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SPACE SHUTTLE PILOT-INDUCED-OSCILLATION RESEARCH TESTING

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SUMMARY

Five approach and landing tests of the space shuttle were made to evaluate low-speed characteristics. During the last flight of this series, a pilot-induced-oscillation (PIO) tendency was noted during the landing. As a result, several piloted simulations were used to evaluate the handling qualities of the orbiter during landing The testing included simulation of the orbiter with a fixed-base ground simulator, with moving-base ground simulations, and with in-flight simulation The two moving-base ground facilities that were used, the flight simulator for advanced aircraft (FSAA) and the vertical motion simulator (VMS), are at the NASA Ames Research Center, Moffett Field, California. The in-flight simulation was performed on the Calspan total in-flight simulator Additional studies on the effect of time delay were performed on the F-8 digital fly-by-wire airplane at NASA Ames-Dryden.

This paper, based on the results of those tests, discusses the simulation requirements for investigation of PIO characteristics during the landing phase The general conclusion is that in-flight simulation is the only reliable method of evaluating the landing characteristics of aircraft with PIO tendencies; even then some form of artificial task needs to be introduced to produce pilot workload levels similar to those encountered in the actual flight environment.

SYMBOLS

ALT	approach and landing test	PIO	pilot-induced oscillation
DFBW	digital fly-by-wire	TIFS	total in-flight simulator
FSAA	flight simulator for advanced aircraft	VMS	vertical motion simulator
L/D	lift-to-drag ratio	τ	time delay, sec

1.0 INTRODUCTION

Five approach and landing tests (ALT) of the space shuttle (Ref. 1) were made to evaluate low-speed characteristics. The orbiter was launched from a B-747 aircraft and the flight regime from about 6100 m (20,000 ft) to touchdown was investigated. The first four landings were on the Edwards dry lakebed and no particular handling problems were exhibited. A tendency for pilot-induced oscillation (PIO) in both pitch and roll was exhibited near touchdown during the fifth landing, which was on the 4570-m (15,000-ft) concrete runway As a result, the cause and significance of the PIO tendency were investigated Analysis indicated that the problem was primarily in the pitch axis, which resulted in rate limiting of the elevons. Because of the priority rate-limiting logic that allocates elevon surface rate for both pitch and roll commands, the rate limiting in the pitch axis produced rate limiting in the roll axis, which resulted in roll oscillations Several piloted simulations were conducted to evaluate the longitudinal landing handling qualities of the orbiter in the ALT configuration and with control system modifications that were developed to improve the landing characteristics (Ref. 2).

The testing included simulation of the orbiter with a fixed-base ground simulator, with moving-base ground simulations, and with in-flight simulation. A fixed-base simulation with a tracking task as the primary maneuver was used to evaluate the PIO characteristics of control system modifications The moving-base ground facilities used were the two high-fidelity simulators at the NASA Ames Research Center, Moffett Field, California the flight simulator for advanced aircraft (FSAA, Ref. 3), and the vertical motion simulator (VMS, Ref 4). The in-flight simulation was performed on the Calspan total in-flight simulator (TIFS, Ref 5). Additional in-flight studies on the effect of time delay were performed on the F-8 digital fly-by-wire (DFBW) airplane at NASA Ames-Dryden (Ref. 6).

The simulation of the landing task has always been difficult, particularly with a vehicle with PIO tendencies. This paper presents some of the results obtained from these tests concerning the simulation requirements for the investigation of PIO characteristics during the landing phase. Pilot evaluations of the PIO characteristics and the handling qualities are presented and compared.

