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INITIAL RESULTS OF STUDIES OF HANDLING QUALITIES
OF A SIMULATED LUNAR LANDING VEHICLE

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The successful accomplishment of the Apollo lunar landing maneuver requires a knowledge of the handling qualities of rocket powered vehicles operating in the lunar environment. There is no direct parallel between the unique piloting problems of the lunar vehicle and normal flying machines operating in the earth's environment. The final phase of the landing maneuver is frequently compared with the landing approach of a helicopter, however, the conditions encountered by the Apollo Lunar Excursion Module or LEM are appreciably different due to the moon's lack of atmosphere and low gravitational force. For example, a vehicle operating in the vicinity of the moon requires the use of control rockets which generally will be operated in an on-off manner thereby producing abrupt changes in control torques rather than the smoothly modulated control torques of a helicopter. Furthermore, inasmuch as a vehicle hovers with a thrust equal to its weight, the lunar vehicle hovers with only one-sixth of the thrust required to hover the same vehicle in earth's gravity. The resulting low thrust to mass ratio requires pitch angles of about six times that required of earth vehicles to generate the same translational acceleration. These conditions are sufficiently different from those of a helicopter, that a need exists to simulate the actual conditions of a man-carrying vehicle operating in the lunar environment. Fixed-base simulation techniques have been used to define many of the problems of the landing maneuver. The Langley Research Center of the NASA, however, recognized in 1961 that a need existed to study the handling qualities of a LEM type vehicle in a simulated

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lunar environment that would produce true vehicle dynamics. A unique simulation facility embodying the capability of producing the dynamics of the LEM vehicle has been constructed at Langley; flight-test operations using this facility have been in progress since the Spring of 1965.

The facility depicted in figure 1 consists of a manned rocket powered vehicle suspended by vertical cables from a traveling crane, supported by a gantry structure 250 feet high and 400 feet long. The traveling crane system is servo controlled to follow the vehicle's linear motions and provide lunar gravitational simulation by constantly producing a vertical force acting through the center of gravity of the vehicle equal to five-sixths of its weight.

The traveling crane system consists of a bridge structure that travels the length of the gantry and an underslung dolly that travels the width of the bridge. The dolly also contains the hoist system that produces the required cable tension for lunar gravity simulation. The drive for these three linear motions is supplied by servo-controlled hydraulic systems that utilize cable angle sensors as the principal signal for horizontal drive and load measuring cells to constantly maintain the tension in the vertical cables. A simulated spacecraft or lunar landing research vehicle is attached to the vertical cables by a gimbal system that provides freedom in pitch, roll, and yaw.

The vehicle can be flown with six degrees of freedom in the flight envelope, illustrated in figure 2. The dimensions of the envelope are 360 feet in the down-range X-direction, 42 feet crosswise in the Y-direction, and 180 feet vertically in the Z-direction. Safety features are provided to

prevent the vehicle from exceeding the envelope during either normal or emergency operation.

The manned lunar landing research vehicle (fig. 3) is rocket powered and weighs 12,000 pounds; including a pilot and 3000 pounds of fuel. The vehicle consists of a tubular steel framework that houses a rocket propulsion system with landing gear "oleo" shock struts attached to the four corners. A two-man pilots' compartment and associated control equipment is centrally located on top of the frame. The propulsion system uses 90 percent hydrogen peroxide as a monopropellant and the system is pressurized with gaseous nitrogen. The main motors, located near the bottom of the frame, produce a thrust that can be throttled from 6000 to 600 pounds. Twenty smaller rocket motors, each ground adjustable over a range of thrust from 125 to 25 pounds, are distributed about the vehicle frame to produce attitude control torques.

Two pilots can be seated, side-by-side in the cockpit shown in figure 4. The pilot flies the vehicle with a LEM type attitude controller, using his right hand, and a throttle control, using his left hand. The attitude controller is a three-axis type that commands the control torques about the roll, pitch, and yaw axes in response to appropriate motions of the pilot's wrist and forearm. Throttle control is obtained using the lever which was originally the collective pitch control in the converted helicopter cockpit. This lever is moved up to increase thrust and down to decrease thrust. The flight instruments; roll-pitch angle indicator, yaw indicator, altimeter, and angular and linear rate meters are located on the right side of a central display panel. The remainder of the gages are used to monitor vehicle subsystems. These instruments are considered to be those necessary to fulfill the basic instrument display needs for the landing maneuver.

The vehicle's pitch control system is illustrated schematically in figure 5. The attitude control systems for roll and yaw are similar. Control is achieved by the use of torques generated by on-off operation of pairs of the attitude control rockets. The firing signal for these motors is the sum of the pilot command and two possible signals derived from the vehicle rate gyros. Adjustment of system gains for a given test flight can be made readily by the pilot to select the set of control system test values and the mode of control; that is, acceleration, rate, or attitude command. With gains K_1 and K_2 set at zero, pilot movement of the controller outside the dead zone fires the motors in an open-loop acceleration command mode. The dead zone can be adjusted to minimize inadvertent control actuation. The motor thrust can be ground adjusted to produce maximum accelerations up to $30^\circ/\text{sec}^2$ in pitch and roll and $17.5^\circ/\text{sec}^2$ in yaw. Adjustment of K_1 will vary maximum available rates as commanded by the pilot's control from ∞ to as low as $5^\circ/\text{sec}$. The switch dead band can be adjusted to vary the rate at which the system drifts with respect to the command rate. This is the rate command mode where vehicle rate is a direct function of controller displacement. By setting K_2 , the rate-integral feedback gain, attitude command mode is activated where vehicle attitude is a direct function of controller displacement. Throttle or main thrust control as illustrated in figure 5 is operated in an open-loop acceleration command mode. The pilot commands thrust with his control lever through a power-booster linearized valve. Parameters in this system such as stick sensitivity, thrust-to-weight ratio, and stick force gradients are variables that can be studied.

