Space Shuttle Longitudinal Landing Flying Qualities

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The Space 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 of pilot-induced oscillation near landing. Changes in the operational procedures reduced the difficulty of the landing task, and an adaptive stick filter was incorporated to reduce the severity of any pilot-induced oscillatory motions. Fixed-base, moving-base, and in-flight simulations were used for the evaluations. In general, flight simulation proved to be the best means of assessing the low-speed longitudinal flying qualities problems. Overall, the Orbiter control system and operational procedures produced a good capability to perform routinely precise landings with a large, unpowered vehicle that has a low lift-to-drag ratio.

Nomenclature

ALT = approach and landing test
DFBW = digital fly-by-wire
FSAA = flight simulator for advanced aircraft
L/D = lift-to-drag (ratio)
PIO(s) = pilot-induced oscillation(s)
STS = space transportation system
TAEM = terminal area energy management
TIFS = total in-flight simulator
VMS = vertical motion simulator

Introduction

THE Space Shuttle program took on the challenge of providing a manual landing capability for an operational vehicle returning from orbit. This required the development of longitudinal flying qualities suitable for the landing in an operational environment of the unpowered Orbiter that had a low lift-to-drag (L/D) ratio. The mission required a space transportation system (STS) vehicle with an operational capability of landing day or night in all types of weather on a 4570-m (15,000-ft) runway. The control system design was 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. Limited 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 was not 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 that only required very simple control systems. The space shuttle vehicle design reflected the optimistic views as to the benefits of active control technology and digital control that were expressed in the 1974 active control technology conferences.[1,2]

Before the orbital flights of the Space Shuttle, five flights were made to evaluate the low-speed characteristics during the approach and landing test (ALT). The Orbiter was launched from a modified Boeing 747, and the flight regime from 6100 m (20,000 ft) to touchdown was investigated. The fifth landing was on the 4570-m (15,000-ft) concrete runway at Edwards, and the tendencies of pilot-induced oscillations (PIOs) in both pith and roll were exhibited near touchdown. In 1978, after the ALT experience, a simulation program was conducted to study the cause and significance of the PIO characteristics observed in flight using the Ames Flight Simulator for Advanced Aircraft (FSAA) moving-base simulation and the U.S. Air Force/Calspan Total In-Flight Simulator (TIFS) flight simulation facility.

Following these simulations, control-system improvements were developed and evaluated on a ground-based simulator using a tracking task to evaluate the PIO characteristics. One of these systems was an adaptive stick gain[3,4] that was designed to reduce the severity of the PIO tendencies by providing a closed-loop bandwidth limiter to prevent the pilot from reaching control surface rate limiting. Flight studies using the F-8 digital-fly-by-wire (DFBW) airplane were conducted to evaluate the effect of time delay on various types of Shuttle approaches.[5]

In 1979 and 1980, another series of simulations were made with the NASA Ames Vertical Motion Simulator (VMS) and the TIFS. These simulations resulted in the control system that was used for the first orbital flights. Further simulations, conducted on the VMS simulator, investigated other control system modifications to improve the low-speed handling qualities.[6] In conjunction with these studies, an experiment to investigate the flying qualities of the Orbiter for the purpose of developing criteria for future re-entry vehicles was undertaken,[7-9] and the analyses provided insight into the development of potentially improved control systems. This paper discusses some of the problems and successes encountered in developing the longitudinal flying qualities required to land the Orbiter manually in an operational environment.

Shuttle Approach and Landing Task Description

The return of the Shuttle from orbit consists of three phases: entry, terminal area energy management (TAEM), and approach and landing. The most significant task in an unpowered vehicle is that of energy management. The TAEM phase begins at a velocity of about 760 m/s (2500 ft/s) and an altitude of about 25,000 m (82,000 ft). In this phase, the Orbiter's speedbrakes are used 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).

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The first part of the landing phase is devoted to the final energy-management maneuver and consists of a steep glide slope (approximately 19 deg) 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. Because 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.

