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DYNAMIC MODEL INVESTIGATION OF THE ROUGH-WATER LANDING CHARACTERISTICS OF A SPACECRAFT

by William C. Thompson

Langley Research Center

Langley Station, Hampton, Va.

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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DYNAMIC MODEL INVESTIGATION OF THE ROUGH-WATER LANDING CHARACTERISTICS OF A SPACECRAFT

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SUMMARY

The investigation was made to study the rough-water landing characteristics of a Gemini type of spacecraft. The investigations were made with a 1/6-scale dynamic model in a simulated sea state 4 rough water. Parachute letdown landings were simulated with the model at various yaw angles and horizontal velocities. The vertical velocity and landing attitude remained constant.

The range of maximum lateral and longitudinal acceleration was from about $3\frac{1}{2}$g to 16g while that for the maximum normal acceleration was from 1g to 15g. The range of maximum angular acceleration was from about 0 to 190 radians per second^2. The smoothest behavior and the lowest angular acceleration occurred at the 90° yaw angle. The normal acceleration was near minimum at this condition.

INTRODUCTION

The primary mode of landing for the Gemini spacecraft is on water (open sea) using a parachute letdown. Previous investigations of a Gemini type of spacecraft (ref. 1) included a limited number of parachute type of landings with the spacecraft directionally oriented at 0° and 180° yaw. The landings were made in both smooth water and moderate waves. Since the parachute usually does not permit yaw control, further studies for various yawed conditions were considered necessary.

The present investigation was made to determine the landing behavior and accelerations that would be encountered by a Gemini type of spacecraft at several yaw angles during landings in severe rough-water conditions (sea state 4). Also, since parachute landings are subject to drift caused by wind, several horizontal velocities were investigated. In order to simulate severe rough-water conditions, the wind was considered to be opposing the sea and, as a result, causing very steep waves. A 1/6-scale dynamic model of the spacecraft was used for the investigation.

A motion-picture film supplement showing some of the tests discussed in this paper is available on loan. A request card form and a description of the film will be found at the back of this paper.

The units used for the physical quantities defined in this paper are given both in the U.S. Customary Units and in the International System of Units (SI). (See ref. 2.) An appendix is included which presents factors relating these two systems of units.

APPARATUS AND PROCEDURE

Description of Model

Drawings of the 1/6-scale spacecraft model are shown in figure 1. Table I gives the scale relationships used to convert the model data to full-scale values, and table II shows the dimensions of the 1/6-scale model with the corresponding full-scale values. The model was constructed principally of plastic-impregnated fiber glass with some interior structure of balsa wood. Lead ballast was used to give the model the correct mass. The ballast weights were located within the model so that the moments of inertia were as given in table II. These values are within -10 percent in pitch and -25 percent in yaw of the desired values. Because of the structure and size limitations of the model, greater values of moments of inertia could not be obtained with the ballast weights located within the model. A photograph of the model is shown in figure 2. Diagrams of the orientation of body axes, flight path, contact attitude, and force directions are presented as figure 3.

Test Methods and Equipment

This investigation was conducted by launching the model as a free body by means of a pendulum apparatus, which is illustrated in figure 4. With the model set at the desired landing attitude, the pendulum was retracted to a point A, from which it was released and allowed to swing through an arc of vertical height AB. Model release occurred at point B (dead center) at a horizontal velocity V_H approximately equal to a free-fall velocity for the preset vertical distance AB. After release, the model dropped the vertical distance BC, preset to obtain the desired vertical velocity V_V. The combination of horizontal velocities at time of model release and vertical velocity at the time of water contact closely simulated the estimated range of velocities for the full-scale spacecraft. The model is shown installed on the pendulum launch apparatus in figure 5.

The investigations were made in rough water simulating a sea state 4 with waves 6 feet high by 88 feet crest to crest (1.8 by 26.8 m) (full-scale). The landings were made into oncoming waves. The investigations were made at various yaw angles and horizontal velocities. The vertical velocity and landing attitude remained constant. The test parameters are shown in table II.

Impact accelerations were measured with strain-gage accelerometers rigidly mounted to the model structure. Normal, longitudinal, and lateral accelerations were measured at the center of gravity with ±20g accelerometers, which had natural frequencies of about 180 cycles per second. Angular acceleration about the center of gravity was measured with a pair of matched ±100g accelerometers, which had natural frequencies of about 650 cycles per second. All accelerometers were damped to about 65 percent of critical damping. The response of the recording galvanometers was flat to about 120 cycles per second. A trailing cable supported by an overhead guide wire was used to transmit the accelerometer signals to an oscillograph recorder. Typical oscillograph records showing the three acceleration traces and their calibrations are presented as figure 6.

RESULTS AND DISCUSSION

A summary of the results is given in table III. All data have been converted to full-scale values by using the scale relationships given in table I.

Longitudinal and lateral acceleration.- Maximum longitudinal and lateral accelerations over a range from about $3\frac{1}{2}$g to 16g are presented in figure 7. At a yaw angle of 90°, the lowest acceleration values were obtained, while at 45° and 0° yaw, some increase occurred, and at 135° and 180° yaw, a rather sharp increase in the maximum acceleration values resulted. Lateral accelerations were measured at the 90° yaw angle only. An increase in horizontal velocity generally resulted in increased acceleration.

Normal acceleration.- The maximum normal accelerations over a range from about 1g to 15g are presented in figure 8. The maximum normal accelerations occurred at 0° yaw angle and the acceleration values decreased rather sharply as the yaw angle was increased. An increase in horizontal velocity resulted in an increase in normal acceleration.

Angular acceleration.- The maximum angular accelerations over a range from about 0 to 190 radians per second^2 are presented in figure 9. The zero and low values of angular acceleration occurred at the 90° yaw angle and there was a very sharp increase in angular acceleration as the yaw angle decreased or increased from 90°. An increase in horizontal velocity resulted in a sharp increase in angular acceleration except at the 90° yaw angle where the increase was small.

Landing behavior.- When the model was landed at a 0° or 45° yaw angle, there was a rapid change in pitch from the 35° landing attitude to a near zero attitude. A model landing at a 0° yaw angle is illustrated in figure 10(a). This rapid change in pitch on landing resulted in angular accelerations from 80 to 190 radians per second^2. (See fig. 9.)

Visual observation indicated very little pitch or roll motion when the model was landed at the 90° yaw angle. See figure 10(b). The landing impact was rather smooth with a maximum lateral and normal acceleration each of about $3\frac{1}{2}g$ to 6g and an angular acceleration near zero. These acceleration values, when compared with the over-all results shown in figures 7, 8, and 9, indicate the 90° yaw angle as the most favorable for a rough-water landing.

When the model was landed at a 145° or 180° yaw angle, there was a tumbling motion in which the model rotated about 180°. This action is illustrated in figure 10(c).

CONCLUDING REMARKS

Results of the dynamic-model investigation of a Gemini type of spacecraft show that landings at various yaw angles in a simulated sea state 4 rough water resulted in maximum longitudinal and lateral accelerations from about $3\frac{1}{2}g$ to 16g and maximum normal accelerations from 1g to 15g. The range of maximum angular acceleration was from about 0 to 190 radians per second^2. The simulated parachute landings in rough water indicated the 90° yaw angle as the most favorable. This yaw angle resulted in the most stable behavior, lowest angular accelerations, and near minimum normal acceleration.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., November 23, 1966,
124-08-04-12-23.

APPENDIX

CONVERSION OF U.S. CUSTOMARY UNITS TO SI UNITS

The International System of Units (SI) was adopted by the Eleventh General Conference on Weights and Measures, Paris, October 1960, in Resolution No. 12 (ref. 2). Conversion factors for the units used herein are given in the following table:

Physical quantity	U.S. Customary Unit	Conversion factor (a)	SI Unit
Length	in.	0.0254	meters (m)
Mass	lbm	0.454	kilograms (kg)
Moment of inertia	slug-ft^2	1.35582	kilogram-$meter^2$ ($kg\text{-}m^2$)
Velocity	ft/sec	0.3048	meters per second (m/s)

[a]Multiply value given in U.S. Customary Unit by conversion factor to obtain equivalent value in SI Unit.

