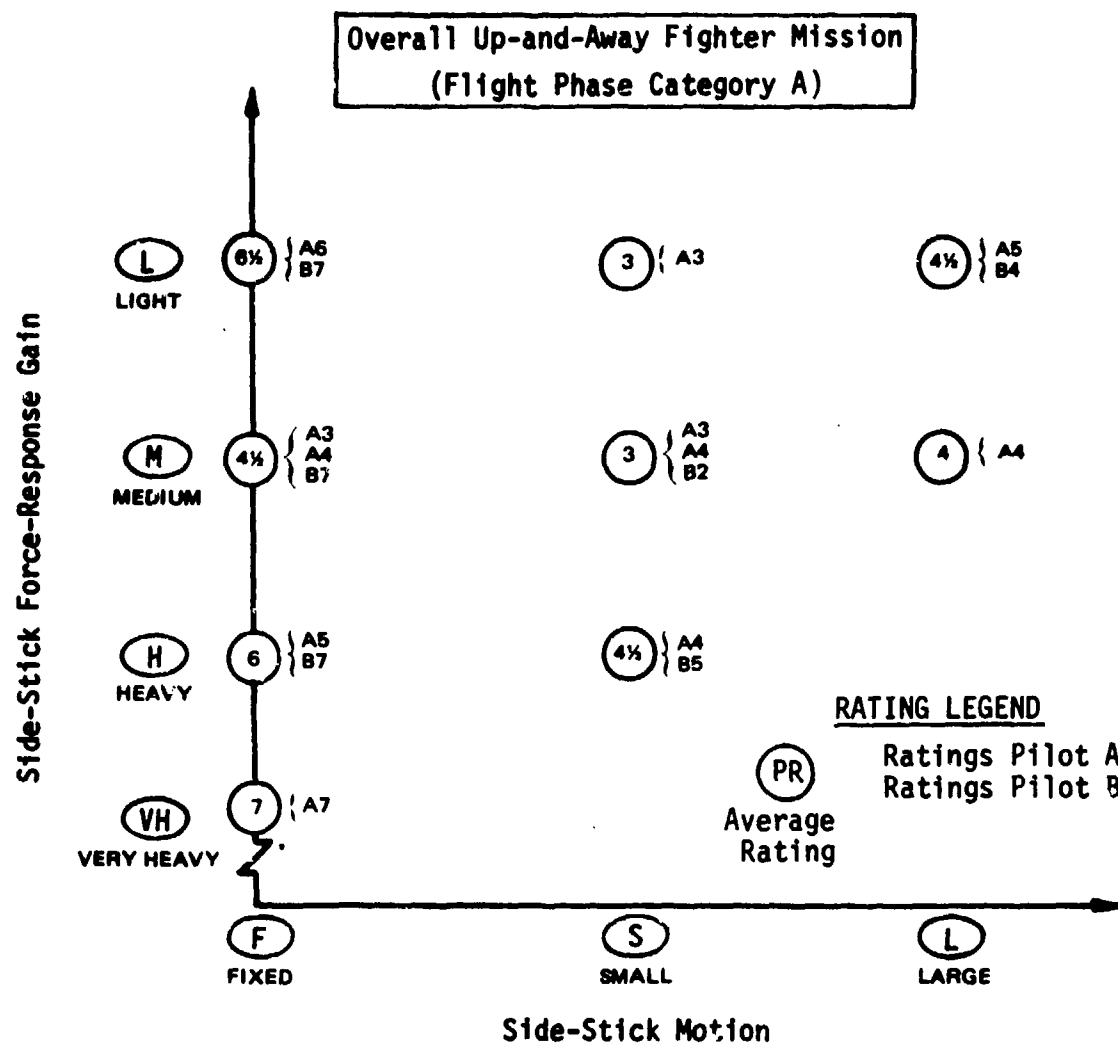
Motion deg/lb			Force-Response Gain lb/g, lb/deg/sec	
Symbol	δ_{ES}/F_{ES}	δ_{AS}/F_{AS}	Symbol	$F_{ES}/n_z, F_{AS}/p$
F	0	0	L	see Figures 5, 6
S	.50	.77	M	
L	.91	1.43	H	
			VH	

Figure 12. Pilot Rating Data for Air-to-Air Tracking Task



Motion deg/lb			Force-Response Gain lb/g, lb/deg/sec	
Symbol	δ_{ES}/F_{ES}	δ_{AS}/F_{AS}	Symbol	$F_{ES}/n_z, F_{AS}/p$
F	0	0	L	see Figures 5, 6
S	.50	.77	M	
L	.91	1.43	H	
			VH	

Figure 13. Pilot Rating Data for Gross Maneuvering Task



Motion deg/lb			Force-Response Gain lb/g, lb/deg/sec	
Symbol	δ_{ES}/F_{ES}	δ_{AS}/F_{AS}	Symbol	$F_{ES}/n_z, F_{AS}/p$
F	0	0	L	see Figures 5, 6
S	.50	.77	M	
L	.91	1.43	H VH	

Figure 14. Overall Pilot Rating Data for Up-and-Away Fighter Mission

The overall results for the fixed stick indicate that the aircraft was unsatisfactory ($PR \leq 3.5$) for all values of force-response gain tested; the best rating was again the nominal value of force-response gain (M). Although this configuration does not necessarily represent the optimum force-response gain value for the fixed stick, the data do indicate that the fixed stick is very sensitive to the value of force-response gain selected. In other words, the range of reasonable values of force-response gain is quite restricted for the fixed stick. For the lighter force-response gain cases (L, M), the primary complaints were centered around the oversensitivity of the pitch axis; whereas for the heavier force-response gain cases (H, VH) the problems were related to heavy forces and overcontrolling, particularly in the roll axis.

In all cases, the addition of a small amount of control motion (S) improved the PR, particularly for the lightest force-response gain configuration (L) where the rating changed from $PR = 6.5$ to 3. In this case, the aircraft was overly sensitive with the fixed stick but the small amount of motion apparently smooths the pilot's input insufficiently to reduce the initial response to a satisfactory level; the stick motion apparently acts like a filter on the pilot's stick force input, much like an electronic prefilter would.

Further increases in control motion for the two lighter force-response gain cases (L, M) result in a degradation in the flying qualities, although the gradient of the changes in PR is small. This degradation is associated with a renewed tendency to overcontrol although the source of this problem is not initial abruptness, as is the case for the fixed stick, but sluggish initial response. The excessive motion apparently interferes with the pilot's force input to the control surface to an extent that the predictability of the response is degraded.

For a given amount of motion (S or L), the results indicate that there is no gradient in PR with changes in force-response gain particularly for the two higher force-response gains tested (L, M). This result is in contrast to the fixed stick cases and indicates that with a little motion, a greater range of

force-response gains can be used satisfactorily.

