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SEAWORTHINESS CHARACTERISTICS OF A GROUND EFFECT MACHINE OBTAINED FROM MODEL TESTS OVER REGULAR WAVES

by

Alvin Gersten
and
Joseph M. Sheehan

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NOTATION

G	Nozzle width
h	Wave height (distance from crest to trough)
$\tilde{h}$	Height of nozzle exit from reference surface
L	Cushion length (50 ft full scale)
z	Single amplitude of heave
η_A	Augmentation efficiency
θ	Maximum wave slope
λ	Wave length
ψ	Single amplitude of pitch
ω_e	Frequency of wave encounter

ABSTRACT

A model representing a ground effect machine (GEM) designed by the Bureau of Ships for over-water operation has been towed over regular waves allowing freedom in pitch and heave. The tests were conducted with the craft traveling in following seas. Measurements were made of the resulting motions, drag forces, and accelerations.

The data reveal that at speeds up to 40 knots, the pitching motion per unit wave height of the GEM is generally more severe than that experienced by conventional small craft and large oceangoing ships. The heaving motion per unit wave height of the GEM is also greater than the characteristic heaving motion of more conventional vessels. It was also determined that pitch and heave motions and surge force are linearly related to wave height throughout the range utilized in these tests. Wave steepnesses (h/λ) as great as 1/32 were investigated.

ADMINISTRATIVE INFORMATION

The study reported herein was performed at the request of the Bureau of Ships as Task 10275 of Project No. S-F013 02 08.

INTRODUCTION

During the past decade, there has been increasing interest in the potentialities of air cushion vehicles. These craft may operate over unprepared terrain and at relatively high speed over water. They are potentially useful to the fleet in antisubmarine warfare missions or as amphibious assault craft. However, it is not possible at present to specify the design characteristics required by ground effect machines (GEM) to efficiently carry out specific tasks.

The Bureau of Ships initiated a program of model studies and full-scale trials on their design of a 20-ton air cushion vehicle. This craft is to operate primarily over water and has therefore been categorized as a Hydroskimmer. BuShips requested the Taylor Model Basin to conduct tests on a model representing this research craft to evaluate its performance when operating over waves. In addition, a contract for detailed design and construction of the prototype was let to Bell Aerosystems Company.

During subsequent tests carried out at the Model Basin, measurements were made of drag over calm water and of pitch, heave, drag, heave acceleration, bow acceleration, and wave height with the model traveling over regular waves. The wave tests were conducted only for the condition where the model and waves were traveling in the same direction (following seas). This paper discusses the test procedures in detail and presents the experimental data obtained.

DESCRIPTION OF MODEL AND PROTOTYPE

The lines and principal characteristics of the Bureau of Ships 20-ton Hydroskimmer are shown in Figure 1 and Table 1, respectively.* In addition to having rough water capabilities at high speed, this vehicle must be able to ride onto a hard surface such as a beach. This ruled out the incorporation of nonducted water-piercing side skegs with transverse bow and stern nozzles because this type of craft cannot maintain its air cushion when traveling over a hard surface. This results from the inability of the solid skegs to provide an effective barrier against leakage of the relatively high pressure air. Moreover, the drag due to the immersed skegs during operation at sea is prohibitive at the design speed of 70 knots. The Hydroskimmer therefore incorporates bow and stern nozzles and short side skegs (not immersed when the sea is calm) with nozzles at their bases as shown in Figure 1. Thus, a full peripheral jet is provided.

A 1/5-scale model was constructed for the tests. The dynamic characteristics of the model represent those of the prototype with regard to motions in the vertical plane. As shown in Table 1, the model weight corresponds to 51,088 lb full scale, which is within the range of gross weights for prototype operation. The longitudinal radius of gyration was established at approximately 28 percent of vehicle overall length, which is the upper limit of gyradii expected during normal operation. The air source and ducting system were made an integral part of the model to simulate the cushionborne performance of the prototype as closely as possible.

The hull and nozzles were fabricated from fiberglass-reinforced plastic. This facilitated reproduction of the complex shapes and kept the weight-to-strength ratio of the model low.

The air was supplied by four electrically powered, axial flow AiResearch fans, each rated at 10 hp. These were located as shown in Figures 1 and 2. The air discharged into four noncommunicating plenum chambers. It then passed through the ducts shown in Figures 3 and 4 and exited beneath the craft. The peripheral ducts oriented the flow at an angle of 60 deg from the vertical. In addition, since the nozzle dimensions were scaled from the prototype, the flow rate at each nozzle was approximately the correct percentage of the total volume flow.

