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AN INVESTIGATION OF THE TOWING CHARACTERISTICS OF THE DEEP SUBMERGENCE RESCUE VEHICLE (DSRV). PART III. SURFACED AND SUBMERGED TOWING IN A REGUALR SEAWAY

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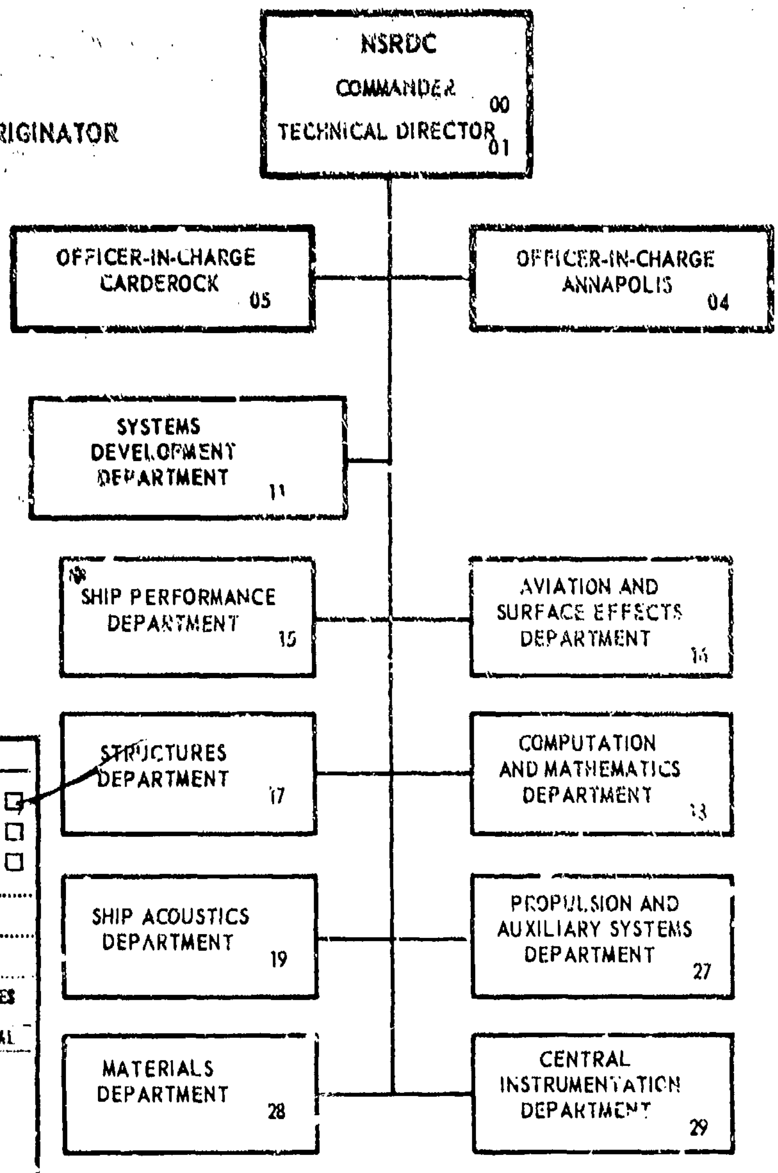

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The surfaced and submerged towing characteristics of the Deep Submergence Rescue Vehicle (DSRV) are examined for a variety of towing ship fantail motions and regular waves. The results indicate that under the conditions examined, the DSRV will tow in a dynamically stable and predictable manner and that, in large waves, approaching those of a State 5 sea, a synthetic towline with a breaking strength of at least 150,000 pounds should be used to provide a satisfactory margin of safety against peak tension loads.

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NOTATION

A_{HTP}	Heaving towpoint double amplitude
a	Specific acceleration
B	Total buoyancy of the hull envelope
g	Local acceleration of gravity
h	Wave height
I_x	Real moment of inertia in roll
I_y	Real moment of inertia in pitch
K	Rolling moment
$K_{\dot{p}}$	Added hydrodynamic moment of inertia in roll
$M_{\dot{q}}$	Added hydrodynamic moment of inertia in pitch
T_{CW}	Calm-water towline tension
T_{PK}	Peak towline tension
T_θ	Natural period of oscillation in pitch
T_ϕ	Natural period of oscillation in roll
W	Total weight including entrained water
Z_B	Vertical location of the centroid of the hull envelope
Z_G	Vertical location of the center of total mass
θ	Angle of pitch
ϕ	Angle of roll

ABSTRACT

The surfaced and submerged towing characteristics of the Deep Submergence Rescue Vehicle (DSRV) are examined for a variety of towing ship fantail motions and regular waves. The results indicate that under the conditions examined, the DSRV will tow in a dynamically stable and predictable manner and that, in large waves, approaching those of a State 5 sea, a synthetic towline with a breaking strength of at least 150,000 pounds should be used to provide a satisfactory margin of safety against peak tension loads.

ADMINISTRATIVE INFORMATION

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INTRODUCTION

At the request of the Naval Sea Systems Command (NAVSEA), the Naval Ship Research and Development Center (NSRDC) undertook a program to develop a contingency technique for towing the Deep Submergence Rescue Vehicle (DSRV) at high speeds with a ship-of-opportunity. The DSRV is a small air-transportable submersible primarily designed to rescue personnel from a disabled submarine and transfer them to another submarine or to the surface. It is envisioned that circumstances might arise in which a specialized support ship would not be immediately available, making it necessary to employ a more or less unequipped ship-of-opportunity. Such a mission would typically involve both submerged towing in deep water and surface towing in shallow water. Calm-water towing characteristics of the DSRV in each of these situations have been treated previously.[1,2]

This report, which concludes the current series, complements the previous work by examining the aspect of towing from a surface ship in a seaway. Basic operational considerations for accomplishing a tow are reviewed; the prototype, the model, the associated

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[1] Sieber, Charles W. and R. Knutson, "An Investigation of the Towing Characteristics of the Deep Submergence Rescue Vehicle (DSRV) - Part I–Submerged Towing in Calm Water," NSRDC Report 4145 (Mar 1974).

[2] Sieber, Charles W. and R. Knutson, "An Investigation of the Towing Characteristics of the Deep Submergence Rescue Vehicle (DSRV)–Part II–Surface Towing in Calm Water," NSRDC Report 4146 (Mar 1974).

experimental equipment and instrumentation, and the procedures that were used in the experimental investigations are described; and the results of these investigations are presented.

OPERATIONAL CONSIDERATIONS AND RESTRICTIONS

There were several basic operational considerations and restrictions imposed in the development of towing techniques. These are listed as follows:

1. The outer envelope of the DSRV is constructed of formed glass-reinforced plastic and is intended only for streamlining purposes. Any towing loads must be taken by two circumferential rings located fore and aft on the vehicle. The vehicle can be towed only from the existing light-alloy fittings protruding through the skin from these rings.

2. The towline(s) should not come in contact with the envelope due to the fragile nature of the glass-reinforced plastic.

3. To provide a margin of safety against accidental submergence, the vehicle should have substantial positive buoyancy.

4. For simplicity and reliability, the use of additional bodies such as drogues, auxiliary surfaces, or appendages on the vehicle should be avoided.

5. The propeller should be free wheeling.

6. The shroud must be fixed in place, preferably at zero deflection, so that the tow can be accomplished without crew.

7. Insofar as possible the same towing conditions should be usable for both surfaced and submerged towing.

DESCRIPTION OF PROTOTYPE AND MODEL

The overall configuration of the prototype vehicle as represented for this investigation is shown in Figure 1. The basic hull is a body of revolution 49.33 feet in length and 8.17 feet in maximum diameter. The hull envelope contains forward and aft sets of vertical and horizontal thrusters which provide control for low-speed maneuvering. At the stern is an all-movable control shroud and a three-bladed propeller for main propulsion. External to the envelope are the transfer skirt assembly (consisting of a mating skirt, a shock mitigation system, and a splitter plate) located below the hull and two small fairings which house electronic components.

The vehicle is represented for experimentation by NSRDC Model 5200, a 2.32-foot-long mahogany model with a linear scale ratio of 21.28. Propellers in the thruster ducts are omitted.

The model is shown in Figures 2 through 4. Detailed geometrical characteristics of the prototype and the model are presented in Table 1.

MODEL PREPARATIONS

The following modifications and preparations were performed on Model 5200:

1. The model was converted to a free-flooding condition to facilitate simple adjustment of ballast.

2. A free-wheeling stern propeller which approximated the prototype propeller was installed.

3. Towpoints were installed at a location corresponding to the forward lifting eyes. This location is detailed in Figure 5.

4. A sand strip to stimulate boundary layer turbulence was installed around the nose of the body at a station corresponding to 2.0 feet aft of the forward perpendicular on the prototype.

MODEL BALLASTING PROCEDURES

The ballasting procedures, all of which were conducted with the model flooded and fully submerged in water, are outlined below:

1. The model was ballasted to a net positive buoyancy condition corresponding to approximately 170 pounds full scale.

2. With this weight condition, the static roll and pitch trim angles were set to zero by adjustment of the lateral and longitudinal ballast locations.

3. A known static rolling moment was applied about the centroid of the hull envelope, and the resulting angle of roll was measured. Using the relationship,[3]

$$K = (Z_G W - Z_B B) \sin \phi \tag{1}$$

[3] Imlay, Frederick H., "Complete Expressions for the Gravitational and Buoyancy Force Terms in the Equations of Motion of a Submerged Body," David Taylor Model Basin Report 1845 (Jun 1964).

the center of total mass of the model was adjusted to coincide with that of the prototype.

4. The model then was oscillated freely in roll and pitch, and the resulting periods of oscillation were recorded. These data were used to determine the moments of inertia in roll and pitch from the relationships[4]

$$T_\phi \simeq 2\pi \left[(I_x - K_{\dot{p}})/(Z_G W - Z_B B)\right]^{1/2} \quad (2)$$

and

$$T_\theta \simeq 2\pi \left[(I_y - M_{\dot{q}})/(Z_G W - Z_B B)\right]^{1/2} \quad (3)$$

The values for $K_{\dot{p}}$ and $M_{\dot{q}}$ in Equations (2) and (3) were obtained from experimental data contained in Reference 5.

