NASA TM- 85910

NASA Technical Memorandum 85910

Active Control Technology Experience With the Space Shuttle in the Landing Regime

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October 1984

NASA
National Aeronautics and
Space Administration

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      85N10071*#   ISSUE 1   PAGE 12   CATEGORY 8   RPT#: NASA-TM-85910 H-1260
      NAS 1.15:85910   84/10/00  12 PAGES   UNCLASSIFIED DOCUMENT
UTTL: Active control technology experience with the Space Shuttle in the landing
      regime   TLSP: Final Report
AUTH: A/POWERS, B. G.
CORP: National Aeronautics and Space Administration. Ames Research Center,
      Moffett Field, Calif.    AVAIL.NTIS   SAP: HC A02/MF A01
      Presented at the AGARD Flight Mech. Panel Symp. on Active Control Systems,
      Toronto, 15-18 Oct. 1984
MAJS: /*ACTIVE CONTROL/*FLIGHT CHARACTERISTICS/*FLIGHT SIMULATION/*SPACE
      SHUTTLES/*SPACECRAFT LANDING
MINS: / DESIGN ANALYSIS/ FLIGHT CONTROL/ FLIGHT TESTS/ FLY BY WIRE CONTROL/
      OSCILLATIONS/ PILOT PERFORMANCE/ TIME LAG
ABA:  Author
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ACTIVE CONTROL TECHNOLOGY EXPERIENCE WITH THE SPACE SHUTTLE IN THE LANDING REGIME

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SUMMARY

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 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, 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 for routinely performing precise landings in a large, unpowered vehicle with a low lift-to-drag ratio.

SYMBOLS

ALT	approach and landing tests	PIO	pilot-induced oscillation
DFBW	digital fly-by-wire	TAEM	terminal area energy management
FSAA	flight simulator for advanced aircraft	TIFS	total in-flight simulator
L/D	lift-to-drag	VMS	vertical motion simulator

1.0 INTRODUCTION

The 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 of the unpowered, low lift-to-drag (L/D) orbiter in an operational environment. A vehicle with an operational capability to land during the day or night in all types of weather using a 4570-m (15,000-ft) runway was required for the mission. 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 would not be fully appreciated until much later, after 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 of the benefits of active control technology and digital control that were expressed in the 1973 and 1974 active control technology conferences.

Before the orbital flights of the space shuttle, five flights were made to evaluate the low-speed characteristics during the approach and landing (ALT) tests. The orbiter was launched from a modified B-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 and tendencies for pilot-induced oscillations (PIO) in both pitch 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. The NASA Ames Research Center's flight simulator for advanced aircraft (FSAA) moving-base simulation and the Calspan total in-flight simulator (TIFS) facility were used. 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 (Refs. 1 and 2) which 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 at the Dryden Flight Research Facility of NASA Ames were conducted to evaluate the effect of time delay on various types of shuttle approaches (Ref. 3). 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 (Ref. 4). In conjunction with these studies, an orbiter experiment to investigate the flying qualities of the shuttle for the purpose of developing criteria for future entry vehicles has been undertaken (Refs. 5, 6, and 7); the analyses have 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, particularly with regard to the adequacy of active control technology design requirements.

2.0 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/sec (2500 ft/sec) and at an altitude of about 25,000 m (80,000 ft). In this 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 glideslope (approximately 19°) 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 glideslope 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 glideslope can be tracked in the autopilot mode or in 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 glideslope can be established visually by using a light-beam system on the ground. In all cases, the speed can be maintained by manual or automatic modulation of the speedbrakes.

Having established the proper energy, the final landing phase is started 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 1.2g to 1.5g preflare is used to transition from the steep glideslope to a glideslope angle of about 1.5°. 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 glideslope is quite shallow, and a small final flare is made to reduce the rate of sink to a desirable level. The preflare, shallow glideslope, and final flare to touchdown are often made as one continuous maneuver without actually establishing the final glideslope. This operational technique provides an extremely versatile capability for establishing the desired touchdown conditions under all types of normal and contingency situations.

