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SIMULATION STUDIES OF ALTERNATE LONGITUDINAL CONTROL SYSTEMS FOR THE SPACE SHUTTLE ORBITER IN THE LANDING REGIME

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Abstract

Simulations of the space shuttle orbiter in the landing task were conducted by the NASA Ames-Dryden Flight Research Facility using the Ames Research Center vertical motion simulator (VMS) and the total in-flight simulator (TIFS) variable-stability aircraft. Several new control systems designed to improve the orbiter longitudinal response characteristics were investigated. These systems improved the flightpath response by increasing the amount of pitch-rate overshoot. Reduction in the overall time delay was also investigated. During these evaluations, different preferences were noted for the baseline or the new systems depending on the pilot background. The trained astronauts were quite proficient with the baseline system and found the new systems to be less desirable than the baseline. On the other hand, the pilots without extensive flight training with the orbiter had a strong preference for the new systems. This paper presents the results of the VMS and TIFS simulations. A hypothesis is presented regarding the control strategies of the two pilot groups and how this influenced their control system preferences. Interpretations of these control strategies are made in terms of open-loop aircraft response characteristics as well as pilot-vehicle closed-loop characteristics.

Nomenclature

EAS	touchdown airspeed, knots
$\dot{h}$	touchdown rate of sink, ft/sec
PI	performance index
PIO	pilot-induced oscillation
PR	pilot rating
q	pitch rate, deg/sec
q_c	pitch-rate command, deg/sec
TIFS	total in-flight simulator
VMS	vertical motion simulator
y	touchdown lateral displacement, ft
$\dot{y}$	touchdown lateral velocity, ft/sec
γ_p	flightpath angle at pilot location, deg
θ	pitch attitude, deg
θ_c	pitch-attitude command, deg
τ_e	equivalent time delay, sec
τ_p	estimate of equivalent time delay, sec
ϕ	touchdown bank angle, deg
ω_{BW_θ}	pitch-attitude bandwidth, rad/sec

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Introduction

The longitudinal handling qualities of the space shuttle orbiter for the landing task have not proven to be as good as desired.[1] Several factors have affected the longitudinal control of the orbiter in the landing condition. In the pitch-attitude control, a major factor contributing to pilot-induced oscillation (PIO) tendencies has been the equivalent time delay between the pilot input and the orbiter response. Contributions to the equivalent time delay have included the actuators, the structural and smoothing filters, and the digital control system. Another factor has been the center-of-rotation location. Because of the lift loss created by the elevon deflection of the delta-wing configuration, a noseup 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. Hence, after a pitch input, a significant delay occurs 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 flightpath accurately. The sluggish acceleration response is the result of the high-gain pitch-rate command system that was designed to provide a response with minimal pitch-rate overshoot. These longitudinal characteristics in combination with the stress of landing an unpowered, low lift-to-drag ratio vehicle have resulted in unsatisfactory landing characteristics. Extensive training has therefore been required to provide the landing capability that has been demonstrated in the flights to date.

Because the orbiter center of rotation could not be easily changed, several new systems designed to improve the longitudinal response characteristics were investigated. This study was conducted by the Dryden Flight Research Facility of NASA Ames Research Center (Ames-Dryden). These systems improved the flightpath response by increasing the amount of pitch-rate overshoot. Reduction in the overall time delay was also investigated. These changes were evaluated on the Ames vertical motion simulator (VMS) and the U.S. Air Force/Calspan total in-flight simulator (TIFS). During these evaluations, a marked difference in preference was observed between the current (baseline) system and the new systems depending on the pilot background. The trained astronauts were quite proficient with the baseline system and found the new systems to be less desirable. On the other hand, the pilots without extensive shuttle flight training with the orbiter had a strong preference for the new systems. This paper presents the results of the VMS and TIFS simulations. A hypothesis is presented on the control strategies of the two pilot groups and how this influenced their control system preferences. Interpretations of these control strategies are made in terms of open-loop aircraft response characteristics as well as pilot-vehicle closed-loop characteristics.

Test and Simulation Description

Shuttle Approach and Landing Task Description

The final approach and landing task of the shuttle consists of two basic parts: the steep glideslope and the final landing (Fig. 1). The first part of the landing phase is devoted to the final energy management maneuver and consists of a steep glideslope (approximately 19.0°) with a fixed aim point relative to the runway and a constant equivalent airspeed. This phase consists of manually tracking the guidance command information displayed to the pilot on the flight director and visually tracking the glideslope using a light-beam system on the ground. The objective of the steep glideslope phase is to reach an energy window at about 2000 ft above the runway with the correct speed and flightpath. Because there is no active energy management below this altitude, the steep glideslope maneuver becomes the critical energy management task. 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 2000 ft above the runway. A 1.2- to 1.5-g preflare maneuver is used to transition from the steep glideslope to a glideslope angle of about 1.5°, which is established visually using a ball-bar light system. 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 maneuver, shallow glideslope, and final flare to touchdown are often made as one continuous maneuver without actually establishing the final glideslope.

Evaluation Pilots

The evaluation pilots from the VMS and TIFS simulation studies comprised two distinct groups. The first group consisted of astronauts with extensive shuttle flight training required for current shuttle flight crews (pilots 1 to 6). This group included those astronauts who had completed an intensive shuttle flight training program and, as a result, were highly trained to fly the current orbiter flight control system. The second group consisted of pilots who did not have extensive shuttle flight training (pilots 7 to 11). This group included test pilots with shuttle landing simulation experience and astronauts who had not completed the intensive shuttle flight training program.

