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LOW-SPEED LONGITUDINAL ORBITER FLYING QUALITIES

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ABSTRACT

The shuttle program took on the challenge of providing a manual landing capability for an operational vehicle returning from orbit. Some complex challenges were encountered in developing the longitudinal flying qualities required to land the orbiter manually in an operational environment. Approach and landing test flights indicated a tendency for pilot-induced oscillation near landing. Changes in the operational procedures reduced the difficulty of the landing task, and an adaptive stick filter has been incorporated to reduce the severity of any pilot-induced oscillatory motions. Fixed-base, moving-base, and in-flight simulations were used for the evaluations, and in general, flight simulation has been the only reliable means of assessing the low-speed longitudinal flying qualities problems. Overall, the orbiter control system and operational procedures have produced a good capability to routinely perform precise landings with a large, unpowered vehicle with a low lift-to-drag ratio.

INTRODUCTION

The flying qualities task of manually landing an unpowered vehicle with a low lift-to-drag ratio (L/D) is a difficult one and has been a subject of NASA research for many years. One of the first flight programs to seriously address the problems associated with an entry from orbit was the X-15 research airplane program from 1959 to 1968. The objectives of the X-15 program included an evaluation of unpowered landings from the last part of an entry from orbit to touchdown. The program consisted of 199 flights, with routine landings made on the Edwards dry lakebed. After the X-15 program, a series of lifting body configurations, which were more representative of the aerodynamic configurations that would be required for entry, were evaluated in the terminal area and landing phases. Two landings were made during the program on the 4570-m (15,000-ft) concrete runway. These early vehicles were quite small and simple in design. The control systems generally consisted of only angular rate feedbacks since the vehicles had aerodynamic static stability. The guidance system consisted of ground controller calls based on radar tracking of the flightpath. Nonetheless, the lifting body program demonstrated the feasibility of having a pilot make a manual landing of an unpowered entry vehicle with a low L/D on a conventional runway.

From this modest beginning, the shuttle program took a bold and pioneering step to produce a vehicle that would return from orbit and land on a conventional runway. To meet this goal would require an entry vehicle with an operational capability to land day or night in all types of weather using a 4570-m (15,000-ft) runway. The low-speed longitudinal control system was further complicated by the requirement for a center-of-gravity position that ranged from statically stable to statically unstable. At the time the orbiter was designed, the flying qualities data base was limited for aircraft with advanced control systems similar to that required to meet the orbiter design requirements. Little experience existed in the use of high-gain, digital flight control systems for statically unstable aircraft, and the influence of the time delay between the pilot input and the airplane response would not be fully appreciated until much later, based on experience with the orbiter and highly augmented fighter aircraft. In general, the flying qualities design criteria reflected experience with more conventional airplanes which only required very simple control systems.

This paper discusses some of the complex challenges encountered in developing the longitudinal flying qualities required to land the orbiter manually in an operational environment. The results of tests that have led to modifications are discussed, as well as the results of some additional testing that may lead to further control system modifications. These studies have included fixed-base, moving-base, and in-flight simulation. Some of the simulation techniques required to examine the low-speed longitudinal flying qualities problems are also addressed.

OPERATIONAL TECHNIQUE FOR MANUAL LANDING CAPABILITY

The most significant task in an unpowered vehicle is that of energy management. In the terminal area phase, the orbiter's speedbrakes are used in conjunction with angle of attack and S-turns to put the orbiter in approximately the correct energy state at the start of the landing phase at an altitude of about 3700 m (12,000 ft). The first part of the landing phase (fig. 1) is devoted to the final energy management maneuver and consists of a steep glide slope (approximately 20°) with a fixed aim point relative to the runway and a constant equivalent airspeed. The objective of this phase is to reach an energy window at about 610 m (2000 ft) above the runway with the correct speed and flightpath.

