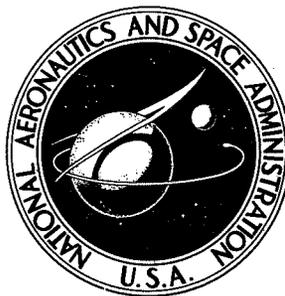


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NASA TN D-7062

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FLIGHT INVESTIGATION OF
THE ROLL REQUIREMENTS
FOR TRANSPORT AIRPLANES
IN THE LANDING APPROACH

by Euclid C. Holleman and Bruce G. Powers

Flight Research Center

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • OCTOBER 1972

1. Report No. NASA TN D-7062		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle FLIGHT INVESTIGATION OF THE ROLL REQUIREMENTS FOR TRANSPORT AIRPLANES IN THE LANDING APPROACH				5. Report Date October 1972	
				6. Performing Organization Code	
7. Author(s) Euclid C. Holleman and Bruce G. Powers				8. Performing Organization Report No. H-711	
				10. Work Unit No. 136-62-01-00-24	
9. Performing Organization Name and Address NASA Flight Research Center P. O. Box 273 Edwards, California 93523				11. Contract or Grant No.	
				13. Type of Report and Period Covered Technical Note	
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D. C. 20546				14. Sponsoring Agency Code	
15. Supplementary Notes					
16. Abstract <p>An in-flight evaluation of transport roll characteristics in the landing approach was made with a general purpose airborne simulator. The evaluation task consisted of an instrument approach with a visual correction for a 61-meter (200-foot) lateral offset. Pilot evaluations and ratings were obtained for approaches made at 140 knots and 180 knots indicated airspeed with variations of wheel characteristics, maximum roll rate, and roll time constant.</p> <p>Satisfactory wheel characteristics were found to be a wheel force gradient less than 1.6 newtons per degree (0.37 pound per degree) with wheel deflection limits of 45° to 60°. The pilots rated maximum steady-state roll rates greater than 12 degrees per second and roll time constants less than 1 second as satisfactory. Approach speed had no effect on the results if the time allowed for the offset maneuver was adequate.</p>					
17. Key Words (Suggested by Author(s)) Roll handling qualities Transport airplanes Approach			18. Distribution Statement Unclassified - Unlimited		
19. Security Classif. (of this report) Unclassified		20. Security Classif. (of this page) Unclassified		21. No. of Pages 48	22. Price* \$3.00

* For sale by the National Technical Information Service, Springfield, Virginia 22151

FLIGHT INVESTIGATION OF THE ROLL REQUIREMENTS FOR TRANSPORT

AIRPLANES IN THE LANDING APPROACH

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INTRODUCTION

The most critical part of a transport airplane flight mission is the approach to landing, where precise bank angle control is required to properly align the airplane with the runway. Several studies have been conducted to investigate the roll requirements for transport airplanes (refs. 1 to 4) using different airplanes and simulation facilities. These studies have defined the roll requirements adequately for current approach speeds (120 knots to 140 knots), but little has been done to assess the effect of approach speed on roll requirements. As a result, the NASA Flight Research Center used the variable-stability JetStar airplane, referred to as the general purpose airborne simulator (GPAS), to investigate the transport roll requirements as a function of approach speed. The use of the variable-stability airplane provided a wide range of parameter variation and an actual in-flight control task for the pilot. Because this was the first program in the approach condition for the GPAS, the tests at the conventional speeds also provided a direct comparison with the well-documented results of previous studies, thus establishing confidence in the GPAS approach simulation.

Normal approach patterns were flown with instrument guidance that provided a 61-meter (200-foot) lateral offset to the runway centerline. At a selected breakout altitude the pilot began a visual correction to the runway. At about 15 meters (50 feet) altitude a go-around was initiated. Variables of the study included approach speed, pilot's control wheel force and deflection characteristics, roll damping, and roll control power. This investigation is an extension of the study of reference 5, which considered roll requirements for transport airplanes during cruising flight.

SYMBOLS

Physical quantities in this report are given in the International System of Units (SI) and parenthetically in U.S. Customary Units. The measurements were taken in Customary Units. Factors relating the two systems are presented in reference 6.

e_p	roll-rate error, deg/sec
e_ϕ	roll-angle error, deg
F_w	lateral wheel force, N (lb)
$L\delta_a$	dimensional roll moment due to aileron control, rad/sec ² /rad of control

p	roll rate, deg/sec
p_c	commanded roll rate, deg/sec
p_m	model roll rate, deg/sec
p_{ss}	maximum steady-state roll rate, deg/sec
r	yaw rate, deg/sec
s	Laplace operator, per sec
t	time, sec
$t_{\varphi=30^\circ}$	time to bank 30° , sec
β_g	sideslip due to gust, deg
δ_a	aileron deflection, deg
δ_{a_c}	commanded aileron servo deflection, deg
$\delta_{a_{max}}$	maximum aileron deflection, deg or rad
δ_r	rudder deflection, deg
δ_w	control-wheel deflection, deg
$\delta_{w_{max}}$	maximum control-wheel deflection, deg
σ	standard deviation
τ_R	roll time constant, sec
φ	bank angle, deg
φ_c	commanded bank angle, deg
φ_m	model bank angle, deg
φ_1	bank-angle change in first second, deg
φ_2	bank-angle change in first 2 seconds, deg
2	

EQUIPMENT AND SIMULATION

The general purpose airborne simulator is a Lockheed JetStar transport airplane with a model-controlled variable-stability system installed to provide simulation capability. The general layout of the airplane is shown in figure 1, and a block diagram of the principal components of the model-controlled system is shown in figure 2. The evaluation pilot's control inputs are routed to the airborne analog computer through the artificial-feel system. The computer is programed with the equations of motion to be simulated. For this investigation the equation used in transfer-function form was simply

$$\frac{p}{\delta_a} = \frac{L_{\delta_a} \tau_R}{\tau_R s + 1}$$

where

$$p_{ss} = L_{\delta_a} \delta_a \tau_R$$

Model response is compared with that of the JetStar, and the difference signal actuates the JetStar control surface to minimize the error. Roll rate and attitude were used as the control loops. With sufficiently high control-loop gain, the error was small and the computer model dynamics were reproduced closely by the JetStar airplane. The gains were:

$$\frac{p_c}{p_m} = 1.0 \quad \frac{\delta_a}{e_p} = 1.0 \text{ sec}$$

$$\frac{\varphi_c}{\varphi_m} = 1.0 \quad \frac{\delta_a}{e_\varphi} = 2.5$$

In addition to the model-following mode of simulation, a low-gain feed forward command from the pilot's control wheel to the aileron was used to give immediate response. This mechanization resulted in negligible delay in commanded roll response and good model following, as illustrated in figure 3(a).

A model was not mechanized for sideslip. A yaw-rate feedback of $\delta_r/r = 0.5$ second was used to damp sideslip, and a 0.2-gain aileron-to-rudder interconnect ($\delta_r/\delta_a = -0.2$) was mechanized to minimize yaw due to roll control.

The basic JetStar longitudinal dynamics were controlled in pitch by the pilot. The airplane's natural frequency for a normal approach in pitch was approximately 1.8 radians per second, and the damping ratio was approximately 0.5. These longitudinal dynamics were rated satisfactory during previous handling-qualities programs and did not detract from the roll evaluation.

Because some of the flights had to be made in turbulence, the bank-angle response to a sideslip disturbance was calculated as an indication of the effects of the GPAS model-following system on the turbulence response of the basic JetStar. The results are shown in figure 3(b) as a function of amplitude ratio and frequency. The GPAS system reduces the bank-angle response to turbulence at the low frequencies, but at the high frequencies the GPAS response is nearly identical to that of the basic JetStar. In the region near the Dutch roll natural frequency (1.3 rad/sec) some reduction in amplitude is obtained with the GPAS system. Because most of the piloting task was lateral maneuvering and concerned the frequencies in the range of the Dutch roll natural frequency, it would be expected that the turbulence response of the GPAS would be similar to that of the basic JetStar.

Controls

Transport airplane controls and displays were used by the evaluation pilot, who occupied the left pilot station (fig. 4). The controls for this station were disconnected from the airplane control system, and the pilot "flew" the model on the analog computer of the simulation system through an artificial-feel system. The artificial-feel system was an electrohydraulic control system designed to provide the capability of simulating a wide range of control system characteristics. Applied force was detected by strain gages which commanded hydraulic servo position which, in turn, moved the control wheel to correspond to the applied force. The control position can be a function of pre-selected force gradients and nonlinearities; however, for these tests no breakout or hysteresis was simulated.

Control wheel deflection limits and force gradient were varied during the program for pilot evaluation. The wheel force gradients used are shown in figure 5. The force gradient increased to a high value, limiting wheel deflection to the desired values.

Guidance

Pilot guidance was provided by the flight director display which was driven by an uplink signal generated by a radar-tracking computer system. With this system the airplane was tracked and guided in the landing approach pattern. On the final approach leg of the pattern, the airplane was guided down a 3° glide slope 61 meters (200 feet) offset but parallel to the runway. The pilot flew by reference to the instruments to the selected breakout altitude, which was changed as a function of approach speed. A visual correction was made to the runway centerline while descending from breakout altitude to a minimum altitude of about 15 meters (50 feet). At the minimum altitude a go-around was initiated to set up for the next approach. Eight to 10 approaches were made on each flight.

Data-Acquisition System

For each flight, 18 parameters were recorded on a 50-channel oscillograph. A 7-cps filter was used to attenuate high-frequency noise on the recordings. A 14-channel tape recorder was used to digitize some of the same recorded quantities. Analog computer model and JetStar responses, as well as pilot inputs and selected model control

system parameters, were recorded. A 12-channel direct-writing oscillograph was used for in-flight analog computer and GPAS-following checks. Pilot comments were recorded with a voice tape recorder.

GENERAL PROGRAM

The primary effects considered on the piloting task were wheel force and deflection characteristics, maximum steady-state roll rate, roll time constant, and approach airspeed. In the initial phase of the program, two pilots made approaches with control wheel deflection limits of $\pm 30^\circ$, $\pm 45^\circ$, and $\pm 60^\circ$ and with wheel force gradients of 1.1, 1.6, and 2.2 newtons per degree (0.25, 0.37, and 0.5 pound per degree) of wheel travel. Maximum commanded roll rate was constant at 12 degrees per second, and roll mode time constant was 0.7 second. During the final flight of this part of the program, the pilots selected wheel characteristics for use in later parts of the program.

In the second phase of the program, approaches were evaluated over a range of maximum steady-state roll rates of 3 degrees per second to 24 degrees per second with a roll mode time constant of 0.7 second and over a range of roll mode time constant of 0.7 second to 5.0 seconds with the steady-state roll-rate capability maintained at 18 degrees per second. Approaches were made at 140 knots indicated airspeed (typical for the GPAS) and at 180 knots indicated airspeed. Three pilots participated in this part of the program.

Approaches were also made at 70 knots and 120 knots indicated airspeed with a light, twin-engined airplane to extend the effect of approach speed results to lower airspeeds.

The primary part of the pilot evaluations occurred during the correction for the offset to the runway after "breakout." However, evaluations were made during the downwind leg of the approach pattern during both visual and simulated instrument flight. Instrument flight evaluations with the pilot hooded were continued during the base and the final legs of the approach pattern. Approximately 80 percent of the approach evaluations were made in smooth air. The others were made in light or light-to-moderate turbulence (pilot's assessment) caused by winds in the test area. The pilots indicated that they did not believe that the level of turbulence significantly affected the evaluations.

The pilot evaluation questionnaires used for each phase of the program are presented in tables 1 and 2. The pilot rating scale used is presented in table 3. The evaluation procedures generally followed the suggestions in reference 7.

RESULTS AND DISCUSSION

The most significant results from this program were obtained from pilot evaluations and ratings of airplane roll flying qualities. Although evaluations were made during flight using outside visual references and instrument cues, the correction for offset to the runway after "breakout" was the most important basis for the evaluations. Flying qualities for transport operations only were considered.

Control Wheel Characteristics

The initial evaluations were designed to determine the control wheel characteristics desired by the pilots for the approach control task. Approaches were made in smooth air and in turbulence judged by the pilots to be light-to-moderate with various combinations of wheel deflection limit and force gradient. The wheel characteristics evaluated were varied randomly. Most approaches were made at an indicated airspeed of 140 knots (normal for the JetStar); however, several were made at 180 knots. Airplane roll mode characteristics were $p_{ss} = 12$ degrees per second and $\tau_R = 0.7$ second. These values have been predicted to be just satisfactory for transport airplane roll response.

Pilot responses to the questionnaire (table 1) on the roll control characteristics are summarized in figures 6(a) to 6(g). The characteristics considered to be most generally satisfactory for one-hand operation in the approach were wheel force gradients of 1.1 newtons per degree to 1.6 newtons per degree (0.25 pound per degree to 0.37 pound per degree) and deflection limits of 45° to 60° . These characteristics were most comfortable to the pilots for approach maneuvering and were most compatible with airplane response. Typical pilot comments are presented in the appendix.

Overall pilot ratings of control wheel characteristics were also obtained and are summarized in figures 7(a) and 7(b). From these data the most satisfactory wheel characteristics appear to result from a force gradient of 1.1 newtons per degree (0.25 pound per degree) with deflection limits of at least 45° . During one flight the pilots were asked to select the most desirable wheel force gradient. Both pilots selected greater than the nominal optimum gradients; however, the pilot ratings were relatively insensitive to wheel force gradient in the range from 1.1 newtons per degree to 1.6 newtons per degree (0.25 pound per degree to 0.37 pound per degree). The succeeding parts of the program were flown using the wheel force gradients selected as being most desirable, and a 60° wheel deflection limit.

Roll Mode Characteristics

Effect of p_{ss} .—Approaches were also made with several levels of steady-state roll rates available to the pilot. Three pilots made approaches at indicated airspeeds of 140 knots and 180 knots and with a roll time constant of 0.7 second. The results of the pilot questionnaire (table 2) are summarized in figure 8. A minimum steady-state roll rate of 12 degrees per second appears to be required for satisfactory control of approach for either approach speed.

The results are also presented in terms of pilot ratings in figure 9. Average values of pilot rating for the three pilots are presented. As expected, the pilot ratings tend to summarize the comments given in the questionnaire. No significant effect of approach speed per se is noted, except possibly at the lowest roll-rate capability (discussed in more detail later). As will be shown, there was rather wide variability in the lowest roll-rate-capability data at the lower approach speed, so the difference shown is not significant. It is indicated that a roll rate of 5 degrees per second would be acceptable (pilot rating less than 6.5) under emergency conditions.

Figure 10 compares the roll control used to that available during approach for the range of roll rate covered. For the 0.7 time constant data nearly all the roll rate

available at the lower p_{ss} values was used by the pilot; whereas at levels of p_{ss} rated to be satisfactory only about half the roll control capability available was used. From the additional roll time constant data, it is apparent that the pilot attempted to compensate for the long roll time constant by commanding larger roll control deflections.

These same data are presented in figure 11 in terms of the maximum roll acceleration used compared to that available. The data show that more roll acceleration was used when more was available. During the offset maneuver, an important consideration was the ability to stop the roll maneuver as well as to start it. Thus for the low roll control capability available, the pilot was reluctant to use as large an input as he would have liked because he was not sure he would be able to stop the bank angle when desired. As a result, the roll control capability used decreased as the roll capability available decreased. A roll control capability margin was maintained to $p_{ss} = 3$ degrees per second, the lower limit of the tests, where all the available roll control capability was required to perform the offset maneuver.

Figure 12 presents the pilot ratings for the maximum roll acceleration commanded by the pilot for the various roll time constants investigated. A roll acceleration of 0.12 radian per second² or greater was satisfactory with a satisfactory roll time constant. Pilot ratings rapidly became unacceptable with decreased roll control acceleration, whether the decreased roll acceleration resulted from low roll acceleration or from a long roll time constant. During an approach, the pilot may not be able to wait for the roll acceleration with a long roll time constant.

Effect of τ_R . - With a level of steady-state roll rate of 18 degrees per second, approaches were made at indicated airspeeds of 140 knots and 180 knots with a range of roll time constants from 0.7 second to 5.0 seconds. Pilot response to a questionnaire (table 2) is summarized in figure 13. For both approach speeds the roll response was not acceptable with roll time constants greater than 1.5 seconds, and roll damping at a time constant of 1.5 seconds was less than desired. Similar trends are noted from the pilot rating data shown in figure 14. Only time constants of 1 second or less were satisfactory; however, time constants as large as 3 seconds were acceptable. The effect of approach speed on pilot rating was not significant, as will be discussed later in more detail.

Comparison of Pilot Ratings With Criteria Parameters

Bank-angle response. - Accurate control of bank angle is more important during approach than in any other flight region, with the possible exception of takeoff. Therefore, the data were converted to the bank-angle change achieved in 2 seconds for summary comparisons. (Bank-angle-response-in-2-seconds more nearly describes the airplane response than the control system response, as bank-angle-change-in-1-second might.) Comments on the preciseness of bank-angle control were requested on the pilot questionnaire, and overall pilot ratings were obtained. Average pilot ratings of bank-angle change in 2 seconds for the three pilots are presented in figures 15(a) and 15(b). The vertical lines indicate the variation about the mean pilot rating (± 1 standard deviation). These data indicate that the pilots downgraded roll response more for roll time constant than for level of roll rate. Comparison of the data for the two approach speeds shows no significant differences attributable to airspeed.

Comparison with previous work.—The results from several studies of roll control requirements are compared in figure 16 in terms of bank-angle change in 2 seconds. The results are for satisfactory roll time constants, 0.7 second to 1.0 second. Included are results from two flight programs during which actual approaches were made (refs. 1 and 2), one cruise flight program (ref. 5), a simulation program (ref. 3), and a summary study of transport handling qualities (ref. 4). The results of the present investigation are in general agreement with those from one of the flight programs (ref. 1) and the summary study (ref. 4). There is somewhat poorer agreement between the present results and the results of the other flight program with a jet transport airplane (ref. 2). Tests utilizing a moving base simulator (ref. 3) indicated that much higher roll rates would be required; however, these tests included simulated light-to-moderate turbulence which would increase the roll-rate requirements. Surprisingly, the results from the cruise flight program (ref. 5) indicate that somewhat higher roll response was desired for cruise than for approach.

Selected comparisons of the referenced results and the results of the present tests are presented in figures 17(a) to 17(e). Good agreement between the results of the present study and those of reference 4 is shown (fig. 17(a)) for the satisfactory range of pilot ratings. In general, the results from the simulated approach study (ref. 3) support the present results in the higher pilot rating (unacceptable) range; however, in the satisfactory pilot rating range the simulation results indicate a requirement for more roll control capability than the present flight tests indicated (fig. 17(b)).

The results of reference 2 and the present study are compared in figure 17(c). At low roll control capabilities, the present study results indicate a requirement for considerably more bank-angle-change capability than indicated by the referenced results.

Comparing the present results with the Military Specification (ref. 8) for transport airplanes (fig. 17(d)), the requirements for roll time constant agree well; however, roll control in terms of time-to-bank-to-30° (fig. 17(e)) indicates wide differences in the Military Specification requirements and the present results. The present results indicate a much greater tolerance to low roll control power than required by the Military Specification. Neither considered the effect of turbulence on roll control.

Analysis of the Sidestep Maneuver

Effect of approach speed.—Although, as indicated, approach speed did not affect the evaluation of roll handling qualities, there was a minimum time required for correction for the offset to the runway. Approaches were made first at 140 knots indicated airspeed. With a breakout at an altitude of 61 meters (200 feet) from a 3° glide-slope approach, correction to the runway could be made before the 15-meter- (50-foot-) altitude guideline selected was reached. This approach allowed 12 seconds (fig. 18) for the correction maneuver along the 3° glide slope. It was reasoned that the time required to decrease altitude from 15 meters (50 feet) to touchdown would be allowed for flare to touchdown.

