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SUMMARY

The results of an investigation of the free-flight characteristics and handling qualities of an experimental manned ground-effect machine (designated GEM III) indicate that the control system was generally poor and would be unacceptable for normal operations over sustained periods of time. Any inherently good handling qualities were masked by high breakout, friction and maximum control forces, excessive control free play, lack of positive control centering, and nonlinear characteristics of the control system. The use of collective deflection of the main nozzle vanes (integrated propulsion system) for propulsion or braking reduced an otherwise acceptable yaw control to an unacceptable level. The maximum forward acceleration was 0.044g when operating with the integrated propulsion system and 0.100g when the separate propulsion engine was added. Pilots' opinions indicated that the longitudinal acceleration of 0.1g was about the minimum acceptable value. The maximum rate of deceleration or braking was 0.055g which was about half of the minimum considered to be acceptable.

Gem III had positive longitudinal and lateral static stability during hovering. The longitudinal and lateral damping were essentially deadbeat and there were no tendencies toward sustained longitudinal or lateral oscillations during hovering except during attempts to dock the vehicle when the inadequate lateral control and the time lag in the vehicle response to control movement caused the pilot to develop inadvertent oscillations. Directional stability increased with speed and no directional stability difficulties were encountered up to the maximum velocity obtained, 47 feet per second (14.3 meters per second). Operation in winds above 5 knots (2.57 meters per second) was unsatisfactory because of the weak lateral control.

In general, GEM III did not appear to be suitable for operations over water. Pitch and roll control effectiveness, longitudinal and lateral accelerations, maneuverability, and forward speed with the integrated propulsion system were greatly reduced when compared with the operation over land. When the separate propulsion engine was operating at full power, the forward accelerations and velocity were comparable to those obtained over land. Spray was heavy during hovering; however, visibility was satisfactory at forward speeds above 2 knots (1 meter per second).

INTRODUCTION

For several years the National Aeronautics and Space Administration has been involved in the investigation of handling qualities for helicopters and airplanes including V/STOL aircraft. With the advent of the ground-effect machine (GEM), it appeared desirable to extend the investigations to include this type of vehicle. An investigation was undertaken with an experimental manned ground-effect machine (designated GEM III) constructed for the Marine Corps and made available to NASA through the Office of Naval Research, U.S. Navy. Results of tethered tests of this vehicle are presented in reference 1. After these tests, the control system was modified because the original dump-valve pitch and roll control system was found to be ineffective. Additional tethered tests and some low-speed free-flight tests were made of the modified vehicle and the results were published in reference 2. As reported in reference 2, the maximum velocity in a straight course was 27.4 feet per second (8.35 meters per second). A higher forward speed was desirable for an investigation of the handling qualities and a separate thrust propulsion unit was installed prior to the present investigation.

Pilot opinion included in this report represents the combined opinions of three experienced NASA pilots.

SYMBOLS

a_{avg} average linear acceleration, ft/sec^2 (meters/sec^2)

$-a_{avg}$ average linear deceleration, ft/sec^2 (meters/sec^2)

a_{max} maximum linear acceleration, ft/sec^2 (meters/sec^2)

$-a_{max}$ maximum linear deceleration, ft/sec^2 (meters/sec^2)

b width of base measured to outer edge of nozzle, ft (meters)

c length of base measured to outer edge of nozzle, ft (meters)

d_e equivalent diameter of base area measured to outer edge of nozzle, 13.82 ft (4.21 meters)

g acceleration due to gravity, ft/sec^2 (meters/sec^2)

h	height above surface measured at center of base to plane containing lower edges of nozzle, ft (meters)
h_1	height of lower edge of the nozzle above surface measured at rear of vehicle, ft (meters)
h_2	height of lower edge of nozzle above surface measured at left side of vehicle, ft (meters)
h_3	height of lower edge of nozzle above surface measured at right side of vehicle, ft (meters)
L	total lift or gross weight, lb (newtons)
M_X	rolling moment, ft-lb (meter-newtons)
M_Y	pitching moment, ft-lb (meter-newtons)
V_{max}	maximum velocity, ft/sec (meters/sec)
β_v	vane deflection, deg
θ	angle of pitch, deg
ϕ	angle of roll, deg

APPARATUS AND PROCEDURE

Vehicle Description

The general arrangement and principal dimensions of GEM III are given in figure 1. GEM III is a peripheral-jet air-cushion vehicle which has an integrated lifting and propulsion system. Air for the peripheral jet is taken on board through two forward-facing nacelle units. Additional forward thrust was obtained from a ducted propeller installed between the two nacelles. Detailed descriptions of the vehicle are presented in references 1 and 2.

Several modifications were made to the vehicle after receipt at the Langley Research Center. An additional plate was installed between the existing armor behind the cockpit as shown in figure 2 as protection for the pilot in case of failure of the thrust propeller which was located directly behind the cockpit.

The two ducted fans were standard ventilating fans rated for operation at 1750 revolutions per minute and had 12 cast aluminum blades. Inasmuch as the test program required operation consistently at 100-percent power and 2020 revolutions per minute, the cast aluminum blades were replaced as a safety precaution. Replacement blades were molded from glass fiber and plastic with a balsa wood core.

The four-blade reversible-pitch propeller supplied with the vehicle for the propulsion unit was found to be unsatisfactory and could not be used for the anticipated high-speed tests. Late in the test program, a two-blade two-position hydraulically operated propeller was obtained from the U.S. Navy and modified to operate with the gas turbine engine. This propeller was capable of forward thrust only and could not be reversed for braking. Although the propeller and the engine were poorly matched, the propeller did permit operation of the vehicle at forward speeds considerably greater than those obtainable with the integrated propulsion system.

Control System

Pitch and roll control were available to the pilot through an aircraft type of control stick mechanically connected by cables to a system of spoiler flaps located in the main nozzles of the peripheral jet below the variable-camber vanes. Movement of the control stick closed the appropriate spoiler section which restricted the airflow in that section of the nozzle, produced a shift in the center of lift, and in turn, produced the control moment. Pitch- and roll-attitude changes inclined the lift vector from the vertical to produce longitudinal and lateral thrust. A collective type of control (similar to those found on helicopters) moved the variable-camber vanes collectively for additional propulsive and braking thrust. Yaw control was available through aircraft-type rudder pedals differentially linked to the variable-camber vanes through a cable system. An interaction between the differential and collective movement of the variable-camber vanes restricted the yawing control when collective control was used for propulsion or braking. Throttles were provided for each of the three engines and a control trim system was installed on the spoiler flaps.

Instrumentation

Instrumentation was provided to measure and record air and ground speeds, longitudinal and transverse accelerations, ground-yaw and sideslip angles, angular velocity in yaw, height above the ground, thrust of the propulsion engine and positions of the control stick, foot pedals, and hand lever used for deflections of the main nozzle vanes. The variables recorded and the sensors used are given in the following table:

Variable	Sensor	Location of sensor
Airspeed	Anemometer	Nose boom (fig. 2)
Ground speed	Tachometer	Rear wheel (fig. 2)
Sideslip angle	Vane	Nose boom (fig. 2)
Angular velocity in yaw	Rate gyro	Cockpit
Ground yaw angle	Control position transducer	Rear wheel (fig. 2)
Pedal position	Control position transducer	Foot pedals in cockpit
Longitudinal acceleration	Accelerometer	Cockpit
Transverse acceleration	Accelerometer	Cockpit
Lateral stick position	Control position transducer	Control stick in cockpit
Longitudinal stick position	Control position transducer	Control stick in cockpit
Variable-camber vanes	Control position transducer	Hand lever in cockpit
Aft height	Control position transducer	Rear wheel (fig. 2)
Side height	Control position transducer	Parallelograms at each side of vehicle (fig. 2)
Thrust of propulsion engine	Strain gage	Engine mount

Angle of roll was obtained from measurements of the difference in heights of the two sides of the vehicle. Angle of pitch was obtained from measurements of the difference in height at the rear of the vehicle and the average of the heights at the two sides.

Test Conditions and Procedures

In general, all tests were made at a gross weight of approximately 2500 pounds (11,120 newtons) and included the pilot, full fuel load, ballast, propulsion engine, instrumentation, and batteries for the instrumentation. Because the performance of GEM III was marginal, most tests were made at the full power setting. The average test run was of about 30 minutes duration with fuel burnoff at about 3 pounds per minute (13.3 newtons per minute) for two-engine operation and about 4.5 pounds per minute (20.0 newtons per minute) for three-engine operation. In order to keep the vehicle trimmed longitudinally, aft ballast was added at periodic intervals to compensate for the burnoff of lift engine fuel. This burnoff caused an increase in nose-down or negative pitching moment of about 12 foot-pounds per minute (16.26 newton-meters per minute) for the two-engine operation.

