Handling Qualities for Pilot Control of Apollo Lunar-Landing Spacecraft

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Piloted simulations of the lunar-landing maneuver were conducted at the Manned Spacecraft Center to determine control problems and required handling qualities of lunar-landing spacecraft. The studies examined control problems and handling qualities required to complete the final approach to landing starting from ranges of 2000 to 3000 ft from the desired landing site. Results of the simulation studies indicated that satisfactory handling qualities could be obtained with control powers of the order of 10 deg/sec^2 for the rate command control using proportional firing thrusters, and that control powers of the order of 5 deg/sec^2 provided satisfactory handling qualities for the rate command control system employing on-off thruster firing logic. Within a satisfactory range of maximum rate command and control power available, the pilots tolerated equivalent time constants up to 1 sec in the proportional system and equivalent time constants of the order of 3 sec in the on-off thruster logic control system. In addition, the simulation studies showed that the direct on-off logic control system (no rate feed-back) would probably not provide satisfactory control handling qualities for the lunar landing.

Introduction

THE Apollo mission lunar-landing maneuver presents a most critical problem of spacecraft control. To overcome some of the difficulties of avoiding local terrain obstructions while locating a good landing site and to utilize fully the crew's judgment capability, provision is being made for the astronaut crew within the lunar excursion module to take over from the automatic control system, select a suitable landing site, and control the landing touchdown. The ability of the astronaut to control this maneuver satisfactorily will depend upon the design engineers' success in anticipating the nature of the control task and upon the subsequent provision of a control system satisfactory for the task. Because the gravitational environment of the moon differs from that of the earth, the astronauts will be able to practice this maneuver only under simulated conditions; hence, the success of anticipating the control requirements of the maneuver will not be known for certain until after the first lunar landing.

The control of the touchdown part of the lunar-landing maneuver will resemble somewhat the control of vertical takeoff and landing (VTOL) aircraft in the earth environment. Some of the wealth of information on VTOL handling qualities may thus be applied to lunar landing; however, the effects attributable to such factors as the differences in gravitational environment and differences in control-system mechanization must first be understood. From an over-all standpoint, the time-critical aspects of the control of the landing-approach maneuver have little parallel experience in earth-atmospheric flight. Consequently, the problem must be considered as a new one that requires careful examination prior to finalizing control-system design.

The purpose of this paper is to describe the lunar-landing maneuver in sufficient detail to allow appreciation of the problem of control and to present the results of simulation studies conducted to date which have been aimed at establishing handling-qualities data that could be used as the basis for a control-system design.

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Description of the Lunar-Landing Maneuver

The Apollo lunar excursion module (LEM) pictured in Fig. 1 must provide the means for retromaneuvering out of lunar orbit, decelerating to a soft landing, and then, after a stay on the surface, accelerating back into orbit for a rendezvous with the Apollo command module. These over-all aspects of the LEM mission are portrayed in Fig. 2. Detailed analysis of the system requirements for performing these maneuvers has led to a design configuration having two stages. Staging would normally occur on the lunar surface so that the weight of the descent stage and the landing gear would not have to be carried back into orbit. An early design decision made in the interest of saving weight was to utilize a single attitude-control system to serve both stages. With a single attitude-control system, the possibility of control-sensitivity problems becomes important because the inertias of the spacecraft, partly because of staging, change by approximately an order of magnitude during the time from initial separation from the command module until rendezvous is completed after the lunar landing. Although the landing maneuver takes place about halfway through the powered portion of the LEM mission, it occurs before most of the change in moment of inertia. As a result, extreme care must be used in selecting control powers that will provide satisfactory landing control and, at the same time, avoid excessive control powers during the powered ascent and/or docking maneuvers.

Analysis of the descent maneuver, including consideration of operational factors for pilot manual control, has led to the three-phase trajectory design shown in Fig. 3. The descent trajectory covers approximately 200 naut miles over the surface of the moon while the altitude is decreased from 50,000 ft to the surface. The first phase, which covers most of the distance traveled, is designed primarily to provide the most reduction in velocity for the least expenditure of fuel. The vehicle during this phase is oriented so that the thrust of the main engine is essentially opposite to the direction of flight. In this attitude, the astronaut crew will not be able to see in the direction of the landing site because of the limited field of view afforded by the windows. As the landing area is approached, however, transition is made to the second phase, where the spacecraft is pitched up to an attitude that allows the astronaut crew to begin observing the landing area. The

