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TECHNICAL NOTE

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HANDLING QUALITIES AND TRAJECTORY REQUIREMENTS FOR TERMINAL LUNAR LANDING, AS DETERMINED FROM ANALOG SIMULATION

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Flight Research Center
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SUMMARY

A six-degree-of-freedom analog study was performed to aid in defining handling qualities and trajectory potential for terminal lunar landing. Results showed that, for a maneuvering task in the pitch mode and a random-motion-correction task in the roll and yaw modes, the pilots preferred rate or attitude command with control accelerations of about 10 deg/sec^2 and reasonable artificial damping. Also, to consistently perform successful landings, the pilots generally used thrust-to-weight ratios throttled between a minimum value of 0.8 lunar g and a maximum value of 1.8 lunar g.

INTRODUCTION

The success of manned lunar-exploration programs will depend on how well astronaut-pilots can execute the lunar landing, since control of the vehicle will be their responsibility. The NASA Flight Research Center, at Edwards, Calif., has awarded a contract for the construction of a free-flying research vehicle (ref. 1) that will be used to clarify the pilot's function and needs in lunar landing. As an aid in defining the variable-stability features and trajectory potential of this craft, a six-degree-of-freedom analog study was performed by the Flight Research Center to augment the manufacturer's preliminary design study. Various attitude-control-system mechanizations and authority levels were examined, as well as a range of trajectories and thrust-to-weight ratios. This paper presents the results of the study, which should have direct application to manned lunar-exploration vehicles as well as to the proposed research vehicle.

The equations of motion used in the investigation are presented in appendix A. Symbols used in this paper are defined in appendix B.

TEST APPARATUS

This study was directed to the terminal phase of manned lunar landings and their simulation in free flight on earth. The investigation was mechanized on an analog computer in six degrees of freedom according to the equations in appendix A. A flat earth or moon was assumed, and heading changes were limited to ±40°.

The vehicle used to provide baseline information for these tests is a free-flying lunar-landing research vehicle (ref. 1) now under construction. An artist's conception of the vehicle (fig. 1) illustrates the salient features of the craft, which is, in essence, a pilot's platform supported by open-trusswork legs. Lift rockets, operating in pairs about the center of gravity, thrust along the Z-body-axis of the craft to provide deceleration during the simulated moon-landing trajectory. Smaller rockets on the legs furnish attitude control about all three vehicle axes. In addition, a jet engine, mounted in a servo-driven gimbal ring at the vehicle center of gravity, compensates for the differential between earth and moon gravity forces and overcomes most of the aerodynamic forces imposed on the craft. Pertinent physical characteristics of the lunar-landing research vehicle are presented in table I.

Although this vehicle will attempt to duplicate maneuvers of a manned lunar-exploration vehicle, it will be operating in the earth gravity field and will be acted upon by aerodynamic forces and moments. In this study, the jet engine of the research vehicle was assumed to support exactly 5/6 of the instantaneous vehicle weight. The effects of aerodynamic forces and moments (estimated conservatively in ref. 1) were considered during a portion of the tests.

The instrument display for the pilot in the tests is shown schematically in figure 2. The display keyed on an attitude ball in the center of the panel. In addition to the basic attitude information, cross-pointer indicators in front of the ball presented longitudinal and lateral horizontal velocities to full-scale deflections of 20 ft/sec. Meters at the side of the ball furnished readings of altitude, total velocity, and vertical velocity. An auxiliary display of range and cross range was presented on a 21-inch oscilloscope to a scale of 1,000 ft/in.

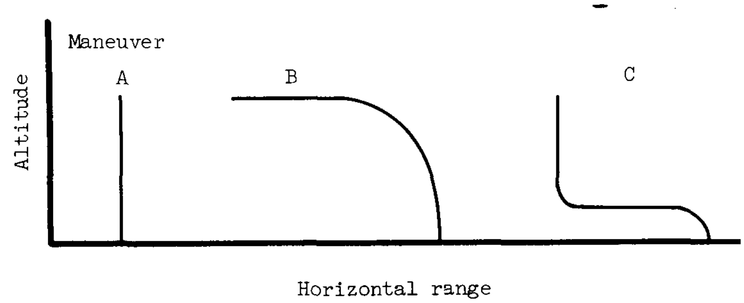
The pilot controlled pitch and roll attitude with a small side controller located on his right-hand console. With his left hand, he operated a collective-type stick (up and down motion consistent with flight direction) that controlled lift-rocket thrust. Foot pedals were used for yaw control. The side controller provided the pilot with light centering forces only; a deadband of approximately 5° of the 30° maximum possible deflection was utilized during all runs.

TESTS

The investigation was divided into two phases: a handling-qualities or attitude-control requirement phase, and a trajectory- or lift-thrust requirement phase.

In the handling-qualities phase of the study, a standard maneuver was performed that enabled direct comparisons to be made from run to run. This standard maneuver started at near-hover conditions ($V = \dot{h} \leqq 10$ fps) at an altitude of 4,000 feet msl (mean sea level). The pilot then translated forward while descending to the touchdown at the Edwards altitude of 2,200 feet msl. In essence, these tests examined a maneuvering task in the pitch mode and a random-motion correction or manual damping task in the roll and yaw modes. Since the lift rockets were assumed to be fixed rigidly to the vehicle, an attitude change was required to accomplish all translational maneuvering. Attitude-control accelerations were examined over a range from about 2 deg/sec^2 to about 20 deg/sec^2. By proper feedback of angular velocity and attitude information, rate and attitude control were mechanized. Pilot ratings were obtained for all conditions flown and are compared with related tests where possible.

In the trajectory phase of the simulation, three different maneuvers, referred to as A, B, and C (see sketch), were used to define limits and capabilities. These maneuvers started at a near-hover altitude of 4,000 feet msl and terminated in a soft landing at 2,200 feet msl. Maneuver A was a free-fall from starting conditions to the altitude where a continuous application of maximum thrust resulted in a soft landing. Maneuver B consisted of a forward translation at initial altitude, followed by a coasting descent, then application of thrust for a soft impact. Maneuver C began with a free-fall, then an application of thrust in such a manner that forward translation could be accomplished at 200 feet above ground level, followed by a descent which resulted in a soft impact.



Maneuvers B and C were performed to ascertain the relative merits of each type of maneuver in obtaining maximum range. For each of these translational maneuvers, the pilot was asked to follow the specified trajectory. However, considerable flexibility was available to him, particularly in the velocities and accelerations used in the maneuvers.

During all tests, the pilot attempted to minimize touchdown velocities, attitude angles, and dispersions from the desired landing point without using more than the available fuel (see table I) in order to accomplish realistic, soft landings.

RESULTS AND DISCUSSION

In the analog-simulator tests, the pilot started with the most difficult control task, that of flying with pure acceleration attitude control, and progressed to rate command, then attitude command. Finally, with an "optimum" attitude-control system, the trajectory portion of the study was conducted. The results of the investigation are presented in this sequence.

Attitude Control

Acceleration command.- Pilot ratings evaluated on a Cooper scale (table II, based on ref. 2) are plotted against maximum available control authority in figures 3(a), 4(a), and 5(a) for an acceleration-command mechanization. A reasonable amount of pilot training was necessary even at the most favorably rated conditions to successfully fly with acceleration command. Also of aid to the pilot was an expanded attitude-angle indication that enabled him to readily correct undesirable motions. When the technique was learned, however, control was considered generally satisfactory at authority levels between 5 deg/sec^2 and 10 deg/sec^2. At values below 5 deg/sec^2, response was judged to be too sluggish, and at values much above 10 deg/sec^2, the tendency for overcontrol was too great. As shown in the figures, the pilots rated the tasks similarly.

Rate command.- The data of figures 3(b) to 3(d), 4(b) to 4(d), and 5(b) to 5(d) show the effect of increasing rate damping as a result of control-system feedback. The expected improvement in pilot rating with increased artificial rate damping is evident, and the band of satisfactory authority levels is widened considerably as damping is increased. As shown, the pilot ratings in roll and yaw are generally more favorable than those in pitch. This rating difference reflects the less severe piloting task of manual damping in roll and yaw, as compared with the maneuvering task in the pitch mode.

The data from figures 3 to 5 are summarized in figure 6. In this figure, rate damping is plotted against control authority. Iso-pilot rating lines separating the satisfactory, unsatisfactory, and unacceptable areas are shown over the range of variables tested. The unacceptable area generally encompasses all control authorities less than about 2 deg/sec^2, regardless of artificial damping. By increasing control authority, satisfactory control was obtained rapidly. Only in the pitch mode was there a noticeable decrement in rating with a further increase in authority.

Previous tests at the Flight Research Center (ref. 3) indicated that an authority of about 10 deg/sec^2 was predicted to be satisfactory. VTOL studies (refs. 4 and 5) showed that more authority would be desirable. In figure 7(a), data from figure 6 are compared with the data from reference 5 for the longitudinal mode. A marked discrepancy between the boundaries is evident. More recent VTOL studies performed to simulate lunar landing (ref. 6) showed that less than 18 percent of the maximum control power available in the pitch mode was used. This comparison indicates that, on the airless moon, control authorities set to meet VTOL requirements would be expected to result in overcontrol tendencies. Discrepancies in the control requirements are attributed to the reserve control power on earthbound VTOL vehicles that is used to cope with unexpected wind gusts. Inasmuch as the moon has no atmosphere, gusts will obviously pose no problem during an actual lunar landing.

Shown in figure 7(b) are data from reference 7, a report on a fixed-base analog-simulation of lunar landing in which a visual presentation was used. Data from the referenced tests and from this investigation agree reasonably well. As was noted previously, the pilots participating in the present tests received a considerable degree of training and were presented with expanded attitude indications. These aids were not available in the referenced tests (ref. 7). Thus, at very low damping levels, pilot ratings were more favorable in the present tests than in the referenced tests. At high damping levels, the rating differences are unexplained.

Attitude command.- Data acquired with attitude command mechanized are plotted in the conventional manner of frequency squared as a function of damping parameter in figures 8 to 10. However, the frequency and damping are not inherent vehicle characteristics, but were artificially derived by using the attitude angle and rate-feedback terms. The stability and damping had to be provided in an artificial manner, since no inherent aerodynamic characteristics will be generated in the airless lunar environment. Stability is proportional to the angular feedback term, and damping is proportional to the angular rate-feedback term. A distinction of acceleration capability is made in the figures, and pilot ratings are noted beside each symbol. These data show that pilot ratings seem to be rather weak functions of frequency, although some unpublished data indicate stronger frequency effects, especially with thrust misalinement. Reference 8 concludes that, for a maneuvering task, control acceleration and damping are the most important parameters in evaluating the excited motions. Therefore, the data of figures 8 to 10 are replotted in figures 11 to 13 as functions of acceleration and artificial damping, with no consideration of frequency. For comparison purposes, the fairings of the data from figures 3 to 5 are reproduced in figures 11 to 13.

The attitude-command data generally agree with the rate- and acceleration-command data. The differences, which are generally small, may result from the limited amount of data available. The greater spread in the data in the roll and yaw modes of figures 12 and 13 is attributed to the piloted manual damping task in these modes. Thus, there appears to be little difference between the effectiveness of rate and attitude command if proper acceleration and artificial damping are provided.

In the runs that averaged 2 to 3 minutes in duration, the total attitude-rocket fuel consumption never exceeded 15 pounds of hydrogen-peroxide propellant. This was almost a negligible quantity of fuel when compared with the 500 pounds of propellant consumed by the lift rockets in the same time interval. The various idealized control mechanizations did not noticeably affect fuel consumption.

Aerodynamic effects.- As mentioned previously, aerodynamic forces and moments that would be encountered on the lunar-landing research vehicle were included during a portion of the tests. The effects of these forces and moments became apparent at velocities greater than 20 ft/sec, particularly during the trajectory phase of the investigation. These effects are discussed, therefore, in greater detail in the following section.