Most of the test program called for calm wind conditions (0 to 3 knots or 0 to 1.54 meters per second) which severely limited the amount of test time available. A few forward-speed runs were made in cross winds of from 3 to 5 knots (1.54 to 2.57 meters per second). The over-land tests were conducted over concrete ramps or runways and the over-water tests over a fresh-water reservoir. Time-history records were made during most of the test runs. In addition to the oscillograph records, the pilot's comments and opinions were obtained.

Pitching- and rolling-moment data were obtained by applying external weight moments to the vehicle. By use of the control stick, the pilot leveled the vehicle in a steady hovering condition. The control stick was then released, an oscillograph record was taken, and observations were made of the attitude and behavior of the vehicle as the stick returned to the neutral position. Damping characteristics were obtained by manual application of external longitudinal and lateral impulses to the vehicle with all controls in the neutral position. Data were also obtained by making step and pulse inputs with the controls and recording and observing the vehicle's responses.

RESULTS AND DISCUSSION

Control System Characteristics

The control system of GEM III was generally poor and would be unacceptable for normal operations over sustained periods of time. Any inherently good handling qualities were masked by high breakout, friction and maximum control forces, excessive control free play, lack of positive control centering, and nonlinear characteristics of the control system. Some of these characteristics are listed in the following table:

Control	Free play		Limit of travel				Maximum control force			
			Forward or right		Aft or left		Forward or right		Aft or left	
	in.	cm	in.	cm	in.	cm	lb	N	lb	N
Pitch	1.50	3.81	10.25	26.04	10.50	26.67	19.5	86.7	19.5	86.7
Roll	3.25	8.26	7.75	19.68	7.75	19.68	7.0	31.1	10.0	44.5

Because control powers were very low and the vehicle did not respond immediately to small control inputs, full deflection of the controls was normally required in maneuvering flight.

Rapid full deflection of the longitudinal control could be applied without difficulty; however, rapid full deflection of the lateral control caused the main side wheel to hit the ground. A slower input allowed the use of maximum lateral control without interference between the wheel and the ground. Hovering was accomplished with less than full control deflections; however, the high control forces, the low control sensitivity, and the low control power were still disagreeable to the pilot.

Collective deflection of the main nozzle vanes for propulsion or braking restricted differential vane deflection and thereby reduced an otherwise acceptable yaw-control system to an unacceptable level.

Although longitudinal and lateral trim systems were installed, these systems were virtually useless during flight because of their limited control effectiveness.

Hovering Characteristics

Static and dynamic stability.- The results of the longitudinal and lateral static stability investigations are shown in figure 3. The vehicle had positive longitudinal and lateral static stability over the small range of pitch and roll angles obtainable at the hover height of approximately 9 inches (22.86 cm). No quantitative directional-stability data were obtained. However, pilots' comments indicated that the directional stability was considered to be rather low.

Longitudinal pulse inputs were performed by moving the control stick in a fore-and-aft direction while hovering at maximum power. Typical time-history traces of the longitudinal control stick movement and the resulting oscillations in pitch are shown in figure 4. The initial pitch response occurred approximately 1 second after the initial movement of the control stick. The vehicle tended to follow the control stick input. However, the oscillation in pitch lagged the control input by about 0.4 second after the initial oscillation had been established. The maximum pitching acceleration obtained from the longitudinal stick control was 0.25 radian/sec^2. A maximum pitching velocity of 0.05 radian/sec was obtained. Pilots' comments indicated that the longitudinal damping appeared to be deadbeat and there were no tendencies toward sustained longitudinal oscillations during hovering. As shown in figure 4, the pitch oscillation damped out in less than 1 cycle and all motion in pitch was completely damped within 3 seconds after the control was released. This small short period damping would undoubtedly appear deadbeat to the pilot.

Lateral pulse inputs were performed by moving the control stick in a lateral direction while hovering at maximum power. Figure 5 shows typical time-history traces of the lateral-control stick inputs and the resulting oscillations in roll. The initial response occurred approximately 1.5 seconds after the initial movement of the control stick, which had a detrimental effect on the lateral handling qualities. As in the case of the pitch, the period of the oscillation in roll was approximately the same as the period of the control stick movement. However, the oscillation in roll lagged the control input by 1 second or more. The maximum rolling acceleration obtained from the lateral stick control was 0.69 radian/sec^2. A maximum rolling velocity of 0.24 radian/sec was obtained. As shown in figure 5, the roll oscillation damped out in less than 1 cycle and all motion in roll was completely damped within 3 seconds after the control was released. These time-history traces and the pilots' comments indicated that the lateral damping was essentially deadbeat and there were no tendencies toward sustained lateral oscillations when hovering with neutral controls. Apparently, the cross coupling of the controls was such that the pilot-induced rolling oscillations consistently induced a pitching oscillation, as indicated by the aft height trace in figure 5, although the pitching oscillation did not induce a rolling oscillation. Nevertheless, this pitching oscillation was small and was not apparent to the pilot.

Typical time-history traces of a directional control step input and the resultant effect on the yaw of the vehicle while hovering are shown in figure 6. An angular acceleration in yaw was obtained approximately 0.1 second after initiation of the control application by the pilot. The traces shown are for a clockwise rotation. In general, the response to a clockwise control application was faster than to a counterclockwise control application. Nevertheless, an angular acceleration in yaw in the proper direction never exceeded 0.2 second after initiation of control application by the pilot. The maximum angular velocity in yaw was approximately 1.2 radians/sec. With full deflection of the foot pedals, a maximum angular acceleration in yaw of 0.2 radian/sec^2 was obtained, and with full reversal of the directional control, a maximum deceleration of 0.3 radian/sec^2 was obtained. Pilots' comments indicated that the maximum angular acceleration in yaw of 0.2 radian/sec^2 and maximum angular velocity in yaw of 1.2 radians/sec was adequate for hovering and the yaw control (with neutral collective deflection of the main nozzle vanes) was acceptable. Yaw control power was substantially reduced when collective control was applied because of the interaction of collective and differential vane movement. Pilots' comments indicated that the use of full collective control restricted the yaw control to an unacceptable level. Damping in yaw was low and the pilot had to supply damping (by use of opposite rudder) in order to obtain a desired heading.

Time-history traces of the workload required of the pilot during hovering in calm air is shown in figure 7. The time-history traces of figure 7(a) were obtained from records of the first instrumented flight which followed a short period of familiarization with operation of the vehicle and its control system. These traces indicate a heavy workload for the pilot with considerable overcontrol which resulted in pitching and rolling motions. The pilot apparently soon learned that very little control was required to hover successfully in calm air as shown in figure 7(b) where the time-history traces indicate little motion of the control stick and foot pedals. A relatively steady hover is indicated by the traces of the motions in pitch and roll.

Performance.- The hovering characteristics of GEM III are shown in figure 8. Hover height is plotted against pitch angle and roll angle. The average hover height during this investigation was approximately 8.7 inches (22.1 cm). The hover height of the basic vehicle at a gross weight of 1850 pounds (8230 newtons) was obtained from reference 1 and is shown in figure 8. The hover height was 14 inches (35.6 cm) before modifications to the basic vehicle were incorporated. As reported in reference 2, modifications to the variable-camber vanes resulted in a reduction in hover height to about 13 inches (33.0 cm). The reduction in hover height to less than 9 inches (22.9 cm) appears to be largely the result of the increase in gross weight from 1850 pounds (8230 newtons) to 2500 pounds (11,120 newtons). However, the cast-aluminum fan blades were replaced with molded glass fiber blades, and although an attempt was made to set these blades at the identical angle setting of the aluminum blades, a slight difference in blade setting could cause a loss in hover height. The data of figure 8 show some scatter and it should be pointed out that these data were obtained over a period of 2 months under varying conditions of temperature and density. The scatter probably resulted from the changes in atmospheric conditions and the performance of the engines.

The slope-climbing ability of GEM III was not determined quantitatively. However, the maximum lateral acceleration was determined to be 0.047g. Based on this acceleration, the steepest slope that the vehicle could climb while hovering would be a 5-percent grade at the present gross weight.

Maneuverability.- Several tasks were assigned in order to determine the maneuverability of the vehicle. A square having sides equal to two vehicle lengths was laid out and the pilot requested to maneuver around the square by holding a constant heading and by changing the heading to head always in a forward direction. The records of these two maneuvers indicated about the same workload for the pilot in each case. Although the time to perform the maneuver was not specified, the average velocity when holding a constant heading was 1.5 feet per second (0.46 meter per second). Changing direction at each corner of the square increased the time to complete the maneuver by 40 percent. Three obstacles were set up at 50-foot (15.24 meter) intervals and the pilot performed a slalom between the obstacles. The average time to complete the 200-foot (60.96 meter) course was 72 seconds with an average velocity of 2.8 feet per second (0.85 meter/sec). No difficulty was encountered by the pilot, but the inadequate control power made precise control impossible.

