NASA TECHNICAL NOTE

NASA TN D-6001

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NASA TN D-6001

LUNAR FLYING PLATFORM SIMULATOR

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • DECEMBER 1970

1. Report No. NASA TN D-6001	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle LUNAR FLYING PLATFORM SIMULATOR		5. Report Date December 1970
		6. Performing Organization Code
7. Author(s) David F. Thomas, Jr., and Paul R. Hill		8. Performing Organization Report No. L-6829
9. Performing Organization Name and Address NASA Langley Research Center Hampton, Va. 23365		10. Work Unit No. 127-51-41-05
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		13. Type of Report and Period Covered Technical Note
		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

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17. Key Words (Suggested by Author(s)) Lunar transport vehicle; Reduced-gravity simulation; Body-motion control; Flying platform	18. Distribution Statement Unclassified – Unlimited		
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 19	22. Price* $3.00

*For sale by the National Technical Information Service, Springfield, Virginia 22151

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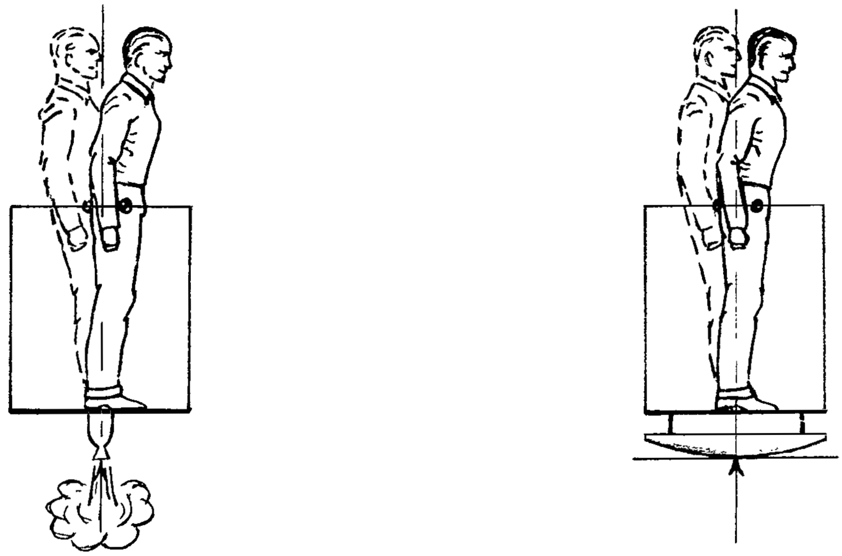
SUMMARY

This paper describes the construction and operation of a body-motion-controlled five-degree-of-freedom simulation of a jet-supported lunar flying platform. Results from a number of short investigations performed with this simulator are presented. In addition, a comparison is made of the equations of motion of a flying platform and this device; this comparison indicates that this device may be used to provide, in earth gravity, a reasonably accurate five-degree-of-freedom simulation of a jet-supported lunar flying platform.

INTRODUCTION

One of the candidate methods of controlling a lunar personnel transport vehicle is by the use of "body motions." Early work on this type of vehicle, for use under earth-gravity conditions, was reported in references 1 and 2. Basically, this vehicle consists of a platform on which the operator stands; fixed to the underside of the platform is a thrust device capable of lifting itself, the platform, and the operator. (See fig. 1(a).) Control is imparted to the vehicle by the operator shifting his weight with respect to the fixed thrust vector. Since the control-torque input rotates the vehicle to reorient the thrust vector in the desired direction, the moment of inertia of the vehicle about the axis of rotation has an effect on the control capability of the operator.

The interest in lunar personnel transport vehicles resulting from planned lunar exploration and escape missions has brought forth the need for simulations of the candidate vehicles not only for astronaut training but also for use early in the selection process as a means of judging the relative merits of body-motion vehicle control and thrust-vector control. This paper describes and gives preliminary qualitative results obtained with such a simulator, namely, a nontranslating two-degree-of-freedom version and a later five-degree-of-freedom simulation of a body-motion-controlled jet-supported flying platform. This simulator is designed to demonstrate the effects of vehicle moments of inertia on the handling qualities of a lunar vehicle.



(a) Flying platform.

(b) Simulator (nontranslating version).

Figure 1.- Balance principle as applied to jet-supported flying platform and simulator. Oscillatory motions of operator greatly exaggerated for clarity.

SYMBOLS

a	linear acceleration
d	distance of center of gravity of an element from center of gravity of total configuration
e	distance of center of gravity of operator from some reference axis
F_i	inertia force
g_e	acceleration-of-gravity constant of earth
I	moment of inertia
l	distance from simulator center of curvature to ballast weight
Q	control torque
R	radius of curvature of spherical surface of simulator

T thrust

W_b ballast weight

W_d weight of air-pad dolly

W_m weight of operator

W_s simulator weight less weight of air-pad dolly

W_t total weight of simulator including simulator, ballast, air-pad dolly, and operator

W_v weight of lunar transport vehicle

θ control angle

$\ddot{\theta}$ angular acceleration about axis of control

Subscripts:

b ballast

d air-pad dolly

m operator

s simulator

t total

v lunar vehicle

DESCRIPTION OF SIMULATOR

This lunar flying platform simulator was designed to utilize comparable earth-gravity body-motion-control inputs to simulate the control of a jet-supported lunar vehicle. A jet-supported flying platform has neutral static and dynamic stability. The basic requirement was to provide a simulator having neutral stability over the range of operating conditions to be tested. The means of attaining this stability was to mount a stand-on platform above a spherical surface, as shown in figure 1(b). The simulator including the operator, stand-on platform, spherical surface, inertia booms, and so forth was balanced so that the center of gravity of the simulator coincided with the center of curvature of the spherical surface for zero control input. The spherical surface rested and was free to rotate on a flat level surface. As the operator shifted his weight with respect to the center of curvature of the spherical surface, the spherical surface rotated. The balancing involved in attitude control of a jet-supported flying platform, as in standing, is an angular acceleration control system.

The description of the simulator up to this point is applicable to the nontranslating (two-degree-of-freedom) simulator as well as to the translating (five-degree-of-freedom) simulator. The remainder of the description, however, is applicable only to the translating version of the lunar-transport-vehicle simulator.