Since only steady-state aerodynamic conditions were simulated, pilot ratings of control effectiveness were not affected. However, it is believed that if gusty weather were considered, as could be expected in operating VTOL vehicles, control requirements would be affected.

Trajectory Phase

Simulator data from a typical vertical free-fall maneuver (A) are shown in figure 14. This maneuver results in the minimum fuel consumption in descending from a hover altitude to a soft lunar impact. The ratio of rocket fuel used to vehicle weight at touchdown for the maneuver shown is 0.055. Vertical descent is not a realistic maneuver from a piloting standpoint, however, because it is anticipated that some horizontal translating will be required in the vicinity of the landing site at least for site selection. For the translational maneuvers (B and C), variations in fuel consumption are shown in figure 15 as a function of range attained at impact. As expected, the fuel required increases with increasing range, but not in direct proportion because of the greater velocity attained on the longer distances. A comparison of maneuvers B and C shows that, for the same amount of fuel, more than twice the range is obtained with maneuver B than could be obtained with maneuver C. Maneuver B is performed at a higher altitude and, hence, reaches higher velocities before the allotted fuel is exhausted. Horizontal velocities and accelerations did not exceed 80 ft/sec and 6.0 ft/sec^2, respectively, during any of the maneuvers.

Figure 16 compares the pilot's use of thrust control in maneuvers B and C. The range of instantaneous thrust-to-weight T/W values for the vehicles during the maneuvers was from zero lunar g to about 2 lunar g. Zero thrust was used for about the same percentage of time in the planned free-fall portion of both types of maneuvers. Throttling ranges corresponding to T/W values between 0.8 and 1.8 lunar g were used more than 50 percent of the time. Values below this range afforded the pilot a finer control over the rate of descent, and values above this range allowed for more rapid braking. However, control capability in these areas was not considered essential to the success of the landings.

The frequency of occurrence of attitude and velocity values experienced at landing is shown in figures 17 and 18. The figures show that velocities less than 10 ft/sec and attitudes less than 10° were obtained in more than 90 percent of the landings. These values are well within the range which is considered soft for lunar impact.

To obtain additional information on translational maneuvering, the retrothrust was doubled to evaluate the effect of an increase in thrust. Although only a limited number of runs were performed, the pilot never used more than one-half of the additional maximum-thrust capability.

Aerodynamic forces and moments that would be encountered on the lunar-landing research vehicle were apparent at the higher velocities attained in this study. At these velocities, the pilot reported that the vehicle had additional angular rate damping and that a greater horizontal thrust component was required to attain a given translational speed than in the airless state. No difficulty was experienced in controlling the vehicle when these effects were considered.

CONCLUSIONS

A six-degree-of-freedom analog study performed to aid in defining handling qualities and trajectory potential for terminal lunar landing showed that:

1. For a maneuvering task in the pitch mode and a manual piloted damping task in the roll and yaw modes, the pilots preferred rate or attitude command.

2. Acceleration levels of about 10 deg/sec^2 afforded acceptable response without a tendency for overcontrol.

3. At optimum acceleration values over the range of artificial-damping values tested, pilot rating became more favorable with increased damping.

4. For the types of maneuvers performed and for a given amount of fuel, range can be maximized by translating at high altitudes.

5. To consistently perform successful landings, the pilots generally used thrust-to-weight ratios throttled between a minimum value of 0.8 lunar g and a maximum value of 1.8 lunar g.

6. Velocities less than 10 ft/sec and attitudes less than 10° were attained in more than 90 percent of the landings.

Flight Research Center,
National Aeronautics and Space Administration,
Edwards, Calif., April 19, 1963.

APPENDIX A

EQUATIONS OF MOTION

The six equations of motion used in this study described the vehicle motion in the conventional three translational and three rotational degrees of freedom. The equations are modifications of those developed in reference 9. The axis system is such that: (a) the yaw axis is the vertical axis when the vehicle is resting on level ground; (b) the roll axis is the axis which is parallel to both the ground and the pilot's plane of symmetry when the vehicle is resting on level ground; and (c) the pitch axis is the axis which is normal to the roll and yaw axes. Because of the limited scope of the problem, a flat earth was assumed, heading changes were limited to ±40°, and glide angles were limited to -120°. The equations used were:

velocity change,

$$\dot{V} = -\frac{D}{m} - g \sin \gamma - \frac{T}{m} \sin \alpha \tag{A1}$$

glide-angle change,

$$\dot{\gamma} = \frac{g}{V} \cos \gamma + \frac{N}{mV} \cos \varphi + \frac{T}{mV} \cos \alpha \tag{A2}$$

sideslip-angle change,

$$\dot{\beta} = \frac{g}{V} \sin \varphi \cos \theta - r + p \sin \alpha \tag{A3}$$

rolling acceleration,

$$\dot{p} = \frac{\left(I_Y - I_Z\right)}{I_X} qr + \dot{p}_c \tag{A4}$$

pitching acceleration,

$$\dot{q} = \frac{\left(I_Z - I_X\right)}{I_Y} pr + \dot{q}_c + \frac{M_Y}{I_Y} \tag{A5}$$

yawing acceleration,

$$\dot{r} = \frac{\left(I_X - I_Y\right)}{I_Z} pq + \dot{r}_c \tag{A6}$$

Lift-rocket thrust T was assumed to act along the Z-body-axis of the craft. It was further assumed that the jet engine would operate vertically at a thrust level 5/6 that of the vehicle total weight, thereby compensating for earth and moon gravity differentials so that $g = 5.367\ \text{ft/sec}^2$. The aerodynamic terms D, N, and M_y were considered during a portion of these tests. The aerodynamic terms were generated as follows, based on values estimated in reference 1:

$$D = (0.000173V^2 + 0.00691V)F_1(\alpha)$$

$$N = (0.0002765V^2 + 0.00029V)F_2(\alpha)$$

$$M_y = (0.000261V^2 + 0.000777V)F_3(\alpha)$$

where $F_1(\alpha)$, $F_2(\alpha)$, and $F_3(\alpha)$ are functions of angle of attack.

The basic control-effectiveness parameters $\dot{p}_c$, $\dot{q}_c$, and $\dot{r}_c$ included feedback terms necessary to mechanize rate- and attitude-command systems as well as an acceleration-command system.

The moments of inertia were programed as linear functions of weight through the range of values of table I. Vehicle weights were changed for fuel consumption of the jet engine, lift rockets, and attitude-control rockets.

In addition to the six equations of motion, a number of auxiliary equations were employed:

$$\dot{\varphi} = p + (r \cos \varphi + q \sin \varphi)\tan \theta \tag{A7}$$

$$\dot{\theta} = q \cos \varphi - r \sin \varphi \tag{A8}$$

$$\dot{\psi} = \frac{r \cos \varphi + q \sin \varphi}{\cos \theta} \tag{A9}$$

$$\dot{h} = V \sin \gamma \tag{A10}$$

$$\dot{x} = V \cos \gamma \tag{A11}$$

$$\dot{y} = \frac{V}{57.3}(\psi + \beta \cos \varphi - \alpha \sin \varphi)\cos \gamma \tag{A12}$$

The equations used posed a serious limitation to maneuvering in that $\dot{\gamma}$ and $\dot{\beta}$ (eqs. (A2) and (A3)) became undefined whenever total velocity went to zero. A system of equations such as those of reference 10 would avoid this difficulty.

APPENDIX B

SYMBOLS

D	drag force, lb
$F(\alpha)$	angle-of-attack function
g	assumed lunar-gravity acceleration, 5.367 ft/sec^2
h	altitude, ft
$\dot{h}$	vertical velocity, ft/sec
I_X	moment of inertia about X-axis, slug-ft^2
I_Y	moment of inertia about Y-axis, slug-ft^2
I_Z	moment of inertia about Z-axis, slug-ft^2
K'	square of equivalent vehicle natural frequency (proportional to angle-feedback signal), sec^{-2}
M_Y	pitching moment, ft-lb
m	vehicle mass, slugs
N	normal force, lb
p	rolling velocity, radians/sec
$\dot{p}$	rolling acceleration, radians/sec^2
q	pitching velocity, radians/sec
$\dot{q}$	pitching acceleration, radians/sec^2
r	yawing velocity, radians/sec
$\dot{r}$	yawing acceleration, radians/sec^2
T	lift-rocket thrust, lb
T/W	lunar thrust-to-weight ratio, lunar g
V	total velocity, ft/sec
$\dot{V}$	linear acceleration along flight path, ft/sec^2
W	earth weight, lb

x	longitudinal distance, ft
$\dot{x}$	longitudinal horizontal velocity, ft/sec
y	lateral distance, ft
$\dot{y}$	lateral horizontal velocity, ft/sec
α	angle of attack, deg
β	angle of sideslip, deg
$\dot{\beta}$	rate of change of sideslip angle, deg/sec
γ	glide angle, deg
$\dot{\gamma}$	rate of change of glide angle, deg/sec
θ	pitch angle, deg
$\dot{\theta}$	pitch rate, radians/sec
$\ddot{\theta}$	pitch acceleration, deg/sec^2
$1/\tau'$	equivalent vehicle angular rate-damping factor (proportional to angular rate-feedback signal), sec^{-1}
φ	roll angle, deg
$\dot{\varphi}$	roll rate, radians/sec
$\ddot{\varphi}$	roll acceleration, deg/sec^2
ψ	yaw angle, deg
$\dot{\psi}$	yaw rate, radians/sec
$\ddot{\psi}$	yaw acceleration, deg/sec^2

Subscripts:

1,2,3	aerodynamic-force designation
c	control effectiveness
e	empty-weight condition
m	maximum available control effectiveness
RF_1	rocket fuel used in descending vertically
RF_2	rocket fuel used in translating maneuver

θ pitch mode

φ roll mode

ψ yaw mode

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TABLE I.- PHYSICAL CHARACTERISTICS OF THE LUNAR-LANDING RESEARCH VEHICLE

Horizontal displacement of thrust vectors from vertical axis, ft:		
Pitch rockets	12.5	
Roll rockets	12.5	
Yaw rockets	12.5	
Lift rockets	2.5	
Jet engine	0	
Attitude-rocket parameters:		
Maximum number of rockets	8	
Maximum available thrust (each), lb	100	
Minimum available thrust (each), lb	0	
Fuel	Hydrogen peroxide	
Specific impulse, sec	120	
Maximum fuel-flow rate, lb/sec/rocket	0.8	
Control	Proportional	
Response	Instantaneous	
Lift-rocket parameters:		
Maximum number of rockets	2	
Maximum available thrust (each), lb	500	
Minimum available thrust (each), lb	0	
Fuel	Hydrogen peroxide	
Specific impulse, sec	120	
Maximum fuel-flow rate, lb/sec	8.2	
Control	Proportional	
Response	Instantaneous	
Jet-engine parameters:		
Thrust, lb	5/6 instantaneous weight of vehicle	
Maximum fuel-flow rate, lb/sec	0.6	
Response	Instantaneous	
Earth weights and moments of inertia:	Full	Empty
Total weight, lb	3,440	2,440
Attitude-rocket fuel weight, lb	100	0
Lift-rocket fuel weight, lb	500	0
Jet-fuel weight, lb	400	0
I_X, slug-ft^2	2,474	2,473
I_Y, slug-ft^2	2,827	2,551
I_Z, slug-ft^2	3,165	2,662

TABLE II.- COOPER PILOT-OPINION RATING SYSTEM[1]

Operating conditions	Adjective rating	Numerical rating	Description	Primary mission accomplished	Can be landed
Normal operation	Satisfactory	1	Excellent, includes optimum	Yes	Yes
		2	Good, pleasant to fly	Yes	Yes
		3	Satisfactory, but with some mildly unpleasant characteristics	Yes	Yes
Emergency operation	Unsatisfactory	4	Acceptable, but with unpleasant characteristics	Yes	Yes
		5	Unacceptable for normal operation	Doubtful	Yes
		6	Acceptable for emergency condition only[2]	Doubtful	Yes
No operation	Unacceptable	7	Unacceptable even for emergency condition[2]	No	Doubtful
		8	Unacceptable - dangerous	No	No
		9	Unacceptable - uncontrollable	No	No
	Catastrophic	10	Motions possibly violent enough to prevent pilot escape	No	No

[1]Based on reference 2.