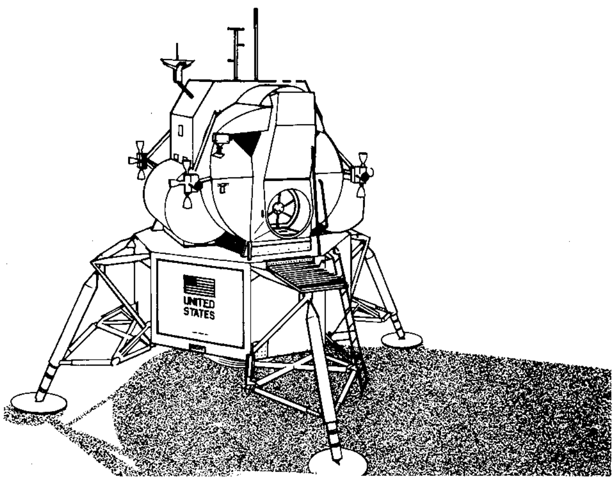


Fig. 1 Artist's concept of LEM spacecraft.

planned position and velocity at the point of transition to the second phase is attained through explicit guidance and is planned to allow the approach to the landing site to be made at a deceleration level considerably lower than the maximum descent engine thrust capability. The advantage of the lower deceleration, obtained by reducing the throttle level of of the descent engine, is that the rate of velocity change becomes more in line with the pilot's ability to keep track of the situation. This phase will last about 2 min, in which time the trajectory will cover 6 to 8 miles and the velocity will decrease from about 800 to perhaps 100 fps entering the final or touchdown phase. Although the second phase is purposely lengthened in time, it represents a maneuver that has no parallel in earth-bound experiences of landing approaches. In addition to monitoring the large changes in velocity and altitude in this short phase, the pilot must also begin to evaluate the suitability of the landing area, to pick out a desired landing position, and to evaluate the need to take over and fly manually the final phase of the descent maneuver. All of these events occur in approximately the same amount of time as that available to an airplane pilot during an instrument approach between the final checkpoint and the landing touchdown.

The third phase of the descent is called the touchdown phase, and during this phase the spacecraft is pitched up to essentially a vertical attitude and flown in much the same way as a VTOL aircraft. In this phase, the final selection of the touchdown position is made, and the spacecraft is maneuvered to the position for the actual touchdown on the lunar surface. Translation velocities over the surface during this phase are controlled by tilting (roll or pitch) the spacecraft in the direction of the desired velocity change in order to use the horizontal component of the descent propulsion to accelerate the spacecraft in that direction.

Because of the similarity of flight maneuver during the touchdown phase to that of VTOL aircraft, there is a temptation to limit the concern about the handling qualities of the

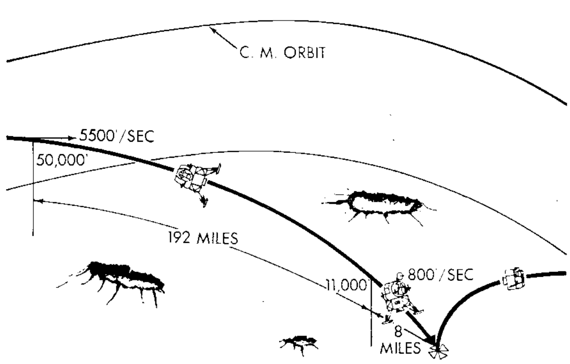


Fig. 2 LEM lunar-landing mission.

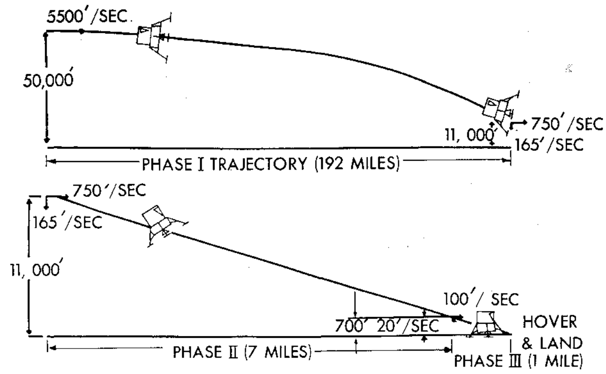


Fig. 3 Velocity and attitude conditions, three-phase trajectory showing nominal.

LEM to just this phase and to extrapolate data for VTOL aircraft to the LEM handling-qualities application. Although such data may have an application to the LEM control problem, the large changes in the attitude of the spacecraft and the short time actually allowed for transition from the landing-approach phase to the touchdown phase must also be considered. The time-critical nature of the pilot task during the landing-approach phase may lead to important and significantly different handling-qualities requirements.