Since there is no active energy management below this point, the steep glide slope maneuver becomes the critical energy management task for both the manual and automatic landings. The pitch-axis task has several levels of automation, depending on the guidance information. With the normal navigational and guidance information available, the glide slope can be tracked in the autopilot mode or the manual control mode. In the manual mode, the task consists of manually tracking the guidance command information displayed to the pilot on the flight director. If no guidance information is available, the glide slope can be established visually using a light-beam system on the ground. In all cases, the speed can be maintained by manual or automatic modulation of the speedbrakes.

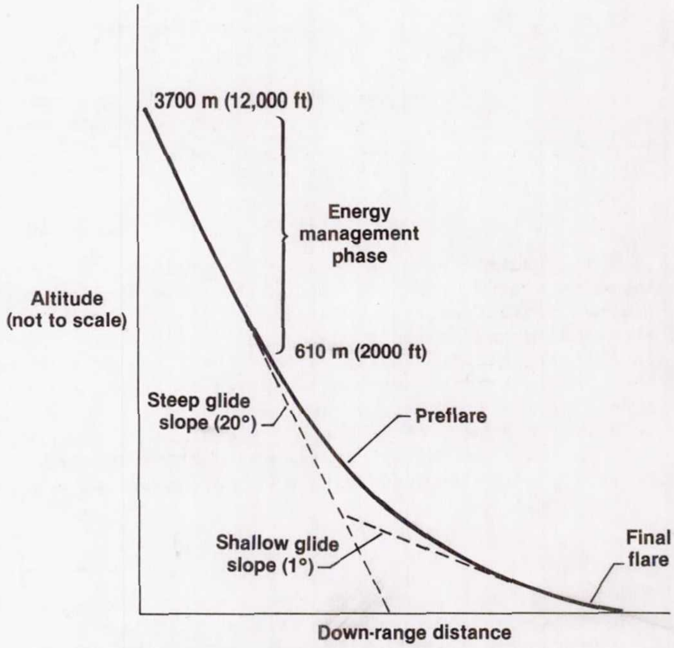

Figure 1. Landing trajectory.

Having established the proper energy, the final landing phase is begun at about 610 m (2000 ft) above the runway. Again, there are several levels of automation available: the autopilot mode; the flight director mode, which when combined with the heads-up display provides guidance information until touchdown; and the completely manual mode, in which the landing is made using the normal visual and motion references. A 1.2 to 1.5g flare is used to transition from the steep glide slope to a glide-slope angle of about 1°. In addition to the visual and acceleration cues, the pilot has cockpit displays of pitch-rate information to assist in establishing the initial pitch rate during the flare. The final glide slope is quite shallow, and a small final flare is made to reduce the rate of sink to a desirable level. The flare to touchdown is often made as one continuous maneuver without actually establishing the final glide slope. This operational technique provides an extremely versatile capability for establishing the desired touchdown conditions under all types of normal and contingency situations.

APPROACH AND LANDING TESTS

In 1977, the low-speed characteristics of the orbiter were evaluated in flight during the approach and landing test (ALT) program. The first four landings were on the Edwards dry lakebed; the fifth landing was on the 4570-m (15,000-ft) concrete runway. These tests validated the concept of landing a large, low L/D vehicle on a standard runway. In general, the flying qualities were quite good. The normal acceleration control in turns was good, although the vehicle was very responsive in pitch, which combined with the light stick forces made pitch control sensitive. The tests were not without problems, however. On the fifth flight (the concrete runway landing), a tendency for pilot-induced oscillation (PIO) in both pitch and roll was exhibited near touchdown. Postflight analysis indicated that the problem, which was primarily in the pitch axis, resulted in rate limiting of the elevons. Because of the priority rate limit 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, resulting in the roll oscillations.

Although this series of flights demonstrated the landing capabilities of the orbiter, it also indicated that additional work would be necessary to make the longitudinal flying qualities satisfactory for the manual landing task. In particular, there was a need to evaluate the cause and significance of the PIO tendencies observed in the ALT flights. In the following sections, the general nature of the longitudinal control problem is discussed, as well as some of the modifications that have been evaluated.