To provide a translational capability in the horizontal plane, three additional items were included in the simulation. (See fig. 2.) First, a set of paired jet nozzles were rigidly attached to the stand-on platform so that the resultant thrust acted through the center of curvature of the spherical surface. High-pressure air for the jet nozzles was supplied from an external source through paired flexible hose lines. Tilting of the stand-on platform resulted in the generation of a horizontal component of thrust. The second item provided was an air-pad dolly which exhibited very little friction when operated on a reasonably smooth surface. The flat level surface upon which the spherical surface rested was mounted on top of the air-pad dolly. The third item necessary to the simulation was a smooth level surface upon which the air-pad dolly with the stand-on

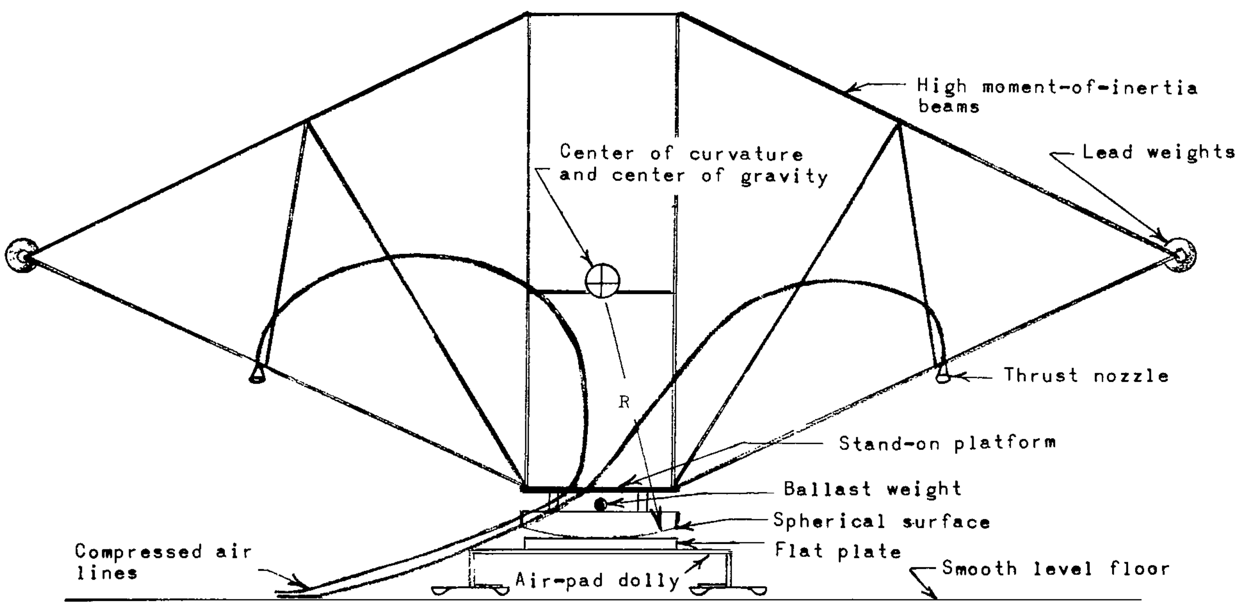


Figure 2.- Translating version of lunar-flying-platform simulator.

platform, and so forth, mounted on it would be free to translate in the horizontal plane. Such a surface was formed by pouring a self-leveling epoxy plastic within an enclosed area.

In use the operator shifted his weight to produce a tilt of the stand-on platform. The jet nozzle tilted with the stand-on platform and resulted in a component of thrust in the horizontal plane. This component of thrust produced a translational acceleration of the operator, stand-on platform, spherical surface, air-pad dolly, and all equipment attached to them. The control input to this device is an angular acceleration control and the horizontal translation is also an acceleration control.

Table I lists the physical characteristics of the simulator as used in the various studies reported in this paper. Both the nontranslating (two-degree-of-freedom) and translating (five-degree-of-freedom) simulator configurations are described.

ANALYSIS

The quality of any simulation depends on the response of the simulator to the operator input. In other words, for a good simulation, the response of the simulator to any given operator input should duplicate the response of the vehicle being simulated.

This investigation involved only a short translation and positioning task. The following analysis, comparing the simulator forces, moments, and motions with those of a jet-supported flying platform, is presented to show that the angular acceleration of the simulator due to operator input and the linear acceleration due to simulator tilt angle are accurate representations of those of a jet-supported flying platform. It should be noted that this analysis is of the translating version of the simulator.

Control Moments

A comparison of the control moments generated by the operator on a jet-supported flying platform and the simulator is presented in figure 3. For the flying platform, the control torque Q_v results from displacement of the center of mass of the operator from its neutral position along the thrust axis (see fig. 3(a)) and may be written as

$$Q_v = F_{i,m} e_m \tag{1}$$

where the inertia force of the operator parallel to the thrust axis $F_{i,m}$ is equal to the mass of the operator times the thrust-mass ratio of the vehicle-operator combination, that is, acceleration along the thrust axis:

$$F_{i,m} = \frac{W_m}{g_e} \frac{T_v}{\dfrac{W_v + W_m}{g_e}}$$

TABLE I.- SIMULATOR CHARACTERISTICS

(a) U.S. Customary Units

Center-of-gravity location relative to center of curvature, ft, for – Simulator	Operator[1]	Static moment relative to center of curvature, ft-lb, for simulator with operator	Simulator weight, lb	Moment of inertia, slug-ft^2 Pitch	Roll	Control sensitivity, (deg/sec^2)/in. Pitch	Roll	Figure	Purpose of study
			Nontranslating simulation[2]						
-3.22	-0.06	-448	136	8	9	8.21	8.10	---	Variation of stability
-2.71	1.19	-219	160	18.7	19.3	4.78	4.74	4	
-1.84	3.19	163	200	56	56	2.40	2.39	---	
-1.84	3.19	163	200	56	56	2.40	2.39	---	Variation of moment of inertia
-.79	3.19	159	471	431	437	1.13	1.11	5	
-1.23	2.19	79	232	107	110	2.54	2.50	6	Instrument control
0	-0.06	-10	304	228	235	2.51	2.43	7	Lunar-gravity control
			Five-degree-of-freedom simulation[3]						
0	-0.06	0	475	900	900	0.88	0.88	---	Variation of moment of inertia
0	-.06	0	435	600	600	1.33	1.33	8	
0	-.06	0	395	300	300	2.65	2.65	---	

[1]Standard man: stature, 69.4 inches; weight, 166.4 lb; pitching moment of inertia, 8.5 slug-ft^2; rolling moment of inertia, 9.5 slug-ft^2.

[2]Moments of inertia given about "instant" center of rotation.

[3]Moments of inertia given about center of curvature; static moment taken with jets on and control angle not equal to zero; center-of-gravity location given with ballast weight neglected.

