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TECHNICAL NOTE

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DYNAMIC STABILITY AND CONTROL PROBLEMS OF PILOTED REENTRY FROM LUNAR MISSIONS

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SUMMARY

A fixed-base simulator investigation has been made of stability and control problems during piloted reentry from lunar missions. Reentries were made within constraints of acceleration and skipping, in which the pilot was given simulated navigation tasks of altitude and heading angle commands. Vehicles considered included a blunt-face, high-drag capsule, and a low-drag lifting cone, each of which had a trim lift-drag ratio of 0.5.

With the provision of three-axis automatic damping, both vehicles were easily controlled through reentry after a brief pilot-training period. With all dampers out, safe reentries could be made and both vehicles were rated satisfactory for emergency operation. In damper-failure conditions resulting in inadequate Dutch roll damping, the lifting-cone vehicle exhibited control problems due to excessive dihedral effect and oscillatory acceleration effects.

INTRODUCTION

Problems of heating, skipping, and acceleration for earth reentry at supercircular velocity have been studied for both ballistic and lifting vehicles. Only recently, however, has consideration been given to piloting and control problems associated with such reentries. As part of a program being conducted by the Langley Research Center on lifting lunar reentry shapes, an analog simulation study was undertaken of dynamic stability and control problems during piloted reentry from lunar flight. The two vehicles considered were simple bodies of revolution, one being a low-drag cone and the other a blunt-face, high-drag capsule. The fixed-base simulator included a two-axis hand controller; foot pedals; a display of trajectory, dynamic, and acceleration parameters; and an analog computer for solving the six-degree-of-freedom equations of motion.

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Simulated reentries were initiated at an altitude of 400,000 feet and flown by the pilot by the use of proportional reaction and aerodynamic controls until the vehicle had decelerated to a velocity of 18,000 to 20,000 feet per second. During the reentry the pilot performed altitude and heading angle tasks. Three-axis damping augmentation was assumed for both vehicles and the effect of different damper-failure conditions on controllability was assessed.

SYMBOLS

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a_l, a_Y, a_N	accelerations along the negative X- and Z- and positive Y-axes, respectively, g units
C_{l_β}	effective dihedral derivative
C_{m_q}	damping-in-pitch derivative
C_{n_r}	damping-in-yaw derivative
C_{n_β}	directional stability derivative
C_{Y_β}	aerodynamic side-force derivative
h	altitude, ft
$\dot{h}$	altitude rate, $\frac{dh}{dt}$, ft/sec
$\bar{h}$	quickened altitude error, $h - h_c + k_{\dot{h}}\dot{h}$
h_c	altitude command, ft
$k_{\dot{h}}$	gain on $\dot{h}$ feedback, sec
L/D	lift-drag ratio
p, q, r	angular velocities about the reference body axes, radians/sec
$\bar{q}$	dynamic pressure, lb/sq ft
R	range, nautical miles
t	time, sec

V	vehicle velocity, ft/sec
V_c	circular orbital velocity, ft/sec
X,Y,Z	reference body-axes system, X-axis coincides with the axis of symmetry with its positive direction in the direction of flight
α	angle of attack, deg
β	angle of sideslip, deg
γ_o	reentry angle at an altitude of 400,000 feet, deg
$\delta_{a,p}$	pilot roll control input, deg/sec^2
θ	vehicle pitch angle, deg
ϕ	vehicle roll angle, deg
Ψ	flight-path angle in horizontal plane, deg

Subscripts:

MAX	maximum
MIN	minimum

PILOTING TECHNIQUE AND TASKS

The earth reentry of lunar vehicles at supercircular speeds introduces control problems with which pilots are generally unfamiliar. Figure 1 presents a typical reentry trajectory at parabolic speed, which is used to illustrate some of the basic control problems involved in making a safe reentry. This type of reentry has received considerable attention in trajectory studies of this problem and was chosen as the standard reentry task used to familiarize the pilots with the problem.

In the pull-out, the pilot held maximum lift until level flight was reached, in order to minimize the peak decelerations and heating rates occurring at this point. The heavy arrows in figure 1 indicate the required direction and relative magnitude of lift at various points on the trajectory. During a steep pull-out the pilot is subjected to a combination of high decelerations, rapidly varying dynamic conditions, and high natural frequencies which can lead to serious control problems. For shallow reentry angles, on the other hand, the critical problem is to avoid skipping out of the atmosphere. The steepest reentry angle considered was determined by limiting the maximum deceleration to 8g. The shallowest reentry angle was limited by the condition that available aerodynamic lift must be able to cancel the skipping tendency caused by the supercircular velocity.

After the pull-out, the pilot must make a transition maneuver to reverse the direction of vertical lift in order to maintain level flight as required in the slowdown portion of the standard trajectory. The two types of transition maneuvers considered in this paper are the roll-only maneuver, in which maximum trim angle of attack is maintained and vertical lift is controlled by bank angle, and the roll-pitch maneuver, in which the pilot rolls 180° and modulates angle of attack. After the transition maneuver, the pilot's two main problems are to learn to control the flight path accurately in the presence of the varying centrifugal force and to control the tendency to increasing oscillations in damper-out conditions, which results from decreasing dynamic pressure. After passing through circular speed the lift is again upward, and the trajectory eventually ends in a final glide which was not considered in this investigation.