Description of Study Approach

General

The need for knowledge of lunar-landing control requirements preceded the evaluation of contract proposals for the LEM, and thus the need, at least for preliminary information, was recognized some 3½ years ago. At that time, such research facilities as the lunar landing research vehicle of the NASA Flight Research Center and the lunar landing research facility of the NASA Langley Research Center were both in the conceptual stage, and there were no flight vehicles suitable for other than extremely limited studies of the lunar-landing control problems. The decision was made to obtain the needed information through fixed-base simulation. After an initial study phase conducted under contract,[1] the studies have been conducted in-house by the Guidance and Control Division of the Manned Spacecraft Center. As a result of these studies, the simulation facilities and the fidelity of the simulated problem have grown as the knowledge of control requirements allowed the definition of the LEM control system. The studies, which are described in the succeeding

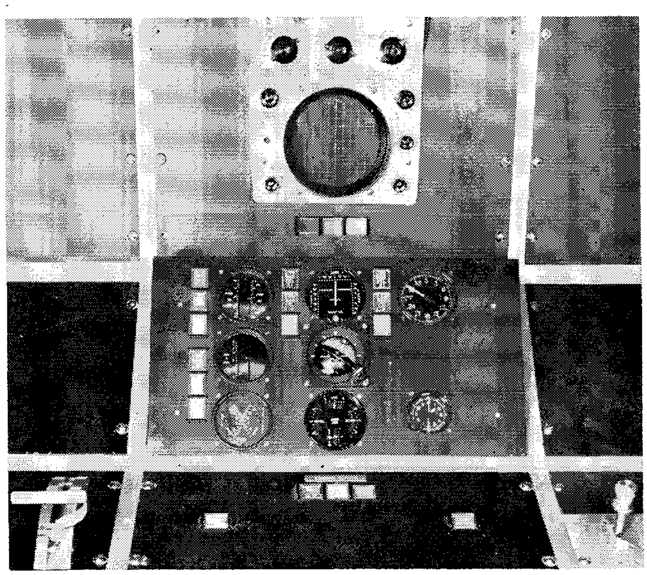
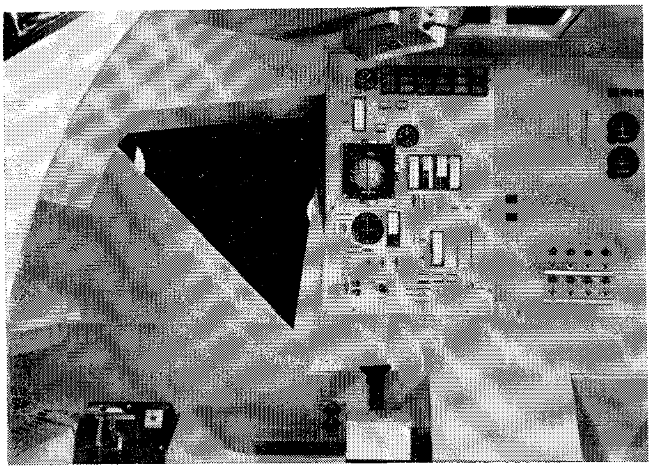
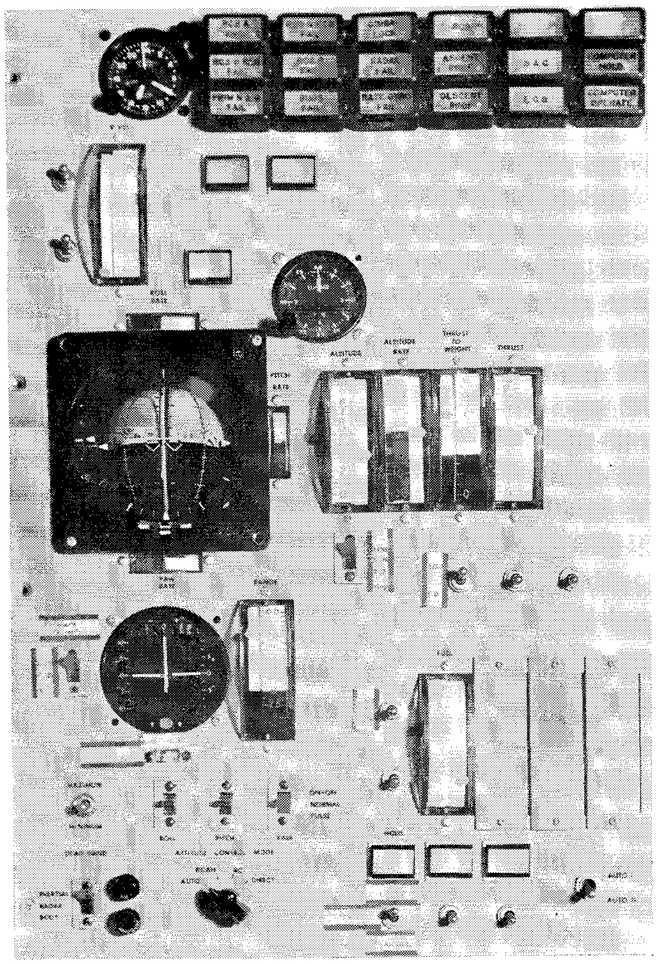


Fig. 4 LEM cockpit simulation.



a) Over-all view



b) Instrument panel

Fig. 5 LEM cockpit used for handling qualities verification.

sections, represent essentially the growth of handling-qualities knowledge from the time before the LEM contract was awarded to the present time.