Control System Descriptions

The current orbiter flight control system was used as the baseline system. The baseline system and three additional systems were the primary configurations evaluated during the simulation studies (Table 1). Time history comparisons of the three additional systems with the baseline system are presented in Fig. 2 for a 1.0-deg/sec step input. Configuration A was considered to be a viable alternative to the baseline system and had a shaped pitch-rate feedback that increased pitch-rate overshoot. Configurations B and C also had increased pitch-rate overshoot and were chosen for ease of implementation on the orbiter. Configuration B was based on shaping of the pilot command with a prefilter, while configuration C was based on a blended normal acceleration and pitch-rate feedback. In addition, the baseline system and configurations A and B were evaluated with reduced time delay. This was accomplished by moving the pitch structural bending filter to the feedback path of the flight control system. This reduced the overall equivalent time delay by approximately 0.05 sec, from 0.20 to 0.15 sec. All systems were evaluated with the adaptive stick-gain system.[2]

VMS Tests

The Ames VMS facility used was a 6-degree-of-freedom moving base simulator with a digitally generated runway visual scene. The simulator was designed to provide very good vertical motion simulation capabilities and had a vertical motion range of ±30 ft and a vertical acceleration capability of ±1.0 g. Primary emphasis was on the landing characterisics under high-stress conditions. The landings were made with the normal out-the-window display information and without the use of the head-up display. The VMS simulation used a computer-generated display of a runway scene that provided adequate cues for performing the approach and landing task.

Two sets of tasks were devised. The first set consisted of the handling qualities tasks that provided six maneuvers representative of a cross section of wind and energy conditions so that a qualitative evaluation could be made of the longitudinal handling qualities. During these handling qualities maneuvers, the emphasis was on obtaining a qualitative evaluation of the handling qualities of each configuration. The approaches included the steep glideslope, preflare, inner glideslope, and touchdown regions. The tasks devised for the second set were high-stress tasks to obtain statistical performance data. These maneuvers consisted of up or down vertical disturbance with and without lateral offsets. The particular disturbance emphasized large flightpath corrections. The procedure was to fly in the automatic control mode to an approximate 110-ft altitude for the lateral-offset cases or to 75 ft with the straight-in cases. At that time, an up or down disturbance was introduced. The disturbance was a 15.0° stick command input for 0.75 sec after which the pilot would take over control, recover the aircraft, and complete the landing. The purpose of these high-stress landings was to provide a statistical data base for the assessment of the ability to touch down accurately during high-stress conditions. The following performance index based on touchdown parameters was determined for all high-stress landings that were performed:

$$PI = |\dot{h}| + |\dot{y}| + |\phi| + (EAS - 200)^2/67 + y^2/4500$$

where

PI	performance index
$\dot{h}$	touchdown rate of sink
$\dot{y}$	lateral touchdown velocity
ϕ	touchdown bank angle
EAS	touchdown airspeed
y	lateral touchdown displacement

With the high-stress landing cases, the pilot workload was believed to be sufficiently high so that little excess piloting capability was available. As a result, the landing performance was used as a direct measure of the pilot-system capability.

Several candidate systems were evaluated during the initial part of the VMS study. As a result of these tests, only one system (configuration A) was found to be a viable alternative to the baseline system. Ten pilots performed the handling qualities and the statistical performance evaluations of the new system and the baseline system. Half of these pilots were trained astronauts; the other half did not have extensive shuttle flight training.

TIFS Tests

The initial TIFS tests included evaluation and development flights for pilot familiarity and simulation validation. Following this phase, TIFS tests were conducted with two primary pilots who did not have extensive shuttle flight training. Pertinent test results were evaluated by a trained astronaut. Each test consisted of three approaches and landings: one was a straight-in approach; the other two had a left or right 200-ft lateral offset at about a 200-ft altitude and a vertical gust at about 50 ft. The approaches began about 4000 ft above the ground on the steep glideslope, and the evaluation concentrated on the flare and landing.

As with the VMS evaluation, the TIFS test data included both qualitative evaluations of the handling qualities and quantitative evaluations of the touchdown performance. However, in the TIFS study, the same maneuvers were used for both sets of data because the VMS high-stress task could not be safely used on the TIFS. Hence, the TIFS task was less demanding than the VMS high-stress performance task.

Results

Qualitative Evaluations

The VMS and the TIFS tests produced very similar results. Configuration A (shaped pitch-rate system) was used in the VMS evaluations, configuration B (prefilter system), and configuration C (blended acceleration and pitch-rate feedback system) were used in the TIFS evaluations. The characteristics of the three new systems are quite similar and are discussed later. A qualitative assessment of the VMS and TIFS results is presented in the following sections.

Steep Glideslope Task. The steep glideslope task was only evaluated in the VMS study. The two pilot groups showed no differences in their pilot ratings (PR) for this task (Fig. 3). Both pilot groups rated the baseline system and configuration A about the same, but the pilot comments indicated a slight preference for the baseline system, especially for small corrections.

Landing Task. In the VMS study, the baseline and configuration A systems were evaluated by a total of 10 pilots. For the landing task, these pilots were about evenly divided between those preferring configuration A and those preferring the baseline system. The average VMS pilot ratings for the high-stress inner glideslope and landing task are presented in Fig. 4. Some variation in the absolute pilot rating values of each configuration can be seen, but the trends of the configuration ratings relative to one another is quite consistent. For the inner glideslope and landing task, the data were divided into the two distinct groups. The trained astronauts preferred the baseline system and found it to be about 1.0 PR better than configuration A. These pilots had the most training with the baseline system. The pilots who did not have extensive shuttle flight training preferred configuration A and found it to be about 2.0 PR better than the baseline system.