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After the subject pilots had familiarized themselves with the basic control problems of the reentry, simulated range-variation maneuvers were introduced for the study of damper-out conditions. In the range-increase type of maneuver, the pilot entered at the steepest reentry angle and was commanded to pull up to an altitude above the pull-out altitude and level off. For range decrease, the vehicle entered at the shallowest angle and was commanded to pull down and level off. In addition, heading commands were sometimes included. These maneuvers are similar to those discussed in reference 1 on the pilot-controlled guidance system.

PILOT STATION AND DISPLAY

Figures 2 and 3 show the pilot station and instrument display. In front of the pilot is the instrument display, while to his left is an X-Y plotter on which the vehicle trajectory was generated. To the pilot's right is a two-axis side-arm controller used for pitch and roll control. Foot pedals were used for yaw control.

The details of the display are shown in figure 3. Initially the pilot uses the "8 ball" and α-meter to establish his proper roll and pitch attitude for reentry. He monitors his pull-out trajectory on the X-Y plotter. As level flight is approached, he observes altitude rate on the $\dot{h}$ meter. As $\dot{h}$ goes to zero, he performs a 180° roll using the 8 ball and continues to hold constant altitude by varying angle of attack.

For the task of climbing or diving to a designated altitude, quickened altitude error h was presented on the altitude-rate meter. Altitude error and rate were combined and used as a zero-reader instrument by the pilot to make accurate altitude changes.

While the display presented is by no means optimum, it was felt to be reasonably good. The two-axis hand stick and rudder pedals were reasonably satisfactory but somewhat sloppy for attempting to damp high-frequency oscillations. The nonoptimum nature of controls and display should tend to make the results presented more conservative.

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CONFIGURATIONS AND ANALOG PROGRAM

Figure 4 shows the vehicles considered in this investigation. These are rather simple examples of the two types of bodies generally considered for earth reentries from lunar missions. The L-2C is a blunt-face, high-drag vehicle and the L-8 is a lifting cone. Each vehicle was designed with some vertical center-of-gravity offset to aid in pitch trim. The figure shows the maximum and minimum trim angles of attack, with the controls deflected appropriately. Both vehicles could be trimmed from $L/D = 0$ to $L/D = 0.5$. The L-2C used a small center-of-gravity offset and both upper and lower pitch flaps. For the L-8 a large center-of-gravity offset was assumed, so that it was self-trimmed at $L/D = 0.5$. A single lower flap was used to trim to $L/D = 0$. The rear view shows the pitch and yaw flaps in deflected position.

For roll control both vehicles were equipped with proportional reaction rockets. Above an altitude of 300,000 feet, proportional rockets were also included for pitch and yaw control. Full stick deflection produced accelerations from reaction rockets of $40^{\circ}/\text{sec}^2$ in roll and $4^{\circ}/\text{sec}^2$ in pitch and yaw. Constant gain automatic dampers about all three axes were included for altitudes less than 300,000 feet.

With the use of the roll-only maneuver, the L-8 vehicle has the capability of making entries with no aerodynamic controls as a result of its self-trimming feature, and some of these results will be presented.

The aerodynamic characteristics of the vehicles were determined from wind-tunnel tests and are reported in reference 2. The nonlinear aerodynamics considered for this investigation and programed on the analog computer were pitching moment as a function of angle of attack and pitch control deflection, chord force as a function of angle of attack, and C_{n_β} and C_{l_β} as functions of angle of attack.

In the analog set-up the chief aims were to obtain accurate trajectories and a good simulation of vehicle dynamics both with and without dampers. The axes system chosen were body axes for the moment equations and local horizontal axes for the force equations. Considerable attention was given to the problem of analog scaling and to the selection of high-response nonlinear equipment, multipliers and resolvers, by the analog computing personnel. As a result, good simulation of both vehicle dynamics and trajectory were obtained.

RESULTS

All Dampers In

Figure 5 shows trajectory results, as recorded on the X-Y plotter for the two extreme reentry angles, with all dampers in. Altitude is plotted in thousands of feet and range in nautical miles. Two cases shown are constant L/D reentries followed by level flight, which were used in pilot familiarization. The other two are a pull-up from a steep reentry and a pull-down from a shallow reentry into level flight, which were the typical range variation maneuvers used in most of the damper-out reentries. Brief consideration was also given to two more extreme altitude maneuvers, in which the pilot pulled down from a shallow reentry and leveled off at maximum g or pulled up to a very high altitude from a steep reentry. The pilot was also given a heading task to either hold 0° or to make a designated turn.

After a brief training period to become familiar with the vehicle control characteristics and the required maneuvers, the subjects were able to make all these reentries with complete consistency and with the accuracy shown here. Although not shown, similar results were obtained with the L-2C.

Effect of Damper Failure

Some results pertaining to emergency conditions in which damper failures were considered are discussed. For these reentries the task was to control the trajectory to a commanded altitude and heading angle. In the event of trouble in controlling motions, the pilots neglected the trajectory tasks and concentrated on making safe reentries. In controlling the vehicle the pilot attempted to damp large oscillations with his pitch and yaw controls. Table I summarizes these results.

The first column of table I shows the damper condition and the second column, the rating. The damper-out conditions are listed in the order of increasing difficulty, and results are included for both vehicles using roll-only and roll-pitch maneuvers. In figure 6 trajectory results for four of the damper conditions are presented.