Information requirements

Simulation program was conducted to provide answers to a series of questions about the LEM control system on the following subjects: 1) required control characteristics, 2) effect of disturbance torques, and 3) effect of deadband and other control-system detail characteristics.

Description of Simulations

Cockpit

The handling-qualities studies have been implemented by coupling an analog solution of the dynamic equations of motion to fixed base, with partial simulation of the spacecraft cockpit containing pilot flight instruments and controllers. The cockpit simulations in these studies have ranged from functional layouts (Fig. 4) to arrangements that are almost identical to the current LEM vehicle (Fig. 5). Flight displays varied in arrangement for the various studies, but all included 1) attitude indicator, 2) body angular rates, 3) forward and lateral velocities, 4) attitude, 5) attitude rate, 6) main-engine thrust-to-weight ratio, and 7) main-engine thrust. The downrange and crossrange landing site location was indicated to the pilot on an oscilloscope for the studies using the early cockpit, but a virtual-image display of the landing was available to the pilot for the simulation using the cockpit of Fig. 5. Two attitude controllers were used; the pencil type shown in Fig. 4 in the early studies, and the hand controller shown in Fig. 5a, which approximates the controller configuration of the LEM. Both were three-axis types. The main engine for these simulations was throttleable over a 10:1 ratio and was controlled by the throttle shown in Fig. 5a. Minimum throttle setting gave a thrust outupt that produced approximately $\frac{1}{2}$ of a lunar g (2.6 ft/sec^2) at landing-approach weights.

Equations of Motion

The equations of motion for the studies were for six degrees of freedom of the spacecraft over a "flat" moon. The simulations were concerned with flight operation within a few thousand feet of the lunar surface; therefore, the gravitational field was assumed constant to simplify the equations. The mass of the vehicle was varied, but the moments of inertia were maintained constant. A flow diagram representative of the simulations is shown in Fig. 6.

Control System

The attitude-control systems investigated in the studies included rate-command systems and an open-loop system in which pilot actuation of the controller produced direct actuation of the attitude thrusters and a corresponding angular acceleration. The rate-command system is depicted by the block diagrams of Fig. 7. The study program included two variations of the thruster response to rate-error signals, as shown in Fig. 7a. Early studies assumed a proportional thruster characteristic, but considerations of limited thruster output led to the quasi-linear thruster characteristic shown in Fig. 7a, in which the thruster output is proportional until thruster saturation. Early design considerations of the LEM control system indicated the probability of utilizing thrusters that would operate either full on or off, and the simulation of such a system configuration is shown in Fig. 7b. This simulated mechanization allowed variations in the electronics

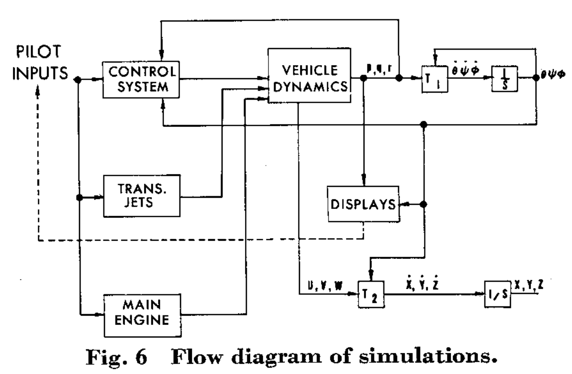


Fig. 6 Flow diagram of simulations.

Table 1 Pilot opinion rating system for universal use

Allowable operation	Adjective rating	Numerical rating	Description	Primary mission accomplished?	Can be docked?
		1	Excellent, includes optimum	Yes	Yes
Normal	Satisfactory	2	Good, pleasant to fly	Yes	Yes
		3	Satisfactory, but with some mildly unpleasant characteristics	Yes	Yes
		4	Acceptable, but with unpleasant characteristics	Yes	Yes
Emergency	Unsatisfactory	5	Unacceptable for normal operation	Doubtful	Yes
		6	Acceptable for emergency condition only[a]	Doubtful	Yes
		7	Unacceptable even for emergency condition[a]	No	Doubtful
None	Unacceptable	8	Unacceptable, dangerous	No	No
		9	Unacceptable, uncontrollable	No	No
None	Catastrophic	10	Motions possibly violent enough to prevent pilot escape	...	...

[a] Failure of a stability augmenter.

deadband shown in the on-off thruster logic block, as well as variations in the thrust output levels. This electronic deadband is separated from the electromechanical deadbands that are incorporated into the pilot's control actuator to avoid inadvertent control input coupling.