Prefixes to indicate multiples of units are as follows:

Prefix	Multiple
centi (c)	10^{-2}
kilo (k)	10^3

REFERENCES

1. Thompson, William C.: Dynamic Model Investigation of the Landing Characteristics of a Manned Spacecraft. NASA TN D-2497, 1965.

2. Mechtly, E. A.: The International System of Units – Physical Constants and Conversion Factors. NASA SP-7012, 1964.

TABLE I.- SCALE RELATIONSHIPS

[λ = Scale of model]

Quantity	Full size	Scale factor	Model
Length	l	λ	λl
Mass	M	λ^3	$\lambda^3 M$
Moment of inertia	I	λ^5	$\lambda^5 I$
Time	t	$\sqrt{\lambda}$	$\sqrt{\lambda}\, t$
Velocity	V	$\sqrt{\lambda}$	$\sqrt{\lambda}\, V$
Linear acceleration . . .	a	1	a
Angular acceleration . . .	α	λ^{-1}	$\lambda^{-1}\alpha$

TABLE II.- PERTINENT DIMENSIONS AND TEST CONDITIONS

FOR THE SPACECRAFT AND MODEL

	Full-scale spacecraft		1/6-scale model	
Configuration mass . . .	3960 lbm	1800 kg	18.3 lbm	8.3 kg
Length of spacecraft . .	97.20 in.	246.9 cm	16.20 in.	41.15 cm
Maximum diameter . . .	90.00 in.	228.6 cm	15.00 in.	38.10 cm
Moment of inertia:[a] . .				
Yaw	560 slug-ft^2	760 kg-m^2	0.07 slug-ft^2	0.10 kg-m^2
Pitch	670 slug-ft^2	900 kg-m^2	0.09 slug-ft^2	0.12 kg-m^2
Landing attitude	35^o	35^o	35^o	35^o
Vertical velocity	30.0 ft/sec	9.1 m/s	12.2 ft/sec	3.7 m/s
Horizontal velocity . . .	33.8 ft/sec	10.3 m/s	13.8 ft/sec	4.2 m/s
	50.7 ft/sec	15.4 m/s	20.7 ft/sec	6.3 m/s
	64.2 ft/sec	19.6 m/s	26.2 ft/sec	8.0 m/s
Yaw angle	0^o	0^o	0^o	0^o
	45^o	45^o	45^o	45^o
	90^o	90^o	90^o	90^o
	135^o	135^o	135^o	135^o
	180^o	180^o	180^o	180^o
Wave size	6 by 88 ft	1.8 by 26.8 m	1 by 14.7 ft	0.3 by 4.5 m

[a]These moments of inertia are 25 percent less in yaw and 10 percent less in pitch than the desired moments of inertia. Structural and size limitations of the model prohibited greater values.

TABLE III.- SUMMARY OF TEST RESULTS

[Acceleration axes are identified in fig. 3. Landing attitude, 35°; vertical velocity, 30 ft/sec (9.1 m/s). All values are converted to full scale.]

Horizontal velocity		Number of test runs	Maximum acceleration		
ft/sec	m/s		Longitudinal, g units	Normal, g units	Angular, rad/s^2
Yaw angle, 0°					
33.8	10.3	4	5.6	9.8	-118
50.7	15.4	3	7.9	11.3	-130
64.2	19.6	5	7.4	14.8	-190
Yaw angle, 45°					
33.8	10.3	4	4.9	7.8	-73
50.7	15.4	4	8.1	13.3	-125
64.2	19.6	4	8.4	13.3	-117
Yaw angle, 90°					
33.8	10.3	8	[a]-3.4	3.6	0
50.7	15.4	8	[a]-3.7	5.6	-15
64.2	19.6	4	[a]-6.1	6.3	----
Yaw angle, 135°					
33.8	10.3	4	-8.6	1.3	74
50.7	15.4	4	-12.5	1.6	96
64.2	19.6	4	-15.7	2.5	118
Yaw angle, 180°					
33.8	10.3	4	-8.3	0.6	59
50.7	15.4	4	-12.5	1.3	95
64.2	19.6	3	-10.3	3.8	141

[a]Lateral acceleration measured along axis 90° to longitudinal shown in figure 3.

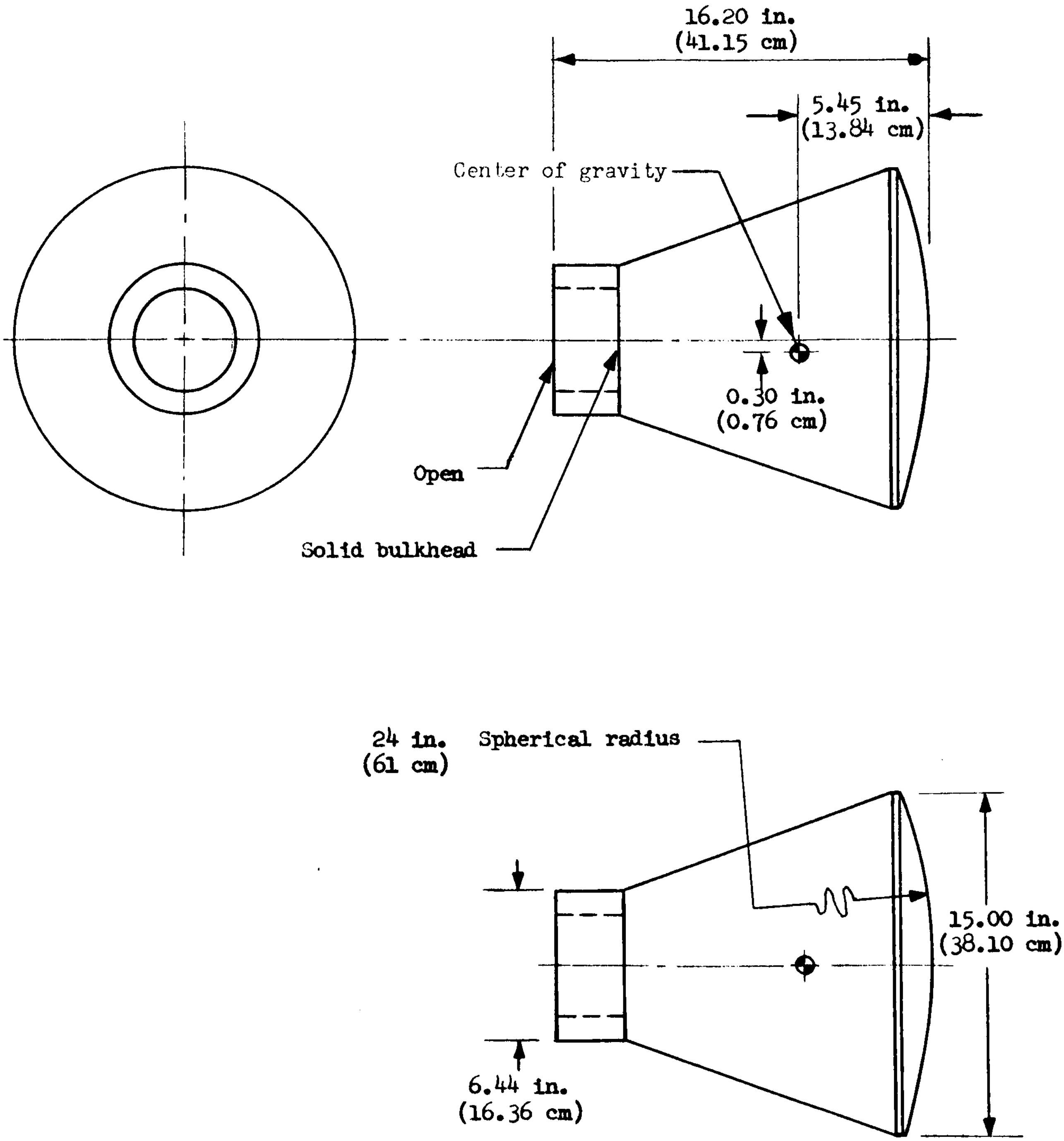


Figure 1.- General arrangement of 1/6-scale spacecraft model. Dimensions are model size.