With the proper energy level established, 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 1.5-g preflare is used to transition from the steep glide slope to a glide-slope angle of about 1.5 deg. 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 preflare. 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 preflare, shallow glide slope, and final flare to touchdown are 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.

Control System Design Considerations

Active control technology offers improved performance plus good handling qualities throughout the flight envelope. Good performance generally requires reduced static margin, and this was the case with the Shuttle. Reduced static margin leads to a full-time, active control system rather than the stability augmentation systems of the past, which only enhanced the basic handling qualities. This leads to the requirement for the control system to be fully operational for the first flight.

As a result, one area that active-control technology systems must address is the robustness of the system; the control system must provide reasonable handling qualities over a range of system parameters that are not completely known before the first flight. Because of the tremendous envelope that had to be traversed during the first orbital flight of the Shuttle, the major unknown system parameters were the aerodynamic characteristics. This included speeds up to Mach 25 and an angle-of-attack range of 0 to 40 deg. To insure that the control system would be robust enough to reasonably provide a successful mission, it was necessary to quantify the expected uncertainty in the aerodynamic characteristics and then, exhaustively, to test the control system with these expected deviations to verify satisfactory system performance. The aerodynamic uncertainties were determined from comparisons of flight and predicted characteristics of past vehicles with similar configurations,[10] and an example is shown in Fig. 1. Extrapolations of these comparisons were augmented with other estimates of the uncertainties to provide a complete set of aerodynamic uncertainties encompassing the Shuttle envelope.

The aerodynamic uncertainties were then combined with other system tolerances and trajectory dispersions to form the basis for evaluating the system performance in both the nominal and off-nominal conditions.[11] Three levels of system performance were required, depending on the type and number of system failures. (These failures were in addition to the aerodynamic and system uncertainties.) Level 1 requirements consisted of system stability margins (high-frequency crossover gain margin of 6-dB and a 30-deg phase margin); time response criteria (an example of which is shown in Fig. 2) that were derived from a conservative composite of the then available time response criteria; and a pilot rating better than 3 from real-time simulation. Level 2 requirements included lower stability margins and a pilot rating better than 6. The level 3 requirements specified that the vehicle would be controllable. Level 1 was generally required for one failure, level 2 was required for two failures, and level 3 was required for two failed auxiliary power units. The process was time-consuming because of the heavy reliance on real-time simulation. However, the process did provide a means of evaluating the performance of the control system, and the net result was an extremely robust system design over a wide range of system and aerodynamic characteristics.

Approach and Landing Test (ALT)

Although the system design allowed considerable margins for the mission, there was concern about the low-speed characteristics, particularly the operational techniques involved in landing an unpowered vehicle. As a result, 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; when combined with the light stick forces, this response made pitch control sensitive. The tests were not without problems, however. On the fifth flight (the concrete runway landing), a tendency of 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

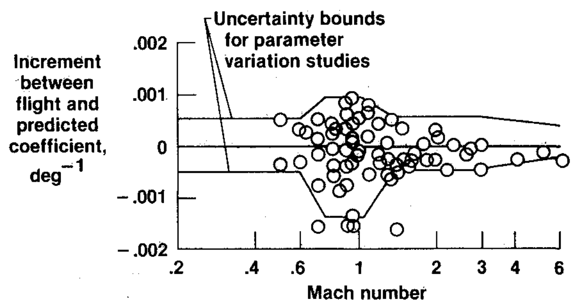

Fig. 1 Correlation of flight and predicted aerodynamic directional stability coefficient.

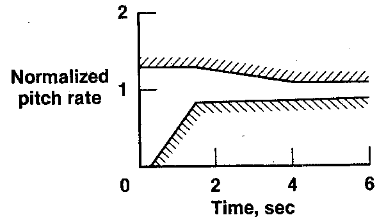

Fig. 2 Pitch-rate response criteria.

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.

Developments for the First Orbital Flight

After the ALT flights, an analysis was conducted to determine the longitudinal characteristics for the Orbiter landing situation. In the following sections, the general nature of the longitudinal control problem is discussed, as well as some of the modifications and tests that have been made to develop the system for the first orbital flight.

