SECTION VII

SESSION 4: SPECIAL PROBLEMS 2

AN EVALUATION OF SIDESTICK FORCE/DEFLECTION CHARACTERISTICS ON AIRCRAFT HANDLING QUALITIES

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ABSTRACT

The growing popularity and acceptance of aircraft sidestick controllers has emphasized the lack of data available to design optimized sidestick configurations. This study was conducted by students of the USAF Test Pilot School using the Calspan NT-33A variable stability aircraft to help expand the data base. The NT-33A was configured with a variable force and motion sidestick controller and was programmed to simulate the handling characteristics of a modern high-performance fighter aircraft. Three separate investigations were conducted in this study.

The tasks evaluated consisted of precision air-to-air tracking of a target aircraft during level and windup turns, gross acquisition and tracking involving large pilot inputs, and landings.

The variables of the investigation were the ratio of stick force to stick deflection and the ratio of stick force to aircraft response (either load factor or roll rate). The influence of sidestick controller first order pre-filter characteristics was investigated by performing the tasks with different pre-filters in each axis for selected force/deflection characteristics.

Pilot comments were obtained for all configurations. Pilot ratings of each task were made using the Cooper-Harper rating scale. From this assemblage of comments and ratings, areas bounding the best and the worst combinations of sidestick force and deflection were defined. This discussion is confined to the air-to-air tracking task.

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Acknowledgement

The authors would like to acknowledge the efforts of Robert Harper, G. Warren Hall, and Michael Parag, engineering pilots, Calspan Corp., who were the safety pilots for the evaluation flights and who provided valuable assistance to the program.

Presented at the Society of Flight Test Engineers National Symposium, October 5, 1978, in Arlington, Texas.

INTRODUCTION

The sidestick controller is a serious contender to the center stick in fighter aircraft design, as evidenced by its introduction into service use in the F-16. The available literature contains very little insight into the nature of desireable sidestick characteristics (i.e., mechanization, force-feel, deflection, harmony, etc) or what influence such factors as control system and aircraft dynamics or class of aircraft have upon these characteristics. Recent experience with sidesticks (references 1 and 2) have borne out the need for a thorough and comprehensive series of investigations of sidestick controller characteristics. In addition, supportive data are required for a quantitative requirement on sidestick controllers in the specification for Flying Qualities of Piloted Aircraft, MIL-F-8785B.

In order to provide this additional data, the USAF Flight Dynamics Laboratory, Wright-Patterson AFB, Ohio, had funded the Calspan Corp, Buffalo, NY, to investigate the influence of force and deflection characteristics on air-to-air tracking and landing task performance (reference 3). To continue this effort, the Laboratory has been sponsoring the USAF Test Pilot School at Edwards AFB, California on a continuing series of sidestick investigations. Three of these test programs, flown and reported on by students of the Test Pilot School (references 4, 5, 6, 7) are the subject of this discussion. These programs made use of the Calspan NT-33A variable stability aircraft equipped with a variable force and deflection sidestick controller to perform the evaluations. The investigations were designed such that each would progress in a logical fashion, building upon the findings and conclusions of the previous one.

TEST PROGRESSION

The first phase in the test series was conducted between 13 May and 3 June, 1977 by students of class 76-B (references 4 and 5) and consisted of 23 flights. The investigation was derived as a follow-on to the progenitor of the series, the Calspan program of reference 3. The objective of this phase was to provide an additional, independent investigation of the same variables considered by Calspan; sidestick force per unit of aircraft response and stick deflection per unit of stick force. An important difference between the Test Pilot School investigation and Calspan's was the task employed in the air-to-air portion of the evaluation. It was a more structured and demanding tracking task than the operationally-oriented task favored by Calspan. It was hoped that this task might be useful in high-lighting tracking deficiencies more clearly.

Phase II of the series was conducted to provide additional information on the effects of the same variables and to extend the ranges of these variables to heavier forces and larger amplitudes. The investigation was conducted between 28 October and 25 November, 1977 by students of Class 77-A (reference 6). Data were obtained on 16 flights.

Phase III was conducted by Class 77-B from 15 May to 9 June, 1978 (reference 7). This phase investigated the influence of an additional variable upon the results obtained earlier. Different longitudinal and lateral control system first order pre-filters were chosen for this study. A range of pre-filter corner frequencies was investigated for two force-deflection configurations. The objective of the evaluation was to determine the preferred pre-filter for each configuration and whether the relative acceptance of two significantly different configurations was effected by the pre-filter values. Data were obtained on 19 flights.

TEST AIRCRAFT DESCRIPTION

The test aircraft, NT-33A USAF S/N 51-4120, is a modified T-33A jet trainer capable of reproducing the dynamic response and control system characteristics of different aircraft. Static and dynamic responses of the basic T-33A were modified by a response feedback, variable stability system which positions the control surfaces through full authority electrohydraulic servos. The normal front cockpit flight controls are disconnected from the NT-33A control system and have been replaced by a variable force and deflection fly-by-wire sidestick controller which was used in this evaluation. Aircraft modification and maintenance were performed by Calspan.

The electrohydraulic variable force and deflection sidestick controller is shown in figure 1. This sidestick is operated with independently variable force gradients and pre-filters in both the pitch and roll axes. The sidestick pivot point for the longitudinal and the lateral axes is the stick base. Control force gradients are achieved through an electrohydraulic system built into the side controller. Aircraft trim is available with a sidestick-mounted trim switch.

The dynamic characteristics of a modern high-performance fighter aircraft were implemented using the NT-33A variable stability system. These characteristics were similar to those used in the Calspan experiment. The test airplane dynamic characteristics are shown in the table below. (The dynamics varied somewhat between phases; these are representative values). Force commands were used in both the lateral and longitudinal axes. Force/response gains were unaffected by changes in feel system force/displacement gradients or pre-filter values.

Parameter		Air-To-Air Dynamics	Approach & Landing Dynamics
n_z/α	g/rad	33	7
ω_{sp}	rad/sec	5.0	2.2
ζ_{sp}	--	0.6	0.5
ω_p	rad/sec	0.09	0.15
ζ_p	--	0.05	0.05
τ_r	sec	0.2	0.5
τ_s	sec	∞	∞
ω_d	rad/sec	3.2	1.2
ζ	--	0.4	0.25
$\lvert\phi/\beta\rvert$	--	0.5	3

During the evaluation, a Calspan safety/instructor pilot varied the computer gains through controls located in the rear cockpit and thus could change the dynamics of the aircraft and the control system characteristics during flight. The aircraft was also equipped with a fixed depression gunsight and a gunsight camera.