LONGITUDINAL CONTROL CHARACTERISTICS

The shuttle orbiter has two modes that affect longitudinal control. The first mode is pitch attitude control. A major factor contributing to pilot-induced oscillatory motions in this mode is the effective time delay between the pilot input and the airplane response. The actuators contribute a significant delay, as they do on most aircraft. The structural and smoothing filters, which are required because of the high-gain feedback control system, contribute additional significant delays. The digital control system also contributes delay because of the average sampling time and the computation time. A second factor that contributes to pitch attitude PIO tendencies is the nonlinear stick gearing, which is a method of obtaining good sensitivity around the neutral stick position while retaining a good maximum pitch rate or normal acceleration capability. Unfortunately, in any kind of oscillatory maneuver, any divergence results in increased stick inputs, which increases the effective pilot/stick gain caused by the nonlinear stick. As a result, there is an inherent tendency for oscillations to diverge rapidly once a slight divergence occurs. In simulations of the PIO it is interesting that there were almost no instances of slowly divergent oscillations. If the oscillation began to diverge, it rapidly became a fully developed PIO, resulting in loss of control.

The second mode involved in longitudinal control is altitude or flightpath control. A primary factor that makes altitude control difficult is the loss of lift caused by elevon deflection. Because of this factor, a nose-up pitch command initially results in a downward acceleration at the center of gravity (fig. 2). At the pilot location, which is near the center of rotation, there is a delay of approximately 0.5 sec before any motion is detected by the pilot. This delay, in combination with the sluggish rise time of the acceleration to its steady-state value, makes it difficult for the pilot to accurately control altitude. The high cockpit location and poor visibility also contribute to the inability of the pilot to accurately judge altitude, especially near touchdown.

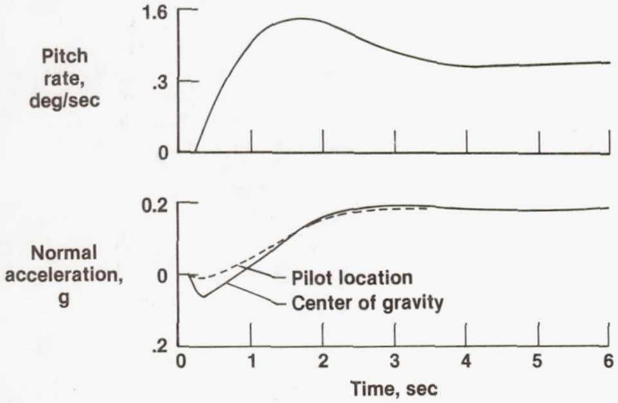

Figure 2. Response characteristics of the orbiter for a step pilot input. Airspeed = 190 knots.

These two modes have been examined in terms of a pilot closed-loop system with a pitch-attitude inner loop and an altitude outer loop (ref. 1). Regions of stability as a function of pilot gain are shown in figure 3 for several magnitudes of control input and indicate that because of the nonlinear stick gearing, stability decreases as stick deflection increases. The Neal/Smith analysis technique of reference 2 has also been used to analyze the closed-loop attitude control; the results are shown in figure 4 in terms of the amount of pilot lead and the amount of resonance experienced for various amounts of closed-loop bandwidth. As the task becomes more demanding, the pilot tries to increase the pilot-vehicle bandwidth to get better response. The pilot lead required is generally indicative of the amount of pilot workload, and the resonance is a measure of the degree of the PIO tendencies. Figure 4 shows that the

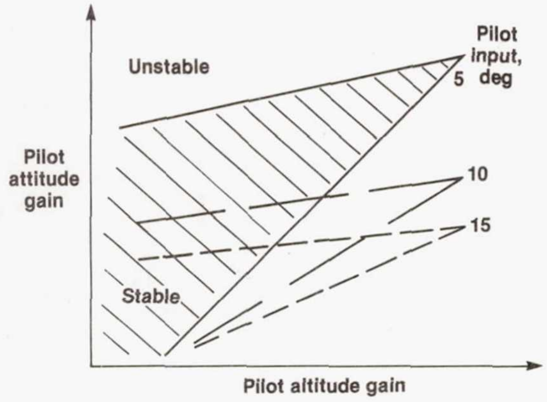

Figure 3. Effect of nonlinear stick gearing on pilot-vehicle closed-loop stability.