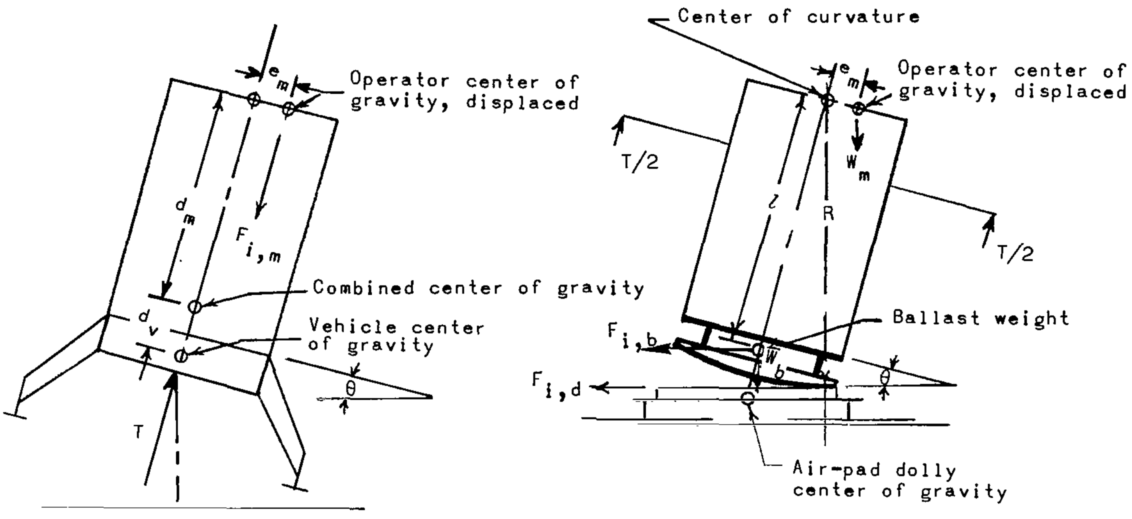
(b) SI Units

Center-of-gravity location relative to center of curvature, meters, for – Simulator	Operator[1]	Static moment relative to center of curvature, m-N, for simulator with operator	Simulator weight, N	Moment of inertia, kg-m^2 Pitch	Roll	Control sensitivity, (deg/sec^2)/mm Pitch	Roll	Figure	Purpose of study
			Nontranslating simulation[2]						
-0.981	-0.018	-607	605	10.8	12.2	0.323	0.319	---	Variation of stability
-.826	.363	-297	712	25.4	26.2	.188	.187	4	
-.561	.972	221	890	75.8	75.8	.095	.094	---	
-0.561	0.972	221	890	75.8	75.8	0.095	0.094	---	Variation of moment of inertia
-.241	.972	216	2095	584	592	.045	.044	5	
-0.375	0.668	107	1032	145	149	0.100	0.099	6	Instrument control
0	-0.018	-14	1352	309	318	0.099	0.096	7	Lunar-gravity control
			Five-degree-of-freedom simulation[3]						
0	-0.018	0	2113	1220	1220	0.035	0.035	---	Variation of moment of inertia
0	.018	0	1935	813	813	.052	.052	8	
0	.018	0	1757	407	407	.104	.104	---	

[1]Standard man: stature, 1.76 meters; weight, 740 newtons; pitching moment of inertia, 11.5 kg-m^2; rolling moment of inertia, 12.9 kg-m^2.

[2]Moments of inertia given about " instant" center of rotation.

[3]Moments of inertia given about center of curvature; static moment taken with jets on and control angle not equal to zero; center-of-gravity location given with ballast weight neglected.



(a) Flying platform. (b) Simulator.

Figure 3.- Forces acting on the flying platform and simulator.

This relation may be reduced to

$$F_{i,m} = \frac{W_m}{W_v + W_m} T_v \tag{2}$$

which, when substituted into equation (1), gives

$$Q_v = \frac{W_m}{W_v + W_m} T_v e_m \tag{3}$$

It might be noted from this relationship that control sensitivity is a function of thrust level, as would be expected.

For the simulator, the control moment results from the displacement of the weight of the operator with respect to the radius from the center of curvature of the spherical surface to the point of contact between the spherical surface and the flat plate (see fig. 3(b)) and may be written as

$$Q_s = W_m e_m \cos \theta_s + F_{i,m} e_m \sin \theta_s - W_b l \sin \theta_s + F_{i,b} l \cos \theta_s + F_{i,d} R \tag{4}$$

where, for reasons to be explained later, the summation of the ballast and air-pad-dolly forces is equal to zero.

The presence of the cosine function of the tilt angle θ reduces the control capability of the operator for a given body displacement from the neutral position by a maximum of 3 percent for the range of tilt angles available on the simulator and, to this extent, results in a conservative simulation. The presence of the inertia term due to the operator tends to restore the exactness of the simulation but not completely.

It should be noted at this point that with a pressure suit and backpack, the earth weight of an operator of the flying platform would be approximately twice his shirt-sleeve weight; thus, the ratio of lunar weight to earth weight of the operator is approximately 1 to 3. This ratio is further modified by the thrust level of the flying platform, as noted above, when the control inputs by the operator are computed.

Translational Acceleration

The horizontal accelerations of the flying platform and the simulator, resulting from their components of thrust in the horizontal plane, may be obtained from figures 3(a) and 3(b), respectively. For the flying platform, the acceleration is

$$a_v = \frac{T_v \sin\theta}{\dfrac{W_v + W_m}{g_e}} \tag{5}$$

and for the simulator

$$a_s = \frac{T_s \sin\theta}{\dfrac{W_s + W_b + W_d + W_m}{g_e}} \tag{6}$$

To reproduce the flying-platform motions for a given tilt-angle time history, the simulator acceleration must equal the flying-platform acceleration so that combining equations (5) and (6) gives the expression for the thrust-weight ratios:

$$\frac{T_s}{W_t} = \frac{T_v}{W_v + W_m} \tag{7}$$

where

$$W_t = W_s + W_b + W_d + W_m$$

Rotational Acceleration

The angular (tilt angle) acceleration of the flying platform resulting from an operator control torque may be written as follows (see fig. 3):

$$\ddot{\theta}_v = \frac{Q_v}{I_v + \dfrac{W_v}{g_e} d_v^2 + I_m + \dfrac{W_m}{g_e} d_m^2} \tag{8}$$

where d_v and d_m are the respective distances of the center of gravity of the vehicle and operator from their common center of gravity and the control torque Q_v is obtained from equations (1) and (2).

