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Summary

Pilot opinion and performance parameters derived from a six-degree-of-freedom ground-based simulator (the Langley Visual/Motion Simulator (VMS)) and a six-degree-of-freedom in-flight simulator (the USAF-AFWAL Total In-Flight Simulator (TIFS)) are compared for a jet-transport airplane having conventional cockpit controllers and instrument displays with 31 different longitudinal dynamic response characteristics. The primary pilot tasks were the approach and landing tasks with emphasis on the landing-flare task. The primary objective of this paper is to provide information to the flight controls/flying qualities engineer that will assist him in determining the incremental flying qualities and/or pilot performance differences that may be expected between results obtained via ground-based simulation (and, in particular, via the Langley VMS) and flight tests.

The results indicate that, in general, flying qualities results obtained from the ground-based simulator may be considered conservative—especially when the pilot task requires tight pilot control as during the landing flare. That is, in general, the Cooper-Harper ratings (CHR's) and the pilot-induced-oscillation (PIO) classification ratings were higher (worse) on the ground-based simulator. The one exception to this, according to the present study, was that the pilots were more tolerant of large time delays in the airplane response on the ground-based simulator. The results also indicated that the ground-based simulator (particularly the Langley VMS) is not adequate for assessing pilot/vehicle performance capabilities (i.e., the sink rate performance for the landing-flare task when the pilot has little depth/height perception from the outside scene presentation). The data show that there is an incremental increase in touchdown sink rate of approximately 3.5 ft/sec that may be expected on the ground-based simulator as opposed to the real-world environment.

The results from this study have indicated that caution must be exercised in the interpretation of simulation results when they may be affected by the limitations of the simulator hardware—particularly the motion cues and visual cues.

Introduction

The primary objective of this study was to determine the areas of applicability and the fidelity of the NASA Langley Visual/Motion Simulator (VMS) for predicting the flying qualities of an airplane for the approach and landing-flare pilot tasks. The in-flight simulation test results from references 1 and 2 were utilized for comparison with the VMS results. The primary goal of the NASA-sponsored flying qualities experiment reported in reference 1 utilizing the USAF-AFWAL Total In-Flight Simulator (TIFS) was to generate a consistent set of data to determine what a pilot requires to satisfactorily flare and land an airplane. In that study, two separate areas of analysis were performed on the flying qualities data obtained. One area was to determine the pilot's preference in commanded response (e.g., angle of attack or pitch rate) and its characteristics. The second area was to refine the time-history predictive criterion of reference 2. Following the in-flight simulator tests, the ground-based simulator study was conducted.

There are many documents giving comparisons of flight and ground-based simulators, but very few indicate whether a given simulation of the airplane and pilot task of interest can produce a reliable representation of the flying qualities. Because of the differences between simulator and airplane and the inability to account for all the situations that can occur in the real world, the pilot cannot be exposed to the "complete tasks" operation of the airplane in a simulator. For example, the apprehension, emotional stress, and responsibility that a pilot feels in actual flight is less, or missing altogether, in the simulator. Thus, simulation cannot wholly replace flight tests of the airplane concerned, but it may highlight many gross "oddities" of the complete pilot-vehicle characteristics and, therefore, markedly reduce the number of flight tests required.

There is information in the literature on the advantages, disadvantages, and practical problems of piloted-airplane simulation. For example, reference 3 discusses the trade-offs between the use of computer graphics and closed-circuit television for simulating the external scene. Likewise, many reports exist giving a detailed discussion of motion cues, how they are used by pilots, and how to best utilize the capabilities of a specific simulator. (For example, see refs. 4 7.) However, there is a lack of information that allows the flight controls/flying qualities engineer to determine/estimate the incremental flying qualities and/or pilot performance differences that may be expected between results obtained via ground-based simulation and flight tests. To this end, pilot opinion and performance parameters derived from the six-degree-of-freedom ground-based simulator (VMS) and the six-degree-of-freedom in-flight simulator (TIFS) are compared for a jet-transport airplane having conventional cockpit controllers and instrument displays with 31 different longitudinal dynamic response characteristics.

The primary pilot tasks were the approach and landing tasks with emphasis on the landing-flare task since this is the most demanding task for transport-class airplanes. Four engineering test pilots participated in both the ground-based and in-flight simulation programs. This paper compares the results obtained on these two simulations by the four pilots.

Symbols and Abbreviations

Measurements and calculations were made in U.S. Customary Units. Dots over symbols denote differentiation with respect to time.

CAP	control anticipation parameter, $\omega_{\text{SP}}^2/(n_z/\alpha)$
CHR	Cooper-Harper rating
℄	centerline
F_s	stick force
G/S	glide slope
g	acceleration due to gravity ($1g \approx 32.174$ ft/sec^2)
$\dot{h}_{\text{TD}}$	rate of sink at touchdown
ILS	instrument landing system
KIAS	knots of indicated airspeed
K_{q_c}	pitch-rate command gain
K_{α_c}	angle-of-attack command gain
L/L	lead/lag filter in the pilot command path
M_q	pitching moment due to pitch rate
M_α	pitching moment due to angle of attack
n_z	normal acceleration
n_{z_p}	normal acceleration measured at pilot station
n_z/α	steady-state normal-acceleration change per unit change in angle of attack for an incremental pitch control-surface deflection at constant airspeed
PIO	pilot-induced oscillation
q	pitch rate
q_c	pitch-rate command
s	Laplace operator
t	time
TIFS	Total In-Flight Simulator
VMS	Visual/Motion Simulator
α	angle of attack
α_c	angle-of-attack command
δ_e	elevator deflection
$\dot{\gamma}$	rate of change of flight-path angle
$\dot{\gamma}_c$	rate of change of flight-path-angle command
ζ_α	damping ratio in numerator of α/δ_e transfer function
ζ_{PH}	damping ratio of phugoid mode
ζ_{SP}	damping ratio of short-period mode
τ_α	higher frequency zero in α/δ_e transfer function
$1/\tau_{\theta_1}$	lower frequency zero in q/δ_e transfer function
$1/\tau_{\theta_2}$	higher frequency zero in q/δ_e transfer function
ω_α	frequency in numerator of α/δ_e transfer function
ω_{PH}	undamped natural frequency of phugoid mode
ω_{SP}	undamped natural frequency of short-period mode

Description of Simulators

In-Flight Simulator

The Total In-Flight Simulator (TIFS), which is owned by the U.S. Air Force and operated by Calspan, was used as the test vehicle in the "in-flight" portion of this study. The TIFS is a highly modified C-131 (which is the military counterpart of the Convair 580) that has been configured as a six-degree-of-freedom simulator (fig. 1). It has a separate evaluation cockpit forward and below the normal C-131 cockpit. When flown from the evaluation cockpit in the simulation or fly-by-wire mode, the pilot control commands are fed as inputs to the model computer, which then calculates the airplane response to be reproduced. These responses, along with the TIFS motion sensor signals, are used to generate feedforward and response error signals that drive the six controllers on the TIFS. (See fig. 2.) The result is a high-fidelity reproduction of the motion and visual cues at the pilot position of the model airplane. (More descriptions of the TIFS can be found in ref. 8.) Figure 3 presents a typical example of the capability of the TIFS to reproduce the model response to a time-step pitch-controller input.

The evaluation cockpit is a dual-pilot, side-by-side arrangement and has the capability of providing much greater than usual visibility for the pilots. By proper masking, the window configuration of any particular airplane can be reproduced. The cockpit displays, controls, and instruments can be duplicated in the extent of detail desired. For the present study, no window masking was used and the cockpit displays, controls, and instruments were representative of those found in transport airplanes at the time of this study. Also for this study, the right seat was occupied by a NASA flight test engineer. The engineer observed all approaches and landings, assisted in the conduct of the flight test card, recorded estimated touchdown dispersion, and recorded summaries of pilot comment evaluations and handling qualities ratings to provide timely postflight analysis. (Note that although the touchdown dispersions were "estimated" by the flight test engineer, the "actual" values were recorded for analysis; e.g., the touchdown sink rate was measured via the radar altimeter traces.)

Ground-Based Simulator

The NASA Langley VMS is a six-degree-of-freedom ground-based motion simulator. (See fig. 4.) For this study, the simulator had a transport-type cockpit equipped with conventional flight and engine thrust controls as well as a flight instrument display representative of those found in current transport airplanes.

The control forces on the wheel, column, and rudder pedals were provided by a hydraulic system coupled with an analog computer. The system allows for the usual variable-feel characteristics of stiffness, damping, coulomb friction, breakout forces, detents, and inertia. The limitations in the force-feel characteristics of the control loader on the VMS were such that the dynamics of the force-feel system did not exactly match those on the TIFS. However, the pilots indicated that these dynamics were matched sufficiently so as not to prejudice the results; and, in fact, the pilots could not detect the differences.

The airport scene display used an "out-the-window" virtual image system of the beam-splitter, reflective-mirror type. The system, located nominally 4.2 ft from the pilot's eye, presented a nominal 48° width by 36° height field of view of a 525-line television raster system and provided a 46° by 26° instantaneous field of view. The system supplies a color picture of unity magnification with a nominal resolution on the order of 9 minutes of arc. The scene depicted in the virtual image system was obtained from a terrain model board. Reference 9 describes the state-of-the-art, television-camera transport system used in conjunction with the sophisticated terrain model board. The maximum speed capability of the system is 444 knots with vertical speed capabilities of ±30 000 ft/min. The translational lags of the system are 15 msec or less, and the rotational lags are 22 msec or less. The average total visual delay, including computational throughput delay, was less than 70 msec.

The motion performance limits of the VMS base are presented in table I. These limits are for single-degree-of-freedom operation. Therefore, conservatism must be exercised in the use of the position limits since these limits change as the orientation of the synergistic base varies. References 10, 11, and 12 document the characteristics of the system which possesses time lags of less than 15 msec. The average total motion delay, including computational throughput, is less than 60 msec and is quite compatible with the visual delays. The washout system used to present the motion-cue commands to the motion base is nonstandard. It was conceived and developed at the Langley Research Center and is documented in references 7, 13, and 14.

The only aural cues provided were engine noises and landing-gear extension and retraction noises.

Description of Configurations Evaluated

The math models were identical on the TIFS and VMS, e.g., aerodynamic terms (including ground effects) and landing-gear model. A thorough description of the 31 longitudinal configurations evaluated on both the TIFS and VMS simulators is presented in reference 1. However, a brief "purpose-of-tests" summary of these configurations is presented here and in table II. (The configuration numbers used in ref. 1 have been maintained in this paper.) The configurations flown during the TIFS tests (ref. 1) were developed, for the most part, by considering both angle-of-attack and pitch-rate command systems in terms of the α/δ_e and q/δ_e transfer functions indicated below:

$$\frac{\alpha}{\delta_e}(s) = \frac{K_{\alpha_c}\tau_\alpha\omega_{\mathrm{SP}}^2\omega_{\mathrm{PH}}^2\left(s+\frac{1}{\tau_\alpha}\right)\left(s^2+2\zeta_\alpha\omega_\alpha s+\omega_\alpha^2\right)}{\omega_\alpha^2\left(s^2+2\zeta_{\mathrm{SP}}\omega_{\mathrm{SP}}s+\omega_{\mathrm{SP}}^2\right)\left(s^2+2\zeta_{\mathrm{PH}}\omega_{\mathrm{PH}}s+\omega_{\mathrm{PH}}^2\right)}$$

$$\frac{q}{\delta_e}(s) = \frac{\left(K_{q_c}\tau_{\theta_1}\tau_{\theta_2}\omega_{\mathrm{SP}}^2\omega_{\mathrm{PH}}^2\right)s\left(s+\frac{1}{\tau_{\theta_1}}\right)\left(s+\frac{1}{\tau_{\theta_2}}\right)}{\left(s^2+2\zeta_{\mathrm{SP}}\omega_{\mathrm{SP}}s+\omega_{\mathrm{SP}}^2\right)\left(s^2+2\zeta_{\mathrm{PH}}\omega_{\mathrm{PH}}s+\omega_{\mathrm{PH}}^2\right)}$$

Configurations 1–8

These eight configurations were developed to form a basic set to evaluate "command-response" types. The first four configurations (1–4) were chosen to have a value of $1/\tau_{\theta_2} = 0.5$, and the low-frequency numerator zeros of the α/δ_e transfer function were defined to have a frequency ω_α of 0.3 rad/sec with $\zeta_\alpha = 0.10$. The next four configurations (5–8) were designed to have a value of $1/\tau_{\theta_2} = 0.9$, and the low-frequency numerator zeros of the α/δ_e transfer function were defined by $\omega_\alpha = 0.1$ rad/sec with $\zeta_\alpha = 0.10$.

Configurations 9 and 10

These configurations (being α-command and q-command, respectively) were designed to have no phugoid residue in either the pitch-rate or angle-of-attack responses. That is, the low-frequency (phugoid) response is eliminated in both q and α by proper zero locations based on configurations 1 and 2.

Configurations 11 and 12

These configurations were defined as flight-path-rate ($\dot{\gamma}$) command configurations with respect to the center of gravity of the airplane, but with the airplane center of rotation located at the pilot location (configuration 11) or at the airplane center of gravity (configuration 12). Both configurations have two zeros at the origin in the $\dot{\gamma}/F_s$ transfer function; and in order to realize a $\dot{\gamma}$ command, two poles at the origin were required to cancel the two zeros at the origin. (Note that the $s^2 = 0$ poles dominate the long-term response and are very detrimental to flying qualities even if the $n_z(t)$ response and, in this case, $q(t)$ also are smooth and well-behaved in the short term.)

Configurations 13 and 14

For these configurations (being α-command and q-command, respectively), a large value of $1/\tau_{\theta_2}$ (i.e., 2.0) was selected to equal the value of the short-period frequency that resulted in a value of CAP that would place the configurations in the level 1 area for the category C precision requirement, but in the area of the level 1/level 2 boundary with respect to the category A precision requirements. (See ref. 15.)

Configurations 17–20

The TIFS program in reference 2 briefly investigated the effects of a washout prefilter on a specific pitch-rate command configuration. During the reference 1 flying qualities experiment, a systematic investigation of the effects of washout was made. Configuration 1-2-2 of reference 2 was chosen as a baseline, level 2, pitch-rate command configuration and was designated configuration 17 in this program. Then, a washout prefilter was added to the pilot command path with various washout time constants (configurations 18–20). These configurations differed from configurations 1–14, in that they were mechanized with a pitch-rate feedback path and a proportional-plus integral compensator in the command path.

Configuration B

This was a baseline conventional airplane configuration that was selected to yield level 1 flying qualities about which time-delay and pitch-sensitivity variations could be made to investigate their effects on flying qualities for the approach and landing-flare piloting tasks. This configuration was based on a TIFS (modified C-131) aerodynamic model with increased M_α and M_q derivatives in order to achieve $\omega_{SP} = 2$ rad/sec, $\zeta_{SP} = 0.7, 1/\tau_{\theta_2} = 0.75$, and $n_z/\alpha = 5.3$ g units/rad. The instantaneous center of rotation was 22.2 ft aft of the pilot.