The moment of inertia in yaw, while not specifically determined, can be assumed to be very near that in pitch. This assumption is considered valid since the vehicle is essentially axially symmetric, especially near the ends, and the center of total mass is near the axis. Table 2 lists the inertial properties and ballast condition of the model and prototype. Periods of oscillation for the prototype were determined from Equations (2) and (3).

EXPERIMENTAL EQUIPMENT AND INSTRUMENTATION

Previous investigations of submerged towing tensions, as well as basic handling considerations, suggested that a fiber rope towline of near-neutral buoyancy and an equivalent full-scale circumference of 6 to 8 inches would be a likely prototype choice. With these parameters as a design rationale, and since direct-wire instrumentation was desirable, the towline selected for these experiments was a low-density nine-conductor electrical cable with an 0.087-inch diameter and a nominal breaking strength of 100 pounds. To scale the elastic properties of the nominal prototype towline, a length of shock cord was inserted in series with the model towline. Table 3 summarizes the characteristics of the various towline lengths employed and compares them to some representative nylon ropes of equal lengths.

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[4] Gertler, Morton and Grant R. Hagen, "Standard Equations of Motion for Submarine Simulation," NSRDC Report 2510 (Jun 1967).

[5] Young, D.B., "Model Investigation of the Stability and Control Characteristics of the Contract Design for the Deep Submergence Rescue Vehicle," NSRDC Report 3030 (Apr 1969).

The towing strut assembly used in the experiments was fabricated from aluminum alloy and was designed to accept a maximum drag load of 10 pounds. This assembly could be adjusted to vary towing height from zero to approximately 3 feet above the undisturbed water surface. In addition, it was fitted with a motor-driven heaving towpoint mechanism to allow simulation of towing ship fantail motions. This mechanism provided an approximately sinusoidal motion with double amplitude variable from 2.0 to 6.0 inches in increments of 2.0 inches and a frequency continuously variable from approximately 1.0 to 9.0 radians per second. This frequency variation was accomplished by adjustments to the voltage applied to the towpoint drive motor by means of a variable autotransformer.

Instrumentation located at the towing strut included a ring-gage tension dynamometer of 10-pound capacity and ±0.05 pound accuracy to provide measurement of towing tension. Also provided was a gear-driven feedback potentiometer which allowed the time history of the heaving towpoint excursions to be continuously recorded. The towing strut assembly and its associated instrumentation are shown in Figures 6 through 8.

The instrument package located within the model included a vertical-axis gyro capable of measuring pitch and roll of the model to an overall accuracy of ± 1/2 degree, and a vertical-axis force balance servo-accelerometer located directly below the towpoint. This accelerometer provided an overall accuracy of ±0.002 g. A second 10-pound-capacity ring-gage dynamometer was incorporated into the towline at the apex of the towing bridle. Figures 9 and 10 illustrate the instrumentation associated with the model.

Wave records during experimentation with waves were provided by an ultrasonic wave probe with an estimated accuracy of ± 0.1 inch. Carriage speed measurements with an accuracy of ± 0.01 knot were obtained with a magnetic pickup.

Analog data readout of all measured quantities was provided by an eight-channel pen recorder. Figure 11 presents a schematic illustration of the towing configuration and depicts the measured data variables.

EXPERIMENTAL PROCEDURES

Towing performance was investigated in the High-Speed Basin over a range of dynamic conditions approximating typical wave heights and frequencies contained in States 3 to 5 seas. Model wave heights and heaving towpoint double amplitudes typically ranged from 0.17 foot to 0.52 foot. The experimentation was separated into two sections: The first consisted of investigations of calm water towing with an oscillating input applied by the heaving towpoint, simulating the heaving motions of the fantail of a towing ship in a regular seaway. The second consisted of investigations of towing in waves without an input from the towpoint. The assumption is made that a conservative estimate of the total influence of the seaway can be made by linearly superimposing the two effects.

Towing performance was investigated in calm water for heaving towpoint motions having double amplitudes corresponding to 3.5 feet and 7.1 feet and frequencies of heave corresponding to a range from approximately 0.3 to 2.0 radians per second. The heaving towpoint was adjusted to oscillate about a mean towpoint height corresponding to approximately 10 feet full scale.

The towing experiments in waves consisted of towing in a head-sea condition in a regular seaway. The five waves detailed in Table 4 were selected for the experiments.

All conditions of heaving towpoint motions and waves were examined for full-scale towing speeds from 3.5 to 15 knots and nominal towline lengths corresponding to 150 feet, 300 feet, and 400 feet. For each set of conditions, run durations corresponded to approximately 3 to 5 minutes full scale and covered distances corresponding to approximately 500 to 1500 yards.

RESULTS

GENERAL TOWING PERFORMANCE

Neither heaving motions of the towing platform nor motions induced by the waves significantly influenced the towing behavior of the model. Under all conditions of experimentation the model towed in a dynamically stable and predictable manner.

The speed at which spontaneous submergence of the vehicle would normally occur[2] is somewhat influenced both by heaving motions of the towing platform and by waves. Whereas in calm water the vehicle would not be expected to submerge under these conditions until a speed of approximately 6 knots is attained, motions induced by the heaving towpoint caused the model to submerge at a speed corresponding to approximately 4.5 knots. This reduced submergence speed is apparently independent of the absolute magnitude of towing platform motions. In waves the model normally submerged at a speed corresponding to approximately 4.5 knots for wave amplitudes below 2.5 feet, but submergence speed was further reduced to a value of approximately 3.5 knots in larger waves.

A slack towline condition occasionally occurred in the experiments during submerged towing at low speeds with the shorter towline. Specific conditions under which this phenomenon might appear will be discussed further in the section entitled DISCUSSION.

TOWLINE TENSION

In all cases, the magnitude of the oscillatory component of the total towing tension was found to approximate a linear function of the amplitude of driving motion, i.e., of heaving towpoint or wave amplitude. Therefore, the tension data were normalized in the following manner: The steady component of tension (towing tension in calm water) was subtracted from the peak tension. The resulting value is the amplitude of the oscillatory component of tension. This value then was divided by the double amplitude of the heaving towpoint or by the wave height. Within the accuracy of the measurement system, for a given set of conditions, the magnitude of this component of tension was the same at the two endpoints of the towline. Furthermore, the tension response in all cases approached in form the approximate sinusoidal motion of the driving force.

The normalized oscillatory components of tension induced by heaving motions of the towing platform are presented in Figures 12a through 12d as a function of towing platform heaving frequency. Each of these figures contains data obtained for both heaving amplitudes investigated. The normalized oscillatory components of tension resulting from towing in waves without heaving towpoint motions are presented in Figures 13a through 13d as a function of the frequency of wave encounter. Each of these figures contains data from all wave heights investigated. Inspection of these figures indicates that the oscillatory component of towing tension is strongly influenced by towline length and to a somewhat lesser degree by towing speed. Figures 12a and 13a indicate that relatively small dynamic tensions will be experienced while towing on the surface at low speeds. All of the data contained in Figures 12 through 13 are valid only for towlines having elastic properties similar to those used in the experiments (see Table 3).

For purposes of analysis the steady components of towing tension (calm water towing tensions) are presented in Figures 14 and 15 as functions of speed for the surface towing mode and the submerged towing mode, respectively. In both sets of data, the longitudinal body forces have been corrected for frictional scale effects using standard reduction techniques, with a correlation allowance of 0.0006 being applied.

BODY MOTIONS

Normalized body pitching motions and accelerations normal to the longitudinal body axis at a position below the lifting eyes induced by heaving motions of the towing platform are presented in Figures 16a through 16d as functions of towing platform heaving frequency. The pitching motions and accelerations obtained during the experiments in waves are presented in Figures 17a through 17d as functions of the frequency of wave encounter. Both sets of figures indicate that body motions induced by towing in a seaway are strongly influenced both by towline length and towing speed. Both the pitch and the heave acceleration motions were in most cases approximately sinusoidal in form. Pitch and heave motions were accompanied by roll motions of up to ± 10 degrees. Roll motions, however, were erratic and were not harmonic in form.

DISCUSSION

The curves presented in Figures 12, 13, 16, and 17 correspond to the vehicle towing response operators in a regular sea. With a knowledge of the sea spectrum and the towing ship response operators, these figures can be used to estimate the tension and motion response of the DSRV to irregular waves by standard methods of superposition and statistical analysis.[6] However, with the allowance of certain simplifying assumptions with regard to the towing ship and the seaway, useful operational information can be inferred directly from the data.

1. A slack towline condition will occur whenever the sum of the oscillatory components of the towline tension equals or exceeds the steady component of towing tension. For example, the steady towing tension in a submerged towing mode at 5 knots is approximately 2600 pounds (Figure 15). Assume then that the vehicle is being towed at 5 knots using a towline 400 feet in length. From Figure 13b, if waves of 8-foot height are encountered at a frequency of approximately 0.5 radians per second, then even neglecting the effects of the towing ship motions, the dynamic oscillatory component of towline tension will reach a value equal to the steady (or calm water) towing tension. The total towing tension thus will alternate between values of 5200 pounds and zero pounds (slack towline). At higher towing speeds, however, with a consequent increase in steady towing tension and a decrease in the dynamic component of tension, this same wave would not produce a slack towline condition.

2. An estimate of the required strength of the prototype towline can be made by assuming *worst* case conditions:

a. The vehicle is being towed in a submerged condition in waves that regularly reach 12 feet in height and the frequency of encounter is somewhere between 0.5 and 1.5 radians per second (these conditions approximate towing in a State 5 sea).

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[6]St. Denis, Manley and Willard J. Pierson, Jr., "On the Motions of Ships in Confused Seas," Trans. SNAME, Vol. 61 (1953).

b. Towing depth restrictions are imposed and a 300-foot towline length is selected (for this length of towline a towing depth of between 100 and 125 feet will be obtained).[1]

c. The towing ship fantail motions have a double amplitude which is twice that of the wave height.

d. The oscillatory components of tension resulting from heaving motions of the towing platform and from the waves can be added directly.

The following approximate peak towing tensions then would be expected to regularly occur: 39,000 pounds at 5 knots (Figures 12b, 13b, and 15); 29,000 pounds at 10 knots (Figures 12c, 13c, and 15); and 32,000 pounds at 15 knots (Figures 12d, 13d, and 15). In designing for such towing conditions a nylon towline having a breaking strength of around 150,000 pounds should be selected. For these conditions, the normally expected peak tensions would be well within the recommended working loads of the towline and an additional margin of safety would be available in the event that higher tensions occurred.