The pilots indicated that ample time for the correction to the runway was available at the 140-knot approach speed on a 3° glide slope.

Approaches were also made with the same conditions at an indicated airspeed of

180 knots. At this approach speed it was apparent from pilot comments that there was insufficient time to satisfactorily complete the approach maneuver. Therefore, the breakout altitude was extrapolated from 61 meters (200 feet) for the approach airspeed of 140 knots to 76 meters (250 feet) for the approach airspeed of 180 knots (fig. 18). This allowed the same time for correcting for the offset to the runway as was allowed at an indicated airspeed of 140 knots. The pilots indicated that the higher breakout altitude allowed satisfactory time for correction to the runway at the higher speed. Therefore, the remainder of the approaches at 180 knots indicated airspeed were made with a breakout altitude of 76 meters (250 feet).

To extend the results to lower speeds, approaches were made at 120 knots and 70 knots with a light, twin-engined airplane. The approach glide slope was 3° , and the offset for correction was 61 meters (200 feet), the same as for the other tests. The 15-meter (50-foot) altitude for maneuver completion was maintained, and the breakout altitude was selected to allow the same time for maneuvering during the approach. The breakout altitudes were 40 meters and 55 meters (130 feet and 180 feet) for the approach airspeeds of 70 knots and 120 knots, respectively. Pilot comments indicated that the selected approach conditions provided satisfactory time for correction for a 61-meter (200-foot) offset to the runway during approach.

Comparison with predicted results. — Data from some of the approximately 100 approaches made during the program were recorded for analysis. From these records, estimates of the time required for the offset correction were made by noting the time that bank-angle change was started and the time that the airplane returned to near-level, zero-roll-rate flight. No actual ground track recordings were made to verify that the offset correction was 61 meters (200 feet). Reliance was placed on the guidance system and the safety pilot's judgment. Only the sidestep maneuvers made with satisfactory roll characteristics ($\tau_R \leq 1.0$ sec and $p_{SS} \geq 12$ deg/sec) were selected for comparison with the requirements of reference 9. Data for 140-knot and 180-knot approaches are presented. No effect of approach speed was evident.

The actual maximum roll control used during the offset correction (fig. 19) shows that decreasing roll control was used for increased time to correct for the offset during approach. Most of the times were somewhat greater than the nominal expected. The maximum roll rate and bank angle used were also noted (figs. 20 and 21) for the offset correction times. These results are compared with the roll-rate and bank-angle requirements (ref. 9) for continuous sinusoidal correction maneuvers for 61-meter (200-foot) offsets to the runway. Little or no correlation with time for the correction is obvious. The variable-stability airplane used for these tests was not cleared for touchdown with the systems operating, so no actual landings were made. In many instances the pilots appeared to use less roll rate and bank angle than had been predicted to be required by the reference. This indicates that either the correction may have been for less than a 61-meter (200-foot) offset, or the maneuvering was not sinusoidal-like and greater distance along the runway was accepted by the pilot. The pilots did use lower rates and bank angles for the final correction to the runway. This was not surprising, in that the airplane was at lower altitude during the final correction and the pilot was perhaps wary of using large rates and attitudes near the ground and therefore accepted longer times.

CONCLUDING REMARKS

An in-flight evaluation of transport roll characteristics in the approach was made with the JetStar variable-stability airplane. Three-degree-glide-slope approaches were performed at indicated airspeeds of 140 knots and 180 knots to investigate the effects of variations of wheel characteristics, maximum roll rate, and roll time constant.

Satisfactory wheel force gradients were found to be less than 1.6 newtons per degree (0.37 pound per degree) for one-hand operation in the approach. Satisfactory wheel deflection limits were 45° to 60°.

Pilot ratings of satisfactory were obtained for maximum steady-state roll rates greater than 12 degrees per second and roll time constants less than 1 second. Pilot ratings of acceptable were obtained for maximum steady-state roll rates greater than 5 degrees per second and roll time constants less than 3 seconds.

For a 3°-glide-slope approach, speed had no significant effect on the results if the time allowed for the offset maneuver was adequate. A satisfactory time to perform a 61-meter (200-foot) lateral offset was approximately 12 seconds.

Flight Research Center,
National Aeronautics and Space Administration,
Edwards, Calif., May 17, 1972.

APPENDIX

TYPICAL PILOT COMMENTS ON WHEEL CHARACTERISTICS

For an evaluation at 140 knots in smooth air with a maximum deflection of $\pm 60^\circ$ and a force gradient of 1.3 newtons per degree (0.29 pound per degree), the pilot comments were:

"The wheel force gradient was definitely acceptable. Maximum deflection was acceptable also. It was 60° . I did not have occasion to use full control during the approach, but you could use full control comfortably. You could control with one hand. I flew with one hand during the approach, and it felt comfortable and safe. The controls were compatible with airplane response. There was no tendency to overcontrol or induce oscillations. The available roll rate was just a little low. That was the only thing that would require improvement. The pilot rating of the controls was 3.5."

For an evaluation at 180 knots in light turbulence with a maximum deflection of $\pm 45^\circ$ and a force gradient of 1.1 newtons per degree (0.25 pound per degree), the pilot comments were:

"The wheel force gradient was a little light, but the maximum deflection was acceptable. I used only maximum control when testing for the maximum. The control compatibility with airplane response was not too bad. There was no overcontrol tendency. The control characteristics did not detract from airplane control. They may have helped in the light turbulence with the light gradient. Control with one hand was safe and comfortable. Overall, the controls were acceptable for a transport. For improvement, increase the wheel force gradient slightly. Pilot rating was 3.0."

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TABLE 1. - QUESTIONNAIRE FOR WHEEL CONTROL CHARACTERISTICS

OBJECTIVE: Define wheel force gradient and deflection limits for a jet transport.

1. Was wheel force gradient acceptable?
2. Was maximum wheel deflection acceptable?
3. Could full control be used comfortably?
4. Were controls compatible with airplane response?
5. Was there any tendency to overcontrol?
6. Did control characteristics detract from airplane handling?
7. Was control with one hand comfortable, safe?
8. Was overall roll control acceptable for a transport?
9. Any recommended changes for improvement?
10. Pilot rating _____

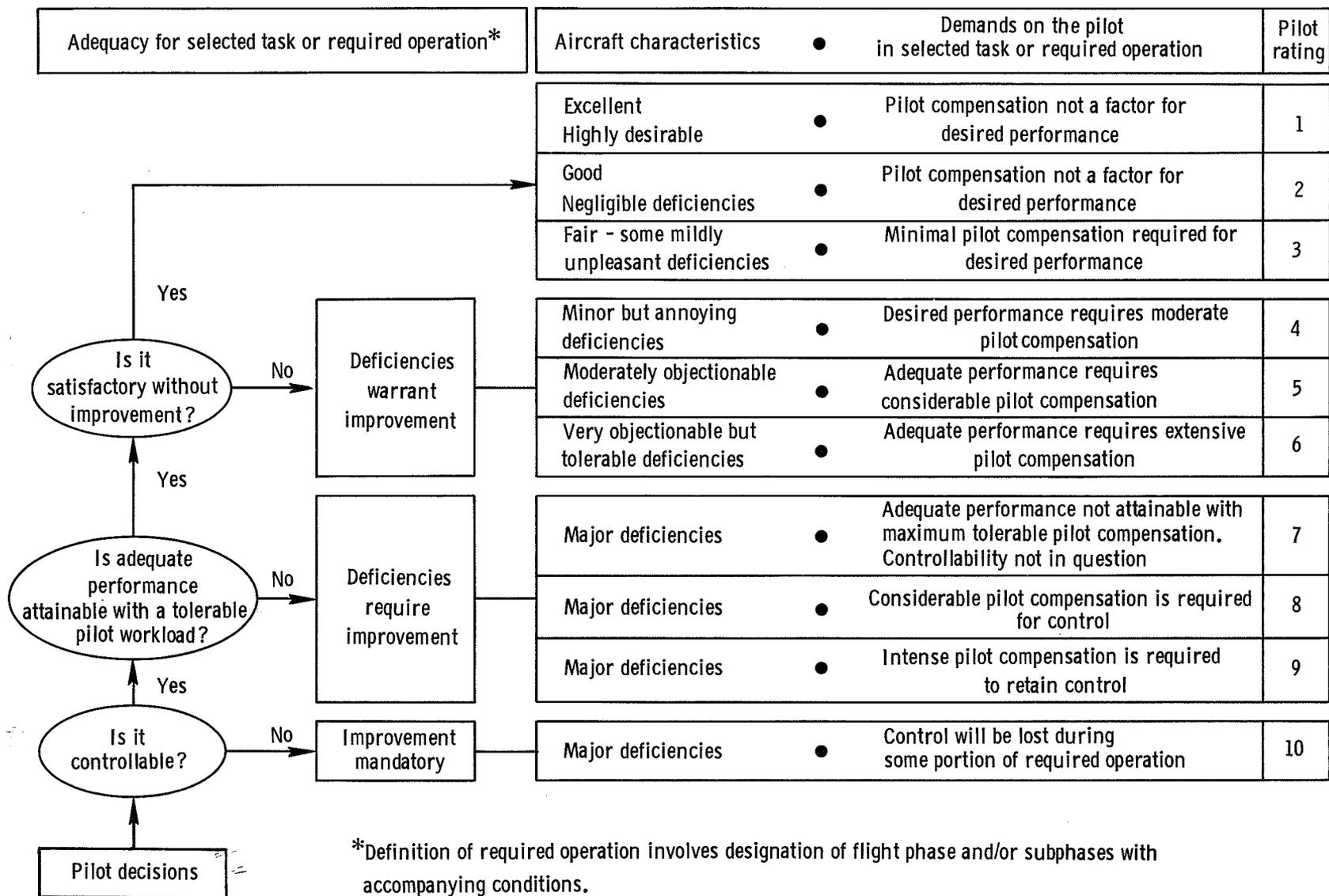
TABLE 2. -QUESTIONNAIRE FOR ROLL-RATE REQUIREMENTS AND DAMPING

OBJECTIVE: Define the roll-rate requirements for a jet transport during approach.

Evaluate roll resulting from aileron only.
Rudder is available for emergency.

1. Ability to roll to and stop precisely at desired bank angle.
2. Any overcontrol tendency?
3. Was roll rate available satisfactory?
4. Could all roll rate (full wheel) be used?
5. Was roll damping acceptable?
6. Any objectionable lag in roll response?
7. Was overall roll response acceptable for transport approach?
8. Pilot rating of roll response.
9. Improvements recommended.
10. Was the time for offset correction acceptable?

TABLE 3. - PILOT RATING SCALE (FROM REF. 7)



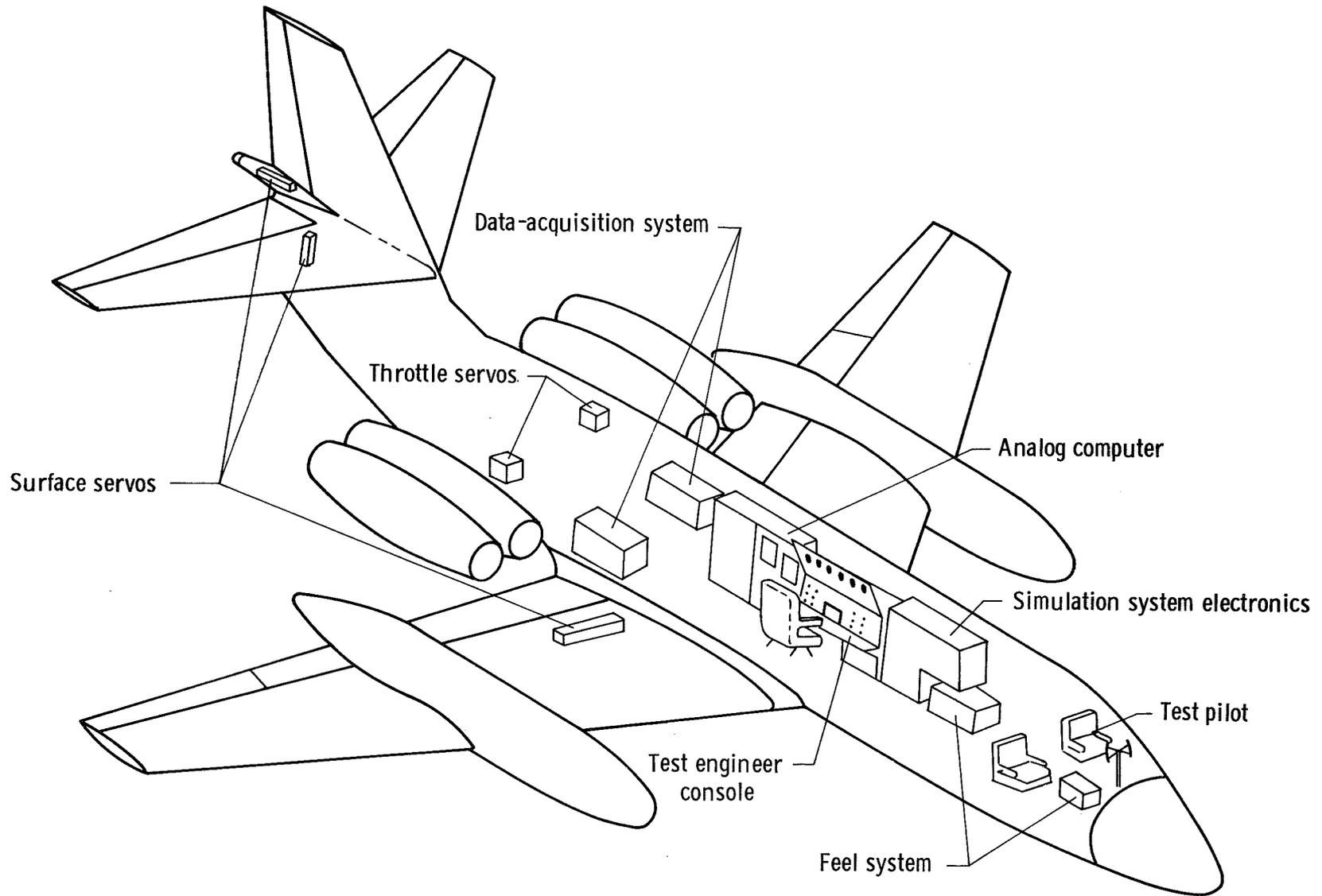


Figure 1. Layout of the JetStar and systems which make up the general purpose airborne simulator.