The research vehicle and the Apollo LEM are compared in the drawing in figure 6. The LEM is slightly larger physically, however, the linear and

angular accelerations produced by the main and the attitude rockets are comparable. The flexibility of the research vehicle's control systems and general similarity of the two configurations permits an accurate duplication of the LEM flight characteristics. Consequently, the research vehicle provides the capability of studying in detail the handling qualities required for a lunar landing vehicle, and provides the astronauts with a valuable tool for perfecting their landing techniques with a vehicle that duplicates the dynamics of the LEM.

Typical landing trajectories that test pilots have flown are presented in figure 7. In translating and descending to a landing the pilot uses primarily pitch attitude and throttle control for the respective management of down-range and vertical velocities. Very little use of the roll and yaw controls is made for these straight-in approaches. In an effort to more fully exercise the lateral controls a modified maneuver is frequently utilized. In this maneuver the pilot proceeds as if he were going to land, but after having adjusted his velocities for the landing, he performs a 180° turn and translates at reasonably low altitude to perform his landing at the opposite end of the flight envelope. The fuel supply is sufficient to allow the pilot a flight time of approximately 2 minutes to complete this maneuver. The trajectory preferred by most test pilots is the slanting approaches as contrasted to the more nearly vertical. This approach allows the pilot to keep his landing site visible throughout most of the flight and requires little use of instrument displays. The vertical approach is more difficult because the pilot cannot see the landing site and loses his normal motion cues, consequently, he must rely more heavily on instrument displays.

An example of the pilot's management of his throttle control in a typical translation and descent maneuver, starting at an altitude of about 100 feet, is represented by the solid line in figure 8 which is a plot of vertical velocity versus altitude. In this example, the pilot set up a comfortable rate of descent and apparently concentrated on maintaining it until he reached an altitude of 30 to 40 feet. At this point apparently he could judge his altitude with a reasonable degree of accuracy using his visual or out-of-the-window cues and he took on the added task of height or position control. The added task is reflected by an increase in frequency of throttle movement, shown by the velocity reversals in the figure. The boundaries of vertical velocity versus altitude resulting from all the landing approach maneuvers is shown by the dashed line in the figure. After the pilots become experienced and confident with the operation of the throttle, they are comfortable with initial rates of descent up to about 10 ft/sec, and rates of descent at touchdown up to about 4 ft/sec. Pilots utilization of landing velocities up to this touchdown rate eases the landing task by shortening the operating time near the ground. The throttle acceleration command system flown with a stick sensitivity of about 0.5 lunar "g's" per inch has produced acceptable pilot ratings. Some exploratory investigations have been performed using stick sensitivities of one-half to one and one-half the nominal value with little degradation of pilot rating. Flight tests performed with various response times of the thrust control from 0.1 second to about 1.5 seconds have indicated the desirability of response times less than 1.0 second.

The boundaries of translational velocity versus range resulting from the landing approaches, including the turnaround maneuver, is presented as X velocity versus range in figure 9. In performing this task, principally with

the pitch attitude control, the pilots have generally limited their velocity to about 7.5 ft/sec. Maximum pitch angles of 10° to 15° have been utilized in accelerating to and decelerating from this velocity and the corresponding pitch rate has rarely exceeded $10^{\circ}/\text{sec}$. To date the pilots have not used the large angles that might be expected in accelerating a vehicle with low thrust-to-mass ratio. Instead they have used smaller angles and accepted the longer time required to reach a desired velocity.

The attitude control system parameters that have been investigated, principally in the rate command mode, are shown in figure 10 in terms of angular acceleration and maximum available rate. Dead zone, or drift rate, was generally varied as a constant percent of maximum available rate; about $0.4^{\circ}/\text{sec}$ at minimum rate to $2.25^{\circ}/\text{sec}$ at maximum rate. The points plotted at an infinite rate represents operation in the acceleration command mode. The pilot ratings for pitch and roll controls have generally been the same. Accelerations in pitch and roll of $10^{\circ}/\text{sec}^2$ to $15^{\circ}/\text{sec}^2$ and lower are characterized by the pilots as smooth, while higher values are described as jerky. There appears to be little requirement for exploring these higher accelerations, inasmuch as the pilots prefer the lower acceleration and the use of higher acceleration will generally result in larger thrusters with an attendant weight increase. Future tests will be run at accelerations of $10^{\circ}/\text{sec}^2$ and below in an attempt to determine the minimum acceptable values.

Maximum pitch and roll rates of $20^{\circ}/\text{sec}$ with an acceleration of $10^{\circ}/\text{sec}^2$ to $15^{\circ}/\text{sec}^2$ represent the best or most desirable combination that has been found to date. Dead zone, or drift rates, for this combination have been varied from $0.5^{\circ}/\text{sec}$ to $2.0^{\circ}/\text{sec}$. The lower drift rate, by virtue of the tightness it gives the system has produced the best pilot rating. Maximum

available rates in excess of $20^{\circ}/\text{sec}$ are not preferred because of a tendency to overshoot the desired angular displacement, while lower maximum rates are described as requiring too much time to acquire the desired angle. The results for the yaw control system have been quite similar except that a higher maximum available rate has been preferred in those maneuvers requiring large heading change.

Utilizing acceleration command, acceptable pilot ratings have been obtained in a limited number of flight tests. The pilots have, however, experienced difficulty in acquiring small angular displacements.

The following movie illustrates typical flight tests utilizing the Langley Lunar Landing Research Facility.

To date we have accumulated flight-test experience with over one hundred flights. The following preliminary conclusions are indicated:

1. The facility provides a useful tool for developing and evaluating flight control systems, and the pilots have been unanimous in their comments with respect to the realism of the simulation.
2. The landing approach can be successfully performed using the unusual control system imposed by the lunar environment.
3. The pilots prefer to fly in a manner similar to that used in helicopters, for example, instead of using the large pitch angles required for comparable earth translational acceleration, they use smaller pitch angles and accept the longer time required to attain the desired velocity.
4. The facility has indicated a need for and a means of providing pilots and astronauts with flight experience in the dynamics of the lunar landing maneuver.