3. Peak towing tensions will be substantially reduced as towline length is increased. For example, if under the same wave conditions as above a towline length of 400 feet were used, peak towing tensions would be reduced to values approximating 16,000 pounds at 5 knots, 12,000 pounds at 10 knots, and 23,000 pounds at 15 knots. Additional towline length would be expected to further decrease peak tensions.

CONCLUSIONS

1. The full-scale vehicle will be dynamically stable in a seaway of at least the magnitude of a State 5 sea when towed from the forward lifting eyes with a vehicle nominal net positive buoyancy of 1200 pounds.

2. In a seaway with wave heights less than 5.0 feet, the vehicle when ballasted to a net positive buoyancy of 1200 pounds will spontaneously submerge at a speed of approximately 4.5 knots. In larger waves, the speed at which submergence will occur is reduced to approximately 3.5 knots.

3. A 2.5-inch-diameter nylon towline having a breaking strength of 150,000 pounds should be adequate for all probable towing conditions even in a seaway approximating a State 5 sea.

4. Peak towing tensions may be minimized by using a long towline. In a State 5 sea, peak towing tensions should be reduced by a factor of at least two as towline length is increased from 300 to 400 feet. Since additional towline length would be expected to further decrease peak tensions, towline lengths of up to 600 or 700 feet should be considered whenever water depths permit (a towline 700 feet in total length would produce a nominal towing depth of approximately 175 feet).[1]

ACKNOWLEDGMENTS

The authors would like to express their gratitude to Mr. William Sandberg of the Naval Ship Engineering Center for his assistance in locating prototype data. Credit for highly adaptive instrumentation design, especially in the case of the package developed for the small-scale Model 5200 goes to Mr. William Vonfeldt of NSRDC Code 1548.

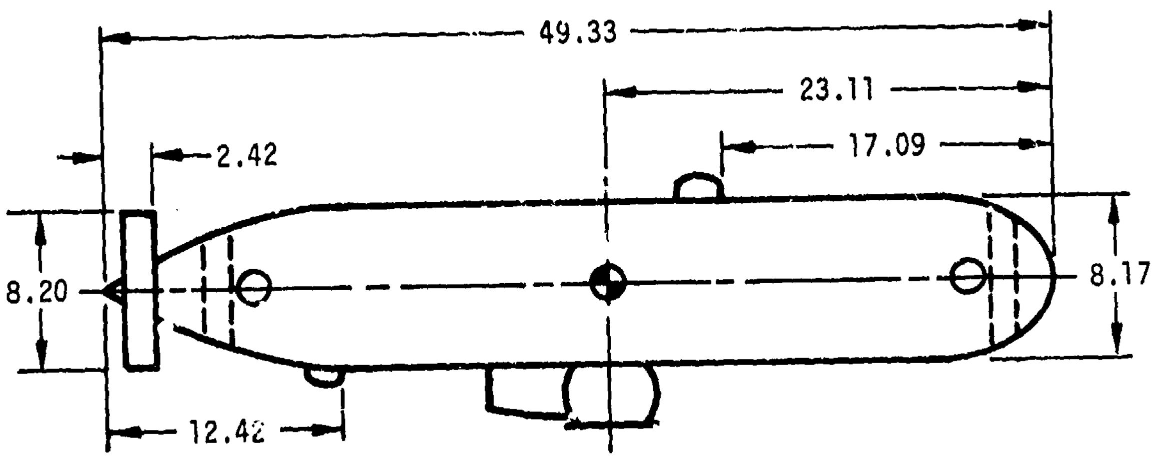

Figure 1 – DSRV Hull Geometry Showing Principal Full-Scale Dimensions

(All dimensions are in feet)

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Figure 2 – Profile View of DSRV Model 5200

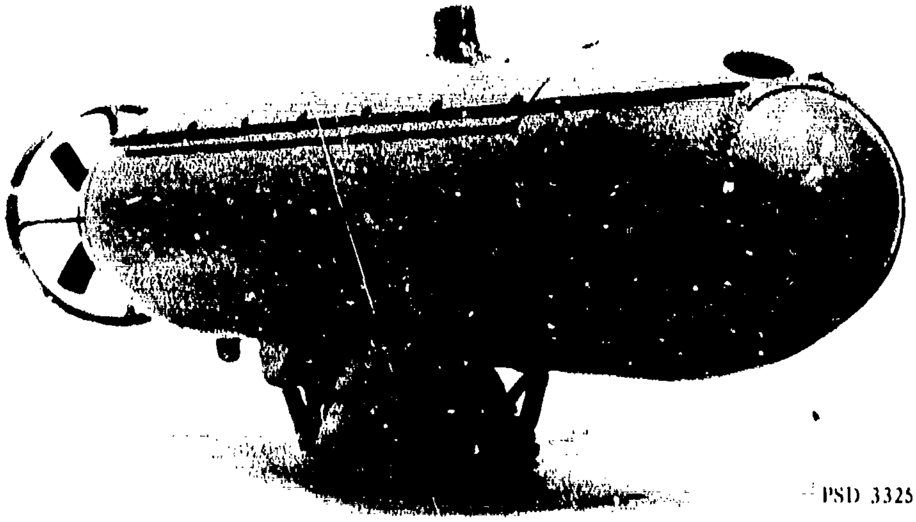

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Figure 3 -- Starboard Bow View of DSRV Model 5200

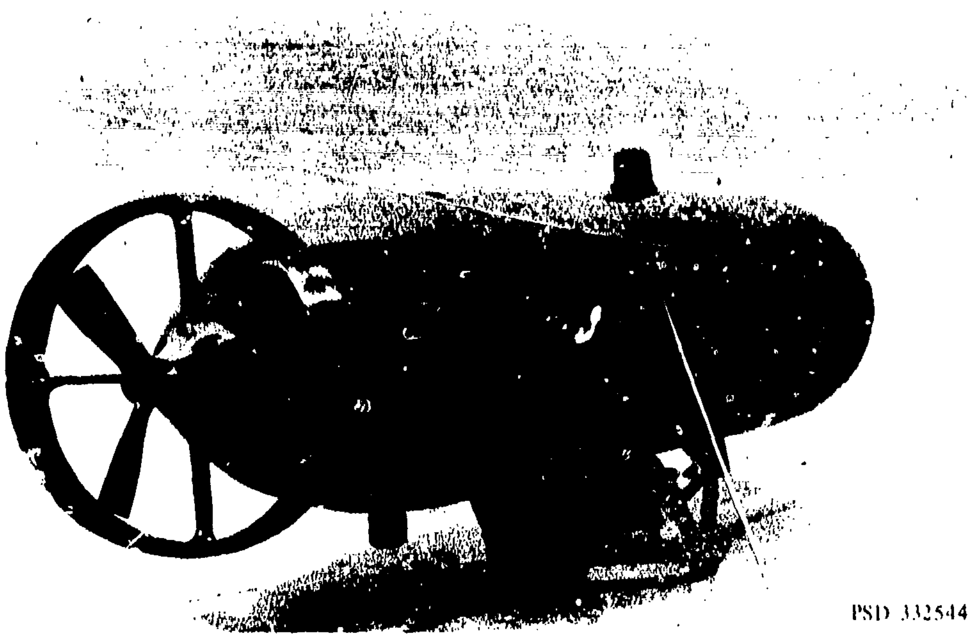

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Figure 4 -- Starboard Quarter View of DSRV Model 5200

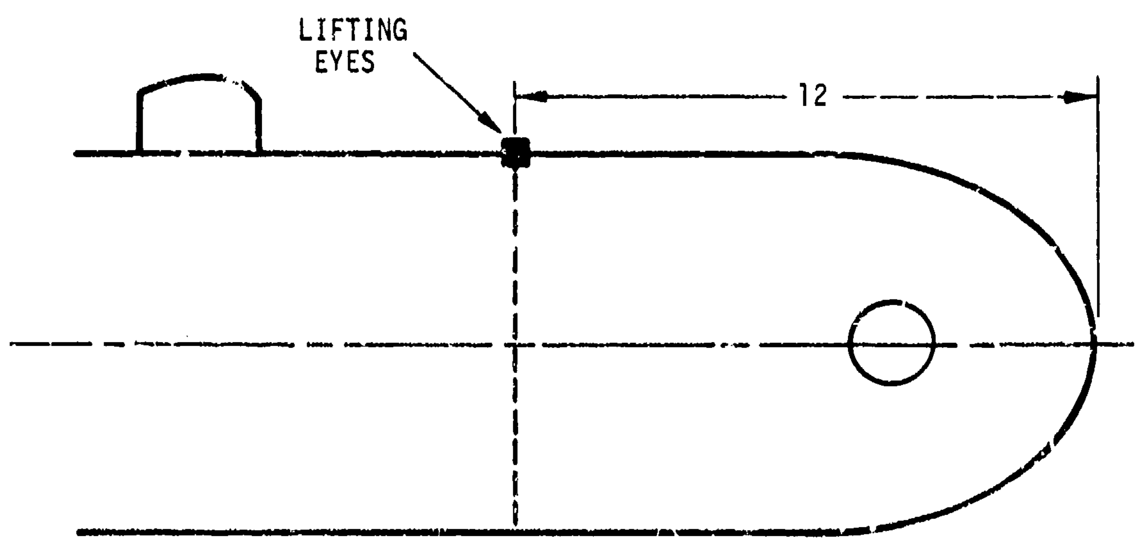

Figure 5 — Side View Showing Effective Full-Scale Location of the Towpoint on the Forward Hard Ring

(All dimensions are in feet)