Simulated docks were set up 100 feet (30.48 meters) apart and forward and side docking maneuvers were performed. The docking maneuvers were performed with little difficulty. In most instances the pilot could maneuver into the forward dock or against the side dock without disturbing the stanchions which were used to simulate the dock.

Because of the inadequate lateral control and the time lag in the vehicle response to control movement, the pilot tended to develop inadvertent oscillations very easily when maneuvering the vehicle into the dock.

In summary, pilots' opinions indicate that in calm air and over level terrain, it is possible to maneuver to almost any desired position, although at a rather low but acceptable rate, with little or no difficulty.

Forward-Speed Characteristics

Static and dynamic stability.- Pilots' comments indicated that at forward speeds the vehicle appeared to be more stable in pitch and roll than while hovering, and at forward speeds the damping characteristics appeared to be the same as when hovering.

No quantitative directional-stability data were obtained. However, pilots' comments indicated that directional stability, although considered to be low at low speeds, nevertheless increased with forward speed and no directional-stability difficulties were encountered up to the forward speed investigated (47 feet per second (14.3 meters per second)).

Performance.- When operating GEM III with the two lift engines only (integrated system), longitudinal acceleration may be obtained by collective deflection of the variable-camber vanes or by longitudinal movement of the control stick or by a combination of control stick and collective deflection. Accelerations, decelerations, and velocities, obtained by the three methods in forward and reverse motion,are given in table I.

TABLE I.- EFFECT OF METHOD OF CONTROL ON ACCELERATION AND MAXIMUM VELOCITY OF GEM III WITH INTEGRATED PROPULSION SYSTEM

Control	a_{max}		a_{avg}		$-a_{max}$		$-a_{avg}$		V_{max}	
	ft/sec^2	m/sec^2	ft/sec^2	m/sec^2	ft/sec^2	m/sec^2	ft/sec^2	m/sec^2	ft/sec	m/sec
Forward										
Collective only	0.75	0.23	0.55	0.17	0.79	0.24	0.74	0.23	7.70	2.35
	.53	.16	.31	.09	.92	.28	.23	.07	4.62	1.41
	.70	.21	.53	.16	.77	.23	.59	.18	4.76	1.45
Stick only	0.98	0.30	0.96	0.29	0.77	0.23	0.70	0.21	7.70	2.35
	1.05	.32	.87	.27	1.33	.41	.82	.25	7.84	2.39
	.98	.30	.87	.27	1.33	.41	.97	.30	8.68	2.65
Collective plus stick	1.40	0.43	1.03	0.31	1.77	0.54	1.40	0.43	15.40	4.69
	1.33	.41	1.22	.37	1.68	.51	1.39	.42	17.07	5.20
	1.45	.46	1.03	.31	1.40	.43	1.07	.33	9.24	2.82
Reverse										
Collective only	0.21	0.06	0.18	0.05	---	---	---	---	2.38	0.73
Stick only	0.84	0.26	0.58	0.18	0.70	0.21	0.65	0.20	4.06	1.24
	.70	.21	.62	.19	.77	.23	.67	.20	4.34	1.32
Collective plus stick	0.80	0.24	0.62	0.19	1.26	0.38	0.93	0.29	7.42	2.26
	.84	.26	.65	.20	1.26	.38	1.02	.31	9.10	2.77

The use of collective deflection alone was the least effective method for acceleration in the reverse direction. The use of collective deflection combined with control stick resulted in a maximum forward acceleration of approximately 1.4 feet per second^2 (0.43 meter/sec^2) or 0.044g and an average acceleration of 0.037g. The maximum acceleration in reverse was about 0.8 foot per second^2 (0.24 meter/sec^2) or 0.030g with an average acceleration of less than 0.022g. The maximum rate of deceleration or braking was approximately 1.75 feet per second^2 (0.53 meter/sec^2) or 0.055g which was slightly higher than the maximum forward acceleration.

The maximum forward velocity using the two lift engines with the integrated propulsion system in a straight course on a concrete runway was 19.6 feet per second (6.0 meters per second). This maximum velocity was 28.5 percent less than the maximum velocity of 27.4 feet per second (8.35 meters per second) reported in reference 2. The maximum velocity of 27.4 feet per second (8.35 meters per second) was obtained at the gross weight of 1850 pounds (8230 newtons) prior to installation of the propulsion engine and its fairings.

The center or propulsion engine provided approximately 55 pounds (245 newtons) of thrust with the propeller in low pitch at engine idle speed and 170 pounds (756 newtons) of thrust with the engine in high pitch at 100 percent fan speed. The maximum longitudinal acceleration with the propulsion engine (collective deflection and control stick neutral) was approximately 2.3 feet per second^2 (0.70 meter/sec^2) or 0.071g. The maximum acceleration obtained from the combination of the propulsion engine, forward control stick, and collective deflection of the vanes was approximately 0.1g. The use of the forward control stick resulted in a nose-down attitude which the pilots considered undesirable during acceleration and forward-speed runs. Pilots' opinions indicated that a longitudinal acceleration of 0.1g in level flight should be about the minimum acceptable value. Pilots' comments indicated, therefore, that the longitudinal acceleration with the propulsion engine was satisfactory but without this engine the acceleration was too low and was unsatisfactory.

The maximum forward velocity using the propulsion engine along with the integrated propulsion system was 47 feet per second (14.3 meters per second) in a straight course on a concrete runway. Inasmuch as the propeller pitch could not be reversed and the propeller provided 55 pounds (245 newtons) of thrust at engine idle speed, the deceleration or available braking was even less than it was with the integrated propulsion system alone and was considered unsatisfactory by the pilots. Pilots' opinions indicated that braking should be equal to or greater than the 0.1g accelerating force.

The results of this investigation indicate the desirability of a separate propulsion system for GEM III. If the propeller had been of a proper design for the engine, the

0.1g acceleration undoubtedly could have been achieved without tilting the vehicle. Some method of thrust reversal is required for braking or deceleration of the vehicle.

The only means of obtaining lateral motion of the vehicle was by use of the control stick with the resultant tilting of the vehicle in the direction of motion. The maximum lateral acceleration was 1.5 feet per second^2 (0.46 meter/sec^2) or 0.047g. In general, acceleration to the left was slightly higher than that to the right; however, the difference was relatively small. The maximum deceleration was approximately 2.0 feet per second^2 (0.61 meter per second^2) or 0.062g. The average lateral acceleration and deceleration was approximately 1.0 foot per second^2 (0.30 meter per second^2) or 0.031g. The maximum lateral velocity was about 10 feet per second (3.05 meters per second). Pilots' comments indicated that a higher lateral velocity would be undesirable because of the possibility of the main landing wheel striking the ground and thereby producing an excessive and possibly unsafe roll attitude.

Maneuverability.- During maneuvering flight, the lag in the longitudinal and lateral acceleration and velocity response required a certain degree of "lead learning" on the part of the pilot in order to control his ground position with any degree of accuracy. The lateral stability appeared to be particularly weak during low-speed maneuvering when large control deflections were required.

Effect of cross winds.- Pilots' opinions indicated that it was undesirable to operate the vehicle in winds above 3 knots (1.54 meters per second) largely because of the weak lateral control. It was indicated further that the vehicle cannot be hovered satisfactorily in cross winds greater than 5 knots (2.57 meters per second) for the same reason. The tests, therefore, were very limited under windy conditions. During high-speed runs with a fairly light wind of 3 knots (1.54 meters per second) at an angle of 45° to the runway, the pilot noted a very large difference in the upwind and downwind maximum speeds as well as in the handling qualities of the vehicle. The pilot reported that it was much easier to control the vehicle on the downwind run, whereas heading into the wind on the upwind runs makes the vehicle very difficult to handle. The lateral control appeared to be ineffective for translation at forward speeds when used as forward slip and the pilot found the vehicle to be more controllable and more easily handled when crabbing into the wind.

Over-Water Characteristics

Photographs of GEM III being lowered to the beach of the reservoir, at rest on the water, hovering, and at forward speeds are shown in figure 9. In general, the results of the over-water investigation are qualitative, inasmuch as the instrumentation provided only a very limited amount of quantitative data. Most of the over-water characteristics were determined from pilots' comments, motion pictures, and observations from the shore.

Static and dynamic stability.- Some unstable pilot-vehicle longitudinal oscillations were encountered at times (at low forward speeds or when operating with the two lift engines only) which the pilot found difficult to damp. At high forward speeds, pilot-controlled pitching oscillations were induced but were easily damped by the pilot.

Some unstable lateral oscillations were encountered when hovering. However, the vehicle appeared to be laterally stable at high forward speeds.

At high forward speeds, the static directional stability appeared to be equivalent to that obtained over land and pilots' opinions indicated no directional stability difficulties were encountered during the high-speed runs over water.

Performance.- When operating over water with only the two lift engines (integrated propulsion system), the maximum longitudinal acceleration was approximately one-third of that obtained over land apparently because of the large reduction in longitudinal stick control effectiveness. The lateral acceleration was greatly reduced also. The maximum forward velocity using the two lift engines with the integrated propulsion system was about 5 knots (2.6 meters per second).