SIDESTICK CONFIGURATIONS

Air-to-Air Evaluation. The combinations of force-to-aircraft response and deflection per unit of force ratios that were evaluated for the air-to-air tasks in all three phases are shown in the matrix of figure 2. The control force gradients denoted by name in the matrix are also depicted in figures 3 and 4 as plots of force versus aircraft response. The non-linearity of the force/response gradients was designed by Calspan to depict modern fighter aircraft control mechanizations. The definitions applied to each force/response gradient were vague, and as seen in the figures, varied from one phase to the next. The variation of deflection with force was linear in each case, and the numerical values are therefore depicted. For each configuration evaluated, the longitudinal and the lateral force and deflection characteristics were chosen as congruous pairs (i.e., a "heavy" lateral force was used in conjunction with a "heavy" longitudinal force) in order to provide control harmony. The breakout forces in both axes were 0.5 pounds.

Approach and Landing Evaluation. The control force gradients employed for these tasks were approximately one-half those shown in figures 3 and 4. The same deflection gradients were used for both approach and air-to-air tasks.

FLIGHT MANEUVERS AND TEST TECHNIQUES

The maneuvers flown in the series varied somewhat between the three phases. All phases, however, utilized a highly structured tracking task described in detail in reference 8. Phases II and III investigated gross maneuvers as additional tasks. Pilots for the evaluations were students from the Test Pilot School. The particular maneuvers are described below.

Precision Tracking (Phases I, II, and III). Air-to-air tracking was commenced with the NT-33A approximately 2,000 feet behind the target aircraft. The pilot trimmed the aircraft prior to start and did not re-trim during the maneuver. At the start of the test, the pilot achieved the aim point as rapidly and aggressively as possible and persistently drove the gunsight pipper to the precise aim point. The aim point was the center of the target fuselage at the wing/fuselage junction. Rudder pedals were not used during the maneuver. The specific tracking task for each configuration consisted of the following:

1. Two 280 KIAS 2-g turns in opposite directions for a heading change of approximately 180 degrees.

2. Two windup turns in opposite directions maintaining 280 KIAS from one to 3.5 g's at an onset rate of 0.1 g/second.

In each maneuver the pilot's task was to continuously minimize the error between the aimpoint and the pipper position.

Formation (Phase II). The target aircraft performed a series of lazy-8 maneuvers with up to 90 degrees of bank with the NT-33A in close formation. A windup turn to 3.5 g's was also included.

Gross Maneuvers - Acquisition (Phases I and II). Initial gross acquisition of the target at the start of the precision tracking maneuver was evaluated as a task. In addition, turn reversals were accomplished following each windup turn. The NT-33A was positioned 1500 feet behind the target aircraft. The target then established a 3-g turn at 280 KIAS. Upon call from the NT-33A, the target executed a rapid, unloaded reversal. The evaluation pilot delayed 3 to 4 seconds, then reversed and attempted to rapidly reacquire the target. This task, which required large, sustained inputs, was evaluated on the ability to reacquire the target.

Gross Maneuvers - Cine-Track (Phase II). The maneuver began with the target aircraft in a 2.5-g turn and the NT-33A positioned 1500 feet behind. Upon call from the NT-33A, the target performed a 2.5-g barrel roll through 540 degrees of bank. The maneuver was then repeated in the opposite direction.

Landing (Phases I, II, and III). Configurations were examined during normal touch-and-go landings. In Phases II and III the landings were repeated with an intentional displacement from the glide slope and the center-line to evaluate ease of recovery.

Test Techniques. The evaluation pilots were not informed as to which configurations they were evaluating. The maneuvers were flown as often as the pilot felt necessary to evaluate the configuration. The gun camera film was run during each task, and pipper position error was later analyzed to help in assessing performance. Following each maneuver, the pilot recorded his comments on tape and assigned a rating from the Cooper-Harper rating scale shown in figure 5 (reference 9). Post flight debriefings were conducted.

EVALUATION PILOTS

The evaluation pilots all had a considerable number of flying hours. Their experience varied from a low of 1100 hours to a high of 3000 hours and from B-52 aircraft to air combat in F-4 or Mirage aircraft. Their experience is tabulated below:

NAME	RANK	PHASE	TOTAL FLYING TIME	AIRCRAFT EXPERIENCE
Cima	Lt(USN)	I	1100 Hrs	F-4J, RF-4C, T-38A
LeBeau	Capt	I	1500 Hrs	B-52G, T-38A, RF-4C
Stebe	Capt	I	3000 Hrs	T-38A, U-2, T-33, B-66
Saxon	Capt	II	1850 Hrs	F-4C/D/E, F-100D/F
Haas	Capt	II	2700 Hrs	T-38A, C-130A/E, T-39
Daniel	Capt	II	2100 Hrs	T-38A, O-2A, A-1E/H, T-39
LeBarge	Capt	II	2200 Hrs	KC-135A, C-123K, T-39
Lewis	Capt	III	1150 Hrs	F-4C/D/E, T-38A
Tilden	Capt	III	2300 Hrs	F-4C/D/E, T-38A
Shmul	Capt(Israel)	III	2900 Hrs	Fuga-Magister, Mirage

SUMMARY OF RESULTS BY PHASE

Phase I. Four levels of stick force/response ratio and displacement/force ratio were investigated. Forces ranged from "heavy" to "very light", and displacements varied from "very small" (near fixed stick) to a fairly large amount of stick motion. The evaluation maneuvers consisted primarily of precision tracking. Air-to-ground and landing maneuvers were also evaluated, but little data were obtained and the results are not discussed.

The results of the air-to-air tracking investigation are summarized in figures 6 and 7 in terms of individual pilot ratings with a synopsis of comments for each configuration. In general, the pilots prefered the larger control force gradients (configurations 13, 14, and 15 in figures 6 and 7) and to a lesser degree, smaller control stick motion with heavier control force gradients (configurations 4 and 7). The former set of configurations fell on the edge of the test matrix; thus the extent of this area of preference could not be determined. the pilots indicated that, within this area, control motion was noticeably large but not uncomfortable. The configurations rated the poorest were the lighter force gradients and the smaller control motions (configurations 1, 2, 3, and 5) and the heavy force gradient with the larger motion (configuration 16). The lighter force/smaller motion configurations resulted in longitudinal and lateral sensitivity. The remaining configurations (6, 8, and 9 through 12) fell in the mid-range of the control motions investigated. They were rated alike - all had average ratings of 4 1/2; however, the pilot comments showed a trend from oversensitivity to sluggishness as forces increased.