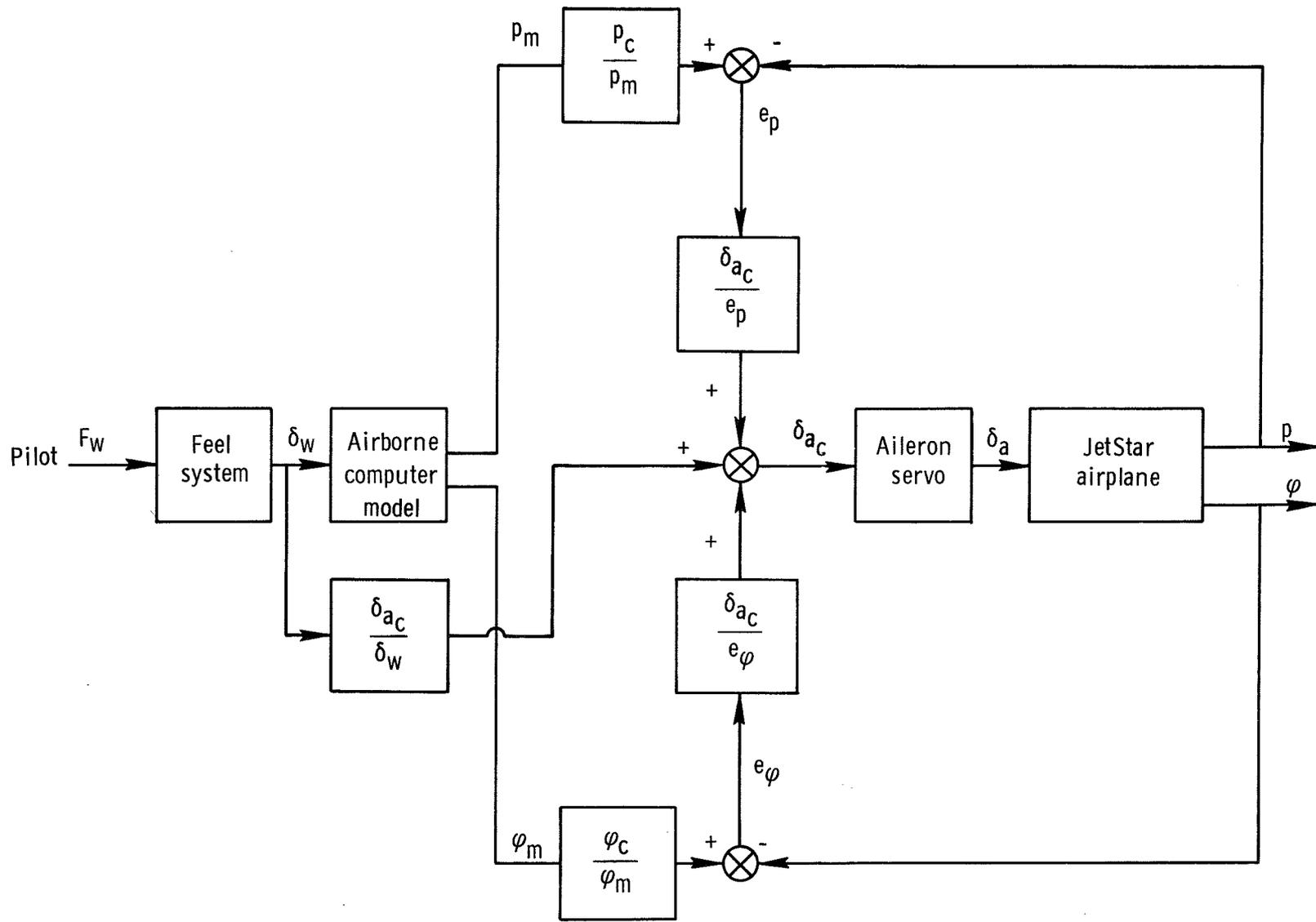
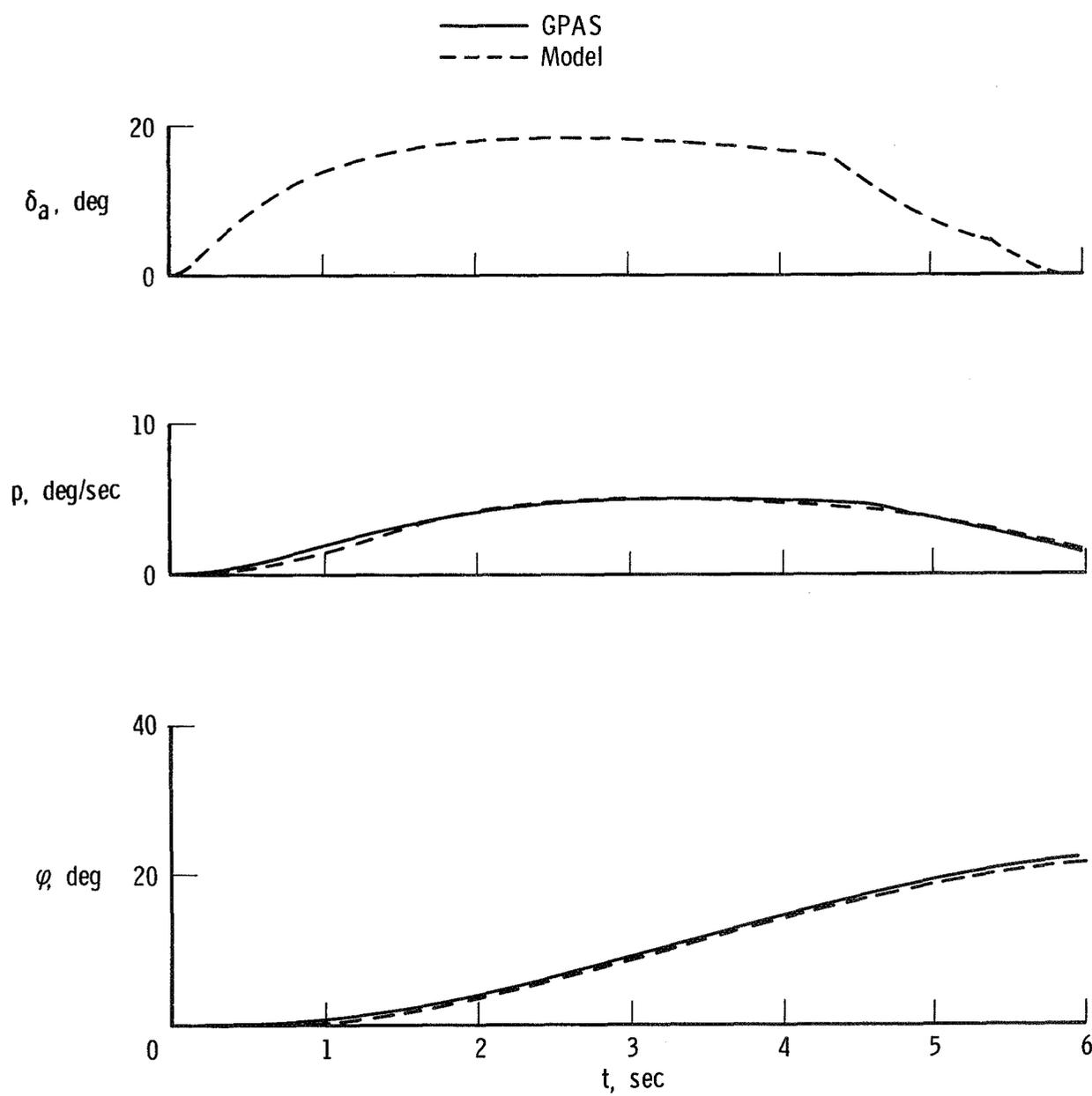
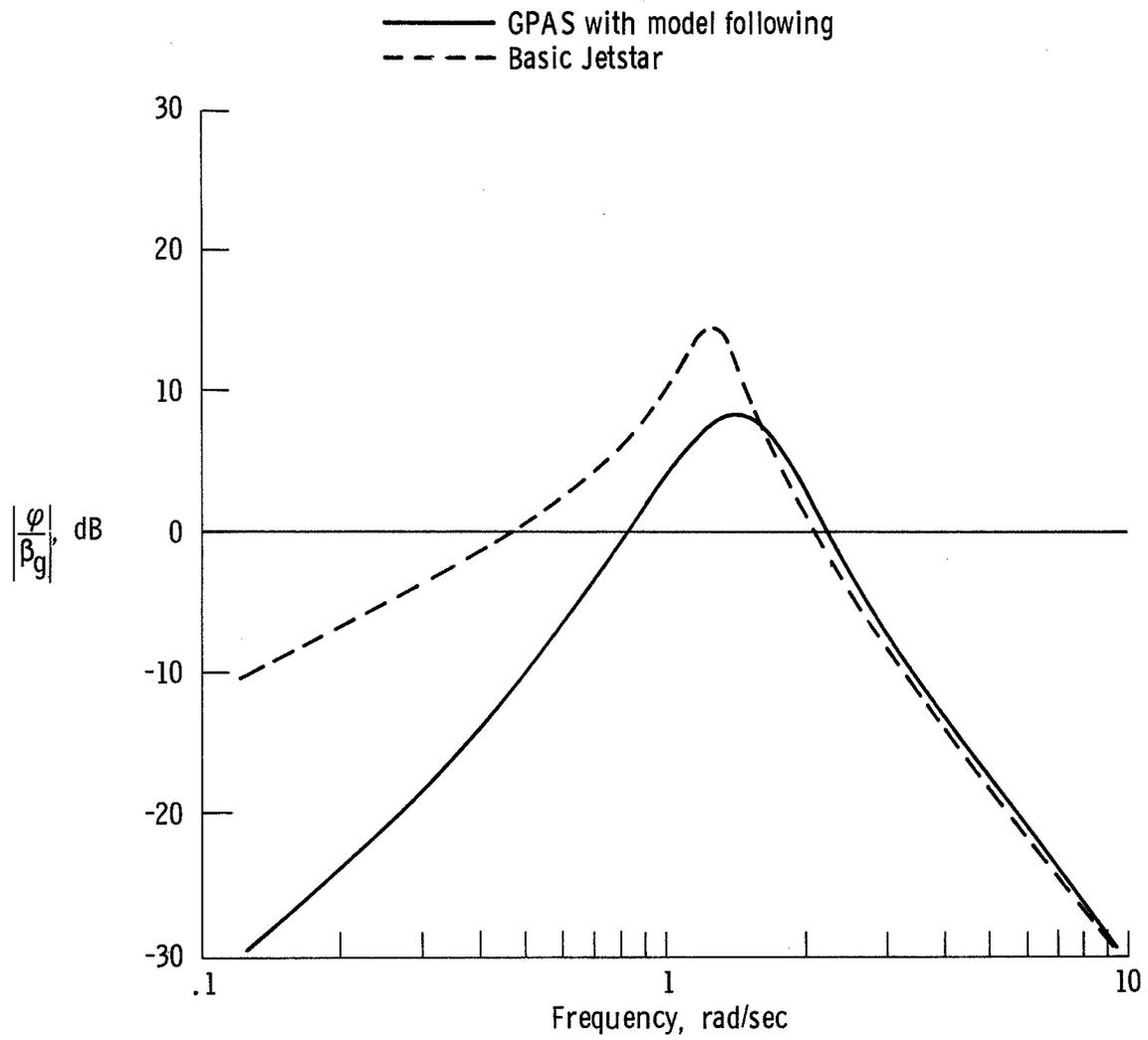


Figure 2. Block diagram of the GPAS model-controlled system.



(a) Satisfactory roll model following.

Figure 3. Example of model following in roll by GPAS and calculated response to side-slip disturbance.



(b) GPAS and basic Jetstar response to sideslip disturbance.

Figure 3. Concluded.

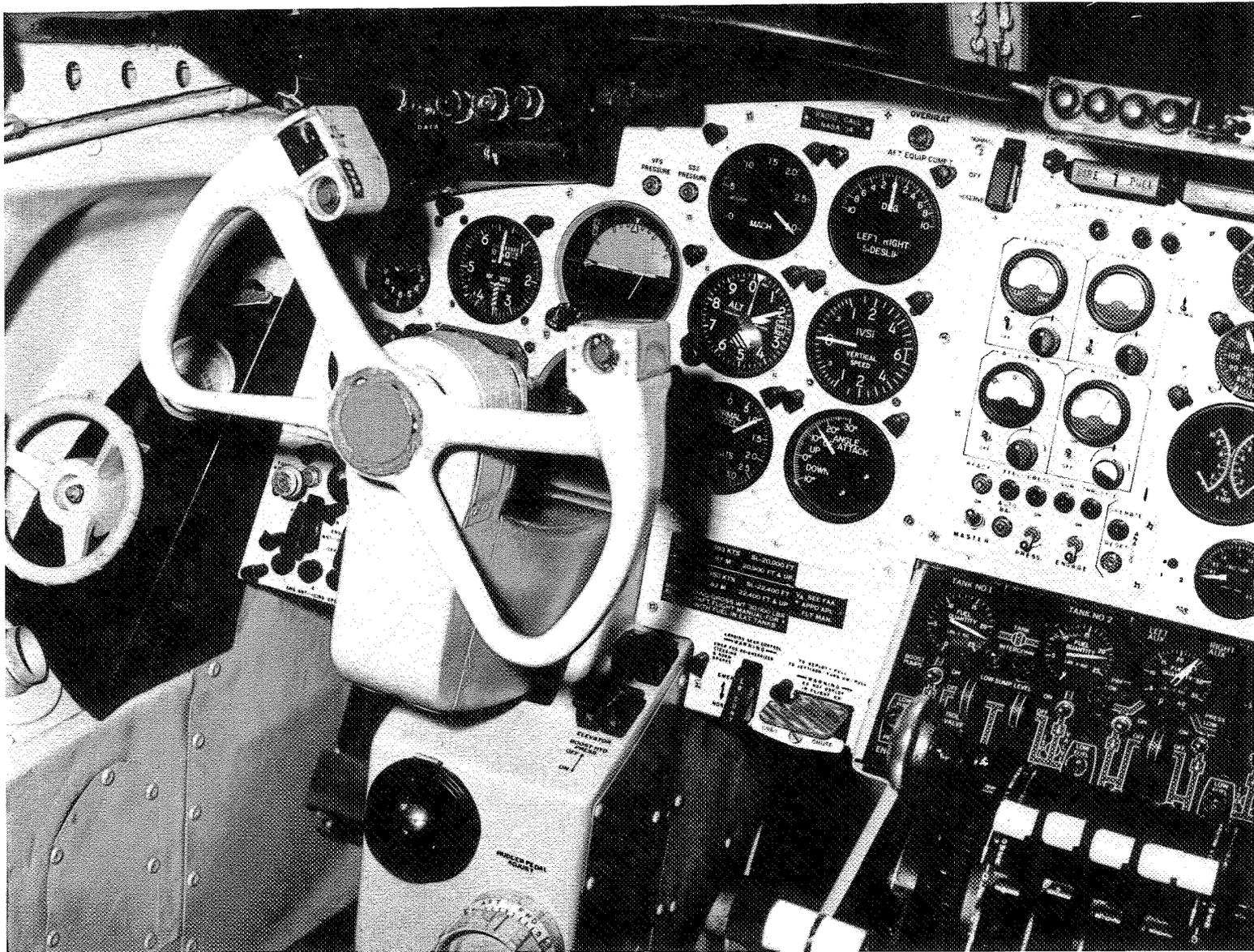


Figure 4. Evaluation pilot's station.

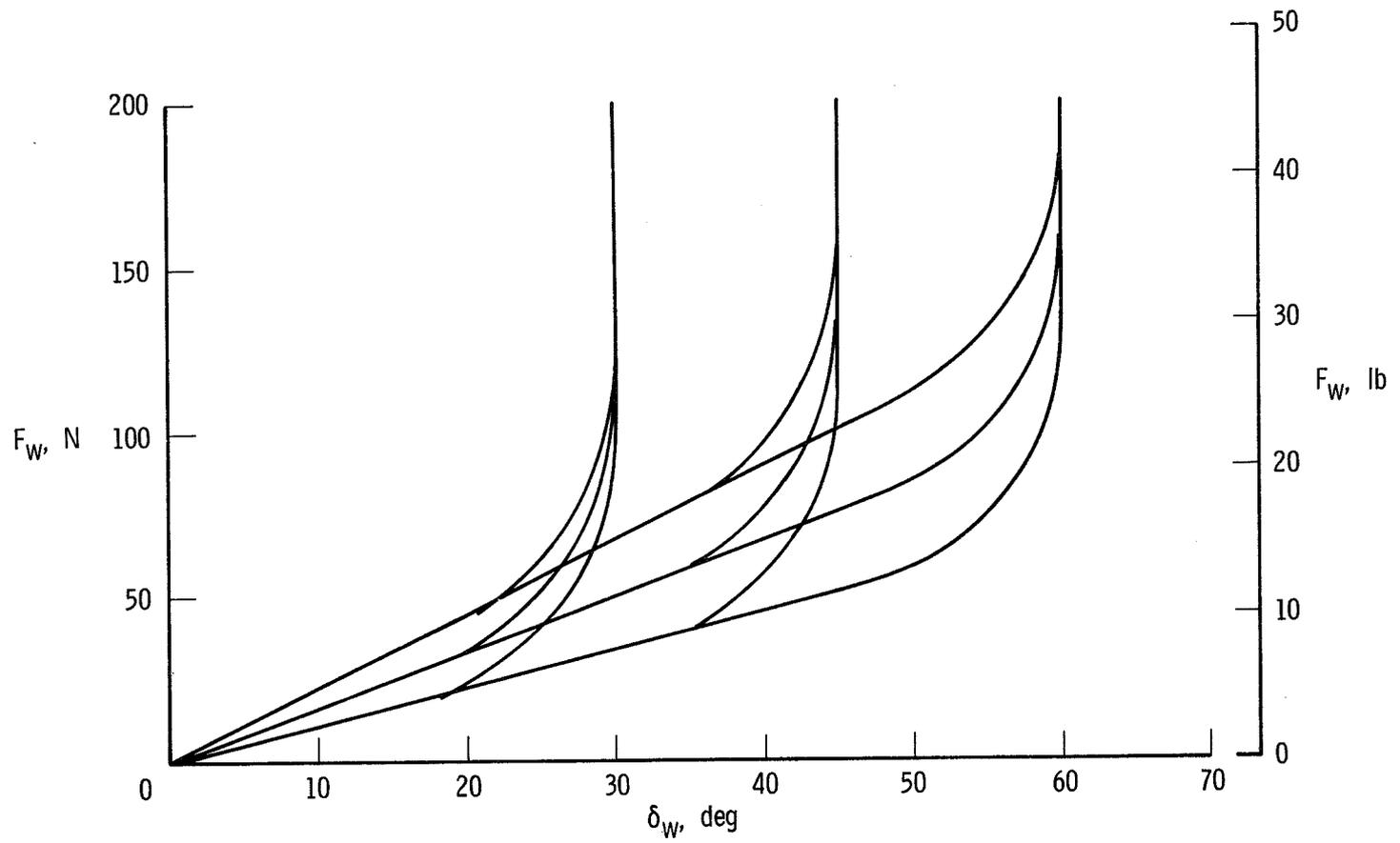
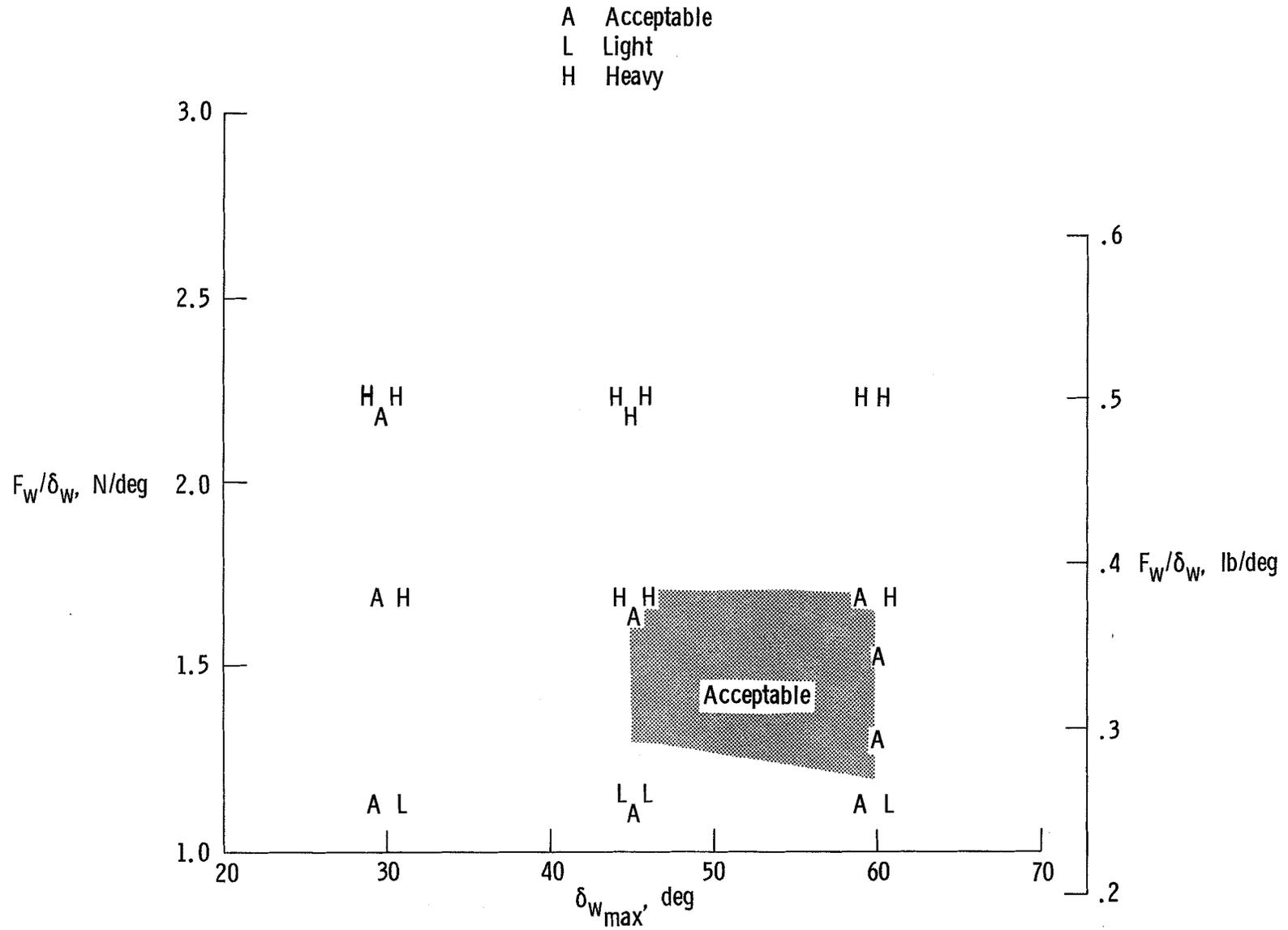
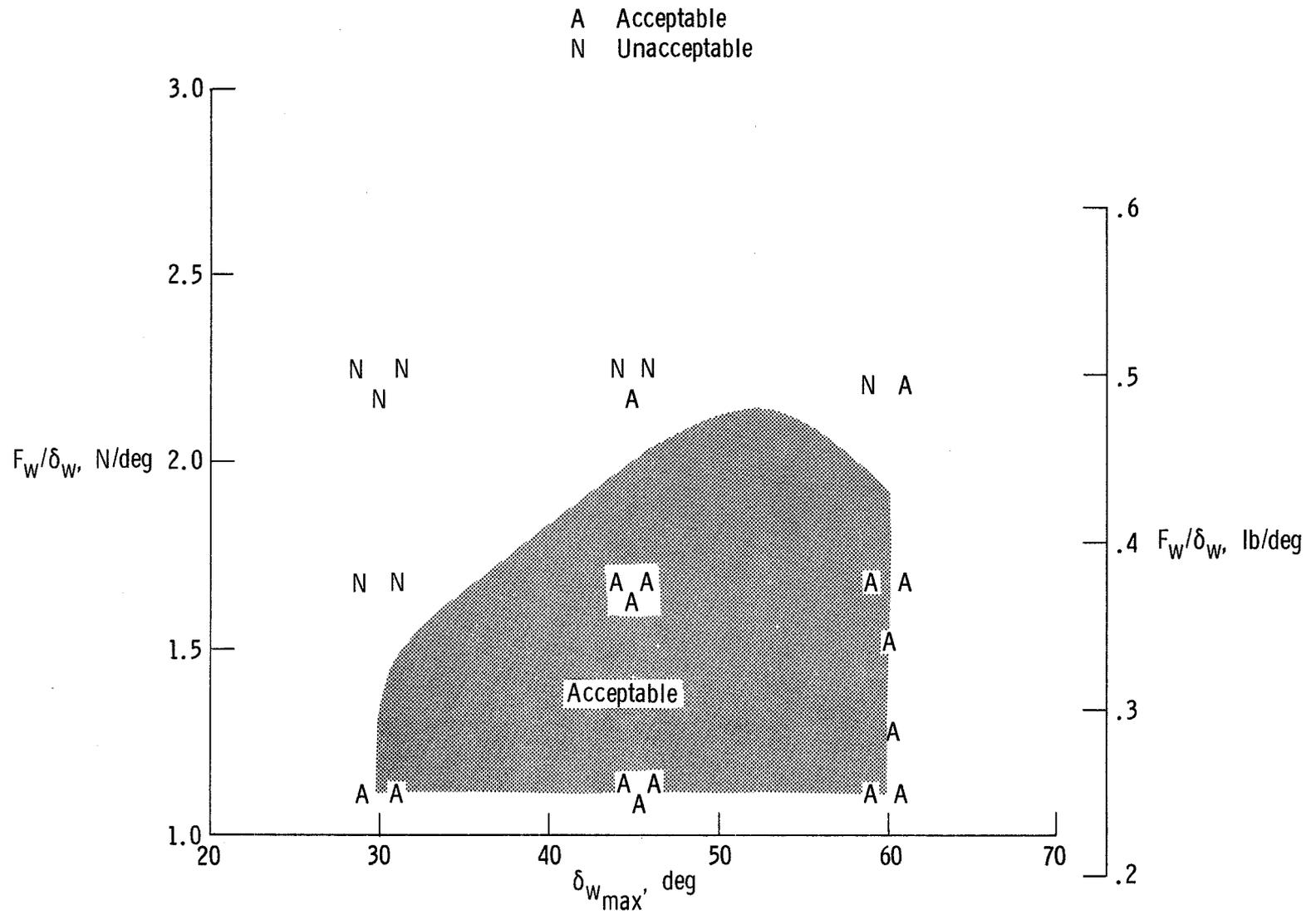


Figure 5. Control wheel force characteristics.