Longitudinal acceleration over water using the third or propulsion engine appeared to be comparable to that over land. The maximum forward speed appeared to be comparable to that obtained over the concrete runway and was estimated to be about 25 knots (13 meters per second). The need for a separate propulsion system was even more apparent for over-water operations than for over-land operation.

Maneuverability.- Pilots' comments indicated that the pitch and roll control effectiveness in maneuvering were greatly reduced when operating over water as compared with operating over land during hovering and at low speeds, whereas the effectiveness of the yaw and propulsion control from the collective deflection of the variable camber vanes located in the main nozzle appeared to be about the same when maneuvering over water and over land. The base pressure of the vehicle was about 16.7 pounds per square foot (798 newtons/meter^2) which resulted in a depression of the water surface under the vehicle of about 3.2 inches (8.1 cm). Therefore, the hover height relative to the free water surface was greatly reduced when compared with over-land operation and thus the angles of pitch and roll obtainable were relatively small. When operating with only the two lift engines, precise maneuvering in calm air was difficult and in a slight breeze became almost impossible. When operating with the propulsion engine, maneuvering was greatly improved. At high forward speeds when using the separate propulsion system, the vehicle appeared to be more controllable over water than over land and the pilots reportedly felt more at ease.

Spray characteristics.- During hovering operations over water, the spray was very heavy with considerable wetting of the complete vehicle, including the pilot, cockpit, instruments, controls, and engines. In addition, there appeared to be some water ingestion by the engines. The spray reduced the pilot's visibility to zero during hovering as shown in figure 9. However, forward visibility was satisfactory at forward speeds above 2 knots (1 meter per second). At high forward speeds, much of the spray was left behind the vehicle and no difficulty as a result of spray was experienced by the pilot.

Horizontal spray rails 6 inches (15 cm) wide were installed around the periphery of the vehicle about 7.5 inches (19 cm) above the base plate of the vehicle. These spray rails had no appreciable effect on the spray during hovering. The spray rails apparently increased the lateral instability and caused large angles of roll. The weak controls of the vehicle apparently prevented the pilot from gaining sufficient control to obtain any forward motion and further tests with the spray rails were discontinued.

In summary, Gem III did not appear to be suitable for over-water operation. The excessive water ingestion and the general wetting of the engines and fuel controls from spray appeared to cause a reduction in the output of the engines. After a short period of operation on the water, the power of the separate propulsion engine was reduced to the point where the propeller could not reach sufficient speed to go into high pitch and develop the required thrust for the high-forward-speed operation. Operation over water required excessive maintenance for the engines in their present installation. In the limited time that was available for testing GEM III over water, a satisfactory method of operation could not be developed.

CONCLUDING REMARKS

The results of an investigation of the free-flight characteristics and handling qualities of GEM III indicate that the control system was generally poor and would be unacceptable for normal operations over sustained periods of time. Any inherently good handling qualities were masked by high breakout, friction and maximum control forces, excessive control free play, lack of positive control centering, and nonlinear characteristics of the control system. The use of collective deflection of the main nozzle vanes (integrated propulsion system) for propulsion or braking reduced an otherwise acceptable yaw control to an unacceptable level. The maximum forward acceleration was 0.044g when operating with the integrated propulsion system and 0.100g when the separate propulsion engine was added. Pilots' opinions indicated that the longitudinal acceleration of 0.1g was about the minimum acceptable value. The maximum rate of deceleration or braking was 0.055g which was about half of the minimum considered to be acceptable.

GEM III had positive longitudinal and lateral static stability during hovering. The longitudinal and lateral damping were essentially deadbeat and there were no tendencies toward sustained longitudinal or lateral oscillations during hovering except during attempts to dock the vehicle when the inadequate lateral control and the time lag in the vehicle response to control movement caused the pilot to develop inadvertent oscillations very easily. Directional stability increased with speed and no directional stability difficulties were encountered up to the maximum velocity obtained of 47 feet per second (14.3 meters per second). Operation in winds above 5 knots (2.57 meters per second) was unsatisfactory because of the weak lateral control.

In general, GEM III did not appear to be suitable for over-water operations. Pitch and roll control effectiveness, longitudinal and lateral accelerations, maneuverability, and forward speed with the integrated propulsion system were greatly reduced when compared with the operation over land. When the separate propulsion engine was operating at full power, the forward accelerations and velocity were comparable to those obtained over land. Spray was heavy during hovering; however, visibility was satisfactory at forward speeds above 2 knots (1 meter per second).

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., November 4, 1966,
721-01-00-08-23.

REFERENCES

1. Johnson, Arthur E.; and Chaplin, Harvey R.: Results of GEM III Tethered Tests. Rept. 1546, Aero Rept. 1012, David W. Taylor Model Basin, Navy Dept., Aug. 1961.

2. Johnson, Arthur E.: Phase II Tethered Tests and Low-Speed Free Flight Tests of GEM III. Rept. 1700, Aero Rept. 1049, David W. Taylor Model Basin, Navy Dept., Dec. 1962.

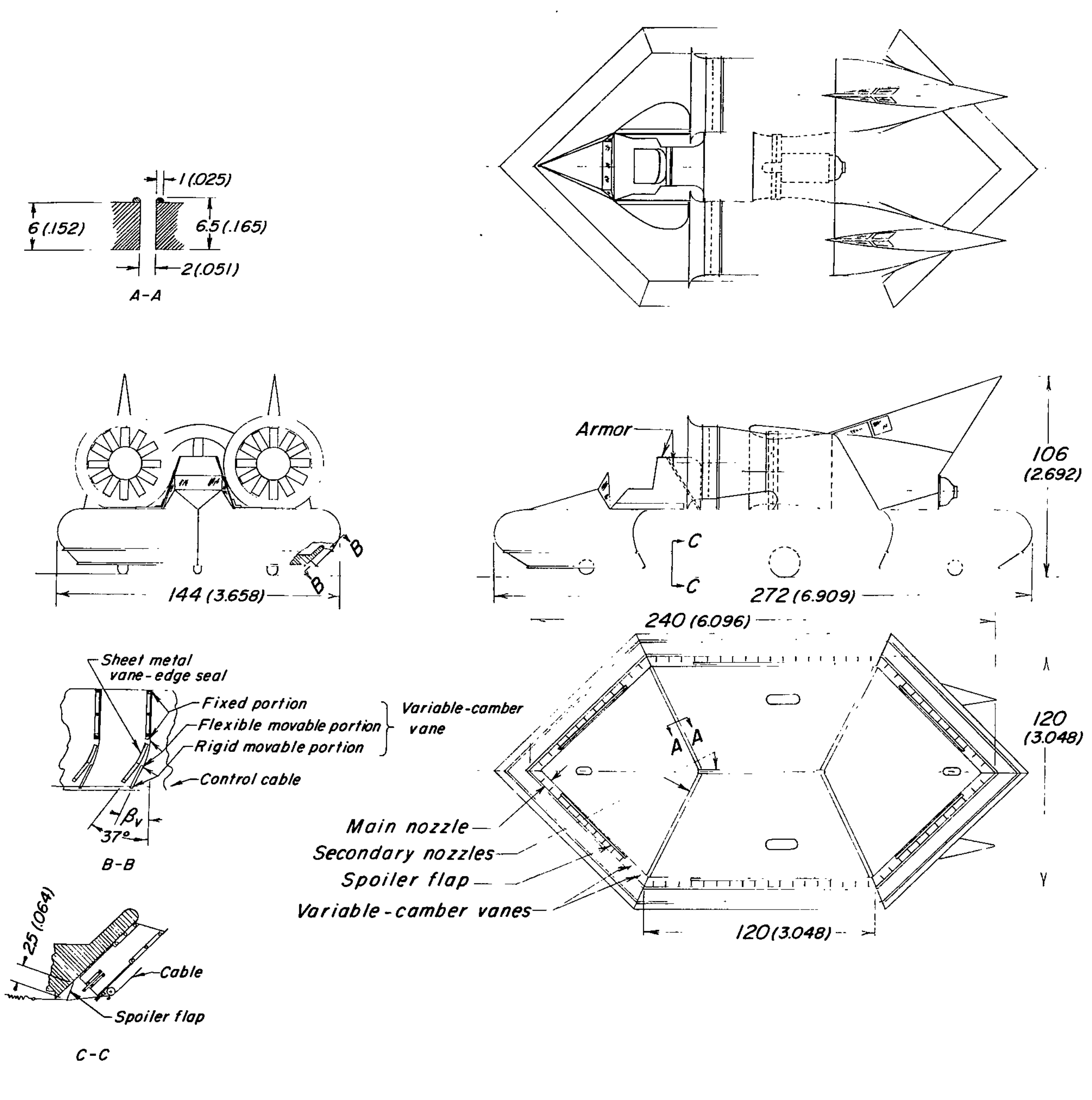


Figure 1.- Principal dimensions and general arrangement of GEM III. Dimensions are given first in inches and parenthetically in meters.