2.0 ORBITER SIMULATIONS

2.1 Background

In 1978, after the ALT experience, a simulation program was conducted to study the cause and significance of the PIO characteristics observed in flight. The study was conducted on the FSAA moving-base simulator (Ref. 3), which has good motion and visual fidelity characteristics A television model-board visual display was used to depict the runway landing scene. In general, the results indicated that the tendency toward PIO was not significant in the normal landing task. In a simulated formation tracking task, there was an indication of a PIO tendency similar to that observed during the ALT flight. At this point, the results were inconclusive There was not a definite PIO tendency in the simulated landing task as had been observed in the ALT flight, but it was not known if this was the result of an inadequate model or of a simulation deficiency. As a result, a flight simulation program was conducted using the Calspan

TIFS to validate the FSAA results. The TIFS (Ref. 5) is an in-flight simulator that can reproduce the six-degree-of-freedom cockpit motions in addition to providing the actual visual scene. This simulation established that the PIO tendencies that were observed in the ALT flight could be reproduced in the in-flight simulator with the predicted model of the orbiter.

Following these simulations, control system improvements were developed and evaluated on a fixed-base simulator using a simple tracking task to evaluate the PIO characteristics. One of these systems was an adaptive stick gain (Ref 7) which was designed to reduce the PIO tendencies. This system reduced the stick gain as the frequency of the pilot inputs approached the frequency of the PIO. After developing this system on the ground-based simulator, another series of simulations was made in 1979 and 1980 with the VMS (Ref. 4) and the TIFS. The VMS was designed to provide very good vertical motion simulation capabilities and has a vertical motion range of ±9 m (30 ft) and an acceleration capability of ±1g. The same visual display that was used on the FSAA was also used on the VMS.

In the following section, these simulations are compared based on pilot ratings of the PIO characteristics and pilot ratings of the handling qualities. During all of these tests, the pilots evaluated the PIO tendencies using the rating scale shown in Fig. 1, they evaluated the handling qualities using the rating scale shown in Fig. 2

2 2 Comparison of Simulator Results

2.2.1 FSAA and TIFS landing evaluations

Normal landings with and without lateral offsets were made in the evaluation of the landing characteristics using the FSAA and TIFS. The results of these two tests are summarized in Fig. 3 in terms of a histogram of the ratings of the PIO characteristics The FSAA ratings of the PIO characteristics indicate that the orbiter had, for the most part, no undesirable pilot-induced motions and only occasional occurrences of undesirable motions On the other hand, the TIFS ratings indicate that undesirable motions are quite prevalent It is clear from this figure that landings using the FSAA produced very little PIO tendency compared to those in the TIFS.

2.2.2 FSAA and TIFS formation task evaluations

The formation tracking task was also evaluated on the FSAA and the TIFS. This task consisted of close formation flying in a simulated aerial refueling position behind the lead aircraft. The objective was to tightly track this position. The results of these tests are shown in Fig. 4. In these cases, both simulations had indications of undesirable motions with PIO ratings around the 3 level. There was excellent agreement between the two simulations in terms of the evaluation of the vehicle PIO tendencies.

2.2.3 Comparison of formation and landing task evaluations

A comparison of the PIO tendencies obtained from the formation tracking task and the landing task with the TIFS is shown in Fig 5. The results indicate that these two tasks produced similar evaluations of the PIO tendencies These results are significant for both ground-based simulation and in-flight evaluations because of the ease and safety in performing formation tracking tasks as compared to performing the actual approach and landing task. Since the ground-based and in-flight simulation results from the tracking task were quite similar, this would suggest that a reasonable preliminary assessment of the PIO potential could be made for the landing condition by using a ground-based motion simulator and a tight-formation tracking task

2 2 4 VMS and TIFS landing evaluations

Three control system configurations were evaluated using the VMS and TIFS. The PIO ratings from these tests are summarized in Fig. 6. The VMS and TIFS correlation is about the same or slightly better than that of the FSAA and TIFS, but there is still a rather significant difference between the moving-base simulation and the in-flight simulation. In both the VMS and TIFS tests, a very demanding task was used to accentuate the PIO tendencies. A 45-m (150-ft) lateral offset was performed at 30 m (100 ft) above the runway and a 4.6-m/sec (15-ft/sec) vertical gust was introduced at an altitude of about 15 m (50 ft). This produced a task that would be unreasonable to expect in actual landings, but it did provide a situation that produced a pilot gain high enough to make the PIO tendencies of the vehicle apparent to the pilot. On both of these simulators, a normal straight-in approach and landing could be made with little evidence of a PIO tendency after the pilot became familiar with the simulator.