A comparison of results of this and of the Calspan test showed similar trends with the exception that ratings and comments for this phase indicated a preference for the larger stick deflections in the very light to medium force gradient range; a result not evidenced in the earlier data.

Phase II. Additional stick force and displacement configurations were investigated in this phase. The evaluation maneuvers consisted of formation, precision tracking, gross acquisition, "Cine-Track", and landing.

Each air-to-air maneuver was rated and commented upon separately. An overall rating was also assigned to the air-to-air tasks. The overall ratings are depicted in figure 8 with pertinent pilot comments summarized in figure 9.

When presented with very heavy force gradients, the pilots found it difficult to make fine corrections during tracking tasks if trimming was avoided during the maneuver. Given the mechanical configuration of the sidestick used in this evaluation, the pilots complained of excessive wrist bending when approximately 20 degrees of deflection was reached.As this coincided with full throw, encountering the stick stop was an additional concern. The loss of stick motion while force command was still available resulted in an inability to make precise corrections. When force or deflection was increased further, the pilots described the aircraft as sluggish. There was a tendency for the aircraft to wander off target and gross acquisition was difficult. With low force gradients, especially when combined with small motion, the aircraft was described as too sensitive and pilot induced oscillation (PIO) tendemcies were apparent. Utilizing the results obtained from this evaluation, an additional configuration was chosen that fell within the region of best performance. Additional flights confirmed the optimum location (figure 9). Configurations using large displacements with light force gradients were not evaluated in this phase.

Phase III. The influence of control system pre-filters was investigated for two force deflection configurations evaluated earlier. These were the "optimum" of Phase II and one with the same force/response ratio but a smaller amplitude of stick motion.

Initially, five pre-filter constants were chosen for each axis with values of 2, 4, 8, 12, and 16 radians/second. Phases I and II employed pre-filters with corner frequencies of 16 and 4 radians/second for air-to-air tracking and for landing, respectively. Following a brief, four flight evaluation, the pre-filters for the bulk of the evaluation were narrowed down to 2, 8, and 16 radians/second. Tasks during this phase included precision tracking, gross acquisition, lazy-8, and landing.

The results are presented in terms of pilot ratings and comments for precision tracking and landing (figure 10). In addition to Cooper-Harper ratings, the pilots assigned a numerical value to each configuration which was based upon an order of preference. Each pilot ranked the configurations he flew on a particular mission in accordance with a preference rating from zero (most preferred) to 10 (least preferred). An overall preference rating was determined for each configuration by determining its rank order for the entire test. Configurations, when rated by the Cooper-Harper method, were rated independent of one another and the ratings varied over a wide range. However, when they were rated in a preferential order, a more consistent result was obtained. For fine tracking, the 2 radian/second pre-filter produced poor results. Pilots complained of sluggish response and high workload with the optimum configuration. With the small deflection configuration, no such clear distinction was evidenced. The landing task showed a definite pilot preference for either the 8 or the 16 radian/second pre-filter. Overall, there was no clear, consistent influence of pre-filter frequency on the acceptability of the two configurations in the air-to-air phase, and it appeared that no selection of pre-filter would have substantially improved one configuration over another.

OVERALL RESULTS

Significant trends can be seen when the results of all the phases are analyzed together. In particular, there were definite areas in the force/response vs deflection/force matrix where performance was significantly better than elsewhere. Conversely, there were other areas where performance was worse than elsewhere. These areas are depicted in figure 11 together with a summary presentation of the averages of all Cooper-Harper ratings for each configuration. The area of best performance is denoted as "adequate". From a compilation of comments, this term fairly describes the pilot acceptance of these configurations. The worst areas are defined simply as "poor". They do not solely encompas the unacceptable configurations, but rather, represent a region where performance of the task requires noticeably more compensation. It also denotes the regions of the matrix where unacceptable performance may be encountered. Between these regions, the results were either "less than adequate" or not well enough defined by the data to base any conclusion.

Certain conclusions drawn in refrence 3 are substantiated by the current results. In the region of very small motion (fixed stick in refrence 3), tracking performance was very sensitive to changes in force/response gradient. There appears to be a narrow area in the medium to heavy force range where performance in air-to-air maneuvers was adequate. As motion increased, the region expands to a point where the results were fairly insensative to changes in force/response gradients.

As stick motion was increased further, comments about excessive stick motion, encountering the stops, and overshoots arose. The region of very light to medium forces with small to moderate stick motion resulted in very sensitive response and a degradation in performance. From pilot comments, it appeared that a fixed stick or a small displacement stick would not give adequate performance in this range.

A comparison of results for both gross maneuvering and precision tracking indicated no noticeable disparity in the results obtained from the two types of maneuvers. The boundaries of figure 11 apply to all air-to-air maneuvers investigated.

The pilots in all phases complained of a lack of good control force harmony for a significant number of configurations. This problem did not appear to be consistent, and complaints relating to control harmony varied with the configuration. It was obvious, however, that harmony was not optimum for a very large number of configurations.

The tracking technique used in the investigation was intended to identify deficiencies in the longitudinal and lateral axis, and did not allow the use of rudder. The comments of objectionable lateral performance may have been accentuated by this technique. However, when rudder was used, as in the Cine-Track maneuver, the lack of harmony between the rudder and the other controls was apparent, and tracking performance was not improved.

Even in the area of "adequate" performance, very few ratings better than four were obtained. It is felt that the ratings across the matrix were uniformly degraded because of the combination of lateral deficiencies and the tracking technique.

CONCLUSIONS

The following conclusions are applicable to the NT-33A in the particular control system and aircraft configuration evaluated. However, they may be extended in general to other configurations, fighter aircraft, or maneuvers although verification is required. The conclusions pertain to the air-to-air phase only.

1. For very small displacements (including fixed stick), the range of stick force/response gradients that result in adequate performance is very restricted. Lighter or heavier forces will result in objectionable or unacceptable handling qualities.

2. There is a region of moderate stick displacements where performance is relatively insensitive to variations in force/response gradients.