Configurations 21–28

These were configurations on which time-delay and pitch-sensitivity variations were made on a level 1 conventional airplane configuration (configuration B described above) to gather data for the refinement of the time-domain flying qualities criterion of reference 2. Three values of time delay and three values of pitch sensitivity were evaluated. The various pitch-sensitivity values were chosen during the calibration test flights in the TIFS. The nominal sensitivity was 0.42 (deg/sec^2)/lbf. This value had been found to be a near-optimum sensitivity for wheel/column controllers in previous programs and was verified during the calibration flights. Minimum and maximum sensitivity values were chosen during flight tests that would still yield level 1 or borderline level 1 flying qualities. The minimum value chosen was 0.25 (deg/sec^2)/lbf, and the maximum value was 0.63 (deg/sec^2)/lbf. These values were selected by controlling the "command gain" of the flight control system. There are a number of ways to change pitch sensitivity, i.e., changing command gain, changing short-period frequency, changing short-period damping ratio, adding prefilters, etc. It was surmised that no matter what method was used to change the sensitivity, the result would be much the same to the pilot. Therefore, the "command gain" method was chosen as it tended to better isolate the effects of sensitivity while keeping other critical factors constant. The three levels of sensitivity (command gain) were used with each of the three levels of time delay to obtain the matrix presented in table III.

Configurations 17 + L/L, 22A, 25A, and 28A

Additional configurations were added during the TIFS evaluation phase of the program to gather time-delay/sensitivity data on a pitch-rate command-type airplane. The baseline configuration selected for this test matrix was configuration 17 with an added lead/lag (L/L) filter in the pilot command path. (See table III for the time-delay/sensitivity test matrix.)

The lateral-directional aerodynamics and control system utilized in this VMS "longitudinal" study were the same as those used in the studies in references 1 and 2 with the TIFS; since they were predetermined to produce level 1 (satisfactory) flying qualities, they were "transparent" to the present longitudinal flying qualities investigation.

Test Procedures

The evaluation pilot was given control of the airplane on the downwind leg and performed a visual turning approach to a 1.5- to 2-mile final approach. The ILS glide slope was intercepted in the turn and held to a point 3500 ft from the runway/glide slope intercept point. A constant airspeed of 132 knots of indicated airspeed (KIAS) was held throughout the approach until the flared landing.

Figure 5 details the final approach and flare geometry. A final approach "barrier" was defined as a barrier projecting up from the ground at a point 3500 ft short of the runway and glide slope intercept point and extending up to the ILS glide path. The evaluation pilot was not allowed to descend below the ILS glide slope until he had passed the barrier. This procedure prevented him from "ducking under" the glide slope and thus making the landing-flare task less demanding. During the TIFS evaluations, the hypothetical barrier location was well-marked by a railroad track. Peer pressure from the safety pilots (during the TIFS tests) and the flight test engineer was found to be quite sufficient to prevent glide slope "duck under."

In addition to the altitude constraint of the barrier, lateral offsets of approximately 200 ft (either left or right) were used to provide a secondary task and thus prevent preoccupation with the pitch task. Also, in order to further assure pitch-task activity, a (1-cosine) angle-of-attack gust was fed to the simulated airplane model between 100 and 50 ft of altitude. The evaluation pilot would fly through the gust to flare and touchdown. The run was terminated at touchdown—the landing rollout was not simulated.

As indicated in figure 5, the "desired" touchdown area was defined as being 500 ft long and 20 ft wide (±10 ft from runway centerline) beginning 250 ft past the runway/glide slope intercept. The "adequate" touchdown area was defined as being 1000 ft long and 40 ft wide (±20 ft) beginning at the same point on the runway. The airspeed requirements were: "desired" = 132 ± 3 KIAS and "adequate" = 132 ± 5 KIAS, both at the barrier passage. The "desired" sink rate at touchdown was defined as 0 to 3 ft/sec and "adequate" was defined as 3 to 6 ft/sec. These values of sink rate at touchdown were obtained from the data records. However, experience has shown that touchdowns of 0 to 3 ft/sec result in "smooth" landings, touchdowns of 3 to 6 ft/sec result in "solid" landings, and touchdowns in excess of 6 ft/sec can be recognized by any crew member as being "hard" landings.

The design goal of the above task was to achieve sufficient pilot gain in the pitch axis to provide an adequate spread in the handling qualities ratings but not be so difficult or easy as to bias the pilot ratings.

The evaluation pilots were briefed on the general experiment purpose and flight task details. They had a general knowledge of what the test configurations were in that they had seen descriptions and time histories, but they had no knowledge of which configurations would be evaluated on any given flight. An evaluation normally consisted of two approaches and landings. The pilot could make comments at any time; however, formal use of the comment card (fig. 6), the Cooper-Harper pilot rating scale (fig. 7), and the pilot-induced-oscillation (PIO) scale (fig. 8) was not made until after the second landing for the configuration. It should be noted that the pilot had the option of making a third landing for any configuration; and in that case, the comments and evaluation ratings were not made until after the third landing. The pilot comments and Cooper-Harper ratings were considered the primary data of this investigation; however, the touchdown dispersions have also been used in the analysis of the results.

Seven engineering test pilots with a wide variety of backgrounds participated in the in-flight (TIFS) simulation program. In addition to the NASA and Calspan pilots who were scheduled to participate in the NASA-sponsored program, NASA invited other flight test organizations to provide pilots if their respective organizations would fund the cost for their flights. The Boeing Airplane Company, the Lockheed-Georgia Company, and the German Aerospace Research Establishment (DFVLR) accepted this invitation. Four of these pilots (NASA, Calspan, Lockheed, and DFVLR) also participated in the ground-based simulator (VMS) tests, and this paper compares the results obtained on these two simulators (TIFS and VMS) by these four pilots.

Results and Discussion

The results of this study are discussed in terms of the previously stated objective, i.e., to provide information to the flight controls/flying qualities engineer that will assist him in determining the incremental flying qualities and/or pilot performance differences that may be expected between results obtained via ground-based simulation (particularly by the Langley VMS) and flight tests. The primary pilot tasks were the approach and landing tasks with emphasis on the landing-flare task. The pilot ratings presented for the various configurations evaluated are an average of the ratings from all pilots who flew that particular configuration.

Flying Qualities

Figure 9 indicates that for the "approach task" the flying qualities Level or ± 1 CHR were predicted from the VMS tests for 25 of the 31 configurations; i.e., 81 percent of the time the pilot opinion was the same as that for the in-flight simulation (TIFS) tests. (It may be noted that 31 configurations cannot be identified in fig. 9 since some of the configurations coincide.) The "± 1 Cooper-Harper rating (CHR)" is grouped with the flying qualities "level" (i.e., Level or ± 1 CHR) in order to include the shaded triangular areas indicated in the figure. It is also shown that the CHR was predicted within ± 2 for 29 of the 31 configurations (94 percent), and the CHR was predicted within ± 1 for 23 of the 31 configurations (74 percent). This is considered to be good agreement since experience has shown that frequently two or more pilots flying the same configuration on the same simulator (or flying the same airplane) may not evaluate the flying qualities of a configuration/airplane any closer than indicated here.

Figure 10 indicates that for the "landing-flare" pilot task the flying qualities Level or ± 1 CHR were predicted from the VMS tests for 25 of the 31 configurations flown; i.e., 81 percent of the time the VMS results agreed with the TIFS results. (Note that this is the same percentage as for the approach task.) Also, the CHR was predicted within ± 2 for 27 of the 31 configurations (87 percent), and the CHR was predicted within ± 1 for 18 of the 31 configurations (58 percent).

Upon comparing the data of figures 9 and 10, it may be concluded that the accuracy of the flying qualities prediction of the Langley VMS for flying qualities "level" is approximately 80 percent for both the "approach" and "landing-flare" pilot tasks. Also, as might be expected, the results show that the capability of the ground-based simulator to predict Cooper-Harper pilot ratings is somewhat better for the "approach" pilot task than for the "landing-flare" task. This is probably because for the landing-flare pilot task, the pilot tends to be "in the control loop" more tightly than for the approach task, and also because the "out-the-window" scene (which is less realistic on the simulator) is more important to the pilot for the landing-flare task. (There is a lack of depth perception on the VMS scene.)

The results discussed henceforth in this paper are those obtained during the landing phase (landing-flare pilot task) unless specifically noted otherwise.

The configurations flown during the TIFS tests (ref. 1) were developed, for the most part, by considering both angle-of-attack and pitch-rate command systems in terms of α/δ_e and q/δ_e transfer functions. Also, the short-period and phugoid modes were considered separately because a system can be designed in which the angle of attack follows the control command in the short term and the pitch rate follows the control command in the long term, or vice versa. The idea was to try to determine pilot preference both in the short term (short-period mode) and in the long term (phugoid mode). The time histories presented in figure 11(a) indicate the response of a configuration that has an α_c system (both short term and long term), and figure 11(b) presents the type of response when a q_c system (both short term and long term) is used. Also, by proper placement of the short-period and phugoid poles and zeros, it is possible to obtain a short-term α_c/long-term q_c system, or vice versa. (See ref. 1 and the time histories in fig. 12.)

In an attempt to determine if the type of command system (i.e., α_c or q_c) had an effect upon the fidelity of the flying qualities evaluations on the Langley VMS, the various configurations evaluated were grouped as such for analysis. First, all configurations with an α_c system (at least in the short term and disregarding the type of command system for the long term) were compared from the TIFS and VMS evaluations. (See fig. 13.) It should be noted that the configurations for which additional time-delay and/or pitch-sensitivity variations were made are not included in this grouping of α_c system configurations. (That is, configurations 21–28 were omitted in order to isolate the effects of various command control systems. Configurations 21–28 will be discussed later in this paper.) Figure 13(a) indicates that with the exception of configuration 1, the flying qualities level was correctly predicted on the VMS. The pilots downgraded configuration 1 on the VMS primarily because of the "unpredictable pitch response" and the "tendency to PIO" in the flare. (These adverse characteristics were not apparent during the TIFS tests.) Figure 13(b) compares the PIO tendency classification of the short-term α_c configurations and indicates that (1) the tendency for PIO in the flare, where the pilot initiates tight control, is much greater on the VMS than on the TIFS; and (2) on 30 percent of these configurations, the VMS did not correctly predict whether the "task would be compromised." (See fig. 8 for the PIO tendency classification scale.)

Figure 14 compares the pilot opinions from the TIFS and VMS for the configurations having an α_c system (at least in the long term and disregarding the type of command system for the short term). (Again, configurations 21–28 were not included in this grouping.) Figure 14(a) indicates that, for the most part, the pilot evaluations from the VMS agreed with the evaluations from the TIFS insofar as predicting the flying qualities level. However, there were substantial differences in the CHR's assigned to these configurations, and the pilot ratings from the VMS tests were always higher (worse). Figure 14(b) presents the PIO classification results for the long-term α_c configurations and indicates that, in general, the tendency to PIO on the VMS was greater than on the TIFS.

A comparison of the pilot opinions on the TIFS and VMS tests for the pitch-rate command (q_c) configurations is presented in figure 15 for short-term q_c systems and in figure 16 for long-term q_c systems. The agreement in the flying qualities evaluations between the ground-based simulator (VMS) and the in-flight simulator (TIFS), in regard to the flying qualities level, was excellent regardless of whether the q_c system was short term, long term, or both. Also, note that the CHR's from the two simulations were in good agreement (ΔCHR < 2) for the configurations simulated having pitch-rate command systems. In addition, figures 15(b) and 16(b) indicate that there was very good agreement between the two simulators for the PIO tendency classification. Furthermore, all q_c configurations (except configuration 14) were categorized as not being PIO prone; i.e., the task performance was not compromised (a PIO rating less than 2.5). The pilot complained about the overly sensitive pitch-response characteristics of configuration 14, which has a very high $1/\tau_{\theta_2}$, during both simulator tests—and this "problem" was more pronounced on the VMS. Note that for configuration 14, the task performance was compromised on the VMS (a PIO rating of 4) and was borderline to being compromised on the TIFS (a PIO rating of 2).

From the results presented in figures 13–16, the following conclusions are given:

1. For the configurations having an α_c system (short term and/or long term), the tendency for PIO, where the pilot initiates tight control, was often much greater on the ground-based simulator than on the in-flight simulator probably because of the lack of sufficient visual cues on the VMS.

2. For the configurations having a q_c system (short term and/or long term), the agreement between the two simulators was excellent in regard to the flying qualities level; the CHR's were in good agreement (ΔCHR < 2 for all configurations); the PIO tendency classification was in very good agreement between the two simulators; and, in general, these q_c configurations were less PIO prone than the α_c configurations on both simulators.

As stated previously, configurations 21–28 were configurations for which time-delay and command gain (sensitivity) variations were made on a baseline, level 1, conventional airplane configuration (configuration B described earlier). The test matrix for the time-delay/sensitivity configurations is presented in table III. It should be noted that the baseline "effective" time delay was approximately 150 and 187 msec for the TIFS and VMS evaluations, respectively. (Additional time delay was added to these "inherent" delays as pure transport delay.)

Figure 17 compares the pilot opinions (CHR's) obtained for the time-delay/sensitivity test configurations on the TIFS and VMS. Figure 17(a) indicates excellent agreement between the two simulators when the low sensitivity was used; both sets of data indicated that for the landing-flare pilot task, the maximum effective time delay would be approximately 240 msec for satisfactory flying qualities (CHR ≤ 3.5). Figures 17(b) and 17(c) indicate the differences in pilot opinion obtained on the TIFS and VMS as the effective time delay was increased for nominal (fig. 17(b)) and high (fig. 17(c)) control sensitivity. The pilot ratings between the TIFS and VMS were considerably different for both the nominal and the high values of sensitivity. For the nominal sensitivity configurations (fig. 17(b)), the results show that the maximum effective time delay for level 1 (CHR ≤ 3.5) flying qualities was approximately 185 msec on the TIFS compared with approximately 315 msec on the VMS. It is also indicated that a maximum time delay for level 2 (CHR ≤ 6.5) flying qualities was 315 msec on the TIFS, compared with a time delay of something much greater than 400 msec on the VMS. Figure 17(c) also shows large differences between the CHR's obtained on the TIFS and VMS when high control sensitivity was evaluated. It should also be noted that for the high-sensitivity configurations, none were rated as being level 1 on the VMS—even with no "additional" time delay.

From the results presented in figure 17, the following conclusions are given:

1. The effect of control sensitivity is more pronounced on the ground-based simulator, particularly at the lower control-system time delays.
2. In general, the pilot is more tolerant of control-system time delays on the ground-based simulator.

Figure 18 indicates the differences in PIO tendency between the TIFS and the VMS for the configurations with no added time delay. It is evident from these data that the pilot has a greater tendency to induce oscillations on the ground-based simulator than when flying the in-flight simulator. However, figure 19 indicates that for configurations having high time delays (table III), the pilot is less prone to induce oscillations on the ground-based simulator than on the in-flight simulator.

Landing Performance

As stated previously, the landing performance was evaluated during the TIFS and VMS tests by recording the touchdown sink rate as well as the longitudinal and lateral touchdown dispersions on the runway. Figure 20 compares these landing-performance parameters between the two simulators. These data indicate that the touchdown sink rate on the VMS was much higher than on the TIFS. The "desired" sink rate ($\dot{h}_{\mathrm{TD}} < 3$ ft/sec) was accomplished for less than 15 percent of the VMS landings compared with approximately 90 percent of the landings on the TIFS. Note also that $\dot{h}_{\mathrm{TD}}$ was unacceptable (greater than 6 ft/sec) for more than 15 percent of the landings on the VMS. This inability to accomplish a good touchdown sink rate on the ground-based simulator was not surprising since the pilot has little depth/height perception from the outside scene presentation. Although not presented in figure 20, the average touchdown sink rate was 1.7 and 5.1 ft/sec on the TIFS and the VMS, respectively. This suggests that there is a $\Delta\dot{h}_{\mathrm{TD}}$ value of approximately 3.5 ft/sec that may be expected from the ground-based simulator as opposed to the real-world environment. This expectation is in agreement with previous studies (for example, refs. 16 and 17) which have shown ground-based-simulator touchdown sink rates to be 2.5 to 3.0 times greater than those experienced during flight tests.