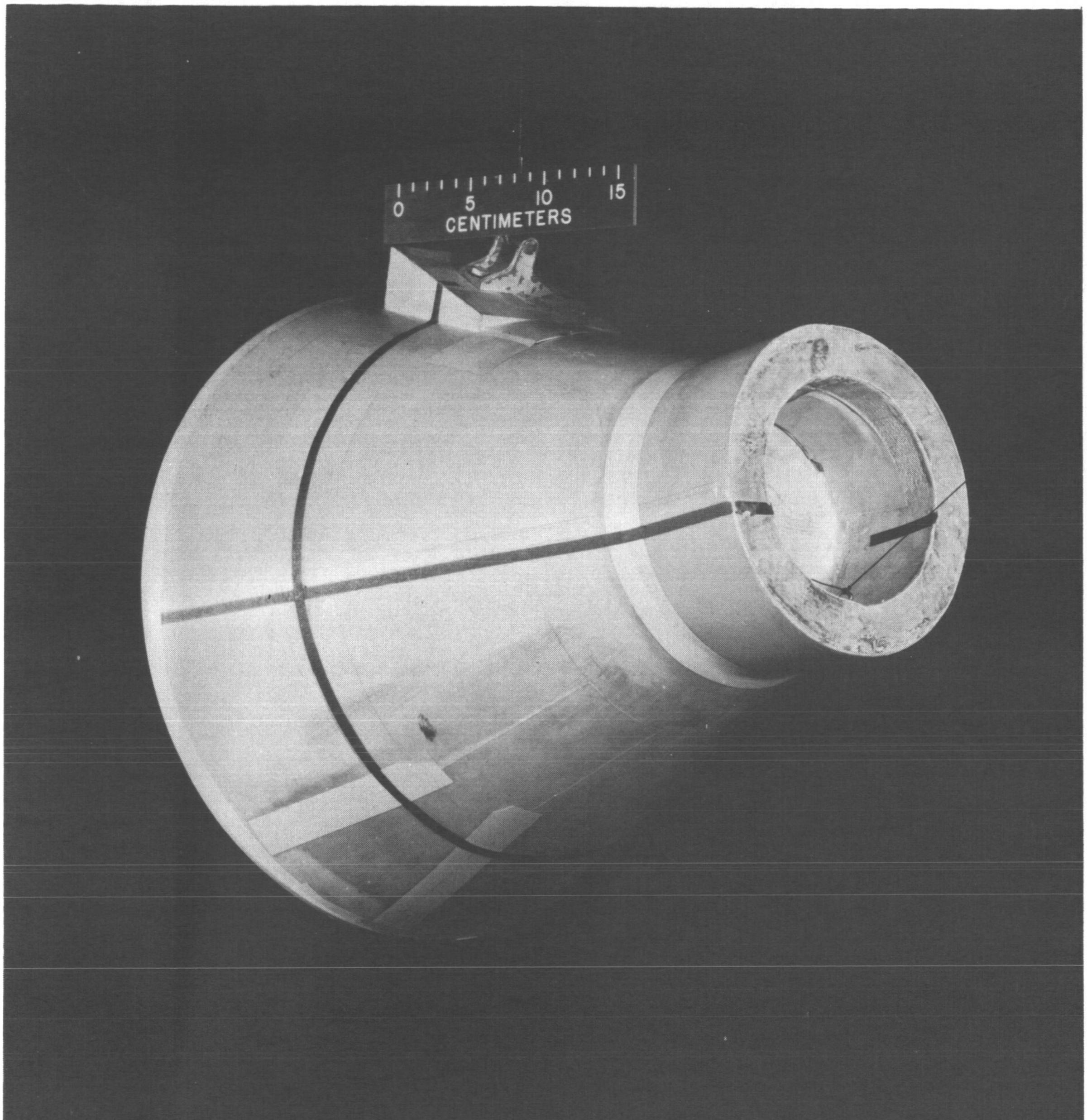


Figure 2.- Photograph of model. L-64-11,055

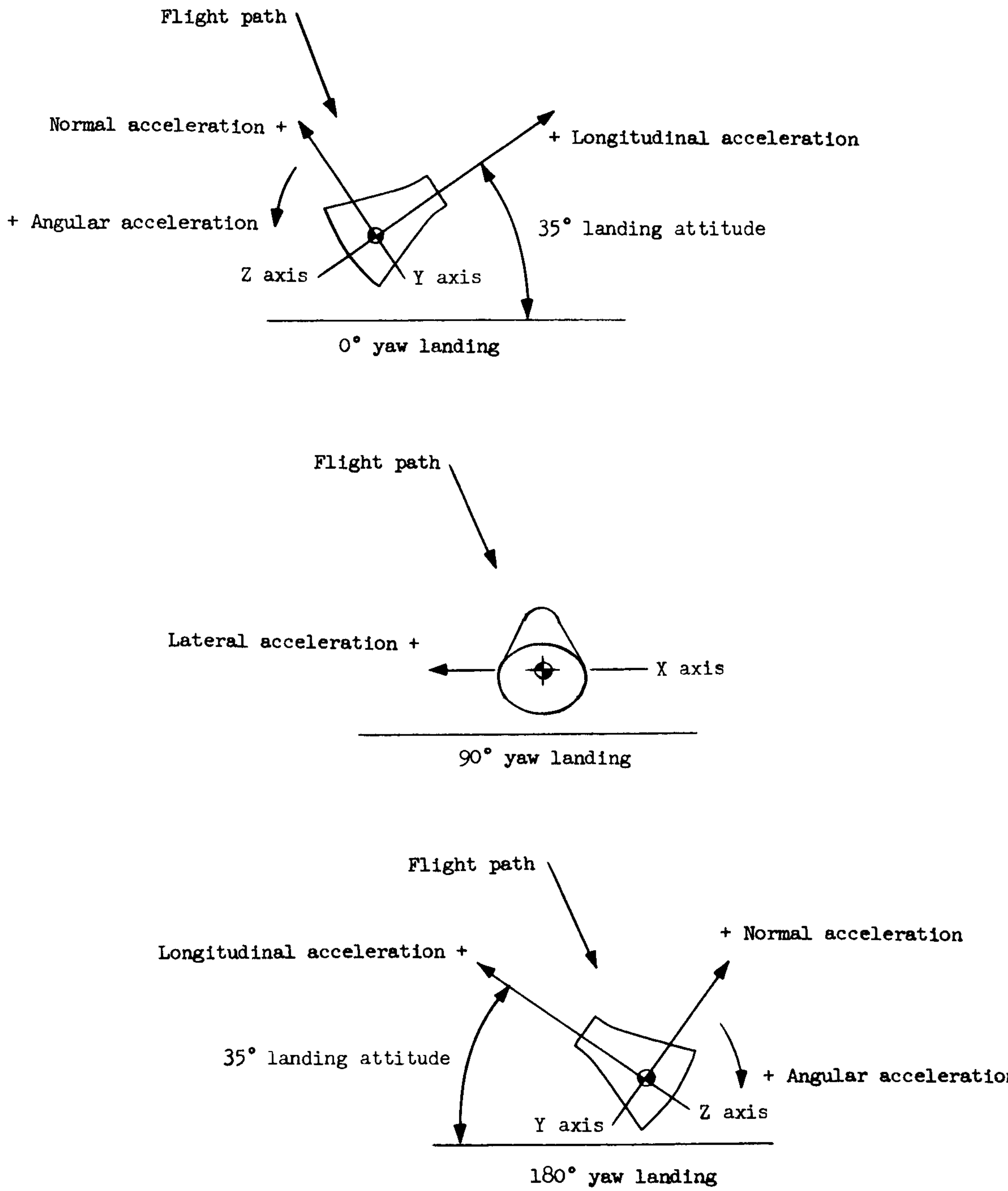


Figure 3.- Sketches identifying body axes and test parameters.