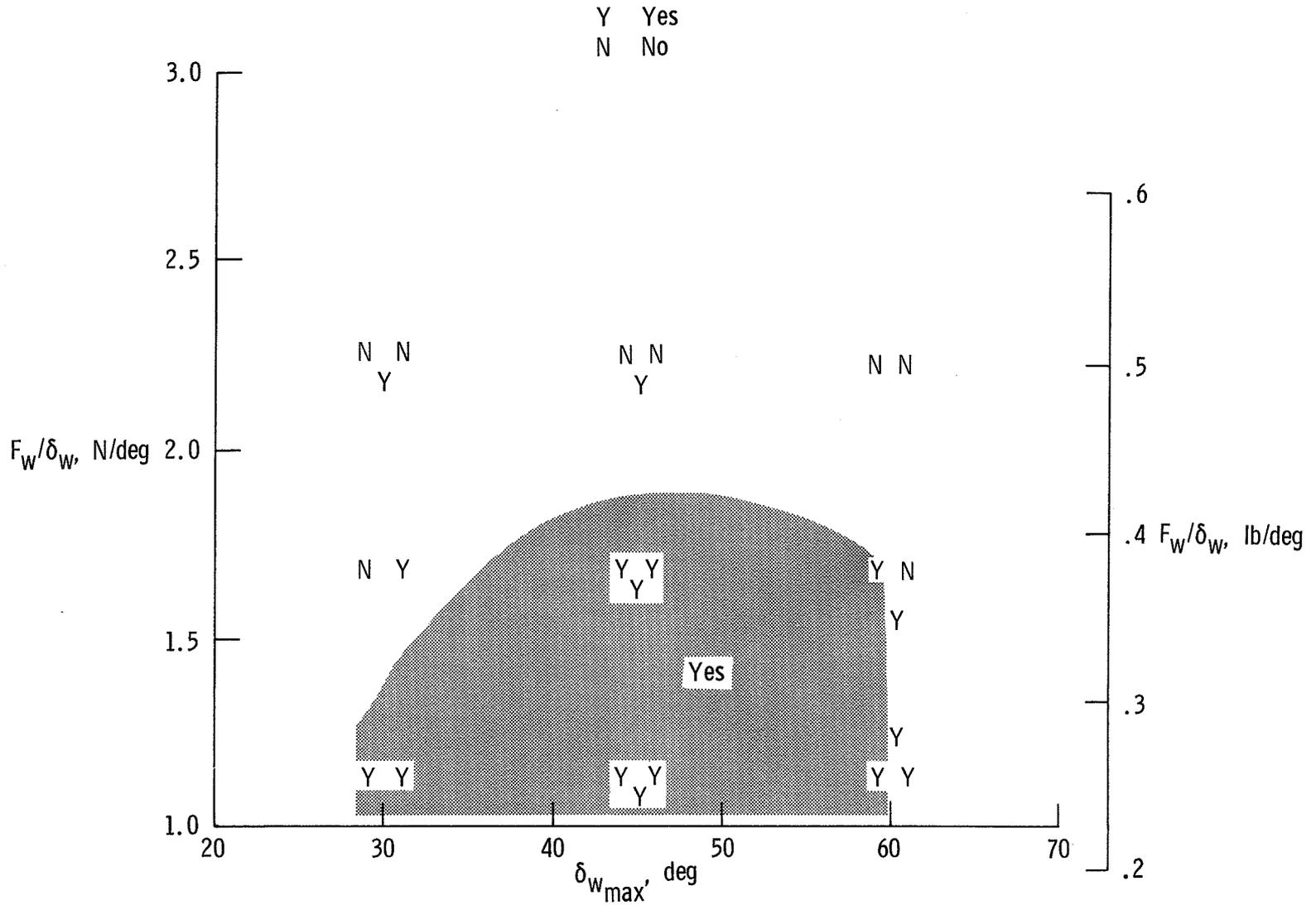
(a) Question 1: Was wheel force gradient acceptable?

Figure 6. Summary of pilot comments on wheel control characteristics using the questionnaire of table 1.



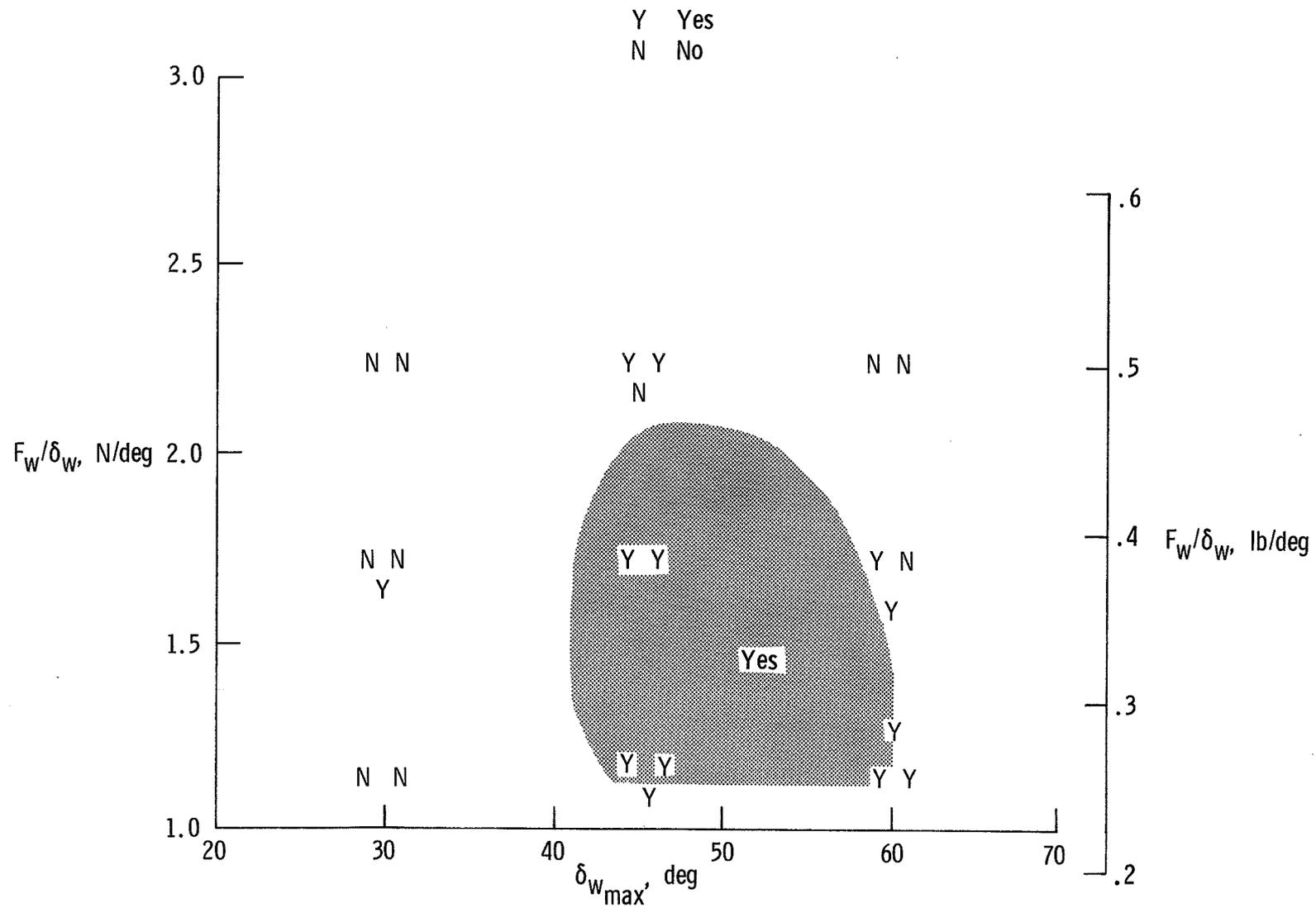
(b) Question 2: Was maximum wheel deflection acceptable?

Figure 6. Continued.



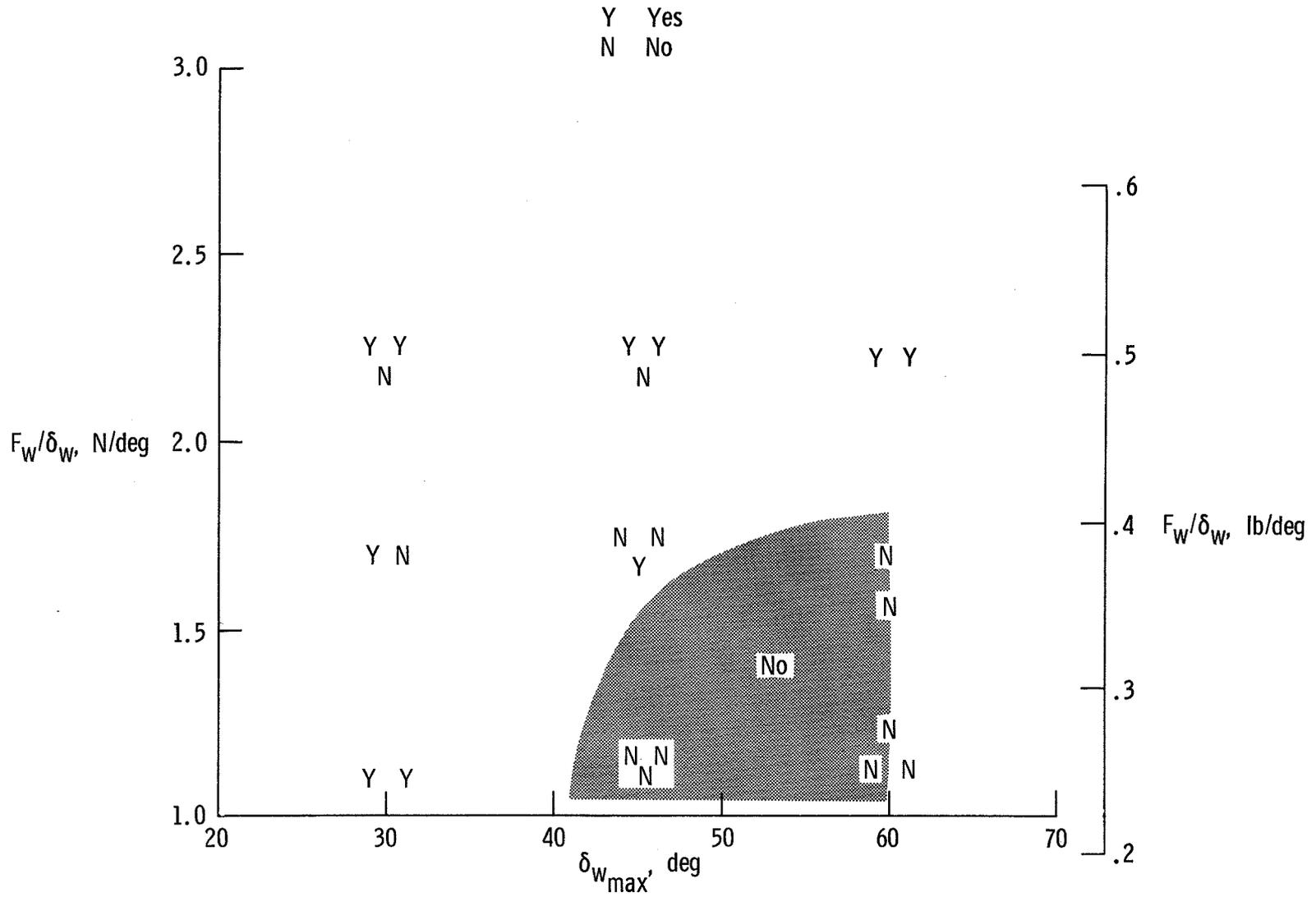
(c) Question 3: Could full control be used comfortably?

Figure 6. Continued.



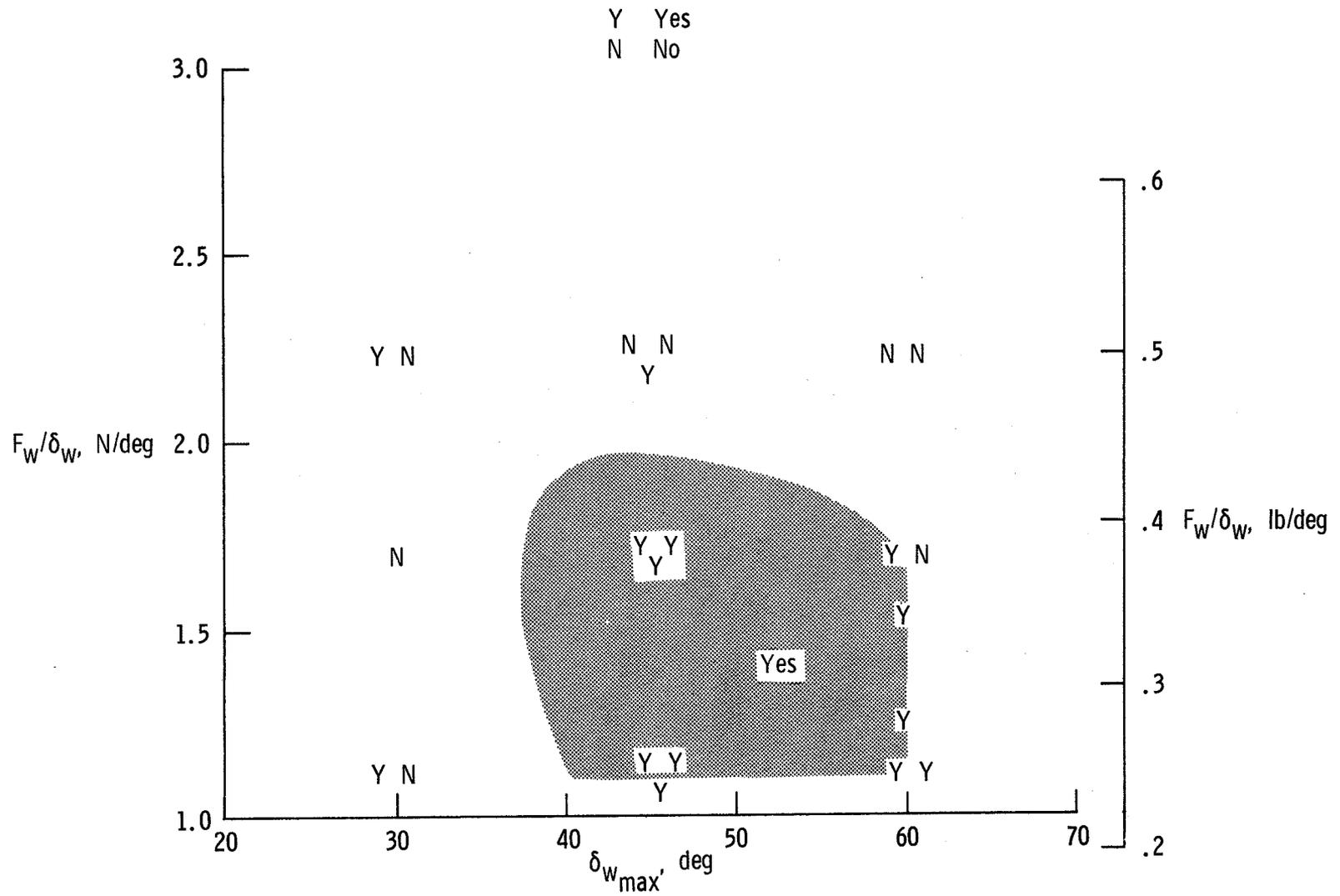
(d) Question 4: Were controls compatible with airplane response?

Figure 6. Continued.



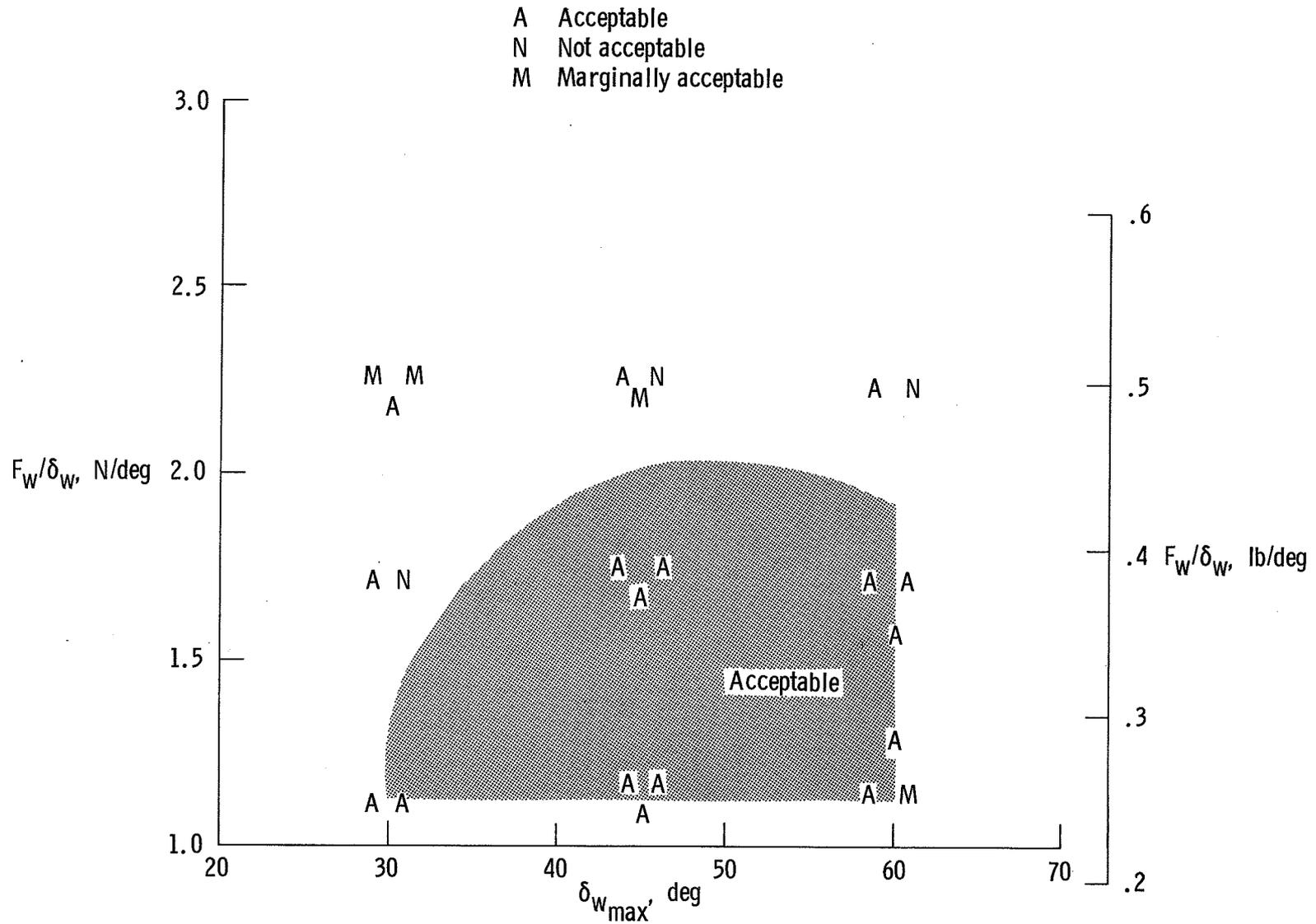
(e) Question 6: Did control characteristics detract from airplane handling?