With all dampers in, both vehicles are rated satisfactory. With the yaw or roll damper out, the subject was able to keep the lateral oscillations small with a minimum of attention. He still did a good job of flight-path control. With the pitch damper out or roll and yaw out, the subject had to devote more time to controlling the dynamic variables. However, a reasonably good job was done of controlling the trajectory, as seen in figure 6(a) for the pitch damper out. For the remaining conditions, successively more time and effort had to be devoted to controlling dynamics and this result can be seen in figure 6(b). Even though the last five cases shown in table I carry the same rating, an extreme degradation of control capability exists between the top and bottom conditions. The pitch-damper-out condition is not very far removed from the acceptable category, whereas considerable practice and training were required in order to make successful reentries with all dampers out. With all dampers out, proper techniques of making control motions in a smooth and gradual manner to minimize disturbances and of using pitch and yaw controls to damp oscillatory motions were important for keeping the vehicles under control. It was also generally noted that the use of roll-only maneuvers with the all-dampers-out condition result in better controlled reentries.

In this investigation no consideration was given to the condition of dampers failing during the run. From X-15 simulator studies, such failures sometime resulted in dangerous situations and consideration should be given to such conditions in future investigations.

Vehicle Dynamics

Before leaving the discussion of damper-out controllability, one significant qualitative difference between the lateral characteristics of the L-2C and L-8 should be mentioned. This difference is attributable to the very large difference in the dihedral effect C_{l_β} of the vehicles: -0.086 for L-8 and -0.006 for L-2C. Figure 7 shows that the L-8 vehicle, because of its relatively large dihedral, presented a much more difficult roll-control problem than the L-2C. In this maneuver the pilot was performing a steep reentry with no aerodynamic damping. He attempted to maintain a 180° bank angle for a while, followed by 0°. Note the irregular and larger ϕ and p variations and more frequent roll-jet operation for the L-8 even though the β magnitudes are almost the same. In fact, only one β is shown, for convenience.

The larger dihedral of the L-8 is partly caused by the larger center-of-gravity offset assumed, but a more important factor is the larger side-force coefficient C_{Y_β} which acts through the center-of-gravity offset to provide the large C_{l_β} dihedral effect. By simple Newtonian-flow theory, it can be seen that the L-2C, because it flies blunt-face forward, develops very small forces normal to its axis of symmetry, whereas the L-8 can develop large off-axial forces. Figure 8 shows the effect of this difference in configurations on the off-axial accelerations imposed on the pilot. (Note that the time scale on this figure starts when the rolling motion is initiated.) Presented in this figure are the normal, lateral, and longitudinal accelerations, beginning at the time of the first roll maneuver. The L-2C has no off-axial accelerations, whereas the L-8 has an appreciable normal acceleration, and a lateral-acceleration oscillation. This level of lateral acceleration would not appear to present any difficulty with a well designed body-restraint system.

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There are two reasons why the lateral accelerations are not larger in this reentry. The first is that the runs shown are rather well-controlled examples for the damper-out condition, as can be seen by the small sideslip angle developed. The second reason is that the pilot's standard damper-out task for a steep reentry was to climb 25,000 feet immediately after pull-out. This caused the dynamic pressure to drop just as the oscillations built up. Figure 9 shows the sort of accelerations that might result if both these factors were less favorable.

In this case the pilot performed a maneuver which represented an attempt at extreme shortening of range. He entered at a shallow flight-path angle, but maneuvered to pull down and level out at 150,000 feet with maximum g. Also, the maneuver was not as well controlled as the others shown. The motions shown are angle of attack, sideslip, normal, and lateral accelerations, all of which became oscillatory at high dynamic pressures. The large lateral accelerations in this run (a maximum of 1.4g) would certainly represent a serious problem. This problem needs to be investigated more closely by using a human centrifuge to determine if such effects are significant enough to influence the choice of a configuration.

Another problem related to the dynamic characteristics of the vehicles was encountered with the L-2C. With this vehicle, a divergence in angle of attack sometimes occurred when a roll maneuver was initiated at very low dynamic pressure. Figure 10 shows a reentry at a shallow reentry angle (-5.25°), in which the subject performed a 180°

roll at an altitude of 300,000 feet, in order to pull down to a lower altitude. Time histories are presented of dynamic pressure, bank angle, and angle of attack. In performing the roll at low $\bar{q}$, large transient motions in angle of attack and sideslip occur, as the vehicle rolls about its principal body axis. Eventually the effect of the vehicle's static stability comes into play and returns the vehicle towards its trim condition, which was 30°. A large overshoot of the trim value occurred, and the vehicle reached an angle of attack at which it is statically unstable. The result is a divergence in angle of attack and loss of control. Solutions to this problem are: (1) perform rolls for low dynamic pressure at 0° angle of attack, (2) restrict rolling to higher $\bar{q}$, (3) include sufficient damping to avoid such an overshoot, or (4) design the vehicle to have stable pitching-moment curve to a higher angle of attack.

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Roll-Control Only Reentries

The L-8 vehicle, as mentioned earlier, is self-trimming at $L/D = 0.5$ and hence has the capability of reentering by using a roll maneuver and roll reaction controls only, that is, with no aerodynamic controls whatever. The L-2C with some modification could be controlled in this manner also. With three-axis damping the L-8 vehicle was flown in this manner with no difficulty, these results having been included in the all-dampers-in case of table I. In addition, entries were made in this mode in which no automatic damping was provided in either pitch or yaw.

Figure 11 presents such results for a shallow reentry. The pilot was given both an altitude and heading task. He did a good job of accomplishing the altitude task and had almost accomplished his heading task when the run was terminated. Although the pilot did a reasonable job of flight-path control, he rated this condition acceptable for emergency use only because of the undamped lateral oscillation, which can be seen in the β and p motions, and pilot effort required to control bank angle, which can be seen in the irregular ϕ and pilot input motions.

With all dampers out, reentries could also be safely made, as shown in table I.