3.0 CONTROL SYSTEM DESIGN CONSIDERATIONS

Active control technology offers improved performance and good handling qualities throughout the flight envelope. Good performance generally leads to reduced static margin; this was the case with the shuttle. Reduced static margin leads to a full-time control system rather than the stability augmentation systems of the past that only enhanced the basic handling qualities. This, of course, leads to the requirement for the active control technology 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°. In order to ensure 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 test the control system with these expected deviations to verify satisfactory system performance. The aerodynamic uncertainties were determined by comparing flight and predicted characteristics of past vehicles with similar configurations (Ref. 8); an example is shown in Fig. 2. 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 (Ref. 9). 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° phase margin); time response criteria, an example of which is shown in Fig. 3; and a pilot rating of better than 3 from real-time simulation. Level 2 requirements included lower stability margins and a pilot rating better than 6. The level 3 requirement 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 auxillary power units. The process was time consuming because of the heavy reliance on real-time simulation, but it did provide a means of evaluating the performance of the control system. The net result was an extremely robust system design over a wide range of system and aerodynamic characteristics.

4.0 APPROACH AND LANDING TESTS

Although the system design allowed considerable margins for the mission, there was concern about the low-speed characteristics, particularly by 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 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 during 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 for 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.

5.0 DEVELOPMENTS FOR THE FIRST ORBITAL FLIGHT

After the ALT flights, an analysis was conducted to determine the longitudinal control characteristcs for the shuttle landing situation. 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 for improving the flying qualities.

5.1 Longitudinal Control Characteristics

There are several factors that have affected the longitudinal control of the shuttle in the landing condition. In the pitch attitude control, a major factor contributing to pilot-induced oscillatory 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 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 and stick gains caused by the nonlinear stick. For the shuttle, 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. In simulations of the PIO it is interesting that there were almost no instances of slowly divergent oscillations. If an oscillation began to diverge, it rapidly became a fully developed PIO, resulting in loss of control.

Another factor involved in longitudinal control is altitude or flightpath control. Because of the lift loss caused 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. With the relatively short nose of the shuttle, the pilot location is near the center of rotation and there is a delay of approximately 0.5 sec 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 accurately control altitude. 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 accurately judge altitude, particularly near touchdown.

The pitch attitude and flightpath modes have been examined in terms of a pilot closed-loop system with a pitch attitude inner loop and an altitude outer loop (Ref. 10). Regions of stability as a function of pilot gain are shown in Fig. 4 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 Ref. 11 has also been used to analyze the closed-loop attitude control; the results are shown in Fig. 5 in terms of the amount of pilot lead and 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 5 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 required and a sharp increase in the PIO tendency. The missing link in both of these analysis techniques is the ability to determine the bandwidth requirements for a new vehicle and task.

5.2 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 flight tests was conducted using the Ames 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 glideslope 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. 6, along with the results from the TIFS orbiter simulation. For time-delay values of approximately 0.20 to 0.25 sec of the TIFS shuttle simulation, the effect of task is 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 in 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 on a fixed point on the runway. This technique, which was used in the TIFS-study results shown on Fig. 6, 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 (Ref. 12). 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.

5.3 PIO Filter Development

To reduce the possibility of developing a large-amplitude PIO near the ground caused by high gain task, time delay, and rate limiting problems, a device was sought that could reduce the severity of any PIO problems that might be encountered while not requiring a major redesign of the control system. The solution to this was an adaptive stick gain (refs. 1 and 2) that would reduce the pilot and system gains whenever PIO conditions were approached. This system can best be thought of as a closed-loop bandwidth limiter. The relationship of resonance to bandwidth (Fig. 5) shows that it would be highly desirable to restrict the pilot and system bandwidths to less than 3 rad/sec to avoid large-amplitude oscillations. The adaptive stick gain algorithm (Fig. 7) accomplishes this by varying the stick gain as a function of pilot stick frequency. This is done by detecting the predominant pilot 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 2-3 sec, and 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 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 is nearly linear. The resulting stick gain for steady-state conditions is shown in Fig. 8. By reducing the overall pilot and stick gains, 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.

5.4 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, 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.

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. The result of these changes was a high-gain, pitch-rate-command control system that 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. 9). This makes it extremely easy for the pilot to establish a precise attitude without using complex pilot control techniques.

6.0 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. Most of the early studies of the 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 Ames FSAA (Ref. 13) and the Calspan TIFS facility (Ref. 14) 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 evaluations, the pilots evaluated the PIO tendencies using the rating scale shown in Fig. 10.