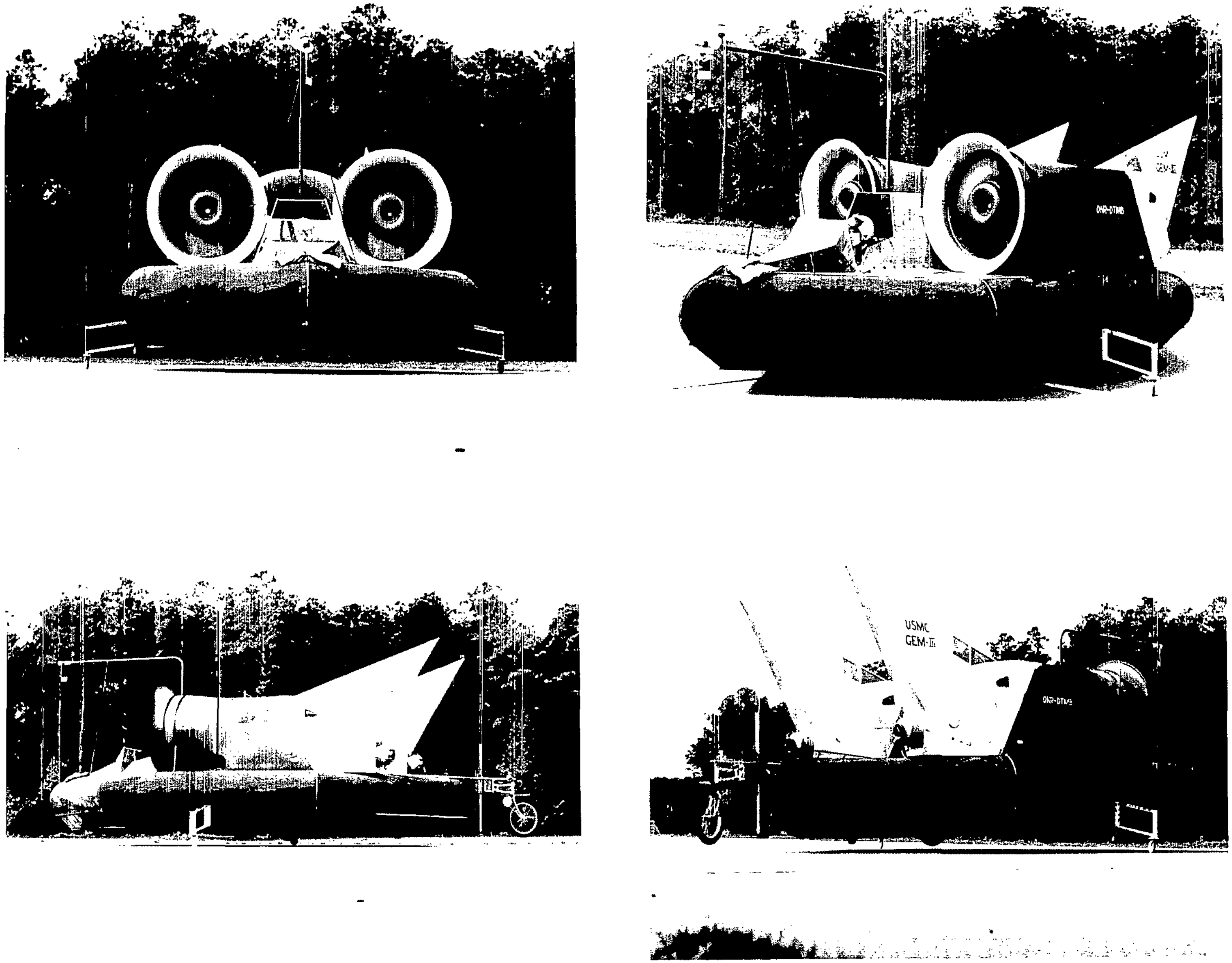


Figure 2.- Photographs of GEM III during hovering operations over land. L-66-7629

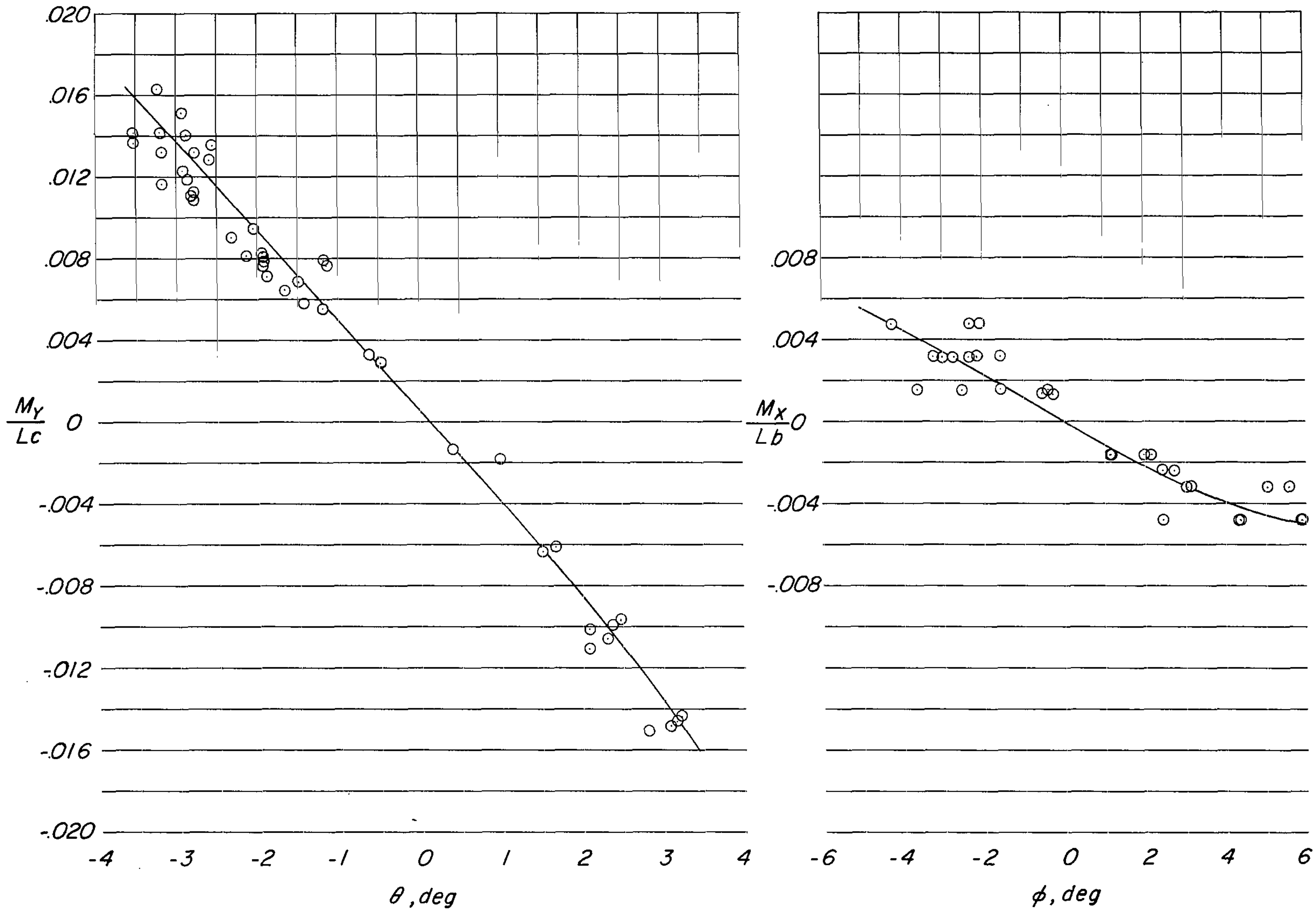


Figure 3.- Longitudinal and lateral stability characteristics of GEM III.