[2]Failure of a stability augmenter.

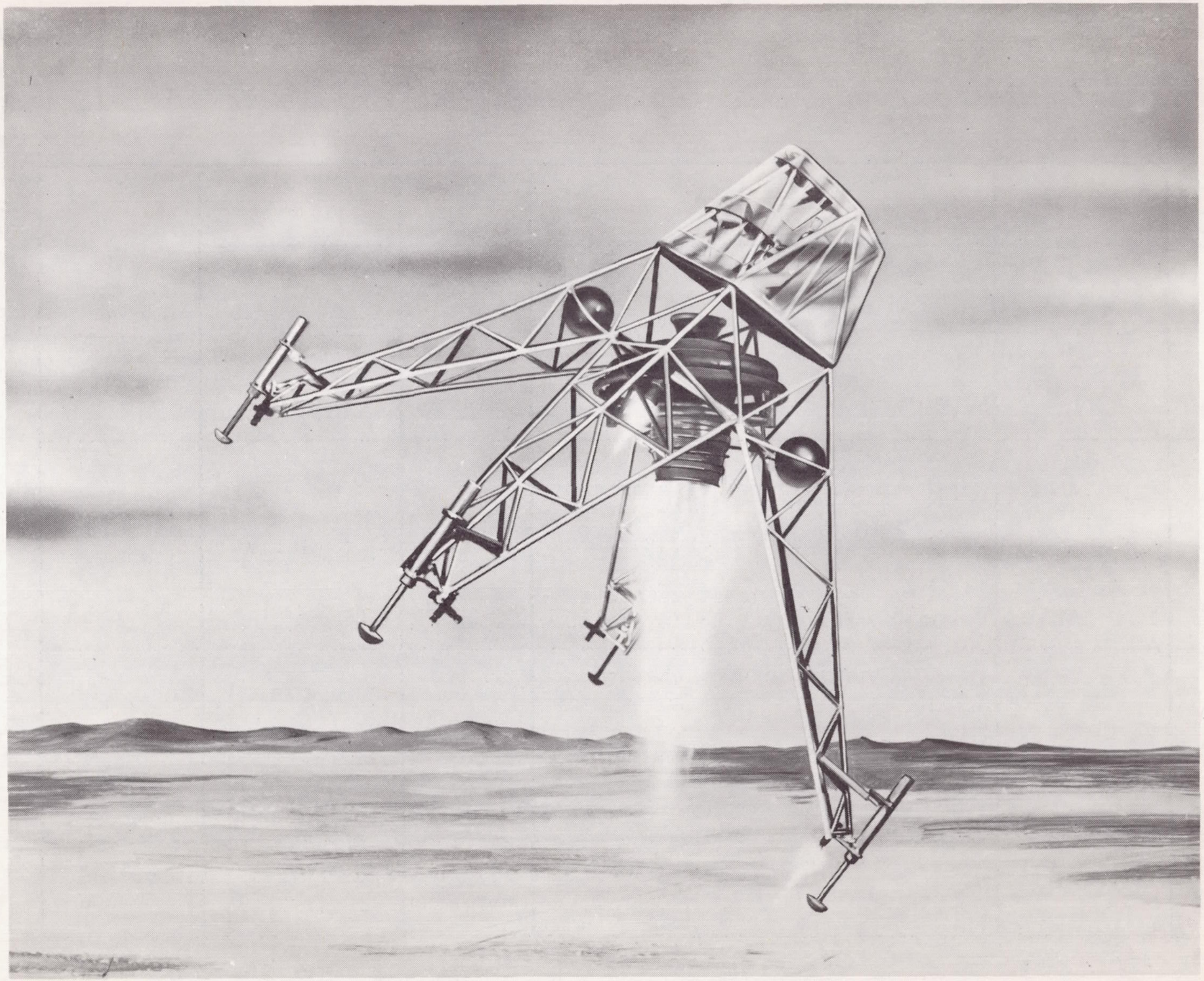


Figure 1.- Artist's conception of lunar-landing research vehicle.

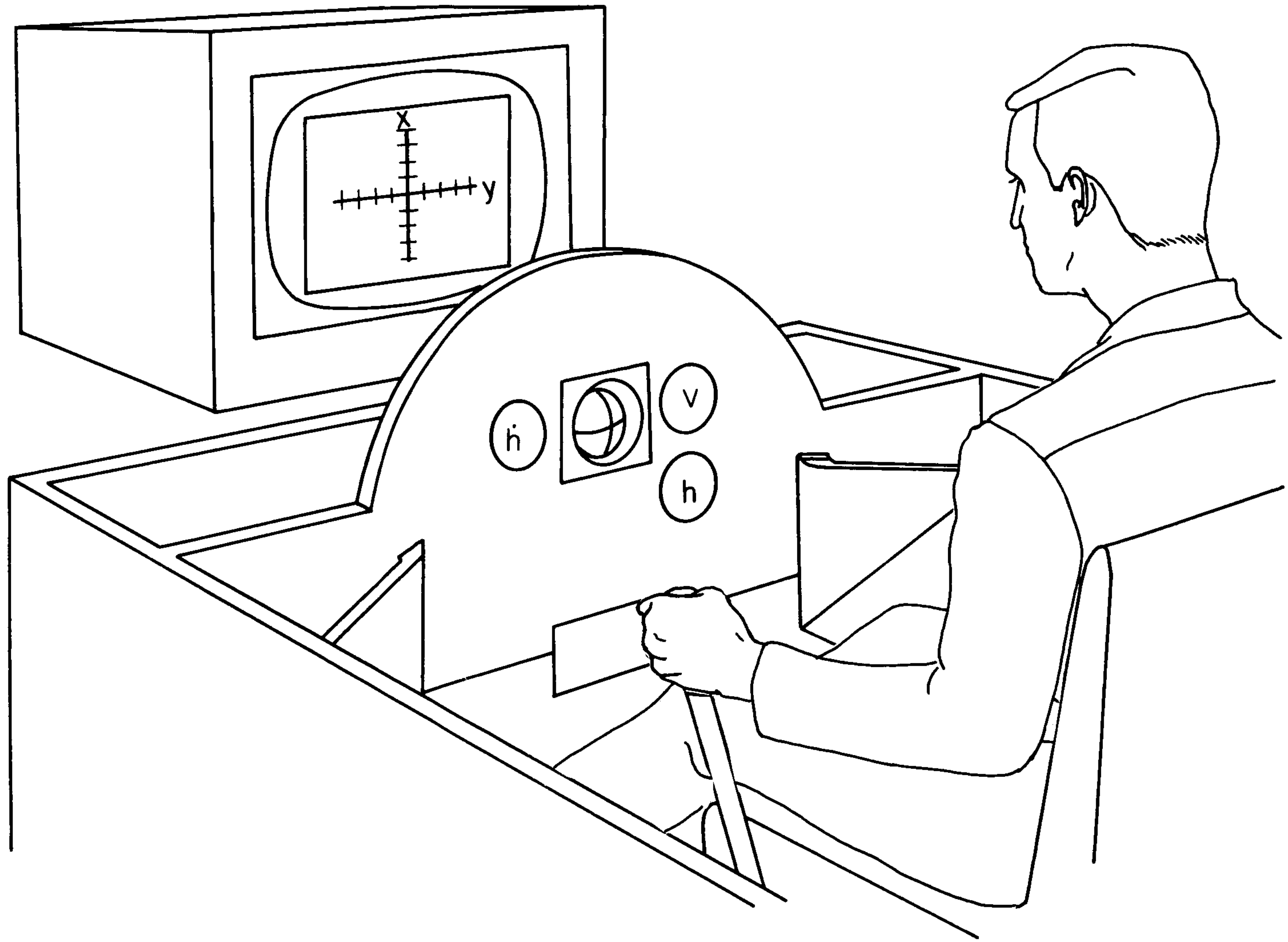
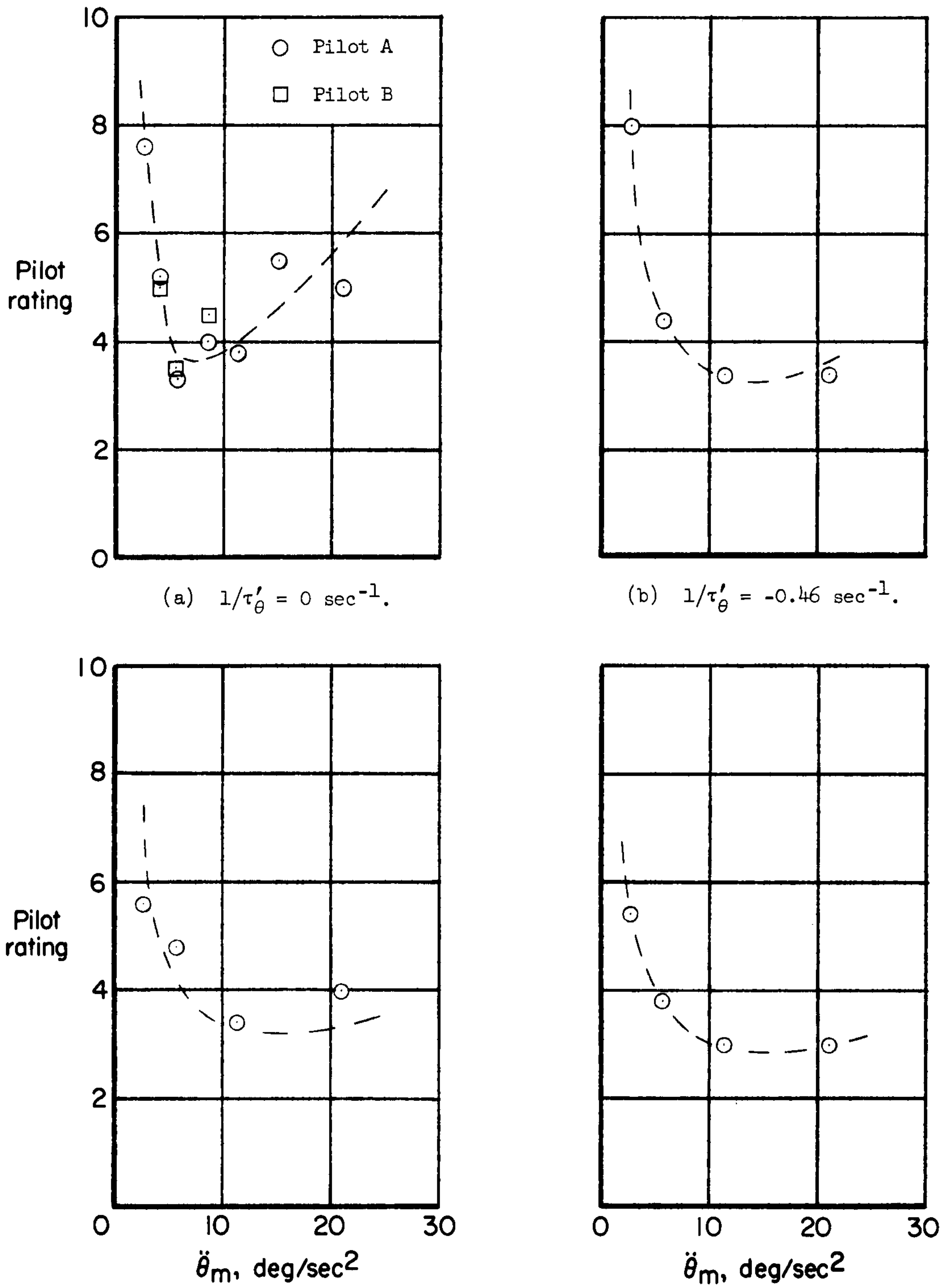


Figure 2.- Schematic drawing of pilot's simulator display.



