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A SIMULATION STUDY OF EMERGENCY LUNAR ESCAPE TO ORBIT USING SEVERAL SIMPLIFIED MANUAL GUIDANCE AND CONTROL TECHNIQUES

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16. Abstract

A fixed-base piloted simulator investigation has been made of the feasibility of using any of several manual guidance and control techniques for emergency lunar escape to orbit with very simplified, lightweight vehicle systems. The escape-to-orbit vehicles accommodate two men, but one man performs all of the guidance and control functions. Three basic attitude-control modes and four manually executed trajectory-guidance schemes were used successfully during approximately 125 simulated flights under a variety of conditions. These conditions included thrust misalinement, uneven propellant drain, and a vehicle moment-of-inertia range of 340 to 16 200 kg-m^2 (250 to 12 000 slug-ft^2). Two types of results are presented – orbit characteristics and pilot ratings of vehicle handling qualities.

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SUMMARY

A fixed-base piloted simulator investigation has been made of the feasibility of using any of several manual guidance and control techniques for emergency lunar escape to orbit. Very simplified, lightweight vehicles were used; they accommodate two men, but one man performs all of the guidance and control functions. Three basic attitude-control modes – kinesthetic, thrust vector control, and small on-off jet – were investigated under a variety of conditions including thruster misalinement, uneven propellant drain, and a rather extensive range of vehicle moments of inertia from about 340 to 16 200 kg-m^2 (250 to 12 000 slug-ft^2). Four similar manually executed trajectory-guidance schemes were used. The basis for each was a series of constant-pitch reference angles and either one or two levels of constant thrust. Four experienced pilots made 125 simulated escape-to-orbit missions.

The two types of data obtained from these missions were (1) orbit characteristics, based on the trajectory end conditions, and (2) pilot ratings of vehicle handling qualities (Revised Cooper Scale). It was determined that safe orbits could be established consistently while using each of the control modes and trajectory-guidance plans considered. It was also determined that the handling qualitites of a simplified lunar-escape-system vehicle were affected (1) significantly by moment-of-inertia levels (particularly when using kinesthetic control), (2) moderately by uneven propellant drain, and (3) very little by thrust misalinement or the presence of an inactive passenger standing next to the control pilot.

INTRODUCTION

This simulator investigation is a continuation of the studies of lunar escape systems (LES) of references 1 to 4. The analytical investigations of references 1 and 2 were conducted concurrent with and in contractual support of a series of piloted LES simulator (LESS) investigations at the Langley Research Center. Results of the initial LESS investigation are reported in reference 3 and a description of the development of the LES simulator is given in reference 4.

The general approach in the LESS study series has been to look first at the most basic guidance and control techniques (and associated vehicle equipment) and evaluate their suitability for an emergency LES in terms of piloting performance and vehicle handling qualities. Then, wherever necessary or desirable, additional features or modifications were included and the system reevaluated. In support of this approach, the contractual-support study (refs. 1 and 2) was directed toward identification and analysis of suitable visual and instrument reference systems. A three-axis, gyro-driven attitude display system was determined to be a minimum requirement because of the possible need to initiate a lunar abort at any time during a 14-day mission. Alinement techniques, weight penalties, and the accuracy requirements associated with various guidance and control systems were also established and are reported in reference 2.

The LESS study of reference 3 involved the use of kinesthetic attitude control and simplified two-step-pitch manual guidance schemes based strictly on vertical and horizontal pitch angles. Trajectory results (i.e., characteristics of the resulting orbits) were generally satisfactory; however, the pilots rated the handling qualities of most LES configurations as "Acceptable – but with objectionable deficiencies" (based on the Revised Cooper Scale developed in ref. 5).

In an attempt to improve vehicle handling qualities (and reduce propellant requirements), several additional manually executed guidance schemes and two additional control modes were defined for use in the present LESS study. For example, under one new guidance scheme ("bent-two-step pitch"), the vertical rise ($\theta = 0^{\circ}$) of the LES lasts only 10 seconds, a constant intermediate pitch angle $\left(\theta_1 = -30^{\circ}\right)$ is included, and the final pitch-angle step $\left(\theta_2 = -103^{\circ}\right)$ is lowered to 13° below the local horizontal. This pitch profile is a rough approximation of the calculus-of-variations propellant-optimized profile developed in reference 2. The trajectory resulting from this approximation is thus more propellant efficient than the nominal trajectory used in reference 3; yet the basic simplicity of constant-angle guidance is retained. The two control modes each involve a different type of manually operated attitude-control system – a complete array of small on-off jets or a double-gimbaled main engine plus a set of yaw jets.

This report contains a brief description of each of the control modes and guidance schemes, and presents piloted LESS trajectory results for a variety of simulated nominal and off-nominal conditions. Pilot ratings of vehicle handling qualities under these conditions are also presented. Even though the orbit results are statistical, they are intended to give only a qualitative indication of how well the escape trajectory was flown under the various sets of conditions. An analysis-of-variance approach has not been used because the purpose of the study was to determine if and under what conditions simplified LES vehicles could be flown, rather than to determine the exact effect of a particular variable on the pilot's performance or on the characteristics of the established orbit. A brief summary of the computer equations and LESS hardware is included in the appendix. (A full description of the LESS system is given in ref. 4.)

The present report completes documentation of results obtained in the LESS study series. A summary of results for the full series is presented in reference 6 along with some supplementary data and cross comparisons. Also, handling qualities results are presented in terms of control-system sensitivities in reference 6, whereas such results are presented as functions of pitch- and roll-axis inertias in the present report.

SYMBOLS

Values are given in both SI and U.S. Customary Units. The measurements and calculations were made in U.S. Customary Units.

a semimajor axis of LES orbit

b_{13},b_{23},b_{33} direction cosines used in transforming the acceleration due to gravity from the local-vertical system to the body-axis system (see eq. (A1))

D_1,D_2,D_3 auxiliary variables used to simplify moment equations in appendix

g_e acceleration due to earth gravity, 9.81 m/sec^2 (32.2 ft/sec^2)

g_m acceleration due to lunar gravity, 1.62 m/sec^2 (5.32 ft/sec^2)

h_a,h_p altitude of apocynthion and pericynthion, respectively

I_1,I_2,I_3 collections of inertia terms (see eq. (A3))

I_{xx},I_{yy},I_{zz} moments of inertia of LES about X_B, Y_B, and Z_B axes, respectively

I_{xz} product of inertia of LES with respect to X_B and Z_B axes

$K_1,\ldots,K_5$ gain factors

M_θ,M_ϕ electrical signals proportional to pitch and roll torques, respectively

m instantaneous mass of vehicle

p,q,r body-axis components of total angular velocity

Q_x,Q_y,Q_z	torques about LES body axes
$Q_{z,j}$	torque about Z_B axis due to yaw jets
R	distance from origin of body coordinates to center of moon
R_p	radius of pericynthion
$\overline{R}$	position vector with respect to center of moon
r_m	radius of moon
$\overline{T}$	main engine thrust
T_x,T_y,T_z	body-axis components of main thrust
t	time
u,v,w	body-axis components of V_T
V_H	horizontal component of LES velocity
V_T	total velocity of LES
V_z	indicated velocity along the thrust axis (see eq. (A10))
W	earth weight of LES
$W_{3,e}$	earth weight of the LESS control pilot
X_B,Y_B,Z_B	body axes with origin at instantaneous center of gravity of the LES (axes rotate with vehicle)
X_I,Y_I,Z_I	inertial axes
X_{LV},Y_{LV},Z_{LV}	local-vertical axes
x_B,y_B,z_B	distances in body-axis system

z_h distance of initial center of gravity of vehicle above the main thruster nozzle

$\Delta x, \Delta y, \Delta z$ body-axis components of shifts of total center of gravity

$\delta x_3, \delta y_3$ horizontal components of shifts of pilot's center of gravity

η downrange central angle (see fig. 9)

θ_1, θ_2 reference guidance pitch angles

μ lunar gravitational constant, 4.9028×10^{12} m^3/sec^2 (1.7314×10^{14} ft^3/sec^2)

ξ_x, ξ_y body-axis components of thrust-misalinement angle

σ standard deviation

ϕ, ψ, θ Euler angles associated with roll, yaw, and pitch rotations relating the body axes to the local-vertical axes (ϕ, ψ, θ order required for the simulator 8-ball used)

Subscript:

BO at thrust burnout

A dot over a variable denotes differentiation with respect to time.

GENERAL CONSIDERATIONS

The same general objectives and ground rules as used in reference 3 were continued in the present study. In particular, the primary piloting objective was to escape from the lunar surface to a "safe" lunar orbit. The only specification considered for the safe orbit was that the pericynthion altitude be greater than 15 km (approximately 50 000 ft).

The following sections cover specific study assumptions, a brief discussion of each of the attitude-control modes, and descriptions of the trajectory-guidance plans. The terms "pitch angle," "roll angle," and "yaw angle" are used interchangeably with the Euler angles θ, ϕ, and ψ, respectively, because ϕ and ψ remain near zero throughout the escape trajectory.

Assumptions

The following assumptions were made:

(a) The moon has an inverse-square gravity field.

(b) The moon does not rotate significantly during an LES flight.

(c) Some form of communications is available, either with the orbiting command-service module (CSM) or Mission Control. Thus, the location of the CSM and the characteristics of its orbit are known prior to LES takeoff.

(d) Both astronauts must ride the same LES, but there is single-pilot control.

(e) The initial mass of all simulated LES configurations was approximately 1190 kg (81.55 slugs); however, a wide range of vehicle moments of inertia was achieved by using a variety of locations for the four propellant tanks.

(f) Only a single burn of the rigidly mounted LES engine is allowed; a single constant thrust level is assumed under one trajectory-guidance plan and two levels of constant thrust are used with several other plans.