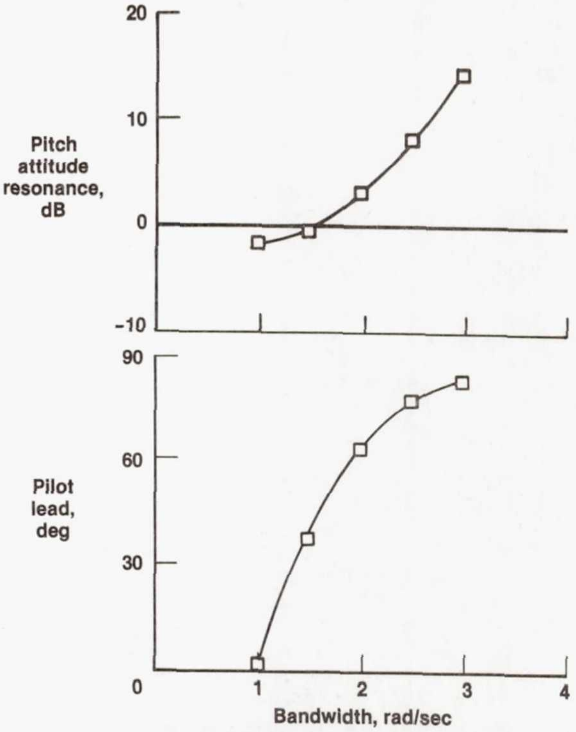

Figure 4. Pilot-vehicle closed-loop characteristics using Neal/Smith analysis of reference 2.

orbiter has reasonably good handling qualities for low bandwidths, but as the bandwidth increases, there is an increase in the pilot lead required and a sharp increase in the PIO tendency.

DEVELOPMENT OF THE STS-1 CONFIGURATION

After the ALT flights, two approaches were pursued to improve the landing characteristics. The first was to make the task easier, thus reducing the need for large values of closed-loop bandwidth; the second was to reduce the tendency toward PIO when large bandwidths were used.

TIME-DELAY AND TASK EFFECTS

One of the main causes of the pitch attitude PIO is the interaction of time delay and high-bandwidth requirements. To study this effect, a series of flights was flown using the Dryden F-8 digital fly-by-wire (DFBW) airplane (ref. 3). The two landing tasks 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 concern for the actual touchdown point. A steep glide slope about half that of the orbiter was used for both cases, and the high-workload case had a 46-m (150-ft) lateral offset at 30 m (100 ft) above the runway. The spot-landing case was similar to the conditions for the ALT flights. After the ALT flights, the orbiter landing task was made easier by basing the touchdown point on velocity rather than a fixed point on the runway. This technique reduced the need for high-bandwidth control and made the task more like the low-workload task evaluated in the F-8 DFBW tests.

The results of the F-8 tests are shown in figure 5 along with the results from the total in-flight simulator (TIFS) orbiter simulation. For orbiter time-delay values of approximately 235 msec, the effect of task is quite significant, and 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. These results also indicate that time delay can cause a significant degradation in handling qualities when a high-workload task is performed. Interestingly, these same results were confirmed in a study of the standard approach task for fighter aircraft (ref. 4). This study was instigated as a result of difficulties with handling qualities in the landing phase for several of the latest generation of fighter aircraft. These aircraft have control systems similar to the control system of the orbiter, with high-gain feedback systems requiring structural bending filters and other filters that introduce significant time delays. The results for the fighter aircraft in the landing task were essentially the same as for the high-workload task of the F-8 study. These tests have contributed significantly to the understanding of time-delay effects in modern aircraft, and the results have now been incorporated into the current specifications for military aircraft.