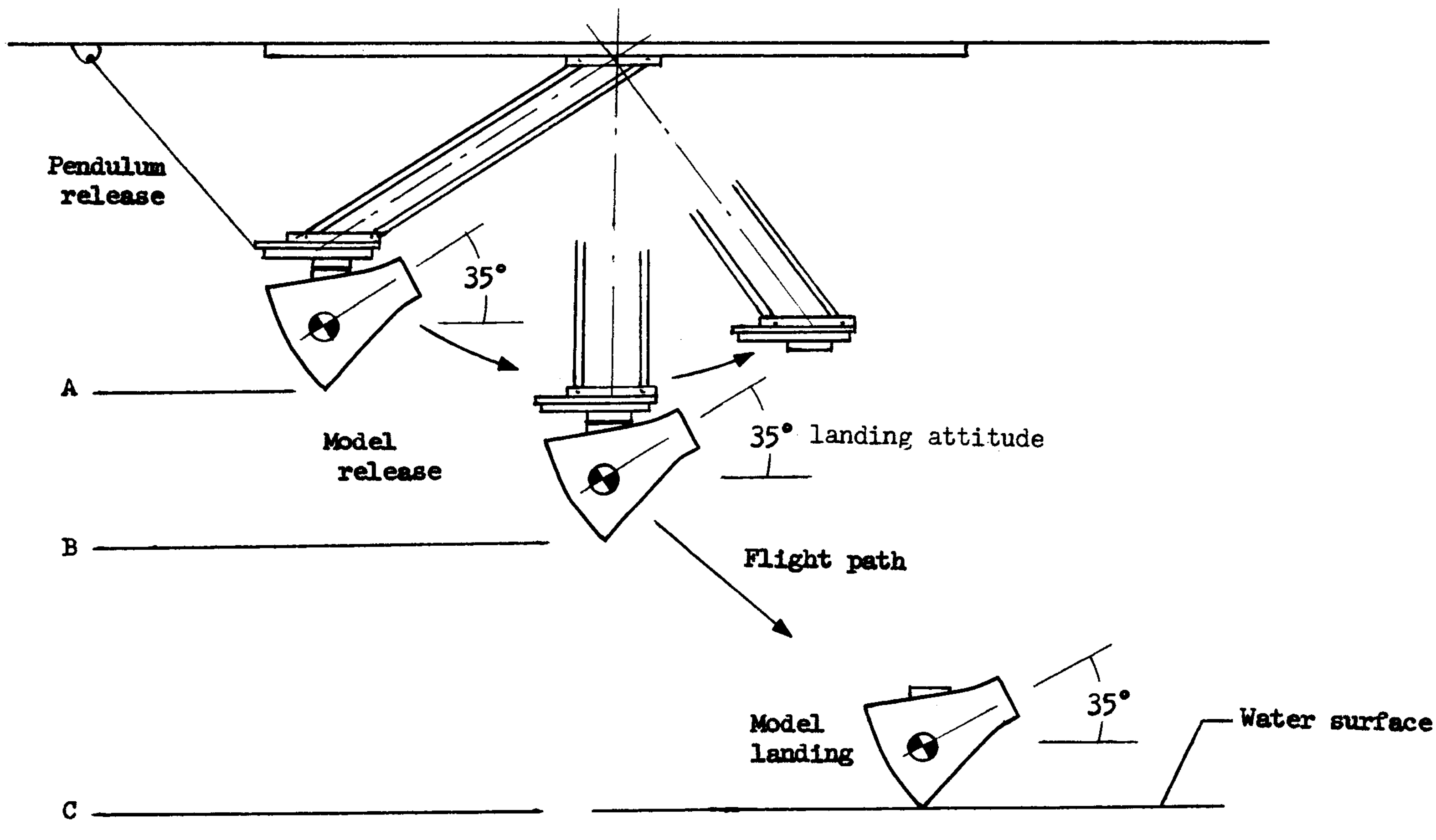


Figure 4.- Pendulum operation during release and landing of model.