(g) Rate gyros for all three axes are installed on the LES; thus, both rate and attitude information can be displayed to the pilot.

(h) A simple integrating accelerometer is affixed to the LES vehicle to give velocity-along-the-thrust-axis information.

Attitude-Control Modes and Techniques

Three basic attitude-control modes – kinesthetic, thrust-vector control (TVC), and small on-off jet – were used in this phase of the lunar escape system simulator (LESS) studies. Both TVC and on-off jet control were performed by pilots while either seated or standing. Small on-off jets were used for yaw control for all control modes. The simulated yaw jets were activated by means of a hand controller which was assumed to be mechanically linked to the jets. The basic logic for each control mode was included in the computer program where it could be easily modified.

Brief descriptions of the control modes and control techniques are given in the following sections. References are also identified which contain additional details and illustrations. A block diagram of the LESS setup is presented in figure 1 for aid in the following discussions.

Kinesthetic control.- The type of kinesthetic control used in this study is the same as that used in reference 3. That is, in response to observed attitude errors of a three-axis attitude indicator (8-ball), the LESS pilot (standing) shifted his center of gravity with respect to the vehicle's designated line of thrust by leaning his body in the appropriate

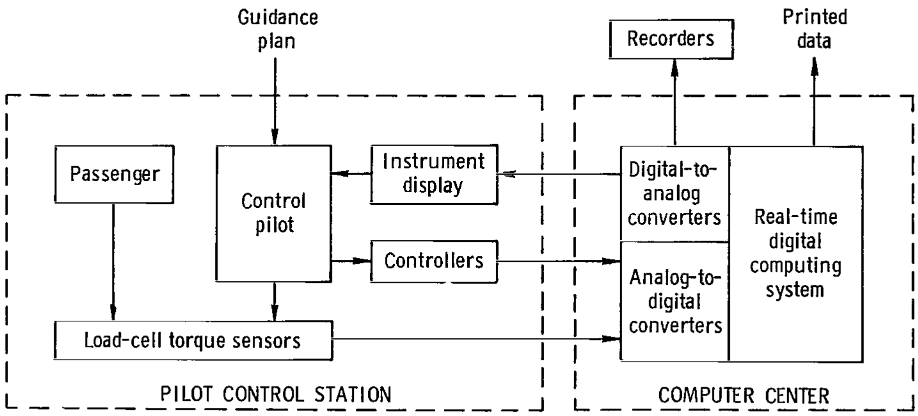

Figure 1.- Block diagram of lunar escape system simulator (LESS).

direction. In most cases the pilot locked his knees and pivoted about his ankles while holding his body relatively rigid. Inertia reactions on the pilot due to vehicle translation and rotation were assumed to be negligible because of the relatively sluggish attitude responses of the LES vehicles. Consequently, very little balance-reflex action is involved and the pilot moves his body as a convenient means of shifting the center of gravity of the total man-vehicle system. (A similar type of control could be achieved by a pilot shifting some lead weights in response to the displayed information.)

The center-of-gravity shift was detected by load cells installed under the floor of the LESS platform – one set on the pitch axis and another set on the roll axis. The roll-axis installation is shown in figure 2, which is a photograph of the LESS pilot control station. The signals from the respective load-cell sets were scaled and transmitted over telephone lines to a real-time digital computing system where they were interpreted as pitching or rolling torques. In turn, the computer solved the equations of motion and returned attitude-angle signals to the pilot control station where they were used to drive the three-axis 8-ball in the display panel.

The pilot control station accommodated two men, but was outfitted primarily for one-man control. During simulated flights in which a passenger stood behind the pilot on the LESS platform (see fig. 2), the pilot had to locate himself forward of the line of thrust to balance the mass of this passenger. The basic technique of kinesthetic control was, however, not altered. The passenger was instructed to stand still and not to attempt to assist the pilot in his control tasks; but, as indicated in figure 1, if the passenger were to make any inadvertent moves, they would be detected by the load cells and summed with the kinesthetic-control inputs of the pilot.

Kinesthetic control was used to some degree to augment the attitude-jet and TVC control modes, particularly when off-nominal conditions (such as uneven propellant drain) were present. (The load cells were operational during all simulated flights made in the LESS study series.)

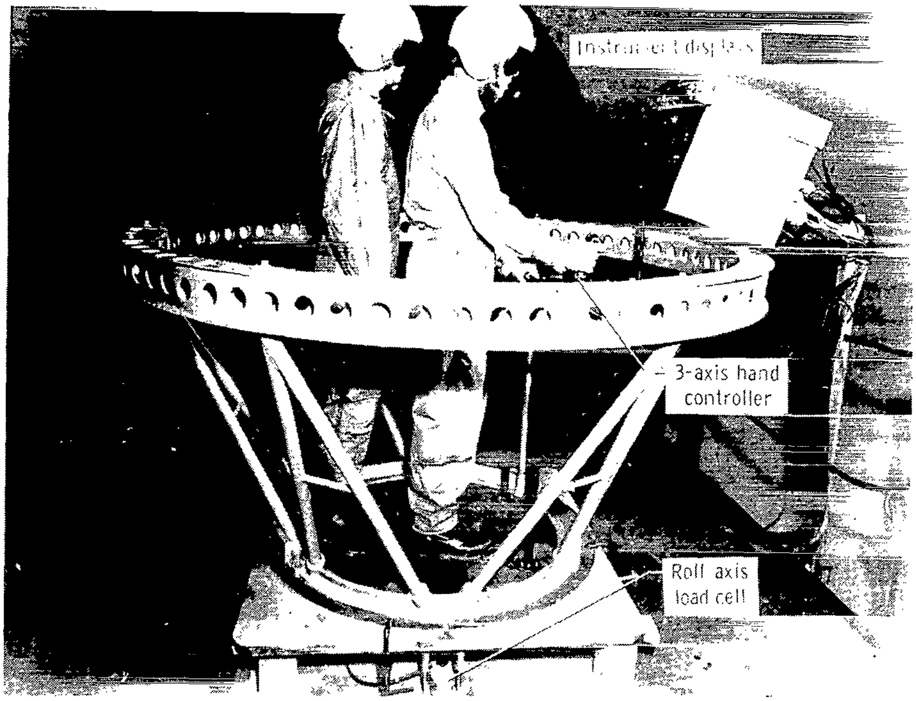

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Figure 2.- The pilot control station of the simulator.

Thrust-vector control.- Thrust-vector control (TVC) is herein applied to the technique of manually tilting the main thruster to achieve pitch and roll control. Several methods of implementing this technique are available, including double-gimbaling the main engine. During the simulation a three-axis hand controller was used to generate electrical signals proportional to the pitch and roll displacements and to deliver plus or minus step voltages from the controller's yaw axis whenever a ±20 percent travel deadband was exceeded.

Stabilization, control, and implementation of typical TVC systems suitable for an LES were investigated rather thoroughly during the contractual support study (refs. 1 and 2). The detailed weight summaries indicate that the dry mass of an LES vehicle equipped for TVC (called "hardwire control" in refs. 1 and 2) should be only about 17 kg (corresponding to 37 lb earth weight) greater than that of a basic LES vehicle employing only kinesthetic control.

On-off jet control.- The attitude-control mode utilizing small on-off jets is an expansion of the technique used to fire just the yaw jets. That is, plus and minus step voltages were delivered from any of, or all three of, the LESS controller axes to fire small pitch, roll, and yaw jets. These jets were independent of the main thruster. The same controller was used for the on-off jet and TVC control modes. No rise or decay characteristics were programed for the small jets; however, the specific impulse of the bipropellant mixture of the lunar module (LM) was degraded from 306 to 250 seconds (for the small jets, but not for the main thruster).

Trajectory Guidance Plans

Guidance plans I, II, and IV were developed for use in the present study. The trajectory guidance plan of reference 3 was also used for a few missions in the present study; it is designated here as plan III. (See fig. 2 of ref. 3.)

Plans I and II are characterized in figure 3. The primary difference between the two plans is a thrust-level reduction (to 40 percent of maximum) in plan II at approximately 510 seconds. This thrust change is intended to improve vehicle handling qualities as the LES nears orbit, and also to reduce the orbit-insertion errors; it extends the total flight time, however, from approximately 537 seconds to 576 seconds. The propellant requirement is about the same for both plans. In order to achieve better circular-orbit conditions at approximately 111 km (60 n. mi.), the θ_2 reference angle for plan II was changed from -103° to -102.9° in the analytical checkout. In the simulation missions (hereinafter called "runs"), however, this distinction was difficult to make because the 8-ball was graduated in 5° increments; thus the pilots used essentially the same θ_2 reference for both plans.

Guidance plan IV was developed analytically but was used only in a qualitative evaluation. The θ_1 and θ_2 reference angles were -50° and -100°, respectively, and a large thrust reduction (to 30 percent of maximum) was made at the second pitch maneuver (and the thrust remained at this level until burnout).

The propellant requirement in plan IV was about $6\frac{1}{2}$ percent less than in plans I and II, or about 2 percent less than required for the trajectory of reference 2 (which was propellant-optimized for a single constant-thrust level). Total flight time for plan IV was extended to approximately 782 seconds. Even though vehicle handling qualities were improved during the reduced-thrust portion of the flight, the increased flight time tended to tire the pilots significantly during the checkout flights (especially when kinesthetic control was being used). Attitude control during these flights was, however, very good.

Because of the large number of successful runs already made with the other plans and because of the increased digital-computing requirements, it was decided to terminate the LESS series without compiling statistical trajectory data during simulation runs using plan IV. This plan, however, appears to be worthy of future consideration.