The histogram in Fig. 11 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 was made with the Ames VMS (Ref. 15) and the Calspan 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 Fig. 12; a significant difference still exists between the moving-base and flight simulations. 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, 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 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.

7.0 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 particularly 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.

8.0 POTENTIAL IMPROVEMENTS

As previously discussed, one disadvantage of the current orbiter control system is the normal acceleration response. The area where this is most significant is near the ground where accurate control of rate of sink is of paramount importance. Leveling off near the ground (such as bleeding off speed to obtain a better touchdown velocity) is difficult and is compounded by a tendency to balloon, particularly 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 fairly rapidly in a low-energy condition.

Flightpath control is difficult because of the lack of initial acceleration cues caused by the center-of-rotation effect and the slow rise time caused by the control-law design. The center-of-rotation effect can only be cured by a configuration change and, as a result, is probably the most significant from a design criteria standpoint. Active control technology allows the designer considerable flexibility in configuration selection and, together with current design trends toward multiple control surfaces, may lead to situations similar to that of the shuttle where the pilot response characteristics are considerably different from responses with 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 normal acceleration rise time has been investigated as a means of improving the flightpath control for landing. To speed up the acceleration response, the amount of pitch rate overshoot must be increased. An example of this system is shown in Fig. 13; faster acceleration response compared to the current configuration is shown. An analysis of this type of system is given in Ref. 16. In addition to speeding up the normal acceleration response, an increase of the pitch rate overshoot produces an attitude response more like that of a conventional aircraft over a limited frequency range as shown in Fig. 14. In the frequency range of 0.5 rad/sec to 1.0 rad/sec the higher overshoot system exhibits attitude command characteristics rather than the rate command characteristics of the baseline system. It is in this frequency range where the pilot performs much of the flightpath control near touchdown.

Evaluations of the current system and the system with the higher pitch rate overshoot (the shaped pitch rate system) have produced some interesting results relative to pilot training. Most of the pilots who have not had a lot of training with the current system generally prefer the shaped pitch rate system for landing. This system is felt to be predictable and has the same general characteristics of conventional aircraft where noseup pitch commands are required during the landing flare. For the baseline system, the flare maneuver often results in the need to use nosedown pitch commands to obtain the desired flightpath. This group of pilots generally felt that the current configuration was less predictable and that there was often a tendency to float near touchdown. For pilots who have had a lot of training with the current system, the response characteristics of the current system are comfortable, and they prefer this system to the shaped pitch rate system for landing. Both groups of pilots find the current system to be very good for all of the nonlanding tasks where very good attitude control is highly desirable. These results are particularly interesting for active control technology designers because although we have the ability to produce almost any type of response that we desire, there will always be a strong tendency in the pilot community to assess these systems in terms of "normal airplane" response characteristics. This could very well lead to the perpetuation of "normal airplane" design criteria.

9.0 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. 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 for pilot-induced oscillation 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. Time delays are somewhat inherent in high-gain digital control systems, but adequate testing has now been performed to provide adequate design criteria for future aircraft. Adequate design criteria do not exist for center-of-rotation effects, and designers of future aircraft should consider nonstandard aircraft response carefully, particularly in those cases where a major configuration change would be required to correct a deficiency. Changes in the operational procedures have reduced the difficulty of the landing task, and an adaptive stick filter has been incorporated to reduce pilot-induced oscillations. Some improvements may still be possible for the shuttle by increasing the pitch rate overshoot to improve the normal acceleration response. This would make the response more like that of a conventional airplane; however, it appears that the current system is acceptable with adequate training. 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. 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 has demonstrated their application in an operational environment for the first time. 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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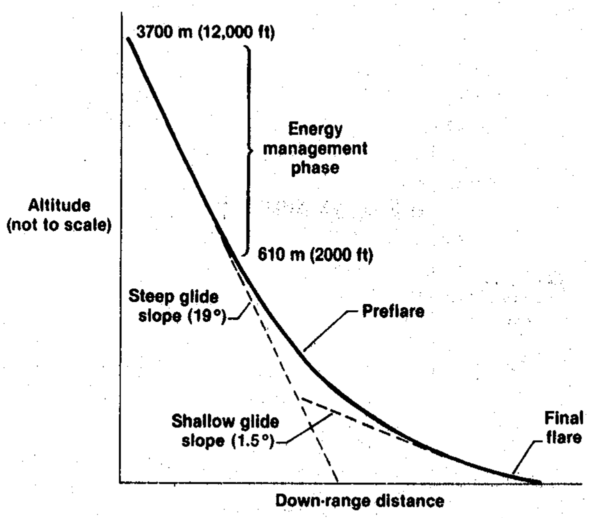


Figure 1. Landing trajectory.