Effect of Aerodynamic Damping

There is considerable controversy whether it is necessary to obtain data on rotary derivatives (such as C_{m_q}, damping in pitch, and C_{n_r}, damping in yaw) for accurate simulation of reentry-vehicle dynamic characteristics. The general opinion seems to be that they can have no importance at these speeds. In this simulation, values obtained from limited wind-tunnel studies were used. For the L-8, for example, stable values of C_{n_r} and C_{m_q} equal to -0.7 were obtained. To see whether rotary derivatives of this magnitude could have any significant dynamic effects, a number of L-8 damper-out reentries were made with the algebraic sign of these quantities reversed.

In figure 12, results are shown for a steep reentry. With the unstable damping values, the motions are much more divergent and the pilot soon lost control of the vehicle. These preliminary results indicate that rotary derivatives can still be important in the marginal damper-out conditions, even at these extreme speeds.

CONCLUSIONS

Although a good dynamic simulation was obtained for this investigation, the limitations of a fixed base simulation are recognized, and more extensive simulator programs will be required employing angular motion simulators and human centrifuges to further investigate problems of the types considered herein. It is hoped that the results of the present study will have a significant input into those studies by better defining the range of capabilities of a human pilot with regard to the basic control and guidance tasks and also in emergency conditions.

The following conclusions are indicated by the results of this preliminary investigation:

1. With all dampers in, both the L-2C and L-8 can be controlled through reentry, with altitude and heading tasks being accomplished with precision.

2. Both vehicles with all dampers out could be controlled to some degree and were rated satisfactory for emergency operation.

3. The existence of excessive dihedral effect makes the precise control of bank angle a difficult task for conditions of dampers out, as shown by the example of the L-8.

4. In damper-failure conditions, lifting-cone vehicles may encounter appreciable oscillatory accelerations. The effects of such accelerations require investigation in a human-centrifuge program.

5. The performance of rolling maneuvers at low dynamic pressures with vehicles having unstable pitching-moment curves at high angles of attack may result in a divergence and loss of control, as shown by the L-2C example.

6. Required reentry maneuvers can be satisfactorily performed without any aerodynamic controls by using vertical center-of-gravity offset to trim at required lift-drag ratio and roll reaction controls to make rolling maneuvers.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Air Force Base, Va., July 18, 1961.

REFERENCES

1. Foudriat, Edwin C., and Wingrove, Rodney C.: Guidance and Control During Direct-Descent Parabolic Reentry. NASA TN D-979, 1961.

2. Rainey, Robert W., compiler: Summary of Aerodynamic Characteristics of Low-Lift-Drag-Ratio Reentry Vehicles From Subsonic to Hypersonic Speeds. NASA TM X-588, 1961.

TABLE I

EFFECT OF DAMPER CONDITIONS ON CONTROLLABILITY

DAMPER CONDITION	CONTROLLABILITY
ALL IN	SATISFACTORY
YAW OUT	ACCEPTABLE
ROLL OUT	ACCEPTABLE
PITCH OUT ROLL AND YAW OUT PITCH AND YAW OUT PITCH AND ROLL OUT ALL OUT	ACCEPTABLE FOR EMERGENCY OPERATION