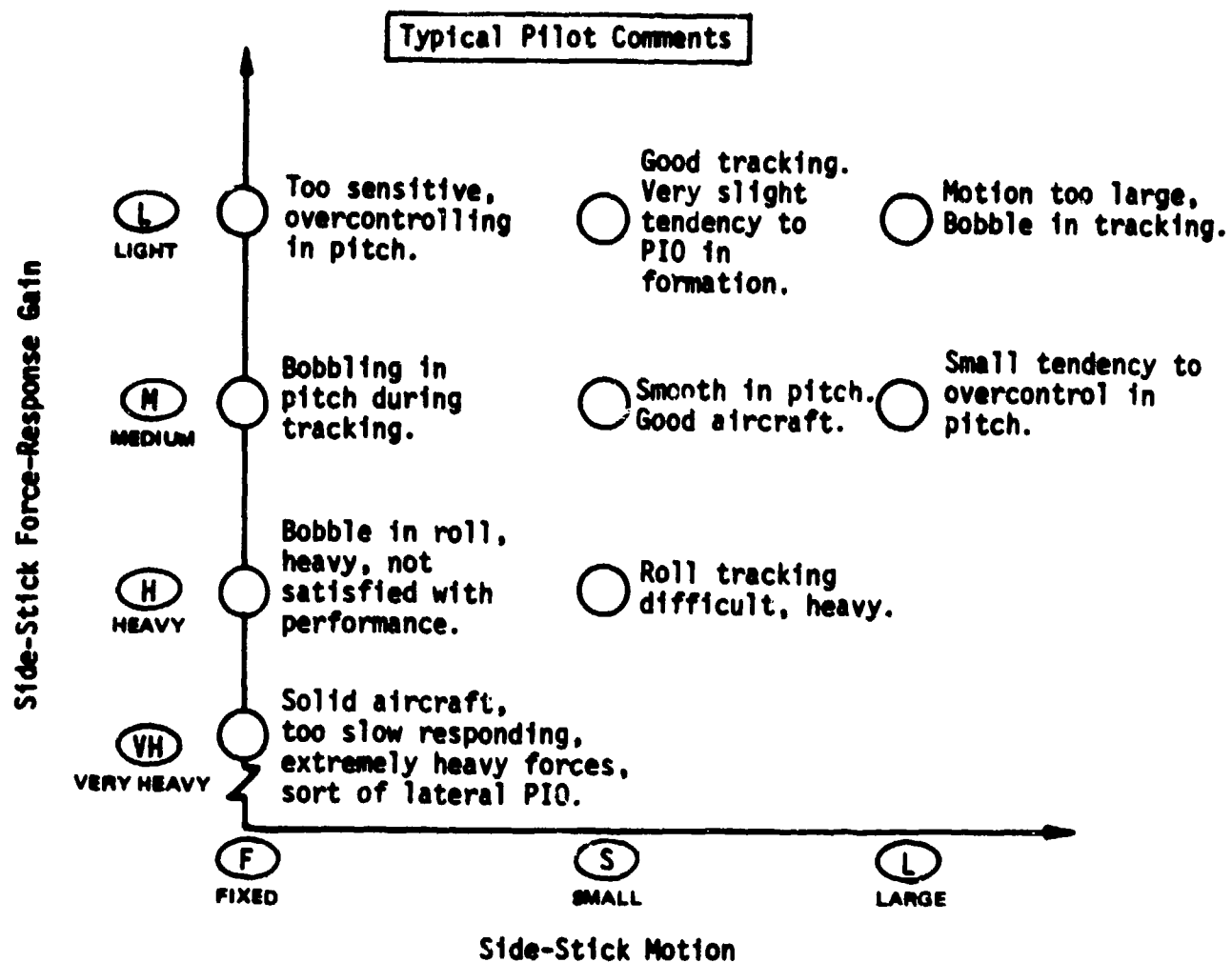
Typical pilot comments are presented in Figure 15 while the results of the up-and-away evaluations (Flight Phase Category A) may be summarized as follows:

- The fixed side stick was not satisfactory ($PR \leq 3.5$) for the up-and-away fighter mission.
- The two configurations with the lighter force-response gains (L, M) were improved to a satisfactory rating ($PR \leq 3.5$) by including a small amount of control stick motion.
- Control stick motion reduced the abruptness of the initial response and, used judiciously, can be beneficial in improving the flying qualities of an overly sensitive airplane.
- Selection of the value of control force-response gain for a fixed stick was more critical than when stick motion was present.
- The air-to-air tracking task was the most critical of the up-and-away tasks.

4.5 Additional Configurations

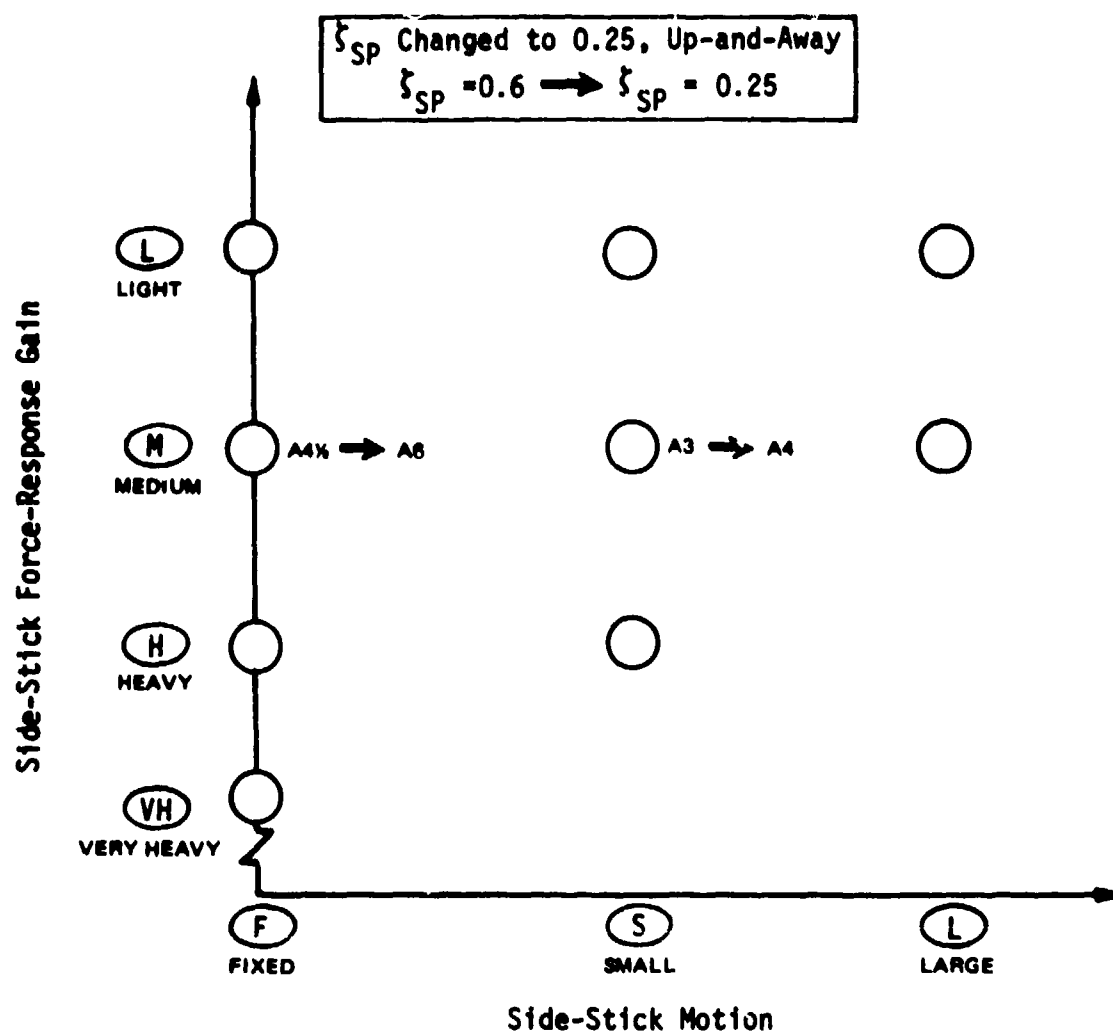
Two configurations with nominal force-response gain (M) and two levels of stick motion, fixed (F) and small (S) were selected for variations in short-period damping ratio, ζ_{sp} , and roll mode time constant, τ_R . The results of varying ζ_{sp} from the nominal value of 0.6 to 0.25 are presented in Figure 16; Figure 17 shows the pilot rating change with a variation in τ_R from 0.2 to 1.0 secs.