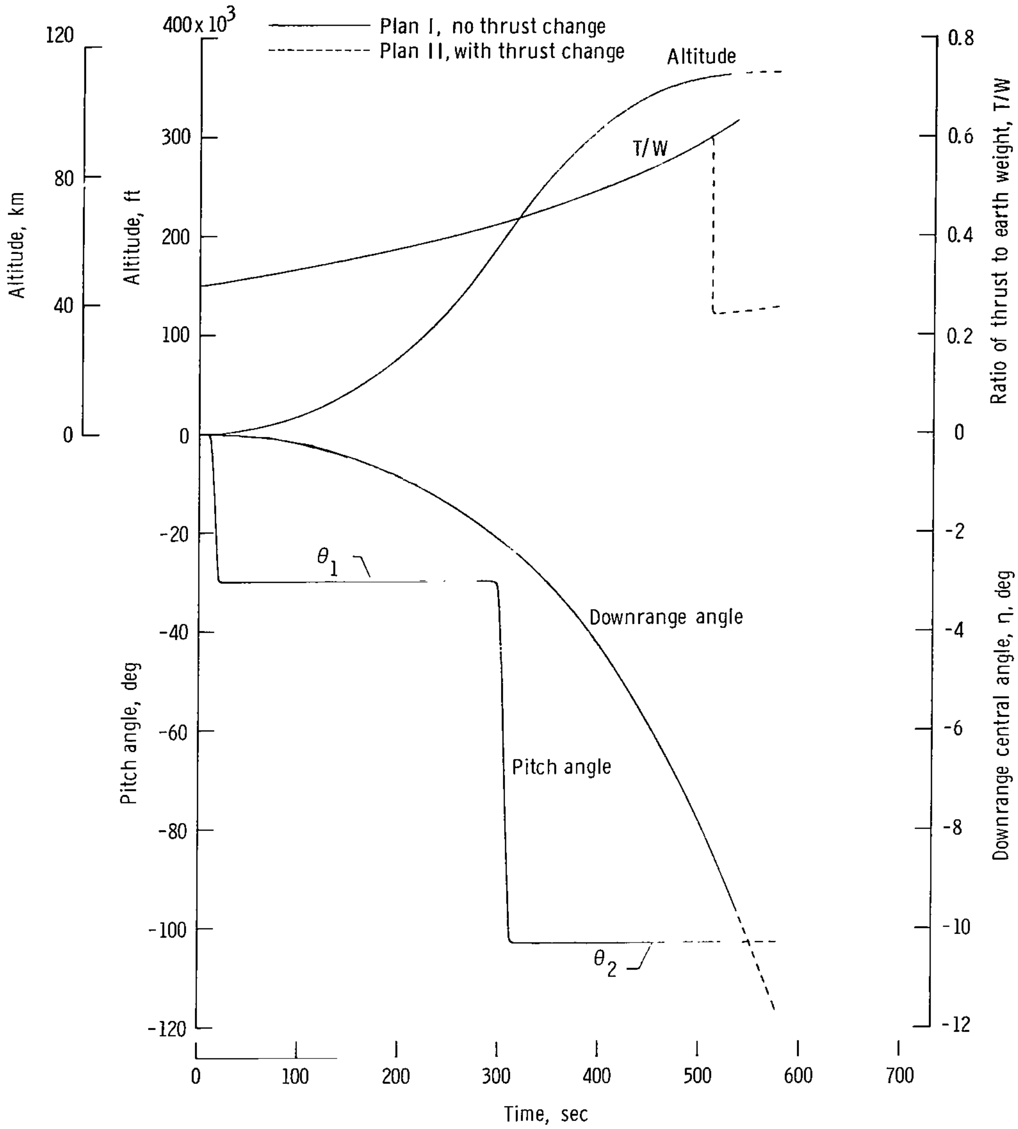

Figure 3.- A time history of the trajectory guidance plans.

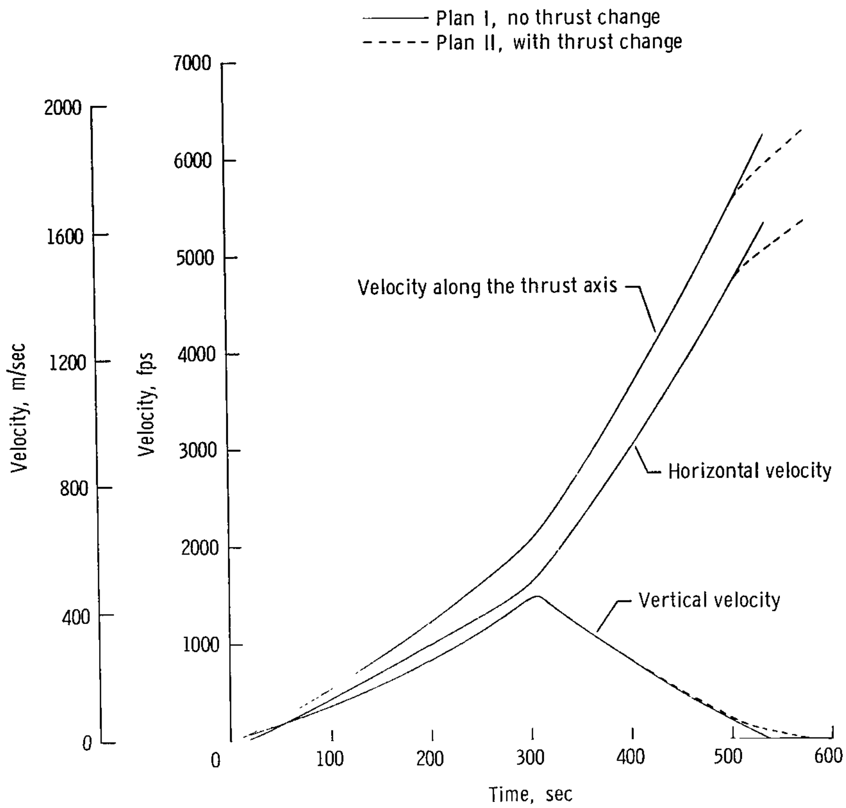

Figure 3.- Concluded.

RESULTS AND DISCUSSION

The lunar-escape-trajectory results which follow are based on 125 simulated escape trajectories by four experienced pilots. A pilot resume is given in table I. These same pilots were used in the study of reference 3 and were given the same A, B, C, and D designations therein. Three of the pilots rated the vehicle handling qualities during the runs.

General Results

Only one of the 125 runs had to be aborted; this abort occurred on the next-to-last day of simulation when the pilot neglected to execute a pitch maneuver. One of the 124 completed runs resulted in the establishment of an orbit which had a pericynthion altitude less than 15 km (50 000 ft); thus, of the 125 runs initiated, 123 resulted in "safe" orbits. This success ratio is an improvement over corresponding results (184 successes in 194 attempts) obtained during the preceding study (ref. 3), and indicates that the additional LESS training was beneficial. It should be noted, however, that in the present study each

TABLE I.- PILOT RESUME

Pilot	Number of LESS runs	Present position	Previous piloting experience	
			Simulator	Flight
A	45	Engineer	Yes	Former Air Force instrument-flight instructor
B	22	Engineer	Yes	Light-aircraft pilot
C	18	Pilot	Yes	NASA test pilot
D	39	Engineer	Yes	Former Navy aircraft-carrier pilot

of the pilots flew his initial TVC and his initial attitude-jet data runs without any practice on the LESS using either of these modes.

A summary of orbit results for 52 kinesthetic-control runs, 51 TVC runs, and 15 attitude-jet-control runs is presented in table II. Because the average values of each of the orbit parameters were generally comparable to those obtained in the study of reference 3, only pericynthion altitude and orbit eccentricity are given in table II.

TABLE II.- SUMMARY OF LESS ORBIT RESULTS

Parameters	Trajectory guidance plan	Pericynthion altitude, m		Pericynthion altitude, ft		Orbit eccentricity	
		Mean	σ	Mean	σ	Mean	σ
Reference conditions (for 111 km (60 n. mi.) circular orbit)	---	111 120	-----	364 567	-----	0	-----
Kinesthetic control:							
39 runs	I	92 924	19 212	304 869	63 032	0.0099	0.0052
13 runs	II	89 798	21 259	294 612	69 746	.0120	.0051
TVC:[a]							
39 runs	I	90 488	22 166	296 877	72 724	.0115	.0062
8 runs	II	76 930	21 161	252 395	69 425	.0120	.0059
4 runs[b]	I	98 737	9 172	323 940	30 093	.0098	.0013
Attitude-jet control:							
12 runs	II	88 304	12 825	289 712	42 076	.0114	.0070
3 runs	III	109 523	21 599	359 327	70 864	.0135	.0011

[a]Omitted are six TVC runs with a programed 8-ball error which are treated in a later section.

[b]A passenger stood behind the pilot for these runs.

The data in this table indicate that the pilots were able to establish good orbits using all three control modes under a variety of nominal and off-nominal conditions. In particular, the range of vehicle moments of inertia was quite extensive, and off-nominal conditions such as thrust misalinement and/or uneven propellant drain were often included (without telling the pilot). The attitude-jet runs were made last in the LESS program; after only 15 attitude-jet runs this phase of the program was terminated because the pilots were controlling attitude satisfactorily for all conditions and obtaining orbit results comparable to those obtained with the other two control modes.

The kinesthetic-control results in table II are somewhat better than those obtained during the study of reference 3, which again may indicate that the pilots had benefited from their accrued LESS experience. This trend of improvement was unchanged when all table II runs involving conditions not investigated during the study of reference 3 (e.g., large inertias) were removed from table II statistical sample.