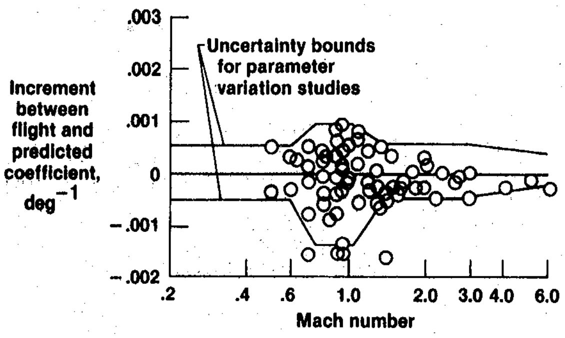


Figure 2. Correlation of flight and predicted aerodynamic directional stability coefficient.

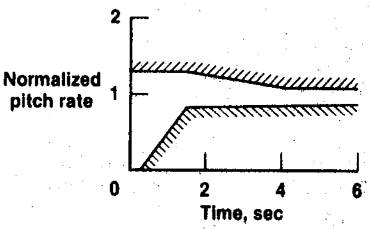


Figure 3. Pitch rate response criterion.

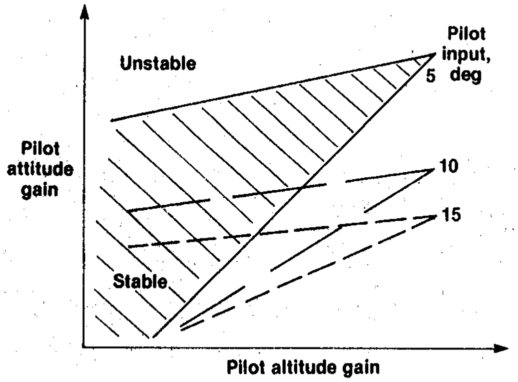


Figure 4. Effect of nonlinear stick gearing on pilot-vehicle closed-loop stability.

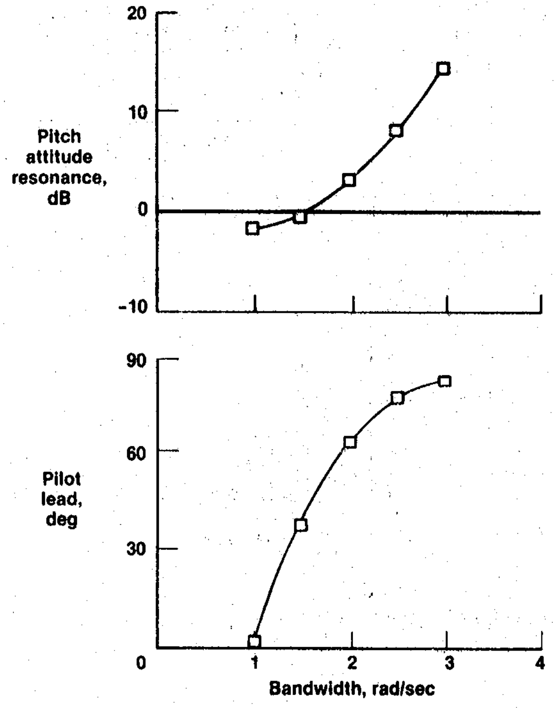


Figure 5. Pilot-vehicle closed-loop characteristics using Neal/Smith analysis.