TABLE 1
Principal Characteristics of
20-Ton Hydroskimmer

	Prototype	Model
Length, overall	65 ft - 6 in.	13.1 ft
Length of Cushion	50 ft - 0 in.	10.0 ft
Beam, overall	22 ft - 0 in.	4.4 ft
Depth	12 ft - 0 in.	2.4 ft
Design Weight	45,000 lb	360.0 lb
Weight for tests	51,088 lb	408.7 lb
LCG Location	Station 25	Station 25
Radius of Gyration	0.28 LOA	0.28 LOA
Design Speed	70 Knots	31.3 Knots
Minimum cushion borne standoff at side nozzles	4.2 in	0.84 in.
Scale Ratio		1:5

*Subsequent to construction of the model used in this series of experiments, the prototype (now designated as SKMR-1) was altered appreciably. All specifications, drawings, etc., given in this paper are for the original Bureau of Ships design.

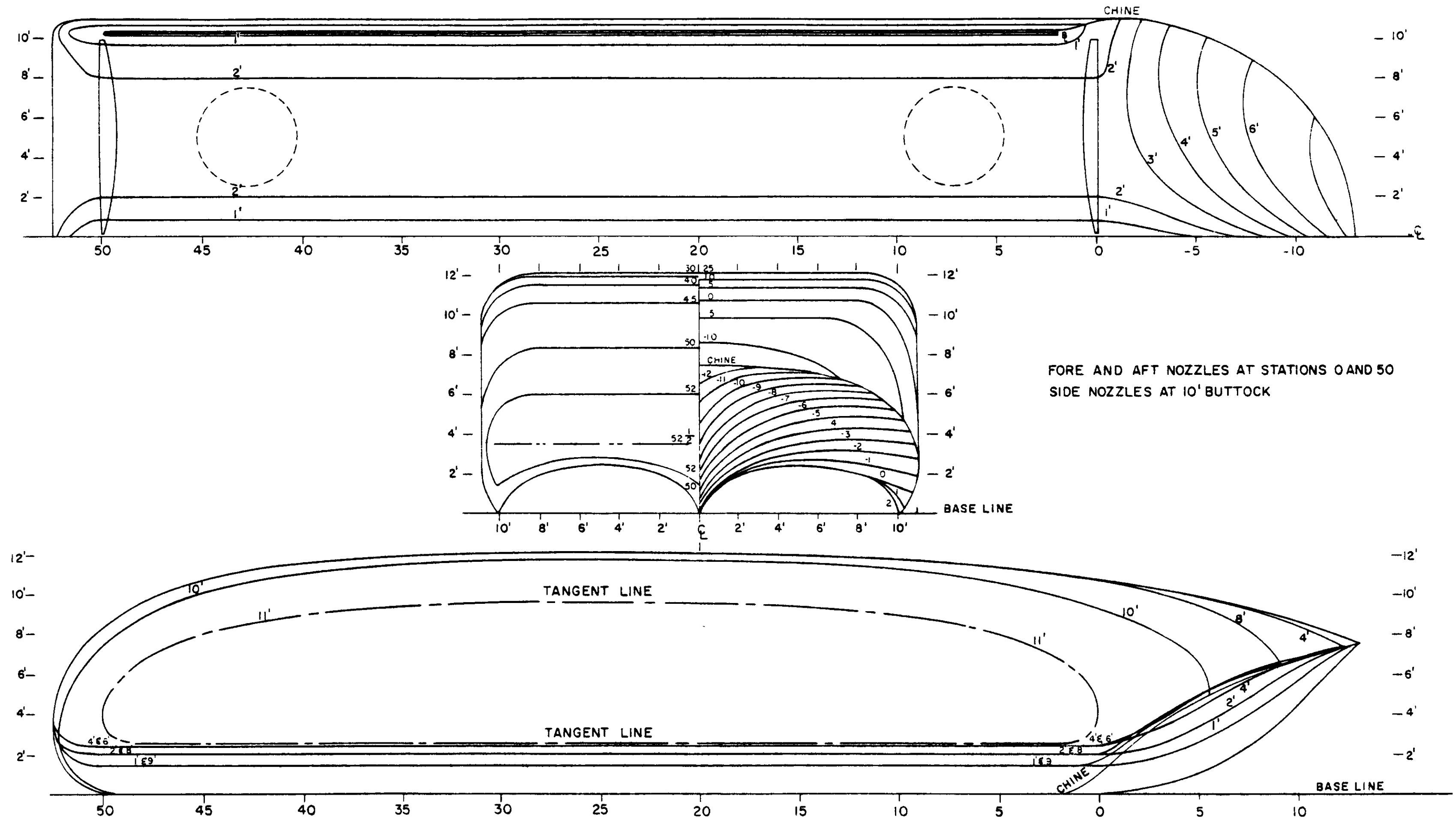