Longitudinal Control Characteristics

Several factors have affected the longitudinal control of the Orbiter in the landing condition. In the pitch-attitude control, a major factor contributing to PIO motions 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 to the delay because of the average sampling time and the computation time. The Neal-Smith analysis technique[12] has been used to analyze the closed-loop attitude control. The results are shown in Fig. 3 in terms of the amount of pilot lead compensation and the amount of resonance experienced for various amounts of pilot-vehicle closed-loop bandwidth. As the task becomes more demanding, the pilot tries to increase the pilot-vehicle bandwidth to obtain better response. The pilot lead compensation required generally indicates the amount of pilot workload, and the resonance is a measure of the degree of PIO tendency. Figure 3 shows that the Orbiter has reasonably good handling qualities for low bandwidths, but as the bandwidth increases, there is an increase in the pilot lead compensation required and a sharp increase in PIO tendency. The missing link in this analysis technique is the ability to determine the bandwidth requirements for a new vehicle and task.

Another factor involved in longitudinal control is flightpath control. Because of the lift loss created by the elevon deflection of the delta-wing configuration, a nose-up pitch command initially results in a significant downward acceleration at the center of gravity and also at the main gear. With the relatively short nose of the Orbiter, the pilot location is near the center of rotation, and there is a delay of approximately 0.5 s after a pitch input before any vertical 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 control the altitude accurately. The sluggish acceleration response is the result of the high-gain pitch-rate command system that was designed to provide very good pitch-rate response with minimal pitch-rate overshoot. The high cockpit location and poor visibility also contribute to the inability of the pilot to judge the precise altitude, particularly near touchdown.

Another 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 command gain because of the nonlinear stick. The pitch-attitude and flightpath modes have been examined in terms of a pilot-vehicle closed-loop system with a pitch-attitude inner loop and an altitude outer loop.[13] Regions of stability as a function of pilot gain for several magnitudes of control input are shown in Fig. 4. Because of the nonlinear stick gearing, the pilot attitude gain for stability changes significantly as the stick deflection increases, particularly if the pilot is attempting to use high gains to achieve increased performance. For the Orbiter, large-amplitude inputs soon lead to control surface rate limiting, which further contributes to the overall time delay. As a result, there is an inherent tendency for oscillations to diverge rapidly once a slight divergence occurs. It is interesting that, in simulations of the PIO, there were almost no instances of slowly divergent oscillations. If an oscillation began to diverge, it rapidly became a fully developed PIO that resulted in loss of control.

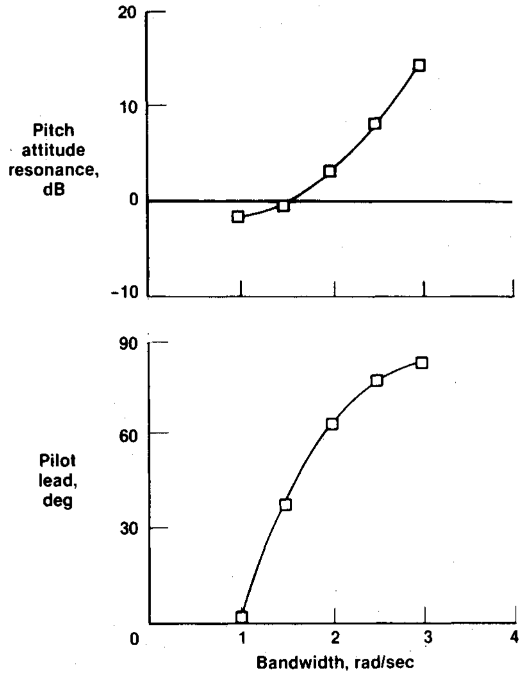

Fig. 3 Pilot-vehicle closed-loop characteristics using Neal-Smith analysis.