(a) $1/\tau'_\theta = 0$ sec^{-1}.

(b) $1/\tau'_\theta = -0.46$ sec^{-1}.

(c) $1/\tau'_\theta = -1.14$ sec^{-1}.

(d) $1/\tau'_\theta = -2.27$ sec^{-1}.

Figure 3.- Pilot evaluation of acceleration- and rate-command mechanizations. Pitch mode; maneuvering task.

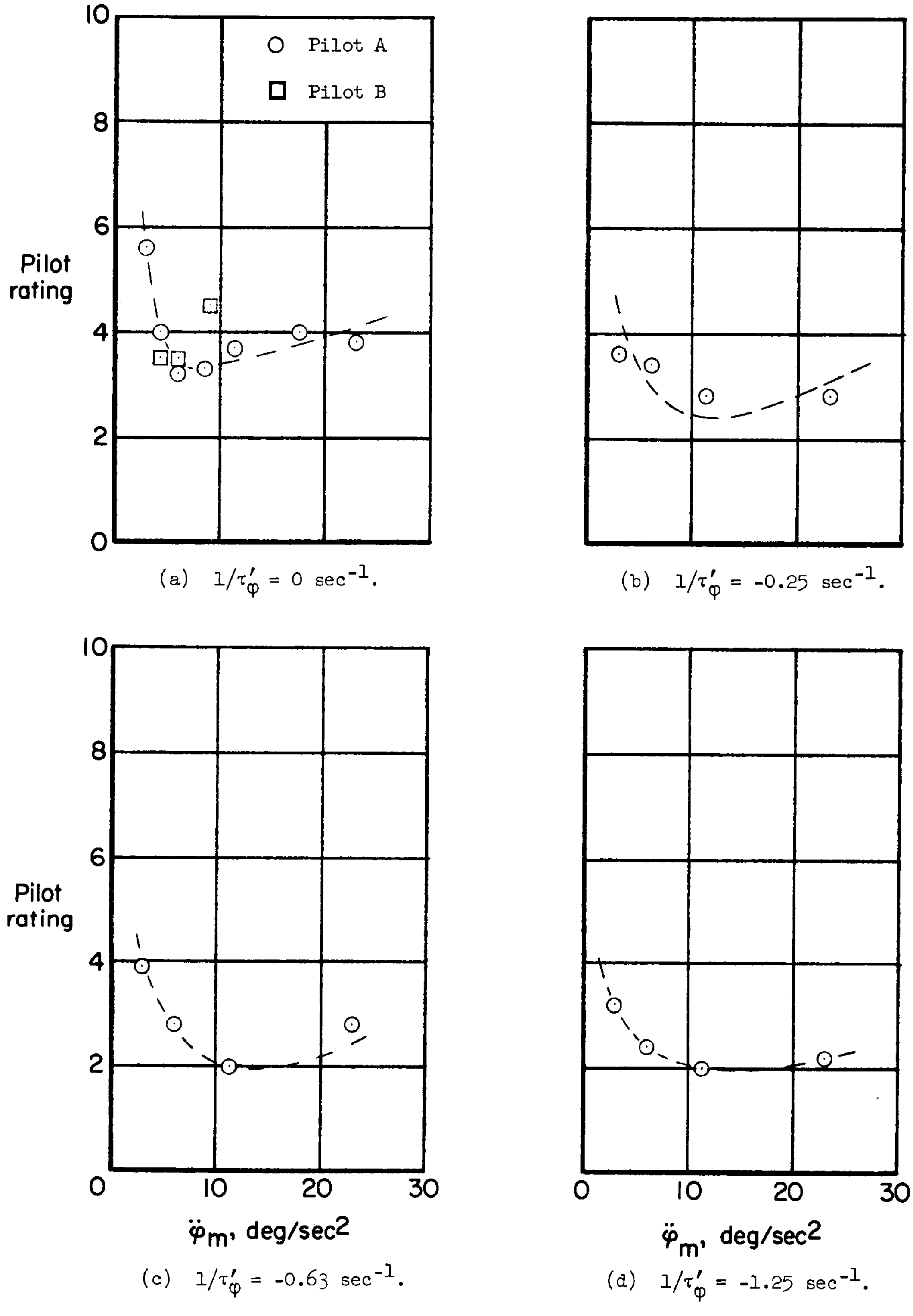


Figure 4.- Pilot evaluation of acceleration- and rate-command mechanizations. Roll mode; manual piloted damping task.

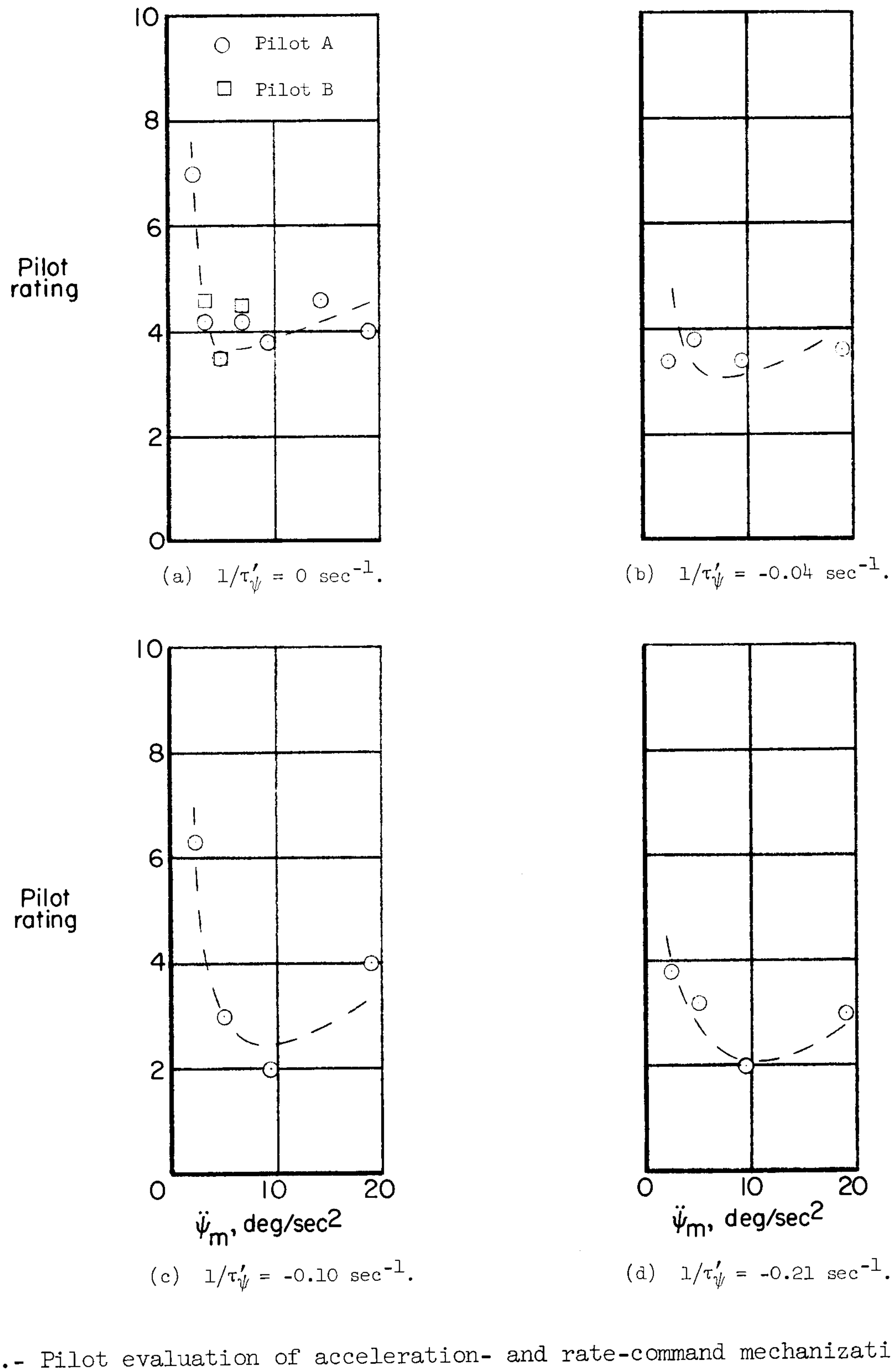


Figure 5.- Pilot evaluation of acceleration- and rate-command mechanizations. Yaw mode; manual piloted damping task.