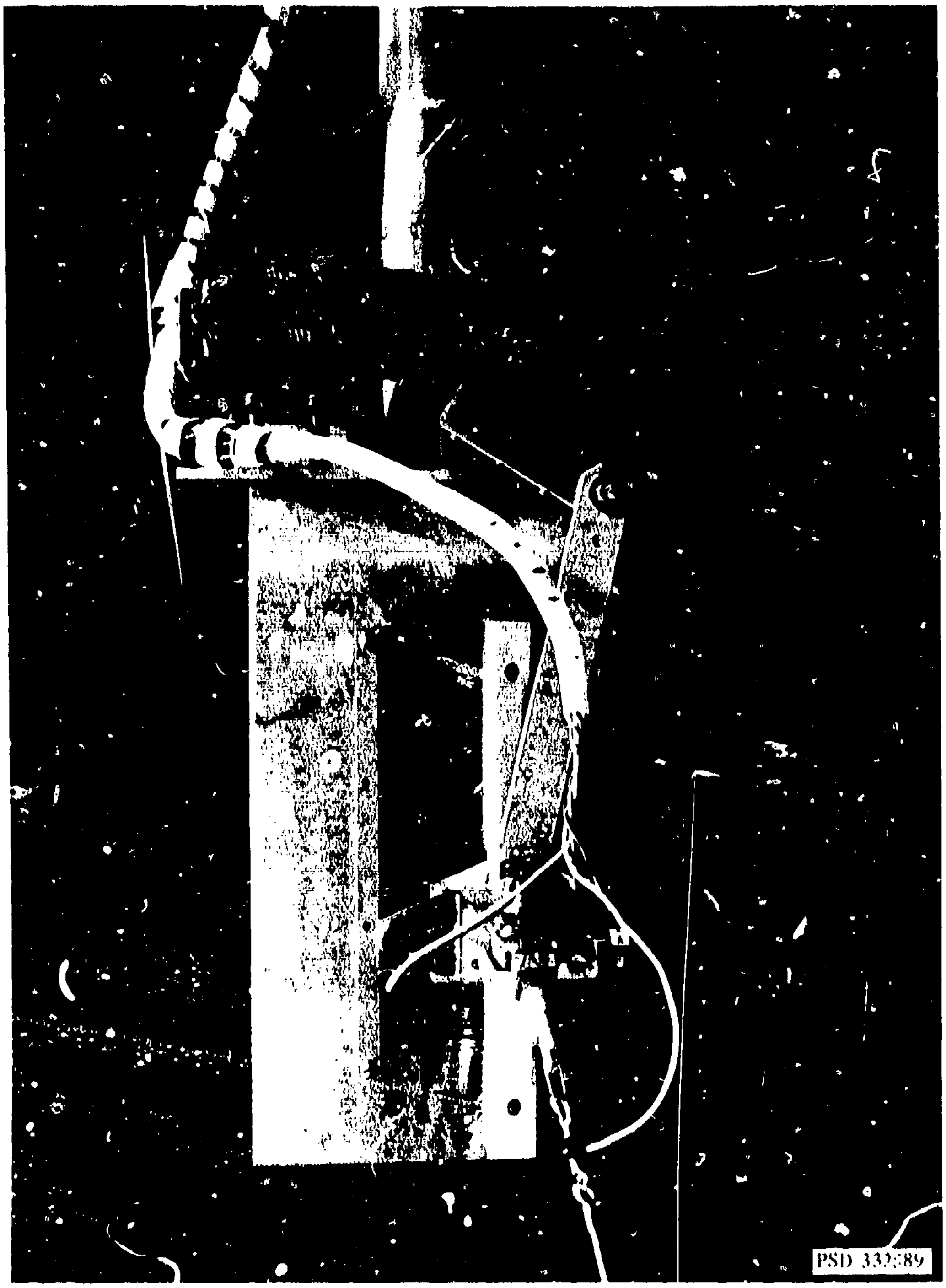

Figure 6 - Front View of Towing Strut Assembly

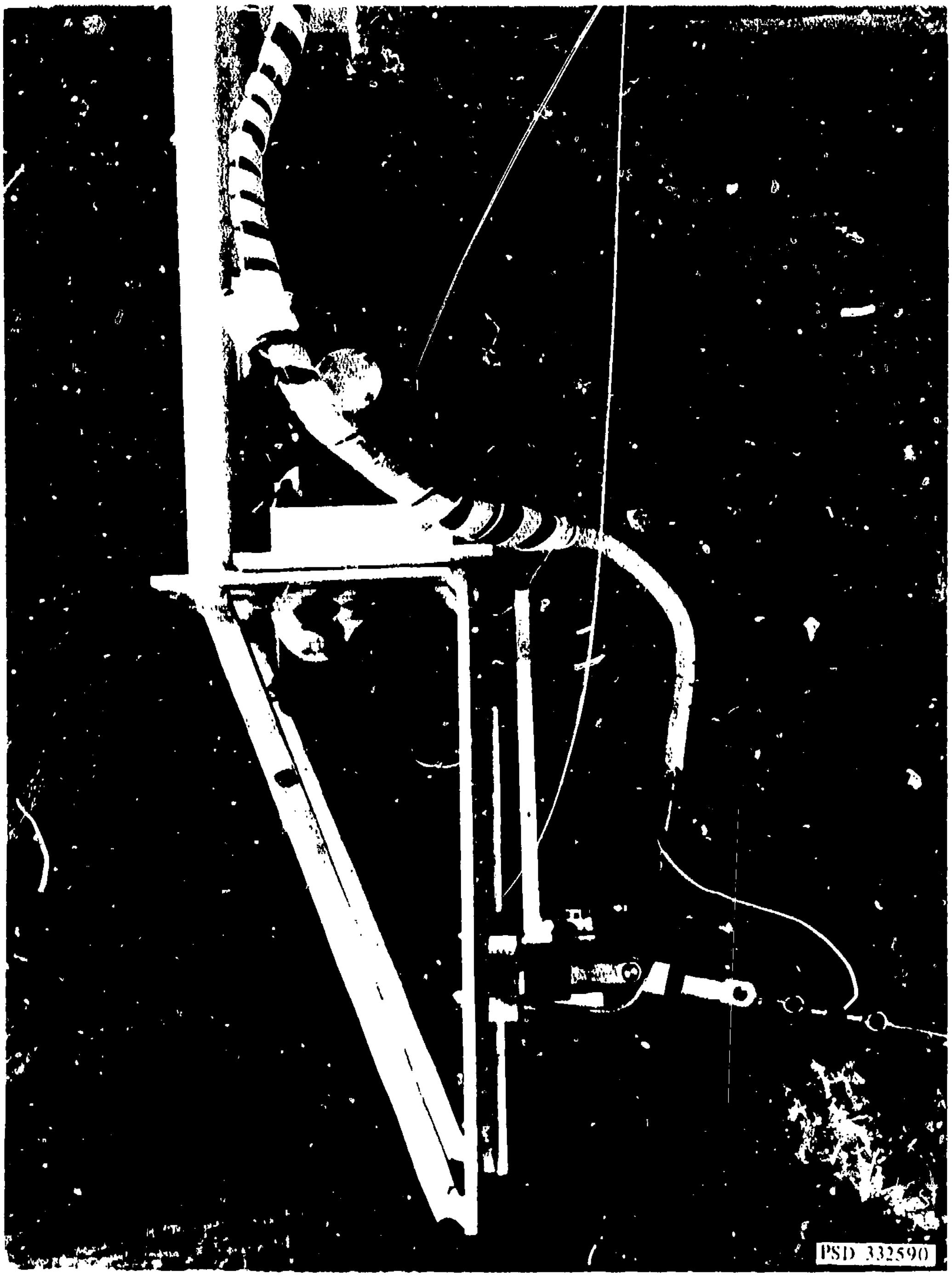

Figure 7   Side View of Towing Strut Assembly

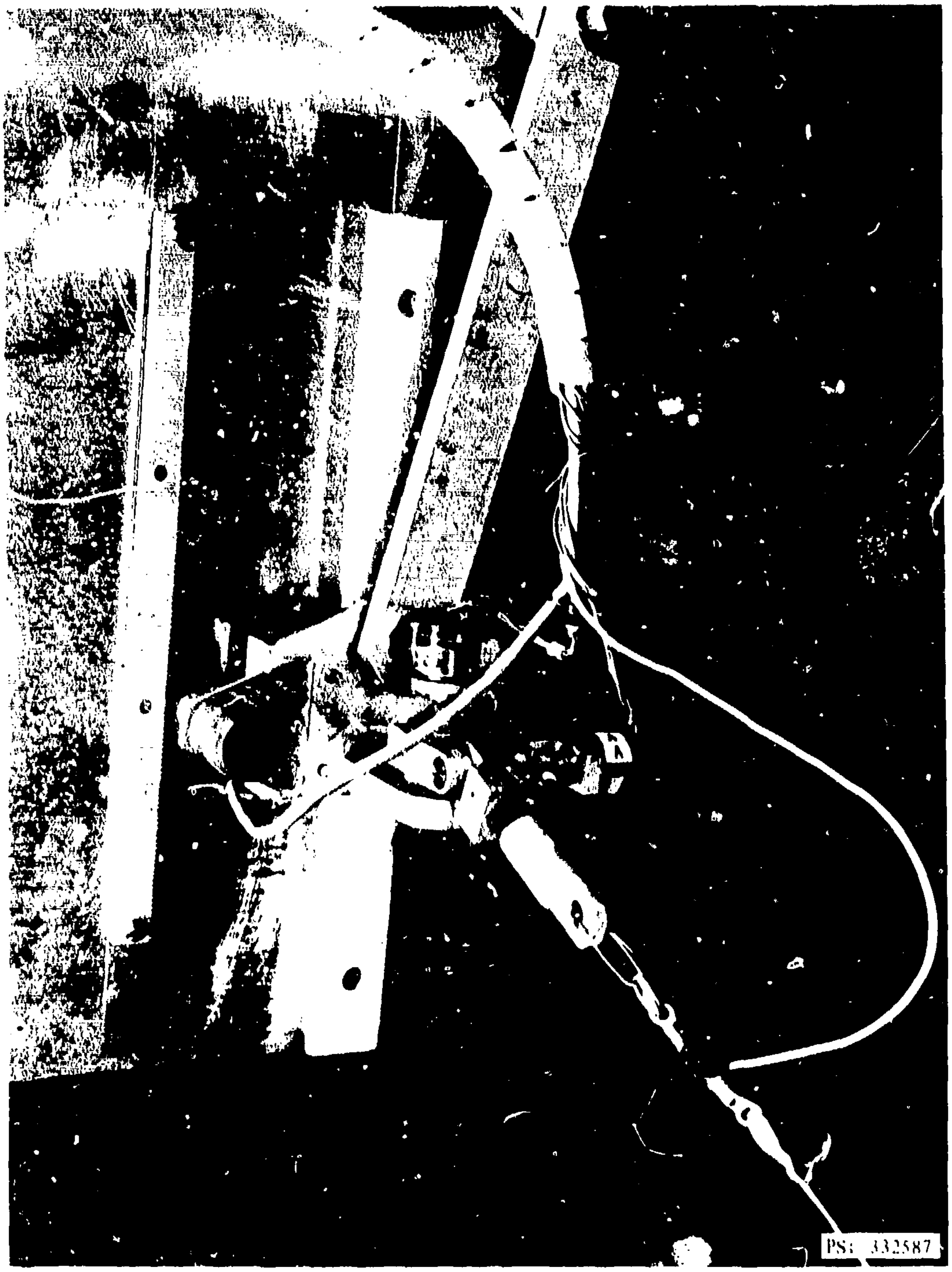

Figure 8 – Details of Heaving Towpoint

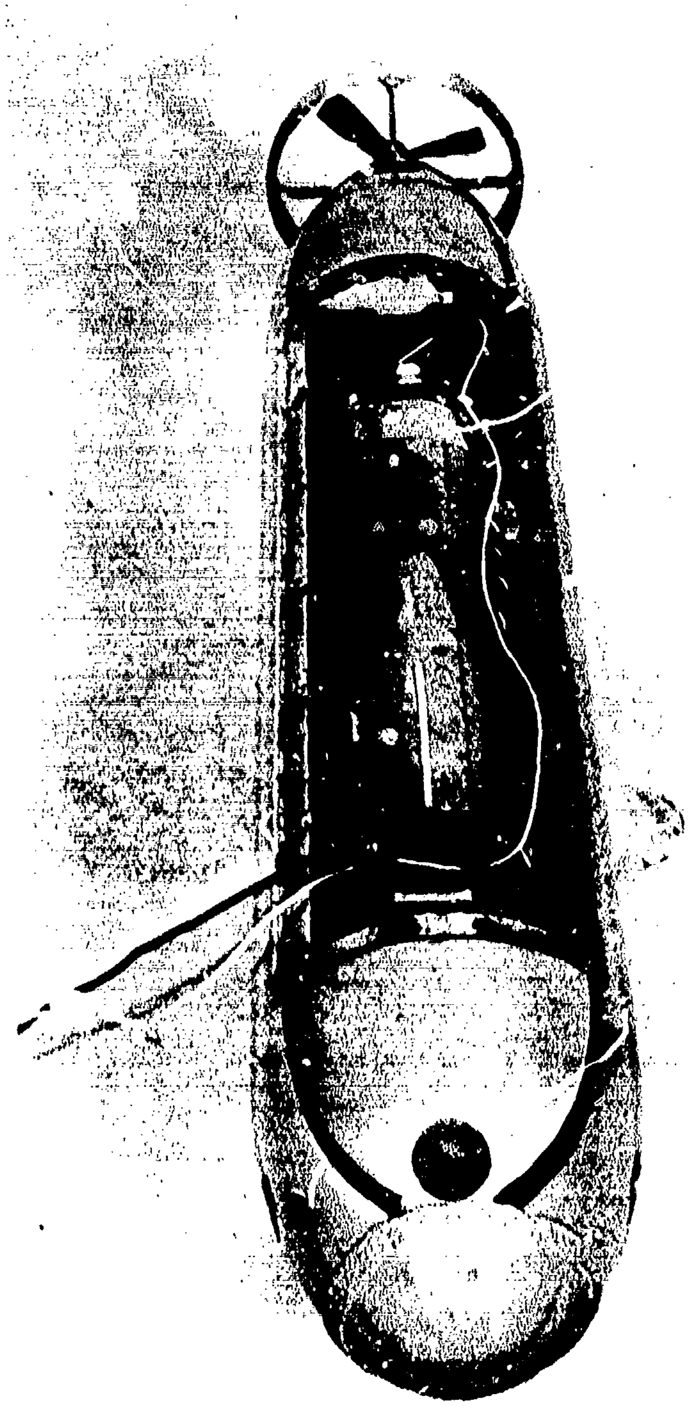