The equation for the angular acceleration of the simulator is

$$\ddot{\theta}_s = \frac{Q_s}{I_s + \frac{W_b}{g_e} l^2 + \frac{W_d}{g_e} R^2 + I_m} \tag{9}$$

The denominator may be considered to be an effective moment of inertia in which the ballast weight term $\frac{W_b}{g_e} l^2$ results from the addition of a ballast weight added to the simulator to achieve neutral static stability as the simulator accelerates horizontally. Without the ballast weight, the simulator is statically unstable while accelerating horizontally because of the inertia of the dolly. The inertia of the dolly appears in the effective inertia of the simulator as the term $\left(W_d/g_e\right)R^2$.

Rewriting the control moment equation (eq. (4)) yields

$$Q_s = W_m e_m \cos\theta_s + F_{i,m} e_m \sin\theta_s - W_b l \sin\theta_s + F_{i,b} l \cos\theta_s + F_{i,d} R$$

To obtain control moments only from the input of the operator, the summation of terms involving the ballast and dolly weights must equal zero.

$$W_b l \sin\theta_s - F_{i,b} l \cos\theta_s - F_{i,d} R = 0 \tag{10}$$

where

$$F_{i,b} = \frac{W_b}{g_e} a_s \tag{11}$$

$$F_{i,d} = \frac{W_d}{g_e} a_s \tag{12}$$

Substituting the expression for a_s from equation (6) into equations (11) and (12) gives

$$F_{i,b} = \frac{W_b}{g_e} \frac{T_s \sin\theta_s}{W_t/g_e}$$

and

$$F_{i,d} = \frac{W_d}{g_e} \frac{T_s \sin\theta_s}{W_t/g_e}$$

which reduce to

$$F_{i,b} = \frac{W_b}{W_t} T_s \sin \theta_s \tag{13}$$

$$F_{i,d} = \frac{W_d}{W_t} T_s \sin \theta_s \tag{14}$$

Substituting equations (13) and (14) into equation (10) gives

$$W_b l \sin \theta_s - \frac{W_b}{W_t} T_s l \sin \theta_s \cos \theta_s - \frac{W_d}{W_t} T_s R \sin \theta_s = 0$$

which reduces to

$$W_b l = \frac{\frac{T_s}{W_t} W_d R}{1 - \frac{T_s}{W_t} \cos \theta_s} \tag{15}$$

The anomaly occurring at zero tilt angle results from the fact that no horizontal acceleration is present and thus no ballast is required. The presence of ballast produces a stable point; however, because body-motion control is a continuously oscillating system, passage through this point is not detectable by the operator.

The ballast weight effect due to tilt angle may be neglected because over the usable range of tilt angles, the variation was less than 3 percent. Also, since, for this test program, only moderate deviations from the lunar hovering case $\left(\text{that is, } \frac{T_s}{W_t} = \frac{1}{6}\right)$ were used, a single value and position of the ballast weight were used.

To produce the same tilt-angle history in the simulator and lunar vehicle, the effective moment of inertia of the simulator needs to be approximately three times that of the lunar vehicle. This relationship results, as noted previously, from the fact that the lunar vehicle operator in his pressure suit and life-support equipment weighs nearly twice as much as he does on earth in his "shirt sleeves" so that comparable body motions result in approximately one-third the control torques under lunar gravity as the same shirt-sleeved operator would generate in earth gravity. This difference in lunar-vehicle-operator and simulator-operator weights needs to be considered in comparing the translational accelerations of the lunar vehicle and the simulator.

LIMITATIONS

A number of limitations, of course, were present in this simulation; the most obvious ones were the lack of vertical motion, the limited operating area (approximately

10 feet by 10 feet (3.05 meters by 3.05 meters)), the 13° limit on tilt angle, and the absence of a throttle control. The limited space and the need to use a yaw control to maintain orientation against the input of compressed-air supply lines compensated somewhat for the lack of a throttling task. In addition to these limitations, the simulator was not always balanced to neutral dynamic stability; however, as will be shown later in the results of a study on the effect of built-in stability for the nontranslating version of the simulator, this condition should have little effect on the controllability of the simulator.

RESULTS AND DISCUSSION

Prior to the originally intended use of this simulator to demonstrate the controllability of the lunar flying platform in translation, a number of short investigations of nontranslating simulations covering several areas of interest were undertaken.

Nontranslating Simulations

Variations in stability.- To determine the ability of the operator to control a jet-supported flying platform as a function of built-in stability, the simulator was varied from a maximum positive value, represented by a negative static moment, to approximately neutral stability. (See fig. 4 and table I.) It should be noted that a body-motion-controlled flying platform would be neutrally stable.

The consensus of opinion of a large group of subjects in this investigation was a preference for a nearly neutral or even slightly unstable configuration. The reasons given were greater precision of control and decreased control effort. This preference would indicate that the neutral stability characteristic of the flying platform did not impair the ability of the operators to balance on or reorient the platform during flight and did not need to be duplicated precisely for a reasonable simulation.

Large moment-of-inertia configuration.- For this investigation a set of four 20-foot-long (6.1-meter) aluminum 3-inch (7.62-cm) angle beams were attached to the platform in the fore-and-aft and side-to-side directions, and resulted in an increase in the moment of inertia from approximately 50 slug-ft^2 (68 kg-m^2) to 300 slug-ft^2 (407 kg-m^2) about these two axes. (See fig. 5.) These beams were added to the nearly neutrally stable configuration. The results of these tests obtained with some of the subjects that were involved in the variation of stability tests indicated that the large moments of inertia were controllable, the main difference being lower attitude control power available and longer times required to initiate and stop rotational velocities.

Control by optical instruments.- Some runs were made with the nearly neutrally stable configuration, the operator being required to reorient the simulator and to hold the position within $\pm 1^{\circ}$ by use of an optical instrument (ref. 3) to provide pitch and roll