As seen in figure 20, the differences in the longitudinal and lateral touchdown dispersions between the TIFS and VMS were much less than the differences in touchdown sink rates. Figure 20 also presents the "overall" touchdown performance difference between the TIFS and the VMS. (The term "overall" indicates that the sink rate, lateral-runway position, and longitudinal-runway position are all satisfied for any given category of acceptance.) It may be noted from this "overall" performance histogram that "desired" performance was achieved on the VMS less than 5 percent of the time—primarily due to the sink rate performance.

Concluding Remarks

Pilot opinion and performance derived from a six-degree-of-freedom ground-based simulator (the Langley Visual/Motion Simulator (VMS)) and a six-degree-of-freedom in-flight simulator (the USAF-AFWAL Total In-Flight Simulator (TIFS)) are compared for a jet-transport airplane having conventional cockpit controllers and instrument displays with 31 different longitudinal dynamic response characteristics. The primary pilot tasks were the approach and landing tasks with emphasis on the landing-flare task. This paper summarizes the results from this "comparative" study.

The accuracy of the flying qualities prediction of the Langley VMS for flying qualities Level or ± 1 CHR was approximately 80 percent for both the approach and the landing-flare pilot tasks.

As expected, the capability of the ground-based simulator to predict Cooper-Harper ratings (CHR's) was somewhat better for the approach pilot task than for the landing-flare task. For the approach task, the CHR was predicted within ± 1 for approximately 75 percent of the configurations evaluated compared with less than 60 percent of the configurations for the landing-flare task.

For the configurations having an angle-of-attack command system, the tendency for pilot-induced oscillations (PIO's), where the pilot initiates tight control, was much greater on the ground-based simulator than on the in-flight simulator—probably because of the lack of sufficient visual cues on the ground-based simulator. For the configurations having a pitch-rate command system, the PIO tendency classification was in good agreement between the two simulators. In general, the pitch-rate command (q_c) configurations were less PIO prone (the task was not compromised) than the angle-of-attack (α_c) configurations on the ground-based simulator. Therefore, the deficiencies of the ground-based simulator (primarily the visual cues) may not be as detrimental for the q_c configurations as for the α_c configurations.

The effect of pitch-control sensitivity was more pronounced on the ground-based simulator than on the in-flight simulator, particularly at the lower control-system time delays. In general, the ground-based simulator showed less sensitivity to time delays in the airplane response than did the in-flight simulator.

The data show that there is an incremental increase of touchdown sink rate of approximately 3.5 ft/sec that may be expected on the ground-based simulator as opposed to the real-world environment. The ground-based simulator was not adequate for assessing sink rate performance for the landing-flare task when the pilot has little depth/height perception from the outside scene presentation.

It is concluded that, in general, flying qualities results obtained from the ground-based simulator may be considered conservative—especially when the pilot task requires tight pilot control. That is, in general, the Cooper-Harper ratings (CHR's) and the pilot-induced-oscillation (PIO) classification ratings were higher (worse) on the ground-based simulator. The one exception to this, according to the present study, was that the pilots were more tolerant of large time delays in the airplane response on the ground-based simulator.

The results from this study have indicated that caution must be exercised in the interpretation of simulation results when they may be affected by the limitations of the simulator hardware—particularly the visual cues.

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Hampton, VA 23665-5225
September 28, 1989

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Table I. Motion Performance Limits of the Langley Visual/Motion Simulator (VMS)

Degree-of-freedom operation	Position	Velocity	Acceleration
Pitch	+30°, −20°	±15 deg/sec	±50 deg/sec^2
Roll	±22°	±15 deg/sec	±50 deg/sec^2
Yaw	±32°	±15 deg/sec	±50 deg/sec^2
Vertical	+2.50 ft, −3.25 ft	±2 ft/sec	±0.6 g units
Lateral	±4.0 ft	±2 ft/sec	±0.6 g units
Longitudinal	+4.1 ft, −4.0 ft	±2 ft/sec	±0.6 g units

Table II. Summary of Configuration Characteristics

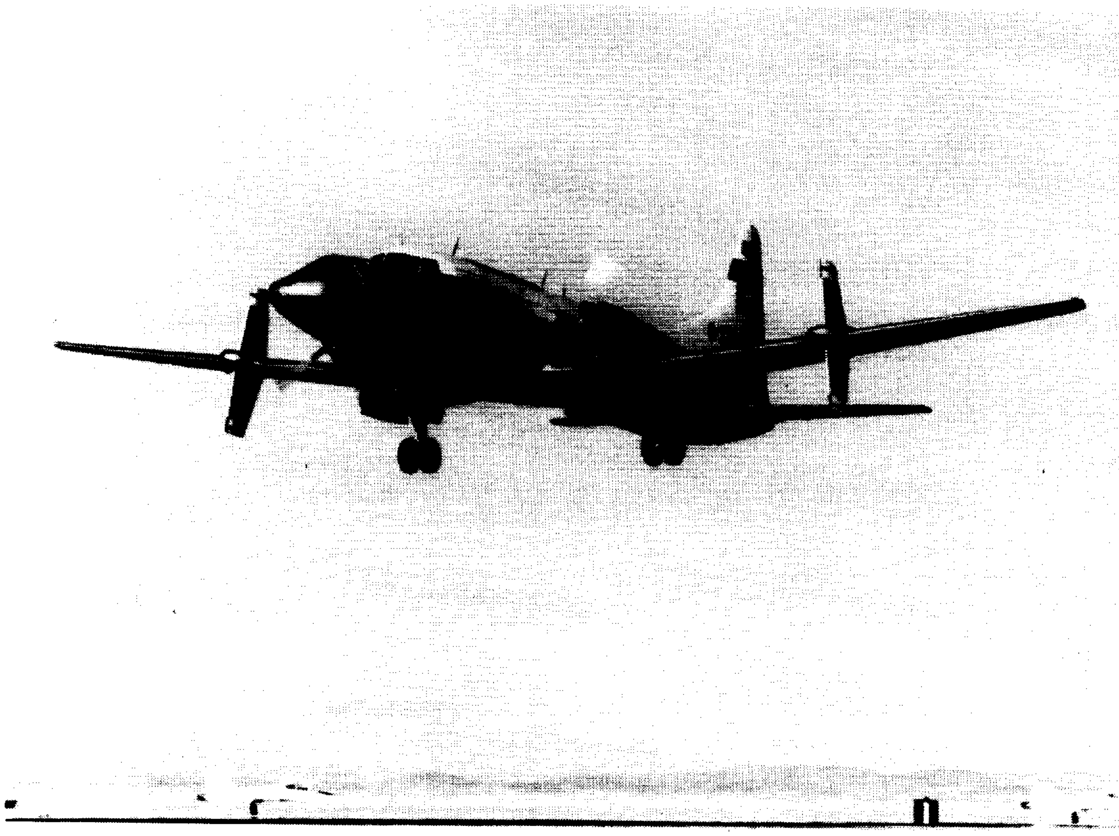
Configuration (a)	Command response type	ω_{SP}, rad/sec	ζ_{SP}	ω_{PH}, rad/sec (b)	ζ_{PH} (b)	$1/\tau_{\theta_2}$, rad/sec	n_z/α, g units/rad
B	Conventional airplane	2	0.7	0.16	0.095	0.75	5.3
1	α_c (short term and long term)	2	.7	.3	.1	.5	3.5
2	q_c (short term and long term)	2	2.1	(-)	(-)	.5	3.5
3	α_c (short term)/q_c (long term)	2	.7	(-)	(-)	.5	3.5
4	q_c (short term)/α_c (long term)	2	1.3	.3	.1	.5	3.5
5	α_c	2	.7	.1	.1	.9	6.3
6	q_c	2	1.3	(-)	(-)	.9	6.3
7	α_c/q_c	2	.7	(-)	(-)	.9	6.3
8	q_c/α_c	2	1.3	.1	.1	.9	6.3
9	α_c	2	.7	(-)	(-)	.5	3.5
10	q_c	2	1.3	(-)	(-)	.5	3.5
11	$\dot{\gamma}_c$	2	.7	(-)	(-)	.5	3.5
12	$\dot{\gamma}_c$	2	.7	(-)	(-)	.5	3.5
13	α_c	2	.7	.3	.1	2.0	14.0
14	q_c	2	1.3	(-)	(-)	2.0	14.0
17–20	q_c	2.9	.78	(-)	(-)	.72	5.0
21–28	Conventional airplane	2	.7	.16	.095	.75	5.3
17 + L/L	q_c	2.9	.78	(-)	(-)	.72	5.0
22A, 25A, 28A	q_c	2.9	.78	(-)	(-)	.72	5.0

[a]Configuration numbers correspond with those in reference 1.
[b]Configurations with phugoid characteristics listed as (-) have real roots.

Table III. Time-Delay/Sensitivity Test Matrix

Configuration (a)	Flight control system	Sensitivity		Time delay, msec	
		$\dot{q}$/lbf (b)	Command gain, deg/in.	TIFS	VMS
B	B	0.42 (nominal)	−3.3 (nominal)	150	187
21	B	.42 (nominal)	−3.3 (nominal)	250	281
22	B	.42 (nominal)	−3.3 (nominal)	350	375
23	B	.25 (low)	−2.0 (low)	150	187
24	B	.25 (low)	−2.0 (low)	250	281
25	B	.25 (low)	−2.0 (low)	350	375
26	B	.63 (high)	−5.0 (high)	150	187
27	B	.63 (high)	−5.0 (high)	250	281
28	B	.63 (high)	−5.0 (high)	350	375
17 + L/L	17 + L/L	.42 (nominal)	−.74 (nominal)	150	187
22A	17 + L/L	.42 (nominal)	−.74 (nominal)	350	375
25A	17 + L/L	.25 (low)	−.44 (low)	350	375
28A	17 + L/L	.63 (high)	−1.11 (high)	350	375

[a]Configuration numbers correspond with those in reference 1.
[b]Pitch acceleration per column force, $(\text{deg/sec}^2)/\text{lb}$.



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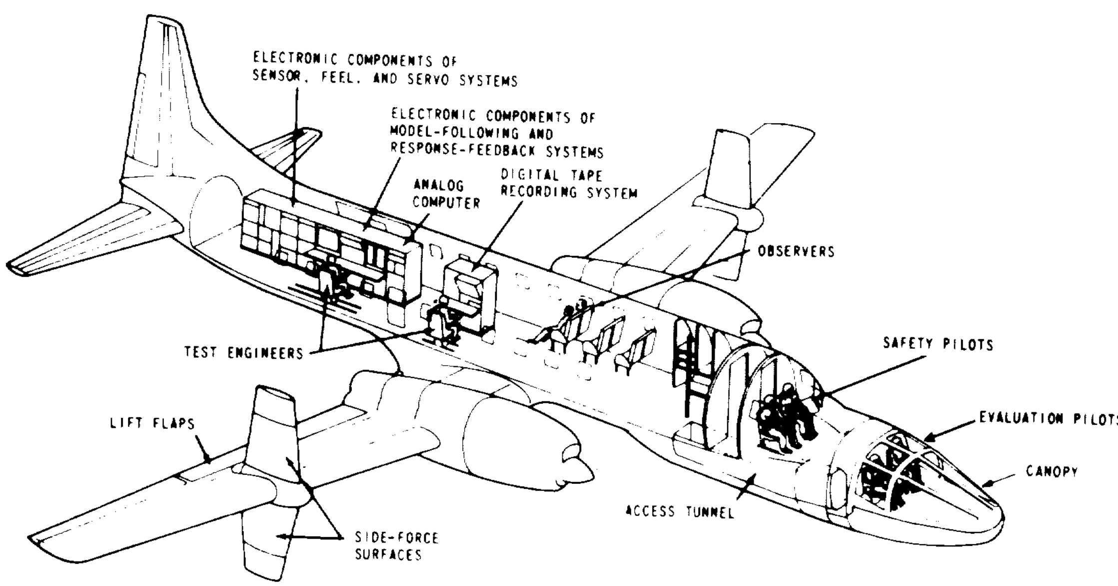
(a) Photograph of the TIFS.



(b) Schematic of the TIFS.

Figure 1. The USAF-AFWAL Total In-Flight Simulator (TIFS) used in the in-flight study.

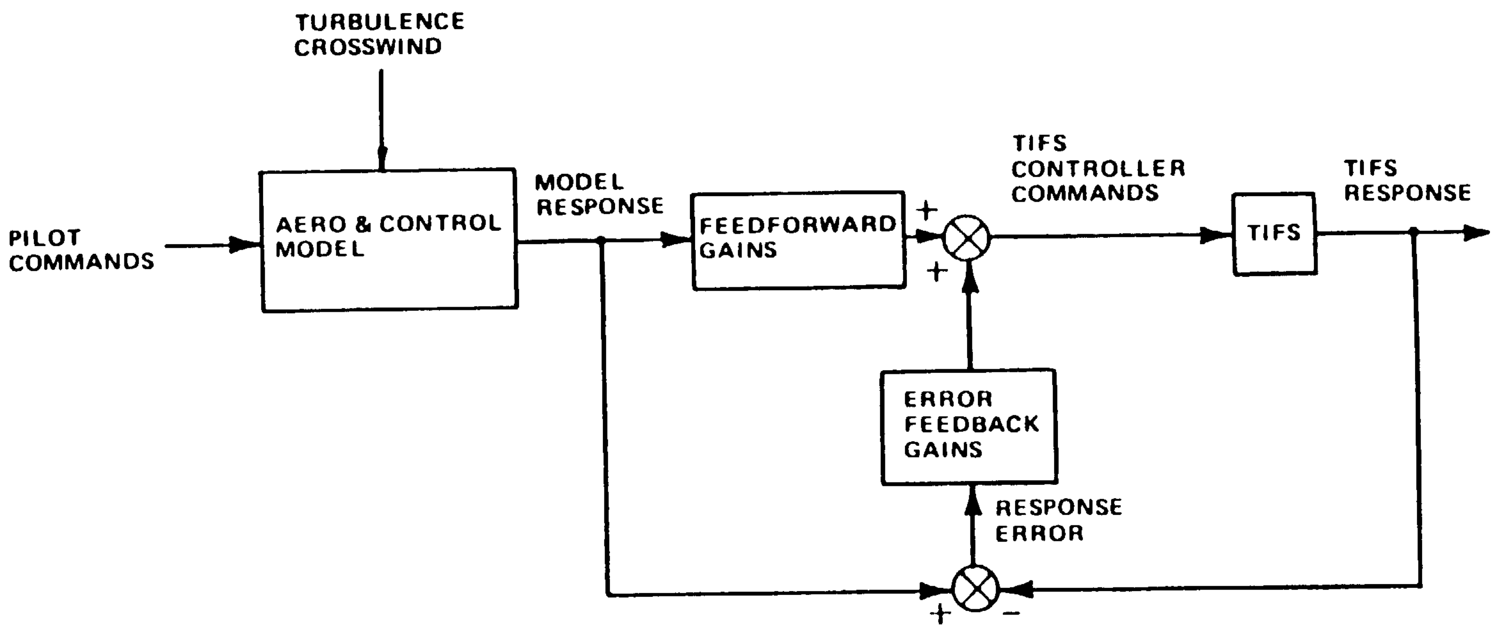


Figure 2. The TIFS model following simulation.