Test Maneuver

The test maneuver used in evaluating the attitude-control system resembled the latter part of the lunar-landing approach maneuver previously described (Fig. 3). For most of the early studies, the initial limits of the run were approximately 3000 ft uprange and 1000 ft crossrange from the intended landing site. The initial altitude was 500 ft, and velocities ranged from 0 to 50 fps. The pilot was instructed to proceed from his initial point to the landing site, establish a momentary hover over the site, and then execute a touchdown. Later in the series of studies, the approach maneuver was started at ranges of up to 50,000 ft, altitudes to 15,000 ft, and velocities of the order of 1000 fps. Throughout the studies, the hovering portion of the maneuver was used to obtain evaluation data that were later verified during the landing approaches of longer duration.

Test Subjects

In the studies of handling qualities, the test subjects were principally currently qualified pilot engineers attached to the Manned Spacecraft Center Flight Crew Support Division. For the later studies when the cockpit simulators began to resemble that of the LEM spacecraft, astronauts also participated in the evaluation.

Evaluation of Simulation Results

The evaluation of the handling qualities of the control systems investigated during these studies was based on pilot opinion using the standard definitions and rating scheme according to the Cooper Rating Scale.[2] On this scale of 0 to 10, a pilot rating of 3.5 defines the boundary between satisfactory and acceptable, and a rating of 6.5 defines the boundary between acceptable and unacceptable handling qualities (Table 1).

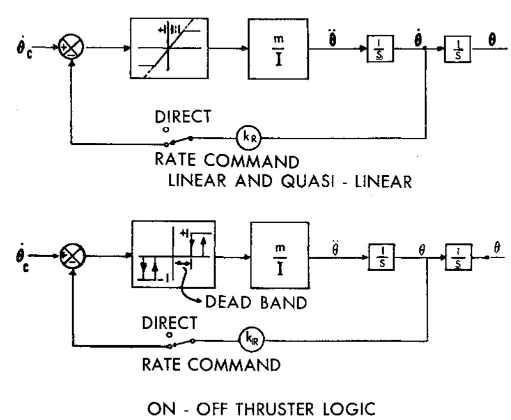


Fig. 7 Block diagrams of control systems investigated.

Results and Discussion

Rate Command

Proportional thruster operation

The evaluation of lunar-landing handling qualities in which a rate-command attitude-control system with proportional firing thrusters was used resulted in curves that defined boundaries of satisfactory, acceptable, or unacceptable control, as shown in Fig. 8. The curves, or boundaries, are plotted for combinations of controller sensitivity in degrees per square second per inch and time constant. Although the boundaries have been shown as distinct lines, there is a degree of uncertainty associated with their determination, and thus they would be more appropriately shown as bands separating the various areas. These lines, however, represent very nearly the center of the bands of uncertainty and can be used to evaluate control characteristics, provided that the bands are considered in the final evaluation. The boundaries shown are applicable to both pitch and roll. For yaw control, a limited amount of test data indicated a slightly larger area of satisfactory control, but not enough to warrant a separate figure. Tests conducted on the quasi-linear (limited thruster

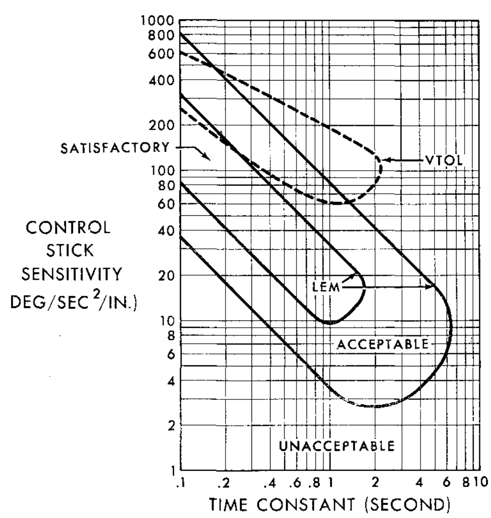
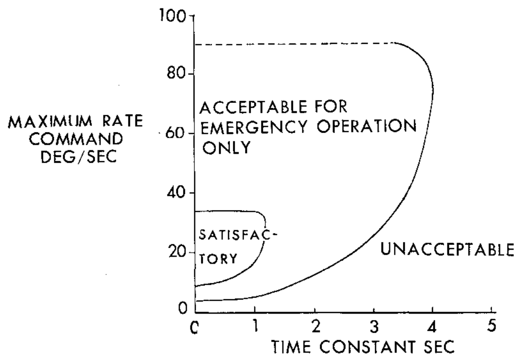
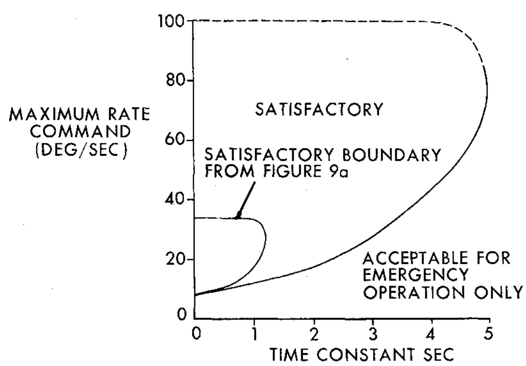


Fig. 8 Satisfactory and acceptable boundaries for rate command system (linear thruster operation).



a) **Proportional thruster operation**



b) **On-off thruster operation, 0.1-deg/sec deadband**

Fig. 9 Satisfactory and acceptable boundaries for rate command control mode.

output) control system indicated that the pilots rated this system very nearly the same as the proportional system, and thus, the boundaries of Fig. 8 are also applicable to the quasi-linear control mechanization.