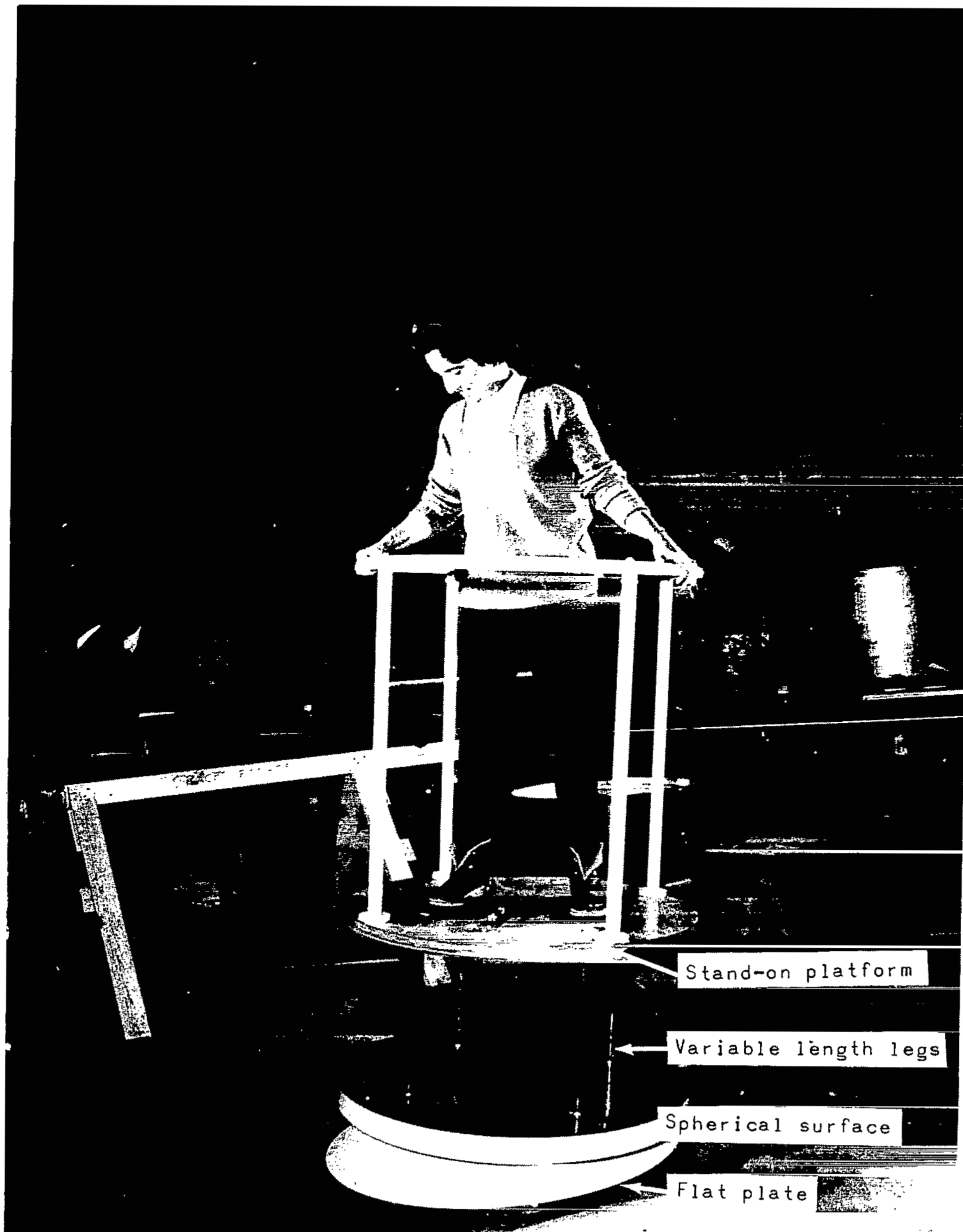


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Figure 4.- Nontranslating simulator with a moderate amount of static stability.

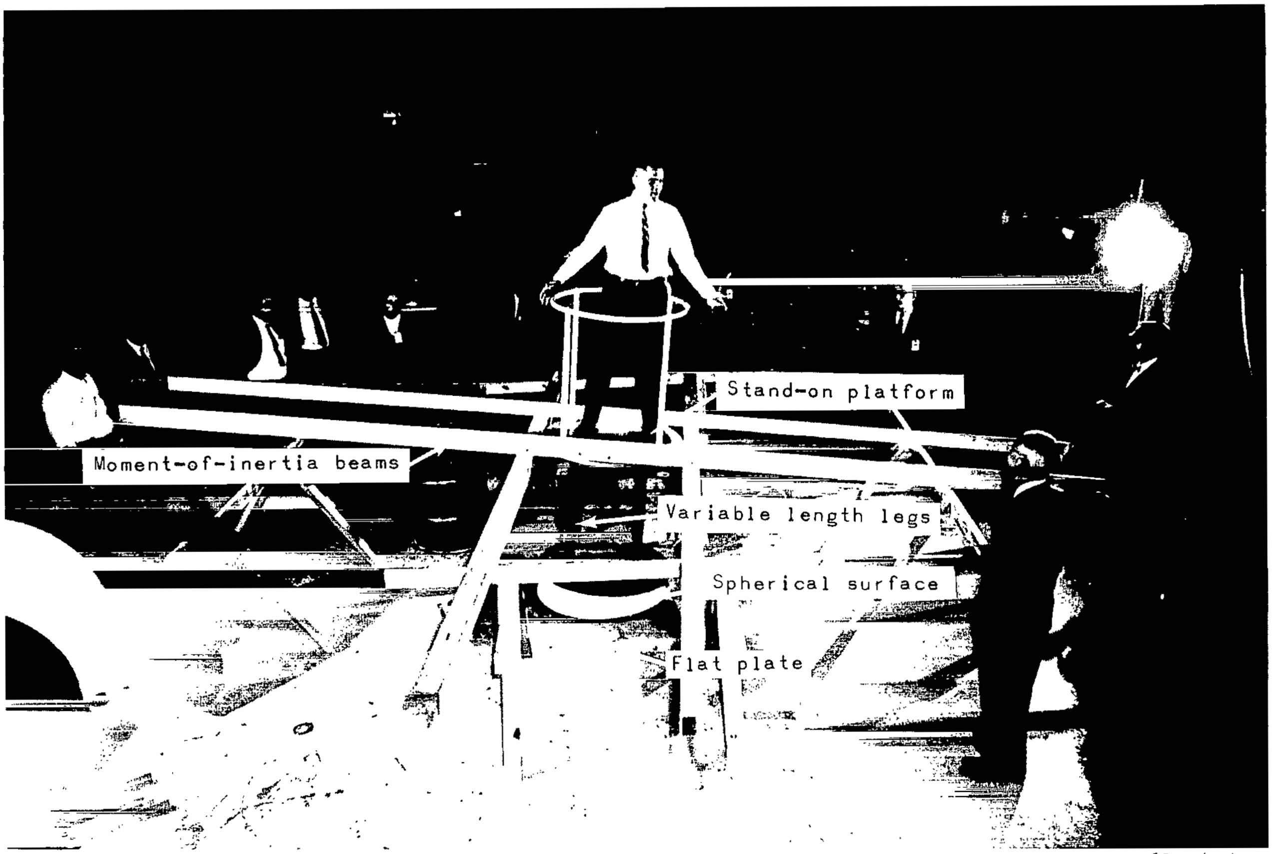

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Figure 5.- Nontranslating simulator with high moment of inertia and very low static stability.

information. (See fig. 6.) The operator had index marks on the instrument for use in judging his performance. The purpose of this test was to simulate the use of a lunar flying platform for emergency escape from the lunar surface. The results indicated that a trained test pilot, given the proper instrument, could perform this maneuver, that is, changing the pitch angle with respect to a reference horizon and holding the attitude within 1°.