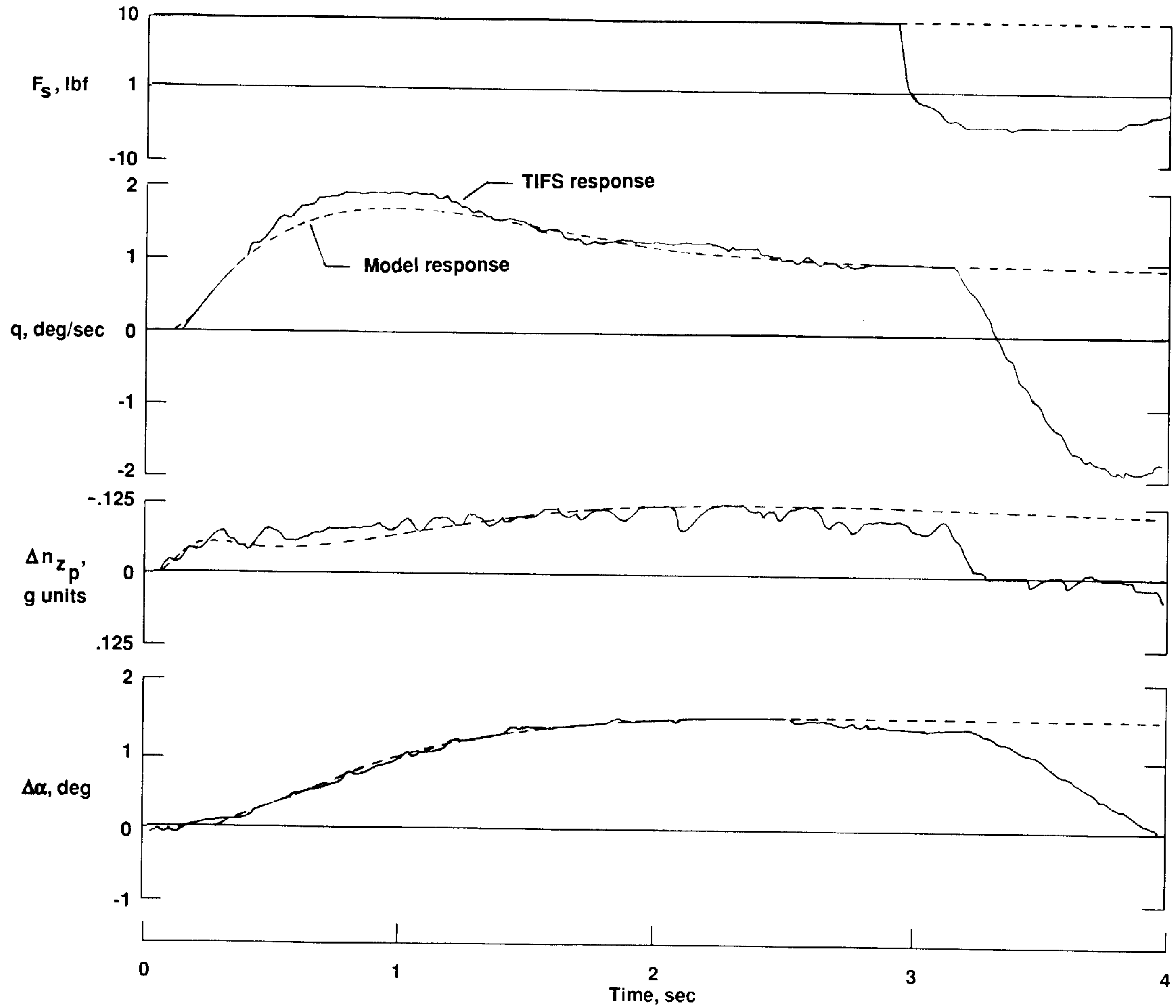


Figure 3. Example of TIFS capability to reproduce the model response to a time-step pitch-controller input.

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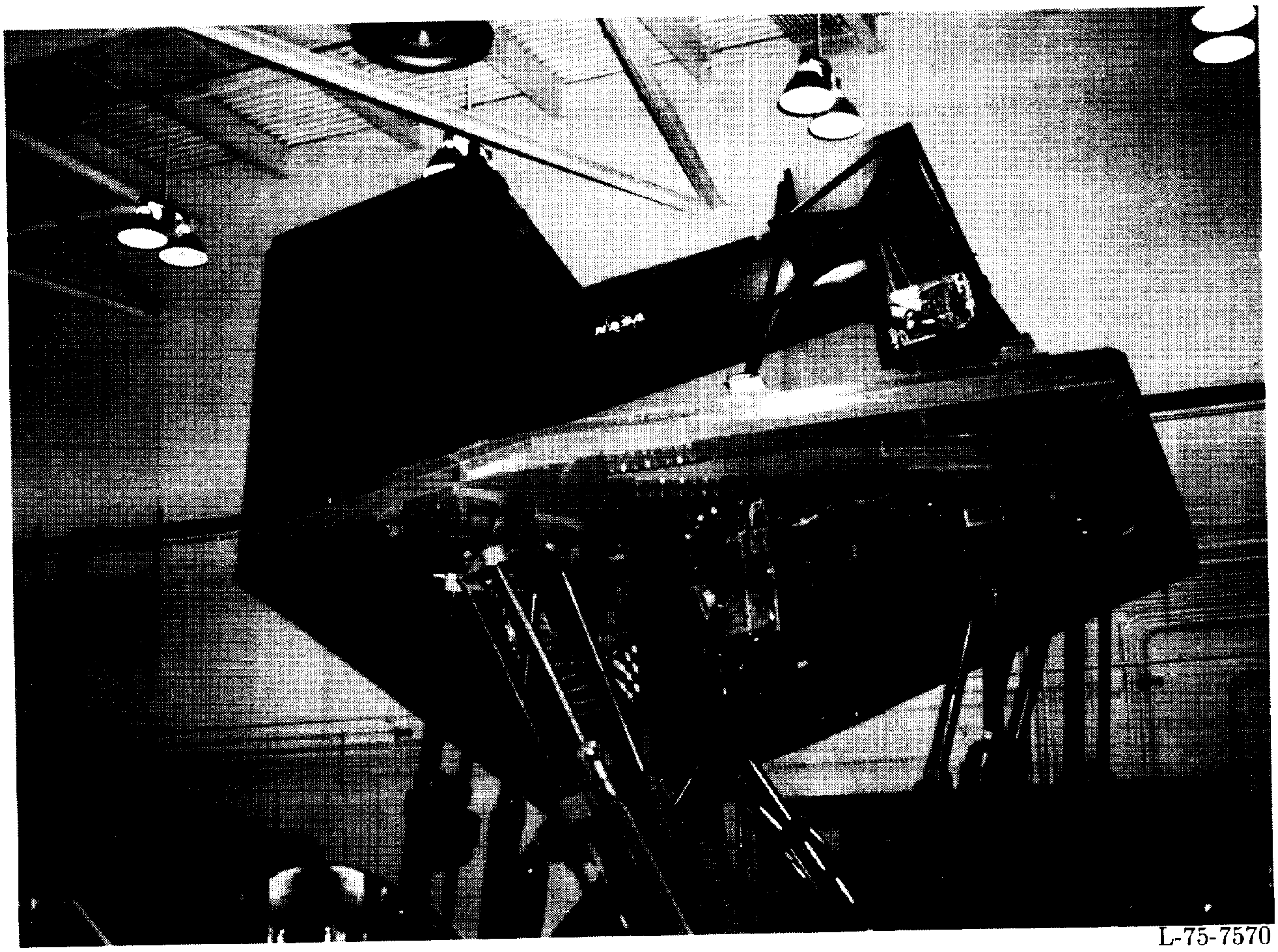

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Figure 4. The Langley Visual/Motion Simulator (VMS).

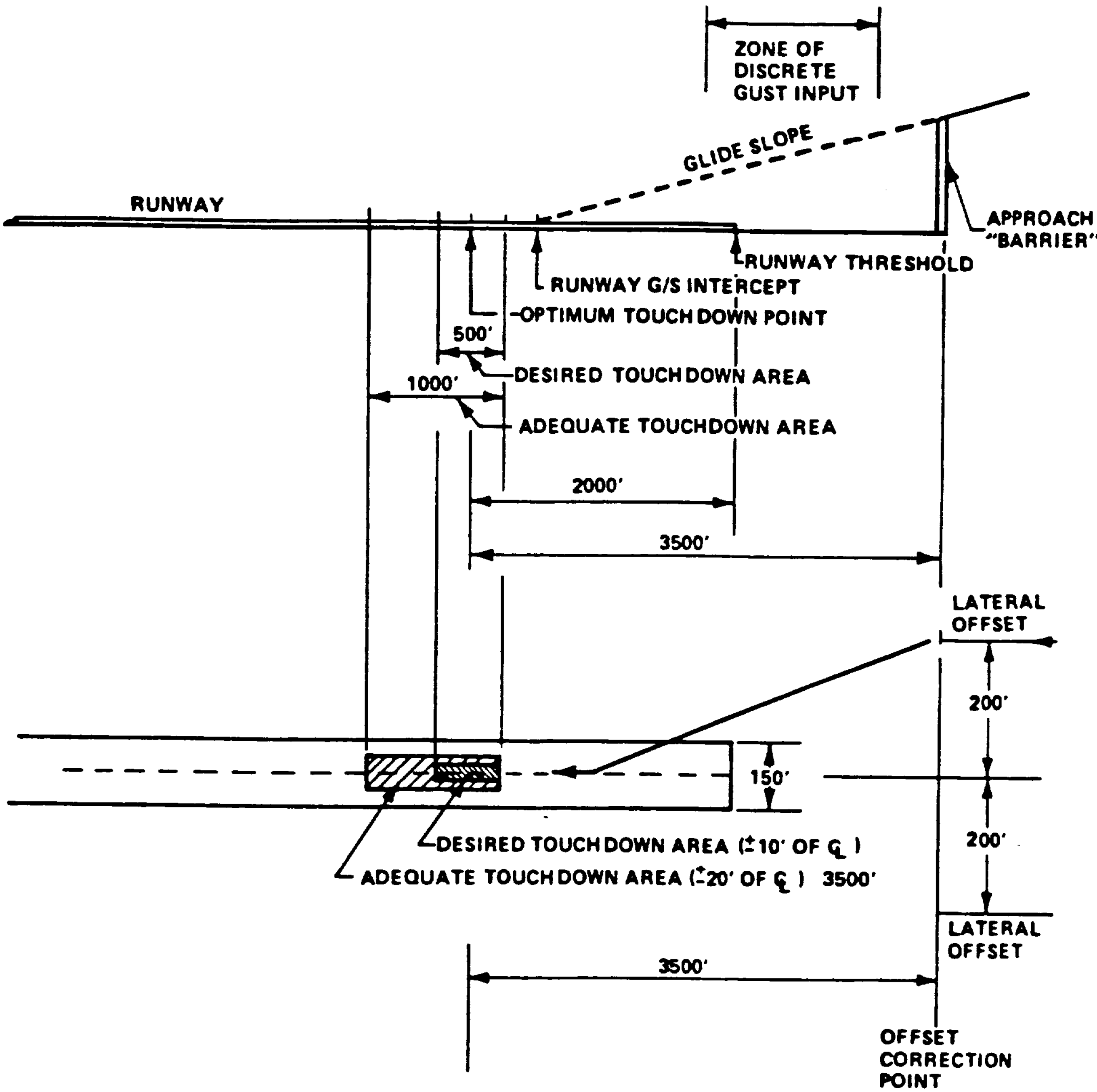


Figure 5. Indication of approach and landing task.

A. Initial Overall Impression

B. Approach

1. Initial/Final response to control inputs
2. Flight-path control
3. Pitch-attitude control
4. Airspeed control
5. Offset correction
6. Atmospheric disturbances
7. Special pilot techniques

C. Flare and Touchdown

1. Pitch-attitude and flight-path control
2. Control of touchdown parameters
3. Atmospheric disturbances
4. Special pilot techniques

D. Pilot Ratings

1. Approaches
2. Flare and touchdown
3. Overall
4. PIO rating

Figure 6. Pilot comment card.

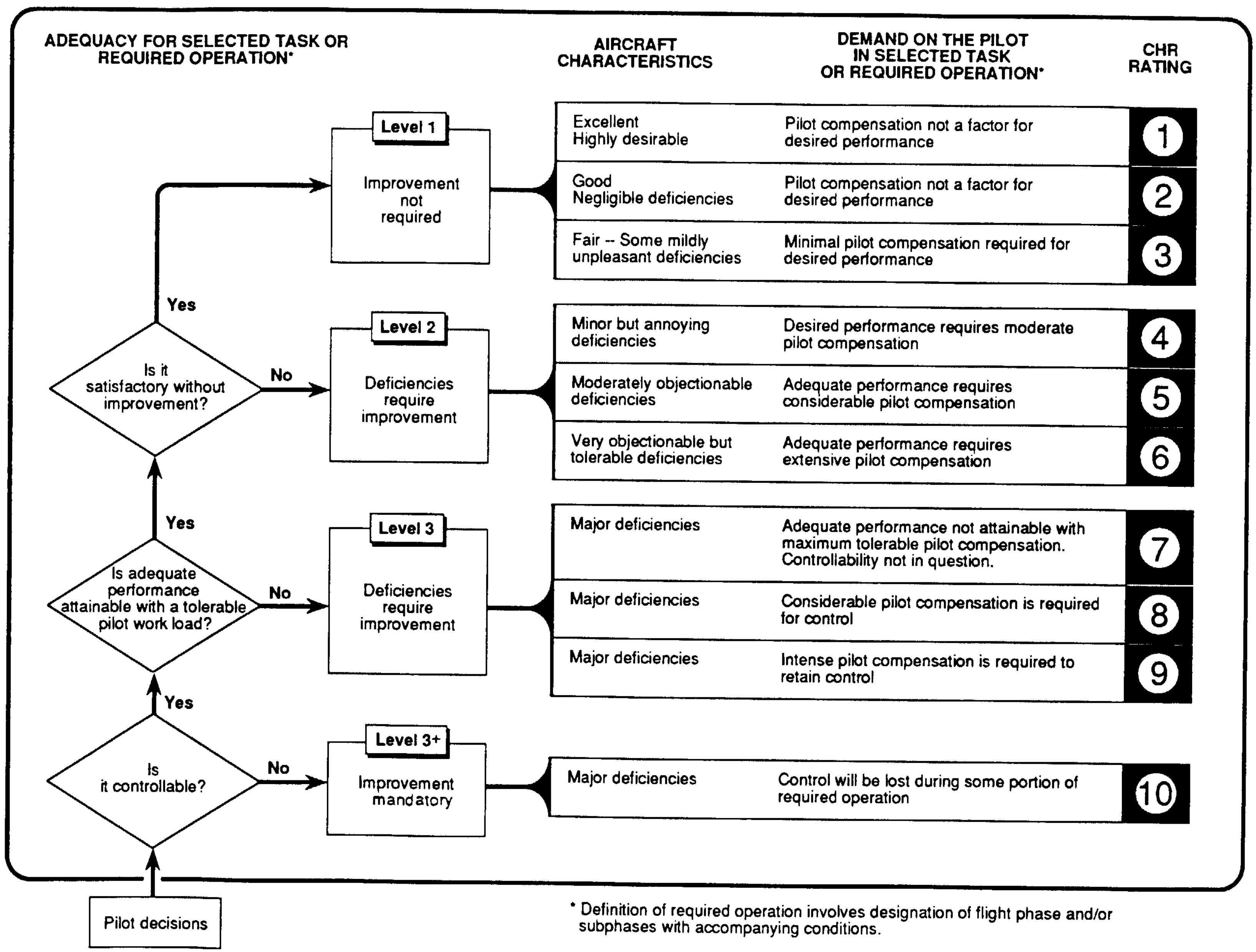


Figure 7. Cooper-Harper pilot rating scale.