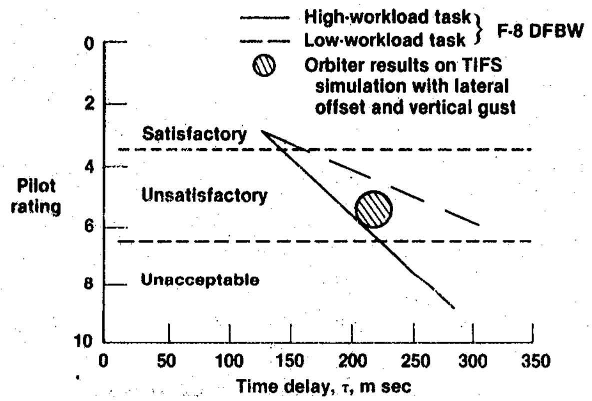


Figure 6. Results of the F-8 time-delay study for the landing task.

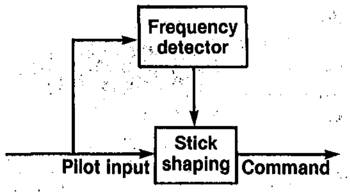


Figure 7. Adaptive stick-gearing concept to reduce PIO tendencies.

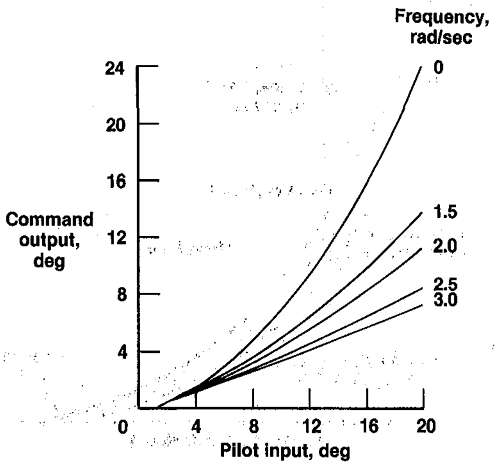


Figure 8. Example of frequency-dependent stick shaping.

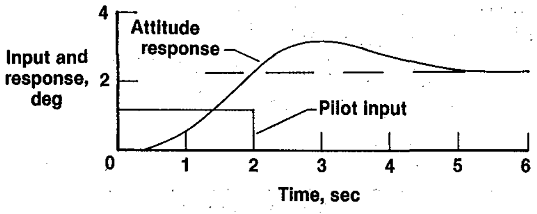


Figure 9. Orbiter attitude response for pilot pulse input. Airspeed = 190 knots.

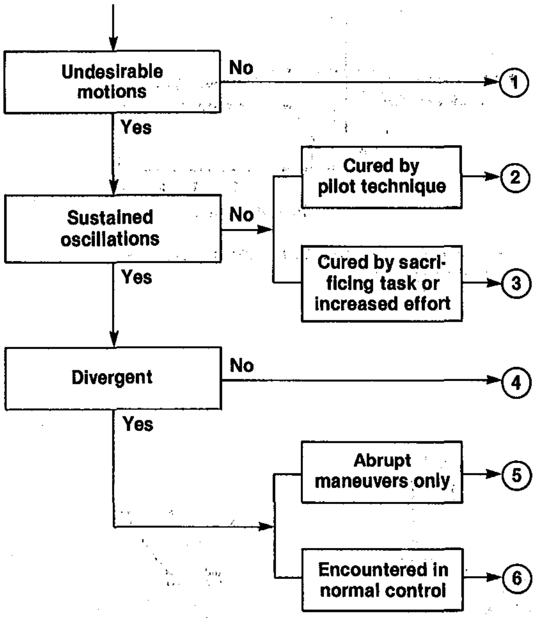
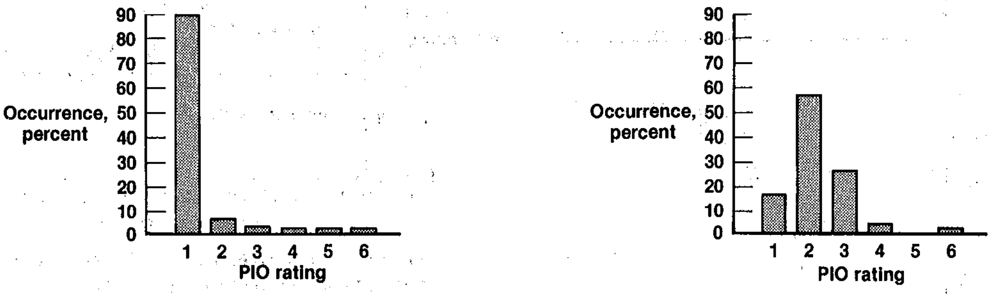