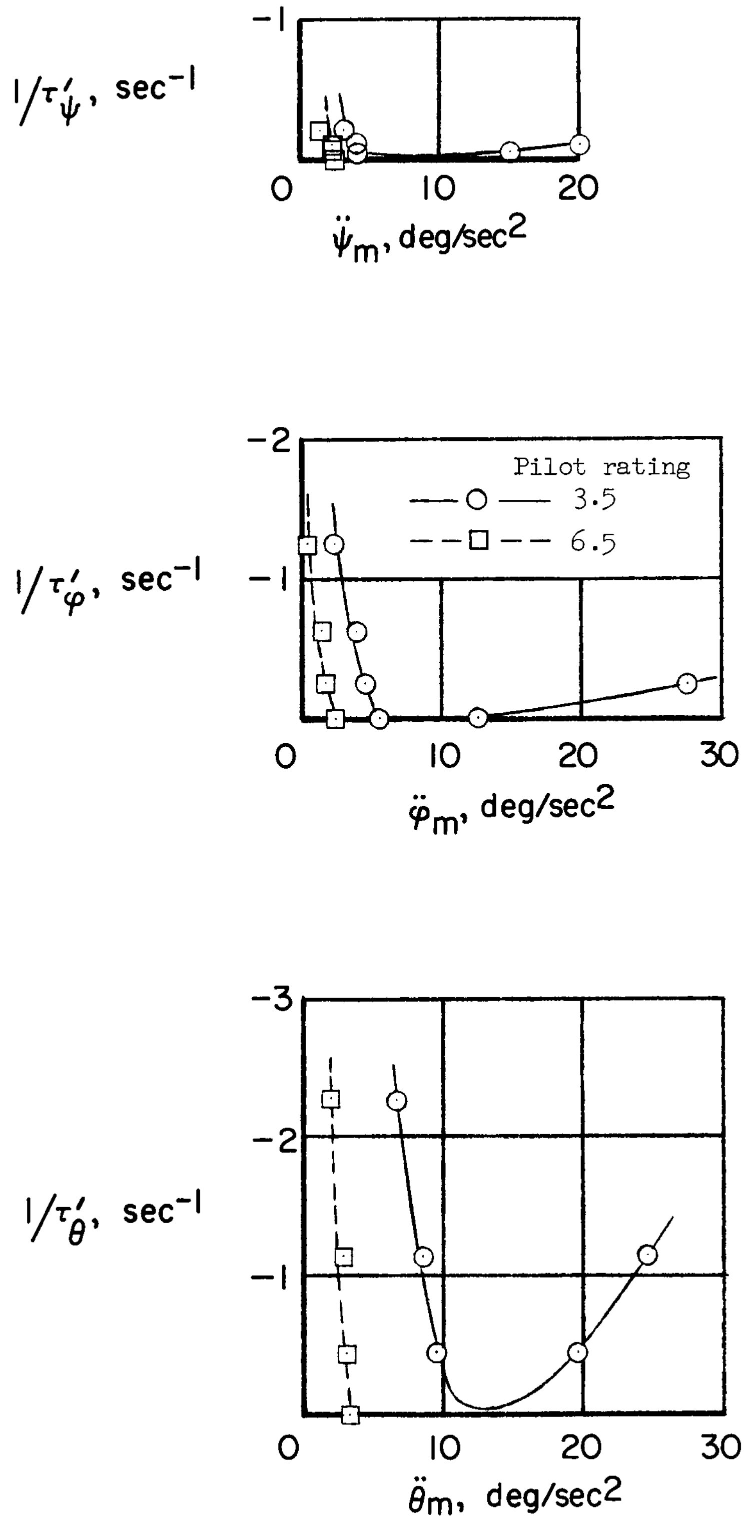
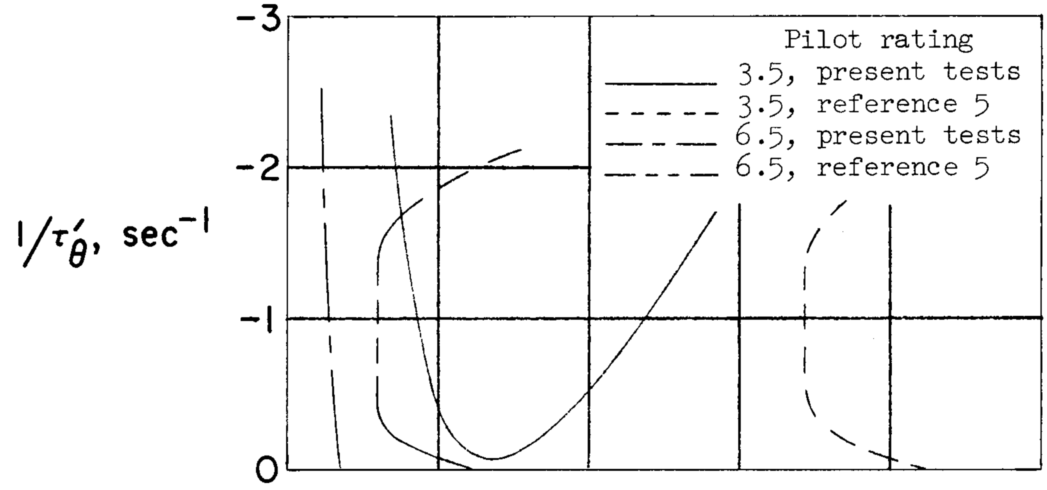
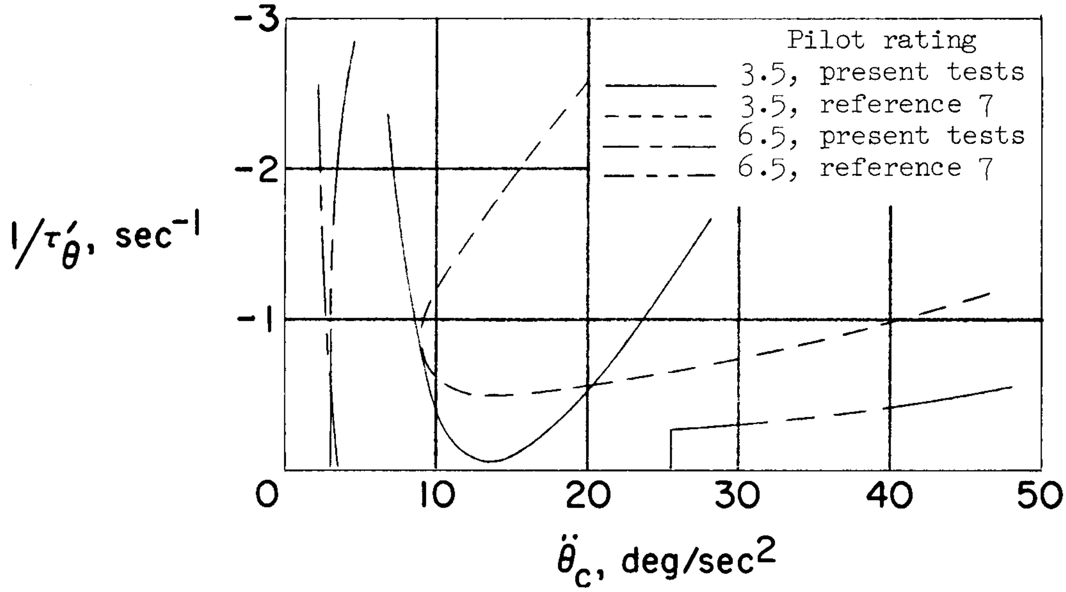


Figure 6.- Summary of rate-command data.



(a) Comparison with VTOL data.



(b) Comparison with similar lunar-landing simulation data.

Figure 7.- Comparison of rate-command data from VTOL tests and similar lunar-landing simulation data. Pitch mode; maneuvering task.

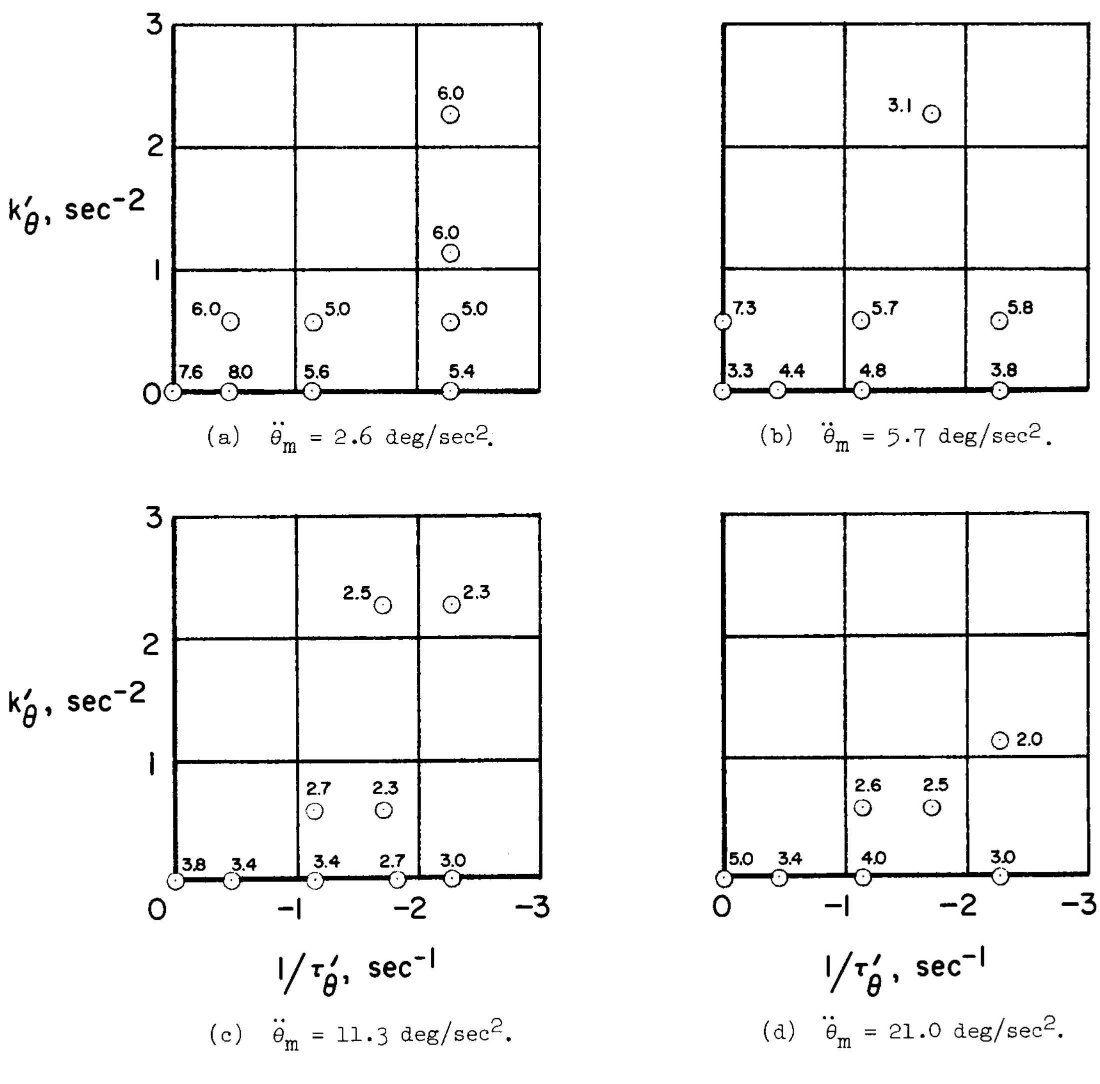


Figure 8.- Summary of attitude-command mechanization. Pitch mode; maneuvering task. (Numbers beside symbols denote pilot rating.)

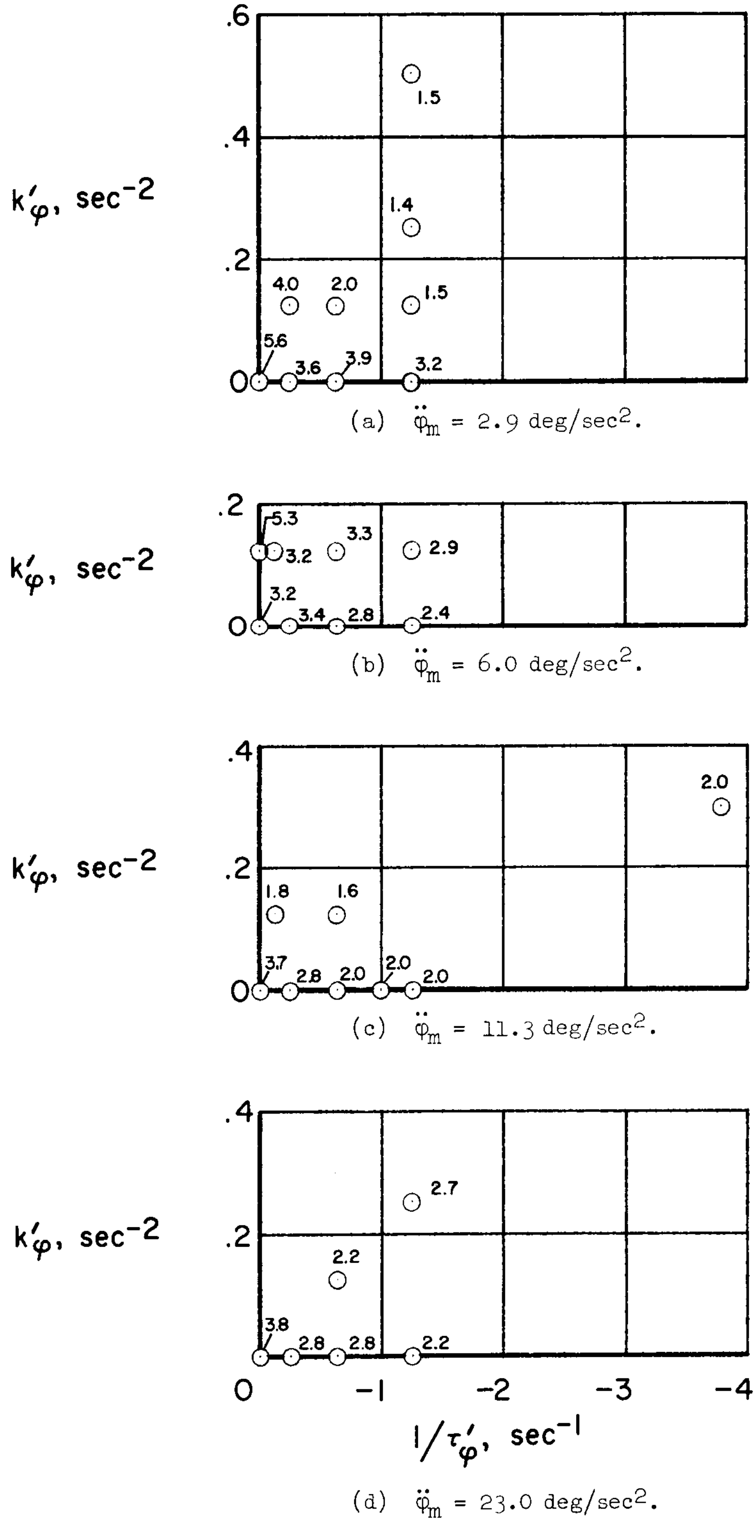
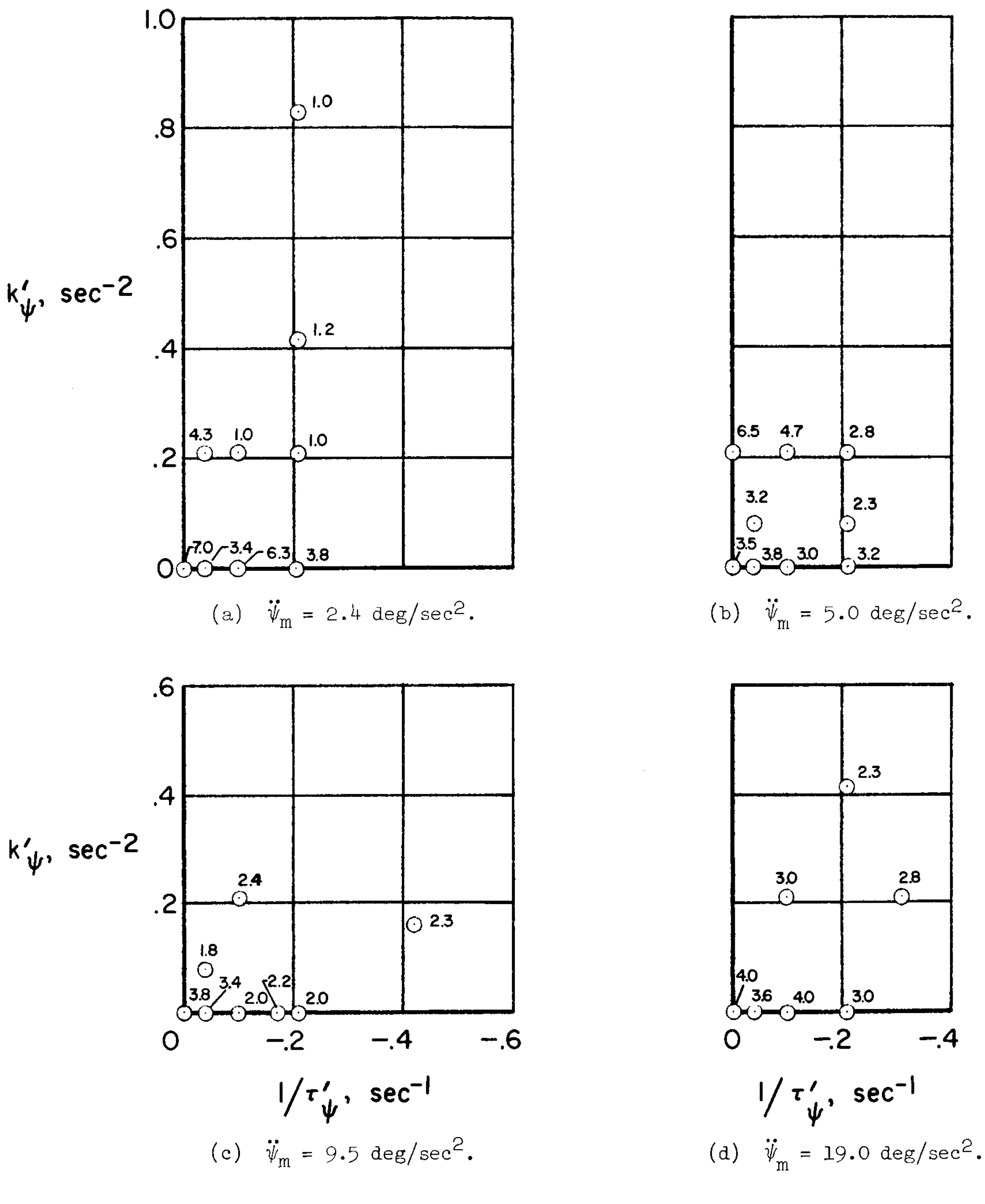