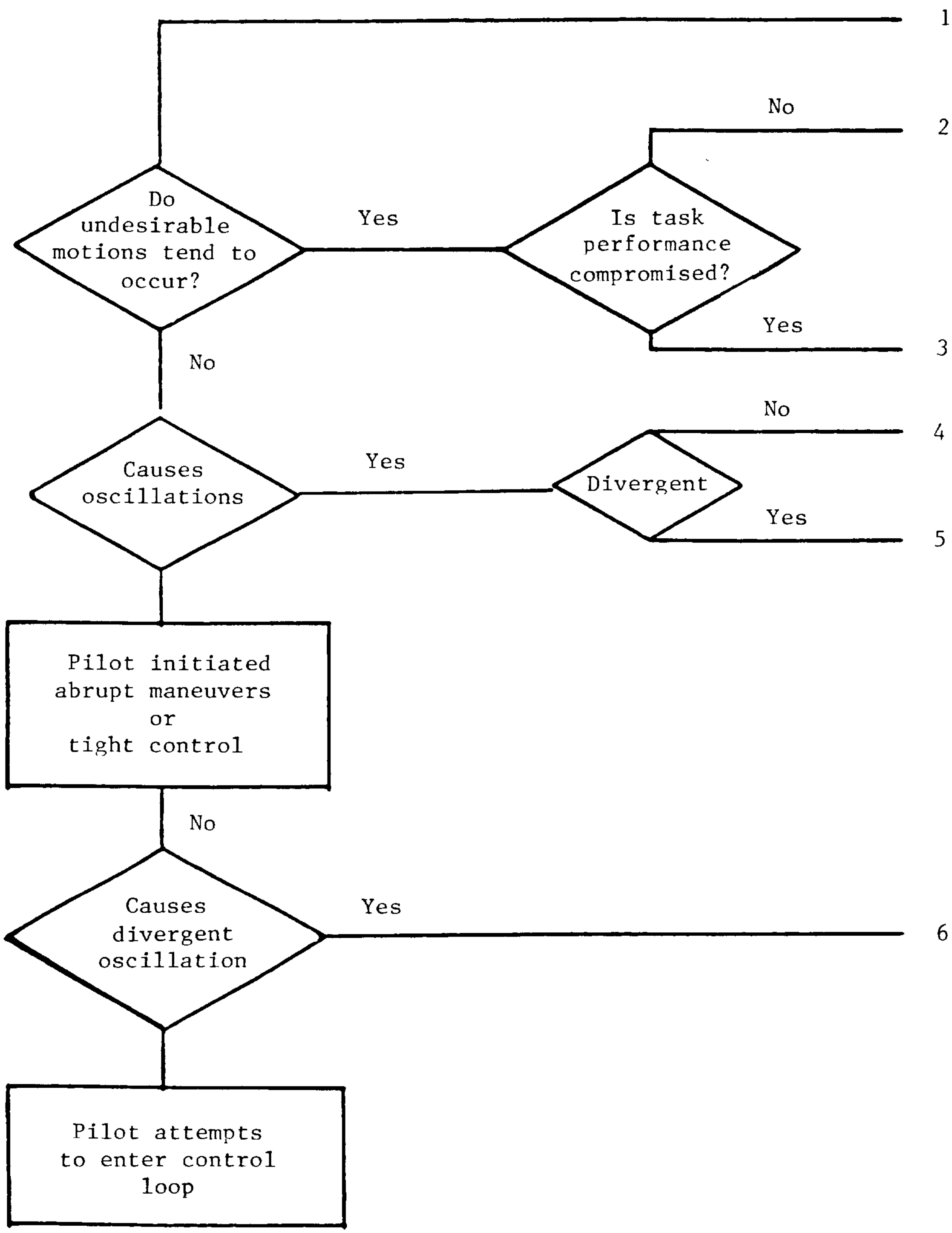
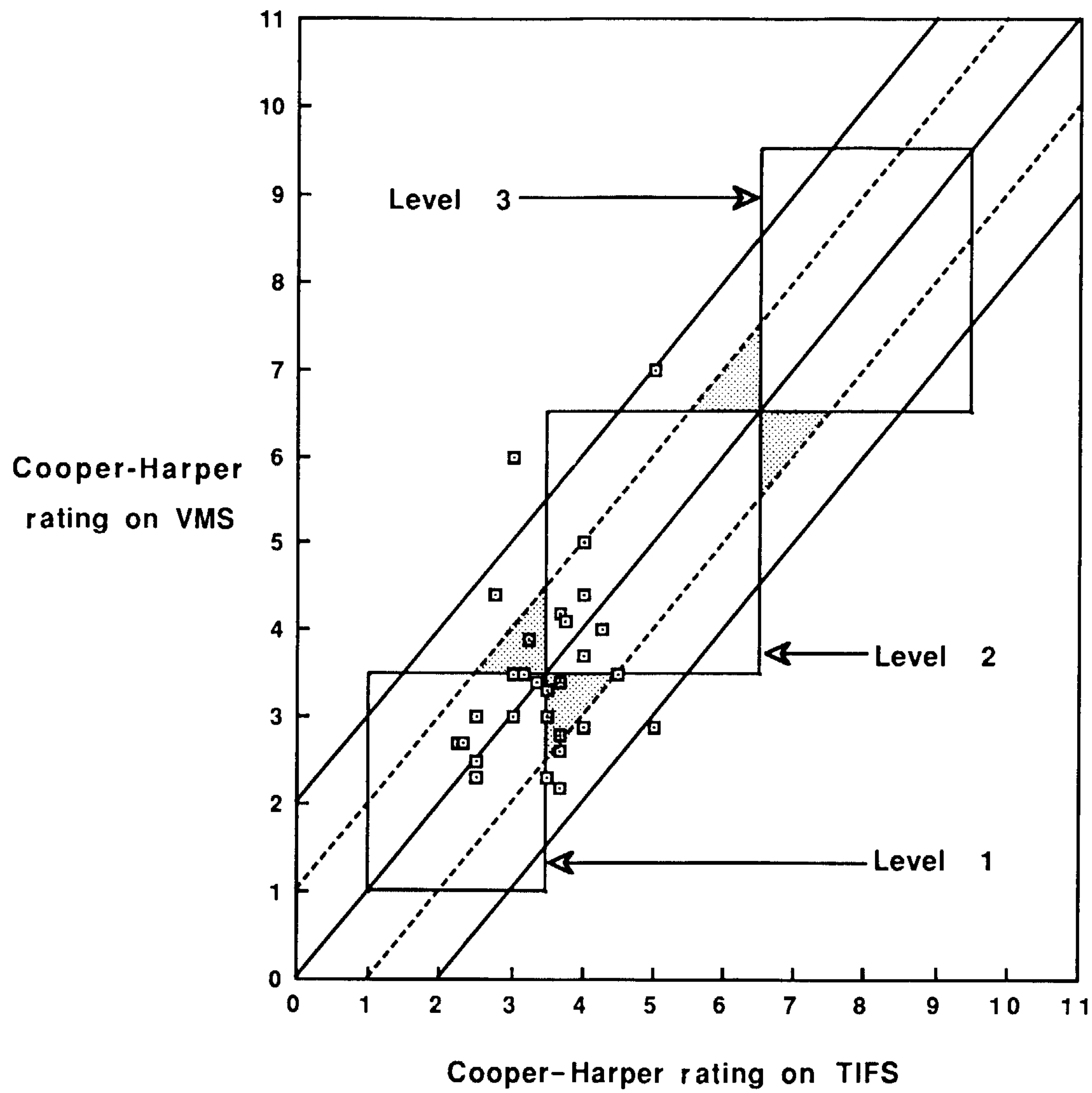


Figure 8. PIO-tendency classification scale.



Flying Qualities

<u>Level or ±1 CHR</u>

25/31 = 81%

<u>CHR</u>

±2	29/31	=	94%
±1	23/31	=	74%

Figure 9. Comparison of pilot opinions of flying qualities obtained on the TIFS and VMS for the approach task for all configurations.

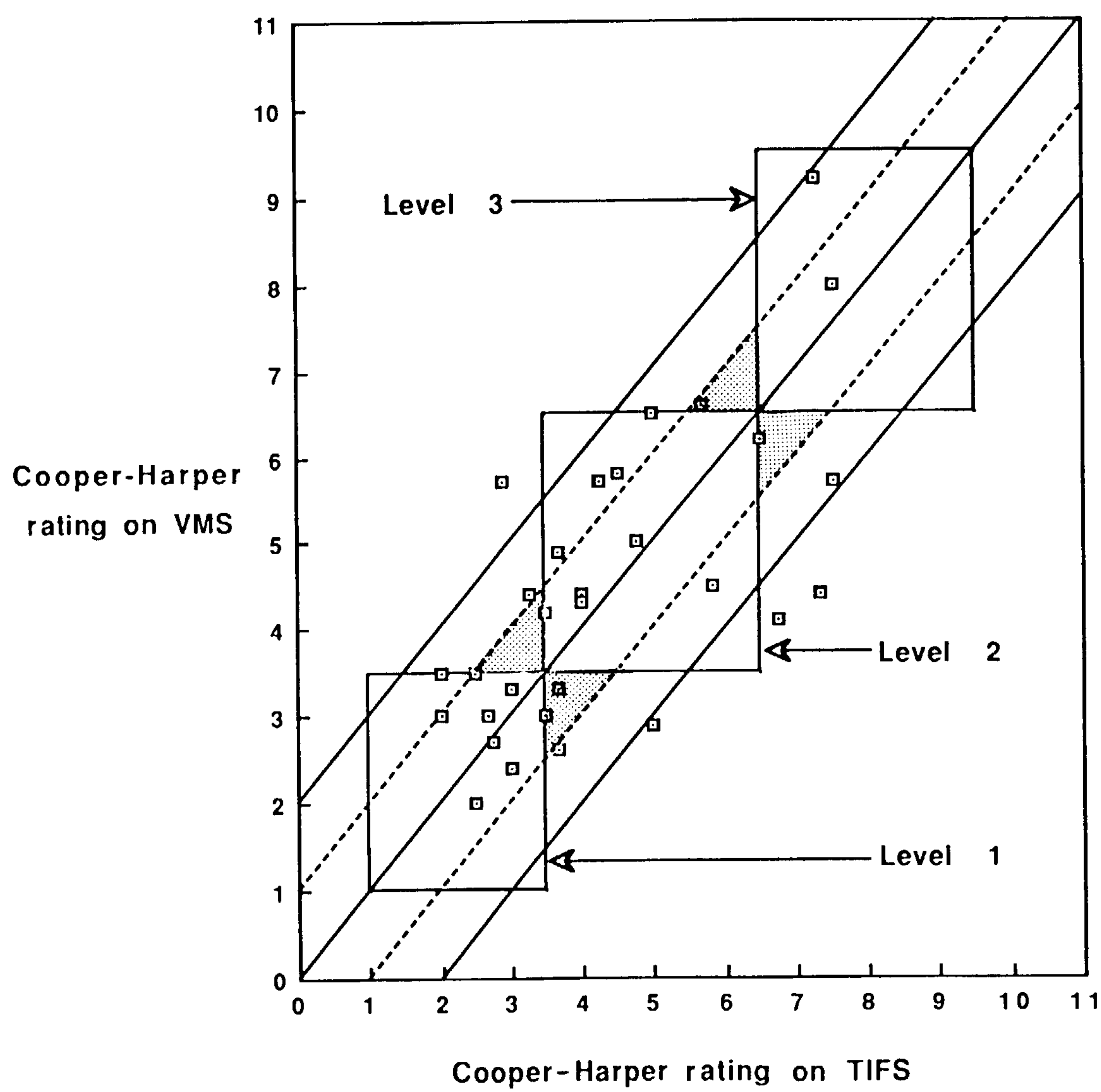
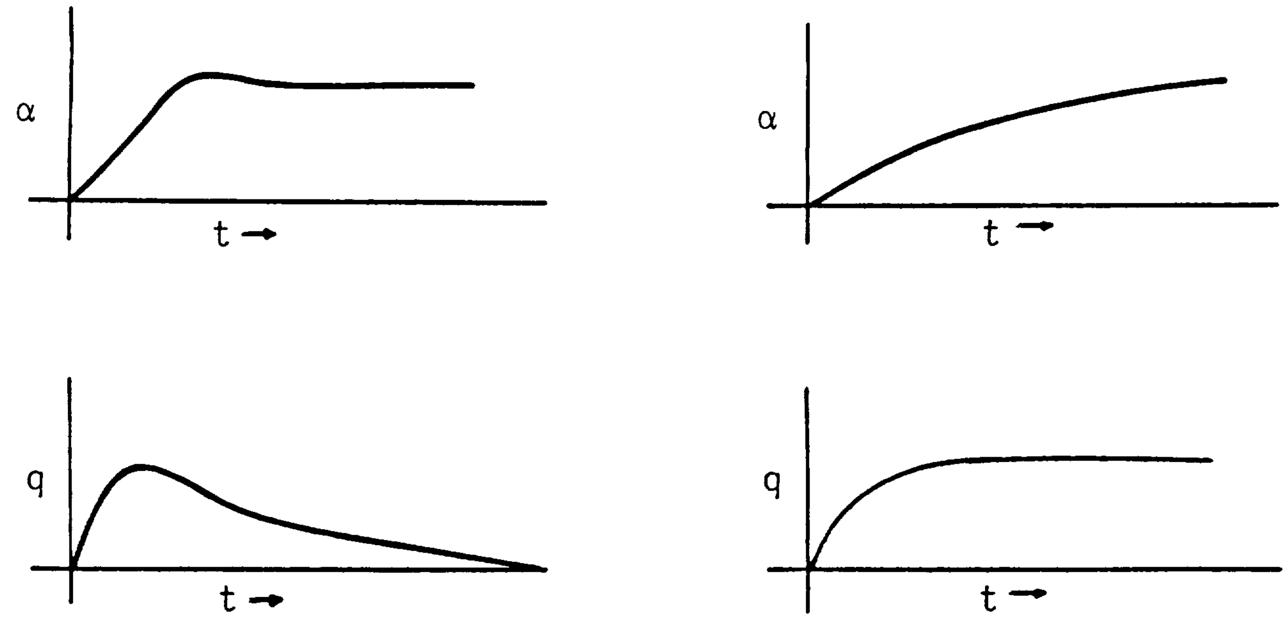


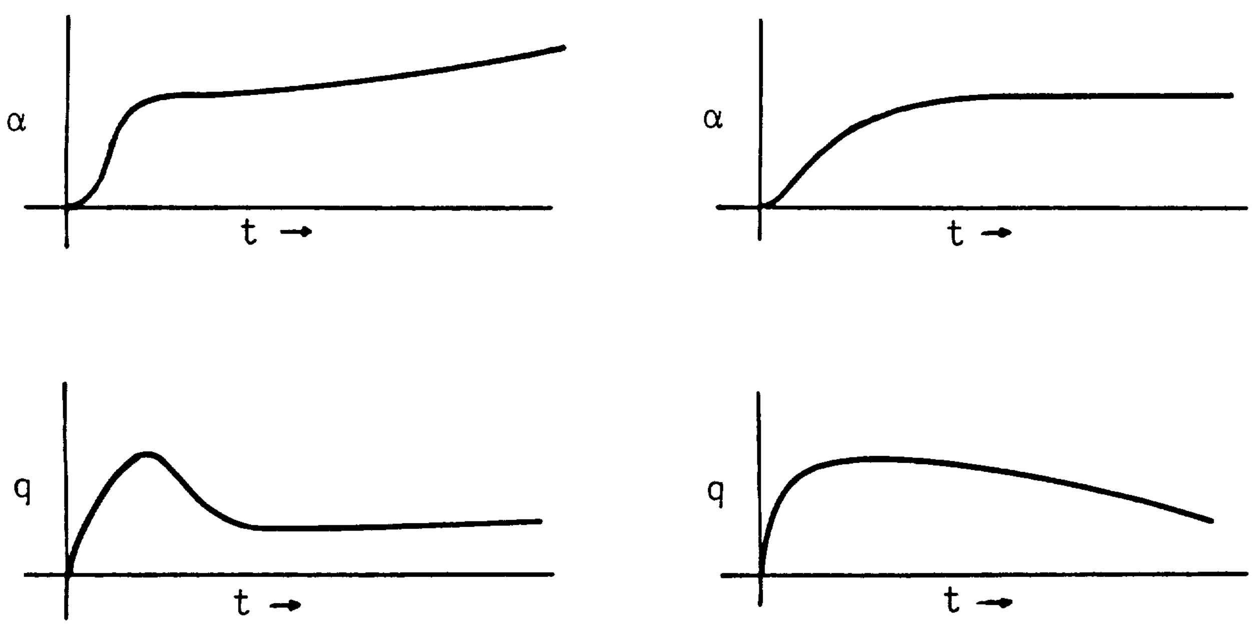
Figure 10. Comparison of pilot opinions of flying qualities obtained on the TIFS and VMS for the landing-flare task for all configurations.