The continuing flight research program will provide additional flying qualities and operational information for lunar landing vehicles.

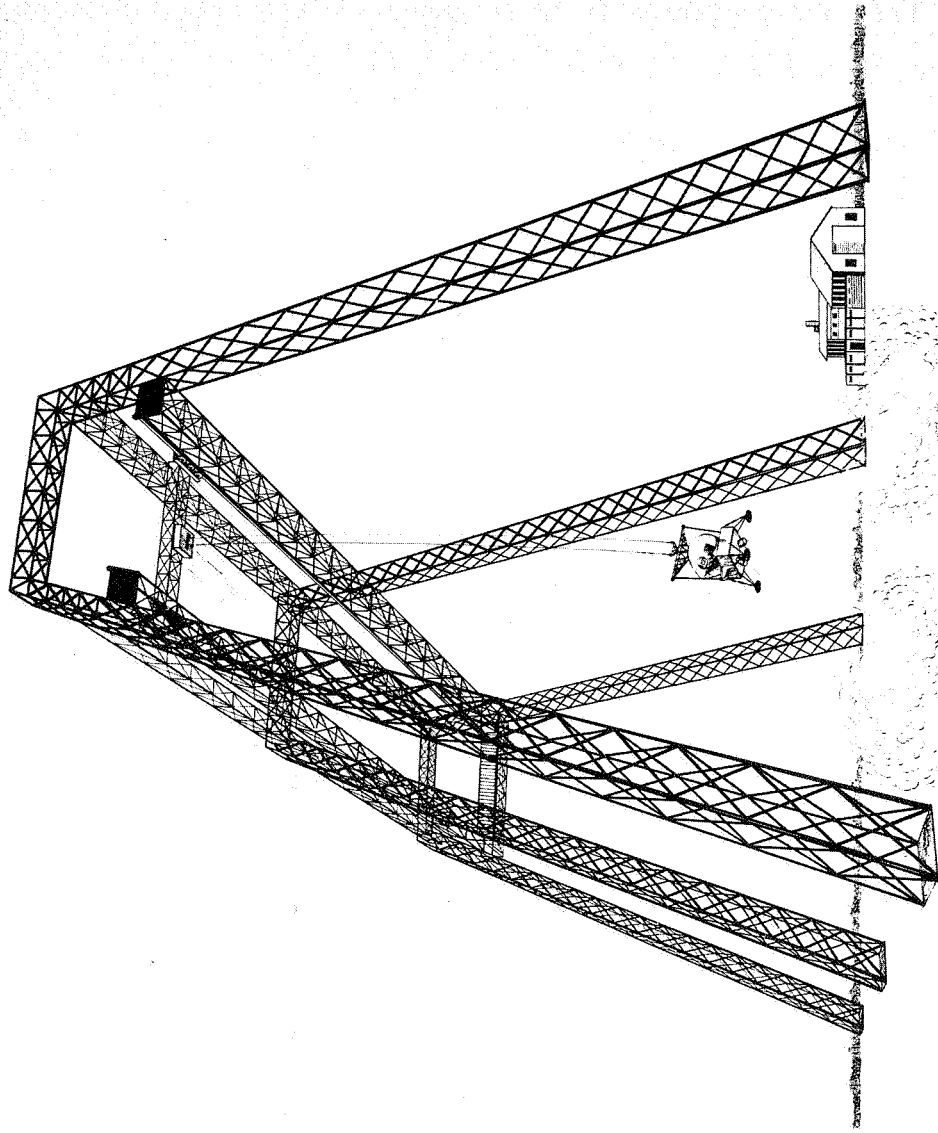


Figure 1.- Langley lunar-landing research facility.

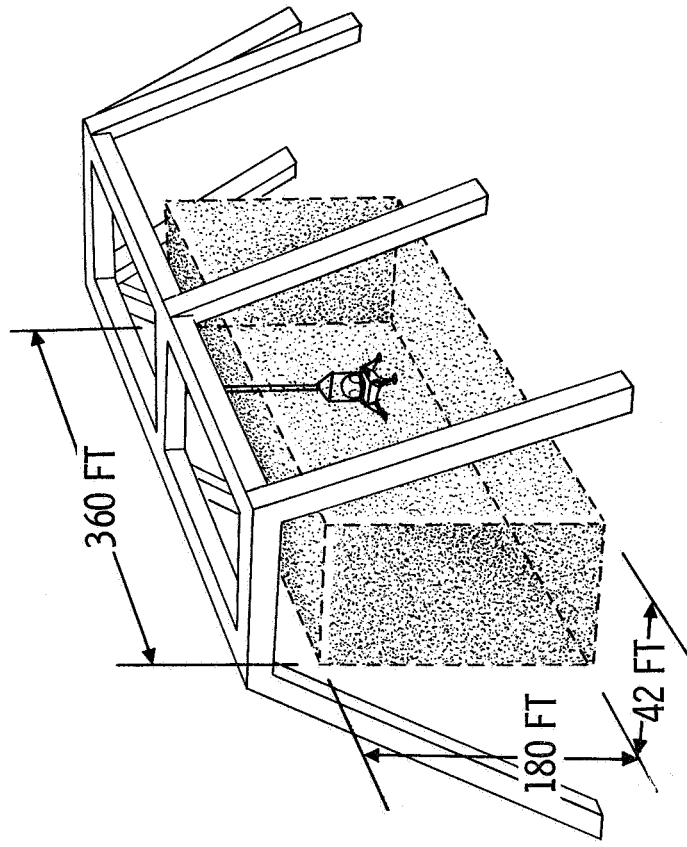


Figure 2.- LLRF flight envelope.