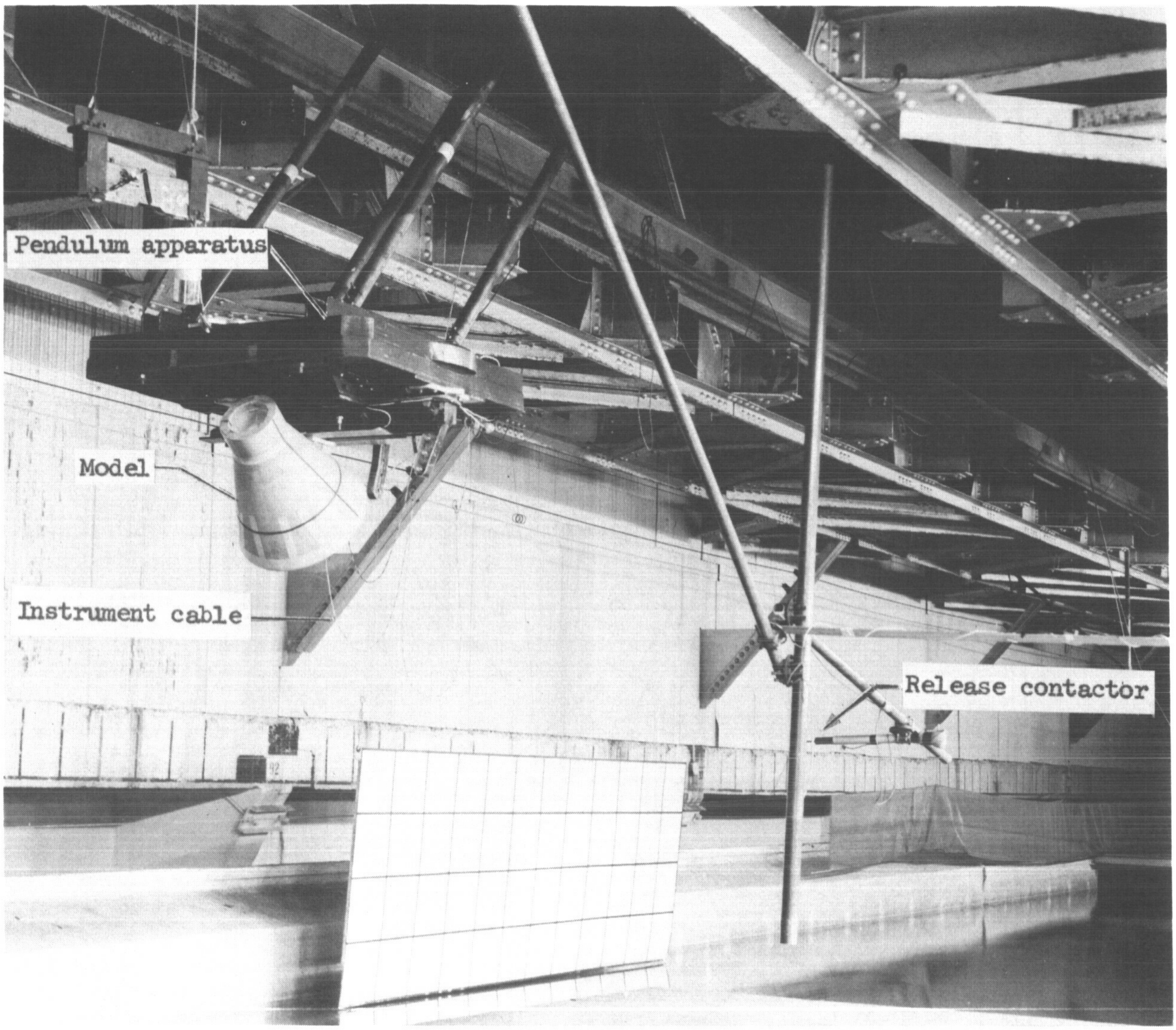
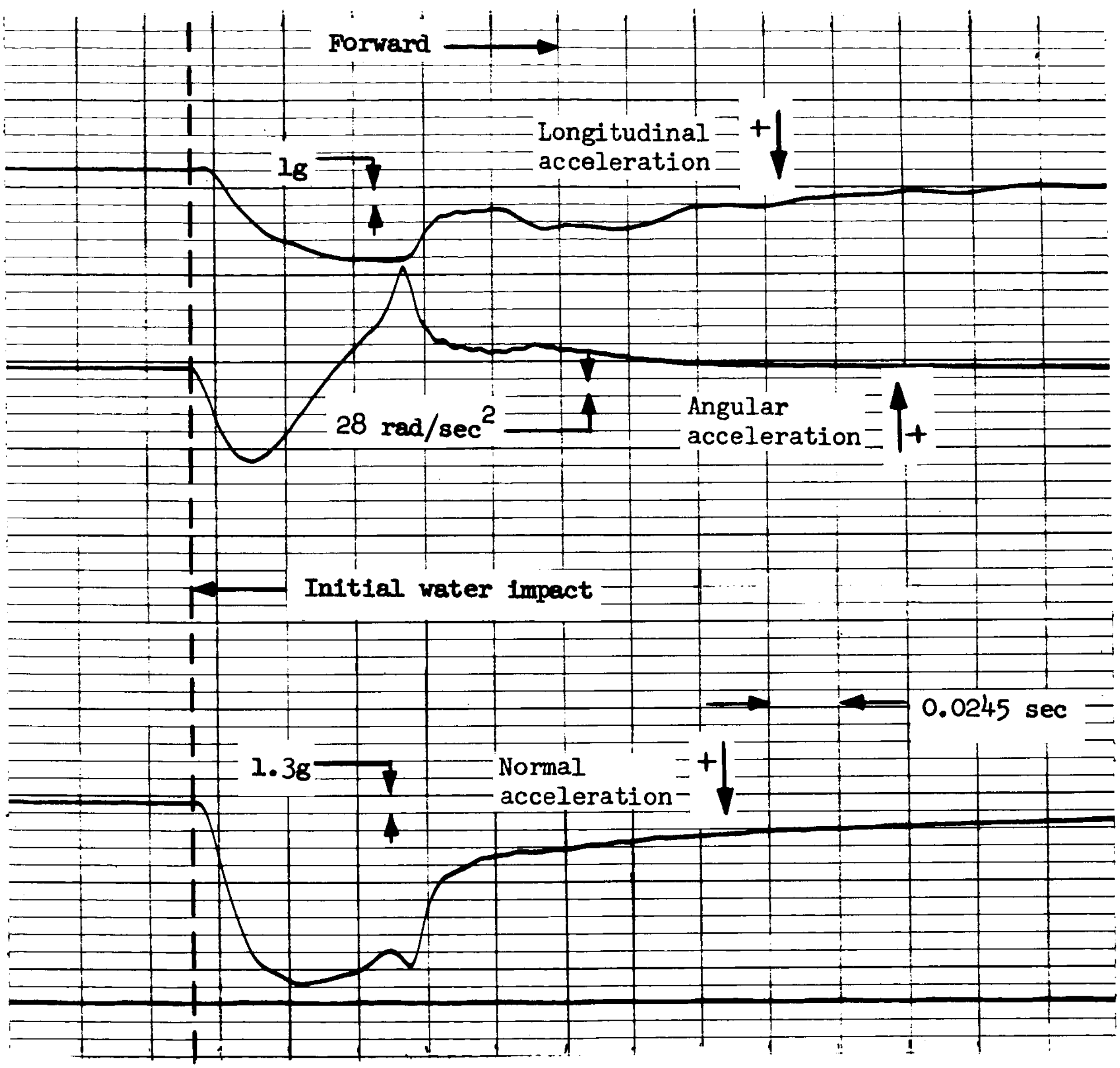
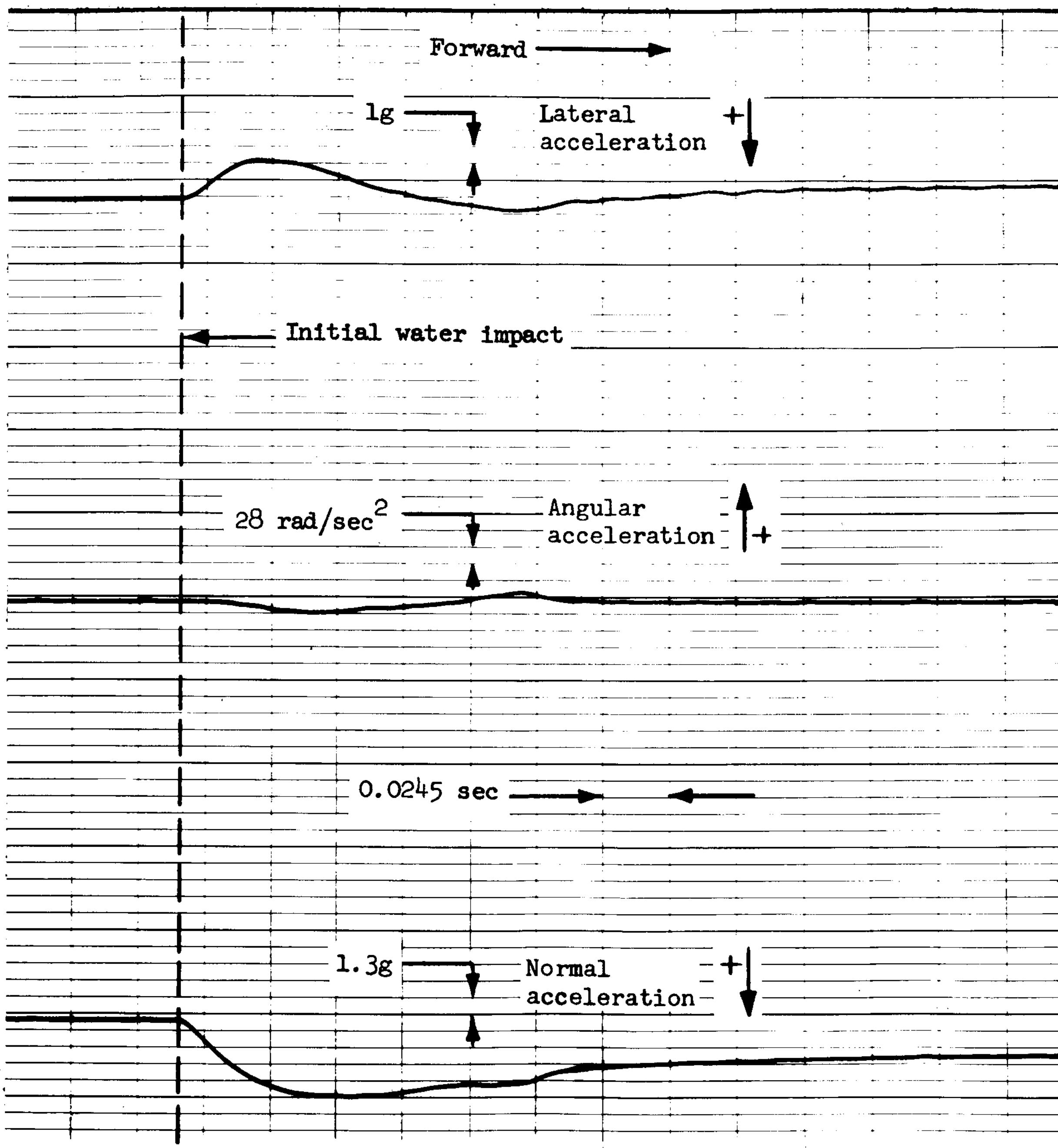


Figure 5.- Test installation with model attached to pendulum launch apparatus. L-64-11,053.1