Figure 6. Continued.



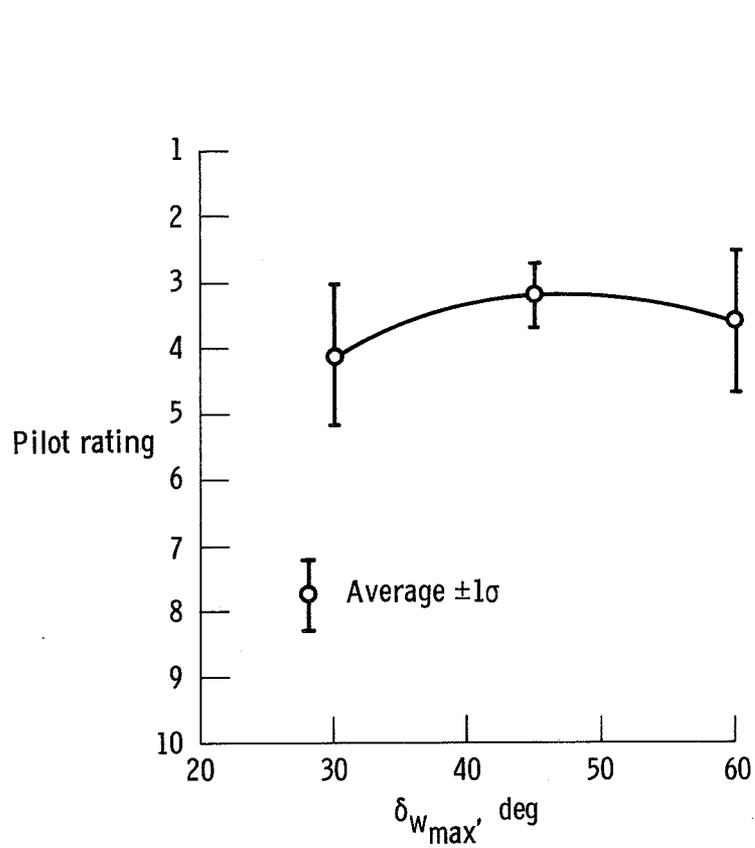
(f) Question 7: Was control with one hand comfortable, safe?

Figure 6. Continued.

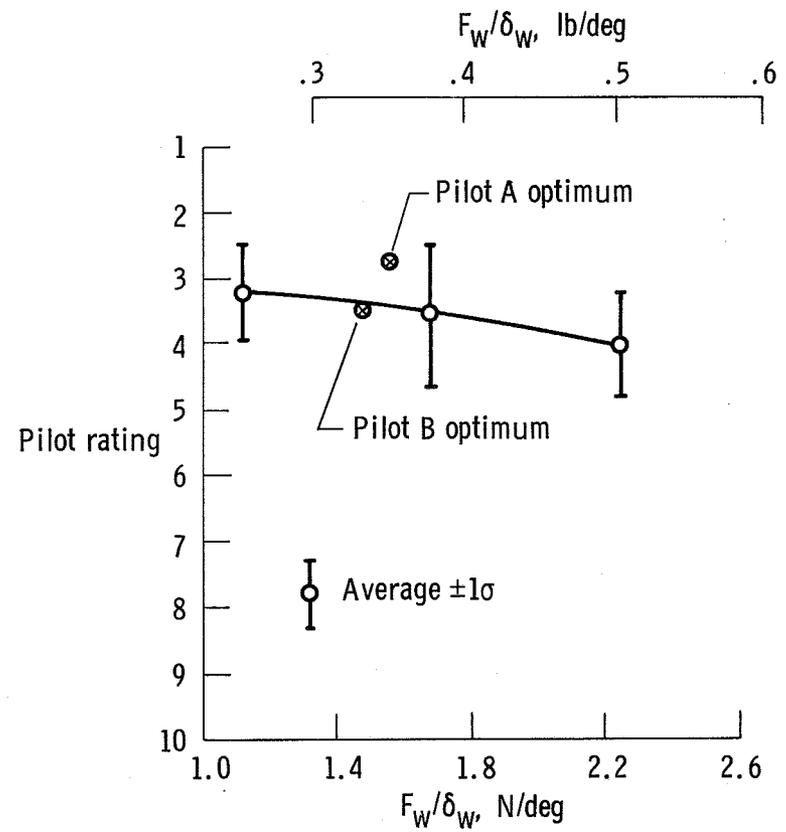


(g) Question 8: Was overall roll control acceptable for a transport?

Figure 6. Concluded.

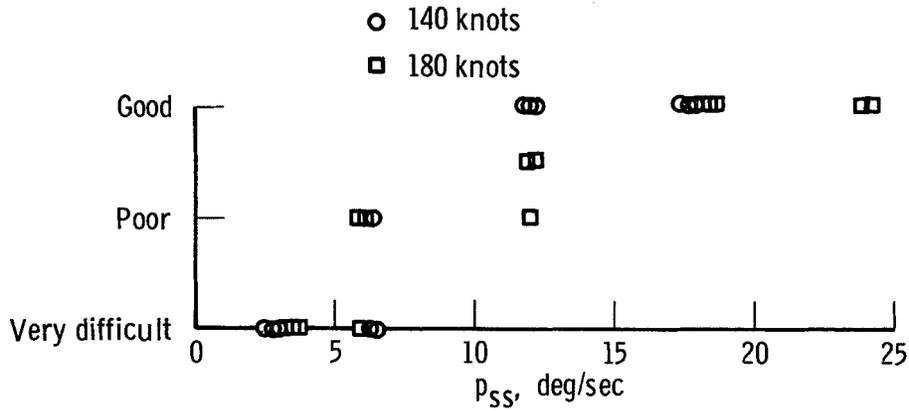


(a) Control wheel limit.

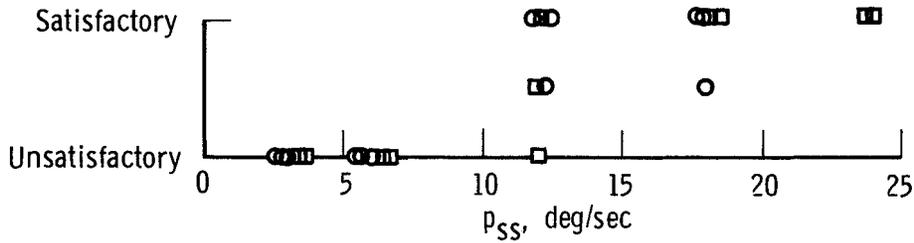


(b) Control wheel force gradient.

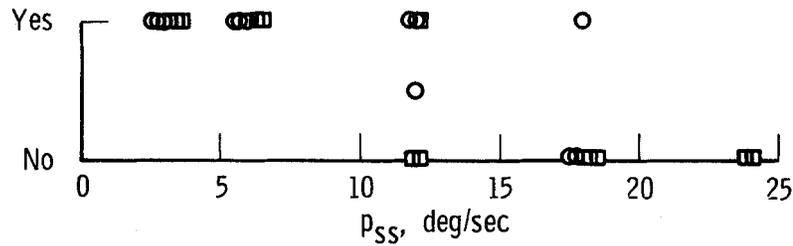
Figure 7. Pilot rating of control wheel characteristics.



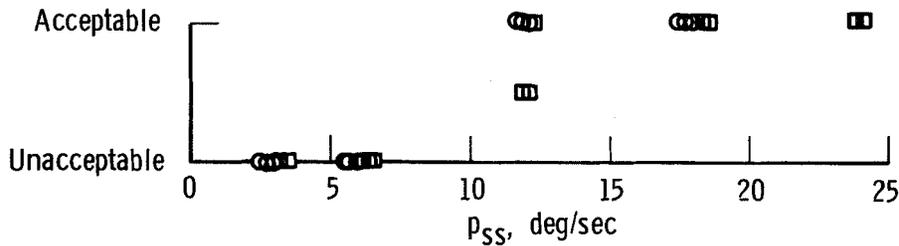
(a) Question 1: Ability to roll to and stop precisely at desired bank angle.



(b) Question 3: Was roll rate available satisfactory?



(c) Question 4: Could all roll rate (full wheel) be used?



(d) Question 7: Was overall roll response acceptable for transport approach?

Figure 8. Summary of pilot comments on roll rate variations from questionnaire of table 2. $\tau_R = 0.7$ second.

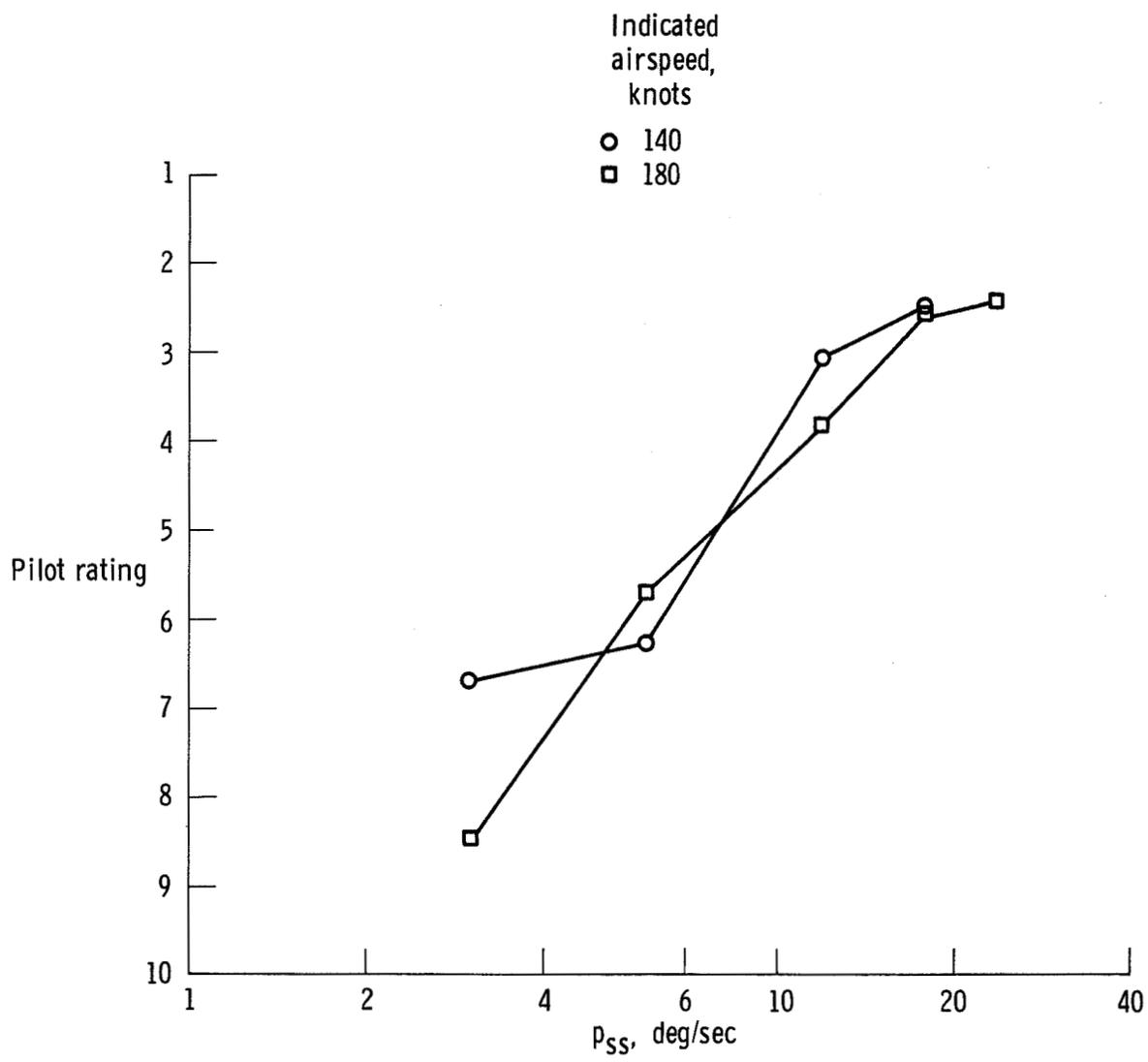


Figure 9. Average pilot ratings of roll-rate characteristics. $\tau_R = 0.7$ second.

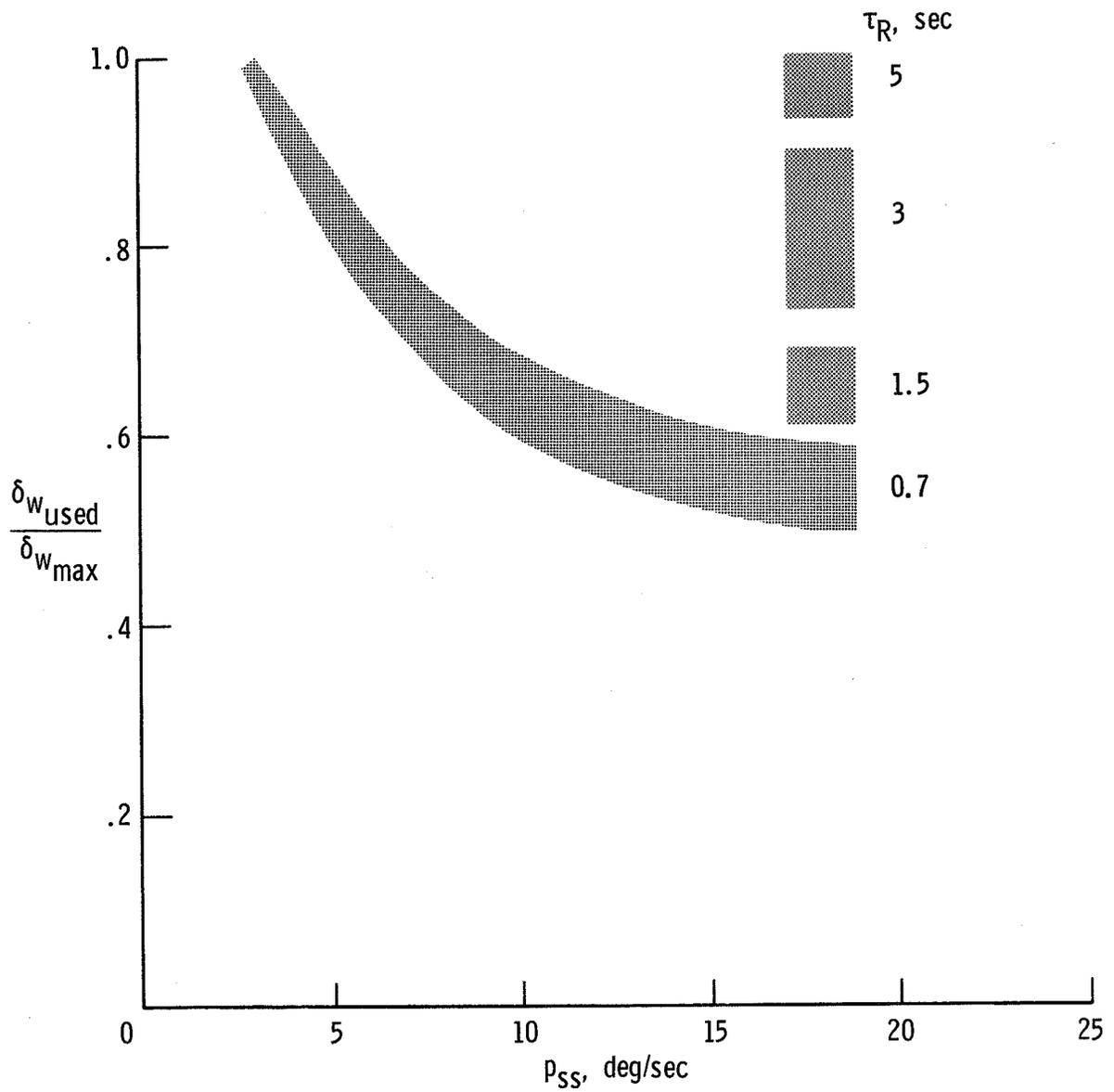


Figure 10. Ratio of maximum control used to maximum control available during the offset corrections. 140 knots and 180 knots indicated airspeed.

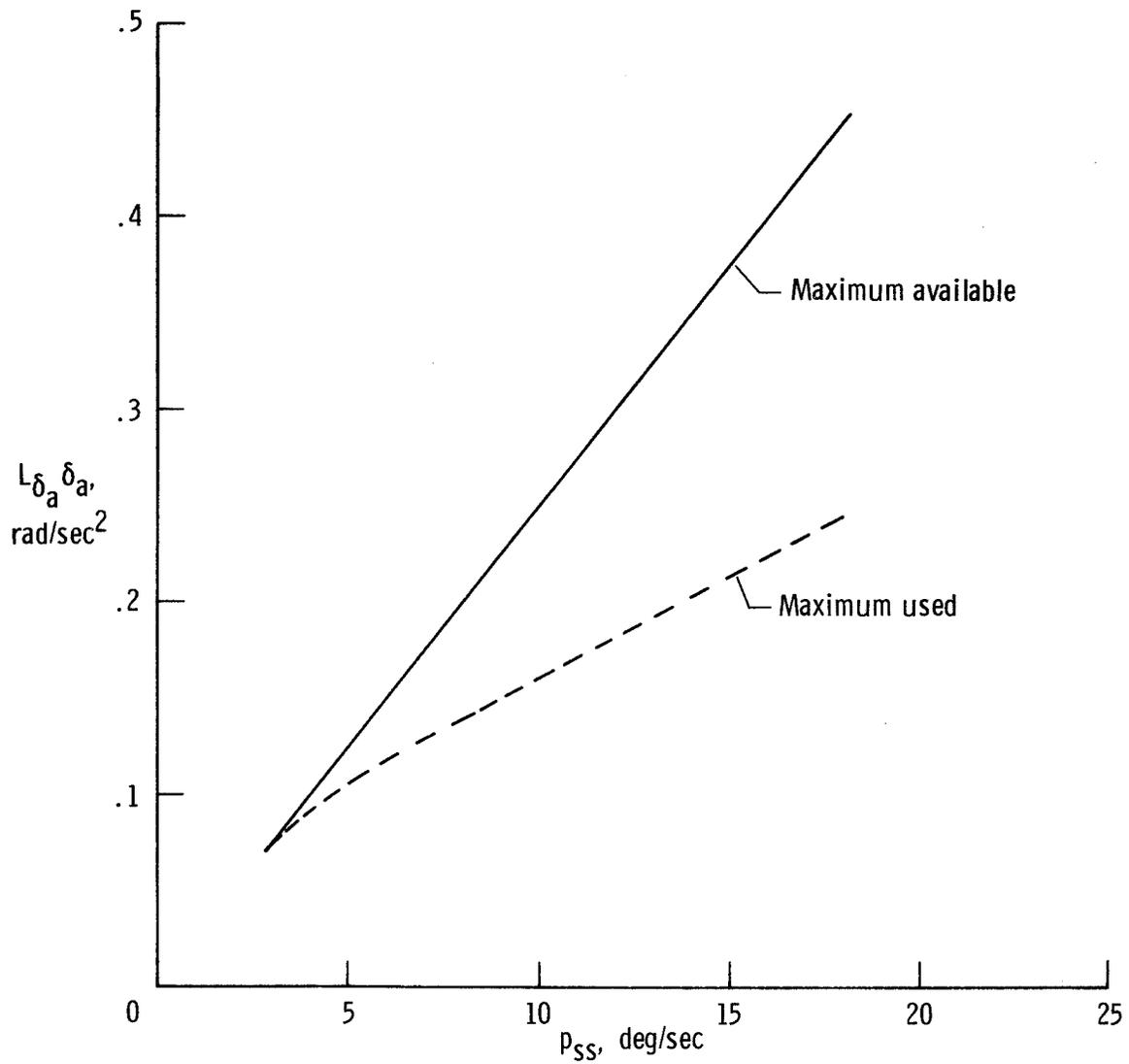


Figure 11. Comparison of the maximum roll acceleration used during the offset correction to that available as a function of steady-state roll rate. 140 knots and 180 knots indicated airspeed; $\tau_R = 0.7$ second.