L-1764

STANDARD REENTRY TRAJECTORY

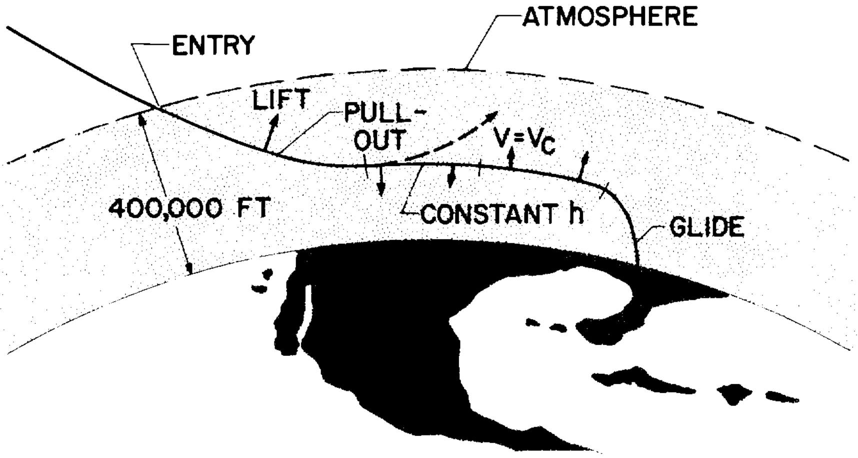

Figure 1

SIMULATED COCKPIT

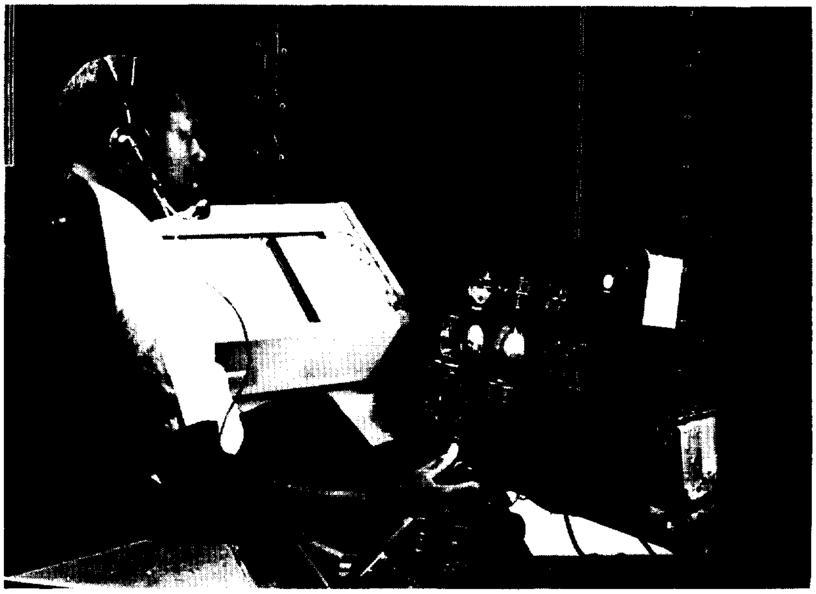

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Figure 2

INSTRUMENT PANEL

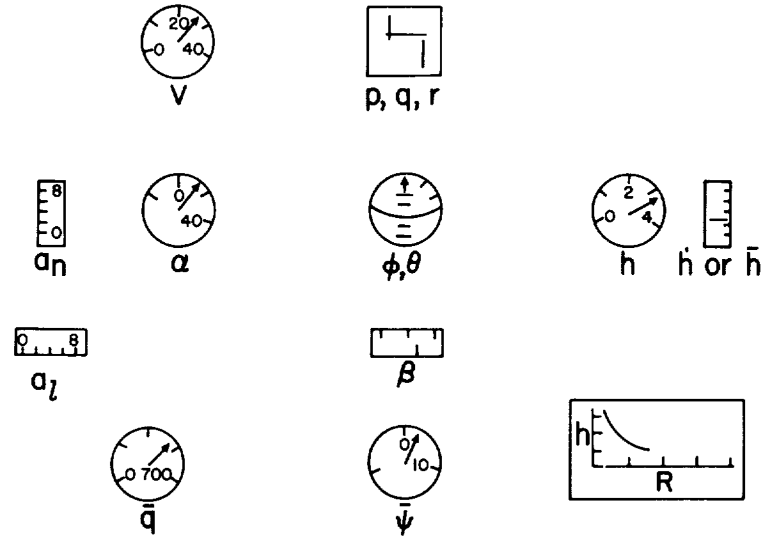

Figure 3

REENTRY VEHICLE CONFIGURATIONS

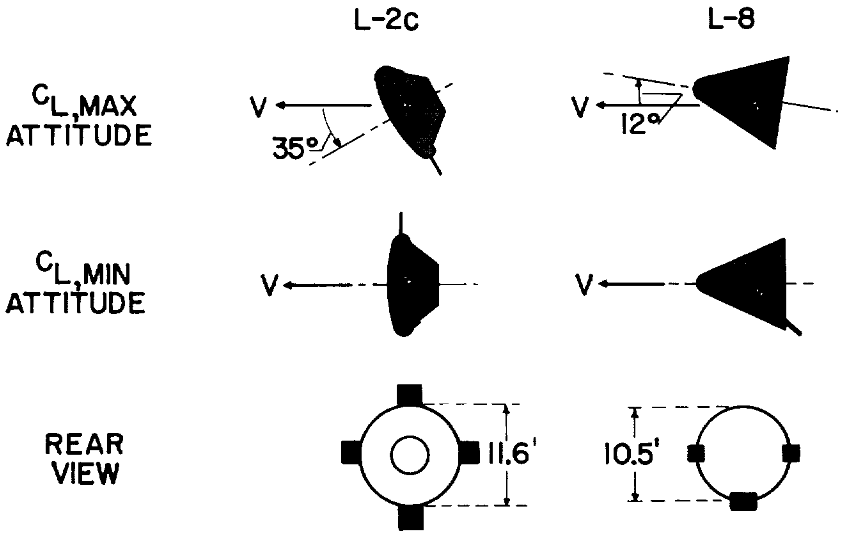

Figure 4

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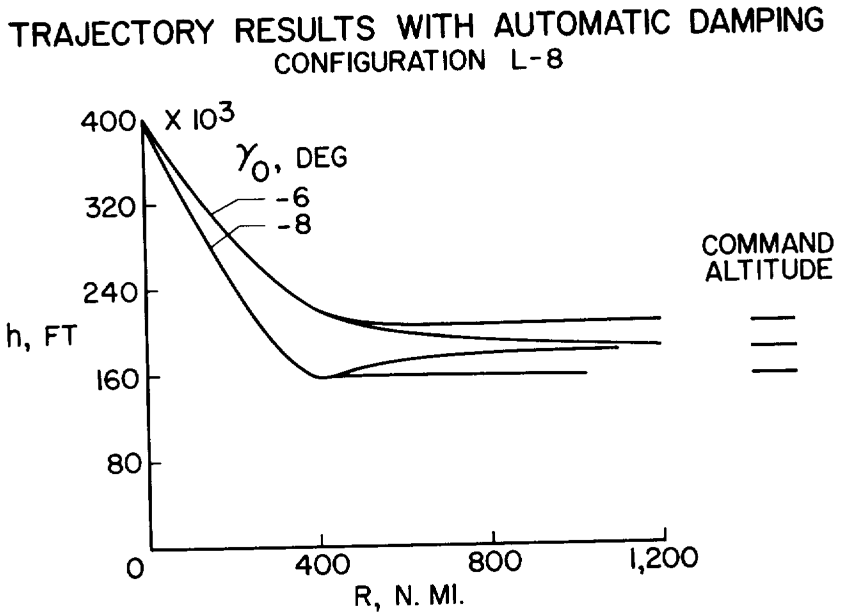