In both cases, the effect of the variation is most pronounced for the fixed stick configuration (F) while the configuration with small motion shows little change in pilot rating. While the data base is obviously limited, it appears that a fixed stick is more sensitive to small changes in characteristics



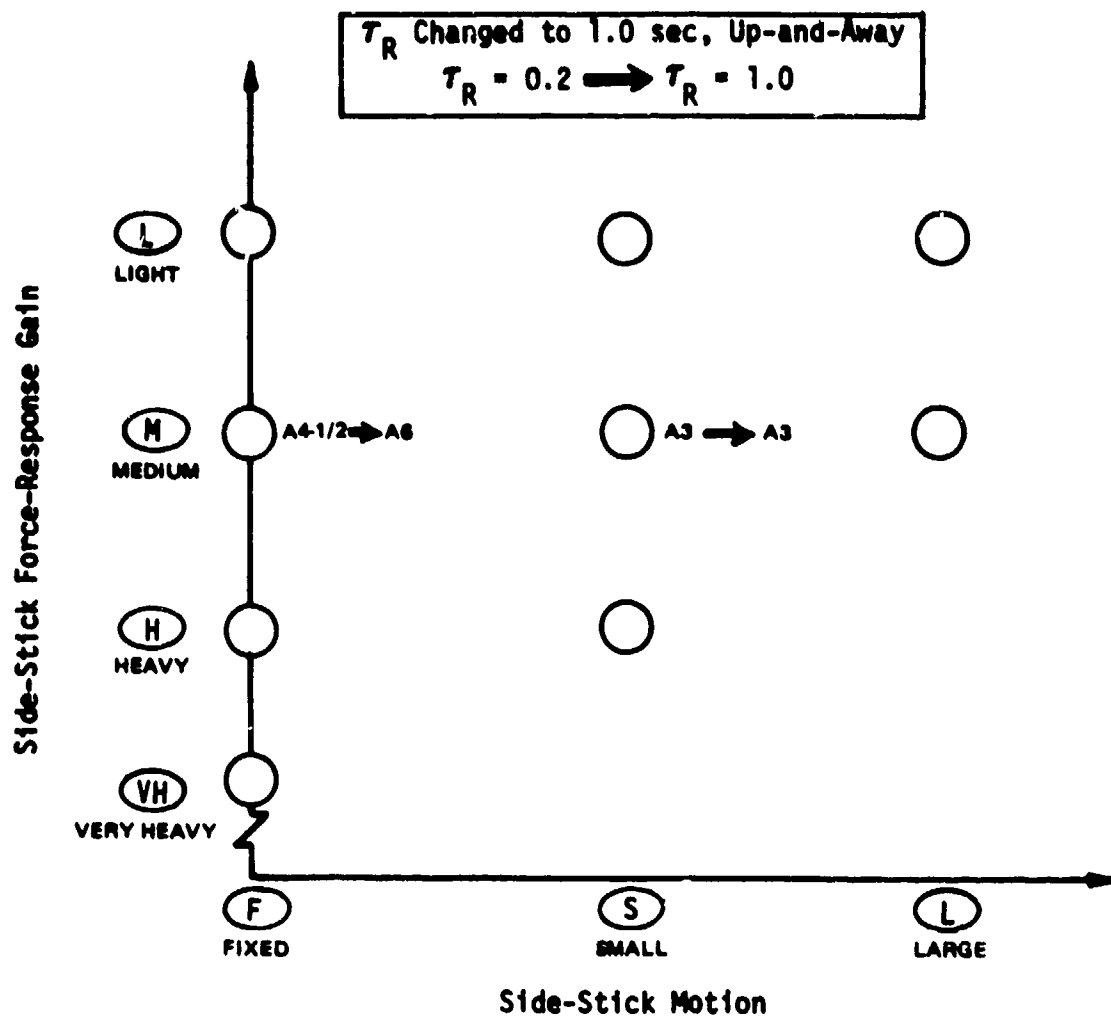
Motion deg/lb			Force-Response Gain lb/g, lb/deg/sec	
Symbol	δ_{ES}/F_{ES}	δ_{AS}/F_{AS}	Symbol	$F_{ES}/n_z, F_{AS}/p$
F	0	0	L	see Figures 5, 6
S	.50	.77	M	
L	.91	1.43	H	
			VH	

Figure 15. Typical Pilot Comments for Up-and-Away Fighter Mission



Motion deg/lb			Force-Response Gain lb/g, lb/deg/sec	
Symbol	δ_{ES}/F_{ES}	δ_{AS}/F_{AS}	Symbol	$F_{ES}/n_z, F_{AS}/p$
F	0	0	L	see Figures 5, 6
S	.50	.77	M	
L	.91	1.43	H	
			VH	

Figure 16. Effect on Overall Pilot Rating of Decreasing ζ_{SP}



Motion deg/lb			Force-Response Gain lb/g, lb/deg/sec	
Symbol	δ_{ES}/F_{ES}	δ_{AS}/F_{AS}	Symbol	$F_{ES}/n_z, F_{AS}/p$
F	0	0	L	see Figures 5, 6
S	.50	.77	M	
L	.91	1.43	H	
			VH	

Figure 17. Effect on Overall Pilot Rating of Increasing τ_R

which affect the precision of control. Increases in τ_R impact on the precision of bank angle tracking and a reduction in ζ_{SP} degrades the predictability of the pitch response. A similar trend was discussed in the previous section where the results indicated that the fixed stick configurations are more sensitive to variations in control gain.

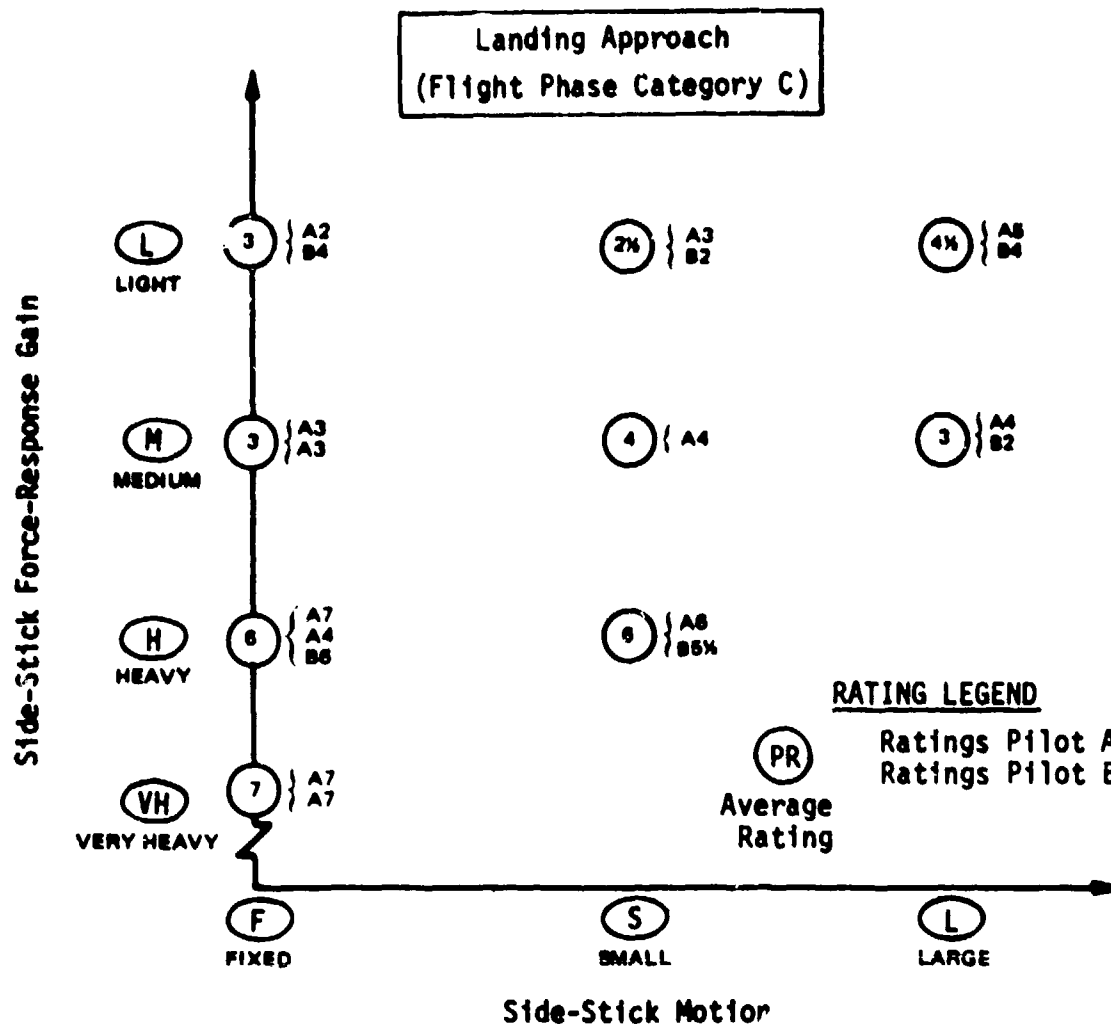
In summary, then, configurations with a small amount of control motion are apparently less sensitive to small variations in parameters such as ζ_{SP} , τ_R and force-response gain than the same configuration with a fixed side stick.