On the log-log scale used in Fig. 8, most of the satisfactory and acceptable boundaries consist of straight-line relationships of controller sensitivity with time constant. These straight lines are lines of constant rate command and are equivalent to an upper rate command of 32 deg/sec/in. and a lower value of 8 deg/sec/in. for satisfactory control. Acceptable control-rate commands are equivalent to 90 and 5 deg/sec/in. for the upper and lower boundaries, respectively.

The results shown in Fig. 8 indicate that satisfactory handling qualities can be obtained over a wide range of controller sensitivities, provided that the time constant is related to the sensitivities, as shown in the figure. Early in the studies, it was recognized that the controller sensitivity of the LEM would be low because of the limited available control power, and these studies showed the existence of a small area of controller sensitivities of less than about 10 deg/sec^2/in. which would provide satisfactory control operation. The existence of this area of satisfactory operation has also been established in fixed base simulation studies conducted by the NASA Flight Research Center.[3]

Satisfactory handling qualities for lunar-landing vehicles can be obtained at significantly lower controller sensitivities than those for VTOL aircraft, as shown by the satisfactory boundary for VTOL[4] plotted in Fig. 8. However, the primary difference lies not so much in the spread of controller sensitivities as in the extremely large differences in the absolute values of control power required to obtain satisfactory handling qualities in the two vehicles. The controllers used in the present studies had throws of approximately 1 in., and thus the total control power available is approximately equal to the magnitude of the controller sensitivity. The vertical/short takeoff and landing (V/STOL) aircraft had a center stick with a throw of several inches, and, therefore, the available control power in the V/STOL is the product of controller throws of several inches and controller sensitivity. This point is significant because the pilot of a lunar-landing vehicle is able to command and use the maximum control power with small displacements, whereas V/STOL control sensitivity requires many times the available LEM control power to maintain these required sensitivities over the total throw limits of the controller.[3] Another factor contributing to the differences in controller sensitivity requirements is reduced lunar gravity, but precisely how much this factor influences handling qualities and controller sensitivities is not known because investigations in this area have been limited. Sufficient tests have been made, however, to indicate that the environment does have some effect.

The straight-line relationship between controller sensitivity and time constant indicated in Fig. 8 leads to the conclusion that the important parameters are rate command and time constant provided that controller sensitivity is compatible with the pilot's desired input. This is a logical conclusion, since it seems that the describing parameter for a rate-command attitude-control system should be rate command. For this reason, the curves of Fig. 8 have been replotted for maximum rate command as a function of time constant, and the results are shown in Fig. 9a. The upper and lower boundaries for satisfactory operation are located at maximum rate commands of 34 and 10 deg/sec, respectively, for time constants of less than about 1.2 sec. The inference here is that maximum rate command is the important parameter, and, within a satisfactory range of this variable, the pilot will tolerate time constants of up to 1 sec. Such an inference is reasonable because, for low control powers, a high maximum rate is undesirable because of the time required to reduce high rates once they have been commanded. The upper limit of rate command is more a function of controller sensitivity than control power.

On-off thruster logic operation

Investigations during the proportional thruster studies have indicated that handling qualities could be improved by increasing the thruster-on slope from its normal 1:1 ratio (Fig. 7a). As the thruster-on slope is increased, the proportional operation approaches the characteristics of an on-off thruster logic. (With the on-off thruster logic, full thruster output is always used to change attitude rather than an output that is proportional to the difference between actual and commanded rates). This is particularly significant for small attitude-rate changes because the maneuver is made rapidly because of the large control moment employed. For large rate changes, the difference between proportional and on-off thruster-system response is not large, but it is still noticeable.

To investigate the effect of on-off thruster operation on handling qualities, further studies were made by using the refined control mechanization shown in Fig. 7b. This control

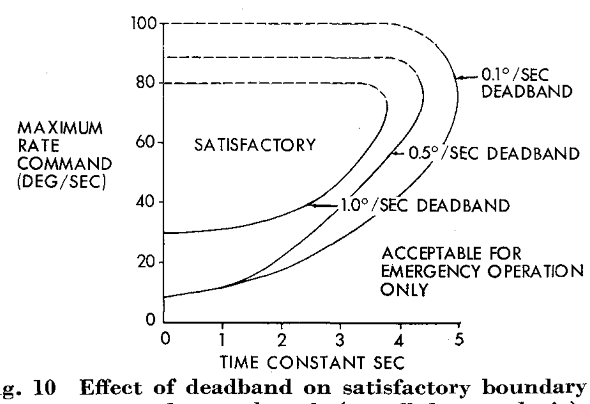


Fig. 10 Effect of deadband on satisfactory boundary of rate command control mode (on-off thruster logic).