Figure 1 – Lines of 20-Ton Hydroskimmer

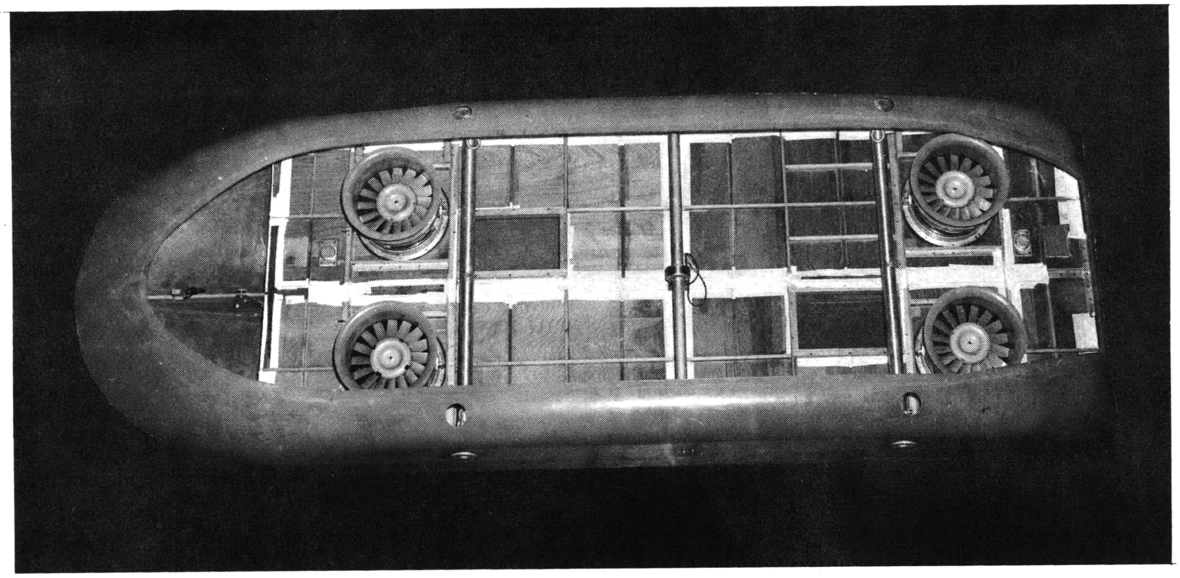

Figure 2 – Bird's-Eye View of Hydroskimmer Model

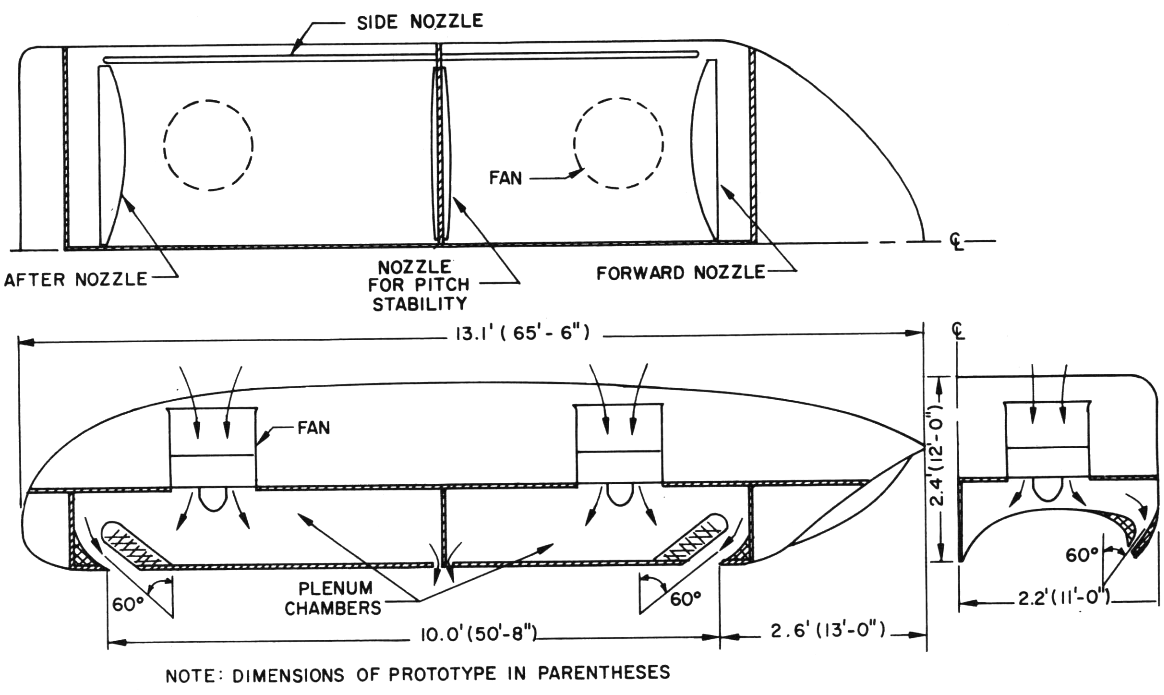

Figure 3 – Air Flow System for Hydroskimmer Model

As shown in Figure 5, the Hydroskimmer has a flared bow. This shape reduces downward pitch in waves by acting as a lifting surface and also reduces structural loading (as compared to a scow-type bow) during wave impacts. The bottom of the craft is recessed in a double arch along its entire length. This diminishes the amount of surface wetted during wave encounters and therefore reduces drag. It also increases the inherent strength of the hull so that fewer internal structural members will be required.