Although the PIO tendencies were not the same for the two simulations, the ratings of the basic handling qualities were quite similar. The pilot ratings for the previous three configurations are shown in Fig. 7. The pilot rating distributions are quite similar, and the average pilot ratings are within 1/2 of a pilot rating of each other. This agreement may be fortuitous, however. The pilot comments generally indicated that PIO was a significant concern in addition to the flightpath control for the in-flight simulations, whereas the flightpath control alone was the dominant factor in the ground simulations. It appears that the ground simulations are adequate to assess the lower workload tasks associated with flightpath control, but the evaluation of the higher frequency, higher workload tasks require the fidelity of inflight simulation.

2.2.5 Fixed-base simulator tracking task evaluations

The correlation between the tracking task and the landing task evaluations has proved extremely useful in the evaluation of alternate control system concepts for the orbiter since the PIO tendencies can be evaluated on a relatively simple fixed-base simulation using the tracking task. The tracking task does not provide any information about the adequacy of the response characteristics for the actual landing task, but only gives an indication of the PIO tendencies The task for the fixed-base ground simulation studies was to rapidly stabilize on a target that was initially displaced. Ten seconds was allowed for this task.

To more nearly simulate an actual landing situation, it was also required that the pilot not overshoot the target, as would be required if the target represented the ground plane.

The closed-loop response characteristics are a function of the pilot gain and lead compensation and of the distance between the tracking aircraft and the target. The closed-loop response results in two modes of interest a relatively high frequency mode associated with pitch attitude response, and a lower frequency mode associated with flightpath reponse. The procedure used in the fixed-base simulation was to adjust the target distance and the time available for the task so that the closed-loop frequencies seen on the simulator matched those seen in the shuttle ALT flight tests. This resulted in a tracking distance of 30 m (100 ft) and a 10-sec time span for acquiring and stabilizing on the initially displaced target. With this task, the PIO conditions observed in flight could be repeatedly reproduced, which made it feasible to evaluate control system changes with a relatively simple simulation. This technique was very useful in developing an adaptive stick gain algorithm that was used to reduce the PIO tendencies of the orbiter (Ref. 7). It should be noted, however, that this technique is of significant value only for evaluating PIO characteristics that have already been observed in flight, because the flight-observed frequencies are required to tune the task.

3.0 F-8 DIGITAL FLY-BY-WIRE AIRCRAFT TESTS

One of the main causes of the pitch attitude PIO is the interaction of time-delay and high bandwidth requirements In an effort to study this effect, flight tests were conducted using the F-8 digital fly-by-wire airplane (Ref. 6). The experiment consisted of several tasks The two of most interest were the high-workload case in which the pilot was attempting to land precisely on a designated area of the runway, and the low-workload case where the pilot was attempting to land on the runway without any concern for the actual touchdown point.

The task was set up to simulate the low lift-to-drag ratio (L/D) approach and landing of the shuttle Approaches were initiated at 260 KIAS, 1460 m (4800 ft) above ground level, about 10 km (6 mi) from touchdown point. A speed of 260 KIAS was maintained until 150 m (500 ft) above ground level. The outer glideslope was approximately 10° Flare was initiated 150 m (500 ft) above ground level. A glideslope of approximately 1° was intercepted about 30 m (100 ft) above ground level. Aim touchdown speed was 190 KIAS; actual touchdown speeds were between 180 and 210 KIAS The outer glideslope aim point was about 1.6 km (1 mi) from the runway threshold.