Effects of Off-Nominal Conditions

Seventy-one of the 118 runs considered in table II were made with some type of off-nominal condition. The average orbit pericynthion altitude for these 71 runs was approximately 89 000 m (292 000 ft), which compares with 91 552 m (300 367 ft) for the 47 nominal-condition runs. The corresponding orbit eccentricities were 0.01117 and 0.01080, respectively. Thus, it appears that the off-nominal conditions had little effect on the characteristics of the established orbits. (Similar results were obtained in ref. 3 for kinesthetic control only.)

Three of the pilots rated the vehicle handling qualities during a large number of the escape flights, finding that (1) up to 0.5° thrust misalinement had very little effect on the ratings, and (2) uneven propellant drain (1 percent) degraded their average ratings approximately one-half of an index point on the Revised Cooper Scale (table III). For example, whenever the handling qualities were rated A4 for a certain set of conditions, they were usually rated A4$\frac{1}{2}$ when uneven propellant drain was included as an additional disturbance. (The pilots were permitted to resolve their ratings to half-points if they considered the handling qualities to fall between two adjacent categories in table III.)

In view of the above ratings, the trajectory results of runs with uneven propellant drain were analyzed separately and were found to differ very little from the average results. Thus, it is concluded that while uneven propellant drain adds to the difficulty of the control task, the pilots can rise to the situation and achieve orbits comparable to those in which no off-nominal conditions are present.

TABLE III.- REVISED COOPER SCALE FOR EVALUATING VEHICLE HANDLING QUALITIES

[From ref. 5]

A1	*Excellent, highly desirable*	SATISFACTORY Meets all requirements and expectations, good enough without improvement. Clearly adequate for mission.	ACCEPTABLE May have deficiencies which warrant improvement, but adequate for mission. Pilot compensation, if required to achieve acceptable performance, is feasible.	CONTROLLABLE Capable of being controlled or managed in context of mission, with available pilot attention.
A2	Good, pleasant, well behaved			
A3	Fair. Some mildly unpleasant characteristics. Good enough for mission without improvement.			
A4	Some minor but annoying deficiencies. Improvement is requested. Effect on performance is easily compensated for by pilot.	UNSATISFACTORY Reluctantly acceptable. Deficiencies which warrant improvement. Performance adequate for mission with feasible pilot compensation.		
A5	Moderately objectionable deficiencies. Improvement is needed. Reasonable performance requires considerable pilot compensation.			
A6	Very objectionable deficiencies. Major improvements are needed. Requires best available pilot compensation to achieve acceptable performance.			
U7	Major deficiencies which require mandatory improvement for acceptance. Controllable. Performance inadequate for mission, or pilot compensation required for minimum acceptable performance in mission is too high.		UNACCEPTABLE Deficiencies which require mandatory improvement. Inadequate performance for mission even with maximum feasible pilot compensation.	
U8	Controllable with difficulty. Requires substantial pilot skill and attention to retain control and continue mission.			
U9	Marginally controllable in mission. Requires maximum available pilot skill and attention to retain control.			
10	Uncontrollable in mission.	UNCONTROLLABLE Control will be lost during some portion of mission.		

Effect of LESS Passenger on the Control Task

The results of four runs with an inactive passenger standing on the LESS platform behind the pilot are shown in table II. These runs were made using TVC. The average orbit characteristics obtained from these runs were actually a little better than for the other groups in table II. About the same result had been obtained for kinesthetic control (with a passenger onboard) in reference 3. The pilots commented that they were more highly motivated to perform the control tasks quickly and precisely when the control situation was (or was expected to be) more difficult. The pilots were quick to mention, however, that they felt that they were controlling to the best of their ability during every run they made. Even though the pilot comments may appear to explain the better results mentioned above (and because it is difficult to measure motivation), the only conclusion that will be drawn here is that the presence of a second man on the LESS does not degrade the pilot's control performance when using TVC.

Effect of Large Moments of Inertia

In the present LESS study 17 runs were made involving five configurations with moments of inertia larger than any used in reference 3. The moment-of-inertia ranges for the simulated escape vehicles were extended to approximately 16 650 kg-m^2 (12 280 slug-ft^2) for I_{xx} and 3250 kg-m^2 (2400 slug-ft^2) for I_{yy}. Time histories of I_{xx} and I_{yy} for these five configurations (designated H, H*, K, L, and N) are shown in figure 4. (Also shown in fig. 4 are inertia configurations A, C, and C* which are typical of the configurations used in ref. 3 and also used in the present study.)

Trajectory results for the 17 runs with high-inertia configurations are given in table IV. Thirteen of the runs were made using the kinesthetic control mode. Attitude control during these runs was good, although characteristics of the established orbits were not as good as the overall average for kinesthetic control (see table II). Examination of the time histories for these 13 runs revealed that many of the pitchover maneuvers were performed more slowly than for the lower inertia configurations, which led to an excess of vertical velocity of 4.4 m/sec (14 ft/sec) upward and a 3.4-m/sec (11-ft/sec) deficiency of both horizontal velocity and total velocity at orbit insertion. The indicated velocity along the thrust axis, displayed to the pilot on a digital voltmeter, was not affected by the slowness of the pitch maneuver and thus reached the thrust-cutoff target value before the horizontal velocity of the vehicle had reached the value required for a circular orbit. Most of the slow pitchovers occurred while using vehicle configurations having

TABLE IV.- TRAJECTORY RESULTS FOR LARGE MOMENTS OF INERTIA

(a) SI Units

Control mode	No. of runs	Orbit altitude, m, at –						Insertion velocity, m/sec			
		Insertion		Pericynthion		Apocynthion		Horizontal		Vertical	
		Mean	σ	Mean	σ	Mean	σ	Mean	σ	Mean	σ
Kinesthetic	13	113 202	4563	85 006	24 364	129 929	18 931	1624.66	7.24	-4.40	15.76
TVC	4	108 113	3910	86 408	15 412	132 875	12 789	1630.13	5.39	11.26	15.67

(b) U.S. Customary Units

Control mode	No. of runs	Orbit altitude, ft, at –						Insertion velocity, ft/sec			
		Insertion		Pericynthion		Apocynthion		Horizontal		Vertical	
		Mean	σ	Mean	σ	Mean	σ	Mean	σ	Mean	σ
Kinesthetic	13	371 398	14 969	278 891	79 936	426 277	62 110	5330.25	23.76	-14.43	51.76
TVC	4	354 702	12 827	283 491	50 565	435 941	41 959	5348.19	17.69	36.93	51.40

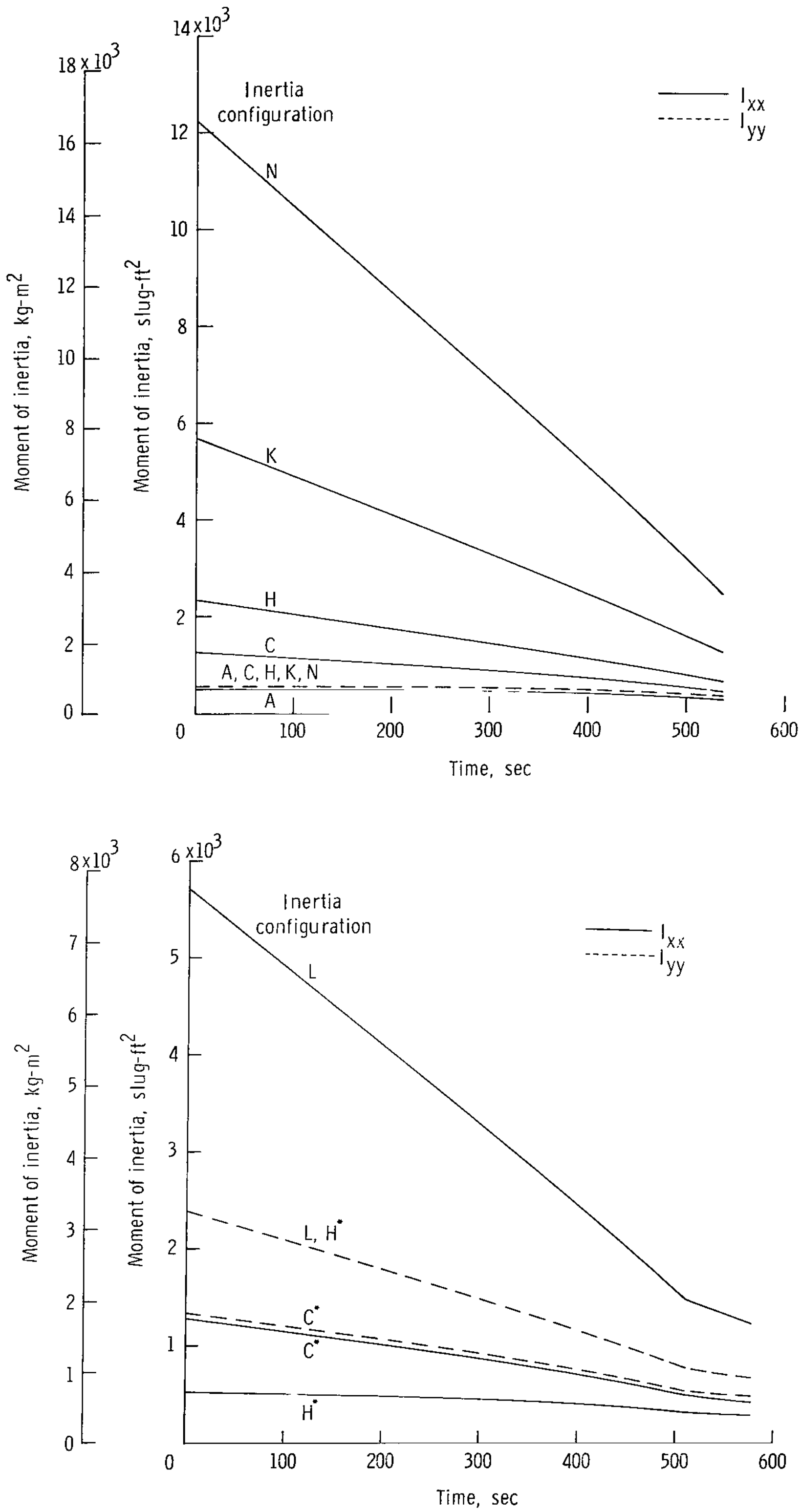

Figure 4.- Time histories of the moments of inertia about roll axis (I_{xx}) and pitch axis (I_{yy}).

relatively large pitch inertias (i.e., large values of I_{yy}). Consequently, the pilot's kinesthetic pitch-control authority was somewhat marginal and he was reluctant to set up any pitch rate which might be difficult to overcome kinesthetically when he arrived at the next pitch reference angle.