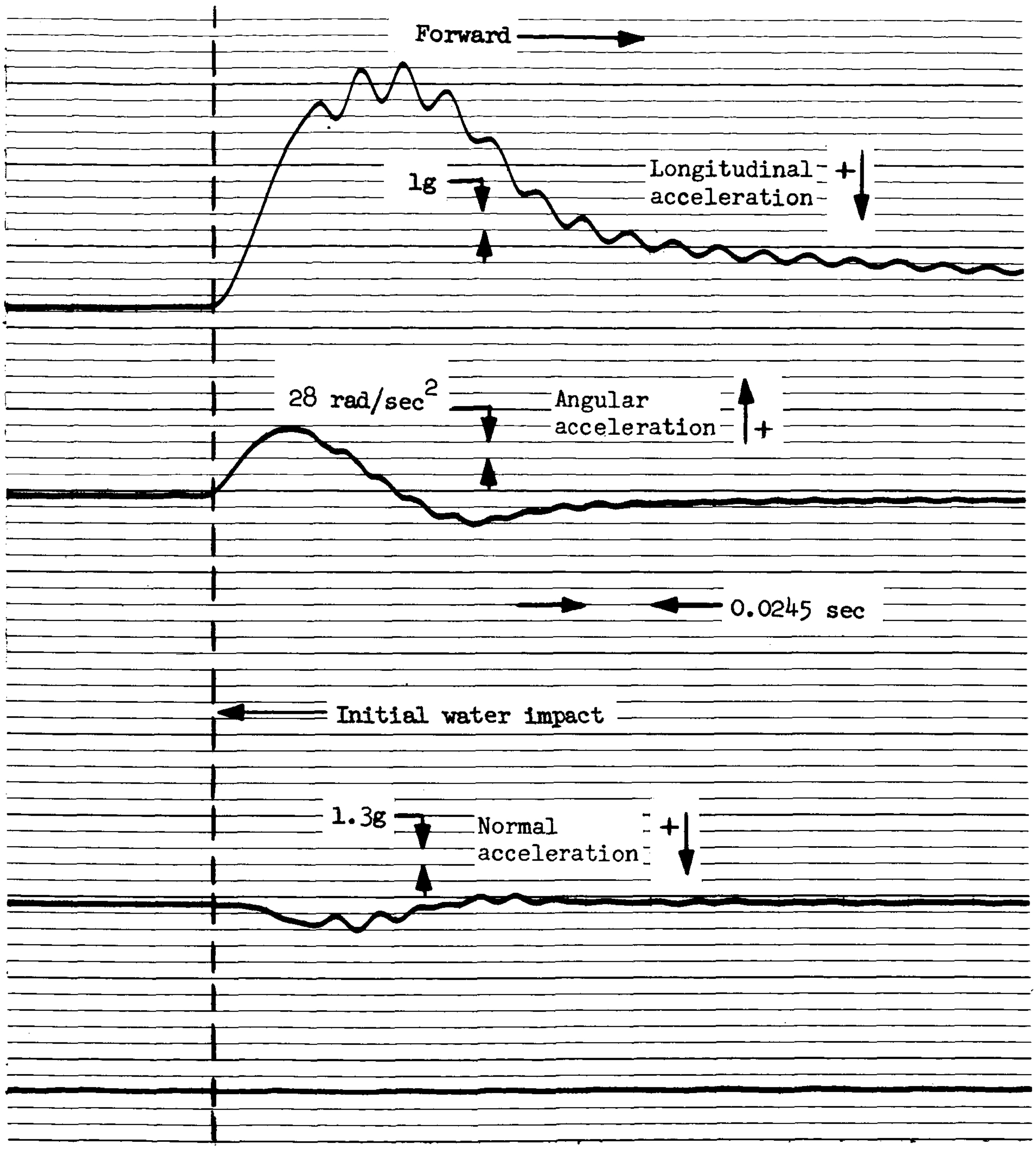
(a) Yaw angle, 0°; horizontal velocity, 64.2 ft/sec (19.6 m/s). Impact into forward slope near crest of wave.

Figure 6.- Typical oscillograph records obtained for landings in rough water. Wave size, 6 × 88 ft (1.8 × 26.8 m); vertical velocity, 30 ft/sec (9.1 m/s). All values are full scale.



(b) Yaw angle, 90°; horizontal velocity, 50.7 ft/sec (15.4 m/s). Impact near crest of wave.

Figure 6.- Continued.



(c) Yaw angle, 135°; horizontal velocity, 64.2 ft/sec (19.6 m/s). Impact into forward slope of wave.

Figure 6.- Concluded.

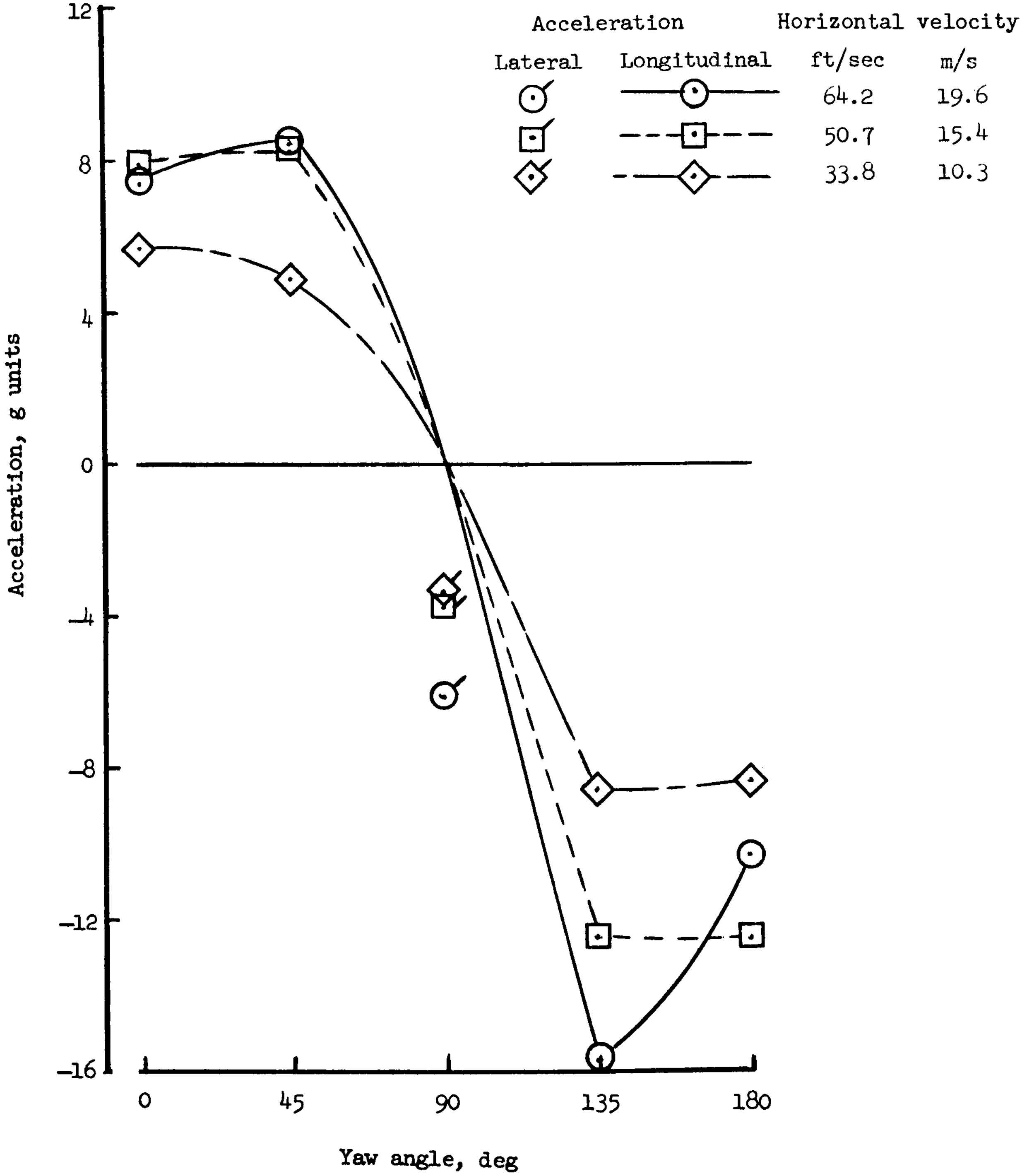


Figure 7.- Maximum longitudinal and lateral accelerations encountered in rough-water landings at various yaw angles and horizontal velocities. Vertical velocity, 30 ft/sec (9.1 m/s). All values are full scale.