Figure 5

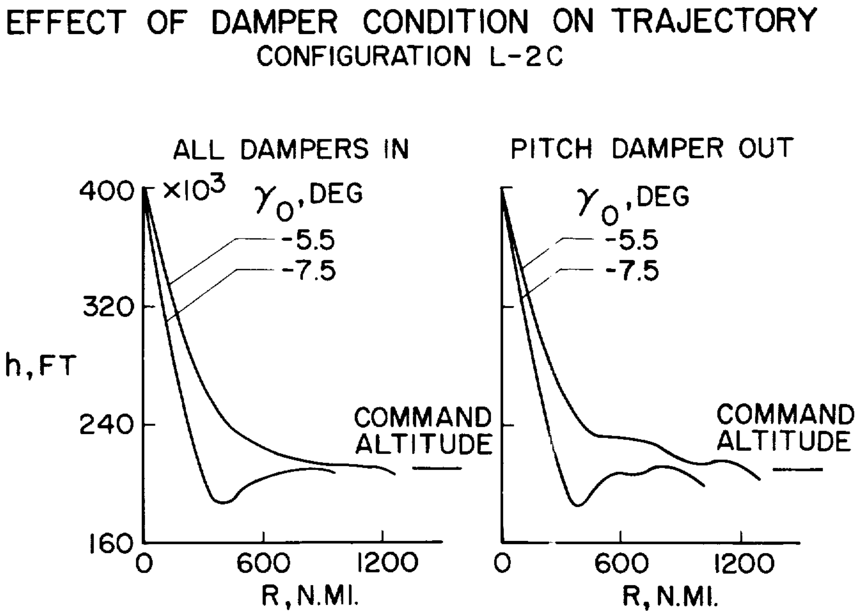


Figure 6(a)

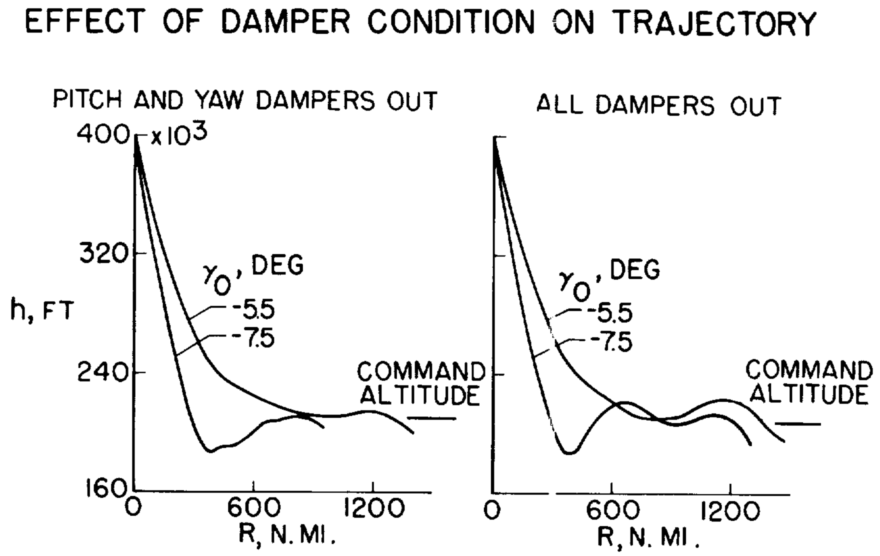


Figure 6(b)