After completing the above-mentioned 13 runs, four runs with high-inertia configurations were made using TVC. The resulting orbit eccentricities were comparable to those for the kinesthetic-control runs, as were the pericynthion altitudes (see table IV), but the orbit-insertion conditions were noticeably different. The pitchover maneuvers for these runs were performed more quickly, apparently because the pilots had sufficient control authority and did not hesitate to use it (being aware of their slow execution of the pitchovers in the 13 kinesthetic-control runs). Consequently, orbit insertion was made about 5 km (16 700 ft) lower in altitude, and with an excess of both horizontal and vertical velocity (downward). Additional TVC runs with high inertias were not deemed necessary because the four established orbits were each satisfactory, and because the pilots considered the tasks easier with TVC than with kinesthetic control.

There was no trend toward better or poorer orbits as larger and larger inertias were used with either control mode. For example, in four kinesthetic-control runs which involved the two largest inertia configurations, average pericynthion altitude and orbit eccentricity values corresponded closely to the average values obtained for all 13 kinesthetic-control runs. Thus orbits established with the small-inertia or compact vehicles can be expected to be about as good as for the larger inertia vehicles, even though handling qualities of the compact vehicles may not be as good.

Emphasis in investigating the handling qualities of large-inertia LES vehicles was primarily on cases where kinesthetic control was used. With kinesthetic control the pilot's control authority (for a given inertia level) was constrained by the limited amount of control torque he could command by moving his body. Typical results of the pilot ratings of LES vehicle handling qualities (for kinesthetic control) are shown in figure 5. The ordinate of this graph is the index scale from table III. The abscissa is either I_{XX} when $I_{yy} = 678$ kg-m^2 (500 slug-ft^2) or I_{yy} when $I_{XX} = 700$ kg-m^2 (520 slug-ft^2).

The solid curve indicates that the pilots preferred the higher values of roll inertia (in conjunction with the relatively low value of pitch inertia). The rationale for this preference is that kinesthetically it is easier to control the vehicle roll angle to zero when roll-axis response is rather sluggish. (No roll maneuver was required during the LESS flights.) The pitch-axis response, however, needed to be rather quick to permit effective execution of the LESS pitch maneuvers. The pilots reported that this combination of pitch and roll response allowed them to separate their control inputs into sequential pitch and roll tasks. For example, they could concentrate on removing a pitch-angle error for an appreciable amount of time before having to switch their attention to arresting a roll rate.

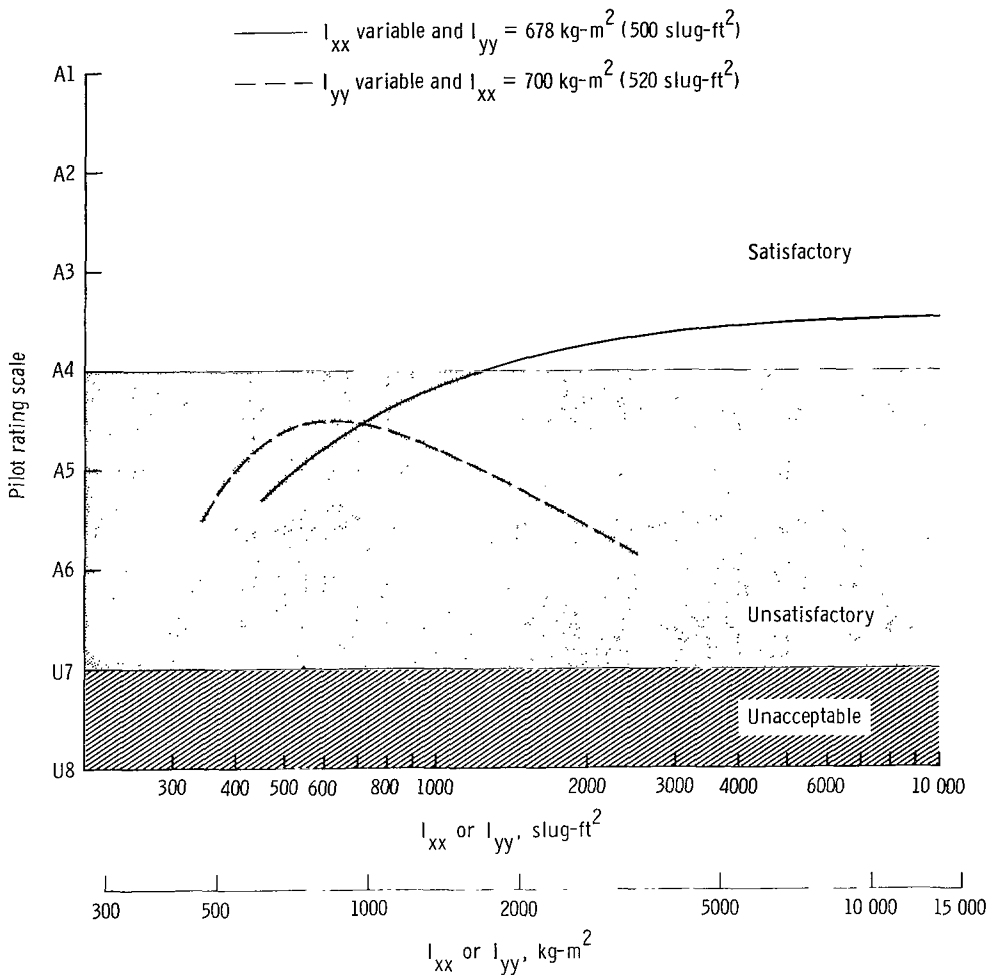

Figure 5.- Typical results of the pilot ratings of LES vehicle handling qualities (for kinesthetic control).

The dashed curve in figure 5 supplements the above-discussed information by indicating that the reverse combination of high pitch inertia I_{yy} and low roll inertia I_{xx} is not desirable, as the ratings associated with the dashed curve deteriorate rapidly toward the unacceptable region for values of I_{yy} greater than 1000 kg-m^2 (738 slug-ft^2).

When both the pitch and roll inertias are increased to relatively large values, the handling quality ratings are fairly good. For example, an average rating of A$3\frac{3}{4}$ was given by three pilots for inertia configuration C*, which had approximately equal values of I_{xx} and I_{yy} during the rating interval $\left(I_{xx} \approx I_{yy} = 1763 \text{ kg-m}^2 \text{ (1300 slug-ft}^2)\right)$. As a second example, an average rating of approximately A3 was given for inertia configuration L, which had the following values during the rating interval: $I_{xx} \approx 7500$ kg-m^2 (5532 slug-ft^2) and $I_{yy} \approx 3200$ kg-m^2 (2360 slug-ft^2). It was observed, however, that during the runs with inertia configuration L the pilot had to lean forward almost into the instrument panel to initiate (kinesthetically) a pitch maneuver and then had to step back through the space designated for the second passenger to terminate this maneuver. Also, the geometry and/or mass associated with an LES having this combination of inertias would probably preclude it from being stowed on the LM. Thus, even though inertia configuration L may not have practical application, the pilot rating of this configuration augments the trend established by the curves in figure 5; that is, the best kinesthetic handling qualities were obtained with vehicles having relatively high values of I_{xx} or high values of both I_{xx} and I_{yy}.

Evaluation of a Reset 8-Ball

To ascertain the usefulness of using a "reset 8-ball" display during the last portion of the escape trajectory, 14 nominal-condition runs were made using kinesthetic control and inertia configuration C. The 8-ball was reset during seven of these runs by means of a manually operated switch. The "reset" scheme involved a flip circuit which drove the pitch axis of the 8-ball quickly back to the $\theta = 0^{o}$ position after completion of the second pitch-transition maneuver. The resulting display allowed the pilot to use the black-white interface (at $\theta = 0^{o}$) on his 8-ball as the θ_2 reference instead of continuously having to interpolate (visually) the $\theta_2 = -103^{o}$ position between the -100^{o} and -105^{o} marks near the pole on the black hemisphere. An exaggerated view of the display afforded by the "not reset" orientation of the 8-ball is shown in figure 6. The indicated attitude was