system arrangement had, for the pilot, response characteristics that were almost identical to those of the control system in the LEM spacecraft. The results of the studies with a control system having a rate deadband of 0.1 deg/sec are given in Fig. 9b. The satisfactory boundary has been plotted as a function of maximum rate command and "time constant;" strictly speaking, time constant has no meaning for a nonlinear system. To obtain the values in Fig. 9b, the normal definition of time constant (time to reach 63% of commanded value) was applied. This allows the proportional and on-off thruster operation to be plotted and discussed in similar terms. As indicated in Fig. 9b, the satisfactory region extends from rate commands of 10 to 100 deg/sec for time constants of up to 5 sec. The upper limit on rate command is probably not closed, as shown by the dotted line, since the upper boundary is a function of controller sensitivity which was not varied during the study. On-off thruster operation, however, results in a much larger satisfactory region than the proportional thruster operation. In fact, the satisfactory boundary for the on-off thruster operation is almost as large as the acceptable region for the proportional thruster operation. No attempt was made to obtain the boundary between acceptable and unacceptable control; thus the region beyond the satisfactory boundary has been described as "acceptable for emergency operation only."

Effect of deadband on on-off thruster operation handling qualities

The effect of the size of the rate deadband on handling qualities of on-off thruster operation was also determined. A knowledge of this effect was necessary, since the rate deadband must be incorporated into the control logic to prevent inner loop instability and also to limit attitude-fuel usage during steady-state control operation. There are, however, tradeoffs in the selection of the proper deadband: Small rate deadbands result in excessive fuel consumption, whereas large deadbands cause high residual rates with the attendant drift from a selected attitude. The deterioration in handling qualities resulting from increased rate deadbands is shown in Fig. 10. The satisfactory boundary decreases as the deadband is increased from 0.1 to 1.0 deg/sec, although the deterioration in handling qualities is not appreciable until the deadband has been increased beyond 0.5 deg/sec. This derating occurs as the deadband is increased because the high residual rates force the pilot to concentrate heavily on attitude control at the expense of other flight variables. The primary effect of increased deadbands is to increase significantly the lower satisfactory boundary. The pilot desires high rates to compensate for attitude drift, although increasing the controller sensitivity might produce the same effect. In addition, the control power required to obtain satisfactory handling qualities for a deadband of 1.0 deg/sec is almost twice the minimum required for a 0.1-deg/sec deadband. This can be seen by drawing lines through the original tangent to the lower boundaries of the 0.1- and 1.0-deg/sec curves and calculating the slopes of the two lines.

The upper boundaries for the three deadbands in Fig. 10 are shown as dotted rather than solid lines. Actually, the upper boundaries for the 0.5- and 1.0-deg/sec deadbands were determined, but since these boundaries are functions of controller sensitivity (which was not varied), they are subject to change. Scattered data indicated that the upper boundary for the 0.1-deg/sec deadband exists near the 100-deg/sec limit, but the rate command used in the study was limited to 100 deg/sec, and thus the boundary may actually be higher than the dotted lines indicate.

Effect of Main Engine Thrust Misalinement

A lunar-landing spacecraft such as the LEM will, of necessity, carry a fuel load that represents a large percentage of the

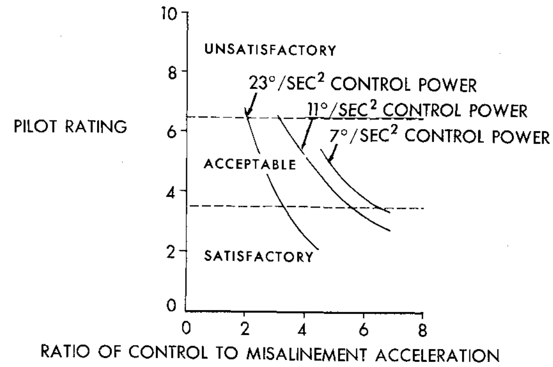


Fig. 11 Effect of misalinement torque on pilot rating.

total weight. Spacecraft design procedures will attempt to locate this fuel load so that, as the fuel is used, the center of mass of the spacecraft remains close to the thrust vector of the main engine to keep disturbance torques to a minimum. In spite of design efforts, the center of mass will undergo adverse shifts, and it is important to assess the effects of the resulting disturbing torques upon control handling qualities. To accomplish this assessment, a range of steady disturbing torques typical of the magnitude attributable to center-of-mass movements was introduced to the spacecraft dynamics, and the handling qualities with a series of typical control powers were evaluated. The results of this portion of the study are shown in Fig. 11, which plots pilot rating as a function of the ratio of control power to misalinement acceleration for three separate control powers.