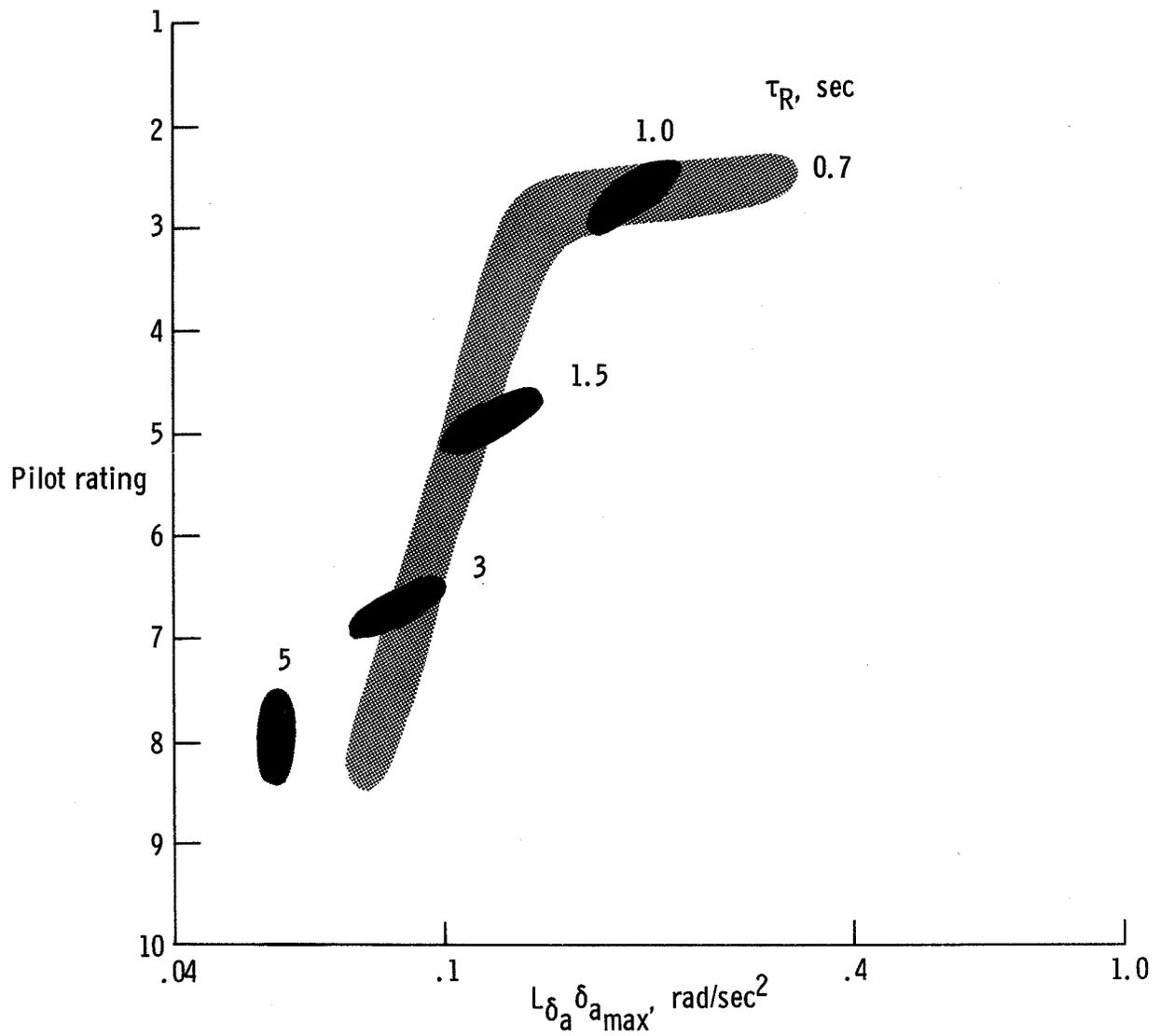
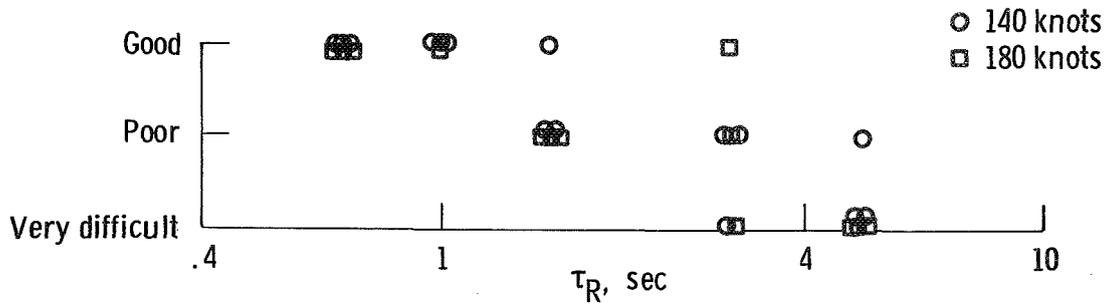
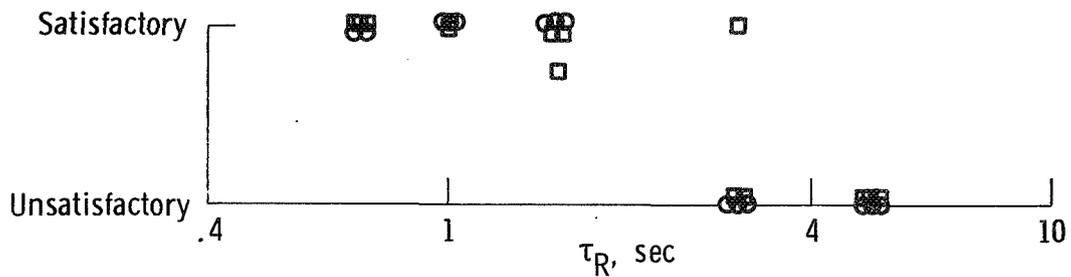


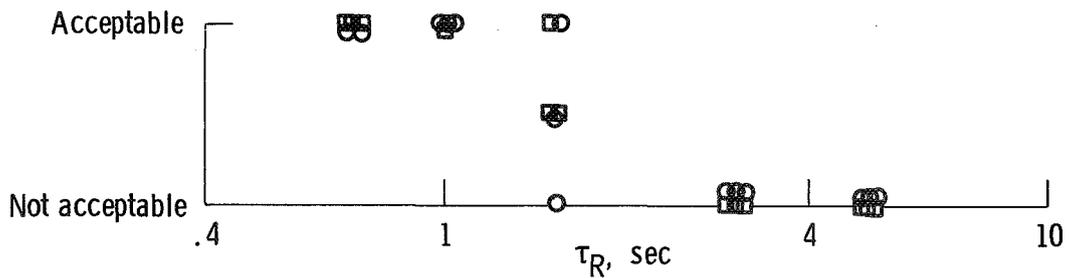
Figure 12. Pilot ratings corresponding to the maximum values of $L\delta_a \delta_{a_{max}}$ used during the offset maneuver. 140 knots and 180 knots indicated airspeed.



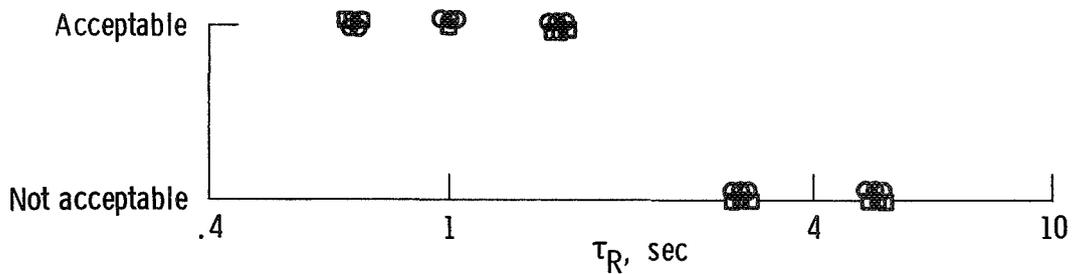
(a) Question 1: Ability to roll to and stop precisely at desired bank angle.



(b) Question 3: Was roll rate available satisfactory?



(c) Question 5: Was roll damping acceptable?



(d) Question 7: Was overall roll response acceptable for transport approach?

Figure 13. Summary of pilot comments on roll time constant variations from questionnaire of table 2. $p_{ss} = 18 \text{ deg/sec}$.

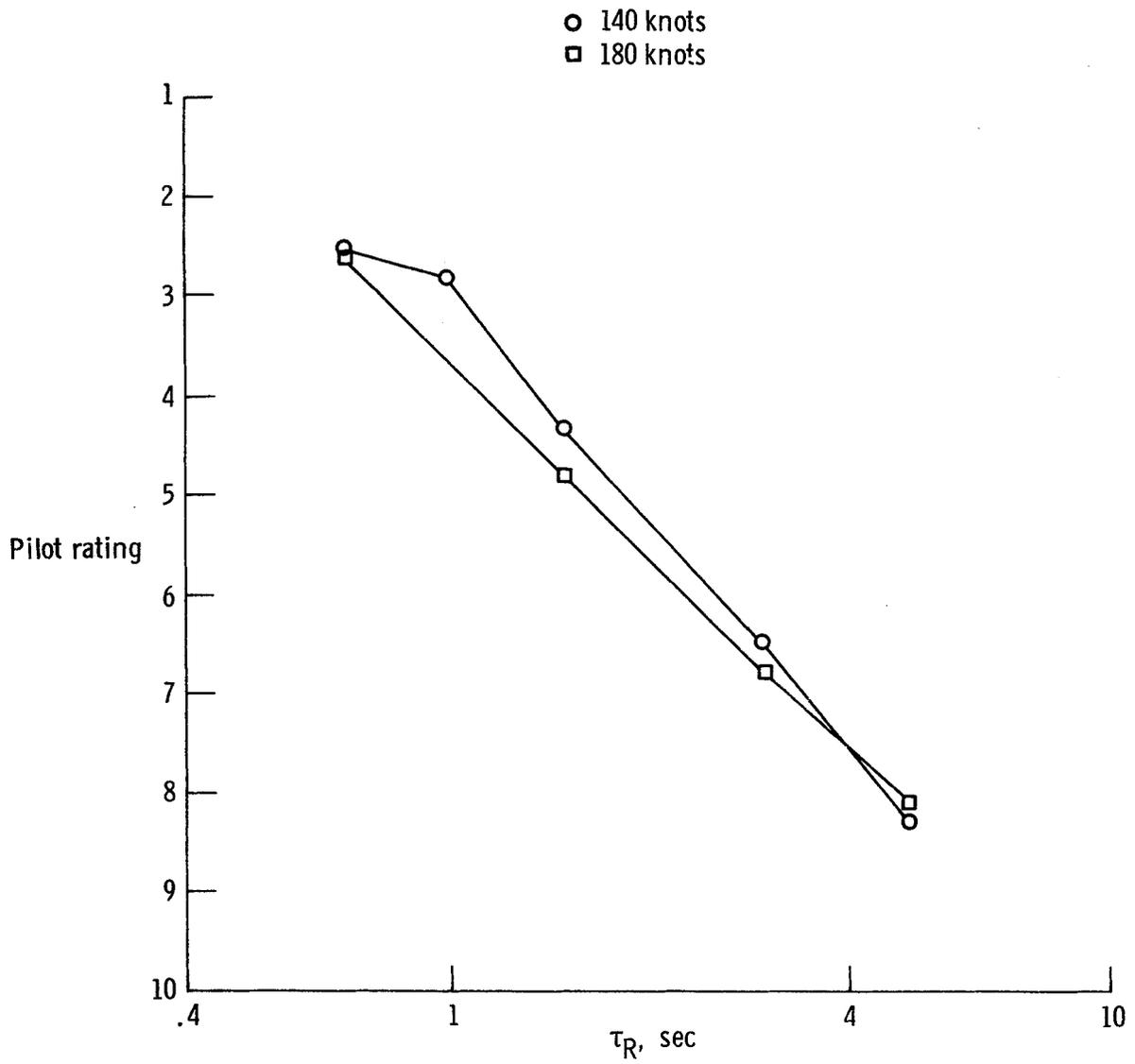
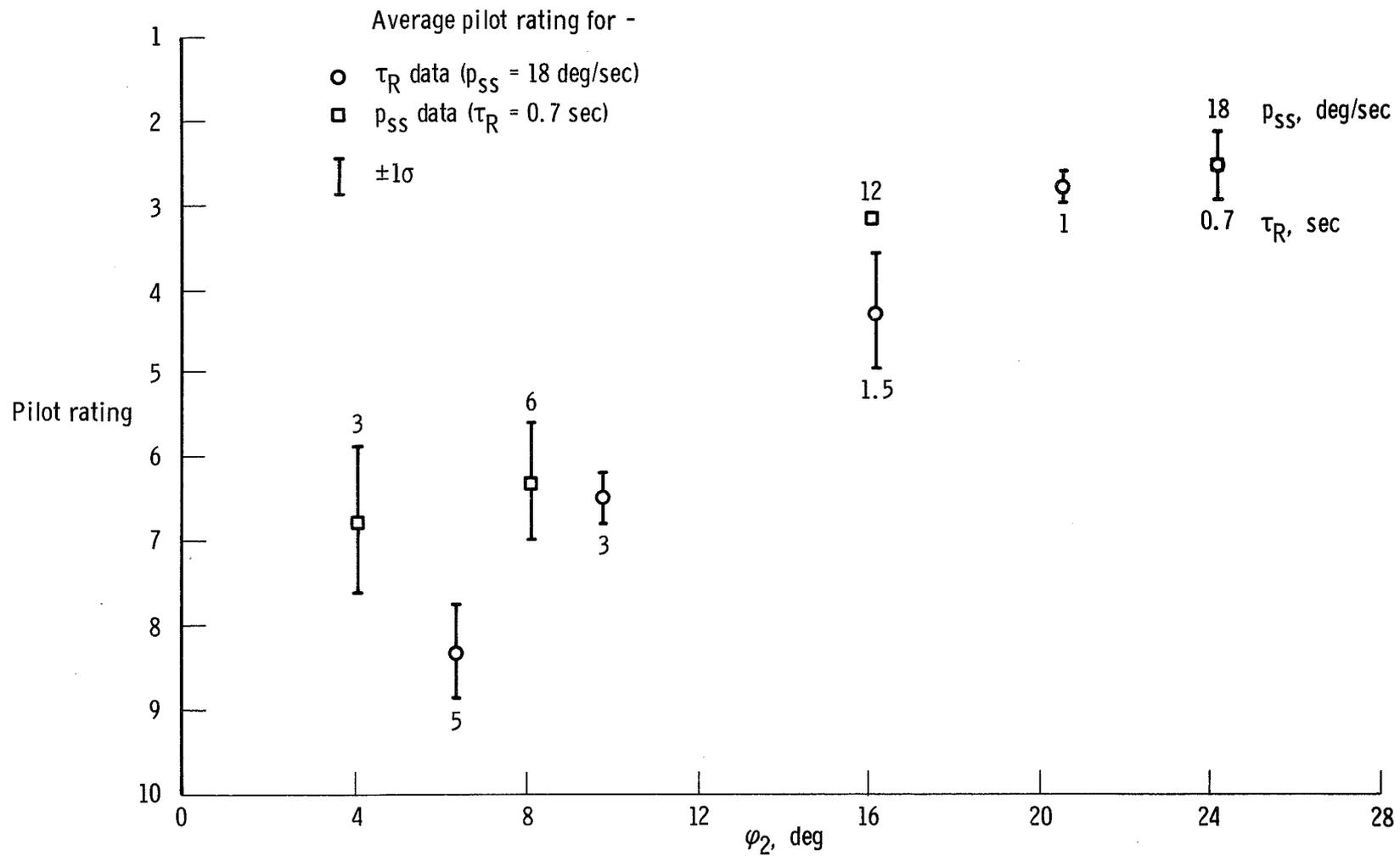
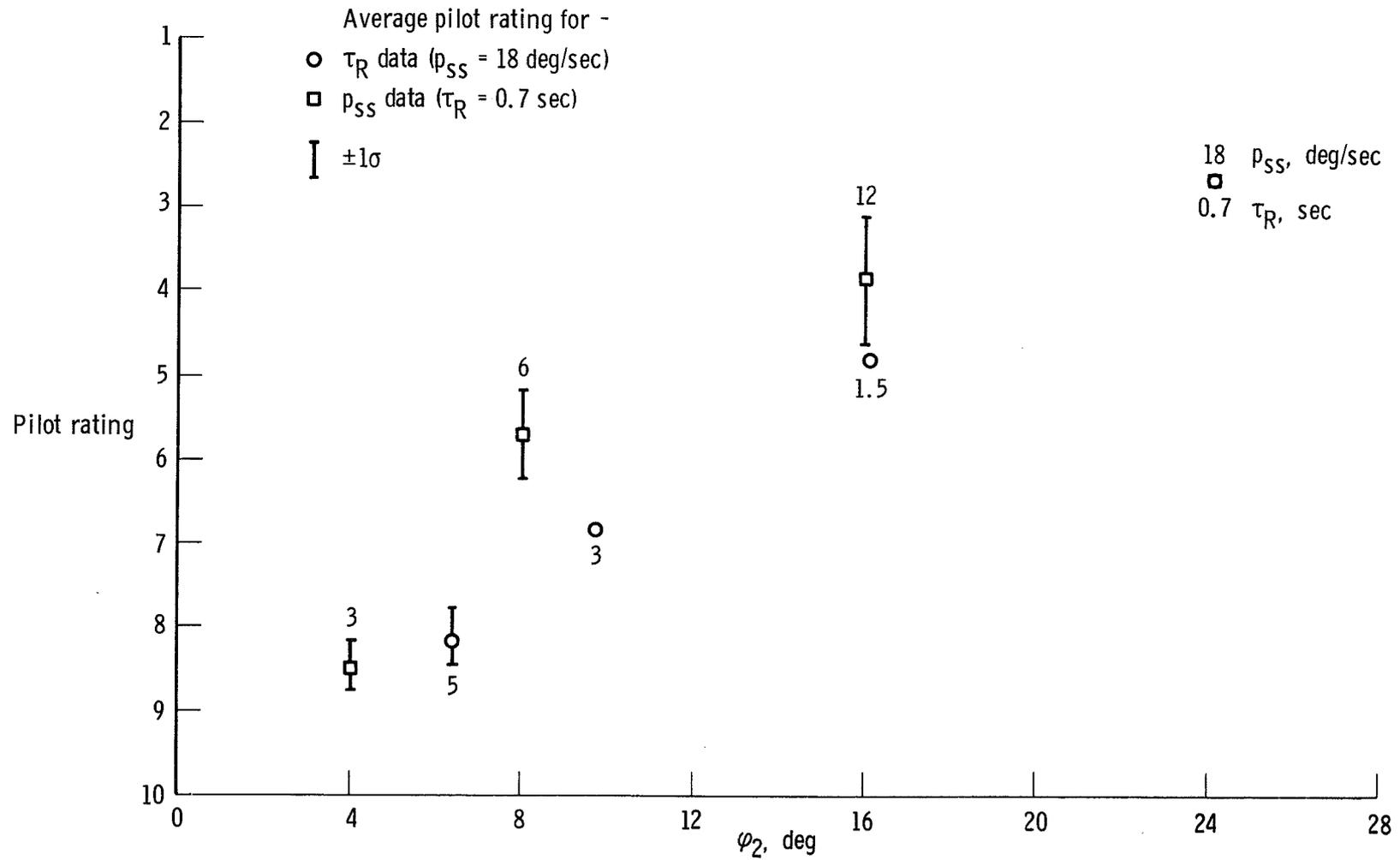


Figure 14. Average pilot ratings of roll damping characteristics. $p_{SS} = 18$ deg/sec.