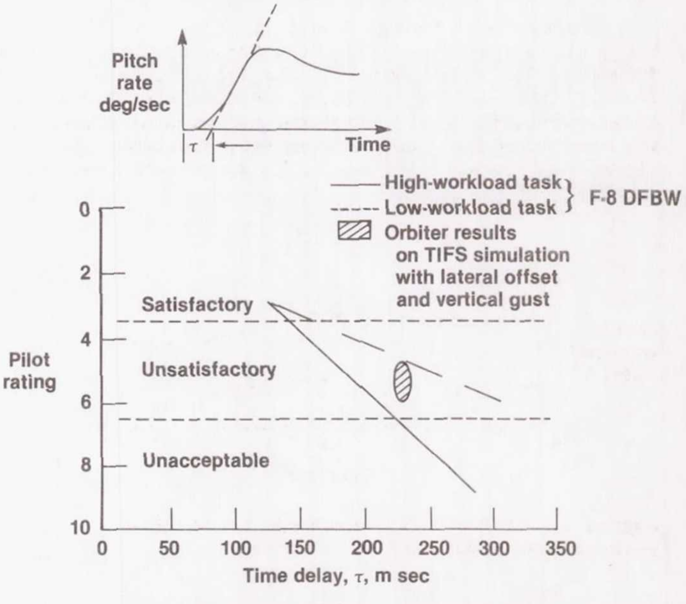

Figure 5. Time-delay effects obtained from orbiter simulations and from the F-8 flight tests of reference 1.

PIO FILTER

To reduce the possibility of developing a large-amplitude pilot-induced oscillation near the ground, an adaptive stick gain was developed (refs. 5 and 6). This system can best be thought of as a closed-loop bandwidth limiter. The relationship of resonance to bandwidth (fig. 4) shows that it would be highly desirable to restrict the pilot to bandwidths less than 3 rad/sec to avoid large-amplitude oscillations. The adaptive stick gain algorithm consists of a frequency detector combined with variable stick shaping (fig. 6). The PIO filter reduces the stick gain by reducing the parabolic portion of the stick gearing so that at its maximum amount of reduction, the stick is very nearly linear (fig. 7). By reducing the overall pilot/stick gain, the PIO tendency is reduced and, in addition, the more linear stick gain reduces the divergent nature of the PIO caused by the nonlinear stick. Tests on the TIFS demonstrated the capability of reducing the PIO tendencies of the orbiter in high-workload situations.

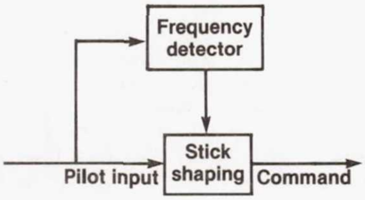

Figure 6. Adaptive stick-gearing concept to reduce PIO tendencies (ref. 6).

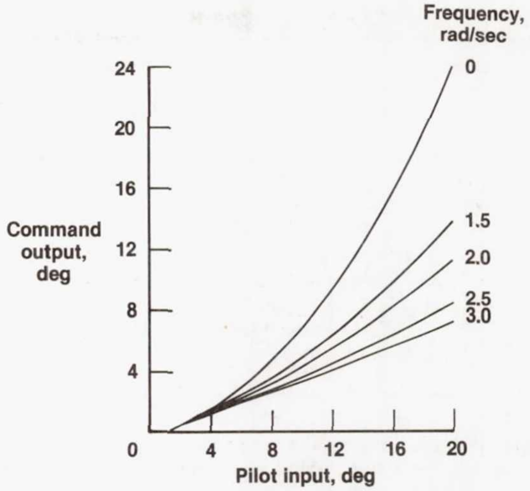

Figure 7. Example of frequency-dependent stick shaping.