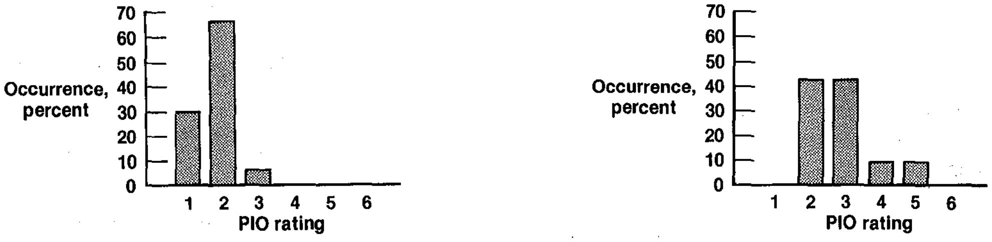
Figure 10. PIO rating scale.



(a) FSAA.

(b) TIFS.

Figure 11. FSAA/TIFS landing task PIO rating comparison. Shuttle ALT configuration.



(a) VMS, configuration B. *(b) TIFS, configuration B.*

Figure 12. VMS/TIFS landing task pilot rating comparison.

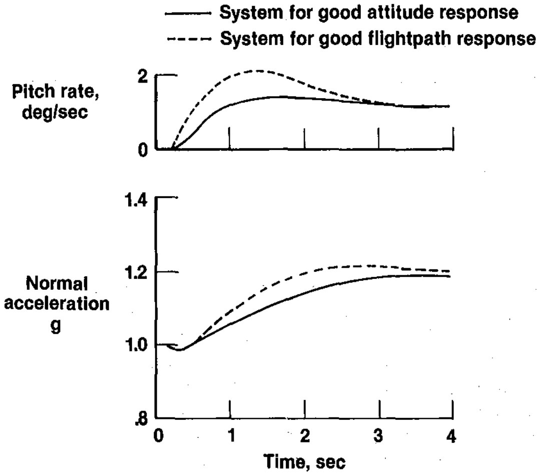


Figure 13. Comparison of response characteristics for good attitude response and for good flightpath response.

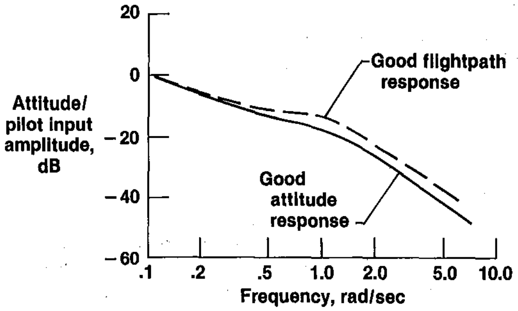


Figure 14. Comparison of frequency response characteristics.

1. Report No. NASA TM-85910	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle

Active Control Technology Experience With the
Space Shuttle in the Landing Regime

5. Report Date
October 1984

6. Performing Organization Code

7. Author(s)

Bruce G. Powers

8. Performing Organization Report No.
H-1260

9. Performing Organization Name and Address

NASA Ames Research Center
Dryden Flight Research Facility
P.O. Box 273
Edwards, California 93523

10. Work Unit No.

11. Contract or Grant No.

12. Sponsoring Agency Name and Address

National Aeronautics and Space Administration
Washington, D.C. 20546

13. Type of Report and Period Covered
Technical Memorandum

14. Sponsoring Agency Code
RTOP 505-34-01

15. Supplementary Notes

This paper was prepared for presentation at the AGARD Flight Mechanics Panel Symposium on Active Control Systems, Toronto, Canada, Oct. 15 to 18, 1984.

16. 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 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, 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 for routinely performing precise landings in a large, unpowered vehicle with a low lift-to-drag ratio.

17. Key Words (Suggested by Author(s))

Space shuttle
Control systems
Flying qualities

18. Distribution Statement

Unclassified-Unlimited

STAR category 08

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 10	22. Price* A02

*For sale by the National Technical Information Service, Springfield, Virginia 22161

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NASA Langley (Rev. May 1988) RIAD N-75