All landings were made on a concrete runway 4600 m (15,000 ft) long and 90 m (300 ft) wide. The evaluation terminated at touchdown, and a go-around initiated. Normal landings were made from straight-in approaches with no particular aim touchdown point Because of the generous proportions of the runway, these landings caused relatively little workload for the pilot The low L/D spot landings from the lateral offset consisted of an approach in line with the edge of the runway, followed by an offset maneuver initiated at 30 m (100 ft) above the ground to align with the runway centerline, and a touchdown at the 1500-m (5000-ft) marker. The lateral offset increased the pilot's workload and stress, providing a more demanding landing task.

After the ALT tests, the orbiter landing technique was changed to make the task easier. This was accomplished by relating the touchdown point to velocity rather than to a fixed point on the runway This reduced the need for high bandwidth control and made the task more similar to the low-workload-task case evaluated in the F-8 DFBW tests. The results of the F-8 tests are shown in Fig. 8 along with the results from the TIFS evaluation of the orbiter. For the orbiter time-delay values of approximately 0.2 sec, the effect of task is significant, it appears that the current operational procedures for the orbiter produce a task that is between the low- and high-workload tasks of the F-8 tests The results also indicate that the task plays a key role in any attempt to assess handling qualities during landing when there is a PIO tendency present.

In addition to the landing task, a formation tracking task was evaluated. It consisted of a simulated aerial refueling task with the airplane initially stabilized 5 to 12 m (15 to 40 ft) below the refueling position. The objective was to rapidly acquire the refueling position and then tightly maintain that position. A comparison of the formation tracking task results with the landing task results is shown in Fig. 9. The tracking task produced pilot ratings between those for the normal- and high-workload landings In this case, unlike the shuttle TIFS results, the tracking task did not produce as much of a degradation due to time delay as the landing task This could be partially due to the realistic landing task of the F-8 experiment. Because the F-8 is a single-seat aircraft with no reset button such as in the TIFS (the time delay could be removed by a push of a button, however), this experiment produced a real-world, high-workload task that cannot be duplicated in any other type of simulation. This produces very high quality results, but high-workload tasks near the ground have an associated high risk The workload induced by the task is real

4.0 CONCLUDING REMARKS

During the approach and landing tests of the space shuttle, a pilot-induced-oscillation (PIO) tendency was noted during the landing. As a result, several piloted simulations were used to evaluate the handling qualities of the orbiter during landing The testing included simulation of the orbiter with fixed-base ground simulators, with moving-base ground simulations, and with in-flight simulation. The two moving-base ground facilities used were the flight simulator for advanced aircraft (FSAA) and the vertical motion simulator (VMS) at the NASA Ames Research Center, Moffett Field, California. The in-flight simulation was performed in the Calspan total in-flight simulator (TIFS) The F-8 digital fly-by-wire (DFBW) airplane at NASA Ames-Dryden was used for additional studies on the effect of time delay

These tests have shown that the ability to assess the PIO characteristics of the shuttle during landing is significantly different for moving-base ground simulation as compared with in-flight simulation. The general conclusion from these tests is that flight simulation is the only reliable method of evaluating the landing characteristics of aircraft with PIO tendencies, and even then some type of artificial task must be introduced to produce pilot workload levels similar to those that can be encountered in

flight. A formation tracking task seemed to offer a better means of identifying PIO tendencies with ground simulation than the landing task did. This technique was used in the development of alternate control system concepts designed to reduce the PIO tendencies. The simulation of the landing task has always been difficult, but it has become more difficult because of the requirement to duplicate PIO characteristics. The simulation, no matter how realistic, does not produce the same sense of urgency as does the flight environment. The accurate representation of PIO-prone aircraft in the landing flight regime remains a challenge to the ground-based simulation facilities.