(a) α_c system (both short term and long term).

(b) q_c system (both short term and long term).

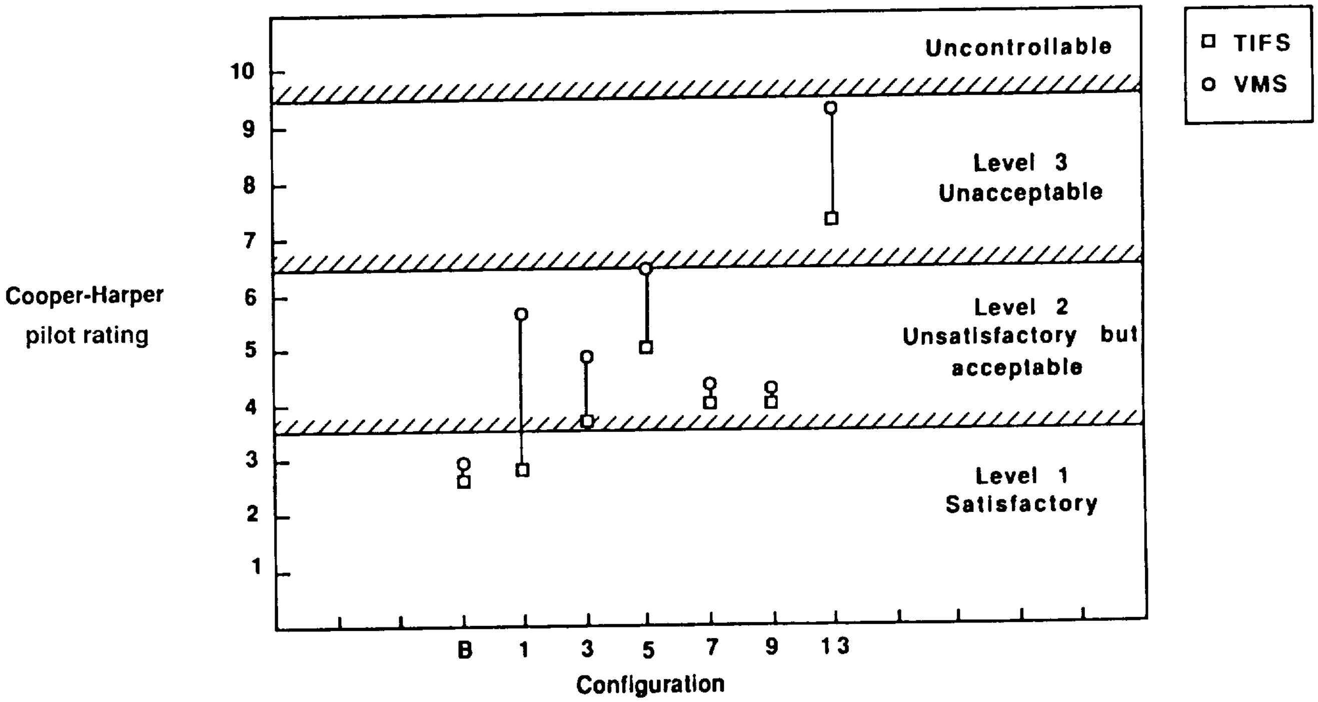
Figure 11. Response to step command for typical angle-of-attack-command and pitch-rate-command flight control systems.



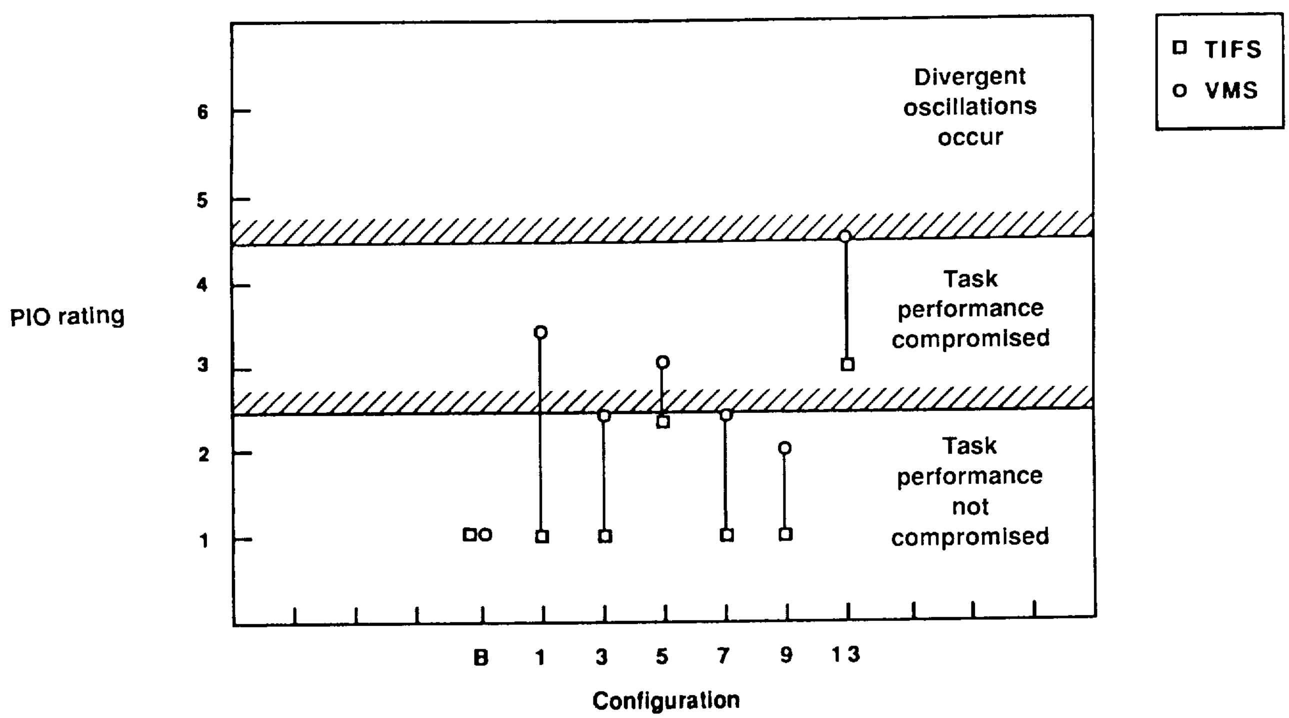
(a) Short-term α_c/long-term q_c system.

(b) Short-term q_c/long-term α_c system.

Figure 12. Response to step command for hybrid α_c and q_c flight control systems.

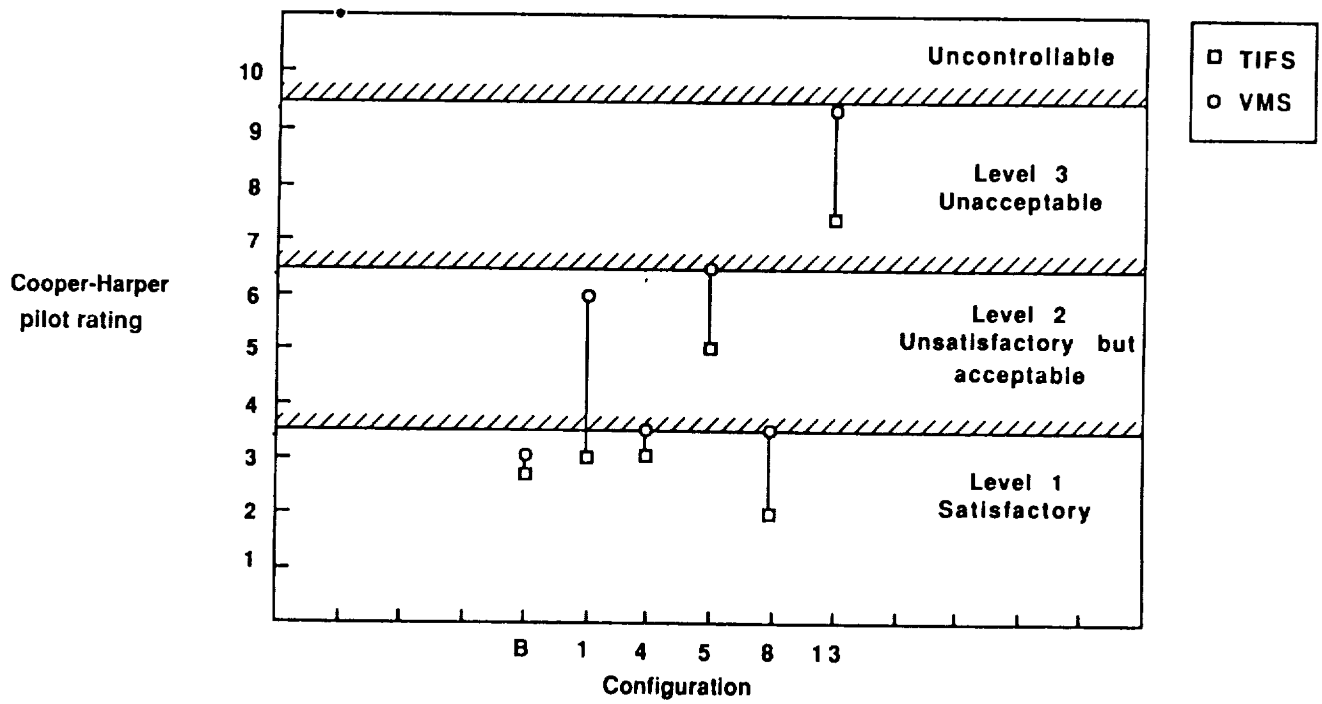


(a) Cooper-Harper pilot ratings.

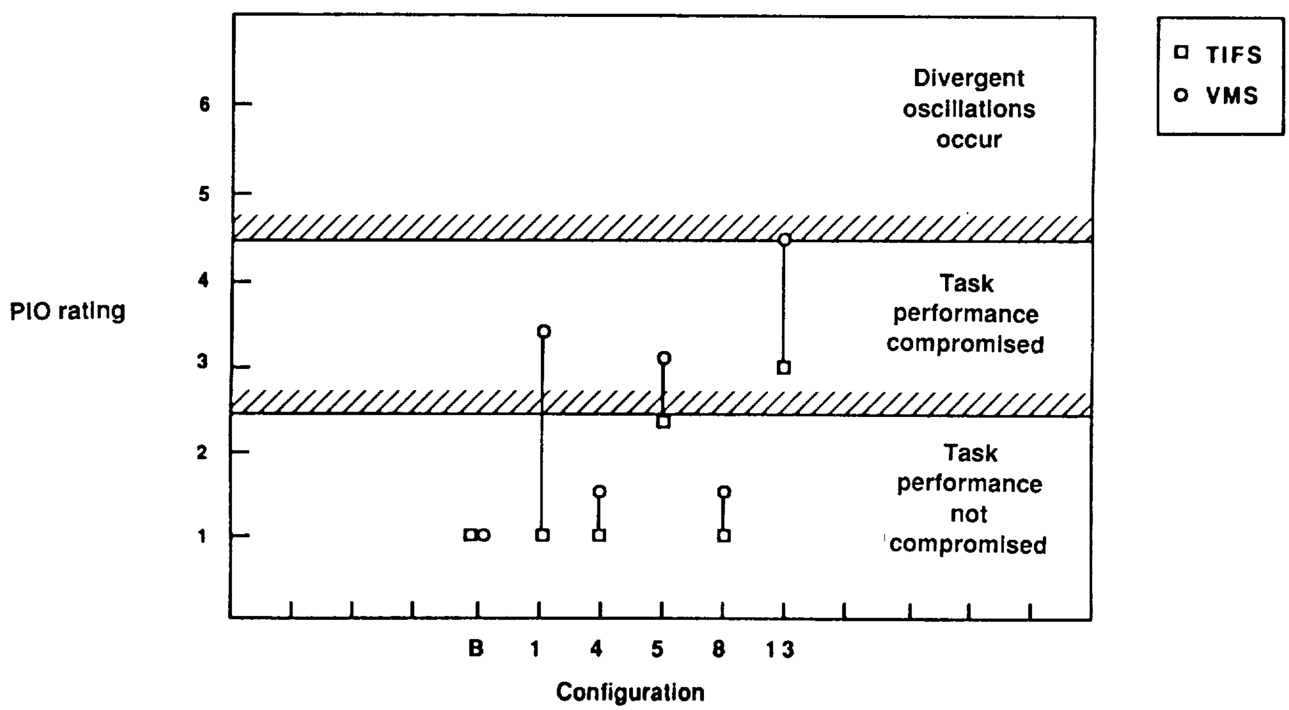


(b) PIO-tendency classification.

Figure 13. Comparison of pilot opinions from the TIFS and VMS for configurations with short-term α_c system for landing-flare pilot task.

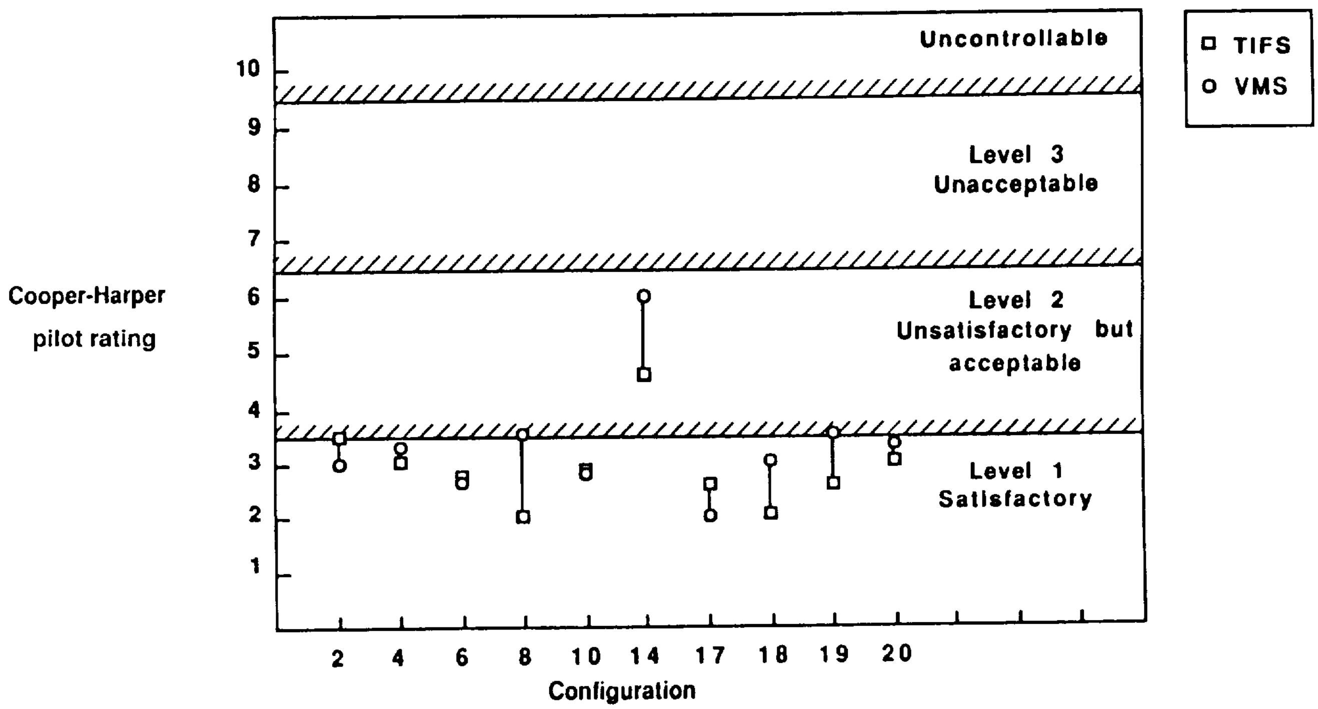


(a) Cooper-Harper pilot ratings.