3. Moderate stick motion coupled with light to moderate stick force gradients results in the best tracking performance.

4. The effect of control system prefilters was not significant.

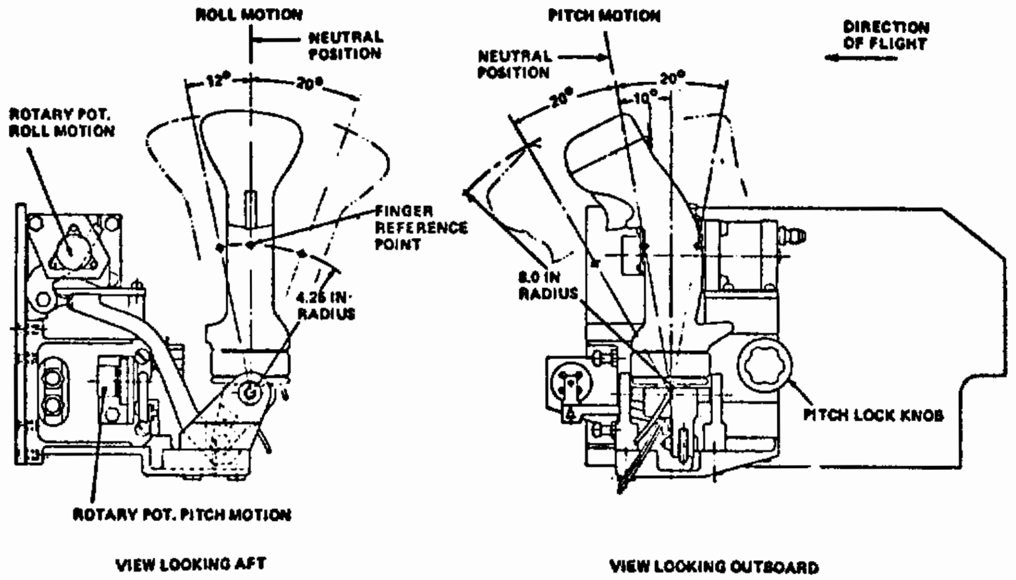

FIGURE 1 NT-33A SIDESTICK

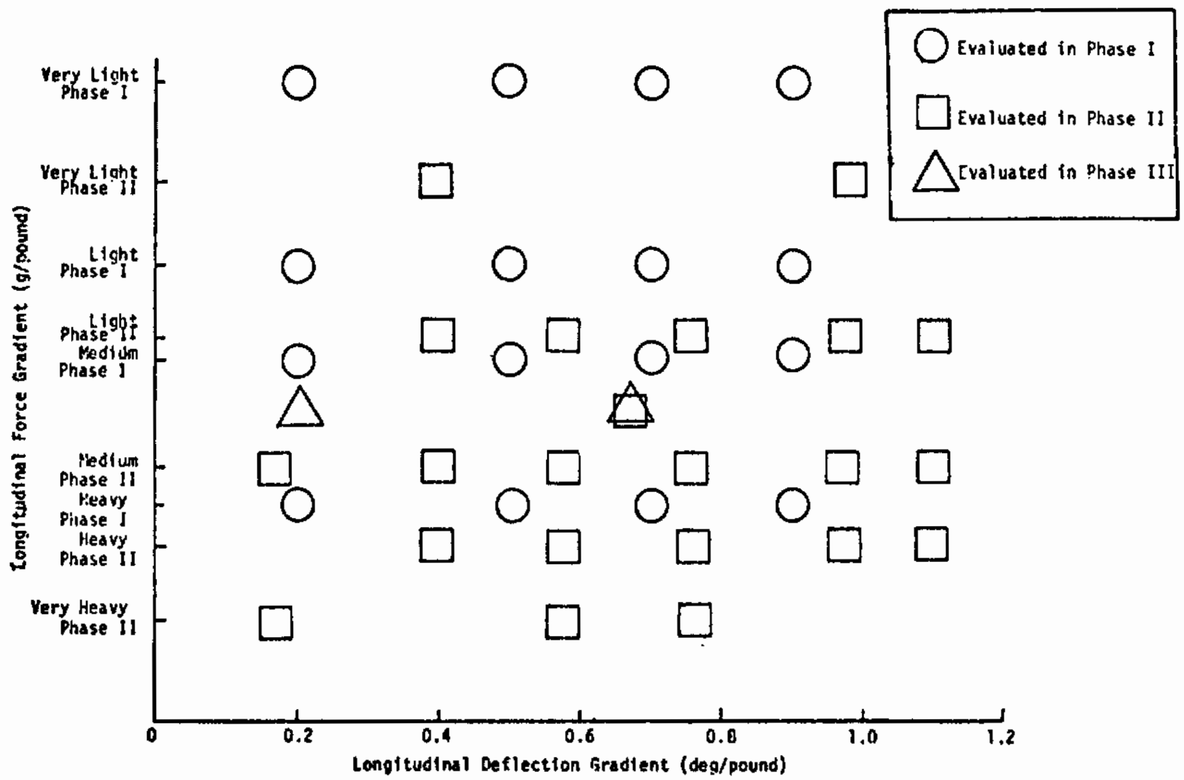

FIGURE 2 MATRIX OF TEST CONDITIONS

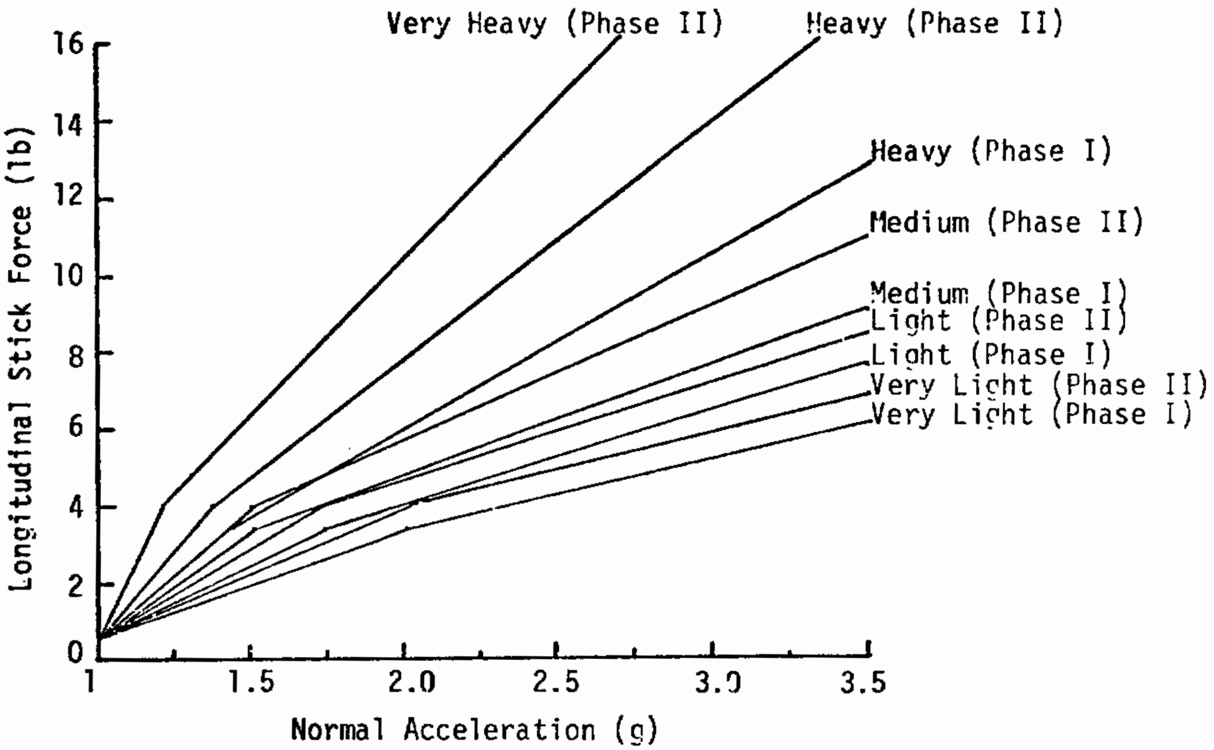

FIGURE 3 LONGITUDINAL STICK FORCE VS NORMAL ACCELERATION

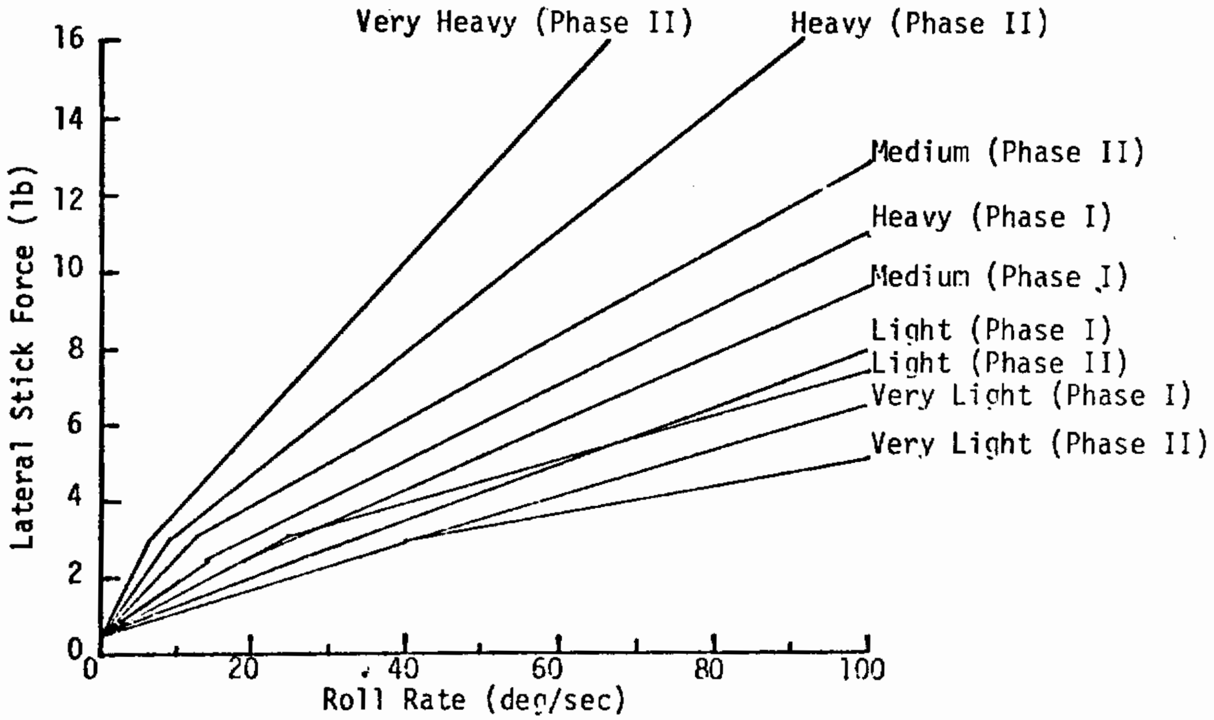

FIGURE 4 LATERAL STICK FORCE VS ROLL RATE

HANDLING QUALITIES RATING SCALE