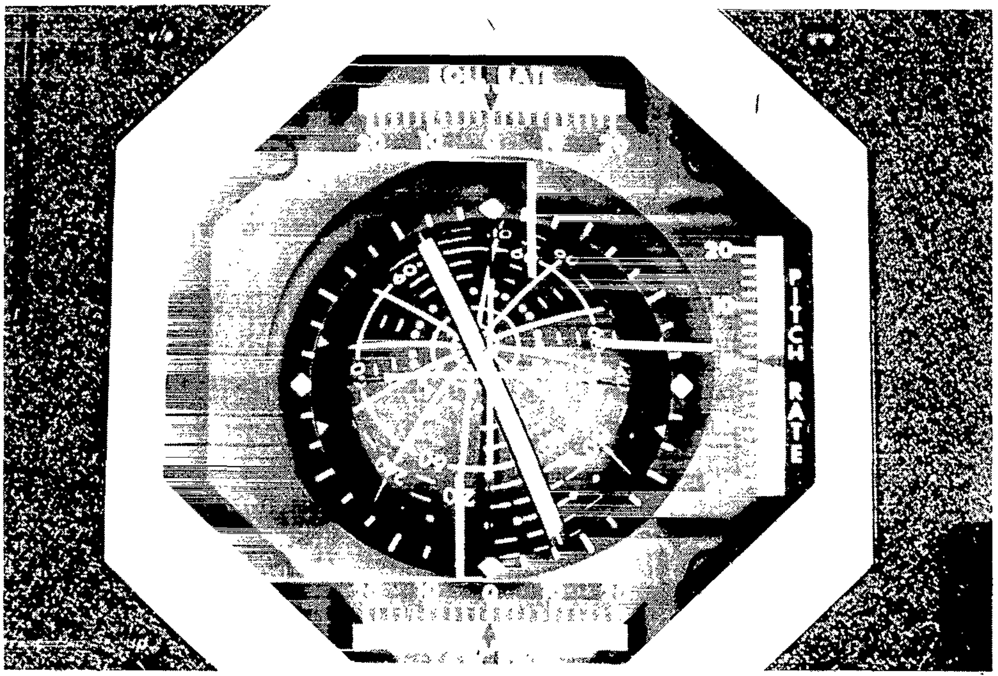

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Figure 6.- Closeup view of the 8-ball near the -90° pitch position.

interpreted as: $\theta = -97^{\circ}$ nose down, $\phi = 23^{\circ}$ right, and $\psi = 3^{\circ}$ right. (Due to parallax the values of these angles may appear to be slightly different in the photograph.)

The trajectory results of the above-mentioned 14 runs are presented in table V. Good orbits were established for both types of runs; in fact, the orbits established with the not-reset 8-ball turned out to be among the best in the LESS study series, and it was thus difficult to improve upon them. The pilots, however, expressed a strong preference for the reset-8-ball display. Unfortunately, formal pilot ratings were not made during the seven runs with the not-reset 8-ball, but in the debriefing session following the seven runs with the reset display, the pilots judged that their ratings for the reset display were at least one-half point (on index scale of table III) better than they would have been for the runs when the 8-ball was not reset (other conditions being the same). For verification, one pilot then made a two-run comparison using inertia configuration A and rated the handling qualities during the reset-display situation one point better (A5 as compared with A6) just prior to burnout. His orbit for the reset-display run was also much better (which is contrary to the trend in table V).

TABLE V.- TRAJECTORY RESULTS OF RUNS TO EVALUATE A RESET 8-BALL

Condition of 8-ball	Pericynthion altitude (mean)		Orbit eccentricity
	m	ft	
Reset (7 runs)	94 514	310 084	0.0092
Not reset (7 runs)	101 854	334 168	.0097

A conclusion derived from this limited investigation of the reset-8-ball scheme is that implementation of such a pitch-bias circuit on a LES would certainly make the attitude-monitoring task easier. An alternate approach would be to use special markings or visual aids (such as a black-white interface) on the 8-ball at each θ reference location.

The 16 runs just discussed were the first 16 runs made in the present LESS study. At their completion, the reset-8-ball scheme was incorporated into the procedures for the remainder of the study. Thus 117 of the 125 runs made during the study involved use of the reset-8-ball display.

Effect of 1° Error in Reset Circuit

To determine the effect of a small error in the reset circuit, six TVC runs were made with a programed bias error equivalent to 1° in the reset circuit (i.e., the reset was 104° instead of 103°). The pilots were not informed that the error was being included. The significant result was that average pericynthion altitude was reduced to 66 864 m

(219 370 ft), horizontal velocity at orbit insertion was approximately 6 m/sec (20 ft/sec) low, and orbit eccentricity was 0.014. These characteristics are acceptable; however, it was determined in the analytical LESS study (ref. 2) that pericynthion altitude is about three times as sensitive to negative pitch-angle errors as to positive errors. Thus if the programed error had caused the 8-ball reset to be 102^{o} (instead of 104^{o}), the resulting pericynthion altitudes might be lowered to near the limit for safe orbits.

Effect of Reduced Thrust Near Burnout

Under trajectory plan II, thrust was reduced to about 40 percent of maximum at approximately 510 seconds. The pilots rated the vehicle handling qualities just before 510 seconds and again just before thrust cutoff at approximately 576 seconds.

The average rating for handling qualities after the thrust change was approximately one-half to one point lower (better) on the index scale of table III. Thus the thrust change effected a significant improvement in vehicle handling qualities during the portion of the trajectory where they had been poorest under plan I. Consequently, the LESS pilots were able to concentrate more on minimizing the angular rates of the vehicle at orbit insertion.

A comparison of angular rates at burnout for 26 plan I and 26 plan II runs is given in table VI. Both series of runs cover the full range of inertias but include nominal conditions only. All three control modes were used in the 26 plan II runs, but only TVC and kinesthetic-control runs were made with plan I. The significant result shown in this table is that the mean values of both p and q are reduced to nearly zero in the plan II runs, although neither appeared to be very high in the plan I runs.

TABLE VI.- RATE AT BURNOUT OF COMPONENTS OF ANGULAR VELOCITY OF TWO TRAJECTORY GUIDANCE PLANS

Parameter	Mean tumbling rate, rad/sec	Worst-case tumbling rate, rad/sec	Standard deviation, σ, rad/sec
No thrust change (trajectory guidance plan I)			
Rolling rate, p	-0.0123	-0.0718	0.0317
Pitching rate, q	-.0129	-.0732	.0315
Yawing rate, r	.0001	.0113	.0049
With thrust change (trajectory guidance plan II)			
Rolling rate, p	0.0021	0.0575	0.0185
Pitching rate, q	-.0008	.0382	.0116
Yawing rate, r	.0001	.0035	.0015

No determination of acceptable tumbling rates (that is, p, q, and r) for a CSM-LES docking situation has been established because the docking technique and mechanisms have been defined only conceptually. It is expected, however, that the best docking conditions will include near-zero tumbling rates of the LES. Thus, a significant reduction in main thrust just prior to burnout could be an effective aid to obtaining near-zero rates when using TVC or kinesthetic attitude control. This procedure would, of course, have less significance when using the small on-off jets because the jets could be activated for angular-rate reduction after main thrust is terminated.

Effect of Increasing the 8-Ball Display Sensitivity

Even though attitude control was generally satisfactory during LESS studies, it became increasingly apparent that the normal 8-ball type of attitude display was a limitation on reducing pitch- and roll-angle excursions to less than approximately $\pm 2^{\circ}$. In particular, it was difficult for the pilot to detect the onset of small 8-ball motions, especially if multiple errors began to appear simultaneously. Consequently, the error in at least one axis approached 2° before appropriate corrective action could be taken and the motion was arrested.

To determine whether greater display sensitivity might enable the pilot to tighten significantly the error bands, three exploratory runs were made wherein the pitch- and/or roll-axis 8-ball drive signals were magnified by factors of 2.0 or 4.0. (The regular pitch-drive signal was, however, switched back on for the two pitchover maneuvers.) The interesting result of this experiment was that the error bands were reduced by nearly the same factor that the drive signals had been magnified. This indicated (1) that the pilot controlled the 8-ball during these runs to approximately the same apparent error band as during the regular runs and (2) that the display sensitivity was still below the level where a pilot's performance deteriorates because of such things as pilot control lag and pilot-induced oscillation.

An example of kinesthetic control with regular drive signals and with the magnified (4.0) drive signals is shown in figure 7. Both runs were made with inertia configuration C. The sample on the left was selected as typical of the nominal-condition kinesthetic-control runs made with inertia configuration C. Both sets of time histories in the figure begin after completion of the first pitchover maneuver, at which time the magnification factor of 4.0 was introduced in the run on the right. This figure illustrates the reduction in error amplitude and a corresponding increase in system frequency. The pilot commented that he did not think the kinesthetic control task was any more difficult during the modified run, although he had to supply a greater number of kinesthetic control inputs, but generally of smaller amplitude.

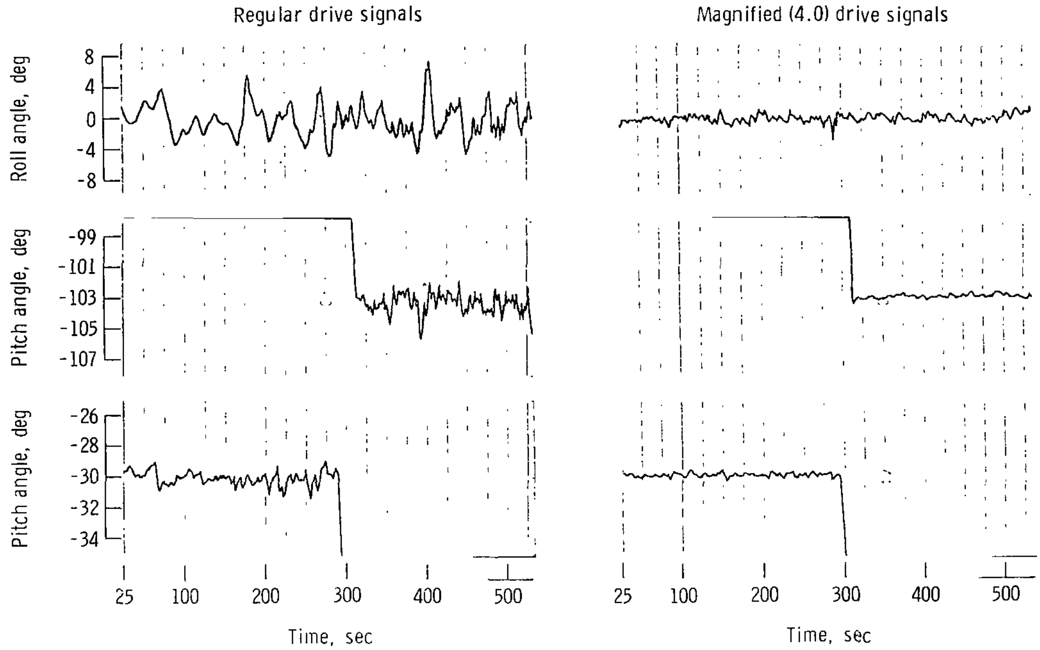

Figure 7.- A comparison of kinesthetic control of attitude during runs with regular drive signals and magnified drive signals.