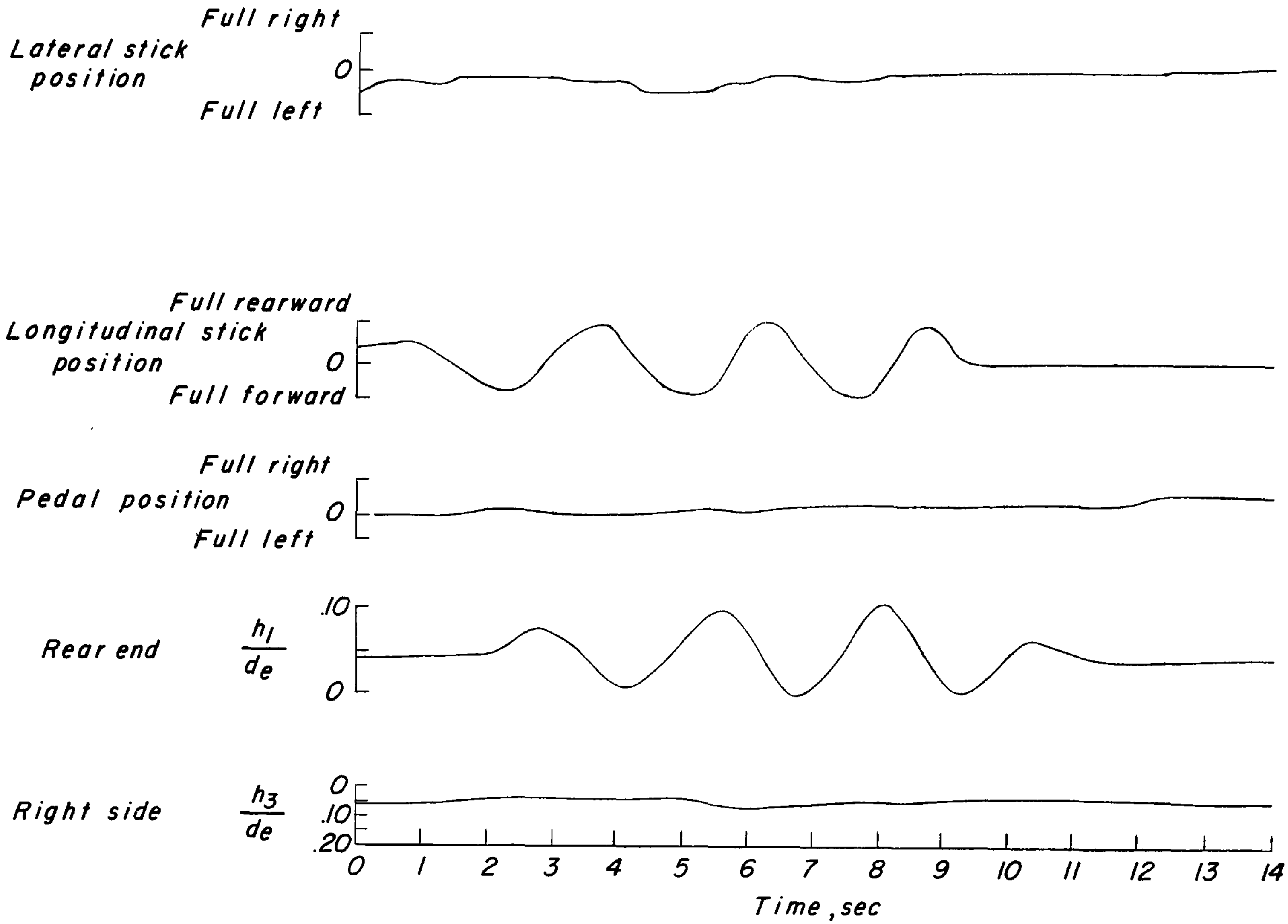


Figure 4.- Time-history traces of the response of GEM III to a control-stick longitudinal pulse disturbance.

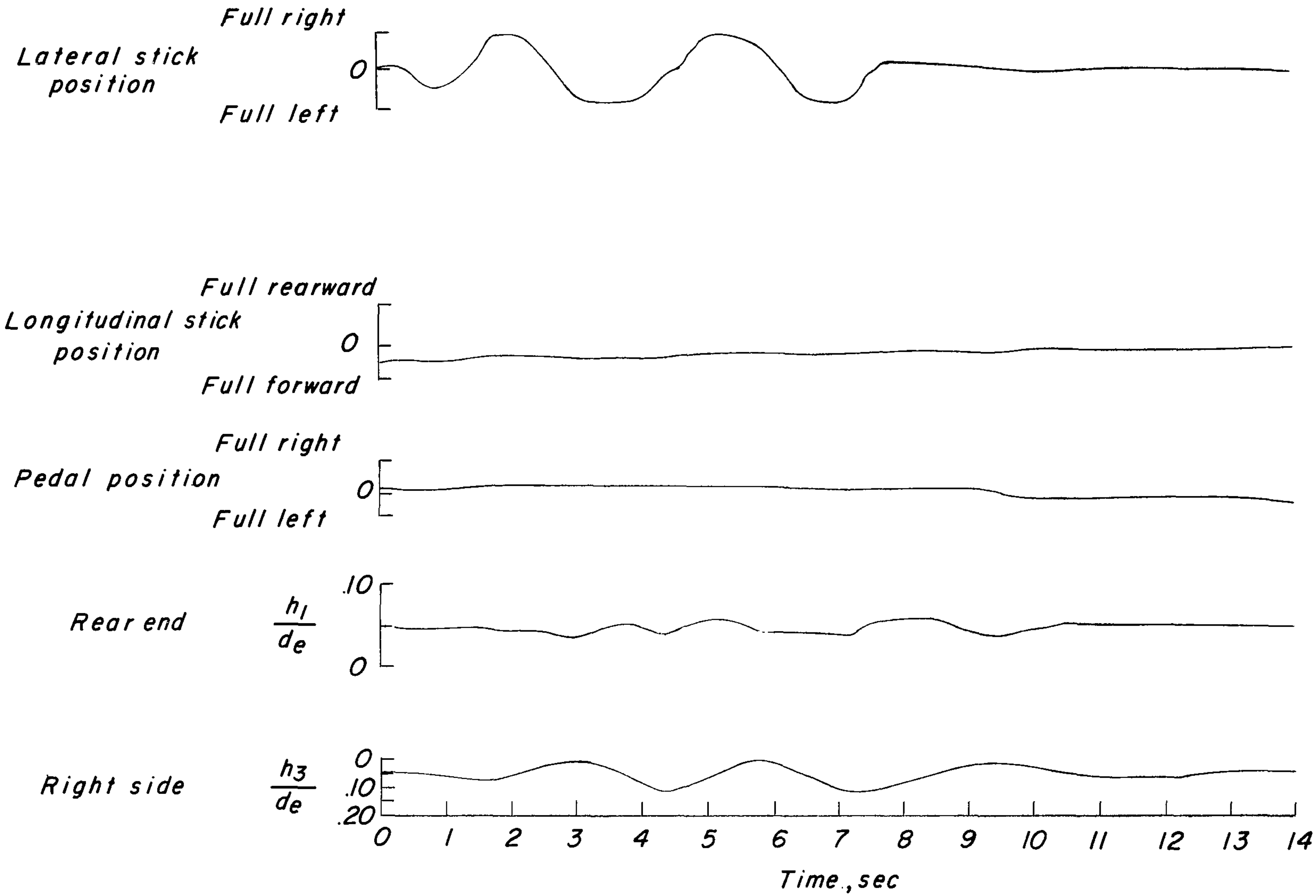


Figure 5.- Time-history traces of the response of GEM III to a control-stick lateral pulse disturbance.