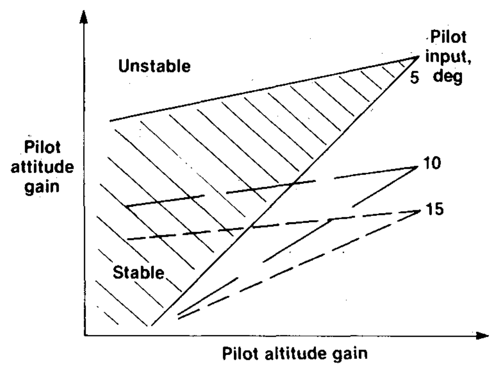

Fig. 4 Effect of nonlinear stick gearing on pilot-vehicle closed-loop stability.

F-8 DFBW Airplane Time-Delay Study

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 F-8 DFBW airplane.[5] The two landing tasks of most interest from this study 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, in which 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 results of the F-8 tests are shown in Fig. 5, together with the results from the TIFS Orbiter simulation. For time-delay values of approximately 0.2 to 0.25 s in the TIFS Shuttle simulation, the effect of task was quite significant. These results also indicate that time delay can cause a significant degradation in handling qualities when a high-workload task is performed. The high-workload, spot-landing case was similar to the conditions for the ALT flights. After the ALT flights, the difficulty of the Shuttle landing task was reduced by basing the touchdown point on velocity rather than a fixed point on the runway. This technique, which was used in the TIFS-study results shown on Fig. 5, reduced the need for high-bandwidth control, and it appears to produce a task that is between the low- and high-workload tasks of the F-8 tests.

Interestingly, these same results were confirmed in a study of the standard approach task for fighter aircraft.[14] 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. The use of high-gain, digital flight-control systems and reduced static stability can introduce time delay; these effects must be examined in the design of all future aircraft. The flight tests described have contributed significantly to the understanding of time-delay effects in modern aircraft and, hopefully, future aircraft designers will be spared the need to examine these effects in flight.

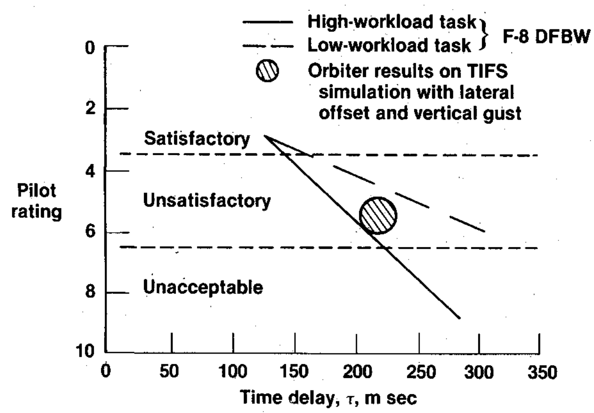

Fig. 5 Results of the F-8 time-delay study for the landing task.

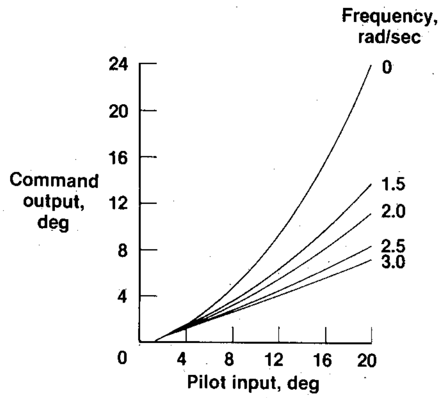

Fig. 6 Example of frequency-dependent stick shaping.

PIO Filter Development

A device was sought that would reduce the possibility of developing a large-amplitude PIO near the ground caused by high-gain task, time delay, and rate-limiting problems while not requiring a major redesign of the control system. The solution to this was an adaptive stick gain[3,4] that would reduce the pilot and system command gain whenever PIO conditions were approached. The relationship of resonance to bandwidth (Fig. 3) shows that it would be highly desirable to restrict the closed-loop pilot and system bandwidths to less than 3 rad/s to avoid large-amplitude oscillations. The adaptive stick gain algorithm accomplishes this by varying the stick gain as a function of pilot stick frequency. This is done by detecting the predominant pilot input frequency, which is nearly sinusoidal and at about a constant frequency when near the PIO conditions. The detection algorithm is based on the fact that the rms magnitude of a sine wave is proportional to the amplitude and that the rms magnitude of the derivative of a sine wave is proportional to the amplitude times the frequency, thus allowing a means of estimating the frequency.