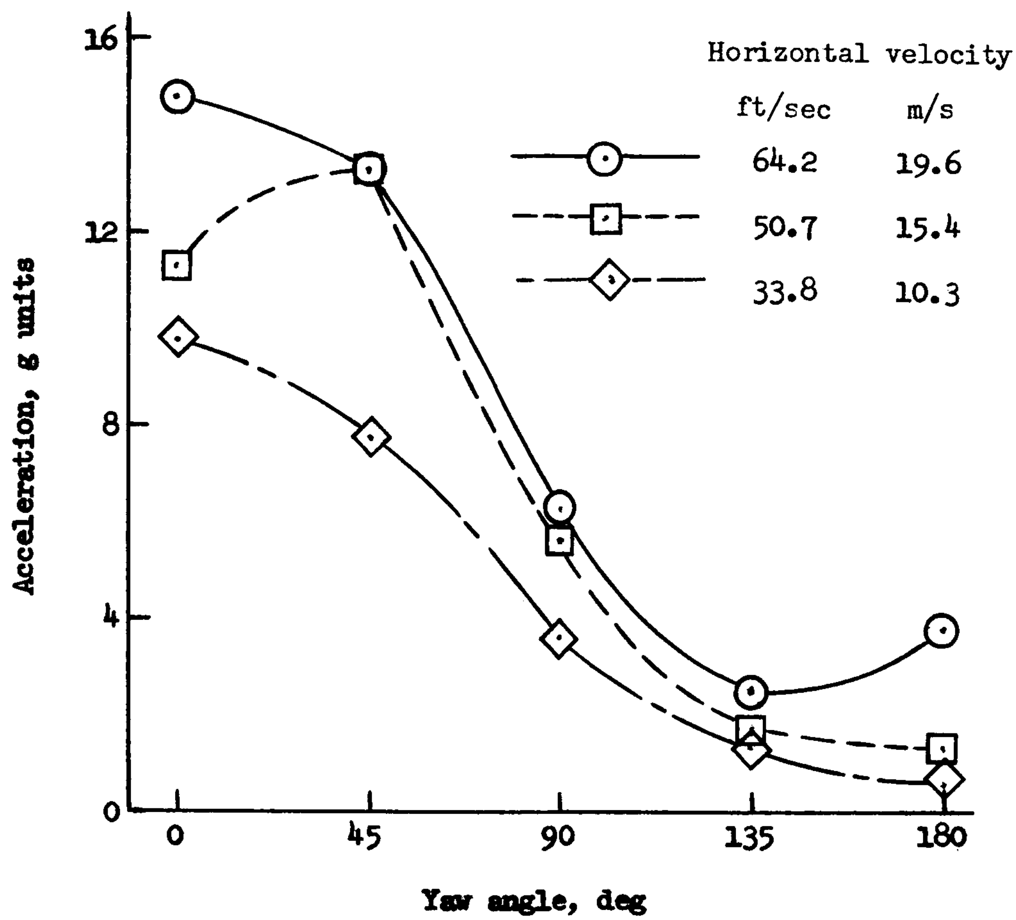


Figure 8.- Maximum normal accelerations encountered in rough-water landings at various yaw angles and horizontal velocities. Vertical velocity, 30 ft/sec (9.1 m/s). All values are full scale.

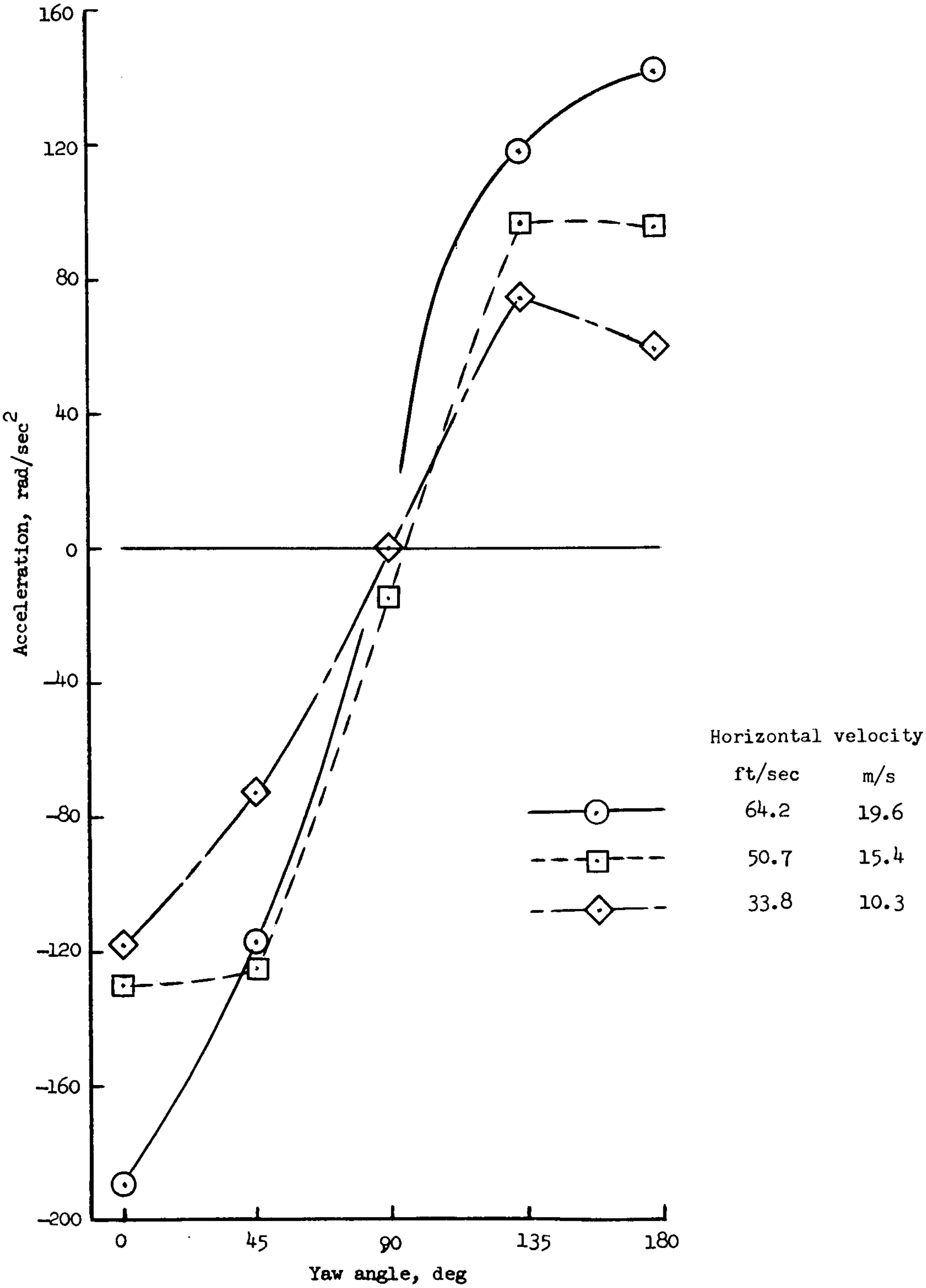
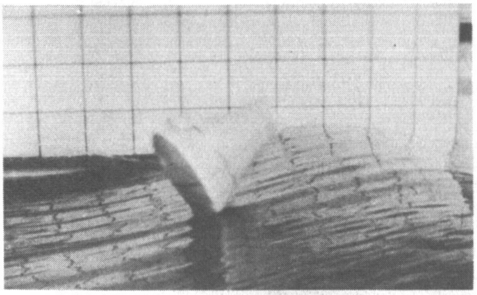


Figure 9.- Maximum angular accelerations encountered in rough-water landings at various yaw angles and horizontal velocities. Vertical velocity, 30 ft/sec (9.1 m/s). All values are full scale.



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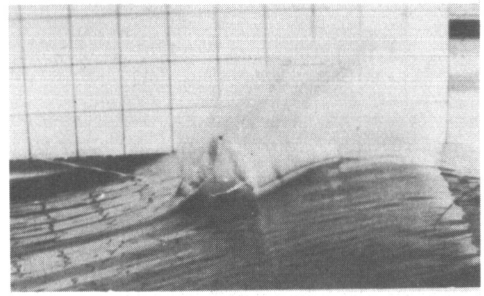

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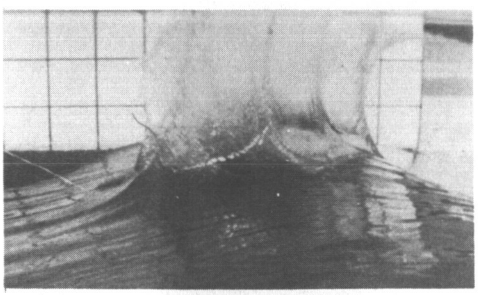

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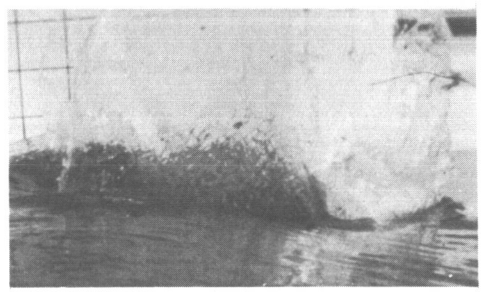

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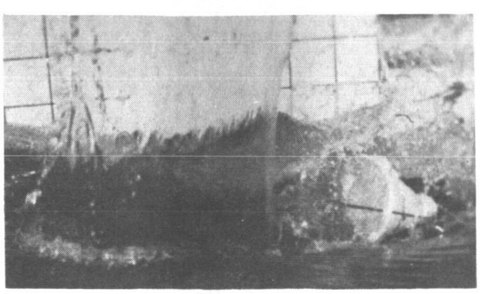