(a) 140 knots.

Figure 15. Comparison of the data obtained from the roll time constant variation and the roll rate variation.



(b) 180 knots.

Figure 15. Concluded.

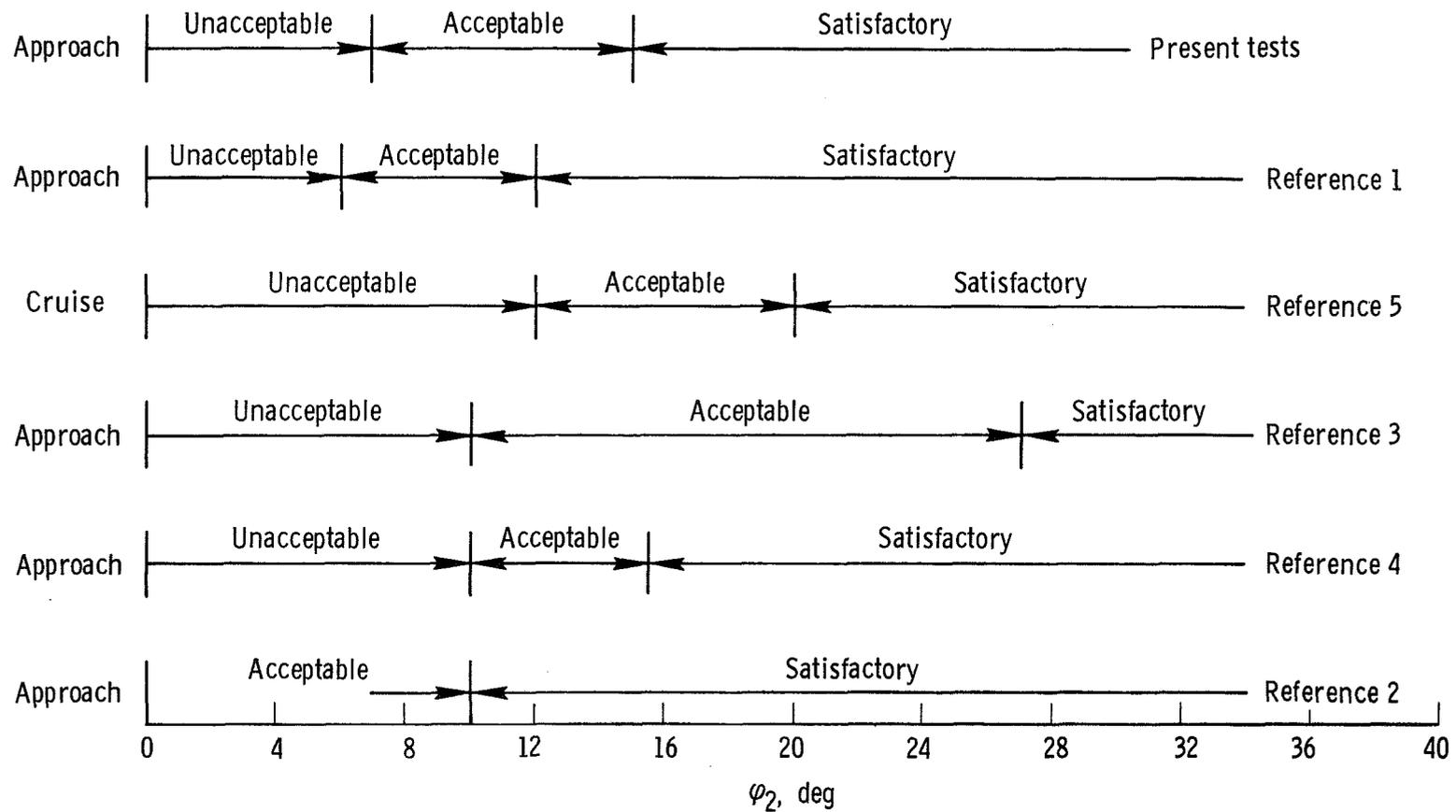
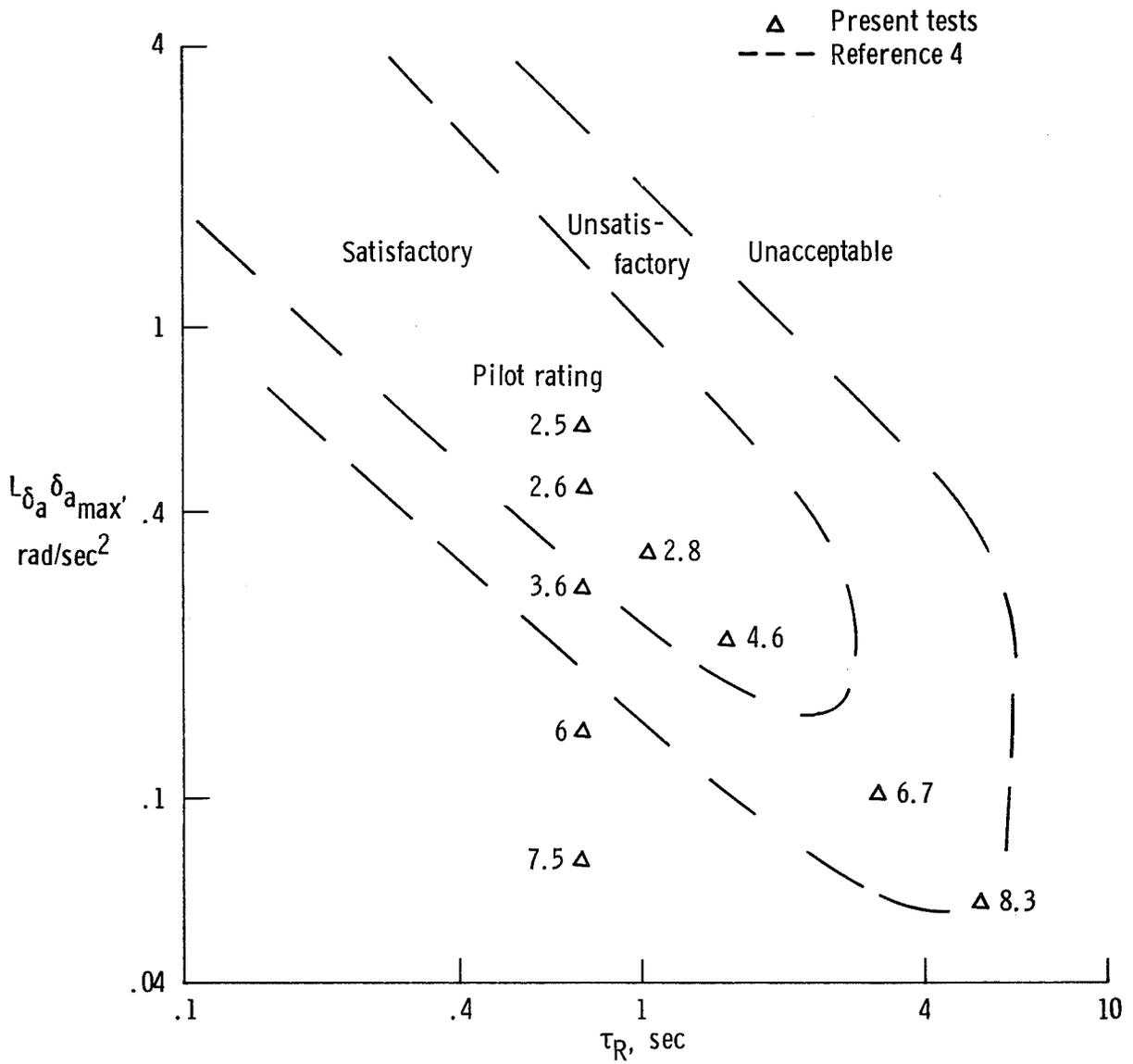
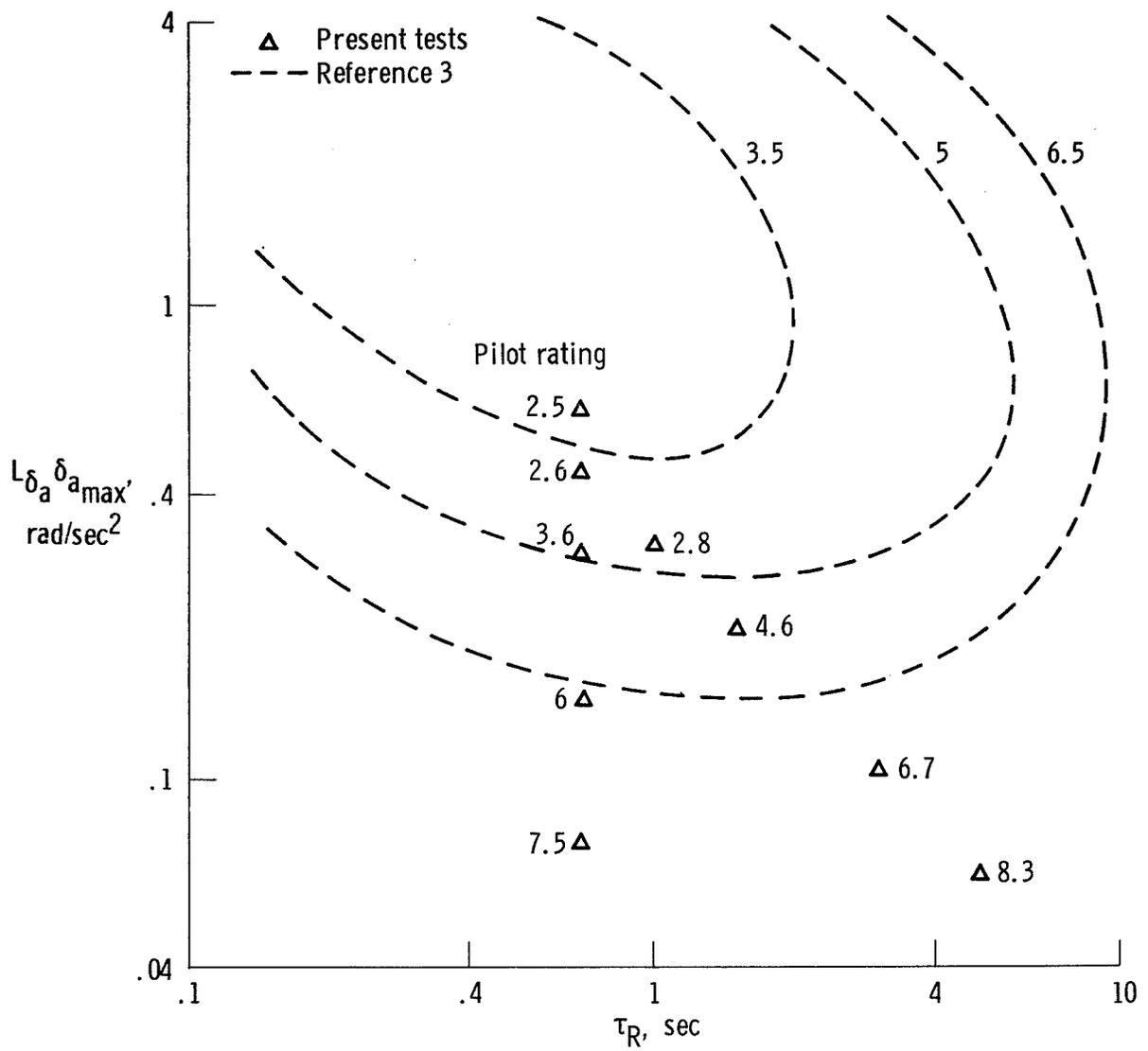


Figure 16. Comparison of roll-response data with results from previous studies.
 $\tau_R = 0.7$ second to 1.0 second.



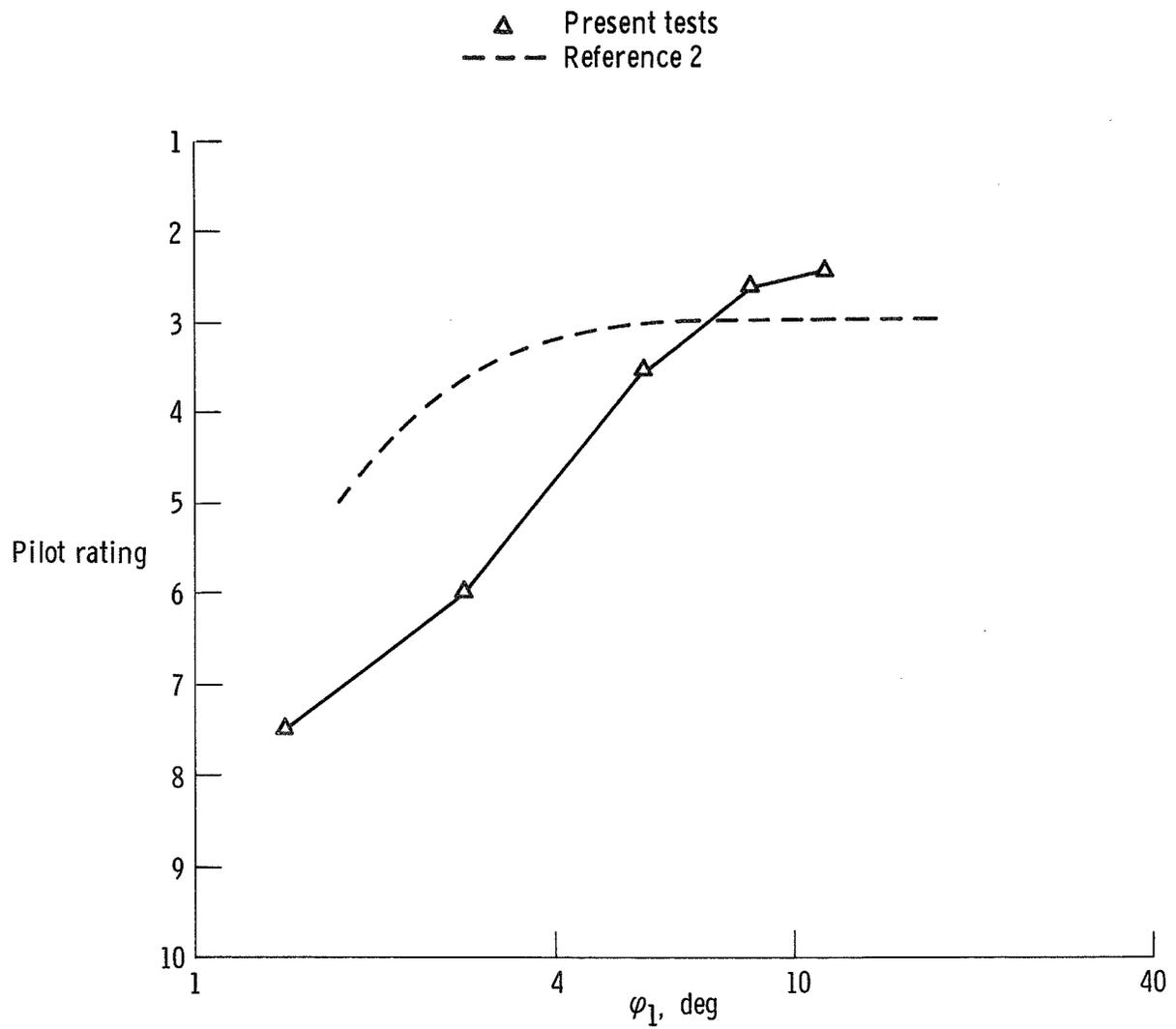
(a) Bisgood (ref. 4) proposed criterion.

Figure 17. Comparison of the results of the present tests with referenced results. 140-knot and 180-knot data combined.



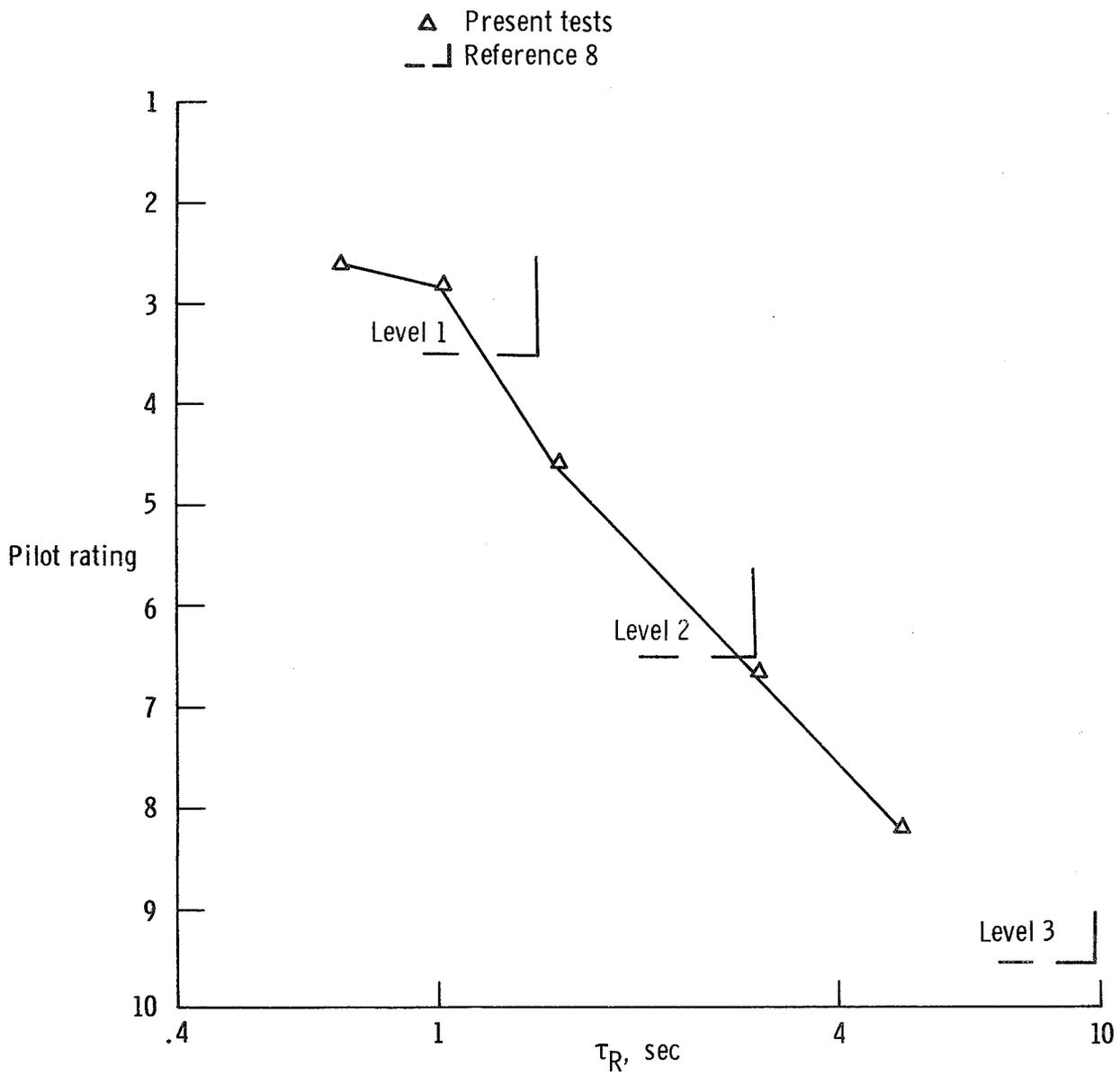
(b) Simulator results of reference 3.