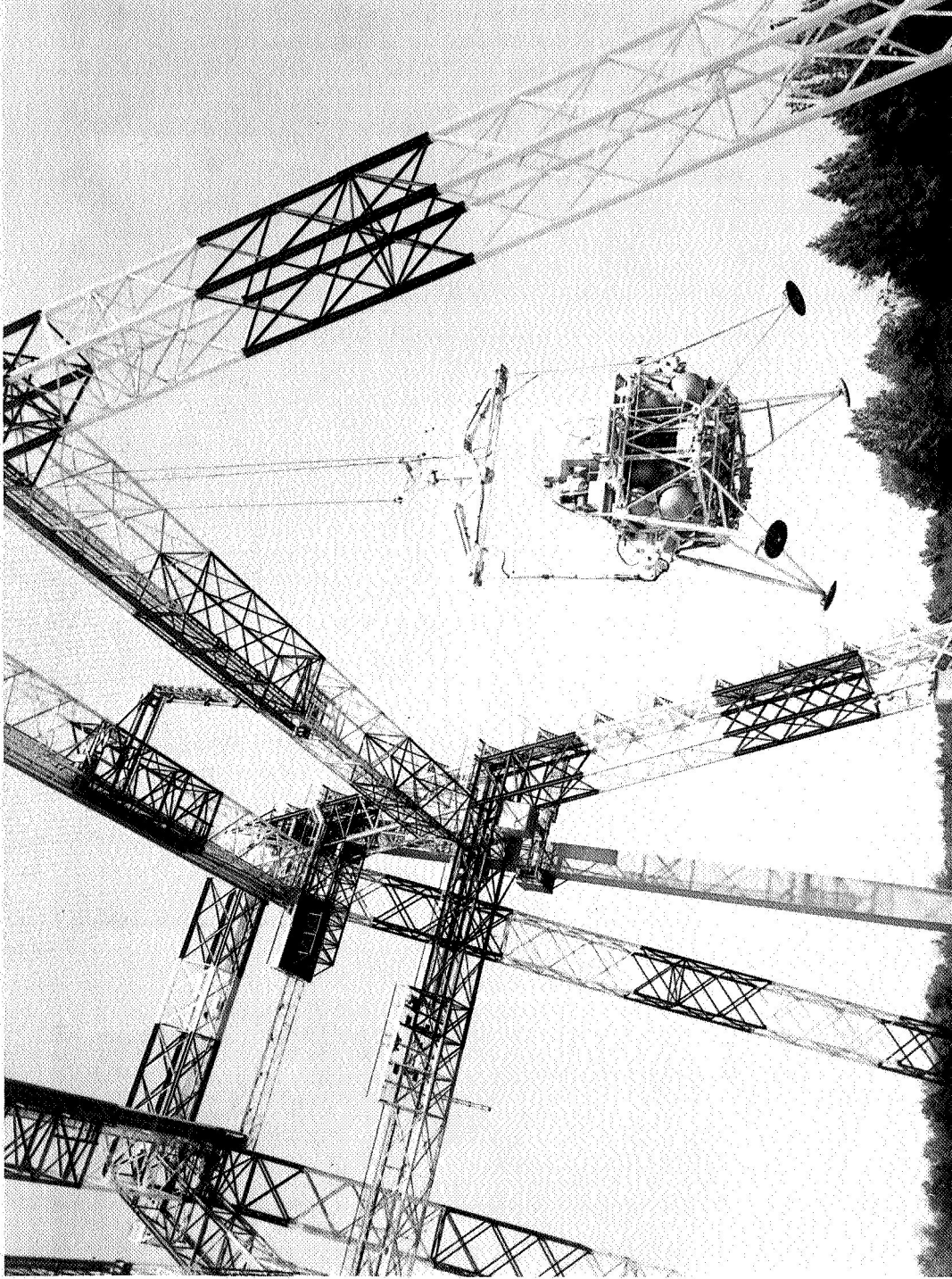


Figure 3.- Research vehicle (LRFV).