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Figure 9 – General Instrumentation Layout in DSRV Model

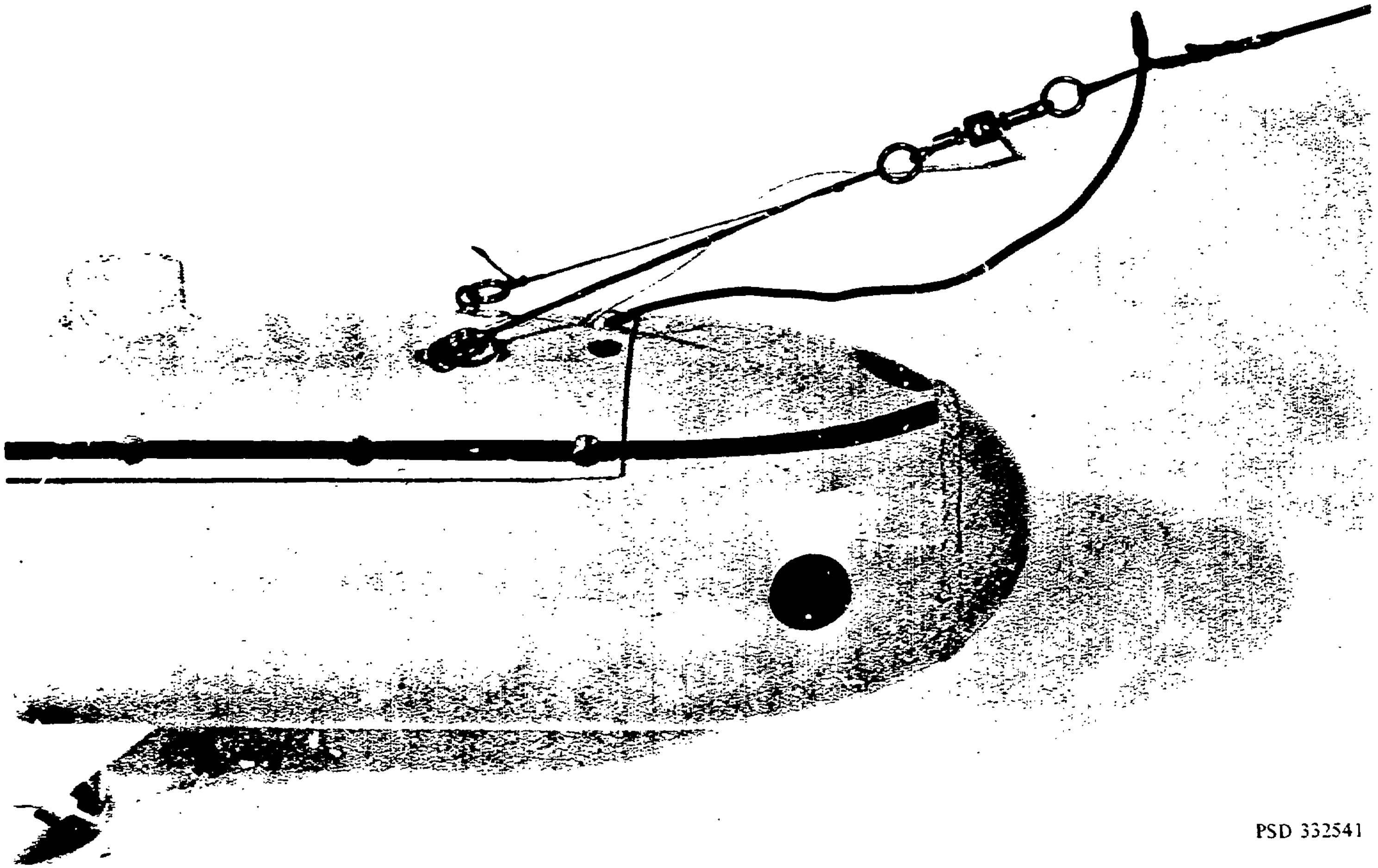

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Figure 10 – Towing Bridle Rigged to Lifting-Eye Towpoint on DSRV Model
Showing Position of Tension Link