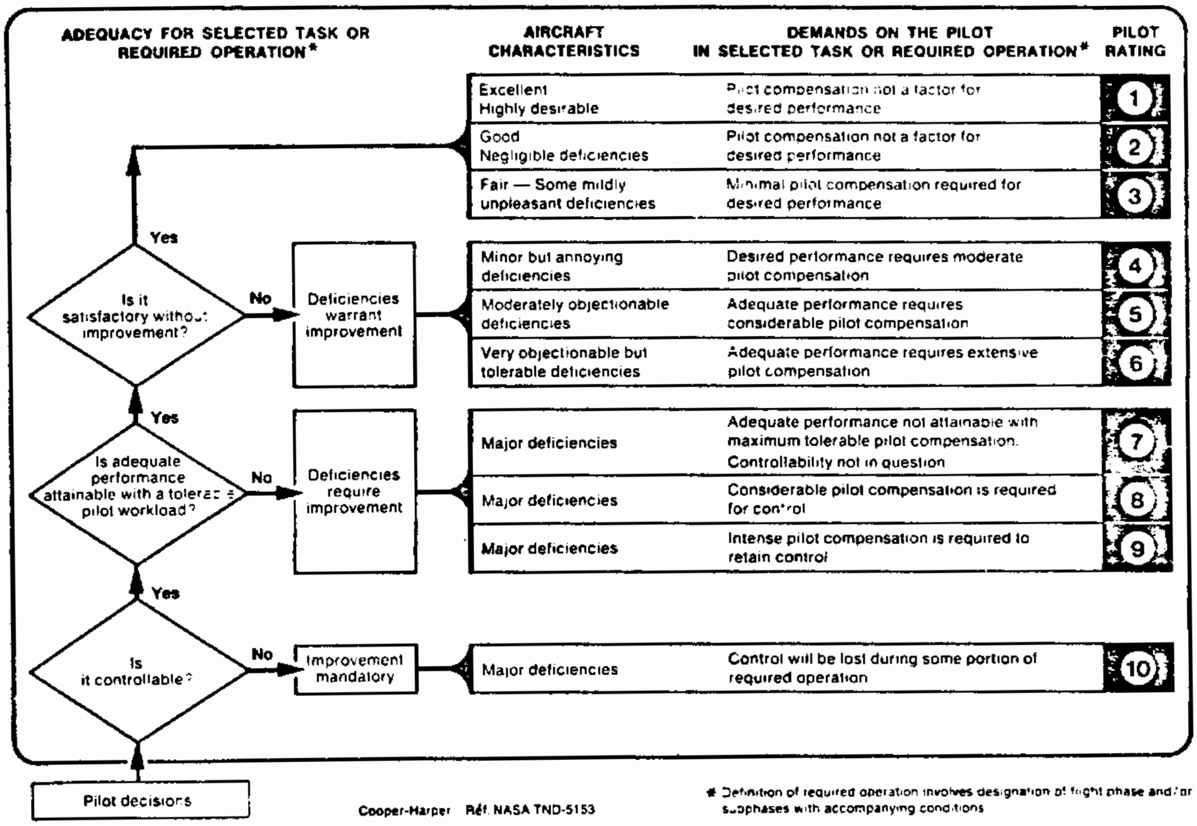

FIGURE 5 COOPER-HARPER RATING SCALE

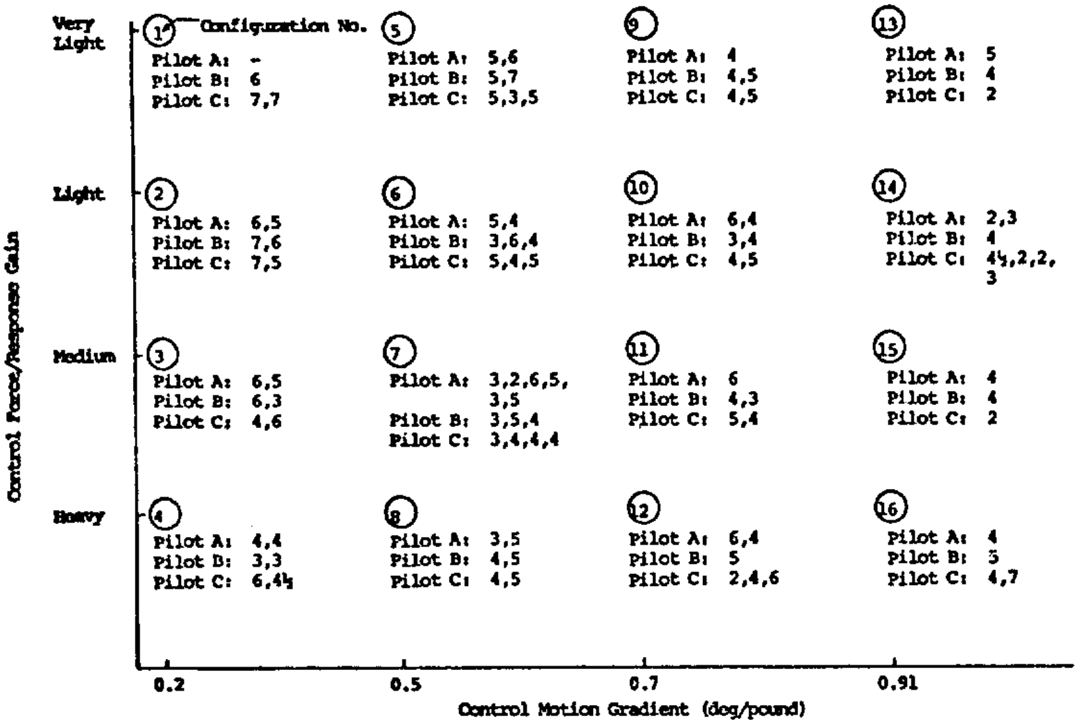

FIGURE 6 PHASE I - PILOT RATINGS FOR AIR- TO-AIR TRACKING

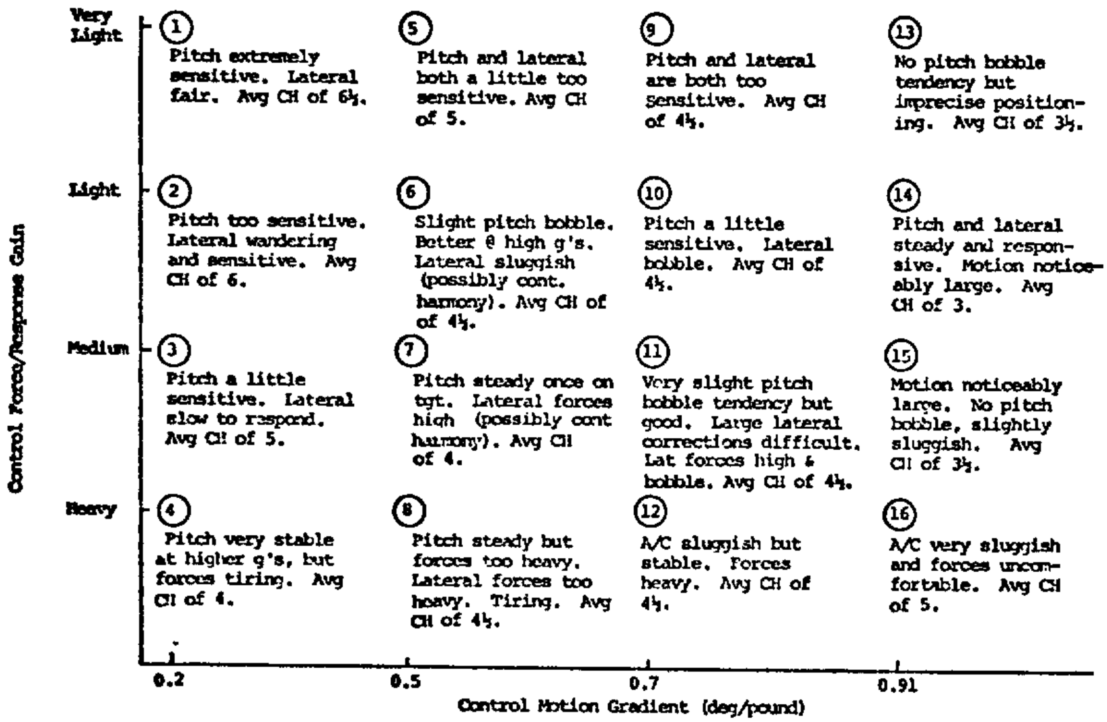

FIGURE 7 PHASE I - PILOT COMMENTS FOR AIR- TO-AIR TRACKING

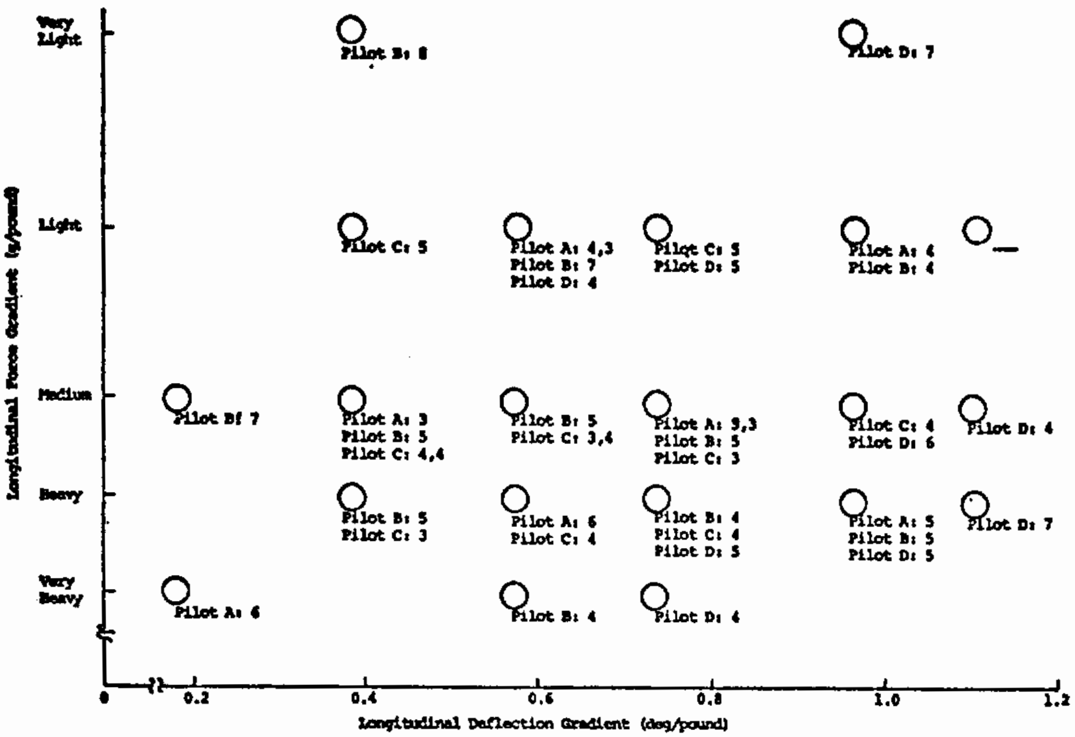

FIGURE 8 PHASE II - PILOT RATINGS FOR OVERALL TRACKING

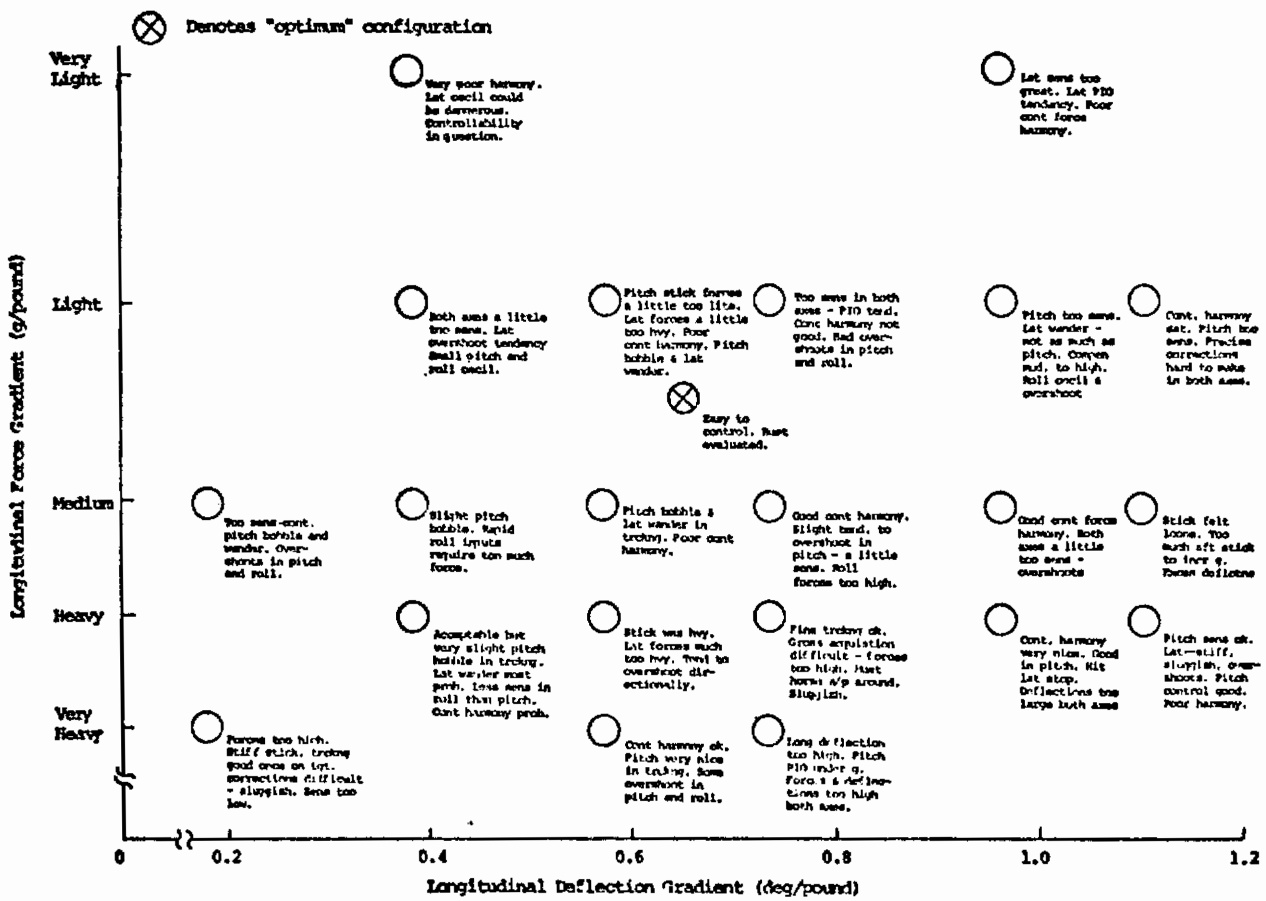

FIGURE 9 PHASE II - PILOT COMMENTS FOR OVERALL TRACKING

Prefilter Corner Frequency (radians/second)	Configuration	
	Optimum Def gradient: 0.7 deg/lb	Small Deflection Def gradient: 0.2 deg/lb
2	Pilot Comments: Continual overshoots. Not responsive. Unpredictable in all tasks. Cooper-Harper Rating 4-8 Preference Rating 8	Pilot Comments: Continual overshoots. Sensitive in g, PIO tendency. Unpredictable in all tasks. Cooper-Harper Rating 4-9 Preference Rating 7.5
8	Pilot Comments: A bit sluggish. Tendency to over control. Noticeable overshoots. Tendency to balloon in landing. Cooper-Harper Rating 4-7 Preference Rating 5	Pilot Comments: Continual overshoots. Too sensitive. Poor predictability. Quite a bit of bobble. Tendency to balloon in landing. Cooper-Harper Rating 2-8 Preference Rating 7
16	Pilot Comments: Sensitive but easy to control. Not g sensitive. Poor predictability but liked the results over-all. Easy to control in landings. Cooper-Harper Rating 3-7 Preference Rating 4.5	Pilot Comments: Poor predictability but can get desired performance. Lateral steps with roll rate. Tendency to over control in roll. Too sensitive in landings. Cooper-Harper Rating 4-8 Preference Rating 7.5