The average pilot ratings from the TIFS study are also shown in Fig. 4 for the baseline system and configurations B and C. Pilot ratings obtained during the program are shown for one astronaut (pilot 6) and two primary pilots (pilots 7 and 8) who had no extensive shuttle flight training. If the baseline system was found to be adequate during the TIFS study, the task was described as easy. When the approach worked well, the baseline system seemed to be quite adequate for making fine corrections for a good landing (3.0 and 4.0 PR). When the approach was not set up well, the pilot had some difficulty in correcting the situation to obtain the desired landing conditions. When the baseline system was found to be deficient, a pilot described it as "touchy" and oscillatory. He was unable to exercise the system as much as he believed was required to achieve the desired performance. Generally, he experienced a high workload without good performance (5.5 PR).

Configurations B and C on the TIFS were generally described as instinctive and natural to fly by the pilots without extensive shuttle flight training (pilots 7 and 8). They rated these systems about the same as configuration A in the VMS tests. In the configuration B evaluation with a trained astronaut (pilot 6), the time delay was also reduced by moving the pitch structural bending filter to the feedback path. In general, pilot 6 liked the quickness of the system but found the overshoot characteristic distracting. (Further discussion of time delay effects is included in the Time Delay section.) For configuration C, pilot 6 found the system to be more oscillatory and the type of response was not desired. One detrimental aspect that was found by all pilots for configuration C was a greater response to the vertical gust than with the other configurations. This would be expected because the normal acceleration feedback in configuration C attempts to restore the flightpath rather than maintain pitch attitude.

Astronaut evaluations in the TIFS during natural turbulence indicated that the response appeared much more sluggish when turbulence was significant and did not seem at all typical of the orbiter. Without turbulence, the simulation was considered to be much closer to the actual orbiter. Due to weather conditions, most evaluations were made with some level of turbulence, and this probably contributed to the scatter in the results.

Time Delay

A brief assessment of the effect of time delay was made by pilot 6 during the TIFS study (Fig. 5). Moving the pitch structural bending filter to the feedback path reduced the equivalent time delay by approximately 0.05 sec for the baseline configuration. This produced a slight pilot rating improvement for a low-stress task (straight-in approach, no gusts). In addition, the high-stress task resulted in a slight pilot rating degradation for the baseline system. Configuration B with reduced time delay (not shown in Fig. 5) was also evaluated by pilot 6 for high- and low-stress tasks. This configuration showed no degradation due to the increased difficulty of the high-stress task (3.0 PR). Reduced-time-delay effects were also determined on the VMS for configuration A, and a small improvement due to time delay was seen for the 0.05-sec time delay change. These VMS and TIFS evaluations were made with the adaptive stick gain[2] which significantly reduces PIO susceptibility. The results in Fig. 5 are consistent with the results in Ref. 3 for large aircraft configurations. This indicates similar pilot rating trends due to additional time delay and shows that pilots are more tolerant to time delay with large aircraft than with fighter aircraft.

Performance Evaluations

The high-stress landing cases in both the VMS and TIFS studies were used to determine touchdown performance using the previously defined performance index as a direct measure of the pilot-system capability. The results of the VMS and TIFS evaluations are compared in Fig. 6. The VMS task was more difficult than the TIFS task, as reflected in the overall performance levels. Although the data base for the TIFS is very limited, the same general level of improvement was seen for the new systems over the baseline for both simulations. Figure 6 data indicate that VMS performance trends for the high-stress task are representative of trends obtained in a real-world high-stress task, such as those found with the TIFS.

The performance results were independent of the pilot rating results in the qualitative evaluations. The results clearly indicate a noticeable improvement in the ability to establish the proper conditions for landing with the new systems. The touchdown sink rates were approximately the same for the baseline and the new systems indicating that the pilots were sacrificing other parameters, particularly speed, to achieve acceptable sink-rate conditions.

Discussion of Pilot Control Techniques

The following is an interpretation of the evaluations and the pilot comments regarding the piloting techniques used for the landing task. In this section, data are presented to support a fundamental difference in the predominant control strategy between trained astronauts who prefer the baseline system and the pilots without extensive shuttle flight training who prefer the new systems. The following is a simplified discussion of the configurations and the control variables that the two pilot groups appear to be using in the landing task. For illustration, the time history comparisons were made using a 2-degree-of-freedom response. In the actual landings, the response is considerably more complicated because of the 3-degree-of-freedom response combined with the rapidly decreasing speed (about 4 knots/sec near touchdown).

Baseline System

General Characteristics. The calculated time history for the baseline system in Fig. 7 shows a 1.0-deg/sec step command held in 2 sec, producing a 2.0° change in flightpath. For this example, speed is held constant so that a 2.0° change in pitch attitude produces a 2.0° change in flightpath. The most significant feature about the baseline system is the characteristic known as dropback.[4] For this example, the pilot held in the control until the attitude changed 2.0° and then released the controls. The attitude overshot slightly but then returned to the 2.0° value that it had when the controls were released. This is known as zero dropback.[4] Because of the dropback characteristics, the pilot knows what the eventual flightpath will be at the time he releases the controls. The flightpath response lags the attitude by several seconds and is quite sluggish compared to the attitude response. Because the center of rotation is near the cockpit, the acceleration and rate of climb of the cockpit do not have the quick initial response of a conventional aircraft in which the pilot is located ahead of the center of rotation. For a conventional aircraft, the cockpit acceleration response provides a significant cue for controlling the flightpath.