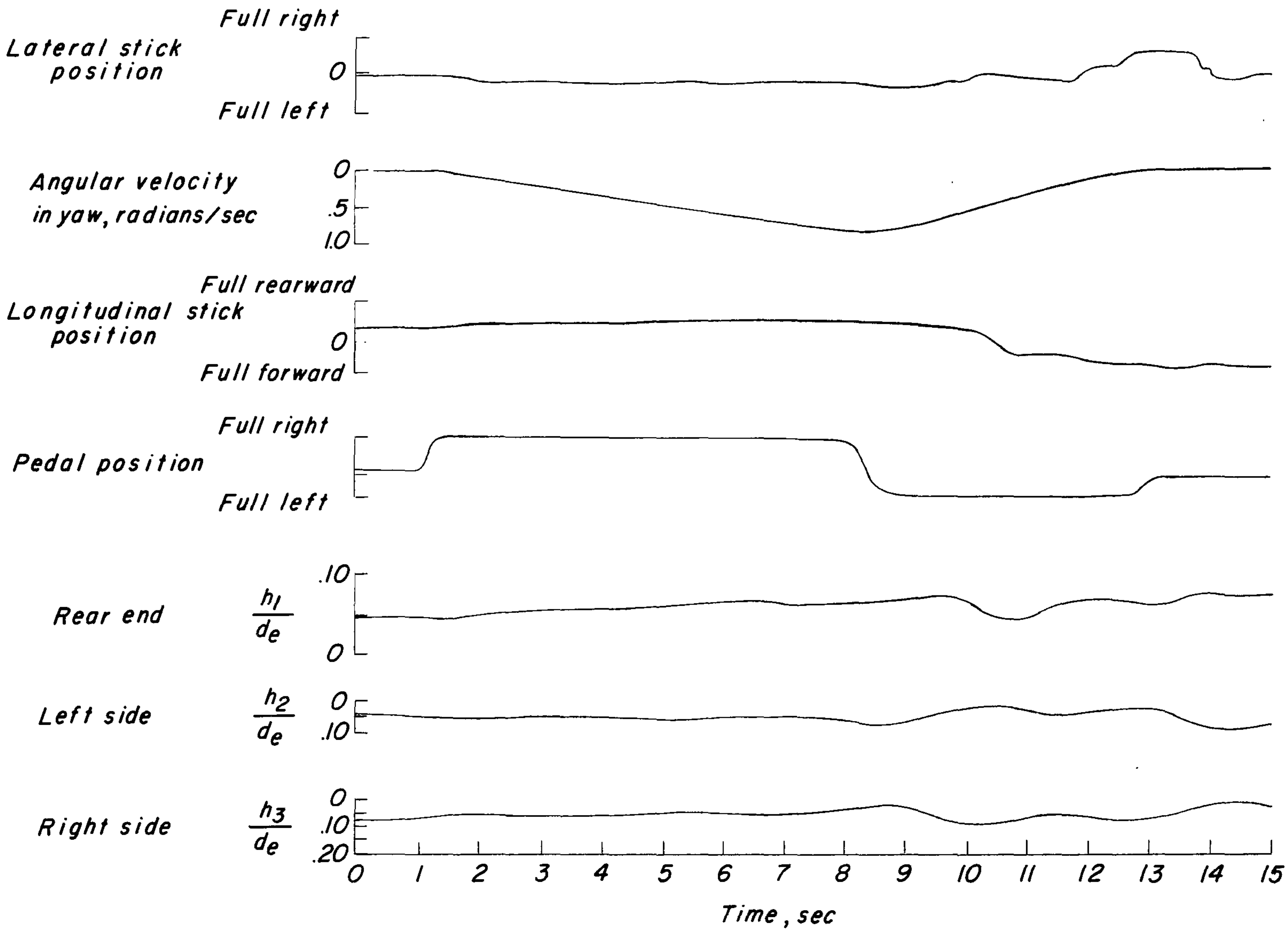
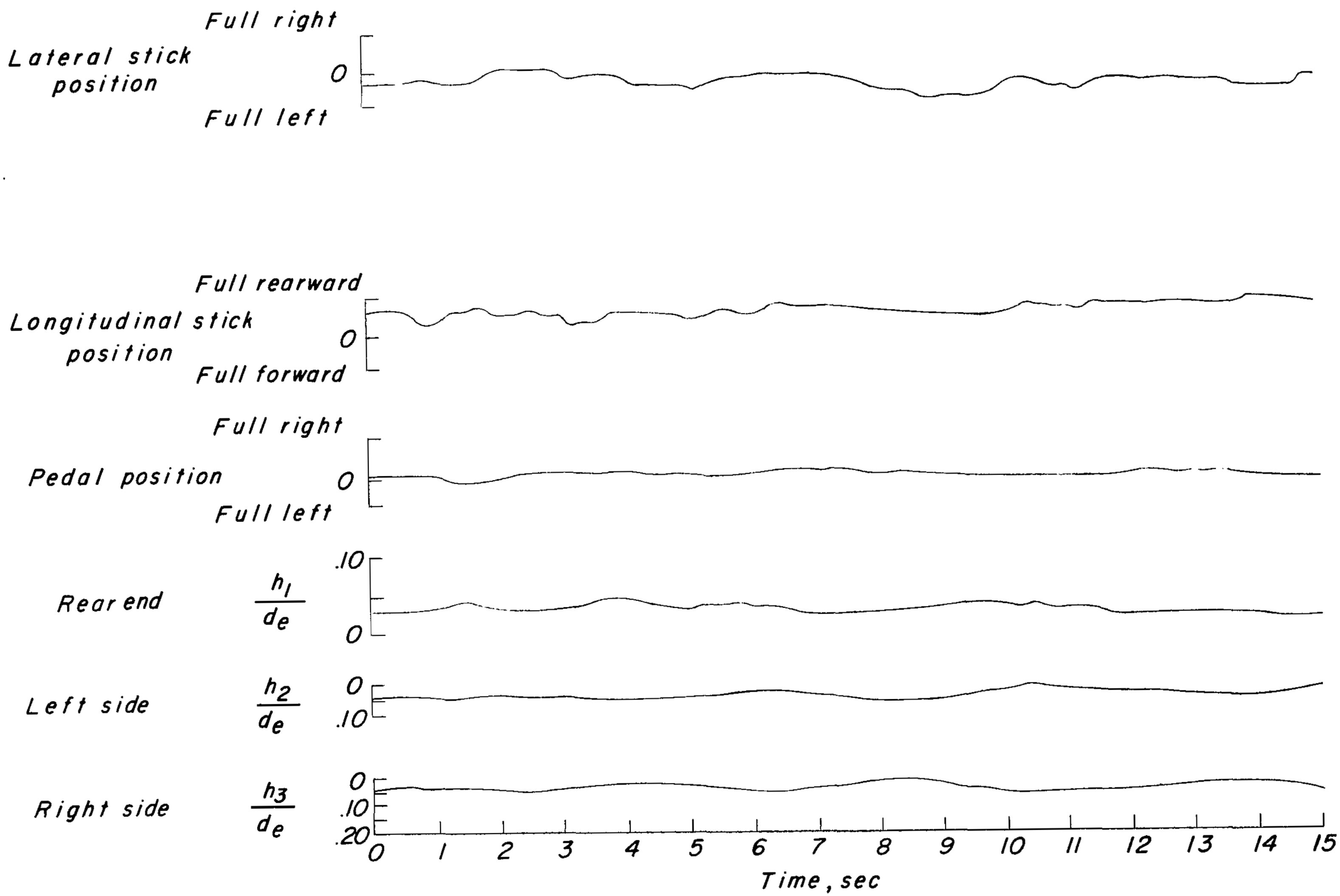
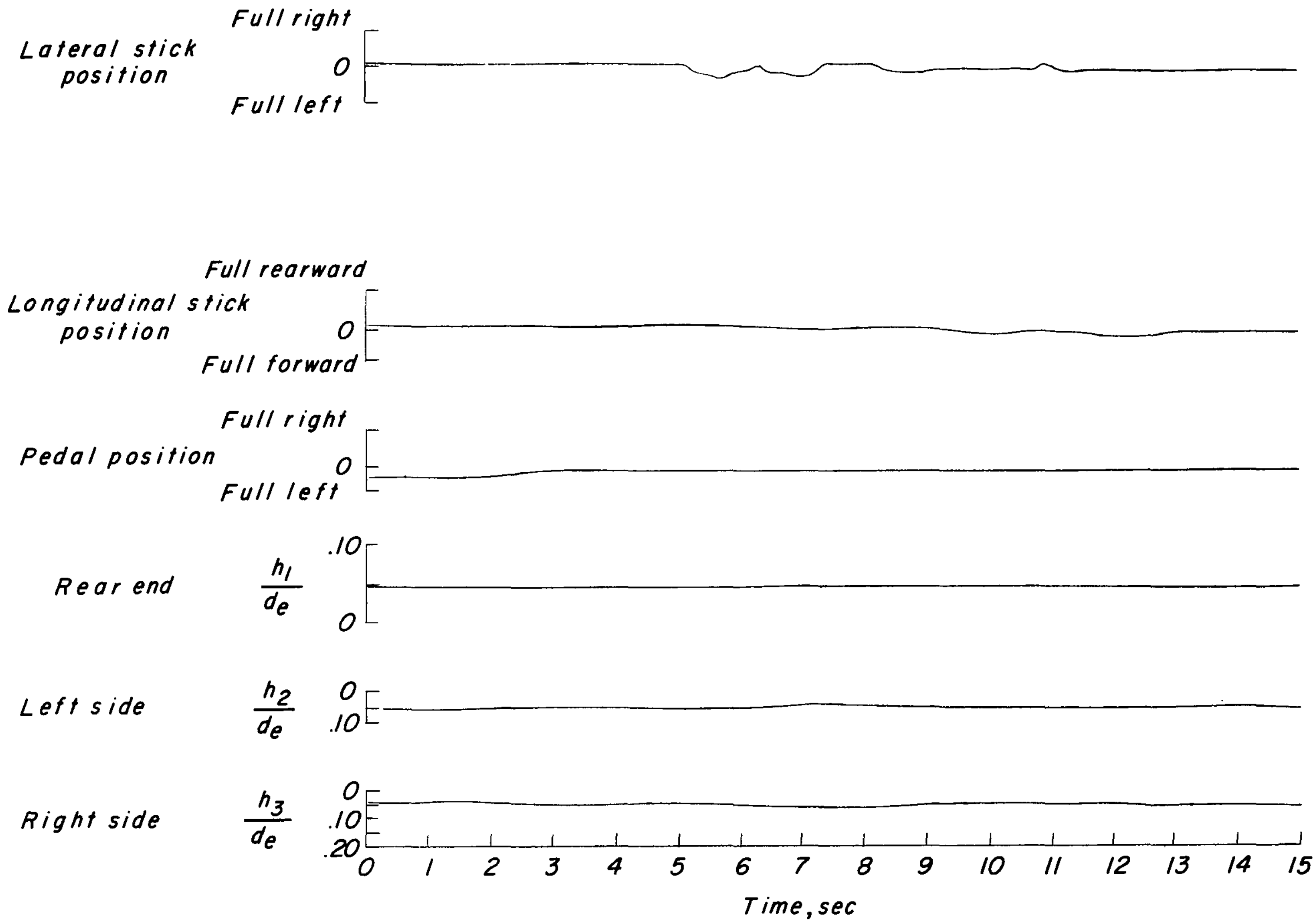


Figure 6.- Time-history traces of the response of GEM III to a directional-control step input during hovering operations.