Control at lunar gravity.- For this investigation a spring motor suspension system, constructed by Case Institute for Langley Research Center (ref. 4), was used to support five-sixths of the weight of the operator. A cable, approximately 45 feet (13.72 meters) in length, used to support the suspension system was attached at a point directly above the flying platform simulator. (See fig. 7.)

The simulator was balanced about its center of curvature by means of an overhead platform and counterweights. In this manner, with the platform adjusted to place the

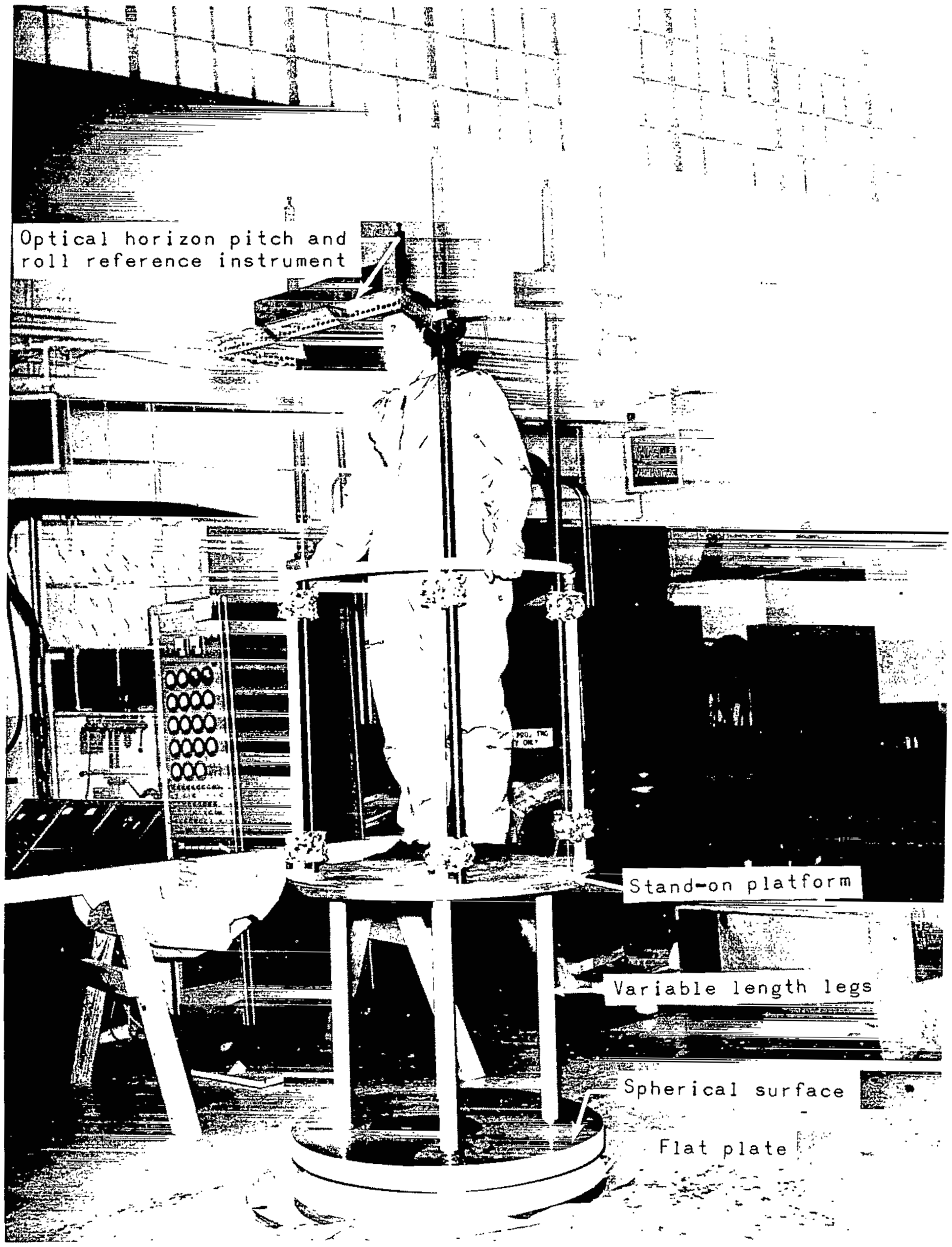

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Figure 6.- Nontranslating, low static stability simulator equipped with optical roll and pitch attitude instrumentation.