Trained Astronauts. One interpretation of the astronauts' technique is they have learned to compensate for the lack of initial cockpit cues by performing the landing task primarily using the visual cues of pitch attitude and attitude rate. When attitude is used as a primary control variable, the zero-dropback characteristic becomes an extremely desirable feature. The attitude can then be used to provide considerable lead in determining the steady-state flightpath. The response to the 2-sec duration step shown in Fig. 7 is more typical of larger flightpath changes, such as the final flare. Smaller changes are often made with small pulse inputs.

Pilots Without Extensive Shuttle Flight Training. These pilots have not had the extensive training with the baseline system and, as a result, have not developed any special technique to compensate for the lack of cues due to the center-of-rotation effects. Direct observation of flightpath (or sink rate) derived from visual as well as kinematic cues appeared to be the primary control variable. The control problem was difficult because of the slow flightpath response. Pitch-attitude response may not have been a primary control variable and, hence, did not provide the same kind of lead information used by the trained astronauts. Reasonable control was obtained for slow changes (low bandwidth). However, problems arose when attempts were made to tighten up the control because of the difficulty of providing the necessary lead from the direct observation of flightpath. An additional factor was the difficulty in establishing the shallow glideslope from the preflare. Because of their lower proficiency in the approach profile, these pilots were required to make large corrections to establish the shallow glideslope. This added to the requirement for systems with good flightpath control characteristics for larger corrections.

Increased Pitch-Rate Overshoot Systems

General Characteristics. The primary difference between these systems (configurations A to C) and the baseline system was the amount of pitch-rate overshoot which, in turn, determined the amount of dropback. A time history of configuration B is shown in Fig. 8 for a 2-sec step input. A dropback in pitch attitude of about 0.5° occurred from the 2.5° that existed at the time the stick was released. The flightpath overshoot from stick release was also significant. The time required to reach 90 percent of the steady-state flightpath angle from the time of stick release was noticeably reduced from 2.2 sec (baseline system) to 1.3 sec. The most noticeable difference from the baseline system was the large amount of pitch-attitude overshoot before reaching the steady-state value.

Trained Astronauts. For large maneuvers, the astronauts had problems establishing flightpath using these systems. Increasing the angle of attack to achieve the correct attitude and the desired flightpath change actually produced a less than desirable flightpath change because of the dropback. An additional attitude correction was required. Because of the overshoot, the initial-to-steady-state response was increased, which incorrectly indicated that the system was much more dynamic. The response was quickened in terms of attitude control, but the improved flightpath response was not immediately apparent. Because of their extensive training, large initial responses associated with overcontrolling led to difficulties with the flightpath control. Near the ground, large pitch motions also produced large main gear motions because of the large lift changes with elevon deflection.

The result of these characteristics was that corrections for large flightpath changes were imprecise and additional corrections were required. The small pitch-attitude corrections were highly dynamic and were not easily correlated to flightpath changes. Because of these effects, the increased pitch-rate overshoot systems were more difficult for these trained astronauts to fly.

Pilots Without Extensive Shuttle Flight Training. As was the case with the baseline system, the pitch-attitude characteristics may have been transparent to these pilots in the control of flightpath. The most significant characteristic to these pilots may have been the quickened response in flightpath and rate of climb. As a result, flightpath control could be made quickly and more precisely than with the baseline system. The quickening of the flightpath response appeared to compensate partially for the lack of initial acceleration cues.

Discussion of Analytical Comparisons

In the Discussion of Pilot Control Techniques section, the apparent control strategy differences between the two pilot groups were examined by time history comparisons of the various systems. Longitudinal frequency-domain flying quality criteria, such as Neal-Smith[5] and the bandwidth[6] criteria, may also be used to provide additional insight into system characteristics. The results of the application of these criteria are presented in the following section.

Neal-Smith Criterion

The Neal-Smith criterion[5] is widely used to analyze the closed-loop pitch-attitude control of aircraft in the landing task.[7] This criterion was previously used to assess shuttle-like flying qualities in the landing task (for example, Ref. 8). The Neal-Smith criterion assumes that pitch-attitude control is the primary task of the pilot. It is based on a pilot model closing a single loop on pitch attitude. The pilot model operates on a pitch-attitude error signal that is the difference between the commanded attitude and the aircraft attitude. The pilot strategy for the Neal-Smith criterion is shown in Fig. 9. The pilot, through the flight parameters he is observing, tries to achieve a certain "standard of performance" which is defined by a specified closed-loop bandwidth. The bandwidth is defined by the 90.0° closed-loop phase requirement. At frequencies below the bandwidth, the pilot attempts to minimize steady-state pitch-attitude tracking errors as defined by a minimum low-frequency droop (typically no more than -3 dB). The pilot also attempts to minimize the closed-loop resonant peak $|\theta/\theta_c|_{max}$, which minimizes oscillatory tendencies in pitch attitude. The pilot model is adjusted so that the -3-dB droop and -90.0° of the closed-loop phase conditions are met for a given bandwidth while the closed-loop resonance is minimized. These parameters then provide a measure of compensation with which the pilot closes the loop in pitch attitude. After the closed-loop conditions are met, closed-loop resonance $|\theta/\theta_c|$ and pilot compensation for a given bandwidth are plotted on a Neal-Smith parameter plane and correlated with the pilot ratings for a longitudinal task.