The PIO filter does not significantly improve the flying qualities of the orbiter, but it does provide some protection from potentially dangerous, large-amplitude oscillations near the ground.

Another modification was to increase the stick force gradient by a factor of two. This decreased the pitch sensitivity, thus reducing inadvertent inputs. It also improved the pilot's awareness of impending PIO situations. In the orbiter, there are almost no acceleration cues because of the location of the center of rotation, and the visual cues of attitude are limited because of pilot location. As a result, the pilot would not be aware of any oscillatory motion until the amplitude grew large. With the increased stick forces, the types of inputs that generate PIOs would be more obvious to the pilot, and proper attention could be given to the oscillatory motions before they became a significant problem.

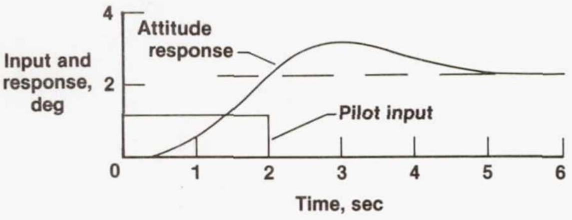

Figure 8. Orbiter attitude response for pilot pulse input. Airspeed = 190 knots.

Other changes made before the orbital flights included a change in the priority rate-limiting logic to reduce the interactions of the roll and pitch axes. In addition, the pitch attitude response was made slightly less sensitive by reducing the overall loop gains at the landing condition. The result of these changes was a high-gain, pitch-rate-command control system which was optimized to give excellent attitude control. With this type of system, the pilot can pull up to a desired attitude and release the stick, and the attitude will overshoot slightly and return to the value at which the stick was released (fig. 8). This makes it extremely easy for the pilot to establish a precise attitude without using complex pilot control techniques.

PIO TENDENCY AND SIMULATION

Analytical results can provide considerable insight into the nature of flying qualities problems, but simulation has also played an important role in the development and evaluation of the control system. Most of the early studies of the flying qualities of the orbiter during landing were performed on a fixed-base simulation with a visual display of the runway. The task was generally not very demanding, and as a result there was little indication of any PIO tendency. In 1978 after the ALT experience, the Ames Flight Simulator for Advanced Aircraft (FSAA) moving-base simulation (ref. 7) and Calspan TIFS facility (ref. 8) were used to examine the PIO characteristics of the orbiter. The FSAA is a moving-base simulator with a TV model-board visual display of a runway. The TIFS is an in-flight simulator that can reproduce cockpit motions in addition to providing the real-life visual scene. A safety pilot is used to prevent the evaluation pilot from getting into any dangerous conditions. During these evaluations, the pilots evaluated the PIO tendencies using the rating scale shown in table 1.

TABLE 1. — PIO RATING SCALE.

Rating	Description
1	No undesirable motions
2	Undesirable motions that are cured by pilot technique
3	Undesirable motions that can be cured by sacrificing the task or by increased effort
4	Sustained nondivergent oscillations
5	Divergent oscillations for abrupt maneuvers only
6	Divergent oscillations encountered in normal control

The histogram in figure 9 summarizes the results obtained. It is clear from this figure that the FSAA with limited motion and visual cues produced very little PIO tendency compared to the TIFS.

In 1979 and 1980 another series of simulations were made with the Ames Vertical Motion Simulator (VMS) (ref. 9) and the TIFS. The VMS had sufficient vertical motion to provide good vertical motion simulation, but it had the same visual display that was used on the FSAA. In both of these simulations a very demanding task was used to accentuate the PIO tendencies. A 46-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 approximately 15 m (50 ft). This produced a task that would be unlikely in real life, but it provided a situation that produced a pilot gain high enough to make the PIO tendencies of the vehicle apparent to the pilot. The results of these tests are summarized in figure 10, and a significant difference still exists between the moving-base simulation and the flight simulation. On both of these simulators, after becoming familiar with the simulator, a normal straight-in approach and landing could be made without evidence of a PIO tendency. Although the PIO tendencies were not the same for the two simulations, for tasks less demanding than those that would produce PIOs, the two simulators produced similar evaluations of the basic handling qualities. The general conclusion from these tests is that flight simulation is probably the only reliable method of evaluating the landing characteristics. The introduction of an artificial task produces pilot workload levels nearer to the workload levels that can be encountered in flight, but even flight simulation does not produce the same sense of urgency that the actual flight environment produces.