The estimation process is performed over a period of 2 to 3 s. The adaptive algorithm response has been experimentally determined so that the stick gain changes faster than the pilot can adapt his gain, but slow enough so that the pilot does not detect the change caused by abruptness of the system response. 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 gearing is nearly linear. The resulting stick gain for steady-state conditions is shown in Fig. 6. By reducing the overall pilot command 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. 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.

Other Changes for the First Orbital Flight

In addition to the PIO filter, another modification included increasing 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 near the pilot's station; the visual cues of attitude are limited because of pilot location. As a result, the pilot would be unaware 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. Other modifications made before the orbital flights included a change in the priority rate-limiting logic of the elevons to reduce the interactions between 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.

PIO Tendency and Simulation

Although analytical results can provide considerable insight into the nature of flying qualities problems, simulation has played an important role in the development and evaluation of the Shuttle control system. An important attribute of simulation is the accurate representation of the characteristics of interest. In the Orbiter, the longitudinal PIO characteristics were the primary concern and a number of simulations were conducted with a variety of facilities. These facilities encompassed ground fixed-base, ground moving-base, and in-flight simulations. From these tests, a comparison was made between these facilities.[15] A summary of the results pertinent to the simulation of PIO characteristics is contained in the following section.

Most of the early studies of the Orbiter flying qualities during approach and 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 FSAA moving-base simulation and TIFS facility were used to examine the PIO characteristics of the Orbiter. The FSAA is a moving-base simulator with a television 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 tests, the pilots evaluated the PIO tendencies using the rating scale shown in Fig. 7. The histogram in Fig. 8 summarizes the results obtained. It is clear from Fig. 8 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 VMS 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/s (15-ft/s) vertical gust was introduced at an altitude of approximately 15 m (50 ft). This produced a task that would be unlikely in any actual circumstances, 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 Fig. 9; the correlation is improved, but a significant difference still exists between the moving-base simulation and the flight simulation. In all of these simulations, after becoming familiar with the simulator, the pilot could perform a normal straight-in approach and landing without evidence of a PIO tendency. Although the PIO tendencies were not the same for the two simulations, the two simulators produced similar evaluations of the basic handling qualities for tasks less demanding than those that would produce PIOs. The general conclusion from these tests is that flight simulation is probably the best method of evaluating the PIO tendencies.

Orbital Flights

The first orbital flight of the STS in 1981 represented a significant event in demonstrating the feasibility of making manual landings with a re-entry vehicle. Subsequent flights

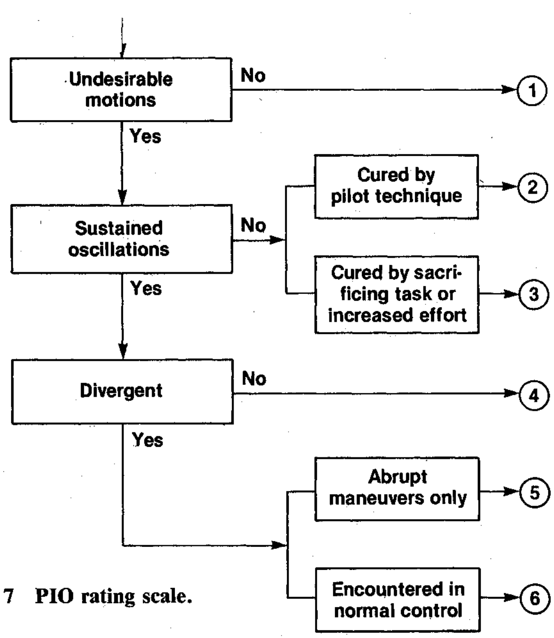

Fig. 7 PIO rating scale.