The Neal-Smith pitch-attitude results for the baseline system and configuration A are presented in Fig. 10. Bandwidths of 1.5 and 2.0 rad/sec were selected as bandwidth values representative of large transport aircraft in the landing task.[3,8] As the pilot increases his low-frequency gain to achieve more precise pitch-attitude response (as indicated by the tighter droop constraints), significant differences are noted between the baseline system and configuration A. At -1-dB droop, the baseline system results in level I to II closed-loop resonance.[9] As a result, the Neal-Smith criterion predicts that the baseline system will provide the pilot with "solid" control and minimum overshoot tendencies in pitch attitude. When configuration A is subjected to the same droop constraints (particularly -1 dB), the required amount of pilot compensation is reduced. However, the closed-loop resonance has increased significantly (solid level II) above that for the baseline system. For the pilot using pitch attitude as the primary control variable, this would result in overshoot tendencies when tight control is attempted, which is undesirable. These results are found with all the new systems (configurations A to C) and their associated reduced-time-delay configurations (Fig. 11). These trends are supported by the observations of the trained astronauts who commented on attempting tight control of pitch attitude with the shaped pitch-rate systems and experienced a slight "bobble" or overshoot tendency during the VMS and TIFS studies.

Bandwidth Criterion

The bandwidth criterion[6] utilizes a bandwidth frequency determined from a closed-loop frequency response as a representative flying qualities metric for a closed-loop task. Lower bandwidths are indicative of less performance (significant tracking errors) as compared to aircraft with increased bandwidth capabilities that are considered desirable. The bandwidth is determined to be the lower frequency of the given closed-loop gain or phase margin. In addition, an estimate of the equivalent time delay is determined from the closed-loop frequency response. The bandwidth and time-delay measurements then provide an indication of the aircraft flying qualities.

The bandwidth criterion was applied to the flightpath closed-loop frequency response at the pilot station of the orbiter. Figure 12 presents the results for the baseline system and configurations A to C. The three new systems have an increase in flightpath bandwidth, which is indicative of the improved flightpath response. In addition, the new configurations exhibit lower flightpath equivalent time delays relative to the baseline system. The reduced-time-delay configurations for all systems also followed these trends. The improvement in flightpath response with the new systems is substantiated by comments from pilots without extensive shuttle flight training. They believed that these new systems were generally more instinctive to control in flightpath near the ground.

Conclusions

A handling qualities simulation was conducted by the Dryden Flight Research Facility of NASA Ames Research Center to determine if an improvement could be made in the longitudinal flight control system of the space shuttle orbiter for the high-stress landing task. The study was conducted using the vertical motion simulator (VMS) and the total in-flight simulator (TIFS) facilities. When compared with the current baseline system, the new systems that were tested had increased pitch-rate overshoot to improve the flightpath response. The pilots who preferred the baseline system were generally trained astronauts with extensive baseline system experience. These pilots appeared to use pitch attitude as a primary control variable. They were aware of the difficulties in controlling the orbiter. However, by using a control strategy based on extensive training with the baseline system, they were able to achieve desired performance. When using this technique with the new systems, these pilots believed that the orbiter was looser in attitude than with the baseline system and that this led to oscillations when making corrections. The pilots without extensive shuttle flight training thought that the baseline system made the orbiter response unpredictable and resulted in poor flightpath control. As a result, they did not have confidence in the system to do the landing task. With the increased pitch-rate overshoot system, these pilots had confidence in the system and believed that they had good, precise flightpath control for the landing task.

In addition to the handling qualities evaluations, a series of very demanding, high-stress landing tasks were performed to obtain a quantitative assessment of each system. Both the VMS and TIFS tests indicated improved landing performance with the increased pitch-rate overshoot systems as compared with the baseline system. This result was independent of pilot background, although control technique appeared to be a major factor in the pilot impressions of the various systems.

For the steep glideslope task, the tests indicated that most pilots believed the baseline system to be as good or better than the increased pitch-rate overshoot systems. They objected to the attitude dropback of the new systems that resulted from the pitch-rate overshoot.

The longitudinal characteristics of the baseline and new systems were examined with the Neal-

Smith and bandwidth flying qualities criteria. The control strategy of the trained astronauts was hypothesized as pitch-attitude control with increased low-frequency gain to achieve more precise pitch-attitude response. With this strategy, the Neal-Smith results indicated that the baseline system provided the pilot with "solid" control and minimum overshoot tendencies. On the other hand, the new systems with increased pitch-rate overshoot resulted in oscillatory tendencies under the same conditions. The pilots without extensive shuttle flight training were hypothesized to use flightpath more directly in their control strategy. A bandwidth criterion predicted that the new systems would have a higher attainable flightpath bandwidth and quicker flightpath response time than the baseline system, which was consistent with the pilot comments.

Overall, the new systems with increased pitch-rate overshoot provided better landing performance for the high-stress landing task. These systems appeared to be more suited to the normal control strategies of pilots with conventional pilot background. They also provided the potential of reducing the need for as much extensive training as that required with the current system.

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Table 1 Space shuttle orbiter flight control system description

Configuration	Description
Baseline	Current orbiter flight control system, low pitch-rate overshoot
A	Shaped pitch-rate feedback, increased pitch-rate overshoot
B	Prefilter-shaped pilot command, increased pitch-rate overshoot
C	Blended normal acceleration and pitch-rate feedback, increased pitch-rate overshoot

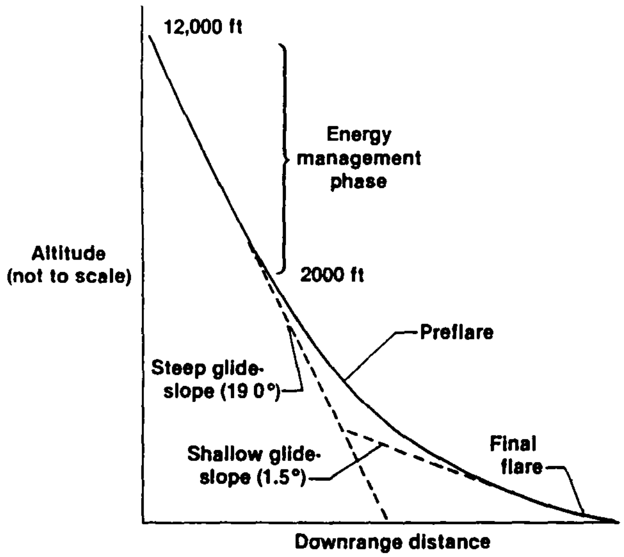


Fig. 1 Space shuttle operational technique.