It was not within the scope of the present study to determine the optimum sensitivity of the display information, but the three exploratory runs indicated that (1) display magnification factors up to 4.0 allowed the pilot to improve his attitude control without imposing any apparent penalties and (2) additional display-sensitivity studies (applied to the LES problem) might be fruitful.

Miscellaneous Results

Comparison of the results of a pilot's first kinesthetic-control run after a layoff of 2 weeks or more with his last run before the layoff was also made in the present study (same conditions used for "before" and "after" runs). The results were the same as obtained in reference 3; that is, there was no degradation in performance due to the layoffs.

Near the end of the study one pilot, while standing, made consecutive runs using the attitude-jet, kinesthetic, and TVC modes (in that order). The trajectory results were comparable for all three, but the pilot commented (as he had several times before) that he preferred TVC or attitude-jet control to kinesthetic control. It was observed, however, that during the TVC run the pilot (unconsciously) had used kinesthetic-control inputs quite often to augment inputs from his hand controller. Thus, it is illustrated again that kinesthetic control is inherently available as a backup control mode and it can also be easily used to augment some other primary mode, if desired.

CONCLUSIONS

A study has been made at Langley Research Center of several manual guidance and control techniques for emergency lunar escape systems (LES). A fixed-base piloted LES simulator (LESS) was used, and on the basis of pilot opinion and overall piloting performance during 125 simulated lunar escape-to-orbit flights, the following study conclusions have been reached:

1. Safe lunar orbits can be established with simplified LES vehicles by using kinesthetic, thrust-vector, or small on-off jet attitude control and any of the simplified manual guidance schemes used in this study.

2. Comparable trajectory results can be expected when using any one of the three attitude-control modes under a variety of nominal and off-nominal conditions. (The off-nominal conditions consisted of combinations of thrust misalinement and uneven propellant drain.)

3. The handling qualities of a simplified LES vehicle are affected

   (a) Significantly by moment-of-inertial levels (particularly when using kinesthetic control).

   (b) Moderately by uneven propellant drain.

   (c) Very little by thrust misalinement or the presence of an inactive passenger standing next to the control pilot.

4. A lunar module prototype 8-ball is an acceptable attitude indicator for use on an LES, but it was concluded that:

   (a) Attitude error bands could be reduced significantly if gain factors greater than 1.0 were selectively applied to the pitch- and roll-axis drive signals when maintaining fixed attitudes.

   (b) The attitude-monitoring task would be less confusing if some type of distinctive visual aids were provided on the 8-ball for each pitch reference angle specified in the guidance plan.

5. A significant reduction in the main thrust level just prior to burnout will result in improved vehicle handling qualities and consequently in lower linear and angular velocity errors for orbit insertion.

6. The following conclusions reached in previous LESS studies were reconfirmed in the present study:

   (a) The pilot's kinesthetic control skills are retained without degradation for periods of at least 2 weeks (or longer than a 14-day Apollo mission).

(b) Kinesthetic attitude control is a simple and reliable backup control technique and is inherently available for use in supplementing some other type of primary control mode.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., October 4, 1971.

APPENDIX

BRIEF DESCRIPTION OF LESS HARDWARE AND SUMMARY OF COMPUTER EQUATIONS

The lunar-escape system simulator (LESS) is designed to accommodate a broad spectrum of lunar take-off studies using simplified guidance and control. In particular, the LESS is specially outfitted for kinesthetic control studies or for kinesthetic augmentation of other modes of simplified attitude control. A full description of the LESS is given in reference 4. A block diagram of the complete LESS system is presented in figure 1.

LESS Pilot Control Station and Interface With Real-Time Digital Computer

Figure 2 is a photograph of the two-man LESS pilot control station, which features simplified hand controls, a limited-information pilot's display, and two pairs of load cells mounted under the outside edges of the simulator platform. The control pilot (front) has a three-position toggle switch at his left hand for commanding one or two levels of constant thrust and thrust off. The three-axis right-hand controller (shown in fig. 2) was used to some degree for all three control modes – all three axes were used during TVC and attitude-jet runs, but only the yaw-axis was used during kinesthetic-control runs.

Figure 8 is a photograph of the pilot's instrument display, featuring a prototype LM 8-ball and a large primary digital voltmeter (DVM). To improve the location of the DVM information in the pilot's field of view, a pair of planar mirrors was used to transfer the DVM image to just below the 8-ball (as shown). Time was displayed as additional information on the small DVM to the left of the 8-ball. In general, however, the pilots tended to ignore this secondary DVM because of the necessity for intense concentration on the 8-ball and the image of the primary DVM.

During runs with trajectory plan I, the DVM integers advanced as fast as 21 per second (corresponding to an acceleration of 21 ft/sec^2, or 6.4 m/sec^2), which made it difficult for the pilot to read V_Z closer than about 10 ft/sec (3 m/sec). Because the velocity information was presented to the LESS pilots in terms of integers indicating feet per second, these units are used in the following discussion (with SI units in parentheses). To alleviate the difficulty of monitoring the DVM, the dial to the right of the 8-ball was programed as a differential-velocity indicator during intervals of 100 ft/sec (30 m/sec) surrounding important control events. For example, in trajectory plan I the V_Z target value for initiation of the 73° pitch maneuver (from $\theta = -30^\circ$ to $\theta = -103^\circ$) was 2028 ft/sec (618 m/sec). The differential-velocity indicator was programed to begin its sweep when the DVM reading reached 1978 and to reach full scale (and reset) at 2078. Thus when the sweep hand reached the triangular tape marker positioned at approximately half-scale (see fig. 8), the pilot initiated the pitchover.

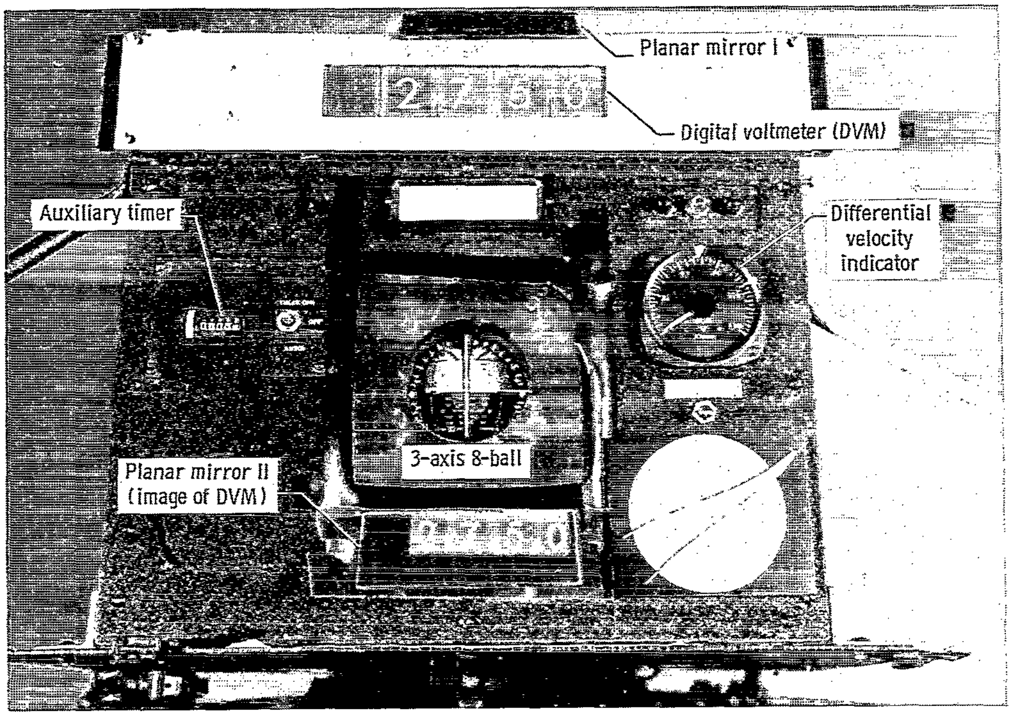

Figure 8.- A pilot's view of the instrument display panel.

Similarly, the sweep hand was again activated when the DVM reading reached 6205, or 50 ft/sec (15 m/sec) before the thrust-cutoff target value of 6255 ft/sec (1907 m/sec).

During runs involving any of the three control modes, pitch and roll command signals were generated when either pilot shifted his center of gravity and thus changed the forces applied to particular load cells (or load-cell pairs). The electrical outputs from these cells were shaped and scaled as analogs of the pitch and roll torques, according to the simulated thrust level and the distance the pilot shifted the center of gravity of the system away from the designated line of thrust. Consequently, it was necessary for the pilots to stand or sit relatively still during the TVC and attitude-jet runs.

All the input signals (controller and load cell) were sent over telephone lines from the vicinity of the pilot control station to analog-to-digital converters at a central computing complex some distance away. The converted input signals were sampled 32 times each second by the real-time digital computer (1/32 second was the selected iteration-time increment for the trajectory calculations). The computer produced selected analog output signals by means of digital-to-analog converters, and returned them over telephone lines to the pilot control station. The primary output signals were the Euler angles ϕ,

ψ, and θ, which were used to drive the three-axis 8-ball, and the indicated velocity V_Z which was displayed to the pilot on an electronic DVM.