(a) First instrumented flight.

Figure 7.- Time-history traces of control movements and vehicle motions during hovering operation of GEM III.



(b) After short period of familiarization.

Figure 7.- Concluded.

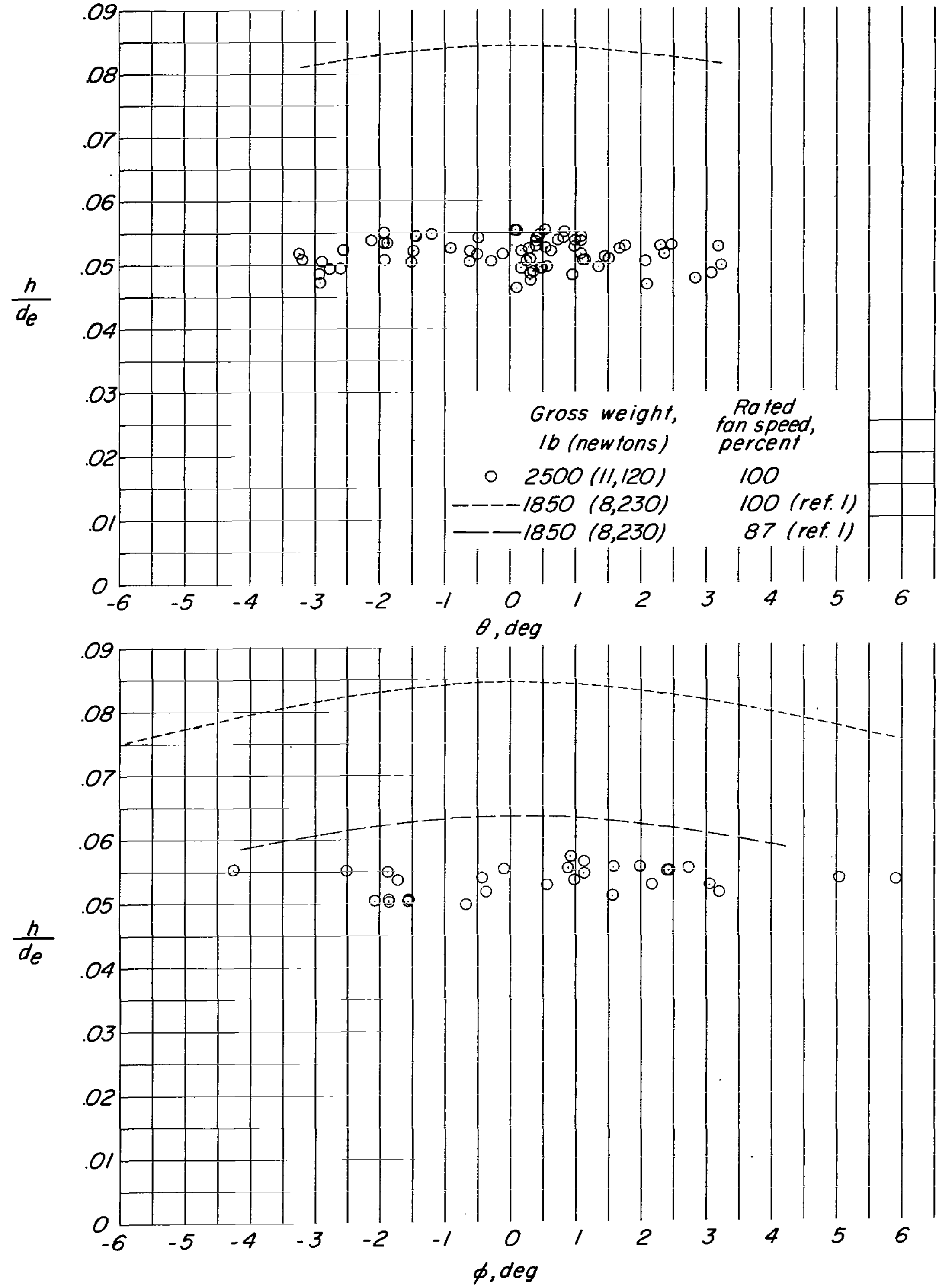


Figure 8.- Effect of pitch angle and roll angle on hover height of GEM III.

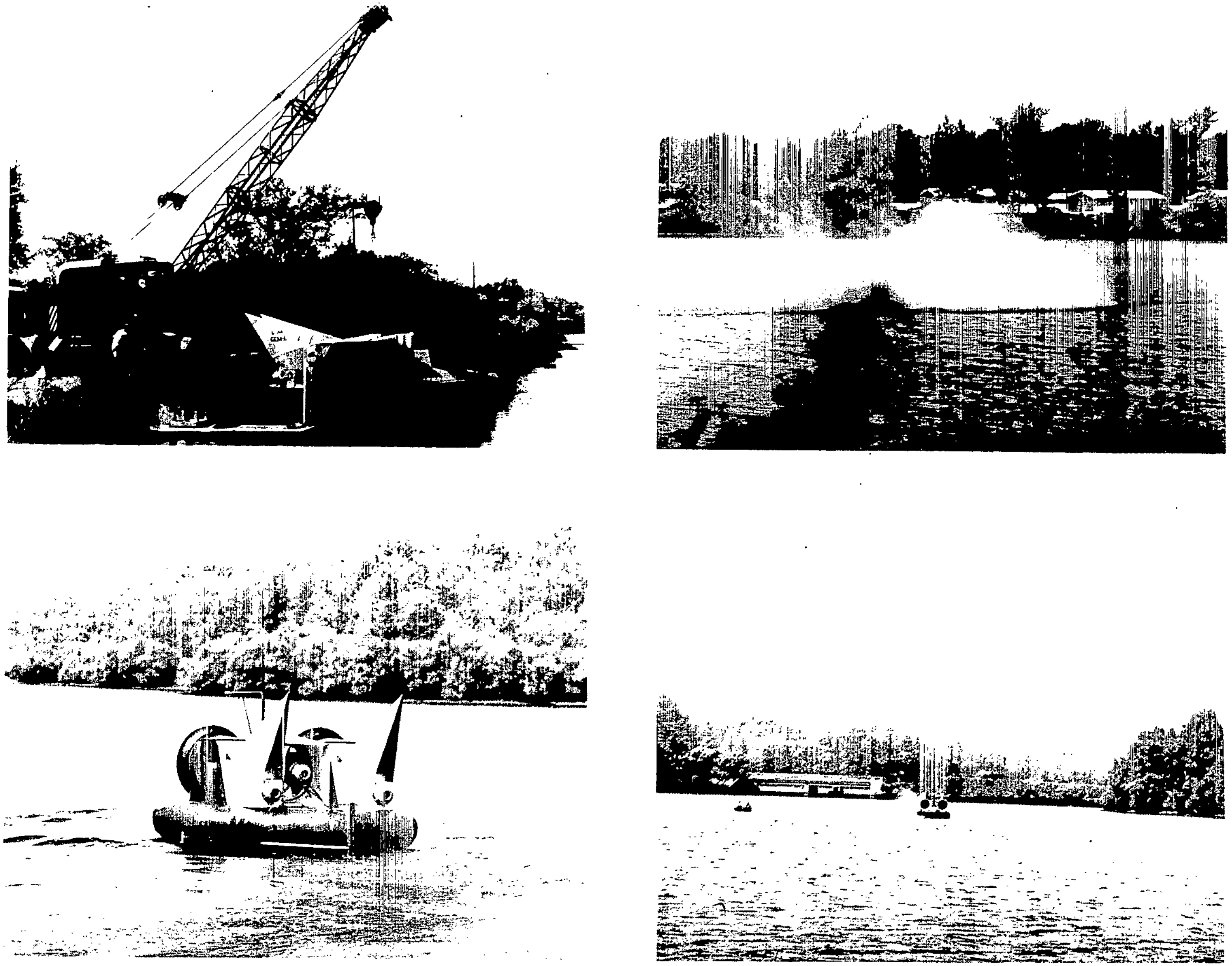


Figure 9.- Photographs of GEM III during operations over water. L-66-7630

NASA-Langley, 1967 — 2 L-4996

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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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