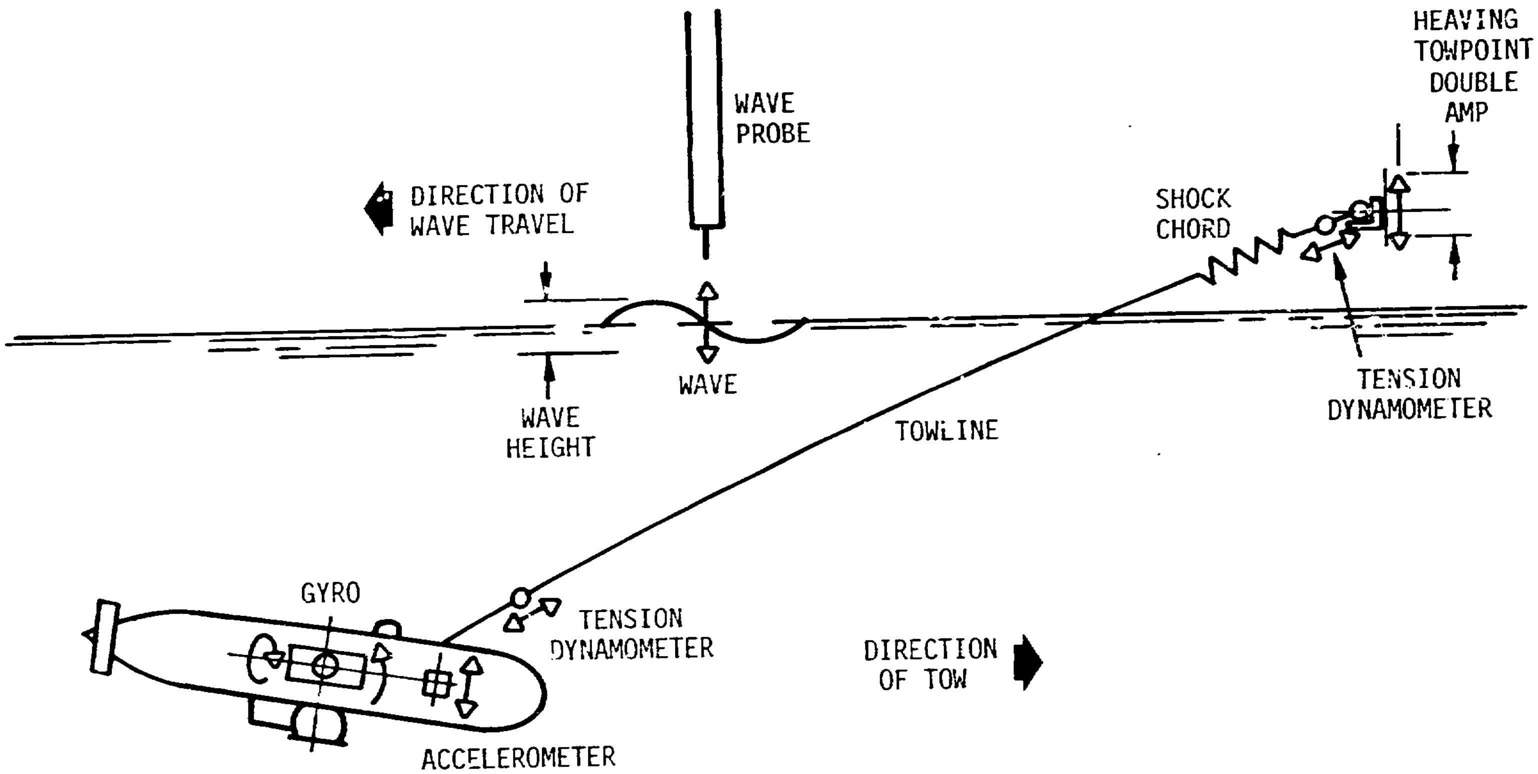

Figure 11 – Schematic Diagram of Model Towing Arrangement

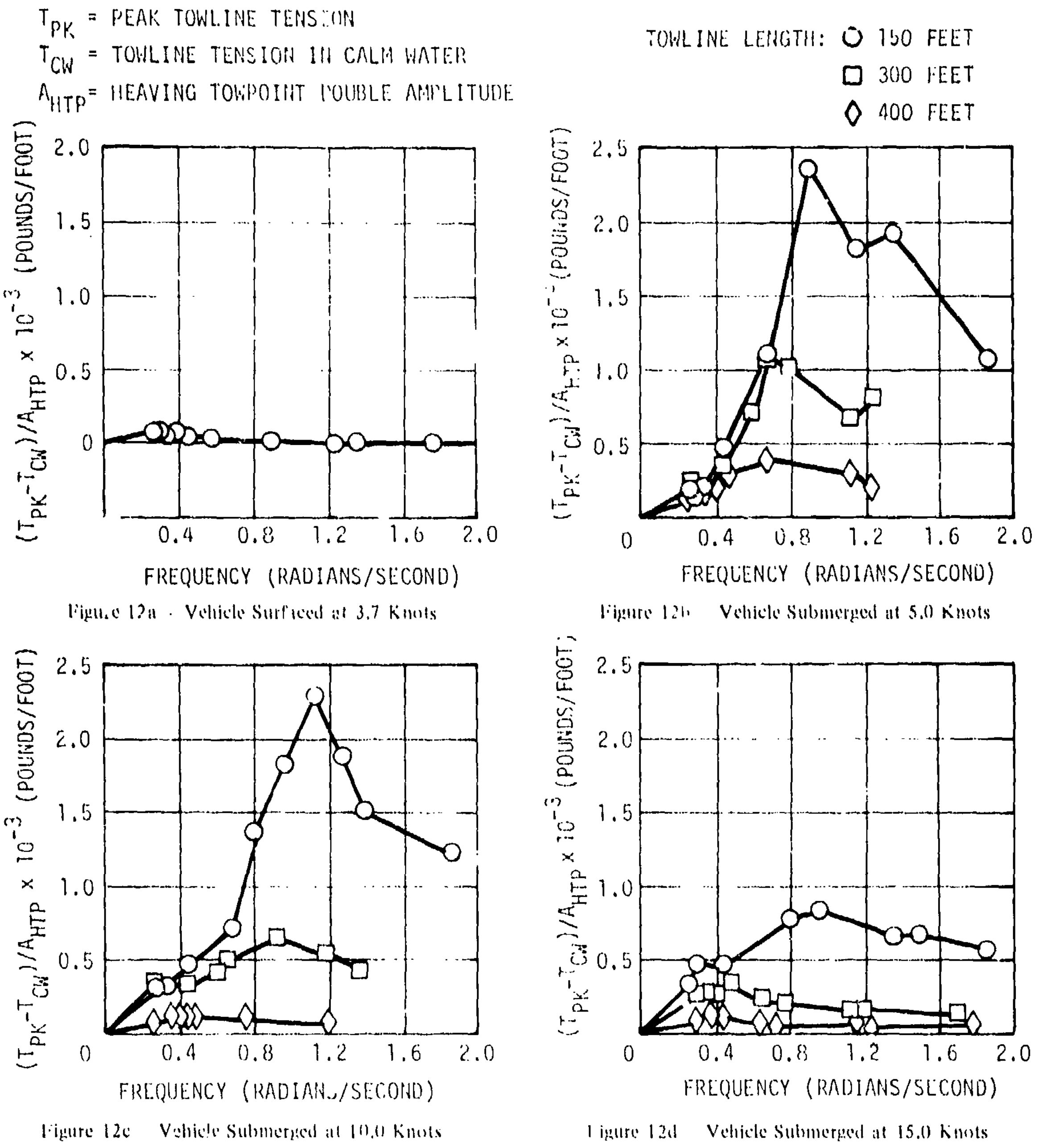

Figure 12a - Vehicle Surfaced at 3.7 Knots

Figure 12b - Vehicle Submerged at 5.0 Knots

Figure 12c - Vehicle Submerged at 10.0 Knots

Figure 12d - Vehicle Submerged at 15.0 Knots

Figure 12 Normalized Towline Tension Response Due to Heaving Motions of the Towing Platform as a Function of Heaving Frequency for Various Towing Speeds and Towline Lengths

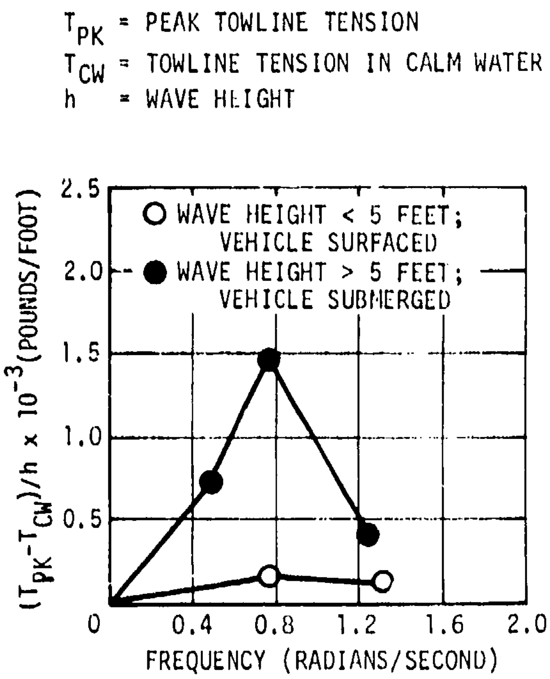

Figure 13a -- Vehicle Surfaced and Submerged at 3.7 Knots

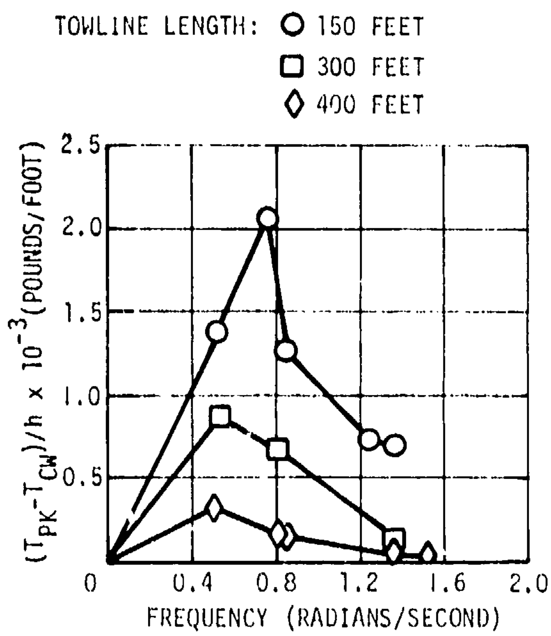

Figure 13b Vehicle Submerged at 5.0 Knots

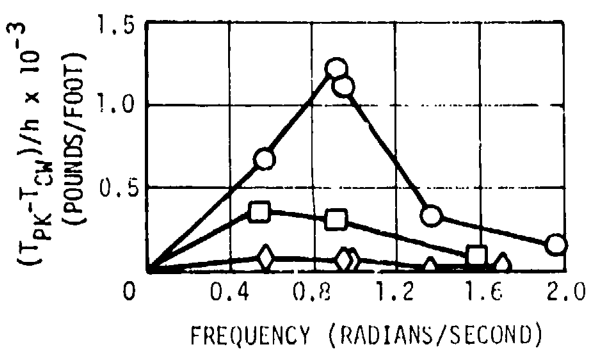

Figure 13c Vehicle Submerged at 10.0 Knots

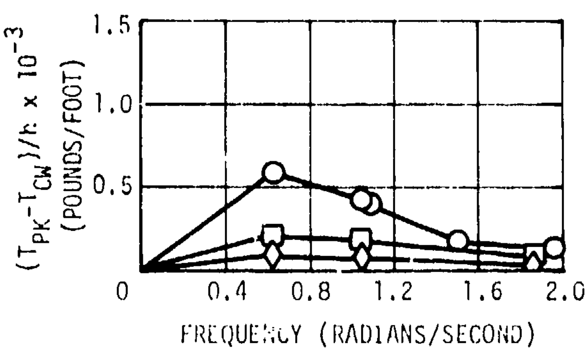

Figure 13d Vehicle Submerged at 15.0 Knots

Figure 13 Normalized Towline Tension Response Due to Regular Waves as a Function of Frequency of Encounter for Various Towing Speeds and Towline Lengths