FIGURE 10 PHASE III - PILOT RATINGS AND COMMENTS FOR ALL TASKS

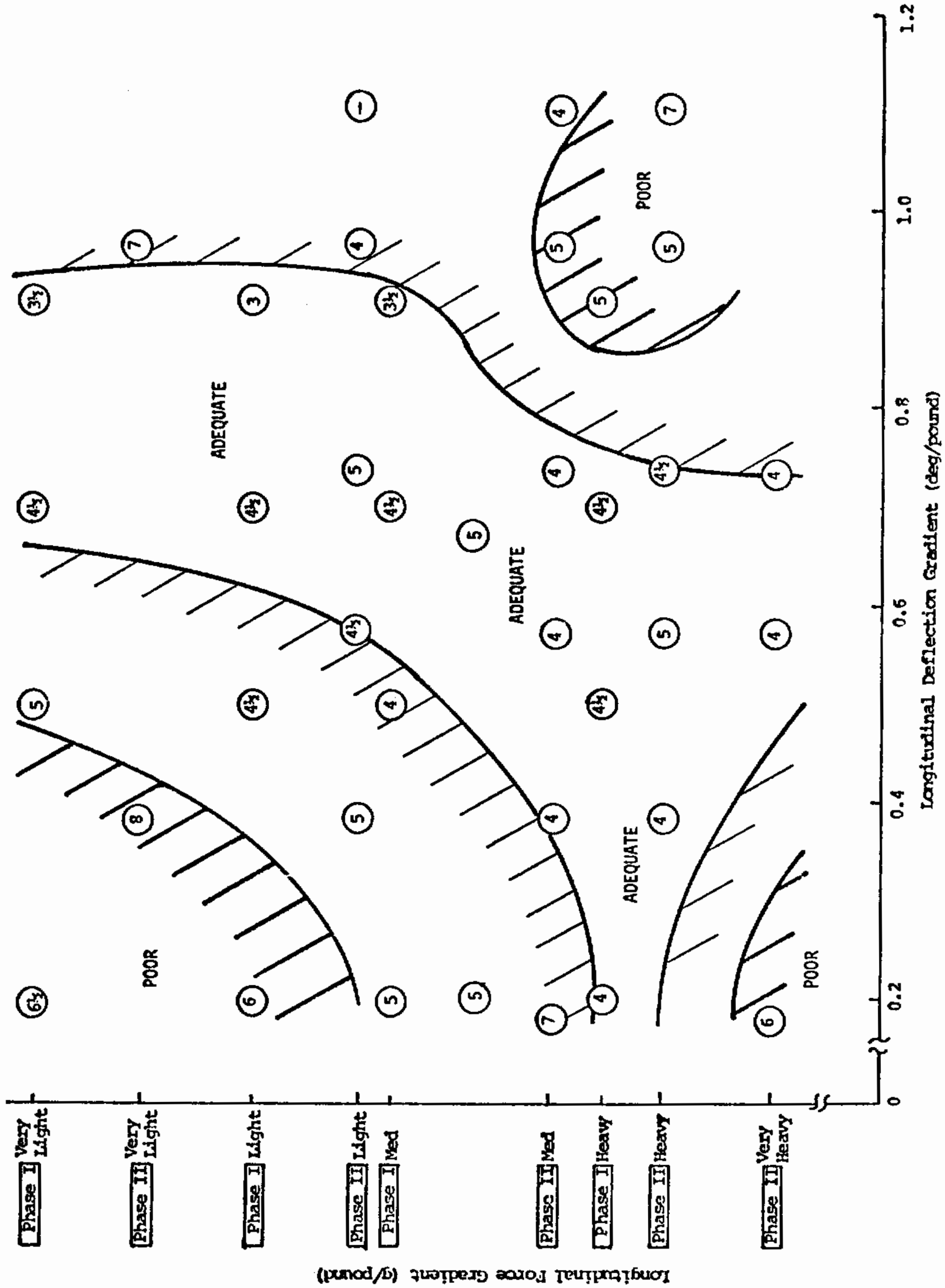

FIGURE 11 AIR-TO-AIR TRACKING PERFORMANCE LEVELS

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8 Tracking Test Techniques for Handling Qualities Evaluation, Twisdale, Franklin, AFFTC-TD-75-1, Air Force Flight Test Center, Edwards Air Force Base, CA, May 1975.

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Rogers Smith, Calspan: What happened to the good configuration of Phase II?
Answer: The "good" is also depicted on the overall summary plot of average Cooper-Harper ratings. It fell within the area defined as "acceptable" performance. It represents the preferred configuration evaluated in Phase II.

Phil Brown, NASA Langley: Can you compare center-stick and side-sticks?
Answer: No evaluations were conducted by the Test Pilot School in this series of tests with a center-stick.

Question: Was there an armrest?
Answer: Yes, it was adjustable vertically and, to a very limited extent, in tilt. There were a few complaints about it but that is a human factors problem and could not be evaluated.

Bud Iles, Grumman: Were there any coupling problems?
Answer: Yes, there was a continual lateral/directional wander throughout all three phases.

Tim Sweeney, ASD: Did you vary breakout forces?
Answer: Breakout forces were fixed at 0.5 pounds for both axes.

Jim Clay: Did you do an analysis of tracking performance?
Gun camera film was analyzed & tracking error time histories were obtained. Little correlation was found between quantitative tracking performance and pilot ratings/comments. Apparently the pilots rated how hard they worked to attain that level of performance.

John Schuler, Boeing: Did you look at characteristics of the pilots?
Answer: Generally, pilot ratings were very closely grouped. There were a few wild points but as long as the pilots performed the tracking in the same manner, they grouped closely.

Rogers Smith, Calspan: Were the pilots equally aggressive?

Answer: To our knowledge they were. If you are referring to Phase III, all pilots had similar backgrounds (they were all fighter pilots). All were briefed to fly the task aggressively.