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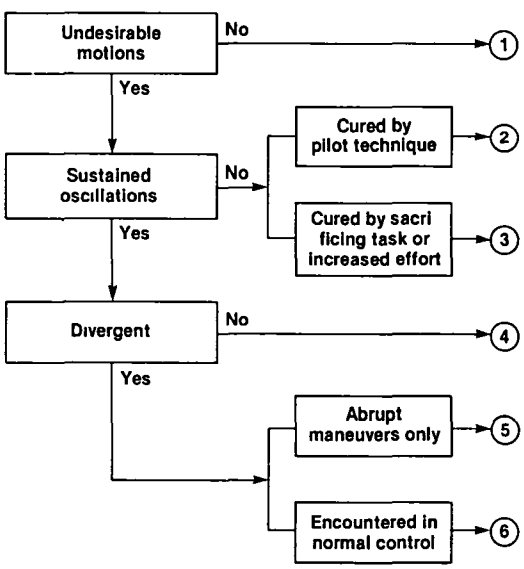


Figure 1. PIO rating scale.

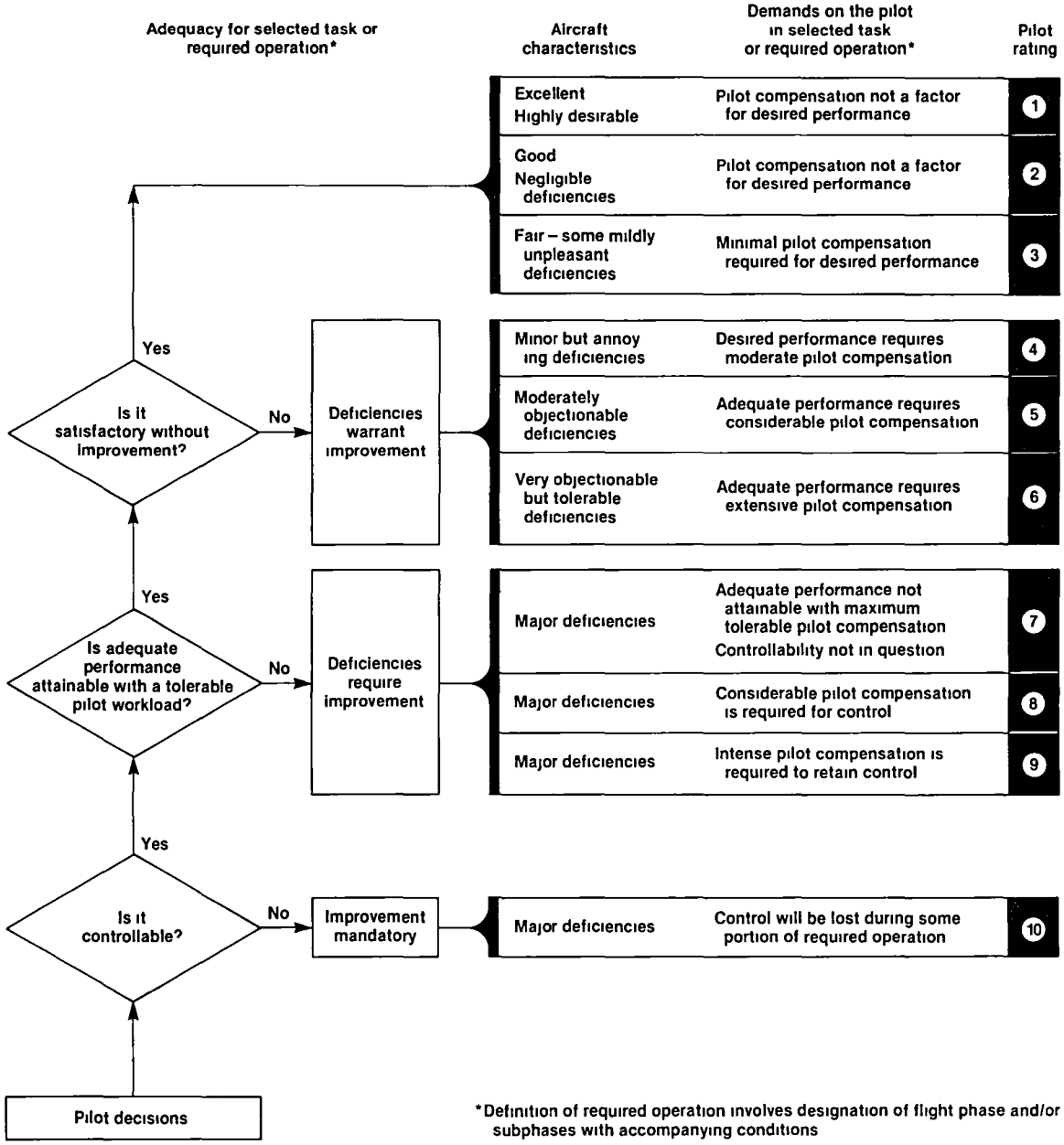


Figure 2. Handling qualities rating scale.

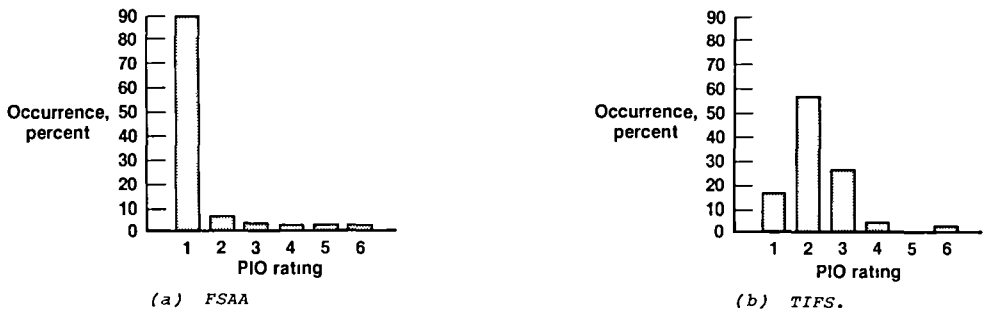