Axis Systems

The simplified guidance schemes used in the LESS studies are based primarily on measures which are related to the local vertical. However, it is convenient to sum the forces and moments acting on the LES in a body-axis system X_B,Y_B,Z_B with origin at the instantaneous center of gravity. Therefore, velocities determined in the body-axis system were transformed by means of direction cosines to a local-vertical system X_{LV},Y_{LV},Z_{LV} and to an inertial system X_I,Y_I,Z_I for the trajectory calculations and orbit determinations. The axis systems are shown in figure 9, and details concerning generation of the various direction cosines are given in reference 4.

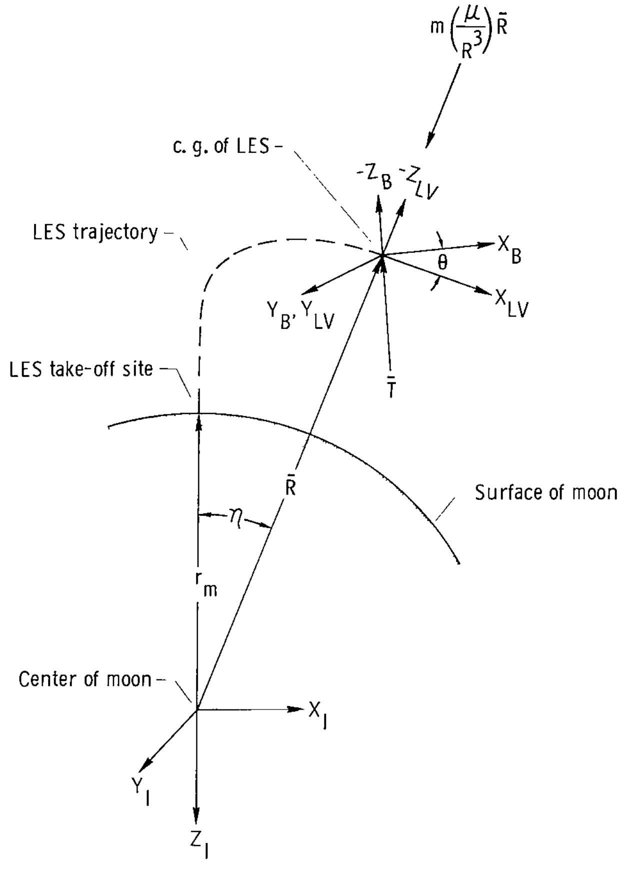

Figure 9.- Sketch showing LES trajectory, force and position vectors, axis systems, pitch angle, and downrange central angle.

Equations of Motion

A summary (from ref. 4) of the translational- and angular-acceleration equations of motion (expressed in the body-axis system) is given below. The three linear-acceleration components are:

$$\begin{bmatrix} \dot{u} \\ \\ \dot{v} \\ \\ \dot{w} \end{bmatrix} = \begin{bmatrix} \dfrac{T_x}{m} + b_{13}\dfrac{\mu}{R^2} - wq + vr \\ \\ \dfrac{T_y}{m} + b_{23}\dfrac{\mu}{R^2} - ur + wp \\ \\ \dfrac{T_z}{m} + b_{33}\dfrac{\mu}{R^2} - vp + uq \end{bmatrix} \tag{A1}$$

where b_{13}, b_{23}, and b_{33} are direction cosines appropriate to transforming the gravity acceleration from the local-vertical system into body coordinates; R is the distance from the origin of body coordinates to the center of the moon; and T_x, T_y, and T_z are body components of the main thrust. Except in cases where the main thruster is misalined, T_x and T_y are zero.

The associated angular acceleration equations are given by:

$$\begin{bmatrix} \dot{p} \\ \\ \dot{q} \\ \\ \dot{r} \end{bmatrix} = \begin{bmatrix} I_1\left(Q_x - D_1\right) + I_3\left(Q_z - D_3\right) \\ \\ \dfrac{1}{I_{yy}}\left(Q_y - D_2\right) \\ \\ I_2\left(Q_z - D_3\right) + I_3\left(Q_x - D_1\right) \end{bmatrix} \tag{A2}$$

where I_1, I_2, I_3, and I_{yy} are inertia terms; D_1, D_2, and D_3 are collections of miscellaneous terms from the moment-equation derivations; and Q_x, Q_y, and Q_z are body-axis torques.

The inertia terms are further defined by

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} = \begin{bmatrix} I_{zz}\Big/\left(I_{xx}I_{zz} - I_{xz}^2\right) \\ I_{xx}\Big/\left(I_{xx}I_{zz} - I_{xz}^2\right) \\ I_{xz}\Big/\left(I_{xx}I_{zz} - I_{xz}^2\right) \end{bmatrix} \tag{A3}$$

Because of assumed asymmetry in each of the LES vehicle configurations, the only nonzero product of inertia is I_{xz}. Examples of inertia variations during the escape flights are shown in figure 4 for several vehicle configurations.

The auxiliary variables D_1, D_2, and D_3 are given by

$$\begin{bmatrix} D_1 \\ D_2 \\ D_3 \end{bmatrix} = \begin{bmatrix} \dot{I}_{xx}p + \left(I_{zz} - I_{yy}\right)qr - I_{xz}pq \\ \dot{I}_{yy}q + \left(I_{xx} - I_{zz}\right)pr + I_{xz}\left(p^2 - r^2\right) \\ \dot{I}_{zz}r + \left(I_{yy} - I_{xx}\right)pq + I_{xz}qr \end{bmatrix} \tag{A4}$$

where the inertia rates are retained because such a large percentage of the total mass is propellant mass, which is expended during a flight.

Body Torques and Horizontal Center-of-Gravity Shifts

Because the kinesthetic-control torques are a function of the horizontal center-of-gravity shift (with components Δx and Δy) off of the line of thrust, it is necessary to sense or determine Δx and Δy continuously. The load cells under the LESS platform were used to generate the electrical signals M_θ and M_ϕ, which were proportional to the pitch and roll torques, respectively, that were created when the LESS pilot shifted his center of gravity with respect to the balance point of the control station. (See ref. 4.) In equation form,

$$M_\theta = K_1 W_{3,e} \delta x_3 \tag{A5}$$

$$M_\phi = K_1 W_{3,e} \delta y_3 \tag{A6}$$

where K_1 is a gain factor (to boost signal strength), $W_{3,e}$ is the earth weight of the control pilot, and δx_3 and δy_3 are distances the pilot moves his own center of gravity from the balancing position. Then the body-axis components of the horizontal center-of-gravity shift of the vehicle system are

$$\Delta x = K_2 \frac{M_\theta}{mg_e} \tag{A7}$$

$$\Delta y = K_2 \frac{M_\phi}{mg_e} \tag{A8}$$

where mg_e is the earth weight of the simulated LES, and K_2 relates the load-cell signals to vehicle torques when the signals are converted at the digital computer.

With Δx and Δy thus continuously determined, the equations for the torques acting on an LES during an escape flight can be written as

$$\begin{bmatrix} Q_x \\ \\ Q_y \\ \\ Q_z \end{bmatrix} = \begin{bmatrix} T\left[\Delta y - \left(z_h - \Delta z\right)\xi_y\right] + K_3 \Delta y \, m \dfrac{\mu}{R^2} + K_4 t \\ \\ T\left[-\Delta x + \left(z_h - \Delta z\right)\xi_x\right] + K_3 \Delta y \, m \dfrac{\mu}{R^2} + K_5 t \\ \\ Q_{z,j} \end{bmatrix} \tag{A9}$$

where $(T\ \Delta x)$ and $(T\ \Delta y)$ are the inflight kinesthetic control torques; ξ_x and ξ_y are thrust misalinement angles; z_h is the distance from the thruster nozzle to the initial center of gravity of the vehicle; and $m\mu/R^2$ is the lunar weight of the LES. The terms containing K_3 permit kinesthetic control on the launch rack during the prebalance period; K_3 has a value of 1 prior to take-off and 0 when thrust is turned on. The terms K_4t and K_5t are used to simulate uneven propellant drain, and $Q_{z,j}$ is the torque due to the yaw jets.

Velocity Along the Thrust Axis

The following equation was used to represent the output of the integrating accelerometer mounted on the thrust axis at the initial center of gravity of the vehicle:

$$V_z = \int_0^t \left[\frac{T}{m} - b_{33} g_m + \Delta z\left(p^2 + q^2\right)\right] dt \tag{A10}$$

where $g_m = 1.62$ m/sec^2 (5.32 ft/sec^2) and the term containing Δz has the form of the factor normally used to correct sensed acceleration to vehicle acceleration; however, in the present application this term is used with the opposite sign in order to generate the uncorrected or sensed acceleration (for display to the pilot) from the computed acceleration.

Orbital Parameters

The primary characteristics of the LES orbits are determined from the following equations based on "burnout" conditions (variables with subscript BO) in the escape trajectory.

The semimajor axis is determined from

$$a = \frac{R_{BO}}{2 - \frac{R_{BO}\left(V_T\right)_{BO}^2}{\mu}} \tag{A11}$$

where V_T is the total velocity of the LES and μ is a lunar gravitational constant. Next the radius of pericynthion is given by

$$R_p = a\left[1 - \sqrt{1 - \frac{R_{BO}^2\left(V_H\right)_{BO}^2}{a\mu}}\right] \tag{A12}$$

where V_H is the local horizontal component of V_T. From this the altitude of pericynthion is

$$h_p = R_p - r_m \tag{A13}$$

where r_m is the radius of the moon. The altitude of apocynthion is thus

$$h_a = 2a - R_p - r_m \tag{A14}$$

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