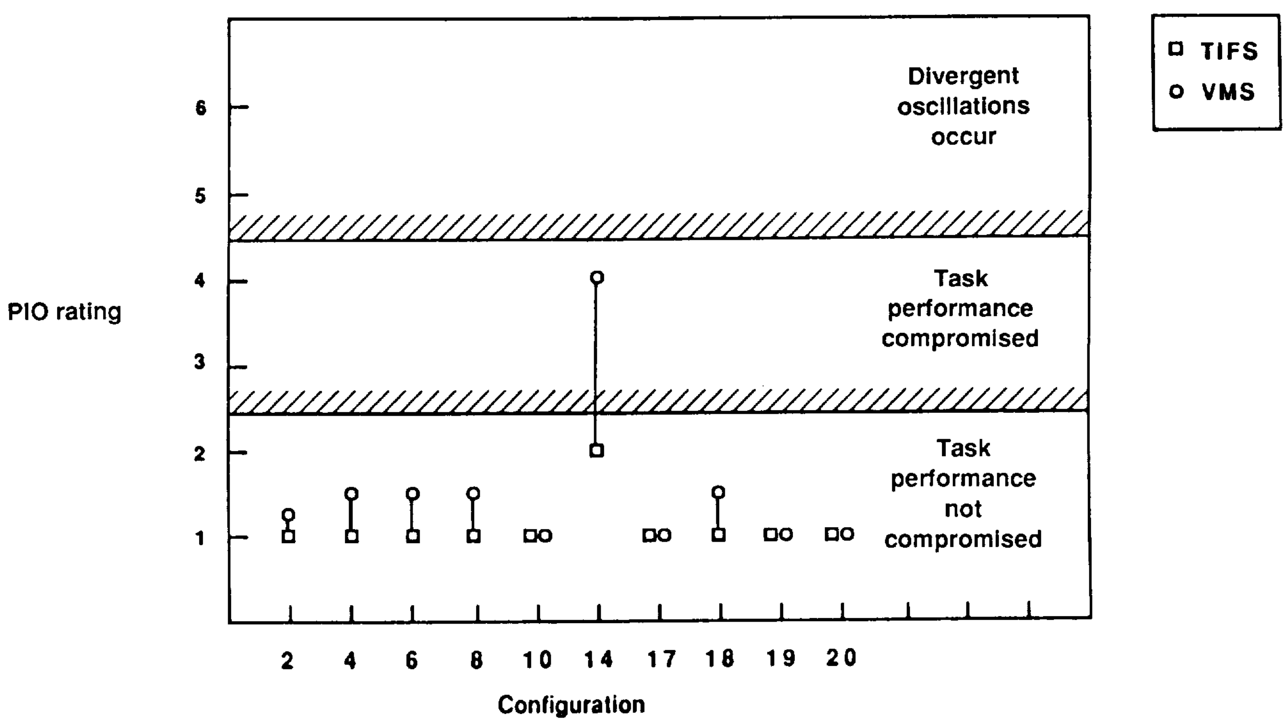


(b) PIO-tendency classification.

Figure 14. Comparison of pilot opinions from the TIFS and VMS for configurations with long-term α_c system for landing-flare pilot task.

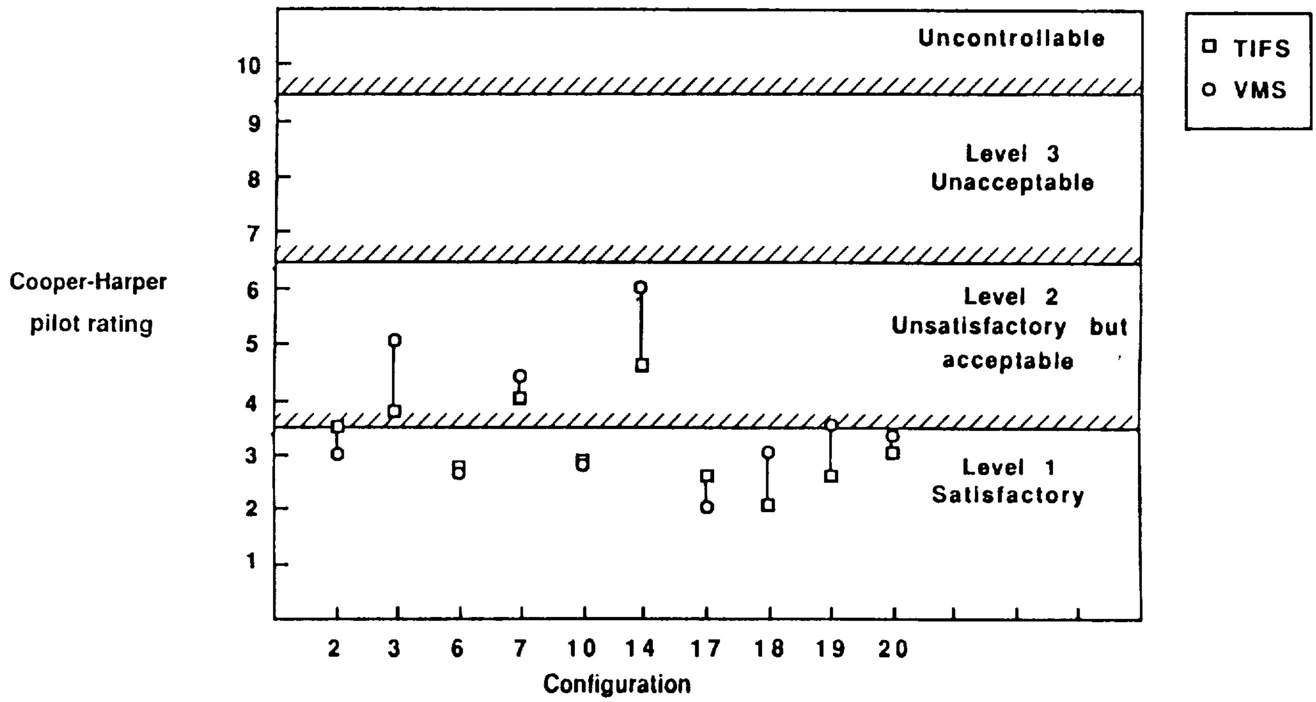


(a) Cooper-Harper pilot ratings.

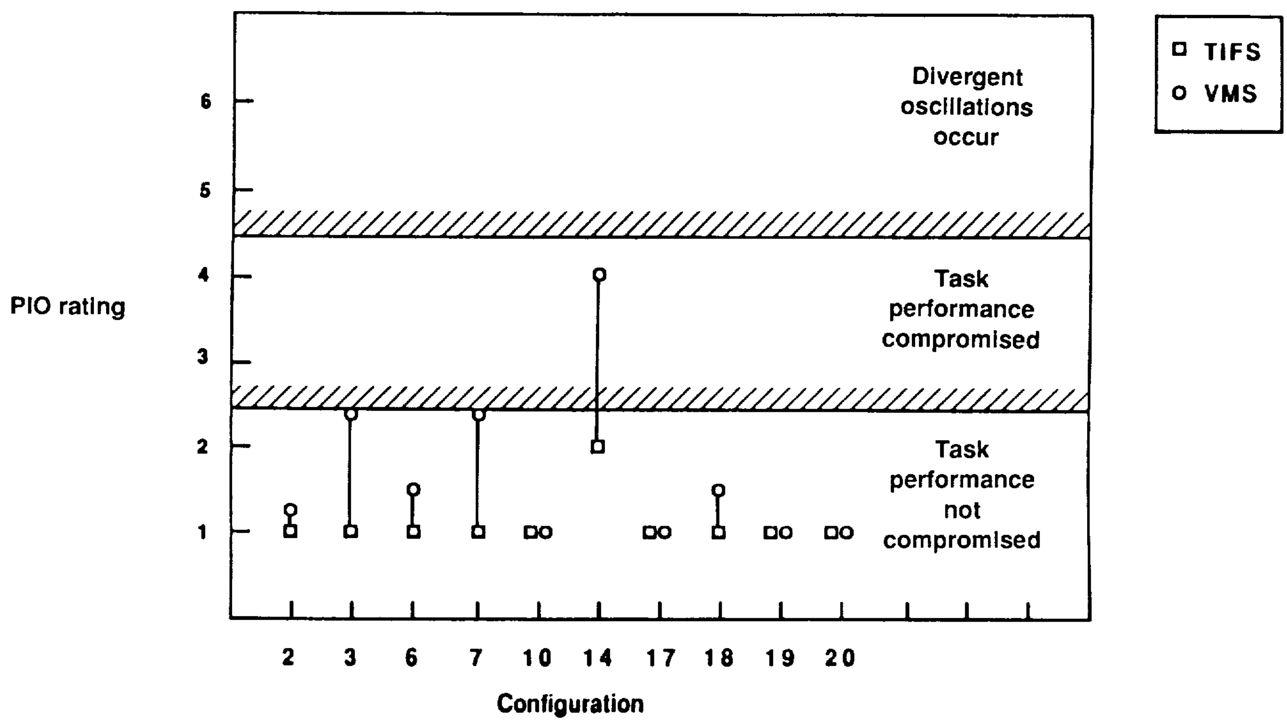


(b) PIO-tendency classification.

Figure 15. Comparison of pilot opinions from the TIFS and VMS for configurations with short-term q_c system for landing-flare pilot task.

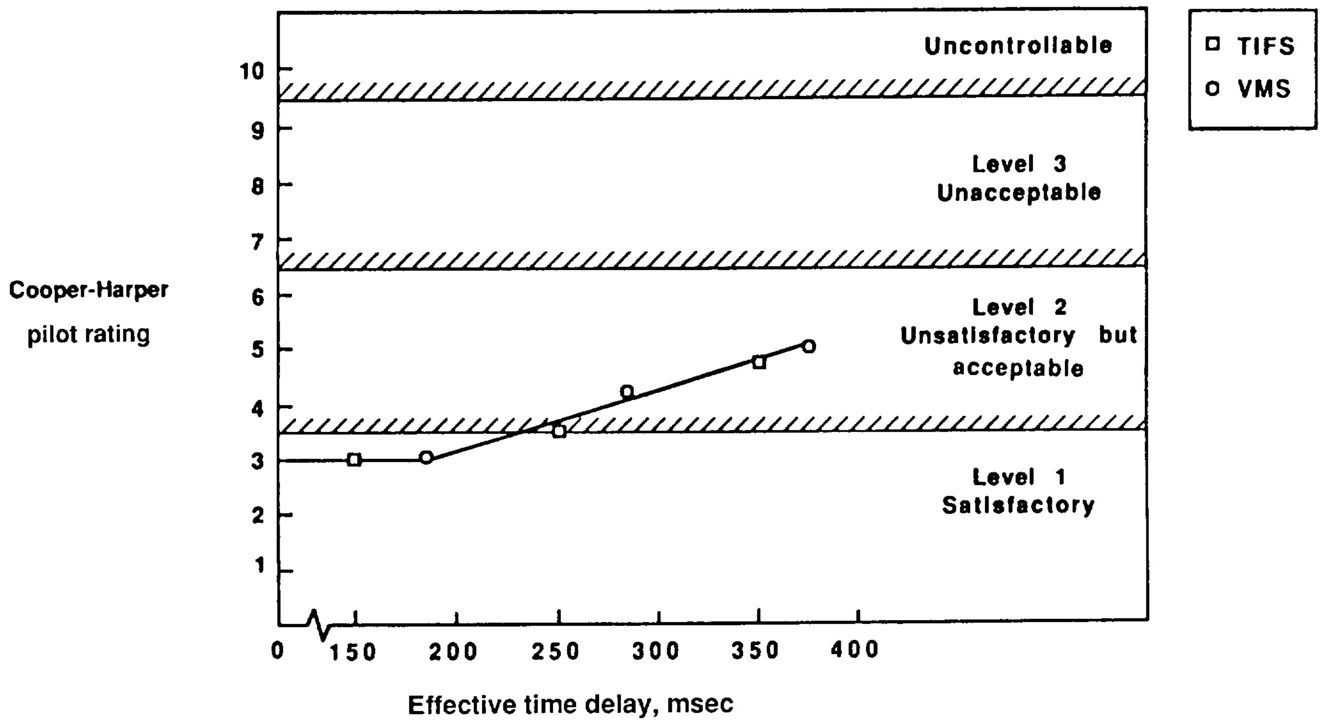


(a) Cooper-Harper pilot ratings.

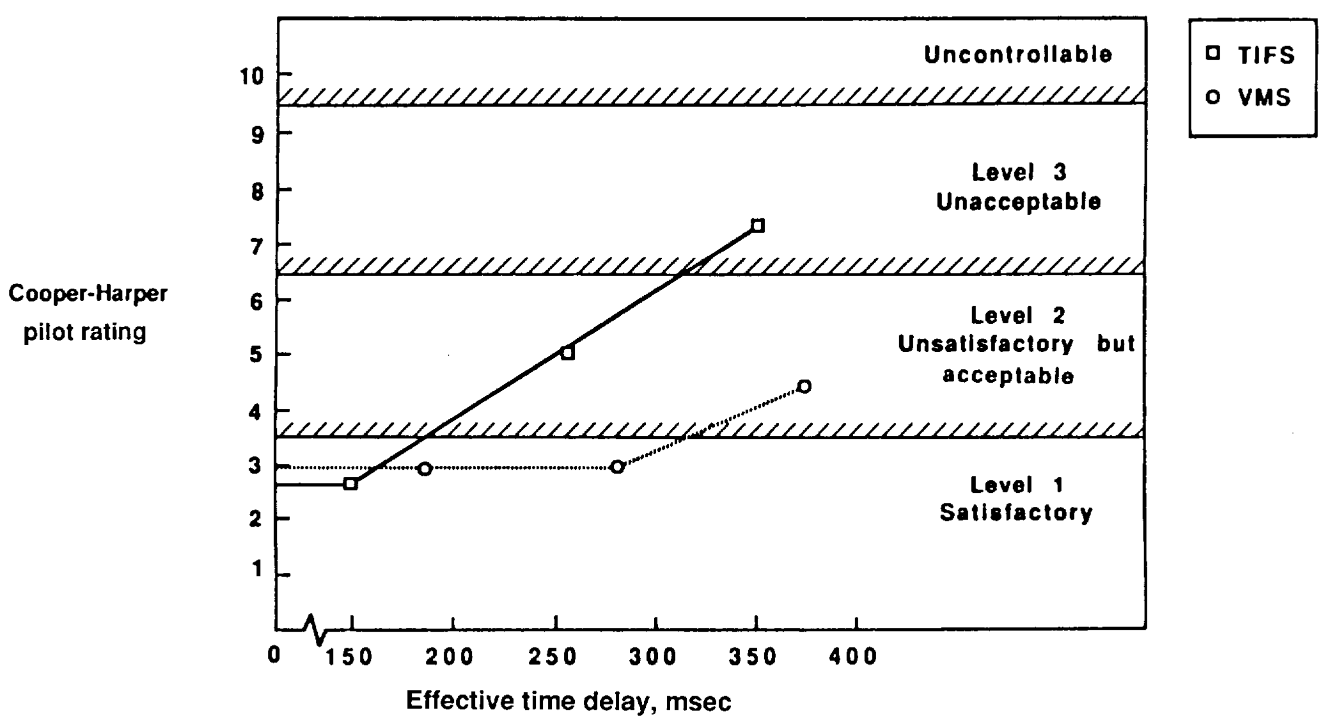


(b) PIO-tendency classification.