Figure 9.- Summary of attitude-command mechanization. Roll mode; manual piloted damping task. (Numbers beside symbols denote pilot rating.)



(a) $\ddot{\psi}_m$ = 2.4 deg/sec^2.

(b) $\ddot{\psi}_m$ = 5.0 deg/sec^2.

(c) $\ddot{\psi}_m$ = 9.5 deg/sec^2.

(d) $\ddot{\psi}_m$ = 19.0 deg/sec^2.

Figure 10.- Summary of attitude-command mechanization. Yaw mode; manual piloted damping task. (Numbers beside symbols denote pilot rating.)

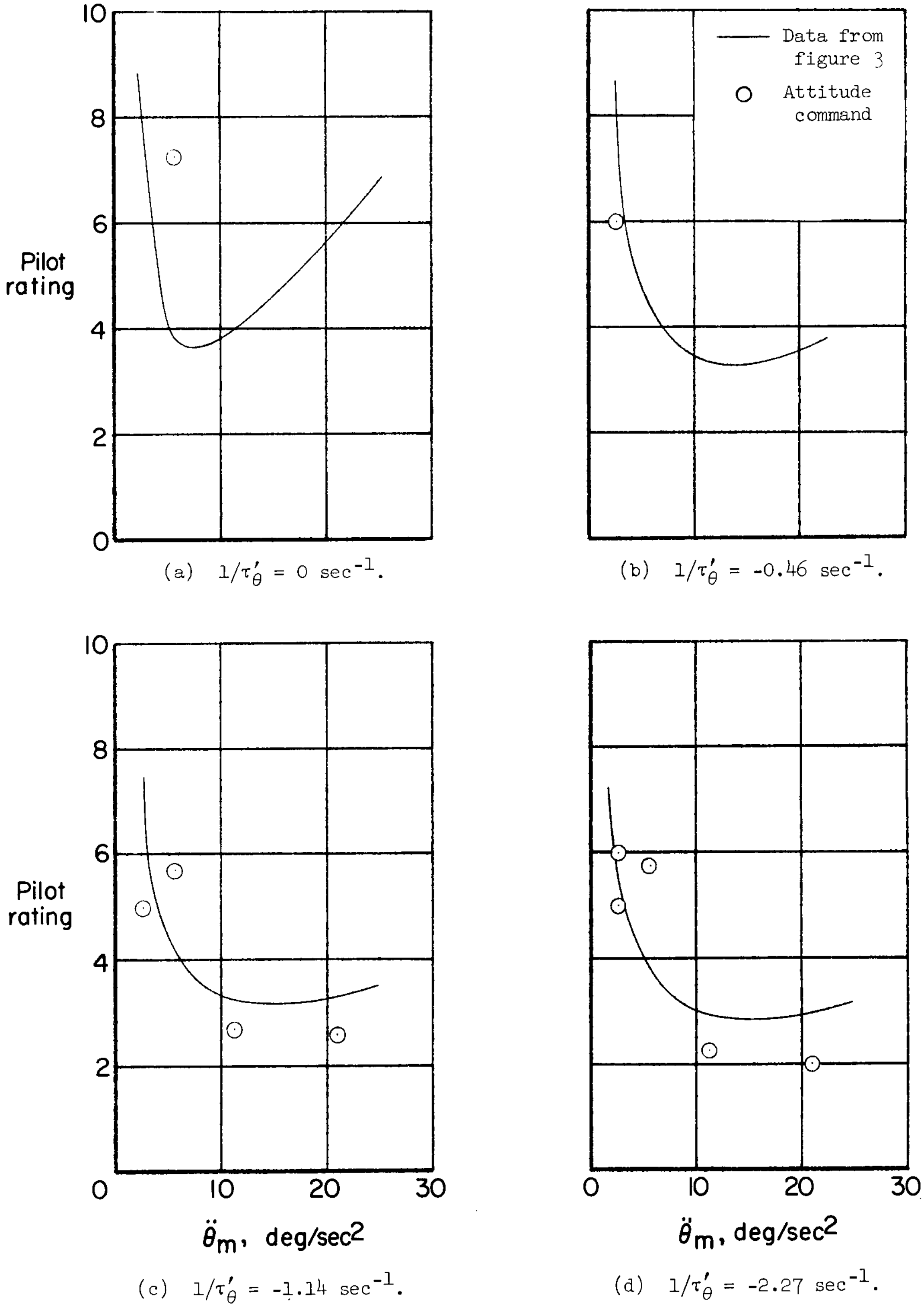


Figure 11.- Comparison of rate- and attitude-command mechanizations. Pitch mode; maneuvering task.