As indicated in the curves, the pilot's ability to compensate for thrust misalinement torques deteriorates rapidly with decreasing control power. The satisfactory boundary for a control power of 23 deg/sec^2 occurs at a ratio of 3.5, at 5.5 for an 11.5-deg/sec^2 control power, and at 6.5 for a 7-deg/sec^2 control power. These boundaries indicate, as would be expected, that pilot reaction in the presence of misalinement torques is a function of both the available control power and magnitude of the misalinement torques. The pilot requires enough control power in excess of the disturbing torques to perform the required maneuver, with response times compatible with the basic handling qualities evaluation. The effect of disturbance torques leads to pilot control difficulties because the vehicle response is different in the two directions about a given axis. (The true control power in the direction of the misalinement acceleration is the sum of the actual control power plus the misalinement acceleration, whereas in the other direction it is the difference between the two accelerations.) Thus, the pilot can maneuver in one direction quite readily, but not in the other. However, if the basic vehicle control power is large compared with the misalinement acceleration, the pilot cannot detect as readily the difference between maneuvering in opposite directions, because the misalinement acceleration is effectively masked.

The results obtained were conclusive enough to indicate that compensation for misalinement torques should not be made by pilot operation of the attitude-control system. Studies of the effect of thrust misalinement on on-off thruster operation were limited, but enough test cases were investigated to determine that the handling qualities were generally unsatisfactory. In any event, practical considerations make it impossible to supply sufficient control power to design a control system with satisfactory handling qualities in the presence of the expected LEM misalinement torques. For example, the results show that a control power of 5 deg/sec^2 with a time constant of 4 sec provides satisfactory handling qualities in the present LEM provided that there are no misalinement torques, but to provide a control system having satisfactory handling qualities without correcting the actual expected misalinement torques of the LEM spacecraft would require a control power of the order of 15 deg/sec^2.

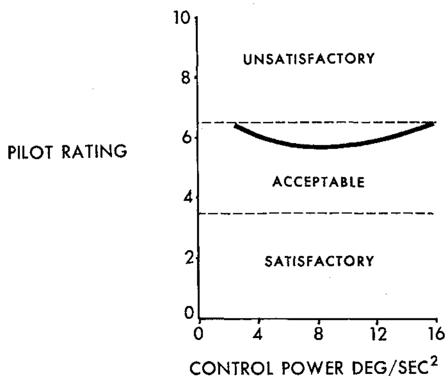


Fig. 12 Pilot rating for proportional direct thruster control mode.

Direct Thruster Operation

The direct attitude control system was examined both as a linear proportional control system and as an on-off control system, although the data obtained for the on-off mode were extremely limited. The data obtained relative to the proportional operation indicated that the system is acceptable for emergency operation only for control powers between about 4 and 16 deg/sec^2. Figure 12, which plots pilot rating as a function of control power for the proportional system, shows that the best pilot rating was about 5.7 on the Cooper Rating Scale and occurred at control powers of the order of 10 deg/sec^2. Scattered data relative to the direct on-off-thruster control mode indicate that the pilots tend to rate it somewhat worse than the proportional system. These results are applicable to control of the lunar landing and should not be taken to infer that direct thruster control of spacecraft attitude during other mission phases, such as in orbit, will be unacceptable.

Relationship of Studies to Present LEM Attitude-Control System

The results of these studies have been applied to the design of the LEM spacecraft attitude-control system. As a primary mode, the attitude-control system employs a rate-command mode having attitude-hold features. Maximum rate command available to the pilot is 20 deg/sec, and the rate deadband is equivalent to 0.2 deg/sec. The operating points for two-thruster operation is at a "time constant" of 2.3 sec, which, for a 0.2-deg/sec deadband, is just within the satisfactory boundary shown in Fig. 9b. Four-thruster operations at 1.15 sec are well within the satisfactory region. As a backup to the primary mode, the attitude-control system can be operated in the direct mode, but the handling qualities are, at best, acceptable. Compensation for misalinement torques is automatically made through the trim gimballed operation of the main engine.

Conclusions

The handling qualities of a lunar-landing vehicle have been examined and assessed in a series of piloted simulations of the lunar-landing maneuver. The results of these studies indicated that the differences between the earth and lunar environment influenced handling qualities of earth-bound vehicles performing maneuvers similar to those discussed in the lunar landing. The studies conducted to date have not examined the effect of gravitational-field differences in sufficient depth to discuss in detail the reasons for the variations in handling qualities.

It is anticipated that the study results will be verified in at least two operational research vehicles. The first of these is a tethered-flight vehicle located at the Langley Research Center, and the second is a free-flight vehicle presently undergoing flight tests at the Flight Research Center. Both of these vehicles will operate in a simulated lunar-gravitational field and will employ control systems similar to the LEM spacecraft.

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