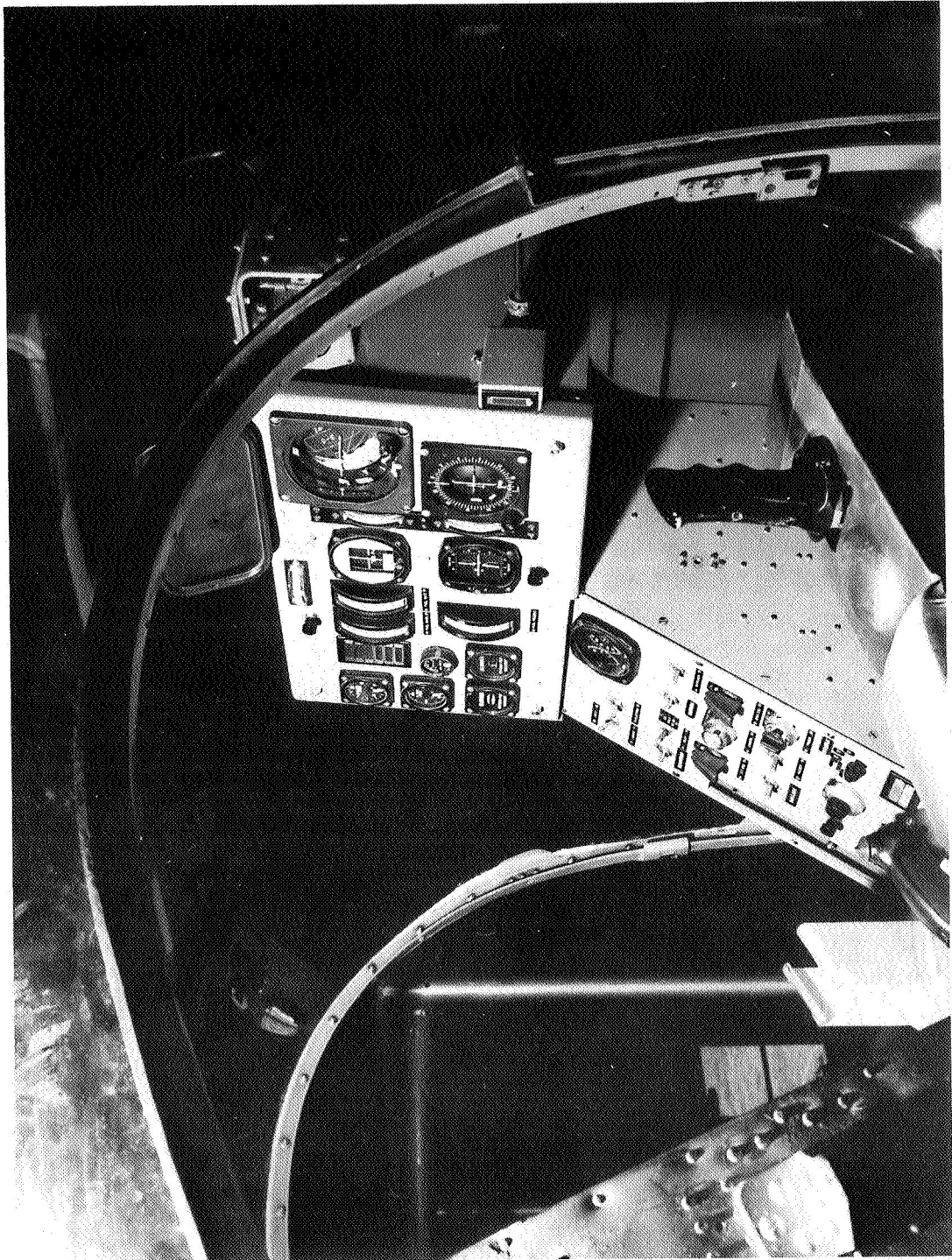
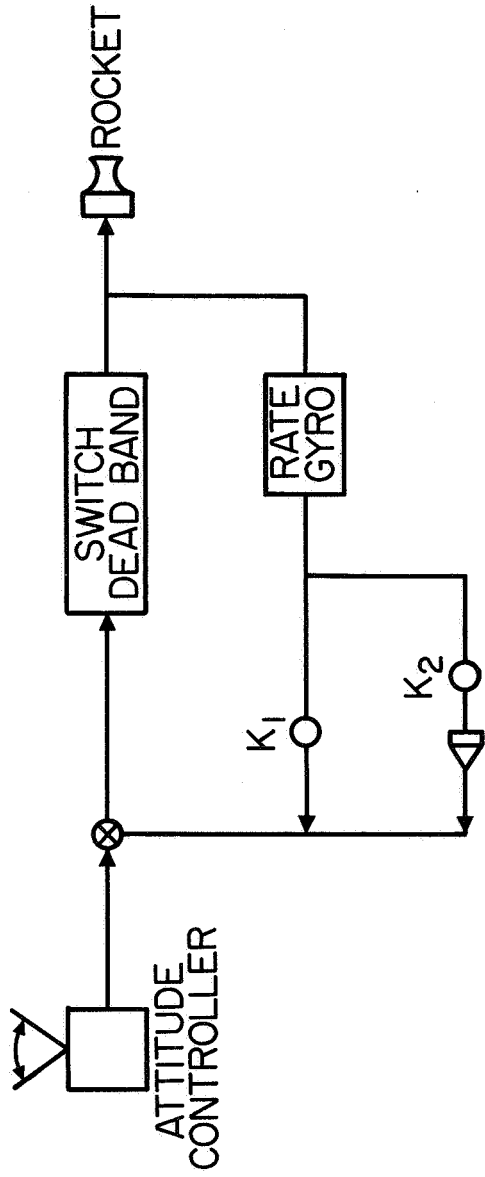


Figure 4.- Cockpit controls and displays.

PITCH SYSTEM



THROTTLE SYSTEM

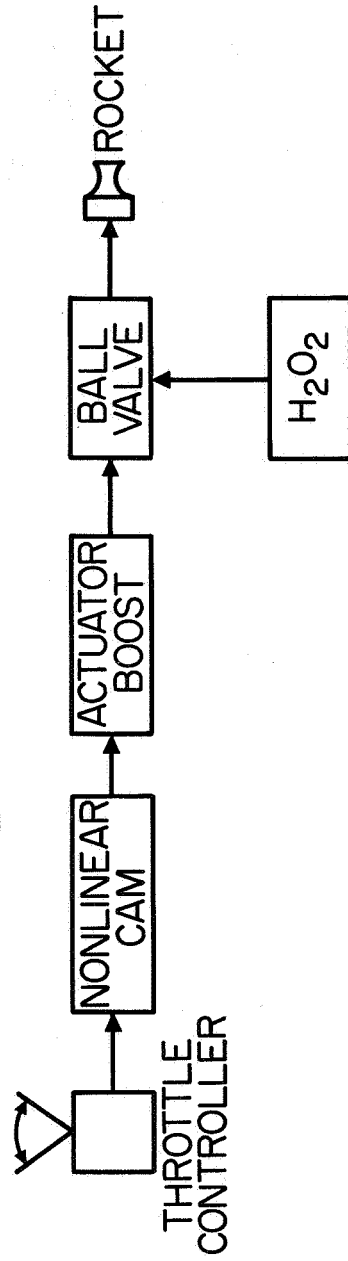


Figure 5.- IIRF vehicle control system.