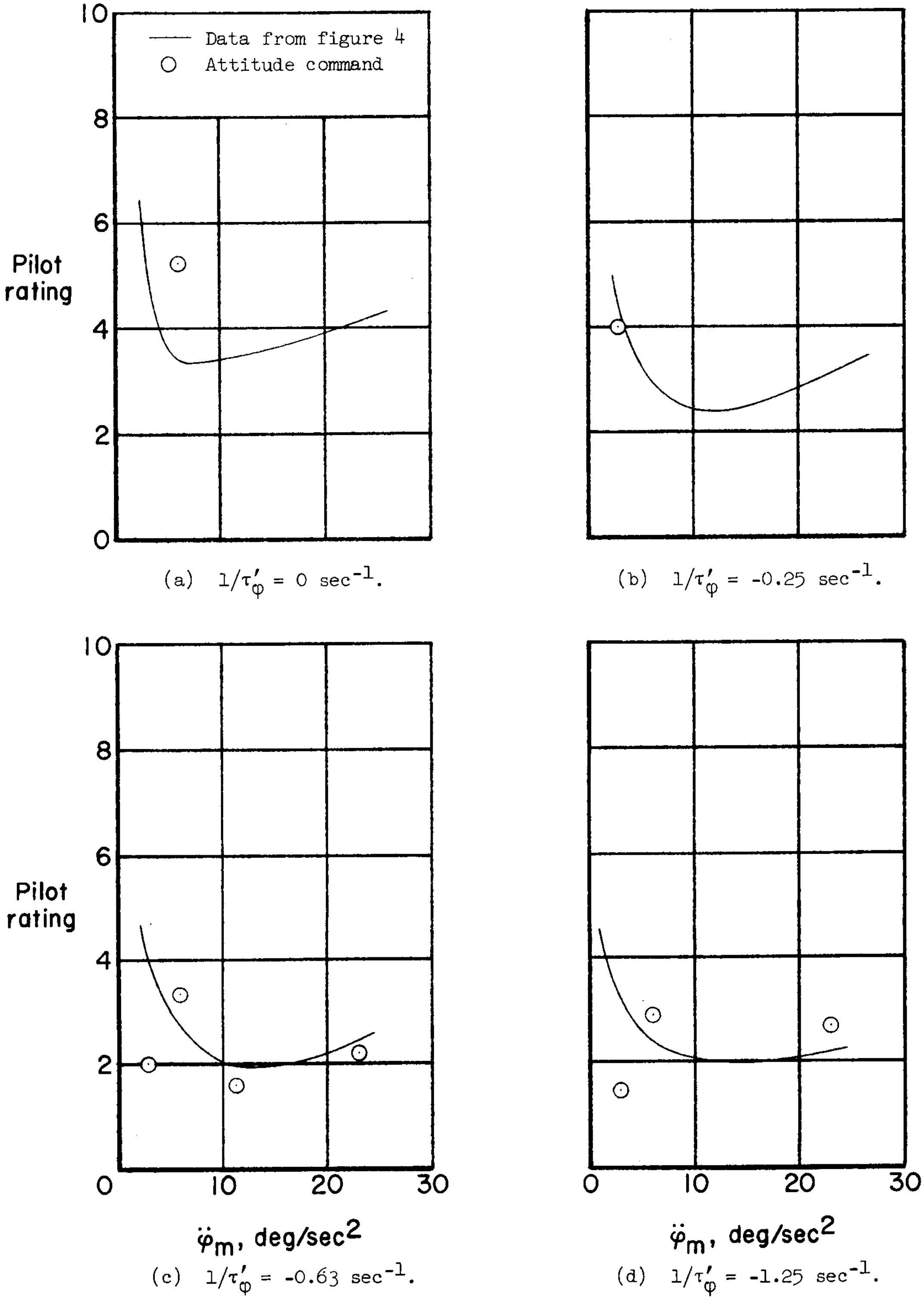
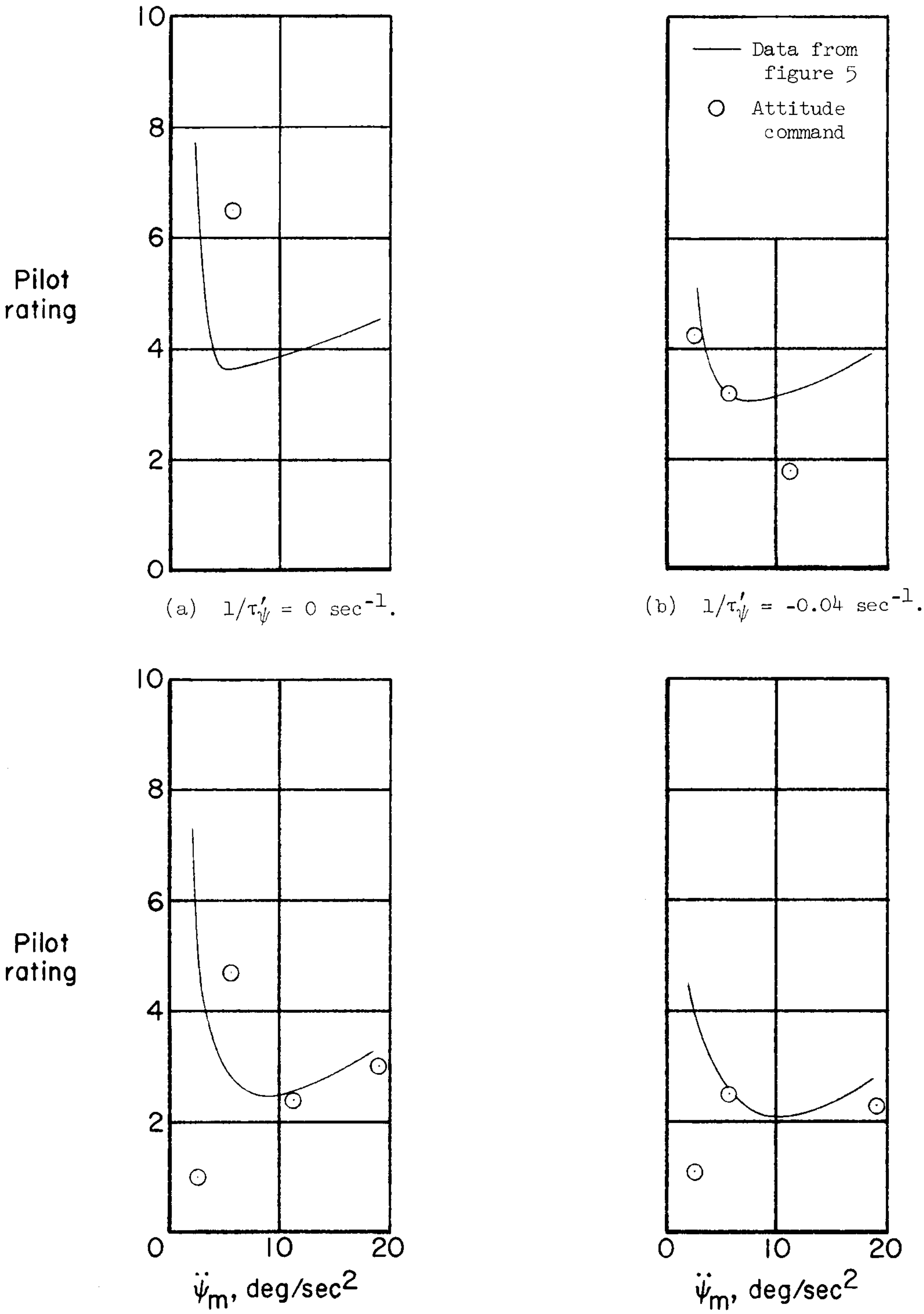


Figure 12.- Comparison of rate- and attitude-command mechanizations. Roll mode; manual piloted damping task.



(a) $1/\tau_{\psi}' = 0$ sec^{-1}.

(b) $1/\tau_{\psi}' = -0.04$ sec^{-1}.

(c) $1/\tau_{\psi}' = -0.10$ sec^{-1}.

(d) $1/\tau_{\psi}' = -0.21$ sec^{-1}.

Figure 13.- Comparison of rate- and attitude-command mechanizations. Yaw mode; manual piloted damping task.

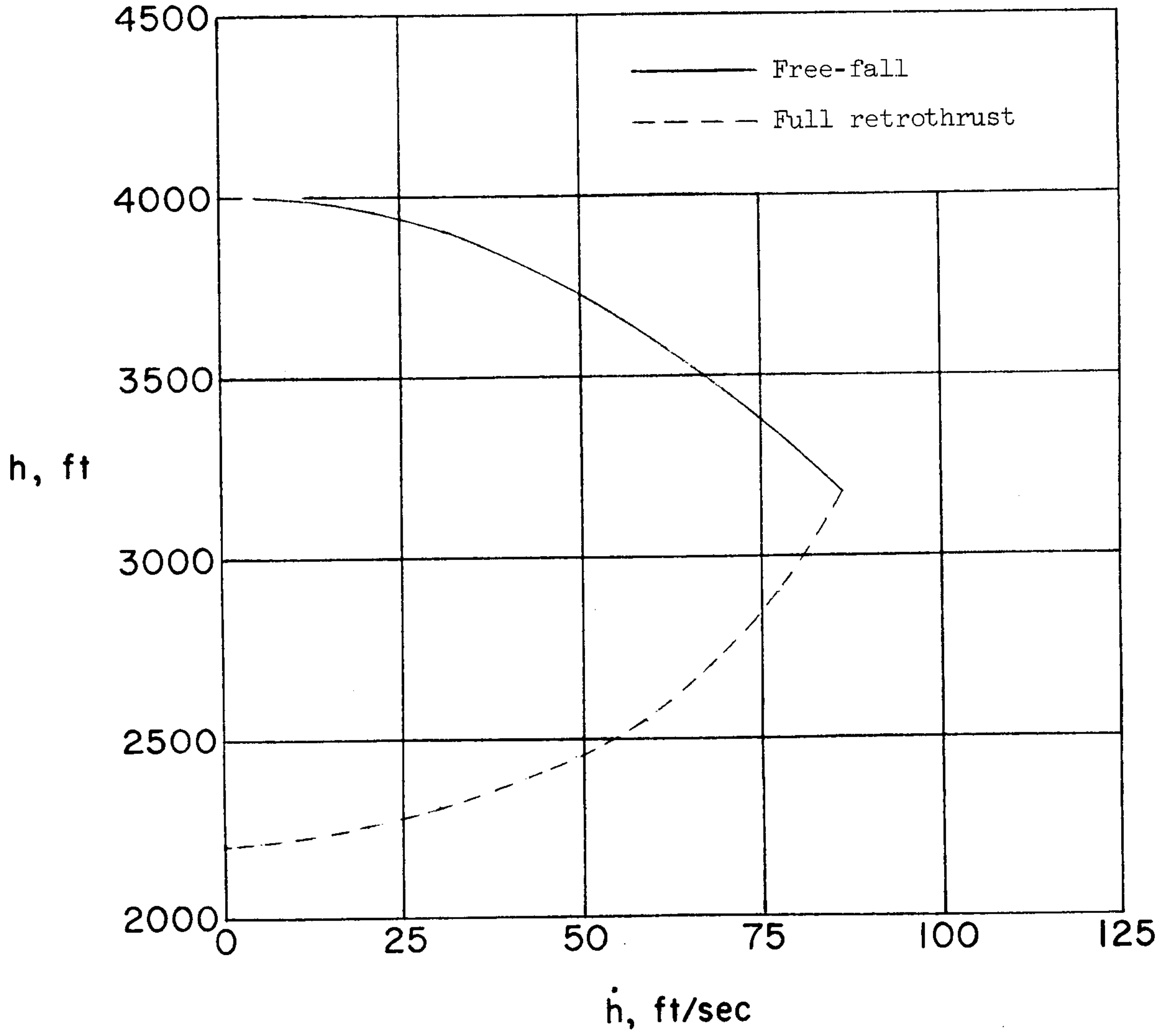


Figure 14.- Vertical-descent maneuver (A).

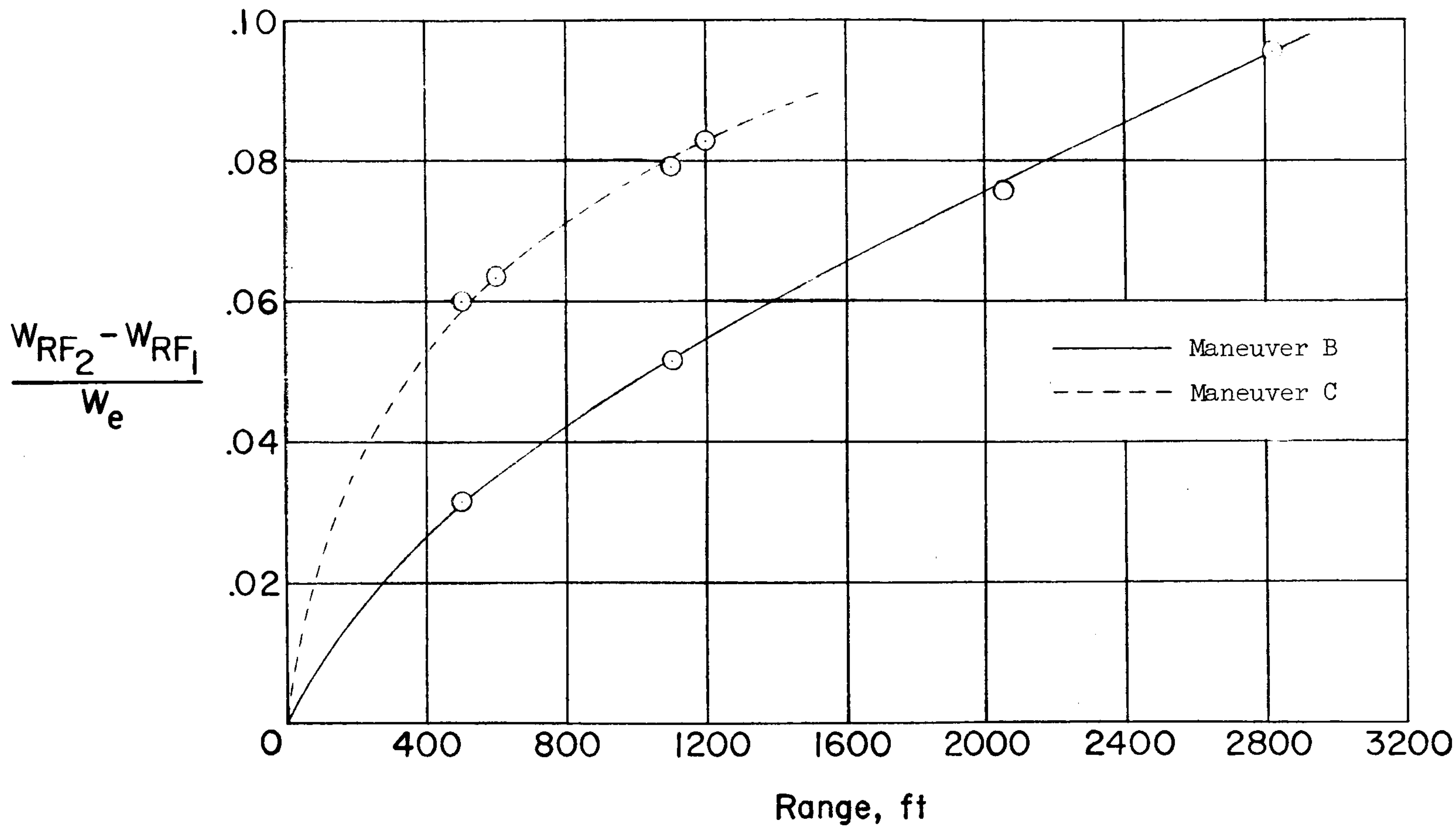


Figure 15.- Comparison of fuel usage for the two translational maneuvers (B and C).