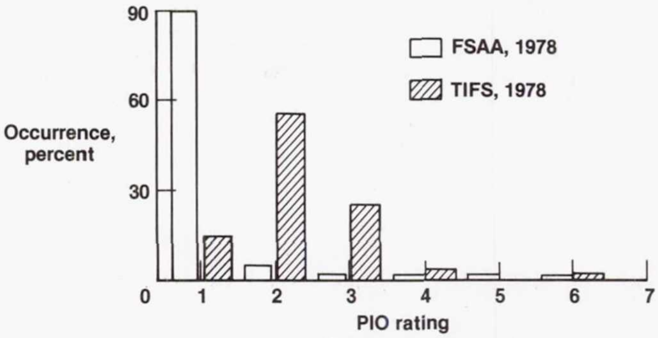

Figure 9. Comparison of PIO rating from the FSAA and TIFS simulators for the landing task with the ALT orbiter configuration.

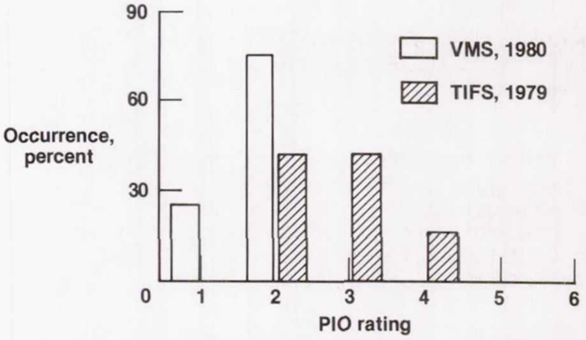

Figure 10. Comparison of PIO ratings from the VMS and TIFS simulators for the landing task with the STS orbiter configuration.

ORBITAL FLIGHTS

The first orbital flight of the space transportation system (STS), made in 1981, represented a significant event in demonstrating the feasibility of making manual landings with an entry vehicle. Subsequent flights have demonstrated a capability to land on a 4570-m (15,000-ft) concrete runway in a routine manner. In the early flights, variations in touchdown point and speed have resulted from a greater-than-predicted value of low-speed L/D. Predictions are extremely important for the landing phase because there is no energy management below 610 m (2000 ft), and increases in L/D result in higher touchdown speeds or longer landings. With the predicted data now updated with the flight results, this problem has been reduced significantly. Overall, the STS flights have demonstrated a good manual landing capability, with acceptable landings being made in a variety of wind and turbulence conditions. The capability demonstrated so far is especially impressive when one considers that each manual landing has been performed by a different pilot, thus reducing any of the pilot training advantages resulting from actual flight experience.