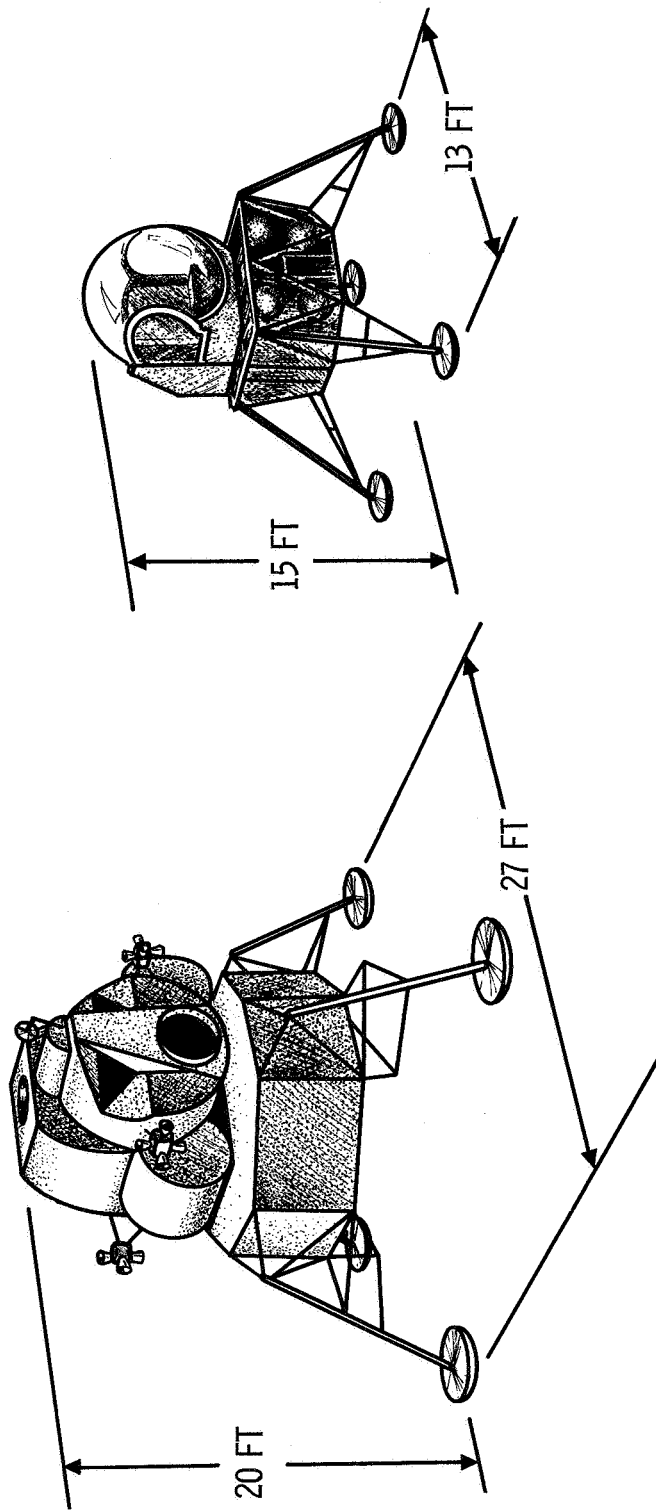


Figure 6.- Comparison of LEM and LIRV vehicle.

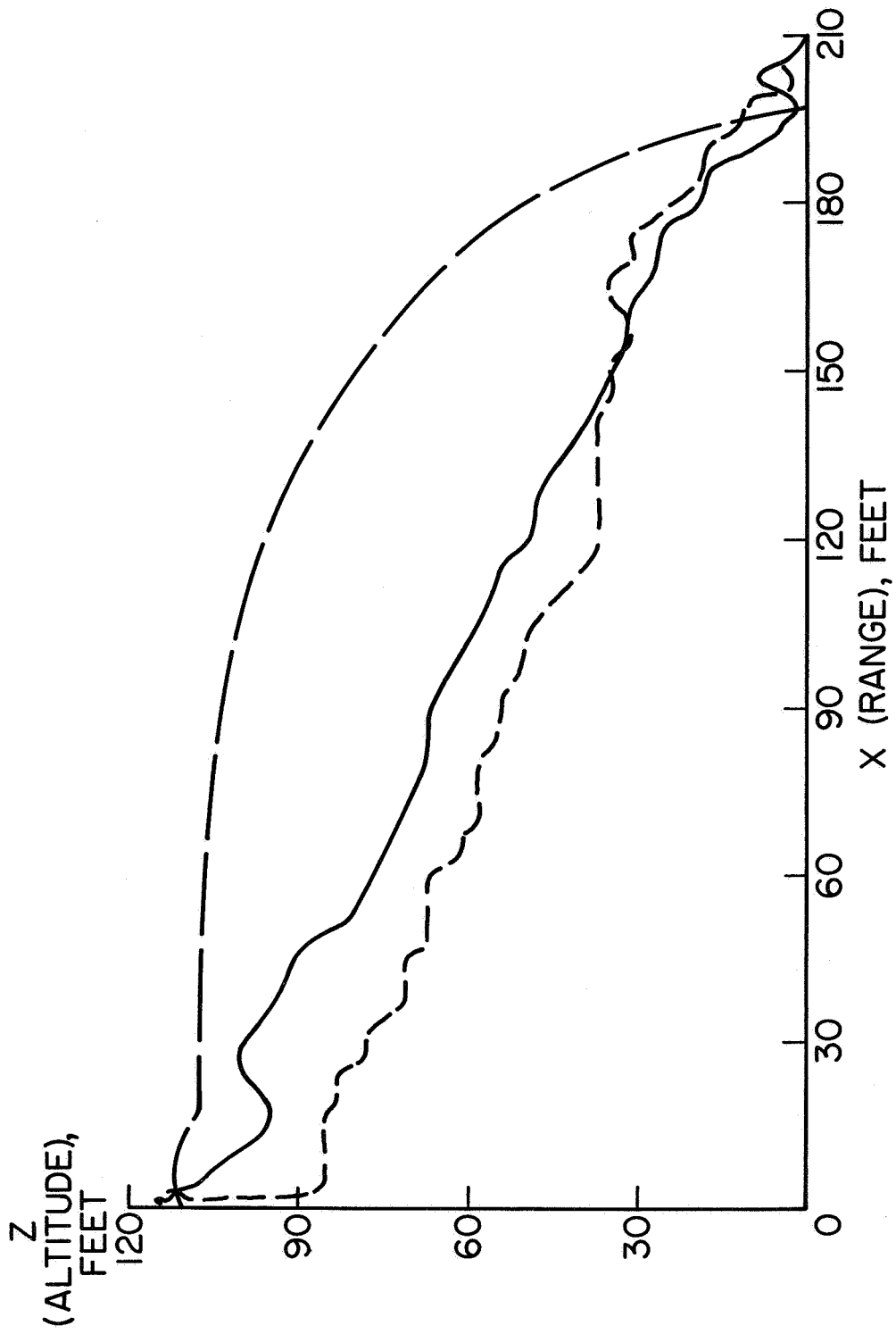


Figure 7.- Typical landing trajectories.