EFFECT OF DIHEDRAL ON LATERAL DYNAMIC CHARACTERISTICS

ROLL-PITCH MANEUVER; STEEP REENTRY ANGLES

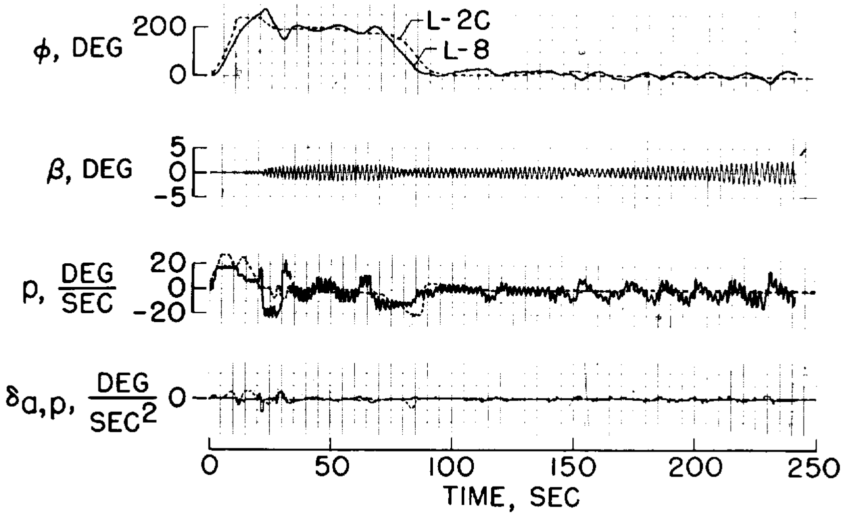


Figure 7

EFFECT OF DIHEDRAL ON ACCELERATION COMPONENTS

ROLL-PITCH MANEUVER; STEEP REENTRY ANGLES

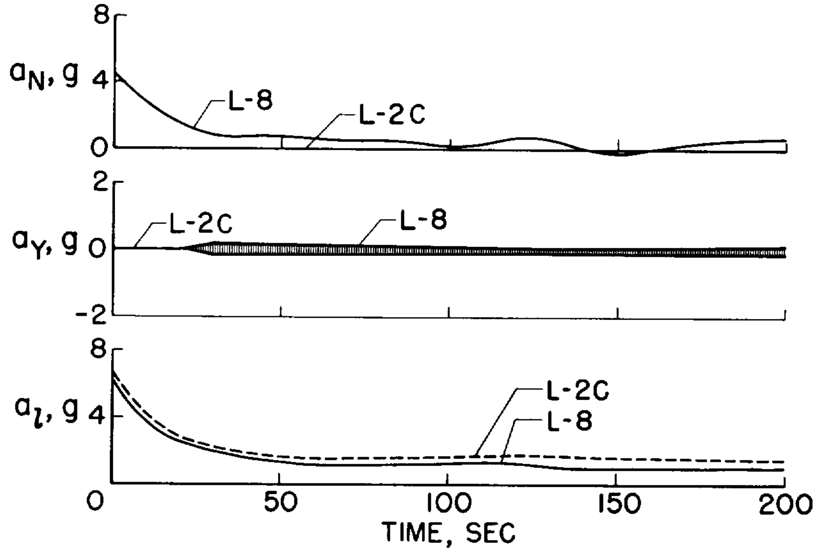


Figure 8

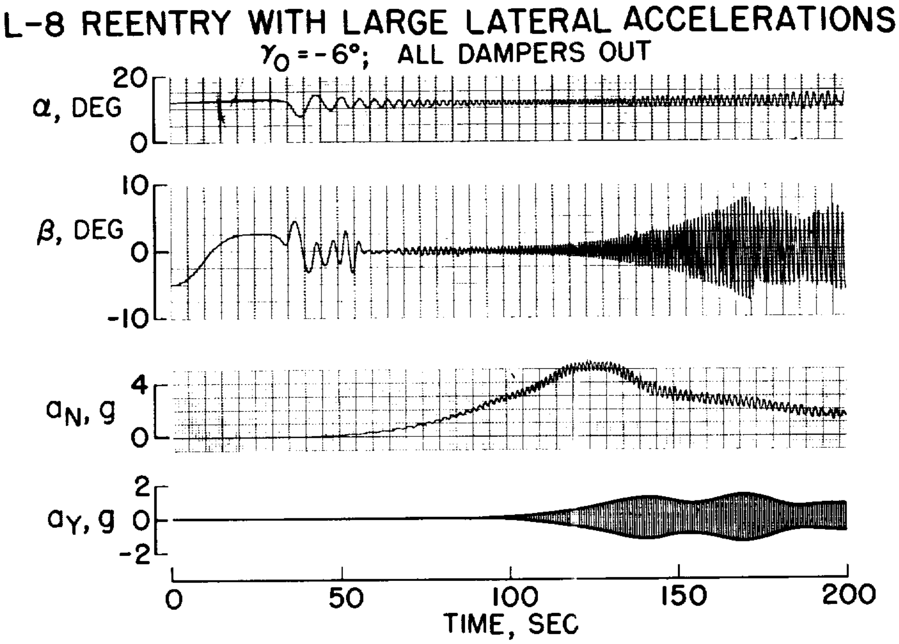


Figure 9

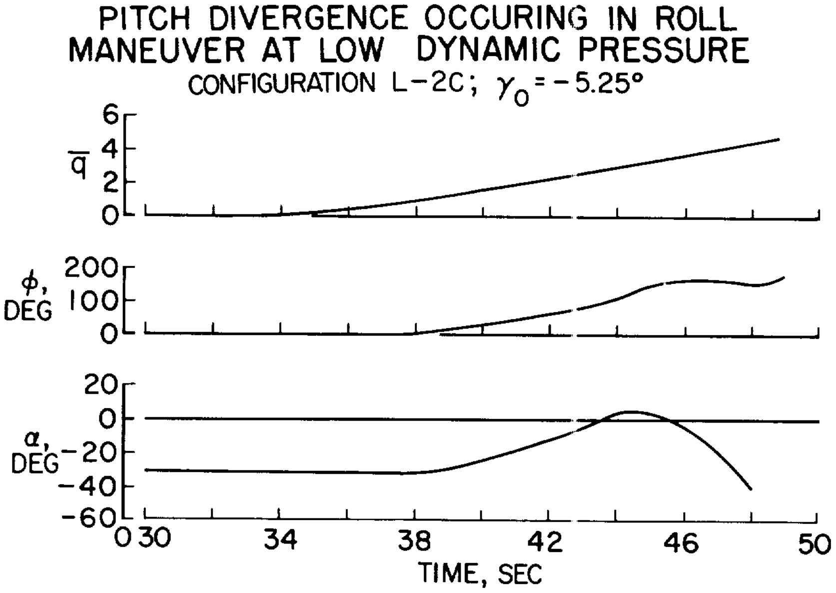


Figure 10

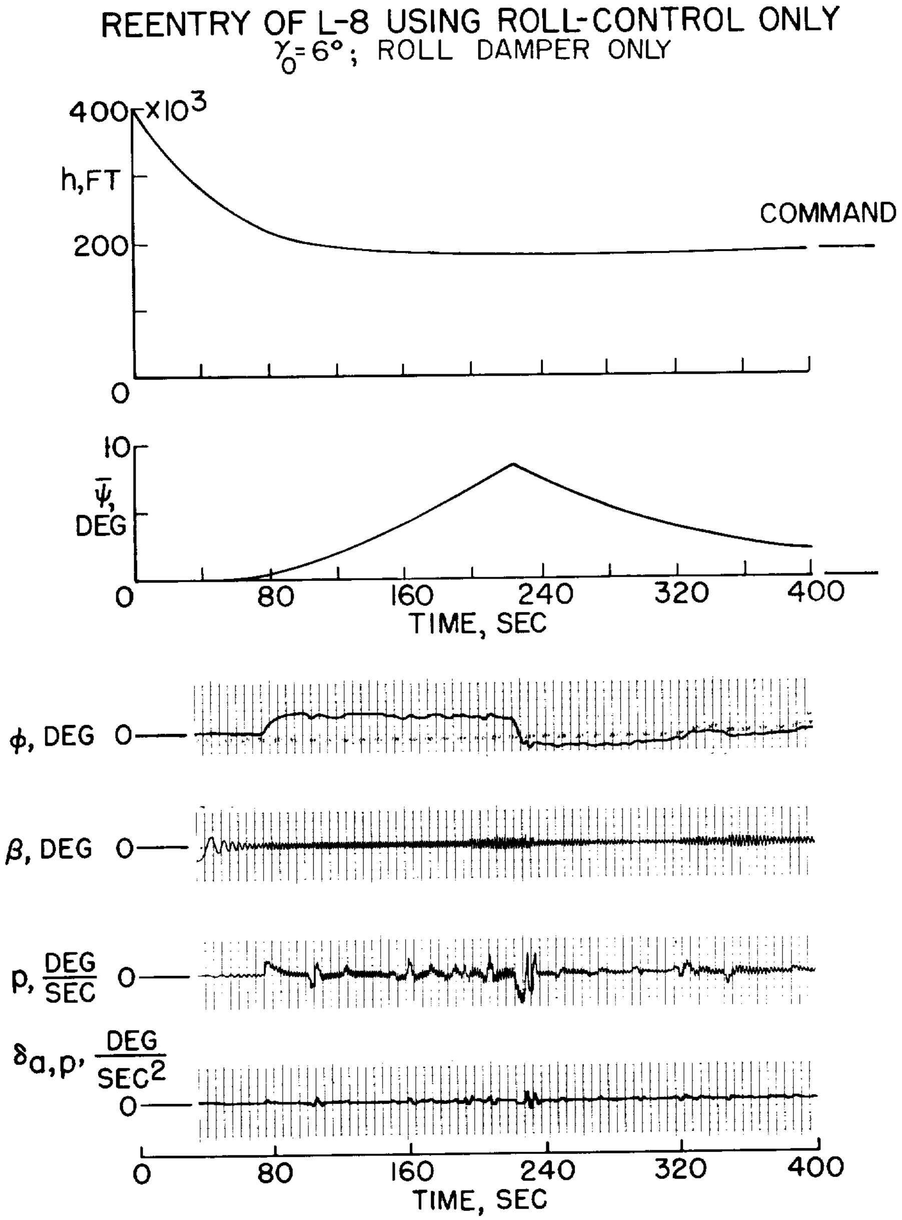