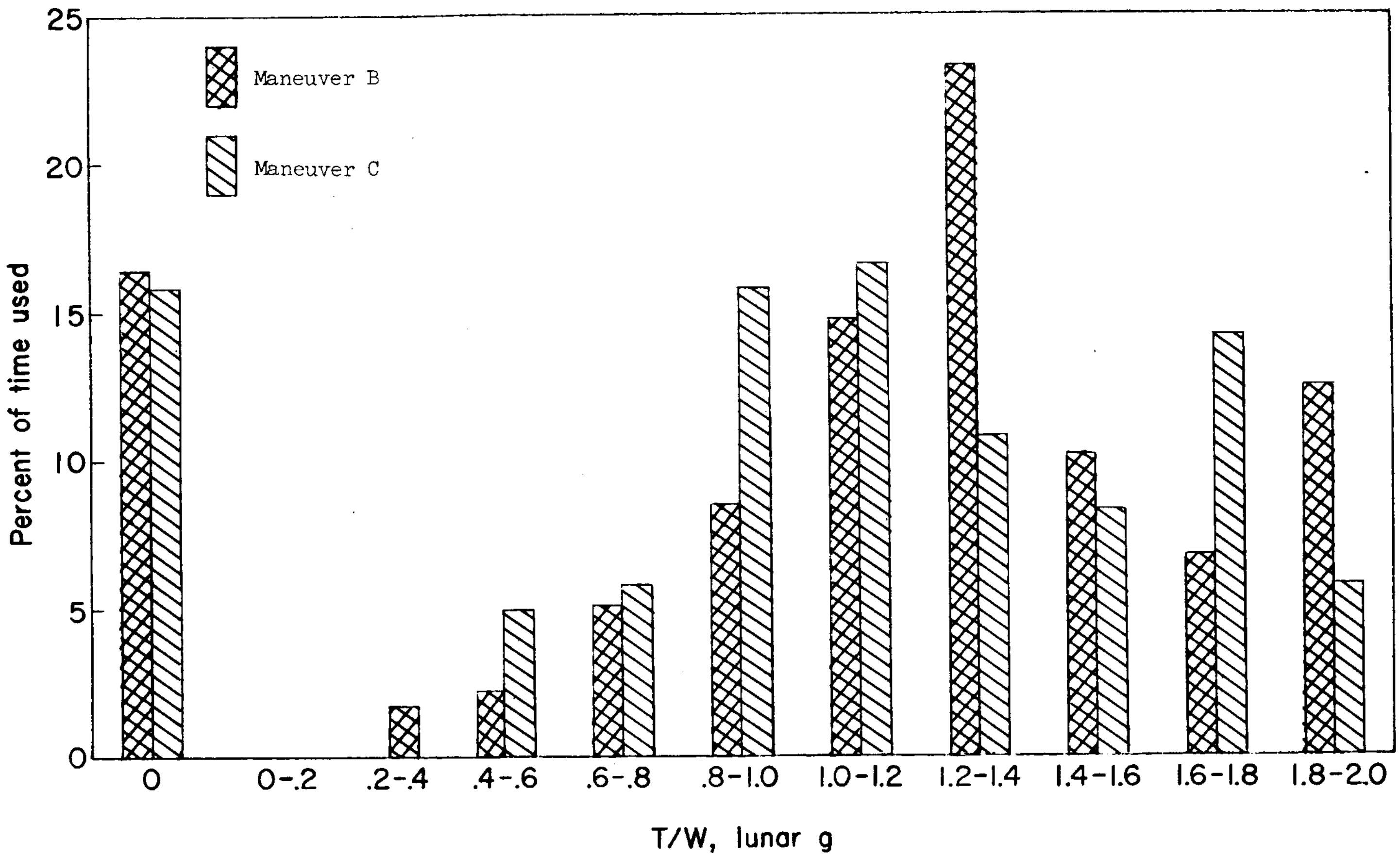


Figure 16.- Thrust control during translational maneuvers (B and C).

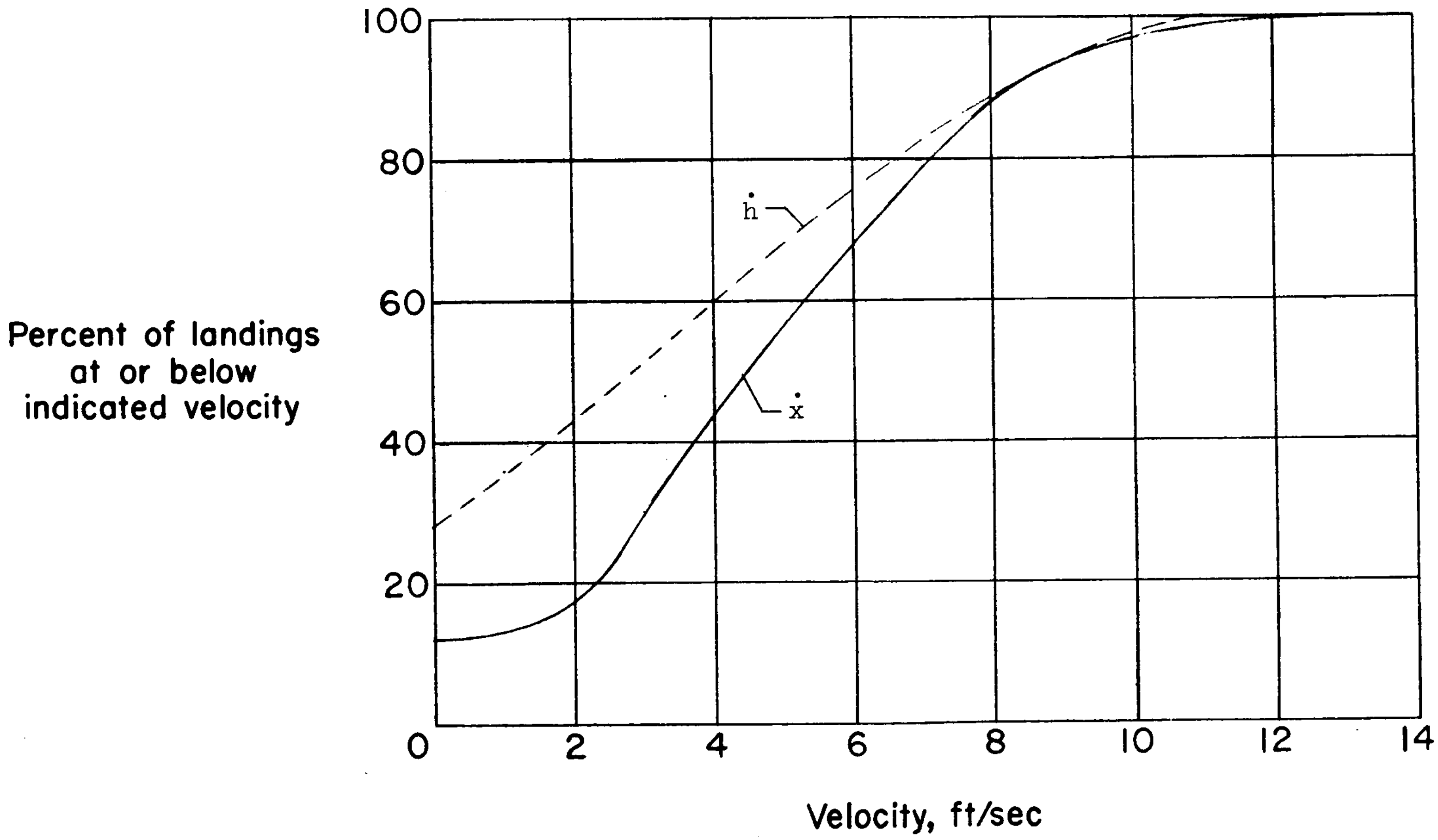


Figure 17.- Velocity at impact.

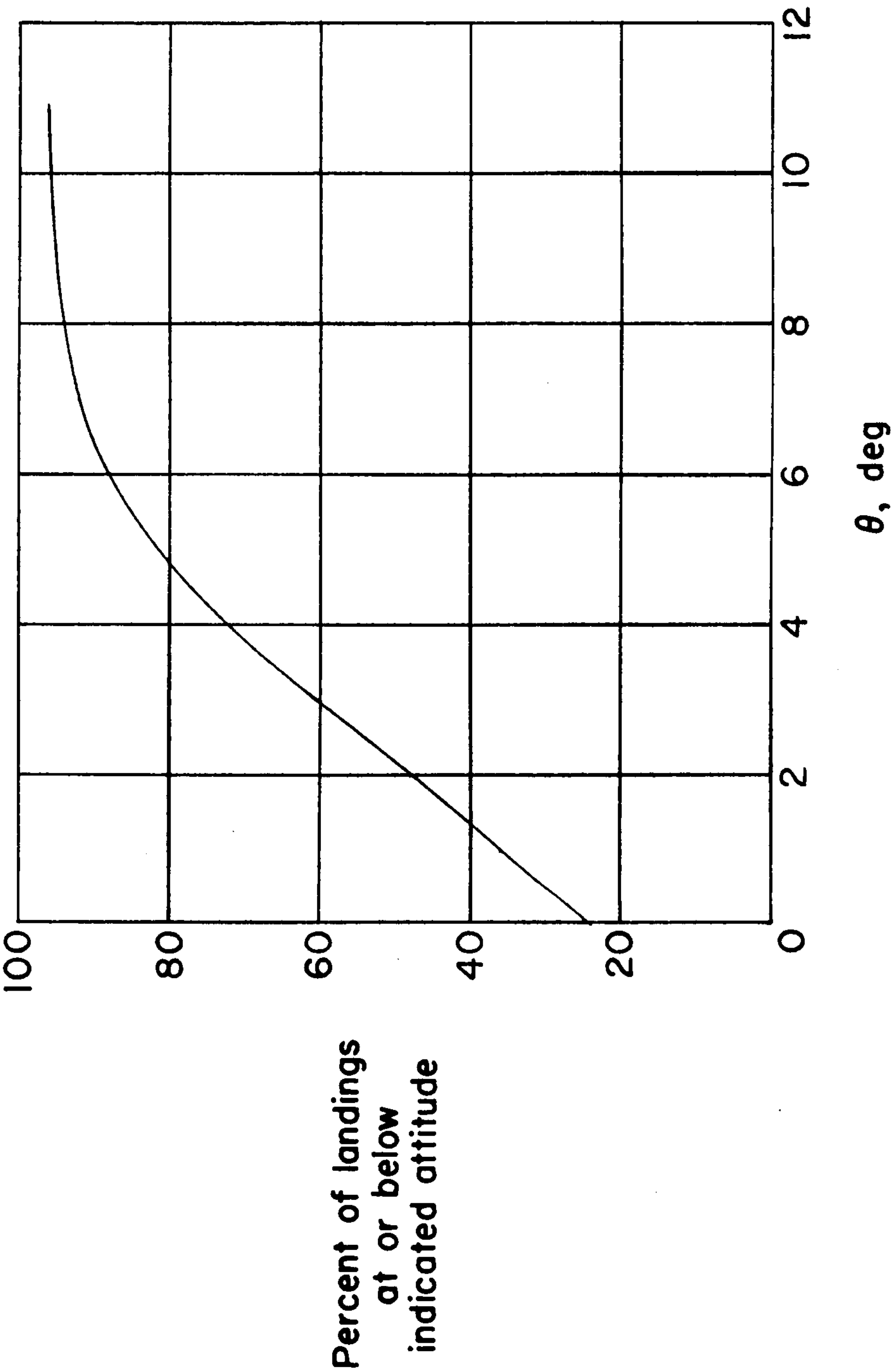


Figure 18.- Pitch attitude at impact.