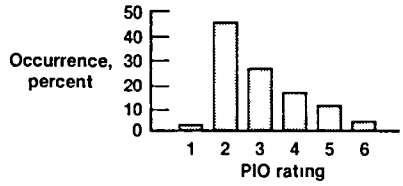
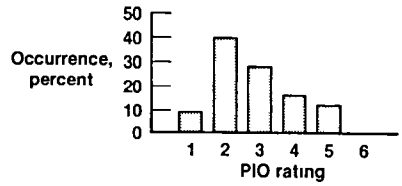


Figure 3. FSAA/TIFS landing task PIO rating comparison Shuttle ALT configuration.

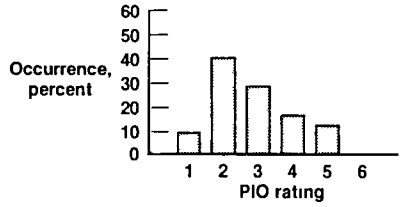


(a) FSAA.

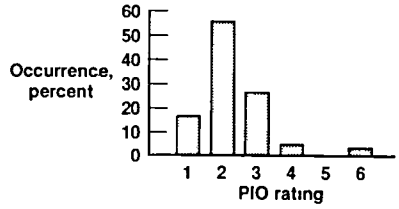


(b) TIFS.