4.6 Landing Approach Tasks (Flight Phase Category C)

For the landing approach evaluations, each pilot flew an ILS approach followed by several touch-and-go landings. A single overall pilot rating was given for each configuration and the results are presented in Figure 18.

Both pilots were highly critical of those configurations that were considered to have heavy forces (low control gain). Two configurations with heavier than the nominal force-response gain (H) were evaluated: one with a fixed controller stick (F) and the other for a small amount of motion (S). Both configurations were given a pilot rating of 6. The heavy control forces were a factor in both ratings; however, the pilot comments indicate slightly different problems. With the fixed controller there was a tendency to bobble the airplane in pitch. With the motion controller there was also a pitch problem but it was described more as a tendency to over-rotate and balloon during the flare. With the motion controller, the pilots complained about the sloppy lateral control and considered it a major objection while no mention was made of a lateral control problem with the fixed stick and heavy forces.

One configuration with very heavy forces (VH) and a fixed stick (F) was evaluated. This configuration was rated unacceptable, with adequate



Motion deg/lb			Force-Response Gain lb/g, lb/deg/sec	
Symbol	δ_{ES}/F_{ES}	δ_{AS}/F_{AS}	Symbol	$F_{ES}/n_g, F_{AS}/p$
F	0	0	L	see Figures 5, 6
S	.50	.77	M	
L	.91	1.43	H	
			VH	

Figure 18. Pilot Rating Data for Landing Approach Task

performance not attainable (PR=7). The major complaint was the extremely heavy forces in both pitch and roll. It was considered necessary to use trim just to flare the airplane, and there was a problem predicting the response in pitch. Lateral control was not particularly a problem.

For the nominal (N) force-response gain, three configurations were evaluated: one with a fixed controller, one with a small amount of motion and a third with relatively large motion. With the fixed stick (F), one pilot noted that the control forces were a little heavy and that there was a slight tendency to PIO in pitch during the flare maneuver, particularly when one's attention was diverted. With a small amount of motion (S), the pilots felt the control forces were light with a slight tendency to over-rotate or overcontrol in pitch during the flare. With the large stick motion (L), they felt the airplane was slow to respond because of the large motion. Although the control forces were considered comfortable, the large stick motion was objectionable but not as much in pitch as it was in roll.

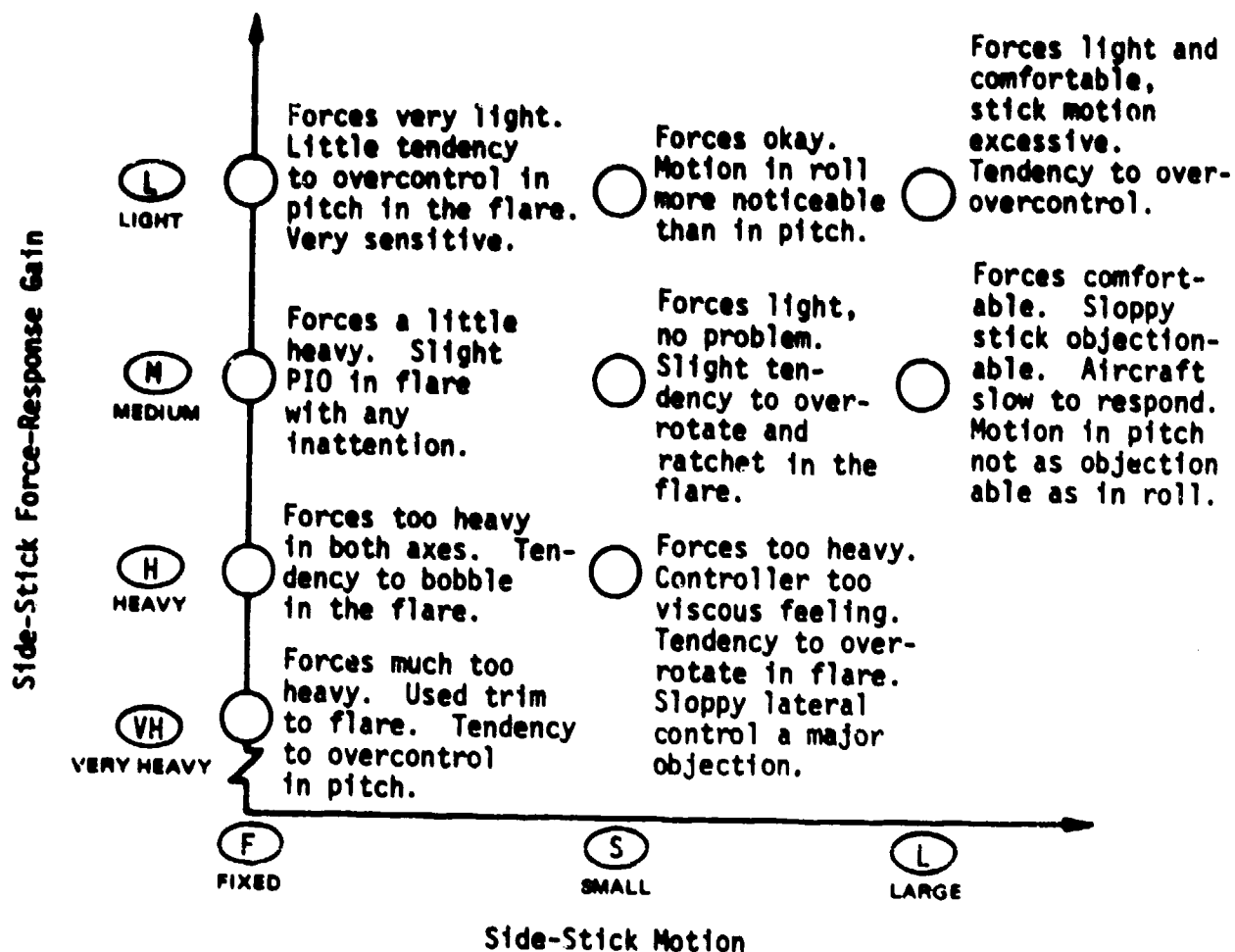
At the lightest force-response gain (L) evaluated, the forces on the fixed controller were considered very light with the comment that you had to be very careful with your control inputs due to the high sensitivity. There was also a little tendency to overcontrol in pitch during the flare. The high force-response gain, small motion (S) controller was the best configuration evaluated for the landing approach task. The pilots reported that they liked the light stick forces and that there was no problem at all with the flare and touchdown maneuver. They did note that the controller motion was more noticeable in roll than it was in pitch. With large controller motion, the pilots complained about the excessive stick motion and noted that there was a tendency to put oscillatory inputs into the pitch stick during the flare. This resulted in a tendency to overcontrol in pitch.