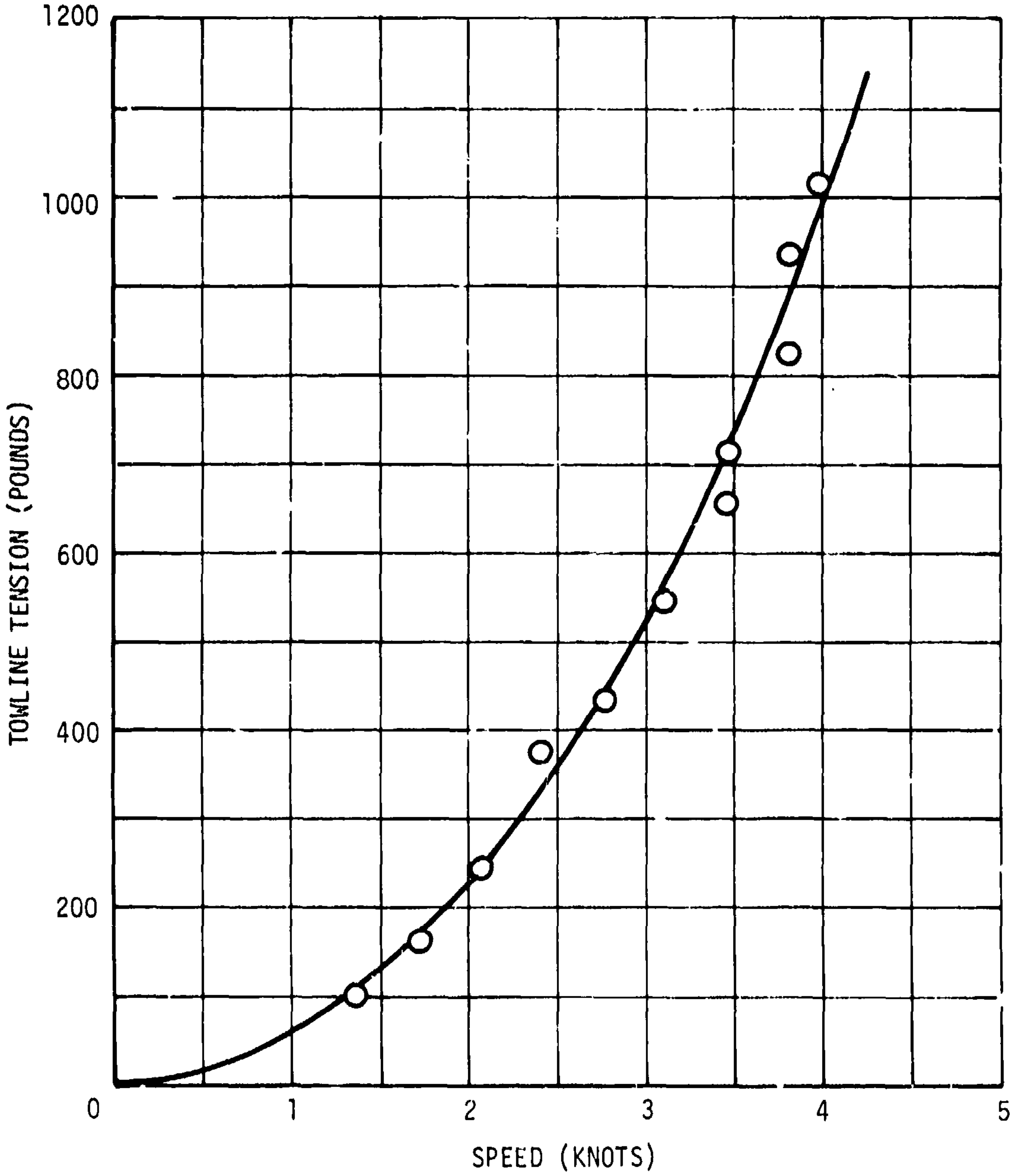

Figure 14 – Calm Water Surface Towing Tension at Vehicle as a Function of Towing Speed using the Lifting-Eye Towpoint
(From Reference 2)

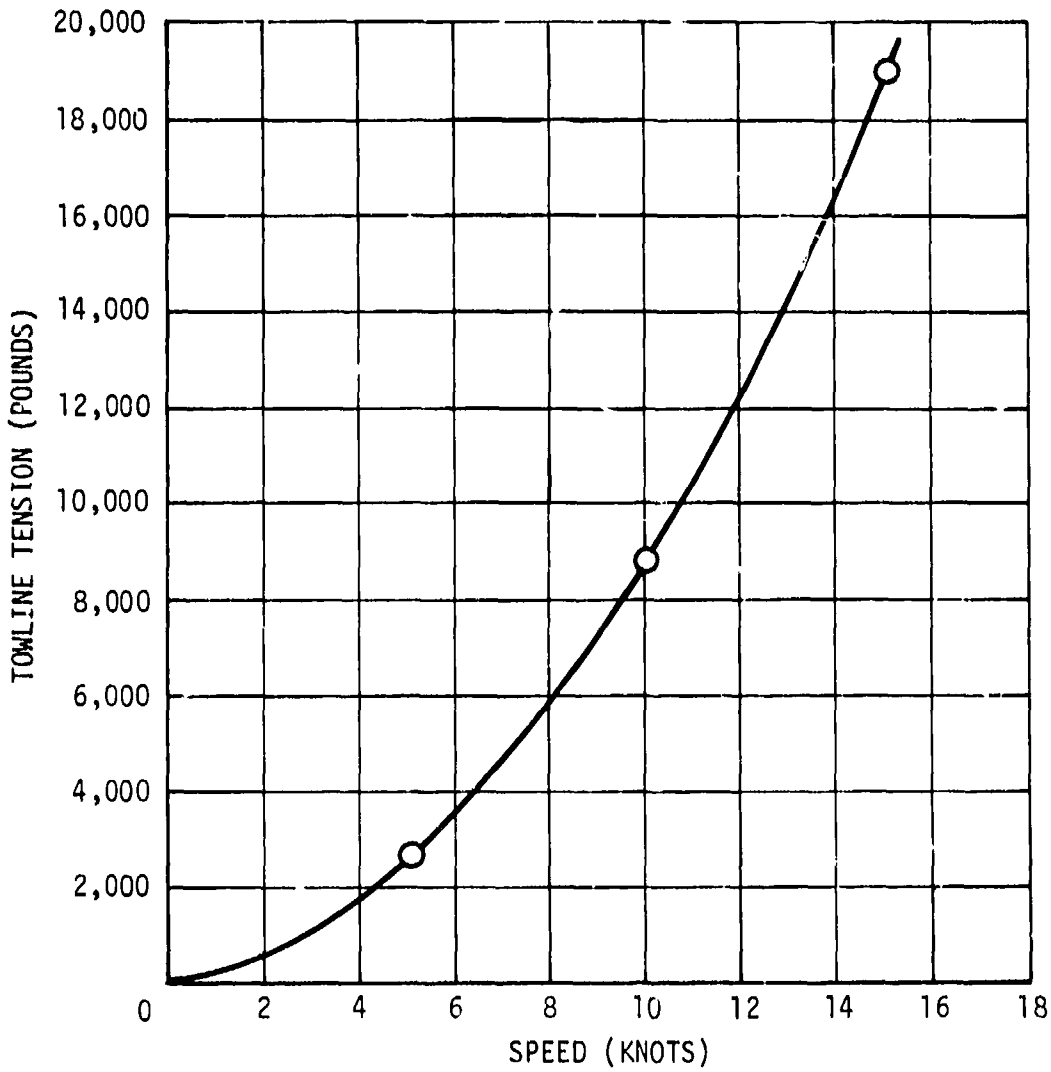

Figure 15 – Calm Water Submerged Towing Tension at Vehicle as a Function of Speed using the Lifting-Eye Towpoint
(Vehicle net buoyancy: 1170 pounds)

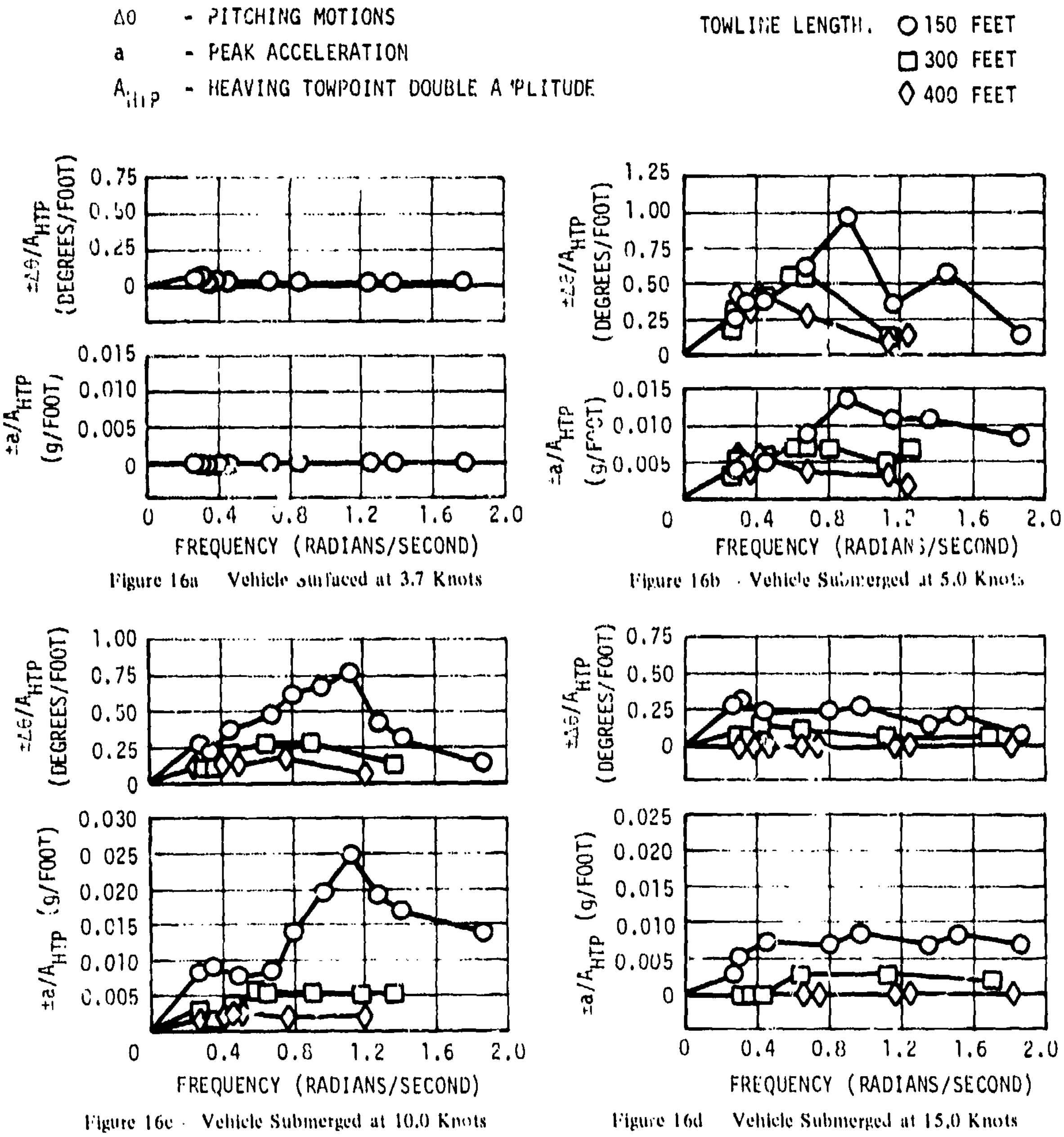

Figure 16a – Vehicle Surfaced at 3.7 Knots

Figure 16b – Vehicle Submerged at 5.0 Knots

Figure 16c – Vehicle Submerged at 10.0 Knots

Figure 16d – Vehicle Submerged at 15.0 Knots

Figure 16 – Normalized Pitching Motions and Vertical Accelerations below Lifting Eyes Due to Heaving Motions of the Towing Platform as Functions of Heaving Frequency for Various Speeds and Towline Lengths