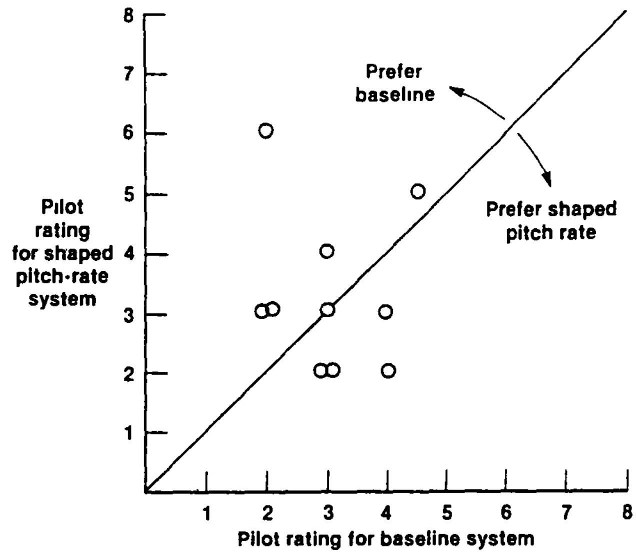


Fig. 3 Vertical motion simulator pilot ratings for steep glideslope.

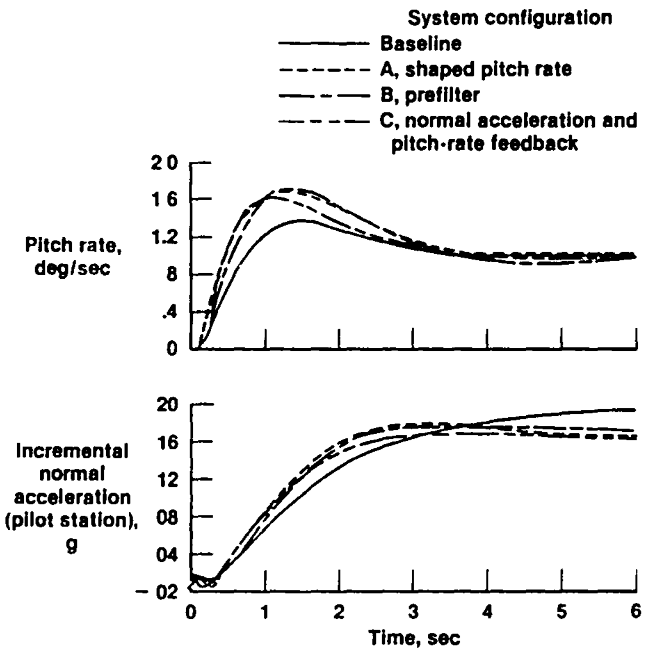
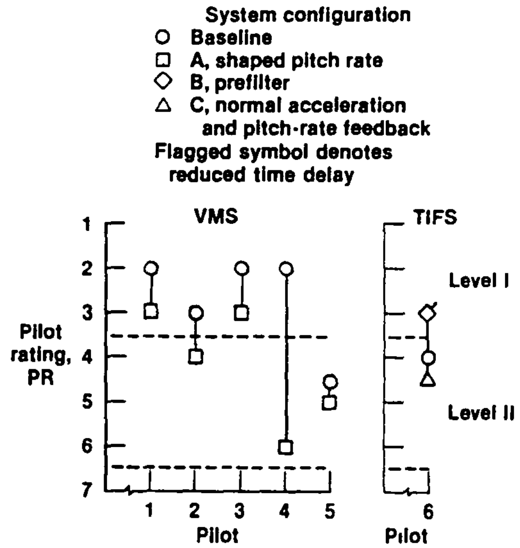
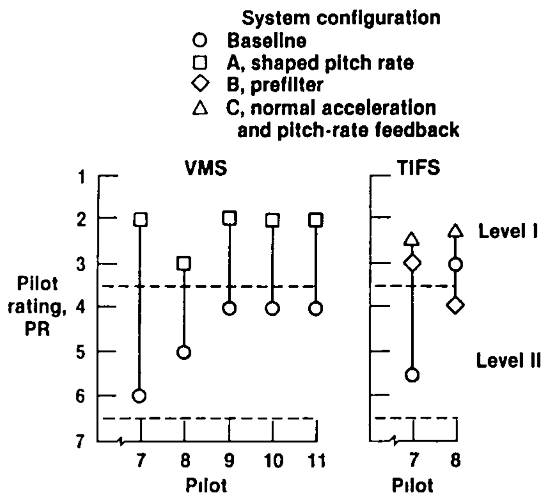


Fig. 2 Calculated space shuttle time histories, 1.0-deg/sec command input.



a) Trained astronauts.

Fig. 4 Average pilot ratings from VMS and TIFS studies (high-stress, inner glideslope, and landing task).



b) Pilots without shuttle flight training.

Fig. 4 Concluded.