In the landing approach, pilot preference favored the small motion side stick with lighter than nominal force-response gain. All of the configurations evaluated with the fixed side stick were noted to have some difficulty,

usually described as a bobble or PIO tendency, in controlling the pitch response during the flare and touchdown maneuver. This is indicative of a high-frequency type control problem. For those configurations evaluated with motion that had a pitch control problem, the description of the problem indicates more of a low frequency control problem. It was also observed that any side stick motion was always more noticeable in the roll axis than in the pitch axis.

Typical pilot comments are presented in Figure 19. The results of the landing approach evaluations (Flight Phase Category C) may be summarized as follows:

- The fixed stick was considered satisfactory for the landing approach task ($PR \leq 3.5$), provided that the forces were not too heavy.
- The configuration considered best had light force-response gain and a small amount of control stick motion.
- All of the configurations evaluated with the fixed stick had some degree of pitch bobble during the flare and touchdown.
- Large amounts of control motion were more objectional in the lateral axis than longitudinal axis.



Motion deg/lb			Force-Response Gain lb/g, lb/deg/sec	
Symbol	δ_{ES}/F_{ES}	δ_{AS}/F_{AS}	Symbol	$F_{ES}/n_z, F_{AS}/p$
F	0	0	L	see Figures 5, 6
S	.50	.77	M	
L	.91	1.43	H	
			VH	

Figure 19. Typical Pilot Comments for Landing Approach Tasks

Section V

CONCLUSIONS

The following conclusions are based on an in-flight investigation of the effects of variations in control motion and control force-response gain on the flying qualities of a modern fighter airplane employing a side-stick controller. These conclusions must be considered in the context of the particular combinations of feel system, control system and airplane characteristics simulated in this experiment.

1. The best configurations evaluated for the up-and-away (Flight Phase Category A) and the landing approach (Flight Phase Category C) tasks were those that had low control force-response gain and a small amount of side-stick motion.
2. The fixed side-stick controller was considered satisfactory ($PR \leq 3.5$) for the landing approach tasks but not for the up-and-away flight tasks.
3. For the up-and-away tasks, a small amount of side-stick motion was beneficial in smoothing the initial response and thus improving the flying qualities of an airplane that was considered overly sensitive with the fixed stick. A properly designed electronic prefilter could possibly achieve the same result.
4. Additional research is required which includes more systematic variations in the characteristics of the various elements in the overall pilot-vehicle combinations, i.e., feel system, control system and aircraft dynamics, before more general conclusions can be reached about side-stick controller characteristics.

Section VI

RECOMMENDATIONS

The desirable force-deflection characteristics for a fighter side-stick controller are influenced by many aircraft and control system parameters. Such factors as command prefilter dynamics deserve more systematic study than was possible within the limited scope of this experiment. For example, the up-and-away results for the fixed side-stick evaluations may well have been improved with altered pitch command channel prefilter dynamics. In addition, desirable control harmony characteristics for side-stick controllers are not well documented and should be studied further. It is therefore recommended that a more thorough in-flight research program be undertaken to provide a more complete data base for the design of modern fighter side-stick controllers.

Appendix A

PILOT COMMENTS

This appendix presents the summarized pilot comments for each configuration evaluated in this experiment. These pilot comment summaries were prepared from transcriptions of the recorded comments made by the pilot during each evaluation in support of his task and overall ratings. Only the important comment headings from the Pilot Comment Card discussed in Section 3.5 are included in the comment summaries. In cases where comments were made on the "Effects of Turbulence" or "Special Piloting Techniques", these comments are included under the "Summary Comment" heading.

The control force-response gain/stick motion identifiers for each configuration used in the heading block for each set of comments are consistent with those presented in Section 3. The letters "A" and "B" after the configuration number refer to the evaluation pilot, while "U" indicates up-and-away (Flight Phase Category A) and "L" landing approach (Flight Phase Category C) evaluation tasks. The pilot ratings (PR) for the up-and-away evaluation tasks are reported in the same order as on the comment card, i.e.,

PR: Formation/Tracking/Maneuvering/Overall

For the landing approach evaluations, only a single overall rating was given.

FLT NO.: 1553
CONFIG.: 1UA
FORCE/MOTION: L/F
PR: 5/7/6/6

PILOT COMMENTS

TRIM	- no problems.
STICK FORCES	- aileron okay, pitch too light.
STICK MOTION	- no comments.
CONTROL HARMONY	- poor, can't avoid pitch inputs when rolling.
PREDICTABILITY OF RESPONSE	- tend to overcontrol in pitch and lateral, especially in turbulence.
FORMATION	- overcontrol in pitch - not a real problem, but more than annoying.
AIR-TO-AIR TRACKING	- pitch control a problem; performance poor.
GROSS MANEUVERING	- no problem with left rolls (using palm of hand) but right can't roll as fast - must be careful. - pitch forces too light, overcontrolling.
SUMMARY	- too sensitive in pitch. - control harmony poor. - turbulence increases overcontrol tendency.

FLT NO.: 1555
CONFIG.: 1UB
FORCE/MOTION: L/F
PR: 7/8.5/6/7

PILOT COMMENTS

TRIM	- difficult to trim in pitch without inadvertant inputs.
STICK FORCES	- light in pitch.
STICK MOTION	- not noticed.
CONTROL HARMONY	- not particularly good, too sensitive in pitch.
PREDICTABILITY OF RESPONSE	- pitch sensitive and roll a bit stiff. - unable to prevent inadvertant pitch inputs. - roll okay.
FORMATION	- difficult to hold position in pitch, tended to overcorrect and get into a PIO.
AIR-TO-AIR TRACKING	- control in pitch in question.
GROSS MANEUVERING	- not as bad as tracking, but requires extensive compensation.
SUMMARY	- primary objection is oversensitivity in pitch. - must fly very smoothly. - difficult to trim in pitch.

FLT NO.: 1557
CONFIG.: 2UA
FORCE/MOTION L/S
PR: 3/3/2/3

PILOT COMMENTS

TRIM	- no problems.
STICK FORCES	- good.
STICK MOTION	- not noticed.
CONTROL HARMONY	- real fine.
PREDICTABILITY OF RESPONSE	- good.
FORMATION	- tend to PIO a little when attempting tight control.
AIR-TO-AIR TRACKING	- best tracking to date. - some very slight lateral pipper oscillations.
GROSS MANEUVERING	- good.
SUMMARY	- good "g" control. - objected to slight tendency to PIO in formation.

FLT NO.: 1559
CONFIG.: 3UA
FORCE/MOTION: L/L
PR: 4/6/3/5

PILOT COMMENTS

TRIM	- no problem.
STICK FORCES	- light.
STICK MOTION	- excessive, felt like a "wet noodle", didn't like it.
CONTROL HARMONY	- no problem, both poor.
PREDICTABILITY OF RESPONSE	- not as predictable as desired, response was slow, seemed delayed.
FORMATION	- almost in a lateral PIO. - tendency to ratchet in roll. - pitch was easy to control, no tendency to overcontrol.
AIR-TO-AIR TRACKING	- lateral PIO develops when tracking. - requires extensive compensation for adequate performance.
GROSS MANEUVERING	- roll response was not as good as desired. - not a problem.
SUMMARY	- pitch control light and predictable. - aileron motion too large, tended to overcontrol.