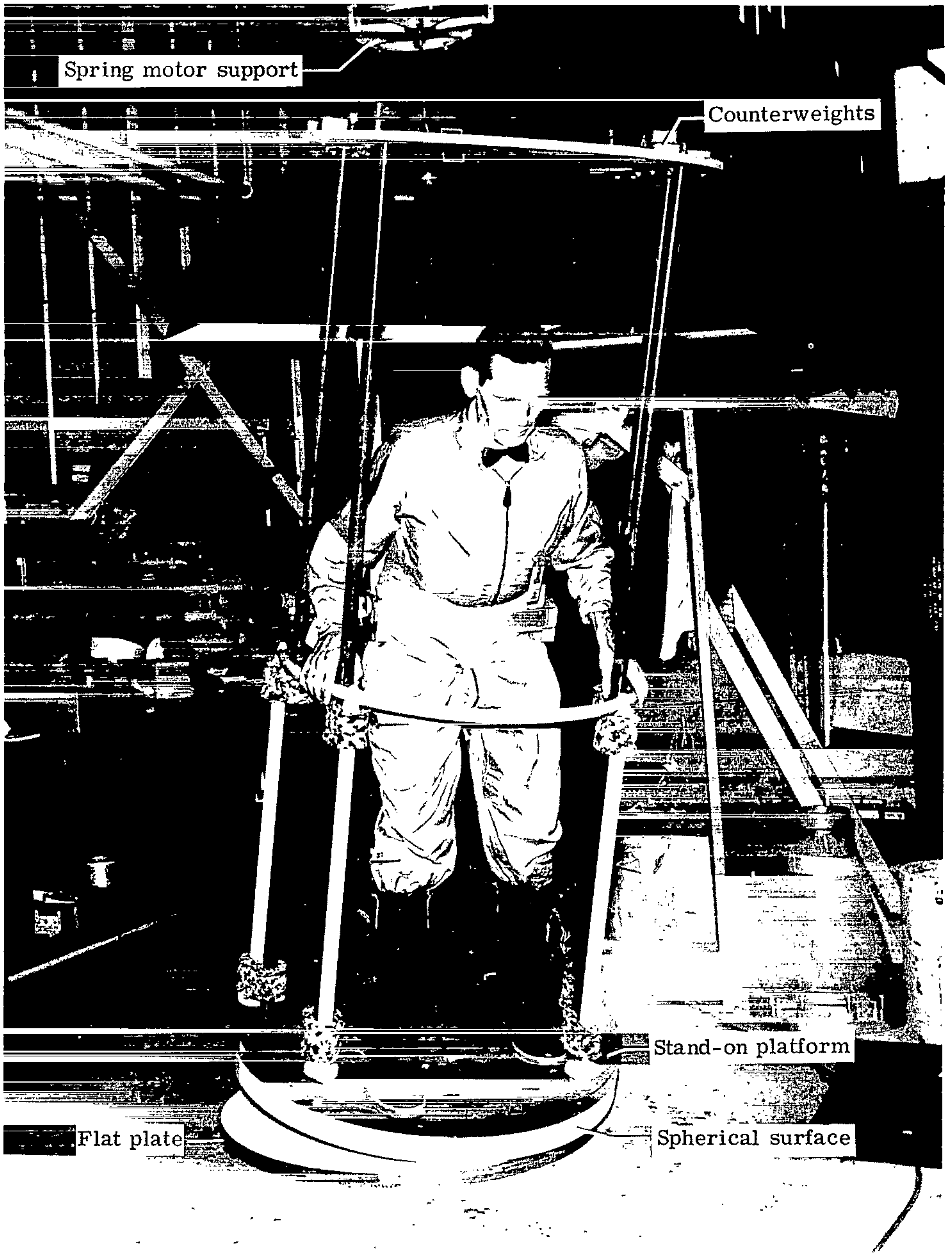

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Figure 7.- Nontranslating, neutrally stable configuration with operator supported to simulate lunar gravity.

center of gravity of the operator at the same elevation as the center of curvature, the operator-vehicle combination was neutrally stable as required to simulate a flying platform. In the process the moment of inertia of the simulator was increased to approximately 230 slug-ft^2 (312 kg-m^2) as compared with the 56 slug-ft^2 (76 kg-m^2) of the nearly neutrally stable configuration of the study on effect of variation in stability and slightly greater than the average value of 200 slug-ft^2 (271 kg-m^2) simulated by the translating versions of the simulator. It became immediately apparent that attaching the spring motors overhead, even with the 45-foot (13.72-meter) suspension distance, had a rather severe limitation in that the operator (a nearly standard man, ref. 5) had an area of only about 1 foot (0.305 meter) in diameter about the center of the platform in which he could move without a strong centering force. However, within the restraints so imposed by the method of suspending the spring motors, the operators could maintain control of the neutrally stable flying platform simulator with a moment of inertia of 230 slug-ft^2 (312 kg-m^2).

Five-Degree-of-Freedom Simulations

The final investigation to be discussed is a series of preliminary runs made on the five-degree-of-freedom version of the lunar flying platform simulator. (See fig. 8.) This

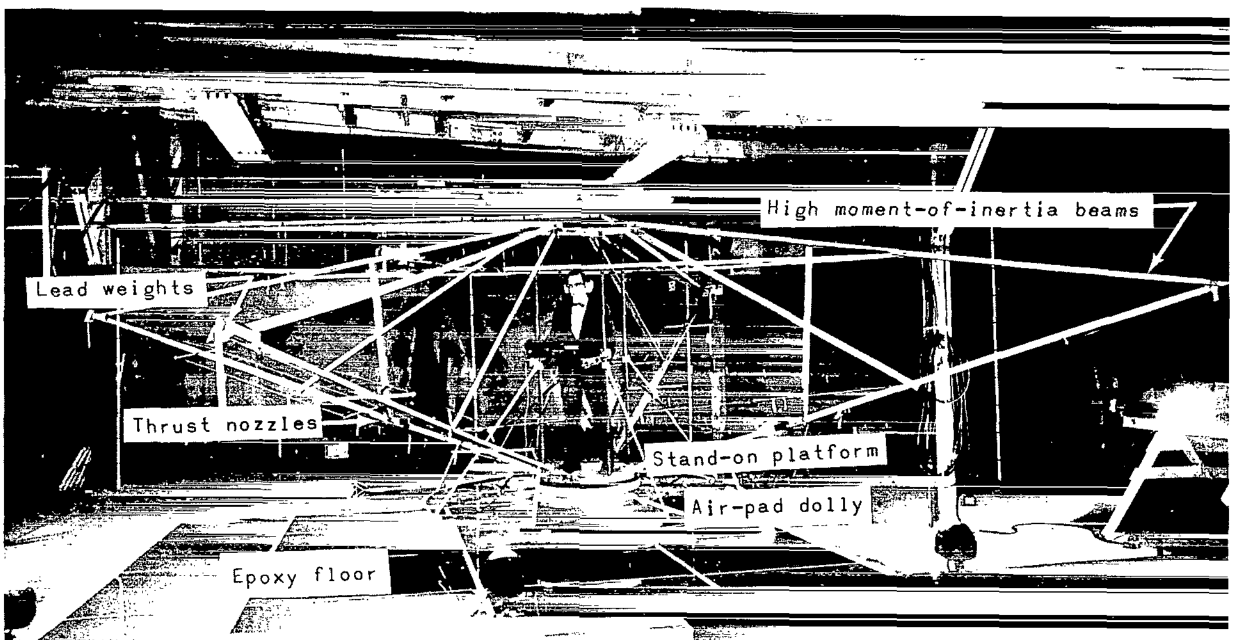

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Figure 8.- High-moment-of-inertia, dynamically balanced, five-degree-of-freedom simulator.

version of the simulator is treated in detail in the section "Analysis." The vehicle moment of inertias covered in this study were 300, 600, and 900 slug-ft^2 (407, 813, and 1220 kg-m^2). These values compare with lunar vehicles of 100, 200, and 300 slug-ft^2 (136, 271, and 407 kg-m^2), respectively.

A task was set up to test the controllability of the vehicle. Cross marks were established on the floor 10 feet (3.05 meters) apart. Beginning at one cross mark, the operator proceeded to the other and stopped as accurately as possible on the mark. Each operator had a total practice time of one-half to three-quarters of an hour before executing the task.