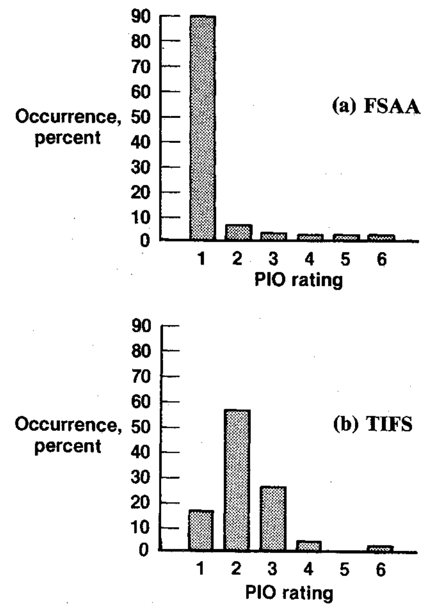

Fig. 8 FSAA and TIFS landing task PIO rating comparison.

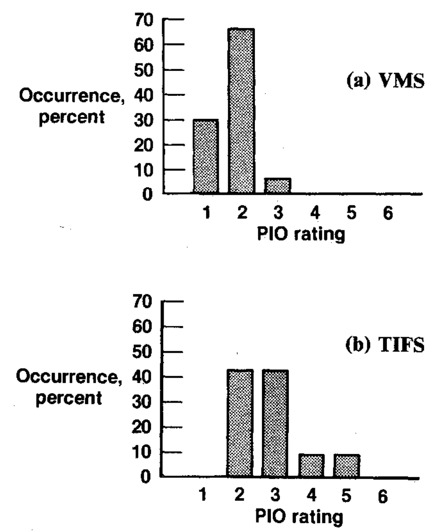

Fig. 9 VMS and TIFS landing task PIO rating comparison.

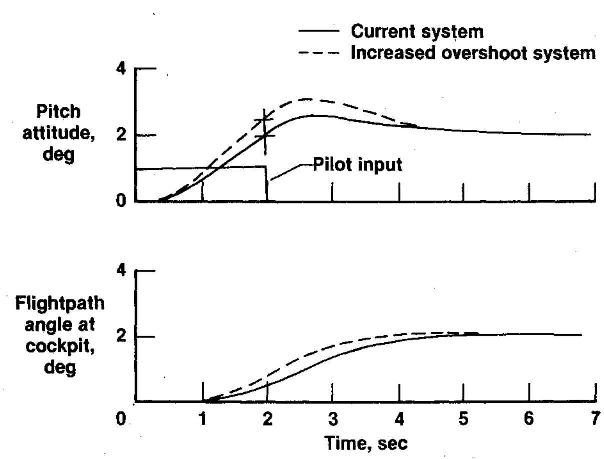

Fig. 10 Comparison of response characteristics for good attitude and flightpath response.

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). With the predicted data now updated using the flight results, this problem has been reduced significantly. PIO tendencies have not been observed during landing primarily because of the improved operational procedures and training. 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 most of the landings have been performed by different pilots, thus reducing any of the pilot training advantages resulting from actual flight experience.

Potential Improvement Studies

As previously discussed, flightpath control is difficult because of the lack of initial acceleration cues and because of the slow rise time. Flightpath corrections near the ground are generally precluded because of the effect of elevon deflection on the main gear response. These characteristics can only be modified by a configuration change such as a canard and, as a result, are the most significant from a design criteria standpoint. Active control technology allows the designer considerable flexibility in configuration selection. This flexibility, combined with current design trends toward multiple control surfaces, may lead to situations similar to that of the Orbiter, where the response characteristics are considerably different from characteristics of other aircraft. There is a strong need for design criteria for pilot motion parameters to avoid these problems in the future, particularly in those areas where basic configuration design is involved.