FLT NO.: 1565
CONFIG.: 3UB
FORCE/MOTION: L/L
PR: 2/5/3/4

PILOT COMMENTS

TRIM	- not required.
STICK FORCES	- light to moderate, comfortable.
STICK MOTION	- noticed, felt excessive at first, but adapted well.
CONTROL HARMONY	- good.
PREDICTABILITY OF RESPONSE	- good except for tracking.
FORMATION	- little bit of looseness in the controls, but nothing particularly bad.
AIR-TO-AIR TRACKING	- could acquire the target, but could not stay on, slight bobble in pitch.
GROSS MANEUVERING	- little excessive on the amount of stick motion.
SUMMARY	- felt comfortable and adapted quickly. - tracking at low speed was the only problem, feeling of sloppiness in the stick.

FLT NO.: 1558
CONFIG.: 4UB
FORCE/MOTION M/F
PR: 5/7/4/7

PILOT COMMENTS

TRIM	- annoying lateral inputs when trimmed in pitch, had to trim more than desired.
STICK FORCES	- heavy in pitch and quite sensitive laterally.
STICK MOTION	- not noticed.
CONTROL HARMONY	- lack of harmony was objectionable.
PREDICTABILITY OF RESPONSE	- not too bad, but had a tendency to overcontrol in roll for small inputs.
FORMATION	- quite jerky in formation, particularly in roll.
AIR-TO-AIR TRACKING	- had to be very careful of pitch inputs, strong tendency to bobble.
GROSS MANEUVERING	- roll was too sensitive and had to work too hard in pitch.
SUMMARY	- bobbling in pitch during tracking was a problem. - hard to get smooth rolls, was jerky, tended to have a step response.

FLT.NO.: 1559
CONFIG.: 4UA
FORCE/MOTION: M/F
PR: 3/5/2/4

PILOT COMMENTS

TRIM	- no problem.
STICK FORCES	- slightly light in pitch.
STICK MOTION	- not noticed.
CONTROL HARMONY	- no problem.
PREDICTABILITY OF RESPONSE	- good.
FORMATION	- sensitive in pitch with a tendency to PIO. - using nose down trim tended to reduce the tendency to overcontrol in pitch.
AIR-TO-AIR TRACKING	- good in pitch, but trouble with aileron control.
GROSS MANEUVERING	- rolls pretty nicely. - can't roll as fast to the right - perhaps due to hand geometry.
SUMMARY	- tendency to rock the wings during tracking and overcontrol in pitch during close formation unsatisfactory.

FLT NO.: 1567
CONFIG.: 4UA
FORCE/MOTION M/P
PR: 2/3/3/3

PILOT COMMENTS

TRIM	- no problems.
STICK FORCES	- good.
STICK MOTION	- none noticed.
CONTROL HARMONY	- no problems.
PREDICTABILITY OF RESPONSE	- okay.
FORMATION	- easy to fly formation.
AIR-TO-AIR TRACKING	- could hold it well laterally, had to work to hold it in pitch.
GROSS MANEUVERING	- overshoot about 0.5 g. - couldn't roll right and pull at the same time easily.
SUMMARY	- don't like the configuration. - ailerons were a little bit heavy. - liked the pitch control.

FLT NO.: 1554
CONFIG.: SUA
FORCE/MOTION: M/S
PR: 2/5/3/4

PILOT COMMENTS

TRIM	- easy.
STICK FORCES	- no problem, good.
STICK MOTION	- not noticed.
CONTROL HARMONY	- no comments initially.
PREDICTABILITY OF RESPONSE	- no comments.
FORMATION	- real nice, smooth.
AIR-TO-AIR TRACKING	- very smooth in pitch, problem in holding lateral position - almost a lateral PIO.
GROSS MANEUVERING	- easy to coordinate, aileron control is a bit of a problem.
SUMMARY	- hard to get a good right roll. - aileron control a problem. - harmony a problem.
COMMENTS	- no problem with turbulence.

FLT NO.: 1558
CONFIG.: SUB
FORCE/MOTION: M/S
PR: 2/3/1/2

PILOT COMMENTS

TRIM	- occasional inadvertant pitch input with lateral trim.
STICK FORCES	- good.
STICK MOTION	- not noticed.
CONTROL HARMONY	- good, rudder too sensitive.
PREDICTABILITY OF RESPONSE	- pitch and roll good, rudder too sensitive.
FORMATION	- satisfactory. - use of rudder to hold position dumped the system.
AIR-TO-AIR TRACKING	- directional control of the pipper a problem.
GROSS MANEUVERING	- no problems.
SUMMARY	- good harmony in pitch and roll. - only objection was the sensitivity of the rudders.

FLT NO.: 1567
CONFIG.: SUA
FORCE/MOTION: M/S
PR: 2/2/3/3

PILOT COMMENTS

TRIM	- easy.
STICK FORCES	- okay.
STICK MOTION	- no comments.
CONTROL HARMONY	- okay.
PREDICTABILITY OF RESPONSE	- okay in pitch. - had a feeling of apprehension about the roll, but didn't have the expected PIO problem in tracking.
FORMATION	- no problems.
AIR-TO-AIR TRACKING	- good.
GROSS MANEUVERING	- felt apprehensive about the ailerons. - problems with using thumb for roll control during maneuvering.
SUMMARY	- good pitch control. - light but noticeable turbulence in air-to-air tracking.

FLT. NO.: 1553
CONFIG.: 6UA
FORCE/MOTION: M/L
PR: 3/4/3/4

PILOT COMMENTS

TRIM	- good.
STICK FORCES	- okay.
STICK MOTION	- never noticed what stick motion was.
CONTROL HARMONY	- good.
PREDICTABILITY OF RESPONSE	- real fine.
FORMATION	- same workload evident in pitch.
AIR-TO-AIR TRACKING	- tended to overshoot slightly.
GROSS MANEUVERING	- had to watch the pitch a little.
SUMMARY	- had to think about flying it in pitch. - small tendency to overcontrol in pitch.

FLT NO.: 1555
CONFIG.: 7UB
FORCE/MOTION: H/P
PR: 4/7/5/7

PILOT COMMENTS

TRIM	- no problem.
STICK FORCES	- heavy in pitch, light in roll.
STICK MOTION	- not noticed.
CONTROL HARMONY	- not bad, pitch a little stiff.
PREDICTABILITY OF RESPONSE	- tough time holding a constant "g" but not bad in the tracking task.
FORMATION	- tendency to bobble in roll. - not really satisfied with the performance.
AIR-TO-AIR TRACKING	- hard to control lateral-directional oscillations.
GROSS MANEUVERING	- could not hold "g" constant.
SUMMARY	- some difficulty in roll. - tired arm in pitch. - lateral-directional overshoots were objectionable.

FLT. NO.: 1557
CONFIG.: 7UA
FORCE/MOTION: H/F
PR: 5/6/5/5

PILOT COMMENTS

TRIM	- okay.
STICK FORCES	- pitch okay, but lateral heavy.
STICK MOTION	- none noticed.
CONTROL HARMONY	- okay.
PREDICTABILITY OF RESPONSE	- good.
FORMATION	- heavy aileron force a problem.
AIR-TO-AIR TRACKING	- trouble longitudinally holding on the target.
GROSS MANEUVERING	- forces too high.
SUMMARY	- arm gets tired from heavy lateral forces.

FLT. NO.: 1561
CONFIG.: 8UA
FORCE/MOTION: H/S
PR: 3/4/4/4

PILOT COMMENTS

TRIM	- easy, used in formation and maneuvering.
STICK FORCES	- right roll forces high.
STICK MOTION	- not much, okay.
CONTROL HARMONY	- ailerons too heavy, real good.
PREDICTABILITY OF RESPONSE	- overcontrolling in roll.
FORMATION	- heavy lateral forces.
AIR-TO-AIR TRACKING	- heavy lateral forces.
GROSS MANEUVERING	- heavy lateral forces.
SUMMARY	- heavy lateral forces tiring.