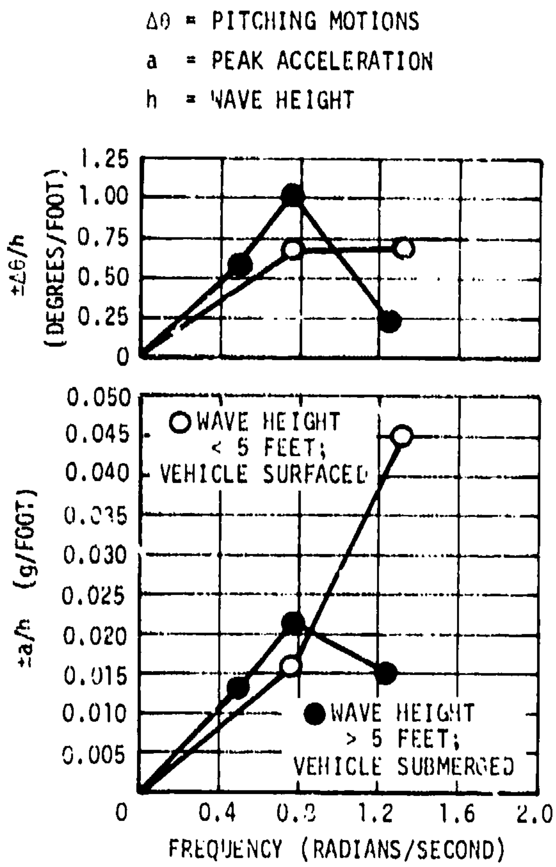

Figure 17a – Vehicle Surfaced and Submerged at 3.7 Knots

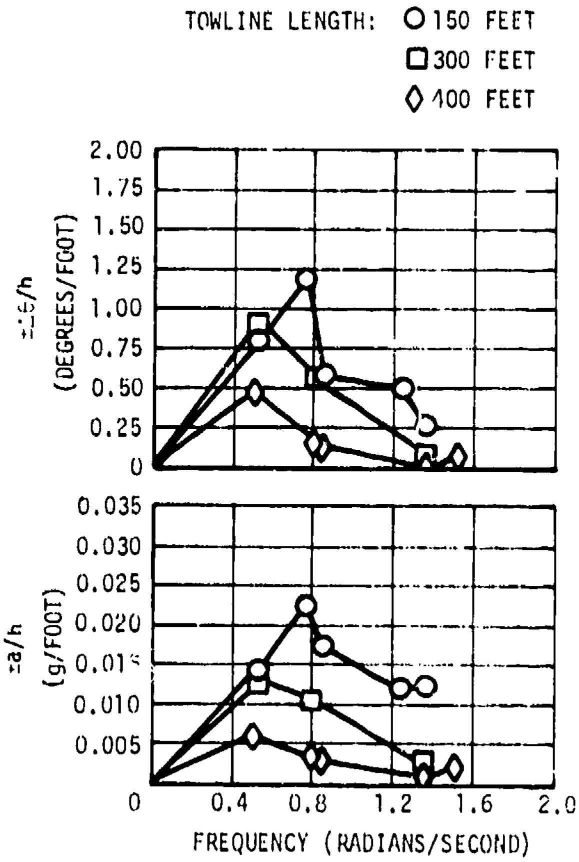

Figure 17b – Vehicle Submerged at 5.0 Knots

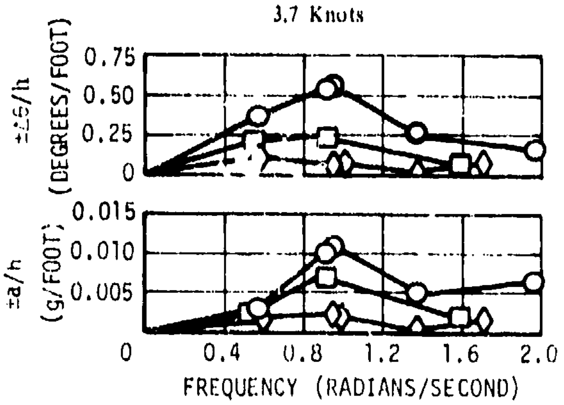

Figure 17c – Vehicle Submerged at 10.0 Knots

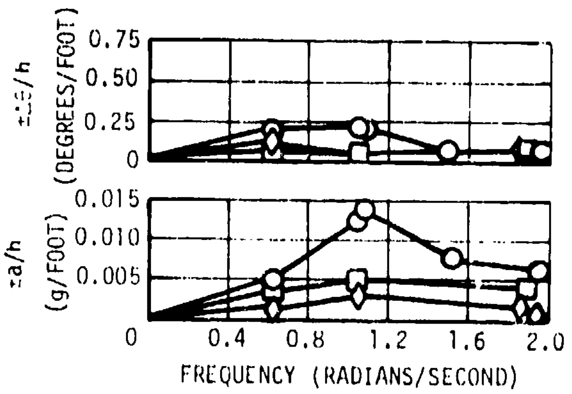

Figure 17d – Vehicle Submerged at 15.0 Knots

Figure 17 – Normalized Pitching Motions and Vertical Accelerations below Lifting Eyes Due to Waves as Functions of Frequency of Encounter for Various Speeds and Towline Lengths

TABLE 1 – GEOMETRICAL CHARACTERISTICS OF THE DSRV PROTOTYPE AND MODEL

(Model number 5200, Linear scale ratio: 21.28)

General Characteristics	Prototype	Model
Overall Length, feet	49.33	2.32
Maximum Diameter, feet	8.17	0.38
Fineness Ratio	6.04	6.04
Wetted Surface Area, square feet	1318.2	2.91
Volume of Hull Envelope, cubic feet	2184.5	0.27
Longitudinal Distance to Centroid of Hull Envelope from Forward Perpendicular, feet	23.11	1.09
Height of Centroid of Hull Envelope above Baseline, feet	3.92	0.18
Stern Shroud		
Maximum Diameter, feet	8.20	0.39
Section Chord, feet	1.83	0.09
Planform Area, square feet	14.62	0.03
Aspect Ratio	4.33	4.33
Section Chord Angle, degrees	3.5	3.5
NACA Section Profile (minus 8.33 percent at trailing edge)	0015	0015
Longitudinal Distance to Leading Edge from Aft Perpendicular, feet	2.42	0.11
Stern Propeller		
Diameter, feet	6.00	0.28
Number of Blades	3	3
Blade Rake Angle, degrees	17.72	0
Pitch Ratio at 0.7 Radius	0.93	0.40

TABLE 2 BALLAST CONDITIONS AND INERTIAL PROPERTIES FOR THE DSRV PROTOTYPE AND MODEL

(Model number: 5200, Linear scale ratio: 21.28)

Ballast Conditions	Prototype	Model*
Total Weight (including entrained water), pounds	138,849	14.030**
Buoyancy of Hull Envelope, pounds	140,019	14.148
Net Positive Buoyancy, pounds	1,170	0.118**
Longitudinal Distance to Center of Total Mass from Forward Perpendicular, feet	23.11	1.086
Height of Center of Total Mass above Baseline, feet	3.76	0.177
Vertical Distance between Centroid of Hull Envelope and Center of Total Mass, feet	0.15	0.007
Moment to Roll 1 Degree, foot-pounds	354.3	0.00173
Inertial Properties		
Moment of Inertia in Roll, slugs-square feet	37,800	0.008
Moment of Inertia in Pitch, slugs-square feet	452,000	0.115
Moment of Inertia in Yaw, slugs-square feet	450,000	----
Natural Submerged Period of Oscillation in Roll, seconds	11.0	2.2
Natural Submerged Period of Oscillation in Pitch, seconds	41.4	9.0

*Experimentally determined.

**Condition for experimentation.

TABLE 3 – ELASTIC PROPERTIES OF THE MODEL TOWLINES AND REPRESENTATIVE NYLON ROPES

	Unstretched Length feet	Elongation at 30,000 Pounds feet
Full-Scale Equivalent of Model Towline	150	17
	300	41
	400	41
2.0-Inch-Diameter, Double-Braided Nylon Rope (breaking strength: 92,000–100,000 pounds)	150	20–24
	300	39–47
	400	52–63
2.5-Inch-Diameter, Double-Braided Nylon Rope (breaking strength: 150,000–160,000 pounds)	150	17–20
	300	34–39
	400	45–52

TABLE 4 – CHARACTERISTICS OF THE REGULAR WAVES SELECTED FOR EXPERIMENTS

Wave Designator	Wavemaker Blower Speed, rpm	Model		Full-Scale	
		Nominal Height, feet	Nominal Frequency, radians/second	Nominal Height, feet	Nominal Frequency, radians/second
B	500	0.19	5.03	4.0	1.09
C	350	0.17	3.14	3.6	0.68
D	1000	0.38	5.03	8.0	1.09
E	650	0.38	3.14	8.0	0.68
F	600	0.47	2.09	10.0	0.45