Figure 4 FSAA/TIFS formation tracking task PIO rating comparison. Shuttle ALT configuration

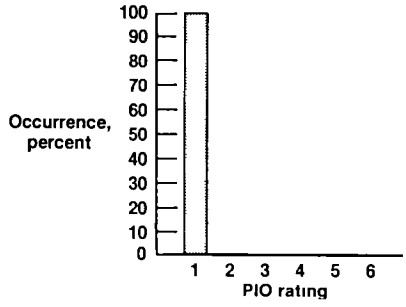


(a) Landing task

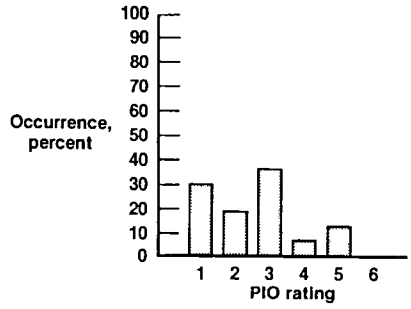


(b) Formation tracking task.

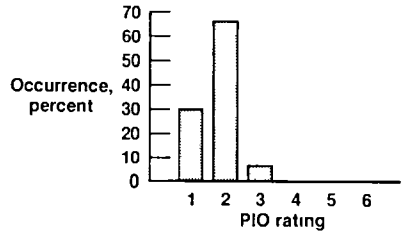
Figure 5 TIFS landing and formation tracking task PIO rating comparison Shuttle ALT configuration.



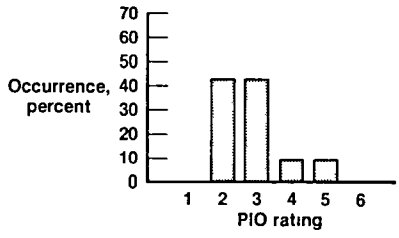
(a) VMS, configuration A



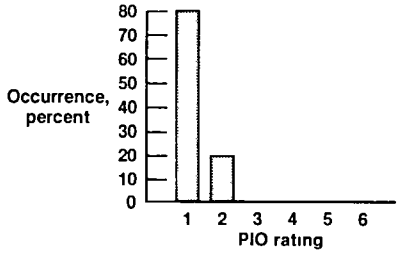
(b) TIFS, configuration A.



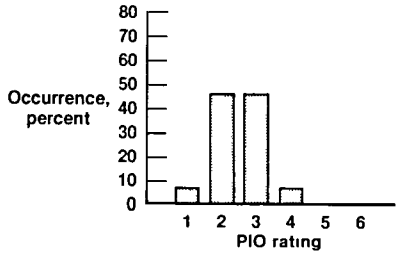
(c) VMS, configuration B.



(d) TIFS, configuration B.