FLT. NO.: 1565
CONFIG.: 8UB
FORCE/MOTION: H/S
PR: 2/6/2/5

PILOT COMMENTS

TRIM	- good.
STICK FORCES	- comfortable.
STICK MOTIONS	- not noticed.
CONTROL HARMONY	- no complaints.
PREDICTABILITY OF RESPONSE	- very good in all but tracking.
FORMATION	- tires the arm but very good generally.
AIR-TO-AIR TRACKING	- difficult to keep pipper directionally on the target - roll control problem.
GROSS MANEUVERING	- good but tiring on the arm.
SUMMARY	- only objection was roll control difficulties in tracking - directional pipper problem. - little tiring on the arm in maneuvering.

FLT. NO.: 1554
CONFIG.: 9UA
FORCE/MOTION: VH/F
PR: 7/7/77

PILOT COMMENTS

TRIM	- no problem.
STICK FORCES	- heavy.
STICK MOTION	- not noticed.
CONTROL HARMONY	- not a factor.
PREDICTABILITY OF RESPONSE	- heavy laterally, but steady.
FORMATION	- can trim it, works fine. - steady, but not quick enough in rolls.
AIR-TO-AIR TRACKING	- lateral position a problem, sort of a lateral PIO.
GROSS MANEUVERING	- lateral forces too high in rolls, heavy in general.
SUMMARY	- solid airplane. - extremely heavy both lateral and longitudinal.

FLT. NO.: 1564
CONFIG.: 10UA
FORCE/MOTION: M/F ($\zeta_{sp} = .25$)
PR: 5/7/3/6

PILOT COMMENTS

TRIM	- easy to trim.
STICK FORCES	- not a problem.
STICK MOTION	- not noticed.
CONTROL HARMONY	- no problem.
PREDICTABILITY OF RESPONSE	- okay.
FORMATION	- unsatisfactory in pitch because of PIO tendency.
AIR-TO-AIR TRACKING	- PIO tendencies in pitch a problem.
GROSS MANEUVERING	- too sensitive in pitch.
SUMMARY	- sensitive in pitch but ailerons okay. - problems with thumb in pitch-roll maneuvers.

FLT. NO.: 1561
CONFIG.: 11UA
FORCE/MOTION: M/F ($\zeta_{sp} = .25$)
PR: 4/4/3/4

PILOT COMMENTS

TRIM	- easy.
STICK FORCES	- no problems.
STICK MOTION	- stick moved a little in rolls.
CONTROL HARMONY	- good.
PREDICTABILITY OF RESPONSE	- good, save ratcheting in right rolls.
FORMATION	- some tendency to PIO at high speeds, aileron okay.
AIR-TO-AIR TRACKING	- little PIO.
GROSS MANEUVERING	- easy, some slight ratcheting in rolls.
SUMMARY	- easy to handle and maneuver. - minor deficiencies are tendency to PIO in pitch and ratcheting in right rolls.

FLT. NO.:
CONFIG.:
FORCE/MOTION:
PR: 3/7/3/6

1564
12UA
M/F ($\tau_R = 1.0$)

PILOT COMMENTS

TRIM	- easy to trim.
STICK FORCES	- light, liked them despite lateral PIO problem.
STICK MOTION	- not noticed.
CONTROL HARMONY	- no problem.
PREDICTABILITY OF RESPONSE	- okay.
FORMATION	- tend to wing rock, ratchet in roll, lateral PIO.
AIR-TO-AIR TRACKING	- pitch control okay, but lateral positioning was difficult, lateral PIO present.
GROSS MANEUVERING	- thumb gets sore in combined pitch-roll maneuvers to the right.
SUMMARY	- tendency to PIO in roll, pitch no real problem.

FLT. NO.: 1566
CONFIG.: 13UA
FORCE/MOTION: M/S (7 = 1.0)
PR: 1/2/3/3 R

PILOT COMMENTS

TRIM	- no problems.
STICK FORCES	- light, good.
STICK MOTION	- noticed in the ailerons, but it's not bothersome.
CONTROL HARMONY	- didn't like stick for rolling.
PREDICTABILITY OF RESPONSE	- good.
FORMATION	- good.
AIR-TO-AIR TRACKING	- wasn't perfectly steady but good enough.
GROSS MANEUVERING	- disliked stick grip for rolling which degraded configuration.
SUMMARY	- didn't like using thumb in rolls to the right. - got a sore thumb from flying.

FLT. NO.:	1566
CONFIG.:	1LA
FORCE/MOTION:	L/F
PR:	2

PILOT COMMENTS

TRIM	- easy.
STICK FORCES	- not too heavy, about right.
STICK MOTION	- none.
CONTROL HARMONY	- good.
PREDICTABILITY OF RESPONSE	- good.
GENERAL AIRPLANE CONTROL	- easy to fly the ILS. - liked it, just a little bit of a tendency to overcontrol in pitch in the flare. - overcontrolled in pitch on the touch and go.
SUMMARY	- forces good. - no noticeable objectionable features. - felt close to a problem with overcontrolling in pitch.

FLT. NO.:	1552
CONFIG.:	1LB
FORCE/MOTION:	L/F
PR.	4

PILOT COMMENTS

TRIM	- could be faster (1.0 setting used), okay.
STICK FORCES	- very light.
STICK MOTION	- none.
CONTROL HARMONY	- okay, heavier aft, easier to roll left.
PREDICTABILITY OF RESPONSE	- good.
GENERAL AIRPLANE CONTROL	- very sensitive, must be careful on approach - flare was natural. - rudder too stiff, would like some motion.
SUMMARY	- quick response in all axes was good. - little wobbly and at times too responsive. - primary deficiencies were the rudder and inadvertant inputs in pitch and roll.

FLT. NO.: 1563
CONFIG.: 2LA
FORCE/MOTION: L/S
PR: 3

PILOT COMMENTS

TRIM	- easily trimmed.
STICK FORCES	- okay.
STICK MOTION	- didn't notice much in pitch, but quite a bit in the lateral for larger turns.
CONTROL HARMONY	- stick moved too much in roll as compared to the pitch.
PREDICTABILITY OF RESPONSE	- some difficulty getting the proper pitch response to coordinate with a roll input.
GENERAL AIRPLANE CONTROL	- no problem with the flare or touch down. - needed to pull the nose up before commencing to roll during the closed pattern.
SUMMARY	- liked the light stick forces, was easy to flare. - there was too much lateral motion in the stick.

FLT. NO.:	1565
CONFIG.:	2LB
FORCE/MOTION:	L/S
PR:	2

PILOT COMMENTS

TRIM	- okay.
STICK FORCES	- comfortable, between light and moderate.
STICK MOTION	- more noticed longitudinal than lateral, no problem.
PREDICTABILITY OF RESPONSE	- no comments.
GENERAL AIRPLANE CONTROL	- no problems in smooth air.
SUMMARY	- very comfortable, easy to adapt to.

FLT. NO.: 1556
CONFIG.: 3LA
FORCE/MOTION: L/L
PR: 5

PILOT COMMENTS

TRIM	- no problems.
STICK FORCES	- okay.
STICK MOTION	- noticed but not a factor.
CONTROL HARMONY	- no problem.
PREDICTABILITY OF RESPONSE	- poor feel in pitch, tendency to overcontrol.
GENERAL AIRPLANE CONTROL	- flare was the major problem where there was a tendency to overcontrol in pitch. - tendency to overbank in left turn was bothersome.
SUMMARY	- primary deficiency was associated with overcontrol in pitch in the flare.