Because the center of rotation could not be changed, the flightpath response was investigated as a means of improving the landing flying qualities. To quicken the flightpath response, the amount of pitch-rate overshoot must be increased; an example of this response is compared to the response of the current configuration in Fig. 10. Evaluations of the current system and systems with higher pitch-rate overshoot were made by trained astronauts as well as pilots with conventional aircraft background and produced some interesting results relative to pilot training. There appears to be a different control strategy for these two pilot groups which leads to different control system requirements. The following is a discussion of the two control systems and the pilot control techniques that each pilot group appears to be using.

Current System

The most significant factor in regard to the baseline system is the characteristic known as dropback. Consider the time history of Fig. 10 of a 1-deg/s pitch-rate command held for a 2-s duration to produce a 2-deg change in flightpath. The attitude overshoots slightly but returns to the value at the time when the controls were released. This is known as zero dropback. Because of the dropback characteristics, the eventual steady-state flightpath is known at the time the control is released. The trained astronauts have learned to use this attitude response to compensate for the lack of initial cockpit cues and to provide considerable lead in determining the steady-state flightpath. For smaller flightpath changes, the pulse technique provides a simple way of fine-tuning the flightpath.

The pilots of conventional aircraft have not developed any special technique to compensate for the lack of initial response cues. Direct observation of flightpath derived from visual as well as kinematic cues appears to be the primary control parameter. Because of the slow flightpath response, this becomes a difficult control problem. Pitch-attitude and pitch-rate responses are somewhat transparent to these pilots. This group of pilots generally believed that the current configuration was less predictable, and there was often a tendency to float near touchdown. Reasonable control was obtained for slow changes (low bandwidth), but problems arose when attempts were made to tighten up the control because of the difficulty in providing the amount of lead compensation necessary from the direct observation of flightpath.

Increased Overshoot System

As can be seen from Fig. 10, the primary difference between this and the current system is the pitch-rate overshoot that increases the amount of dropback. The flightpath overshoot from stick release and the time to reach steady state is also significantly reduced. With this system, the trained astronauts had problems establishing flightpath. Pulling up to what would appear to be the correct attitude to give the desired flightpath produced less than the desired flightpath change, because of the dropback, thus requiring additional corrections. For the pulse inputs, the large overshoot in pitch attitude made it difficult to use the initial pitch response to provide lead information about the flightpath response.

For the pilots of conventional aircraft, the quicker response in flightpath resulted in flightpath corrections being made quickly and more precisely than with the current system. It appears that the quickening of the flightpath response partially compensated for the lack of initial motion cues. An additional benefit is that direct use of flightpath appears to be more consistent with previous conventional pilot training.

Concluding Remarks

The Space 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 Shuttle Orbiter manually in an operational environment. The longitudinal control system consists of a high-gain pitch-rate command system. The design process made heavy use of simulation, and a robust system design was ensured by using a combination of aerodynamic and system uncertainties during the evaluations.

Before the orbital flights, approach and landing test flights were made. The longitudinal flying qualities were quite good, except for a tendency of pilot-induced oscillation (PIO) near landing. Two of the major contributions to the landing characteristics are the time delay and the center-of-rotation effects caused by the elevons. Adequate time-delay design criteria are now available for future aircraft. However, adequate design criteria do not exist for cockpit motion effects. Designers of future aircraft should therefore consider nonstandard aircraft response carefully, particularly in those cases in which a major configuration change would be required to correct a deficiency.

PIO tendencies have been reduced by changes in the operational procedures that have lessened the difficulty of the Orbiter landing task and by incorporating an adaptive stick filter. Some improvements may still be possible by increasing the pitch-rate overshoot to improve the flightpath response. However, the current system, with a control technique based on attitude, seems to be acceptable if pilot training is adequate. Ground moving-base and in-flight simulations have been used during the evaluations and, in general, flight simulation was the best means of assessing the longitudinal PIO characteristics. Both ground and flight simulation provided similar results in the evaluation of flightpath control.

Overall, 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 routine. 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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