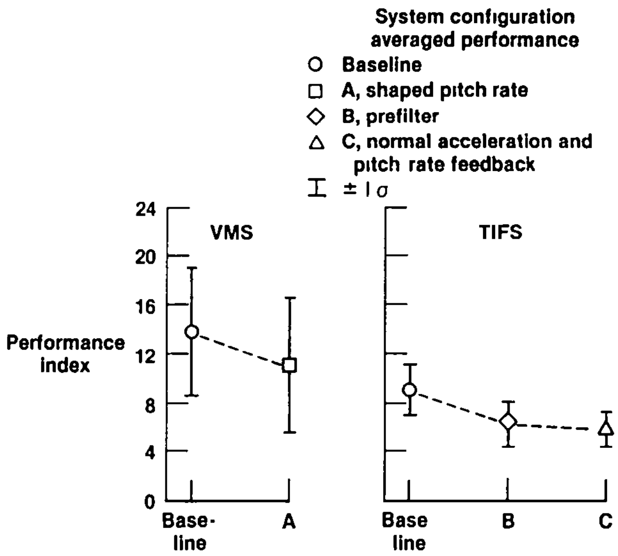


Fig. 6 Performance statistics for high-stress landing task.

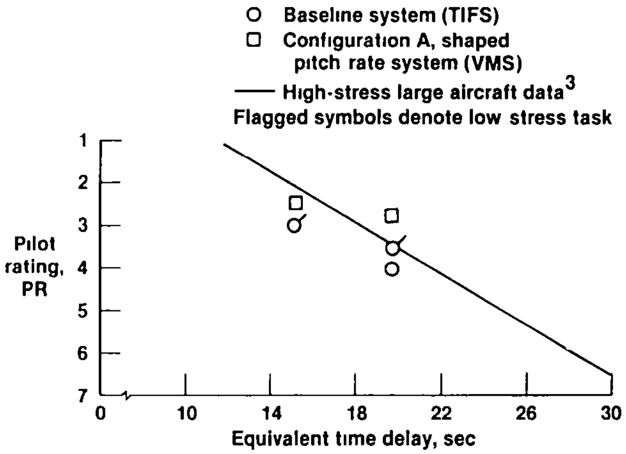


Fig. 5 Reduced-time-delay results of VMS and TIFS studies.

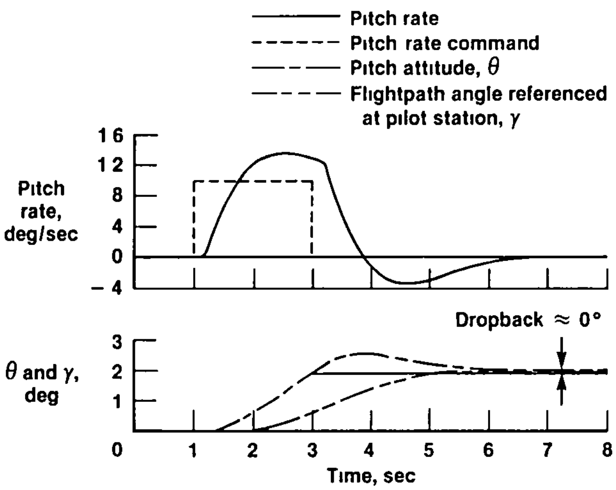


Fig. 7 Calculated response for baseline system, 2 degrees of freedom.

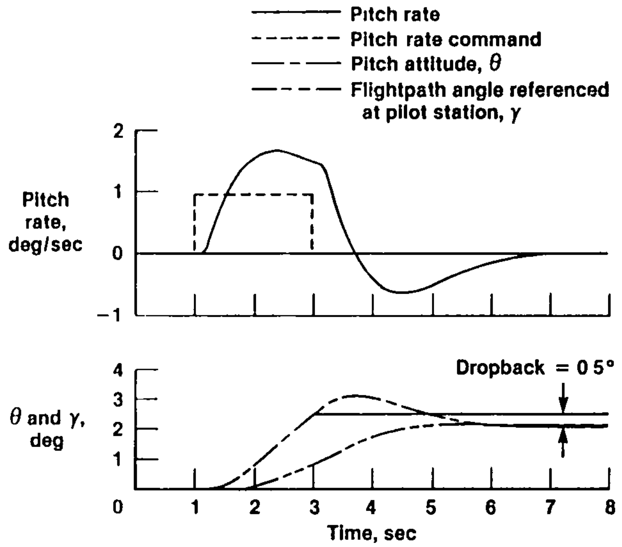


Fig. 8 Calculated response for prefilter system, 2 degrees of freedom.

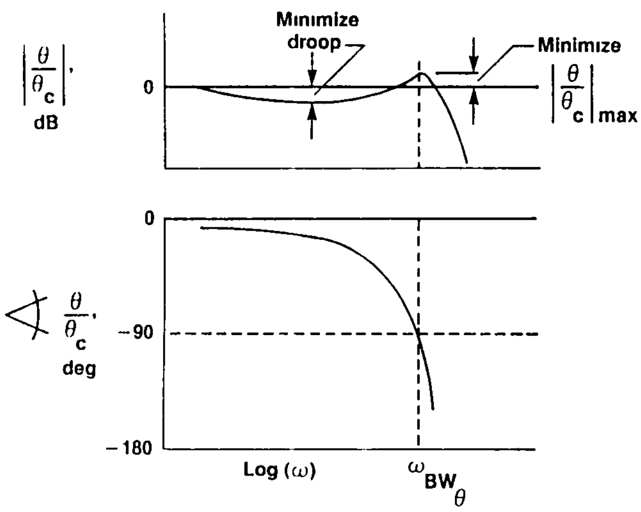


Fig. 9 Neal-Smith pilot strategy, closed-loop pilot-vehicle frequency response.