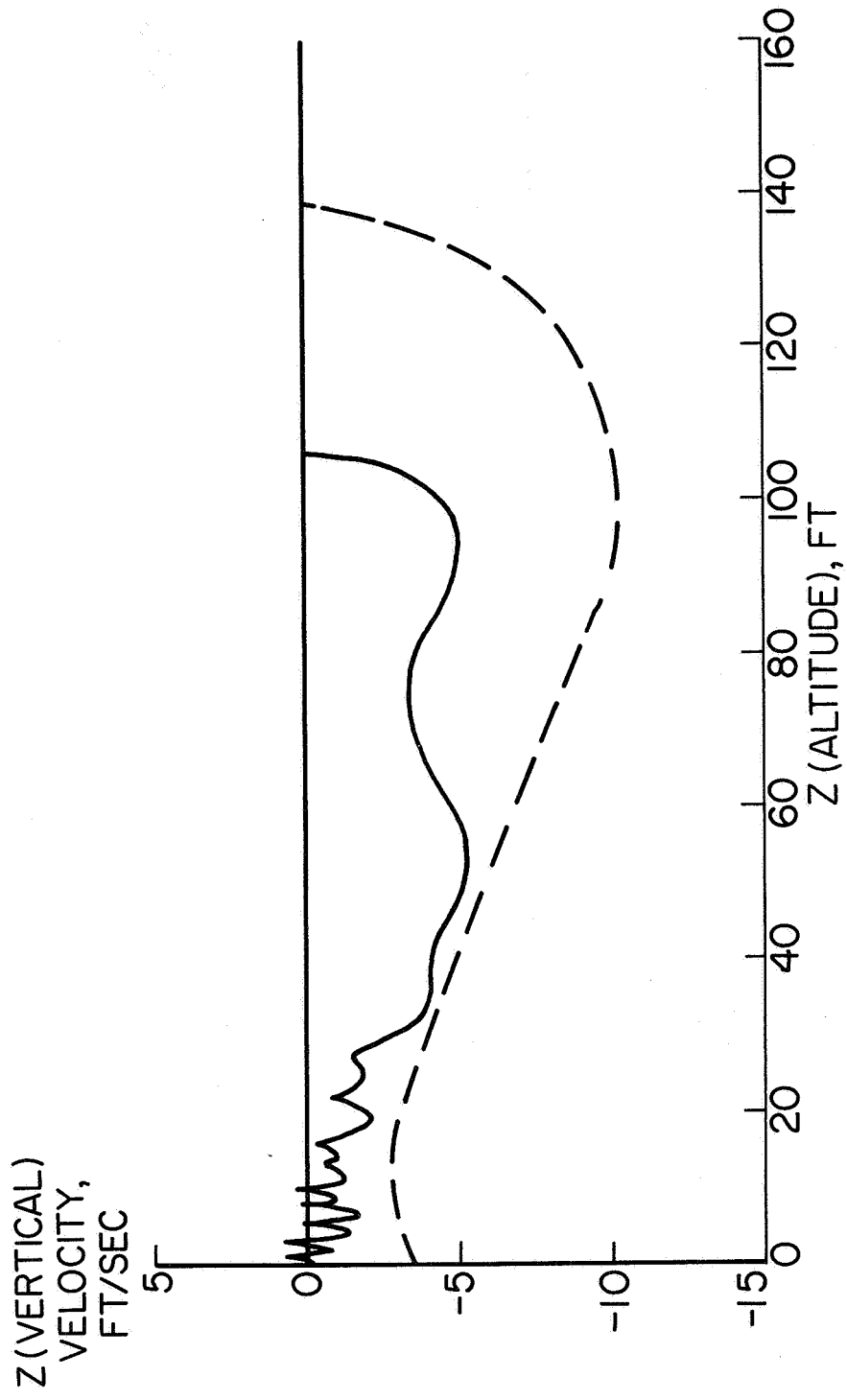


Figure 8.- Vertical velocity management.