Figure 9 depicts the range of control sensitivities covered by this simulator as compared with a number of earth and lunar vehicles. Figure 10 is the results of the test program for the various operators. The average time required to perform the task was approximately 12 seconds with miss distances of 1 foot (0.305 meter) or less over the range of moment of inertias simulated.

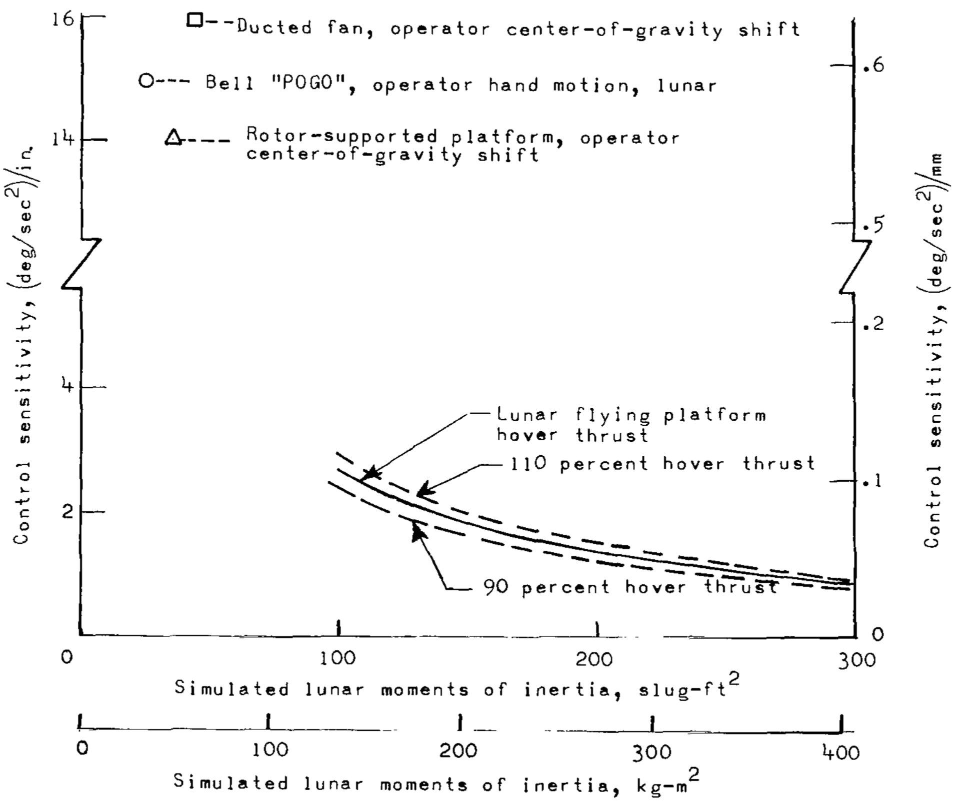

Figure 9.- Comparison of control sensitivity of various thrust-supported vehicles.

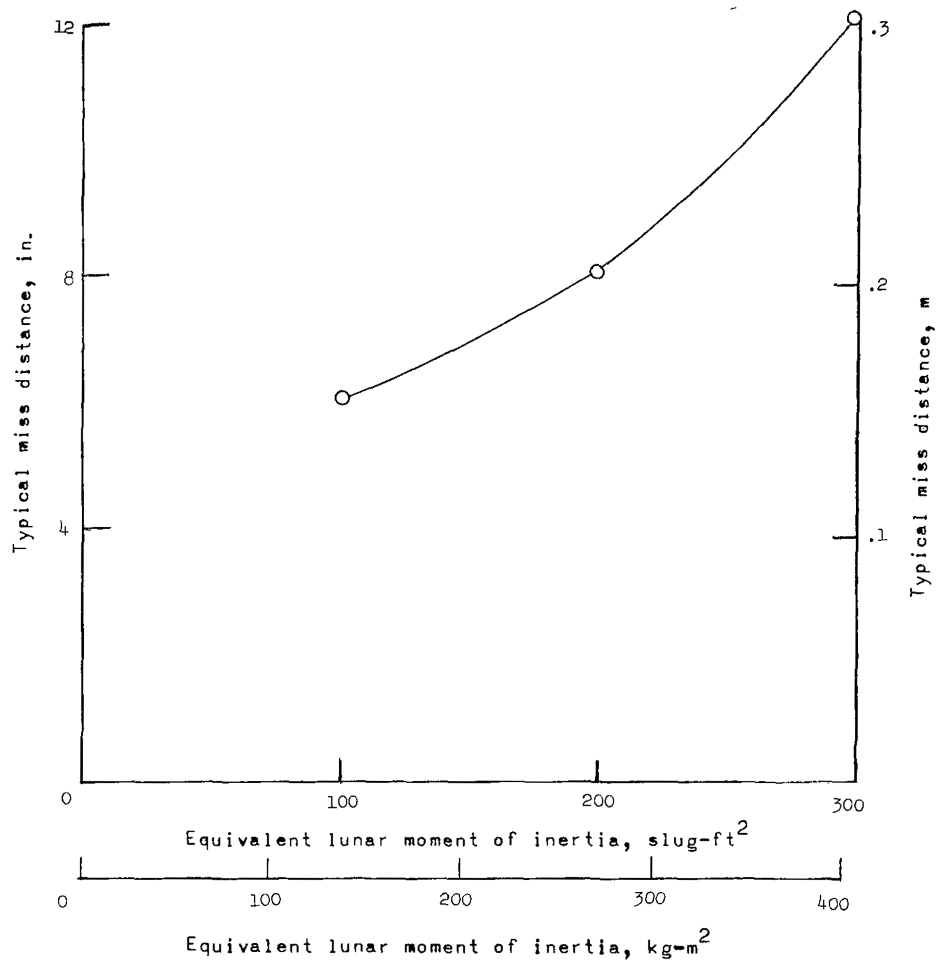

Figure 10.- Limited task results using five-degree-of-freedom flying platform simulator. Average time to complete 10-foot (3.05-meter) translation and stop on target is approximately 12 seconds.

CONCLUDING REMARKS

The principal conclusion derived from this study is that this simulator provides a readily available tool for "quick-look" investigations of the problems of the lunar flying platform vehicle using body-motion control. The simulator has demonstrated the controllability of realistic moment-of-inertia flying platforms with the possibility, with some practice, of extending the useful range to higher moments of inertia.

Balancing the various nontranslating configurations could be done with ease by any novice without training. However, beginners tended to overcontrol the translating simulators, the tendency increasing with increasing moment of inertia. With practice, the operator, by taking angular rates into account, was able to maintain control of the simulator.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., August 13, 1970.

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