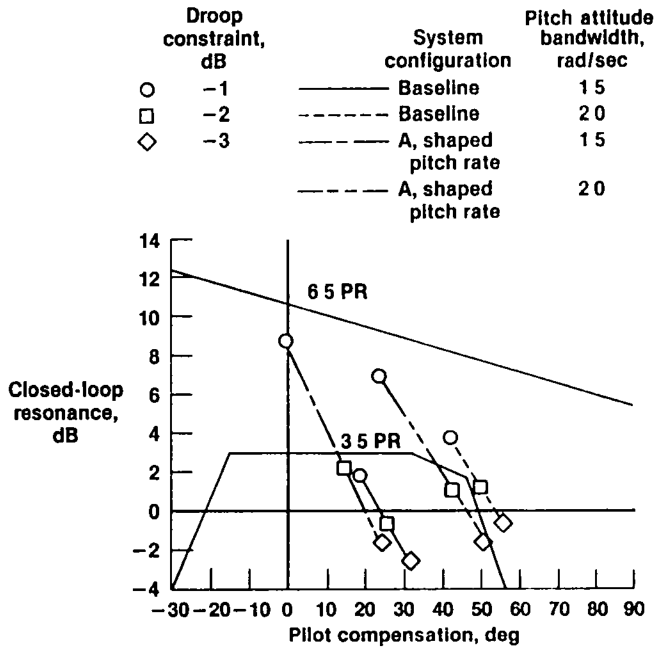


Fig. 10 Neal-Smith results for pitch-attitude loop closure for baseline system and shaped pitch-rate system.

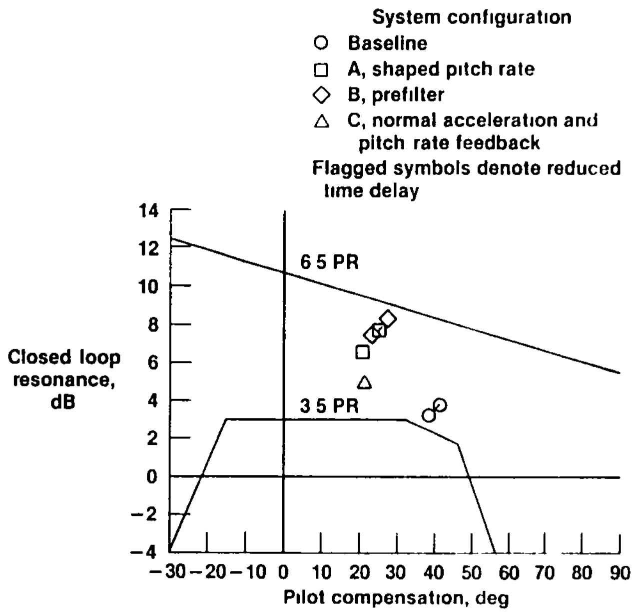


Fig. 11 Neal-Smith results for pitch-attitude loop closure, 1-dB droop constraint.

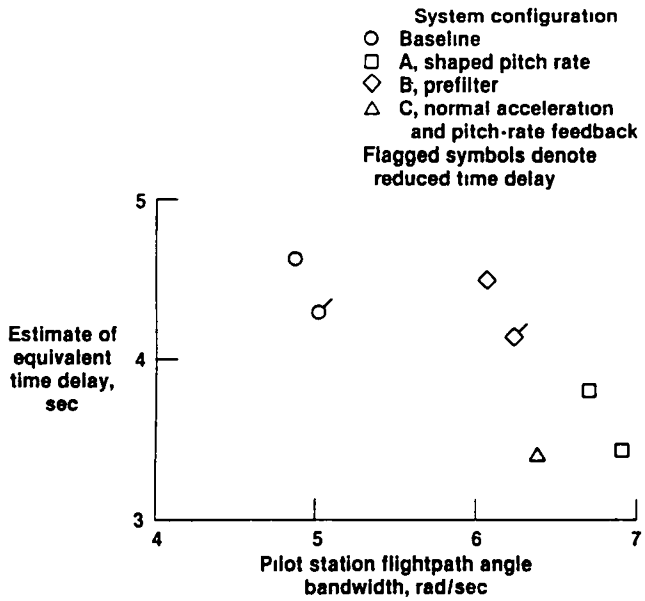


Fig. 12 Bandwidth and time-delay results, flight-path angle at pilot station.

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15 Supplementary Notes

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16 Abstract

Simulations of the space shuttle orbiter in the landing task were conducted by the NASA Ames-Dryden Flight Research Facility using the Ames Research Center vertical motion simulator (VMS) and the total in-flight simulator (TIFS) variable-stability aircraft. Several new control systems designed to improve the orbiter longitudinal response characteristics were investigated. These systems improved the flightpath response by increasing the amount of pitch-rate overshoot. Reduction in the overall time delay was also investigated. During these evaluations, different preferences were noted for the baseline or the new systems depending on the pilot background. The trained astronauts were quite proficient with the baseline system and found the new systems to be less desirable than the baseline. On the other hand, the pilots without extensive flight training with the orbiter had a strong preference for the new systems. This paper presents the results of the VMS and TIFS simulations. A hypothesis is presented regarding the control strategies of the two pilot groups and how this influenced their control system preferences. Interpretations of these control strategies are made in terms of open-loop aircraft response characteristics as well as pilot-vehicle closed-loop characteristics.

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