Figure 16. Comparison of pilot opinions from the TIFS and VMS for configurations with long-term q_c system for landing-flare pilot task.

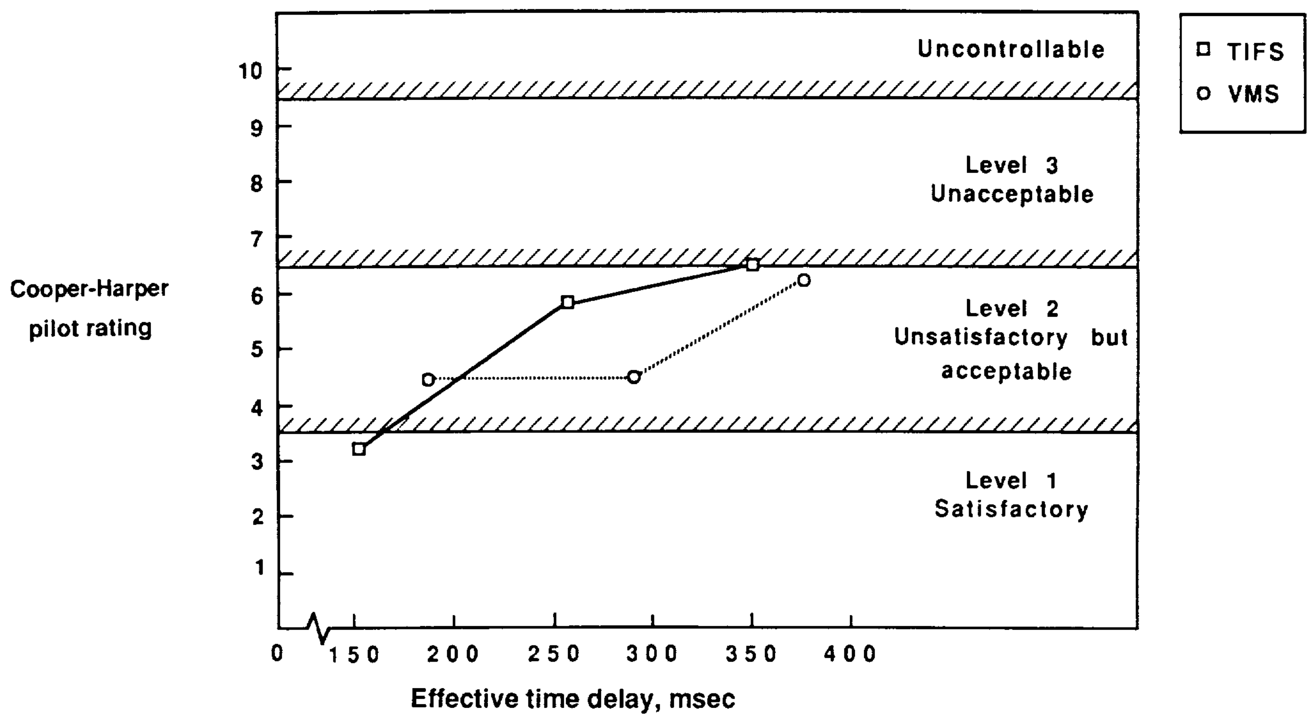


(a) Low sensitivity.



(b) Nominal sensitivity.

Figure 17. Comparison of pilot opinions from the TIFS and VMS for evaluating effects of time delay and control sensitivity for landing-flare pilot task.



(c) High sensitivity.

Figure 17. Concluded.

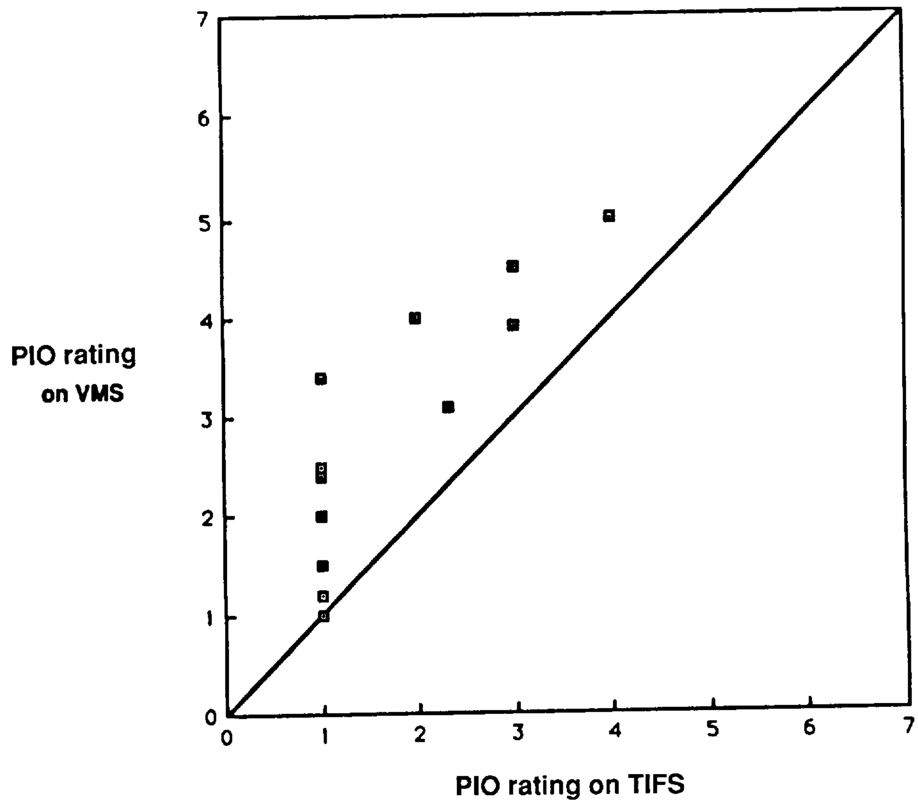


Figure 18. Comparison of PIO-tendency classification between the TIFS and VMS with nominal control sensitivity and no additional time delay. The solid line indicates perfect agreement.

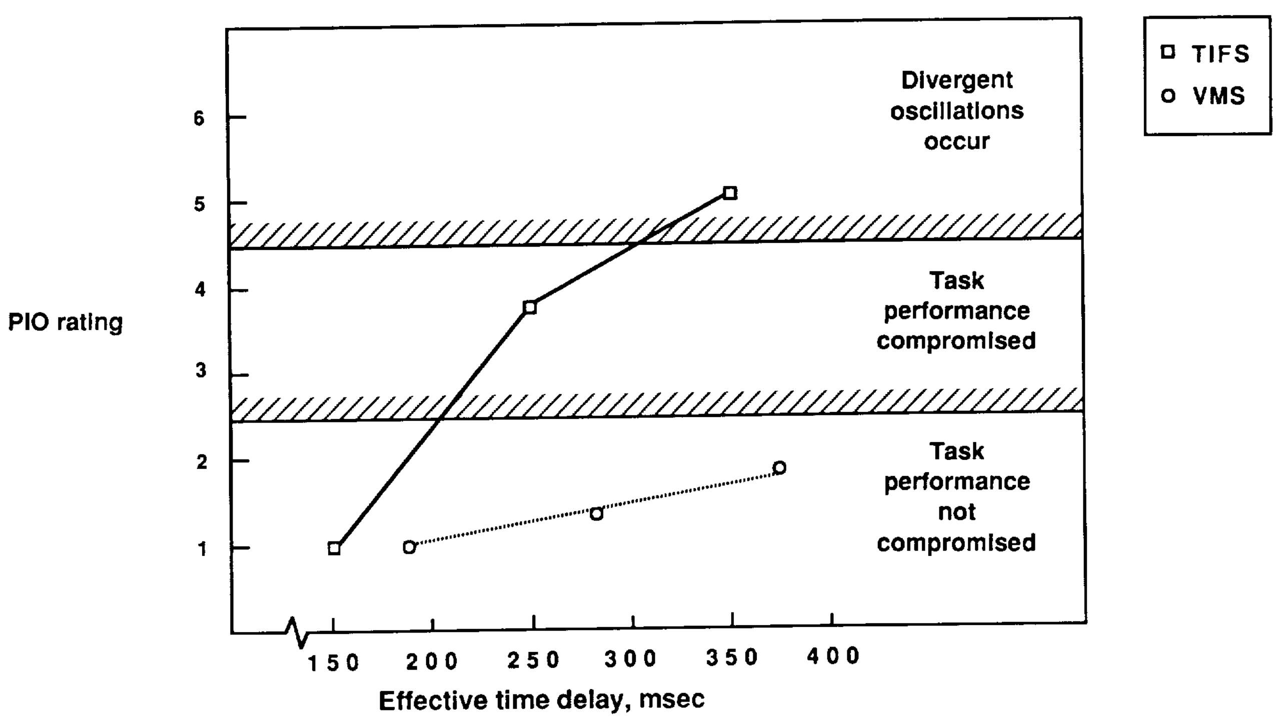
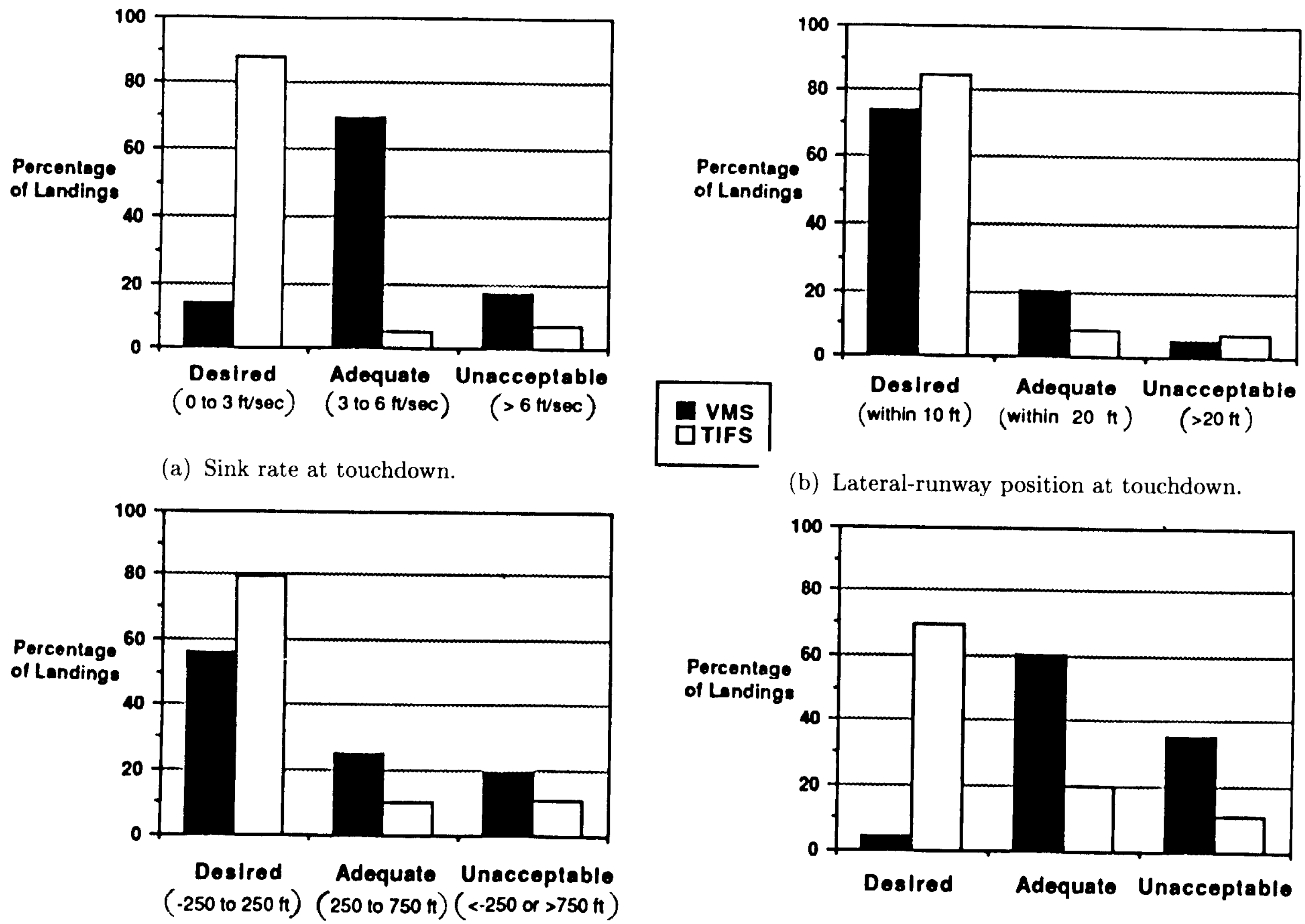


Figure 19. Comparison of PIO-tendency classification between the TIFS and VMS with nominal control sensitivity and variations in control-system time delays.



(a) Sink rate at touchdown.

(b) Lateral-runway position at touchdown.

(c) Longitudinal position at touchdown.

(d) Overall performance at touchdown.

Figure 20. Landing-performance differences between the TIFS and VMS.

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Report Documentation Page

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15. Supplementary Notes

16. Abstract

The primary objective of this paper was to provide information to the flight controls/flying qualities engineer that will assist him in determining the incremental flying qualities and/or pilot-performance differences that may be expected between results obtained via ground-based simulation (and, in particular, the six-degree-of-freedom Langley Visual/Motion Simulator (VMS)) and flight tests. Pilot opinion and performance parameters derived from a ground-based simulator and an in-flight simulator are compared for a jet-transport airplane having 31 different longitudinal dynamic response characteristics. The primary pilot tasks were the approach and landing tasks with emphasis on the landing-flare task. The results indicate that, in general, flying qualities results obtained from the ground-based simulator may be considered conservative—especially when the pilot task requires tight pilot control as during the landing flare. The one exception to this, according to the present study, was that the pilots were more tolerant of large time delays in the airplane response on the ground-based simulator. The results also indicated that the ground-based simulator (particularly the Langley VMS) is not adequate for assessing pilot/vehicle performance capabilities (i.e., the sink rate performance for the landing-flare task when the pilot has little depth/height perception from the outside scene presentation).

17. Key Words (Suggested by Authors(s)) Flying qualities In-flight simulators Ground-based simulators Pilot performance Approach and landing		18. Distribution Statement Unclassified—Unlimited Subject Category 08	
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