Figure 17. Continued.



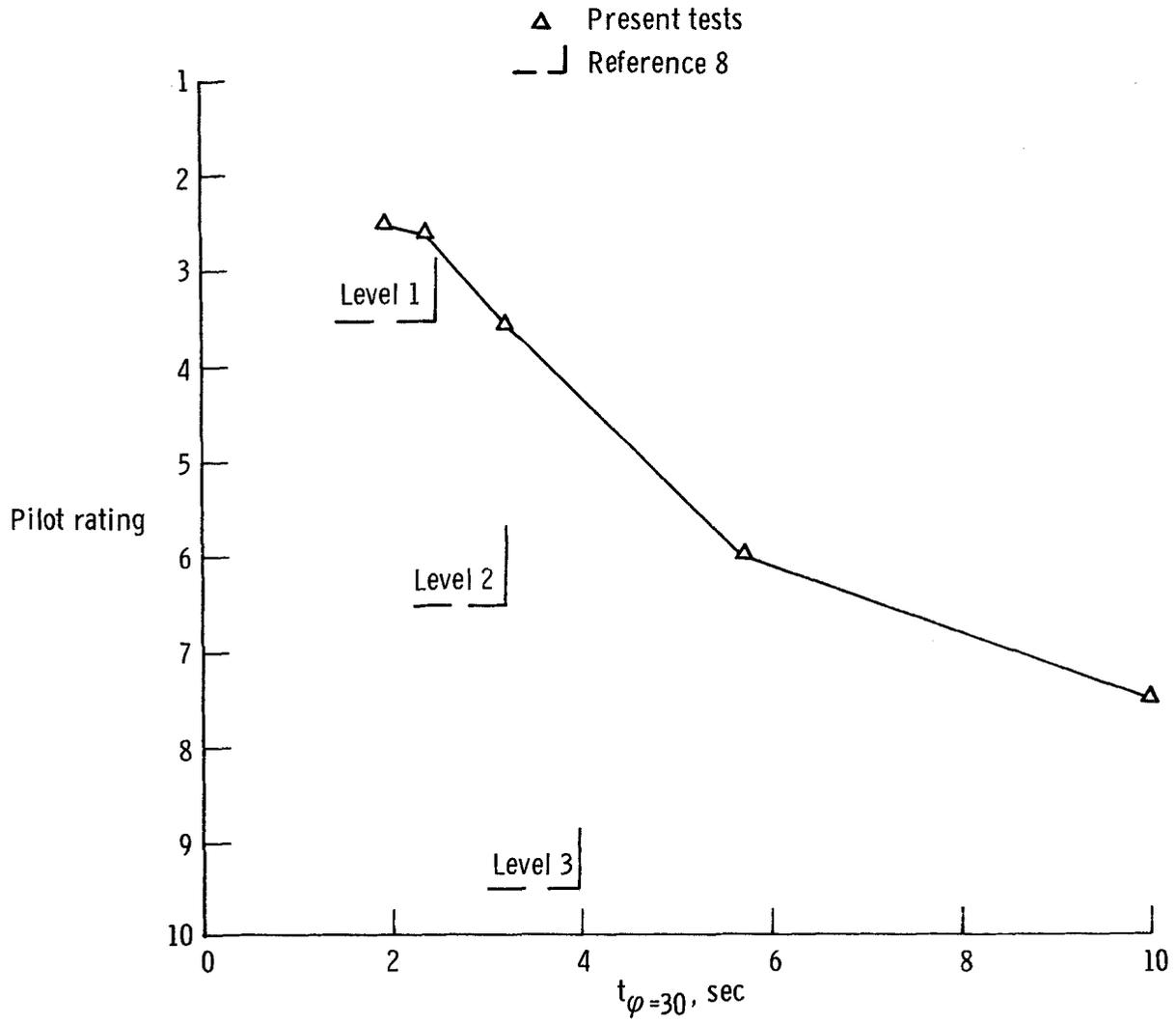
(c) Results from reference 2 flight program.

Figure 17. Continued.



(d) Military Specification 8785B (ref. 8).

Figure 17. Continued.



(e) Military Specification 8785B (ref. 8).

Figure 17. Concluded.

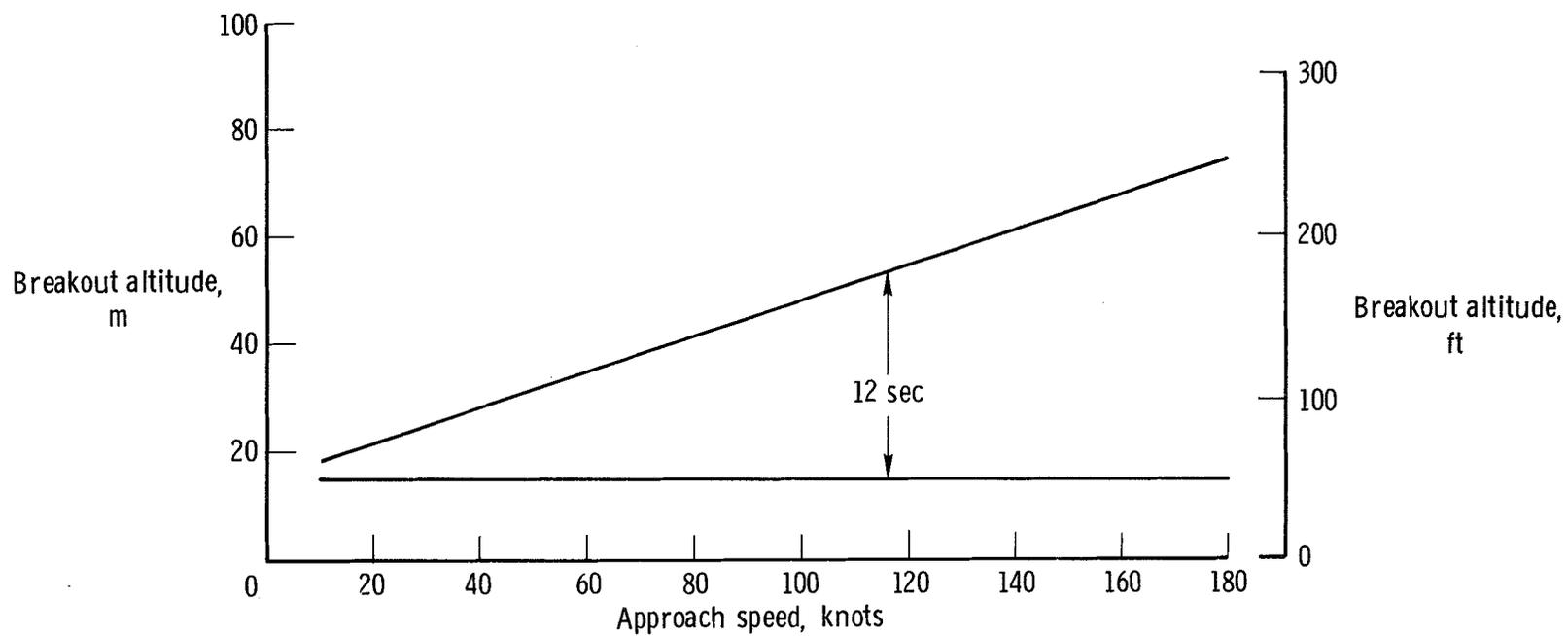


Figure 18. Breakout altitude for 12-second maneuvering time to 15 meters (50 feet) altitude. 3° glide slope.

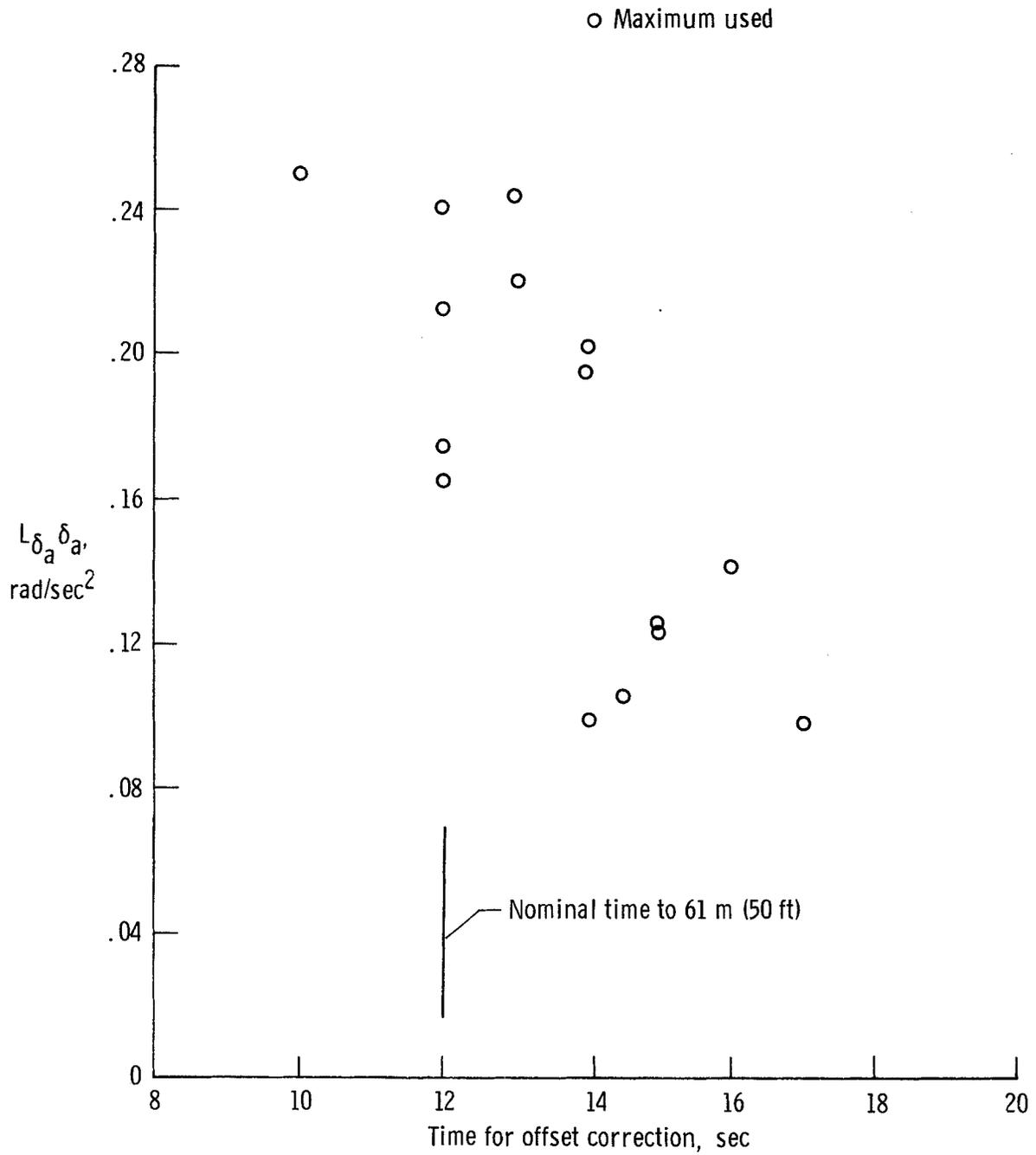


Figure 19. Maximum roll power and time used during the offset correction maneuver with satisfactory roll characteristics.

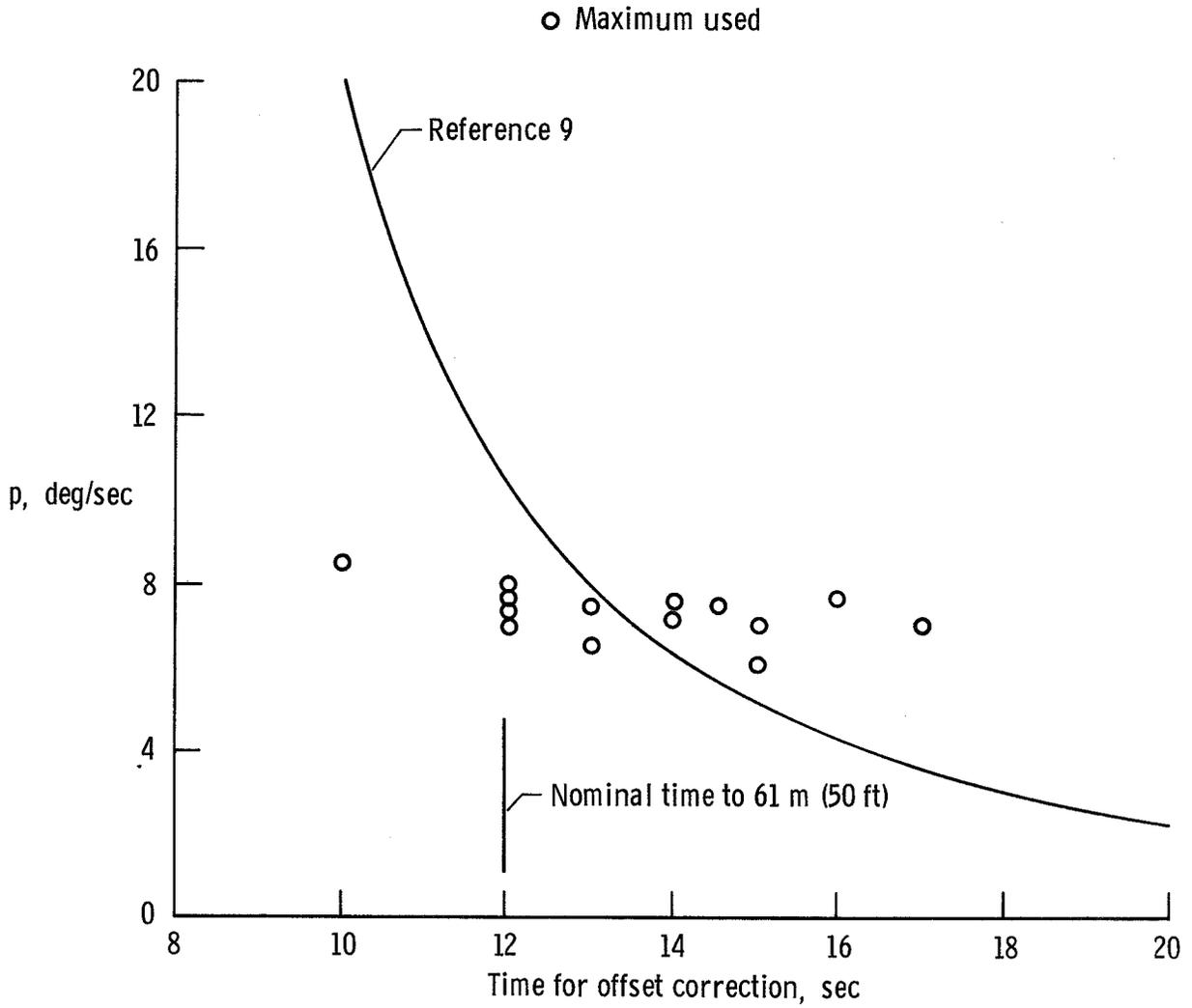


Figure 20. Comparison of maximum roll rate used during the offset correction maneuver with the predictions from reference 9.

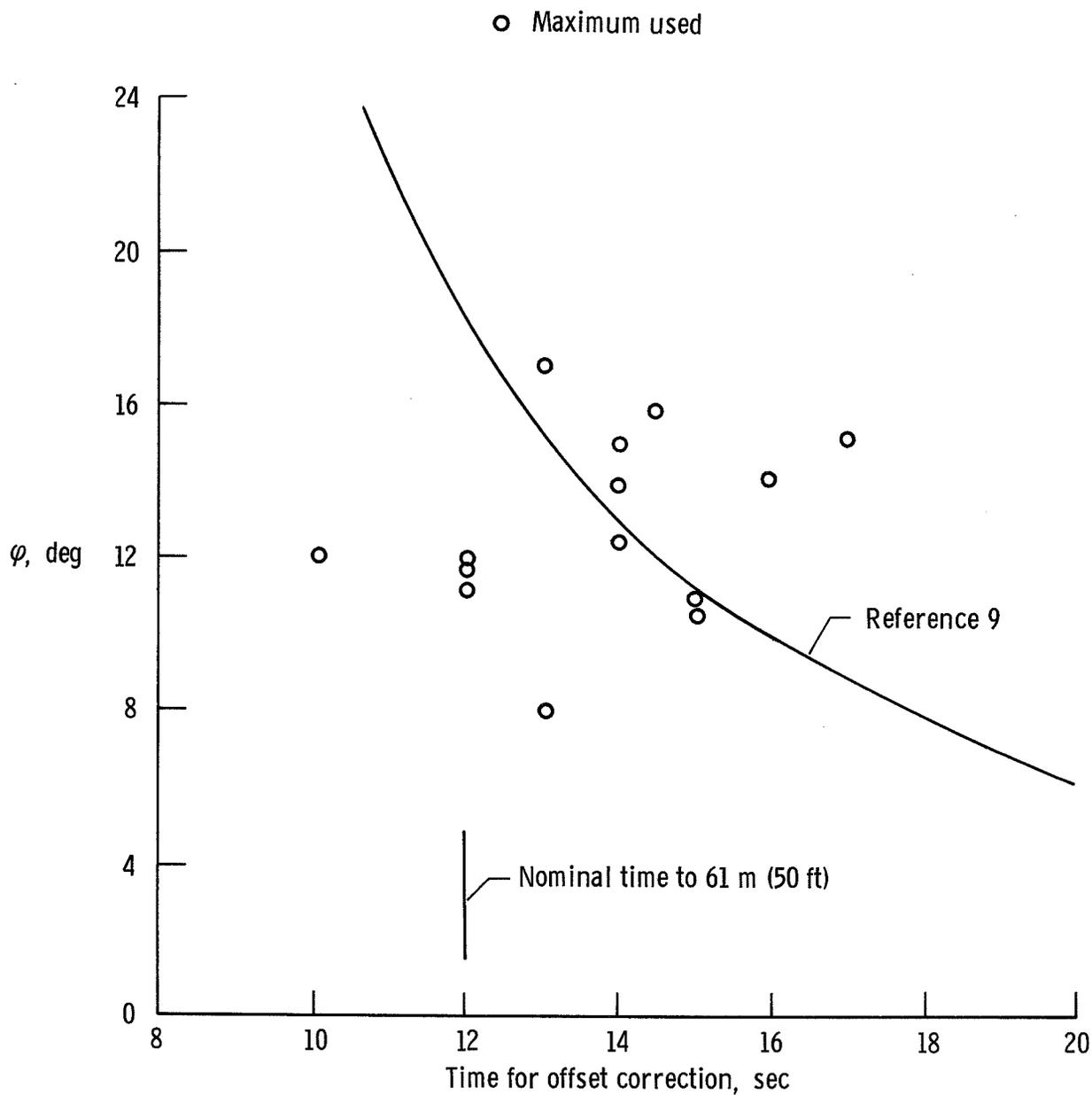


Figure 21. Comparison of maximum bank angle used during the offset correction maneuver with the predictions from reference 9.

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