POTENTIAL IMPROVEMENTS

As discussed previously, one disadvantage of the current orbiter control system is the sluggish response in normal acceleration, which makes flightpath control more difficult. One maneuver that is especially difficult is leveling off near the ground (such as to bleed off speed to obtain a better touchdown velocity). This difficulty, caused by the problem with ballooning, is especially noticeable when in ground effects. Unlike a conventional transport, the orbiter has a considerable amount of excess energy at a nominal landing speed of 200 knots, but because of the rapid deceleration (4 to 5 knots/sec), any significant ballooning can result in a low-energy condition fairly rapidly. To improve the flightpath response, it is necessary to speed up the acceleration response by increasing the amount of pitch rate overshoot. The example in figure 11 shows a faster acceleration response, which results in better flightpath control, but the attitude response drops back when the stick is released, which makes accurate pitch attitude control more difficult. Simulator studies of systems of this type are currently being conducted, and an analysis of this type of system is given in reference 10. An interesting problem has developed in the effort to improve the longitudinal flying qualities. On the one hand, an effort has been made to make the landing task easier, while on the other hand, an effort has been made to improve the flightpath control at landing. These efforts have resulted in conflicting requirements for the pitch response characteristics. As the task becomes easier, it is generally performed in a more open-loop fashion and attitude becomes the primary variable to be controlled, which produces a requirement for extremely good pitch attitude control. One example of an open-loop control strategy is in the final flare and landing in which the pilot increases the vehicle attitude a predetermined amount at the final flare point and then lets the airplane land with minimal pilot inputs. Several of the landings to date have been of this type and have been quite successful. In contrast to this technique, there is the control strategy that requires a more closed-loop control of the flightpath. This technique would be especially appropriate for nonstandard landing situations, such as during recovery from an automatic landing system failure near the ground. To improve the normal acceleration response, this technique requires an increase in the pitch rate overshoot, which is in conflict with the good attitude response required with the more open-loop tasks. Further test results from both flight and simulation will be required to determine which control technique (and therefore, control system) will provide the best overall capability for the manual control task in the operational environment.

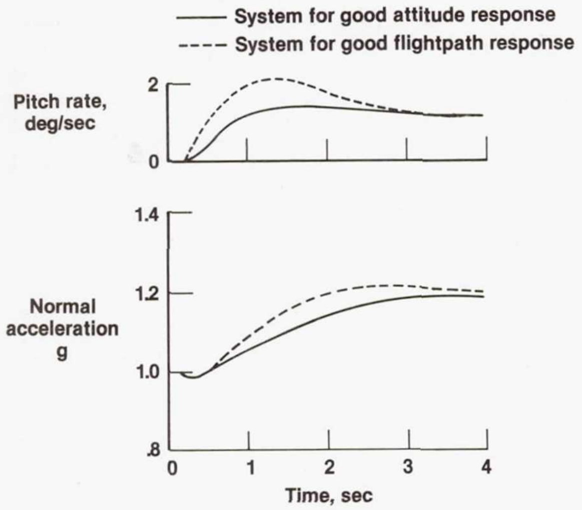

Figure 11. Comparison of response characteristics for good attitude response and for good flightpath response.

CONCLUDING REMARKS

The shuttle program was initiated as a bold and pioneering effort to develop a true spaceplane capable of returning from orbit and landing on a conventional runway. Some complex challenges were encountered in developing the longitudinal flying qualities required to land the orbiter manually in an operational environment. Approach and landing test (ALT) flights indicated a tendency for pilot-induced oscillation near landing. Changes in the operational procedures have reduced the difficulty of the landing task, and an adaptive stick filter has been incorporated to reduce the severity of pilot-induced oscillatory motions. Fixed-base, moving-base, and in-flight simulations have been used during the evaluations, and in general, flight simulation has been the only reliable means of assessing the low-speed longitudinal flying qualities problems. Some additional refinements may still be required to improve the flying qualities for the manual landing task, and two types of systems appear viable, depending on the nature of the task: one emphasizes attitude control, and the other emphasizes flightpath control. Further flight experience will contribute additional information about the manual landing task, especially in regard to the interfacing of the manual task to the automatic landing mode and the heads-up display (HUD) flight director mode in the operational situation. Overall, however, the orbiter control system design and the operational procedures have met the objective of providing the flying qualities necessary for a manual landing. An impressive manual landing capability for an unpowered vehicle with a low lift-to-drag ratio has been demonstrated, and precision landings are now being made routinely. The shuttle program has used many advanced technologies and demonstrated their application for the first time in an operational environment. In addition to providing an operational space transportation system, the orbiter development program has also made a significant contribution to the generic flying qualities and flight control system technology for advanced aircraft.

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