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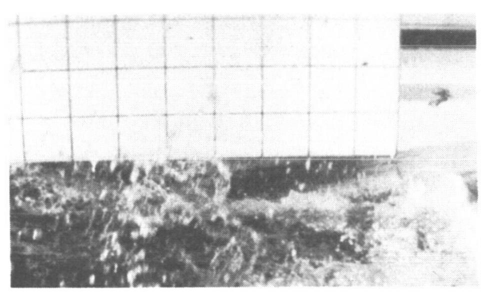
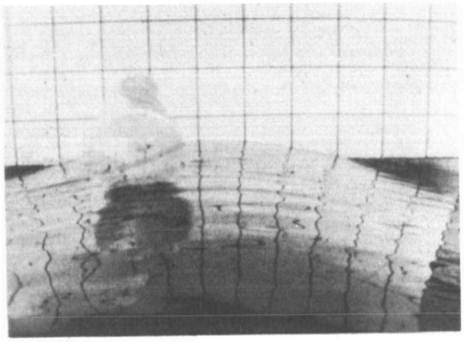


4.29 sec

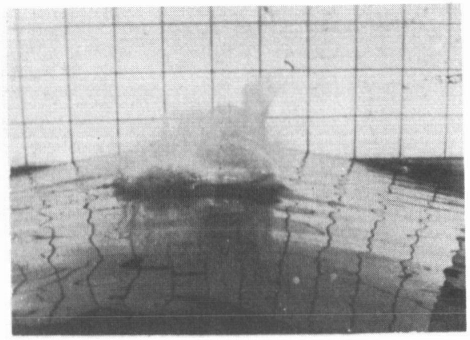
(a) Yaw angle 0°.

L-67-916

Figure 10.- Photographs illustrating behavior of model when landed at various yaw angles into oncoming waves. All values are full scale.



Near contact



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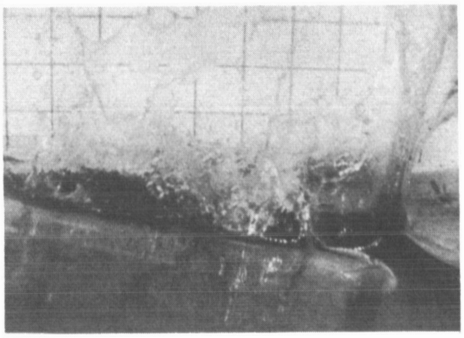

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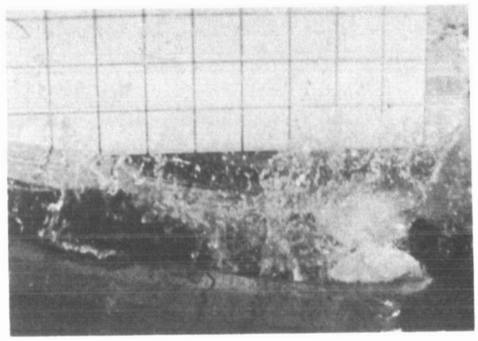

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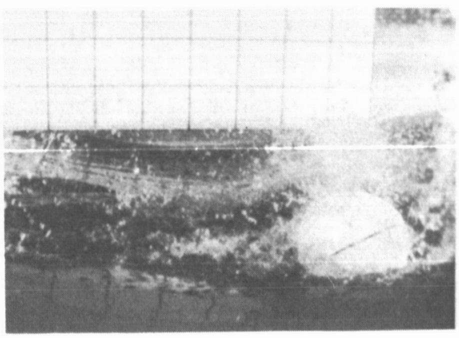

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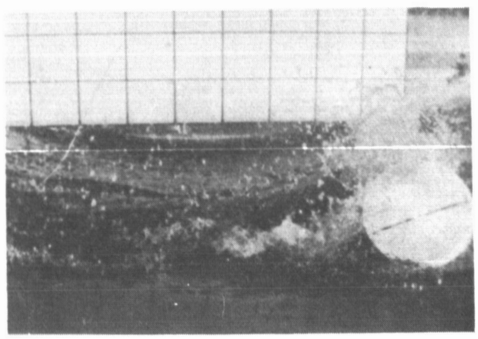

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(b) Yaw angle 90°.

Figure 10.- Continued.

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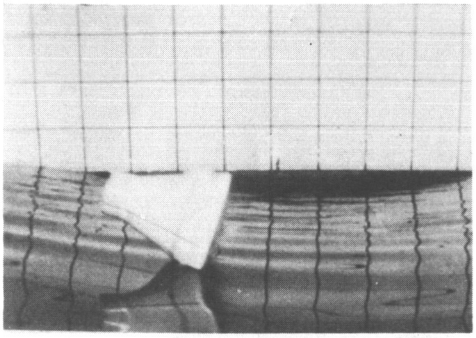
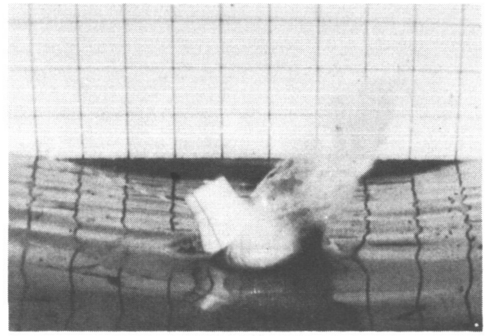


Near contact



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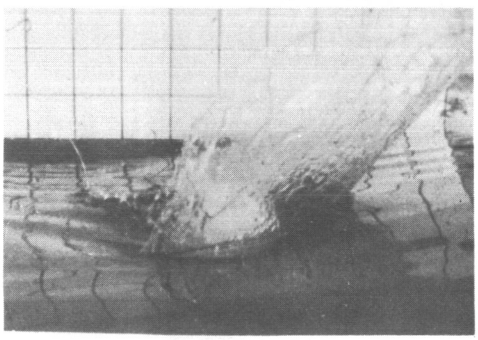

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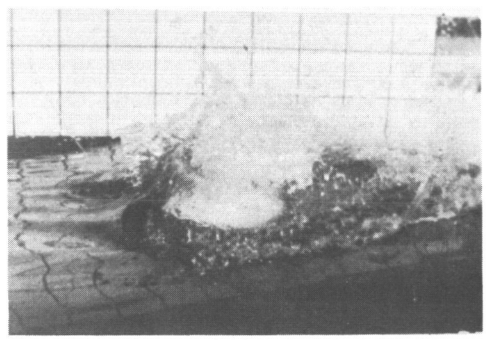

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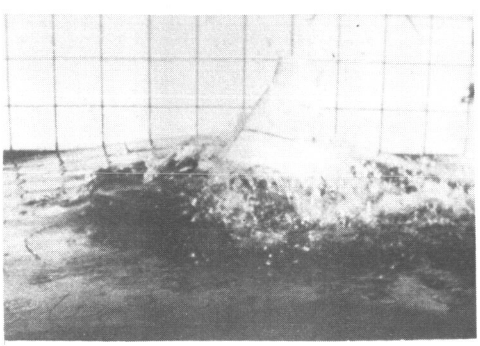

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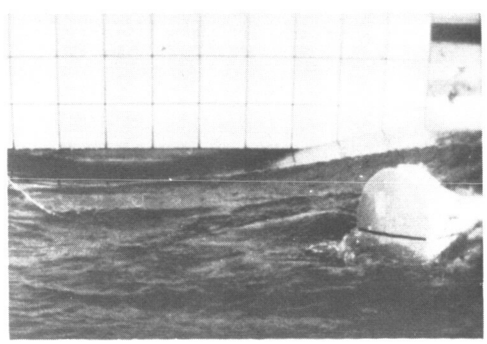

8.40 sec

(c) Yaw angle 180°.

Figure 10.- Concluded.

L-67-918

A motion-picture film supplement L-940 is available on loan. Requests will be filled in the order received. You will be notified of the approximate date scheduled.

The film $\left(16 \text{ mm}, 4\frac{1}{2} \text{ min, color, silent}\right)$ shows free-body dynamic model landing tests made with a 1/6-scale Gemini type model landing at various yaw angles into oncoming waves.

Requests for the film should be addressed to:

Chief, Photographic Division
NASA Langley Research Center
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