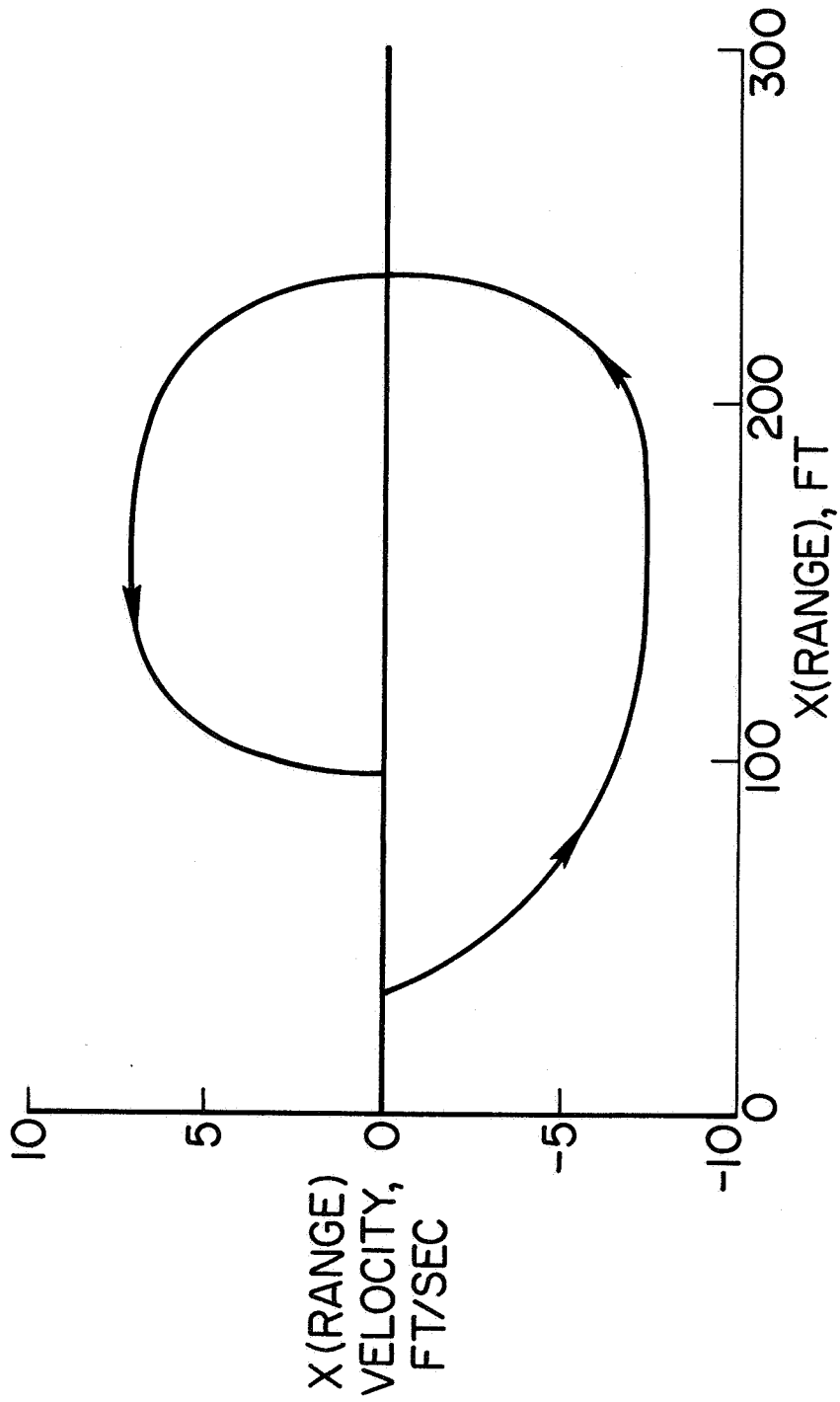


Figure 9.- Translational velocity management.

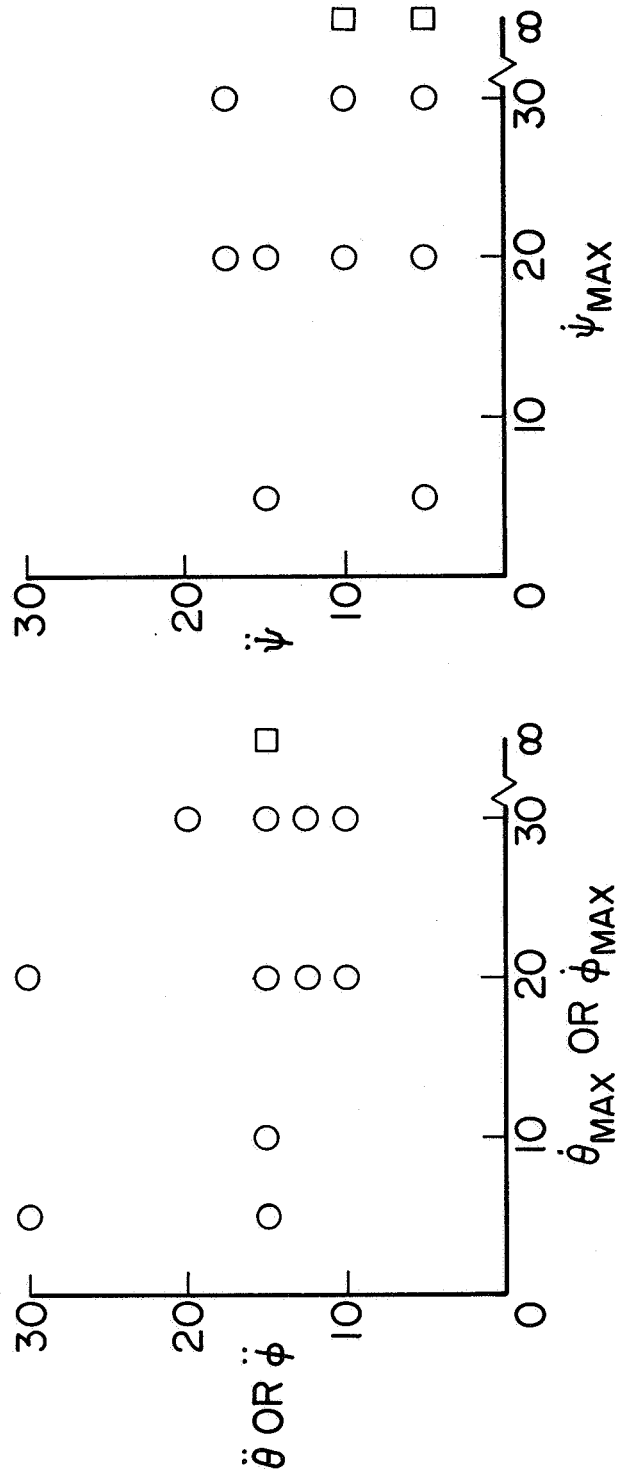


Figure 10.- Attitude control test parameters.