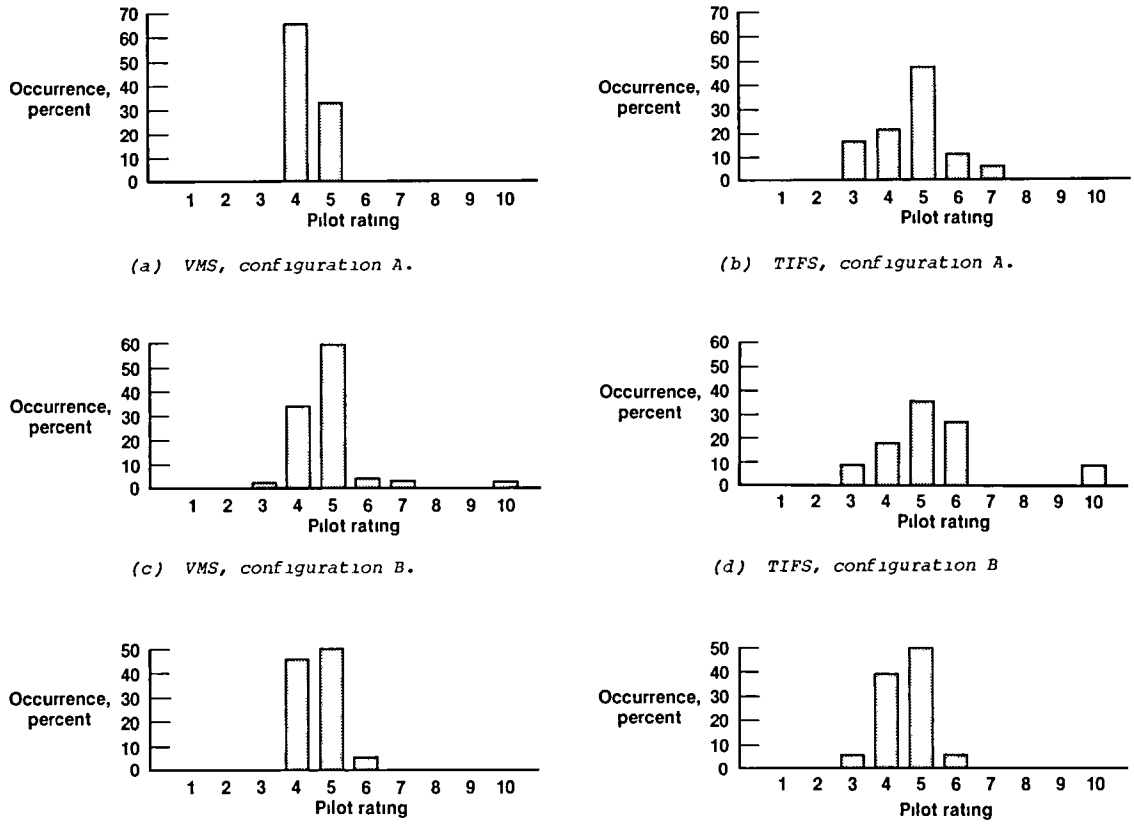


(e) VMS, configuration C



(f) TIFS, configuration C

Figure 6 VMS/TIFS landing task PIO rating comparison



(a) VMS, configuration A.

(b) TIFS, configuration A.

(c) VMS, configuration B.

(d) TIFS, configuration B

(e) VMS, configuration C.

(f) TIFS, configuration C.

Figure 7 VMS/TIFS landing task pilot rating comparison.

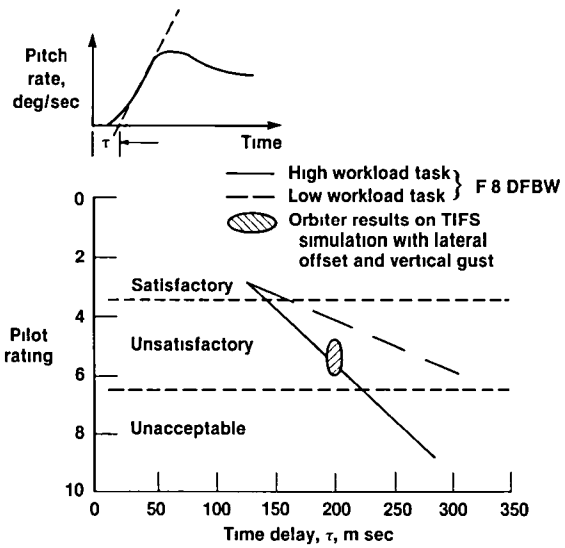


Figure 8. Results of the F-8 time-delay study for the landing task.

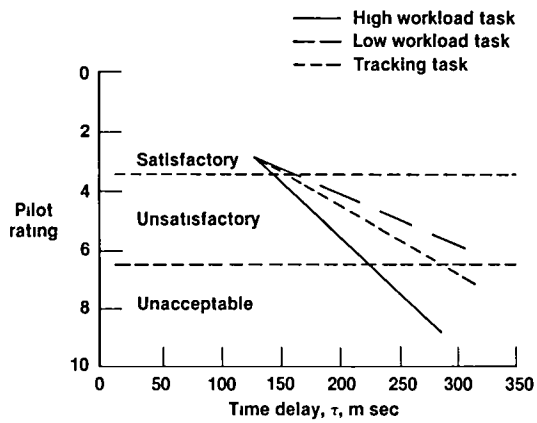


Figure 9. Comparison of the formation tracking task and the landing task for the F-8 time-delay study

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16 Abstract

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