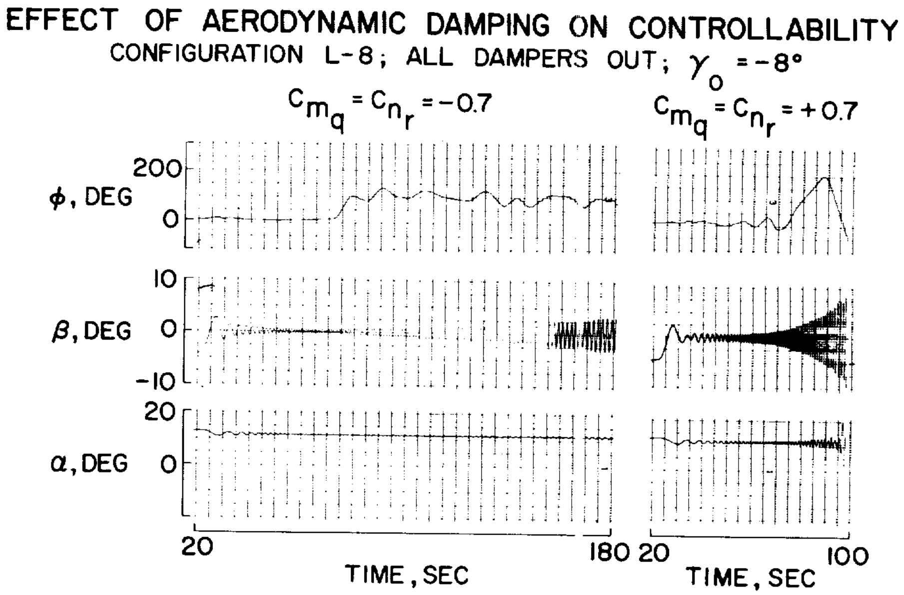

REENTRY OF L-8 USING ROLL-CONTROL ONLY
$\gamma_0 = 6°$; ROLL DAMPER ONLY
400
$\times 10^3$
h,FT
200
0
COMMAND
10
$\bar{\psi}$,
DEG
0
80
160
240
320
400
TIME, SEC
ϕ, DEG 0
β, DEG 0
p, $\frac{DEG}{SEC}$ 0
δ_a, $\dot{p}$, $\frac{DEG}{SEC^2}$
0
0
80
160
240
320
400
TIME, SEC

Figure 11



EFFECT OF AERODYNAMIC DAMPING ON CONTROLLABILITY

CONFIGURATION L-8; ALL DAMPERS OUT; $\gamma_o = -8°$

Figure 12

NASA-Langley, 1961 L-1764