FLT. NO.: 1560
CONFIG.: 3LB
FORCE/MOTION: L/L
PR: 4

PILOT COMMENTS

TRIM	- good.
STICK FORCES	- light and comfortable.
STICK MOTION	- excessive, a lot of motion for a response.
CONTROL HARMONY	good.
PREDICTABILITY OF RESPONSE	- good.
GENERAL AIRPLANE CONTROL	- top aileron required on turns to final. - hand moving back and forth in the flare - oscillatory type inputs to get desired response.
SUMMARY	- comfortable to fly, forces light. - too much stick motion, not enough direct control of aircraft. - noticed a hunting motion in pitch sometimes.

FLT. NO.: 1554
CONFIG.: 4LA
FORCE/MOTION: M/F
PR: 3

PILOT COMMENTS

TRIM	- no direct problem.
STICK FORCES	- little heavy.
STICK MOTION	- not noticed.
CONTROL HARMONY	- no problem.
PREDICTABILITY OF RESPONSE	- no problems.
GENERAL AIRPLANE CONTROL	- PIO in flare when attention diverted to trim. - must concentrate when trimming or it would PIO.
SUMMARY	- easy to fly the ILS. - had to compensate just slightly or you could get into a pitch PIO.

FLT. NO.: 1567
CONFIG.: 4LA
FORCE/MOTION: M/F
PR: 3

PILOT COMMENTS

TRIM	- easy to trim.
STICK FORCES	- fine.
STICK MOTION	- not noticed.
CONTROL HARMONY	- okay.
PREDICTABILITY OF RESPONSE	- no comments.
GENERAL AIRPLANE CONTROL	- ILS not a problem.
SUMMARY	- main objection was rolling right, required too much strength in the thumb.

FLT. NO.: 1566
CONFIG.: SLA
FORCE/MOTION: M/S
PR: 4

PILOT COMMENTS

TRIM	- easy to trim.
STICK FORCES	- light, no problem.
STICK MOTION	- none, okay.
CONTROL HARMONY	- good.
PREDICTABILITY OF RESPONSE	- good.
GENERAL AIRPLANE CONTROL	- a little bit of overcontrolling in pitch. - small problem with rotation.
SUMMARY	- objected to slight tendency to over-rotate in the flare and ratchet the flare just a little bit.

FLT. NO.: 1566
CONFIG.: 6LA
FORCE/MOTION: M/L
PR: 4

PILOT COMMENTS

TRIM	- easy to trim.
STICK FORCES	- very light, good.
STICK MOTION	- noticed slop in the ailerons, not desirable - some in pitch but not as much of a problem.
CONTROL HARMONY	- no problems.
PREDICTABILITY OF RESPONSE	- little slow to respond, too much motion required.
GENERAL AIRPLANE CONTROL	- had to work quite a bit, particularly in the flare.
SUMMARY	- easy to fly ILS. - no trouble with thumb. - sloppy stick was objectionable, especially laterally.

FLT. NO.: 1555
CONFIG.: 6LB
FORCE/MOTION: M/L
PR: 2

PILOT COMMENTS

TRIM	- okay.
STICK FORCES	- low and comfortable.
STICK MOTION	- large, but not a problem in pitch and roll.
CONTROL HARMONY	- good.
PREDICTABILITY OF RESPONSE	- toward the sloppy side. - no tendency to overshoot.
GENERAL AIRPLANE CONTROL	- good.
SUMMARY	- a little bit sloppy or sluggish but not objectionably so. - no objectionable features. - easy to fly with no special thoughts.

FLT. NO.: 1561
CONFIG.: 7LA
FORCE/MOTION: H/L
PR: 7

PILOT COMMENTS

TRIM	- fly it with the trim.
STICK FORCES	- too heavy in both axes.
STICK MOTION	- didn't notice any.
CONTROL HARMONY	- both heavy, okay.
PREDICTABILITY OF RESPONSE	- predictable, but too much work.
GENERAL AIRPLANE CONTROL	- tendency to PIO. - seems to require large force to hold bank angle in a turn - wants to overturn.
SUMMARY	- instrument flying no problem. - flare and touch down were problem areas due to high forces. - must use trim because of heavy forces.

FLT. NO.: 1563
CONFIG.: 7LA
FORCE/MOTION: H/L
PR: 4

PILOT COMMENTS

TRIM	- easily trimmed.
STICK FORCES	- higher than desired in both axes, but especially on the ailerons.
STICK MOTION	- not noticed.
CONTROL HARMONY	- okay, equally heavy.
PREDICTABILITY OF RESPONSE	- good.
GENERAL AIRPLANE CONTROL	- flew pretty well, especially on the ILS approach. - flare and touch down were pretty easy.
SUMMARY	- aileron forces were too high. - difficult to hold aileron forces in the outboard direction with the normal motion of the hand.

FLT. NO.: 1560
CONFIG.: 7LB
FORCE/MOTION: H/F
PR: 6

PILOT COMMENTS

TRIM	- used trim more than normal, okay.
STICK FORCES	- heavy.
STICK MOTION	- not noticed.
CONTROL HARMONY	- good, both heavy.
PREDICTABILITY OF RESPONSES	- not too good, a lot of force required to get the aircraft moving.
GENERAL AIRPLANE CONTROL	- slight tendency to bobble in pitch in the flare and touch down. - large force required in pitch for the closed pattern.
SUMMARY	- felt "stiff" in pitch and roll. - required lots of trim due to heavy forces. - a lot of effort required to get the desired initial response.

FLT. NO.: 1556
CONFIG.: 8LA
FORCE/MOTION: H/S
PR: 6

PILOT COMMENTS

TRIM	- good.
STICK FORCES	- pitch okay, but ailerons too heavy.
STICK MOTION	- noticed in roll.
CONTROL HARMONY	- poor, could not seem to apply simultaneous inputs.
PREDICTABILITY OF RESPONSE	- aileron response too slow and sloppy.
GENERAL AIRPLANE CONTROL	- easy to balloon in the flare because of the attention required in roll.
SUMMARY	- poor harmony and heavy, sloppy, lateral control was major objection.

FLT. NO.:	1558
CONFIG.:	8LB
FORCE/MOTION:	H/S
PR:	5.5

PILOT COMMENT

TRIM	- not used.
STICK FORCE	- heavy.
STICK MOTION	- noticed heavy "glue pot" type motion, moved a little but required a large force.
CONTROL HARMONY	- good.
PREDICTABILITY OF RESPONSE	- relatively good, a little tendency to overshoot in pitch.
GENERAL AIRPLANE CONTROL	- easy to fly ILS. - tendency to overrotate in the flare and bobble as well as balloon. - touchdown predictability was poor.
SUMMARY	- liked the side stick motion - seemed to harmonize nicely with the traffic pattern. - control forces were too heavy and controller too viscous. - had to compensate for the tendency to overrotate a little in the flare.

FLT NO.: 1557
CONFIG.: 9LA
FORCE/MOTION: VH/F
PR: 7

PILOT COMMENTS

TRIM	- no problem.
STICK FORCES	- too much force in roll and pitch.
STICK MOTION	- no comments.
CONTROL HARMONY	- both bad, no problem.
PREDICTABILITY OF RESPONSE	- okay, too heavy.
GENERAL AIRPLANE CONTROL	- ILS no problem. - forces objectionable, had to use trim to flare.
SUMMARY	- critical task is the flare and touchdown. - stick forces are heavy, heavy.

FLT. NO.: 1559
CONFIG.: 9LA
FORCE/MOTION: VH/F
PR: 7

PILOT COMMENTS

TRIM	- okay, used a lot.
STICK FORCES	- pitch and roll forces too high.
STICK MOTION	- not noticed.
CONTROL HARMONY	- no comments.
PREDICTABILITY OF RESPONSES	- good, but forces too high.
GENERAL AIRPLANE CONTROL	- very stable aircraft. - a lot of trim required to get a good flare and touchdown, otherwise overcontrolled. - ailerons were not much of a problem.
SUMMARY	- stick forces too heavy - had to use trim to flare.