The nozzle configurations (width and angle) specified for this craft result in a high lift to air horsepower ratio.[1] A "nozzle width parameter" $\left(\frac{G}{\tilde{h}}\ \eta_A\right)$ is used to express the ratio of the nozzle width G to the height of the nozzle exit from the reference surface $\tilde{h}$. In this dimensionless ratio, η_A is the "augmentation efficiency." It is the ratio of the actual pressure acting on the base of the vehicle to that which would be calculated by means of simple momentum theory; η_A was assumed equal to 0.75 which is a probable value based on good design practice.[1] A nozzle width parameter value of 0.2 was established for all nozzles in order to keep the fan size and power requirements within a reasonable limit.

Since the $\tilde{h}$ values for the bow and stern nozzles varied with distance from the centerline of the craft, it was necessary to vary the width of these nozzles to keep $\frac{G}{\tilde{h}}\,\eta_A$ equal to 0.2. In addition, since $\tilde{h}$ is constant for the side nozzles (assuming zero trim), they have a constant thickness.

Initial experiments with the model hovering over a groundboard revealed that it had positive static stability in roll (due to transverse partitioning of the base by the longitudinal skeg on the centerline) but was unstable in pitch. To remedy this, a transverse nozzle was added midway between the bow and stern nozzles to provide longitudinal compartmentation of the base. No internal ducting was provided. This transverse nozzle, which can be seen in Figure 4, has a width three-fourths that of the end nozzles. It is split by the transverse and longitudinal bulkheads within the plenum chamber so that each of the four sections is fed by a different fan.

TEST SETUP AND INSTRUMENTATION

The deep water basin (1800 ft long, 52 ft wide, and 20 ft deep) was utilized for the experiments. It is equipped with a pneumatic-type wavemaker which generates regular waves. The carriage spanning the basin is capable of speeds up to approximately 18 knots but, for safety reasons, maximum speed is restricted to approximately 12 knots when traveling toward the wavemaker.

The Hydroskimmer model was towed under the carriage by the apparatus shown schematically in Figure 6. The attachment was made on the port and starboard sides of the model to a transverse tube passing above the center of gravity.

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[1]References are listed on page 27.

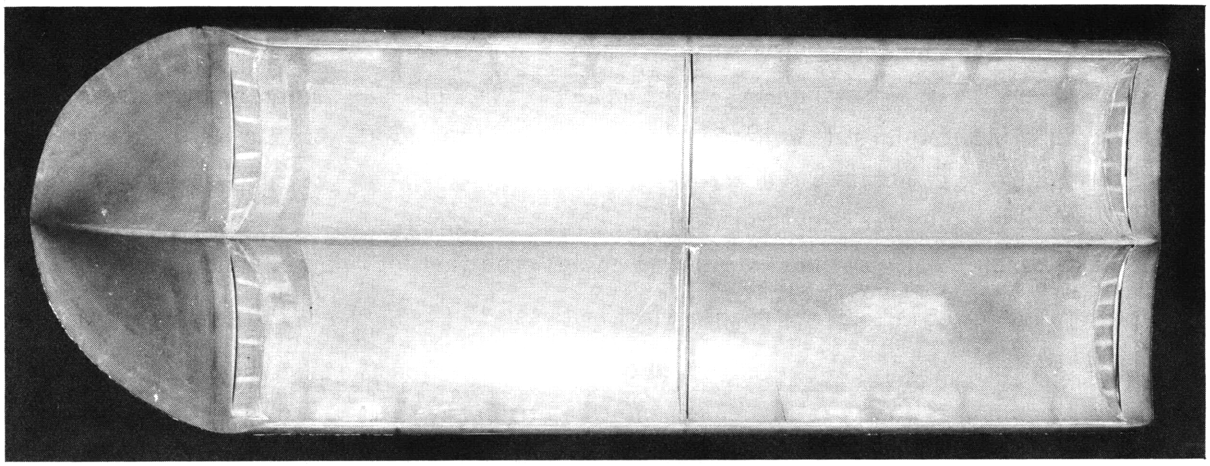

Figure 4 – Bottom View of Hydroskimmer Model

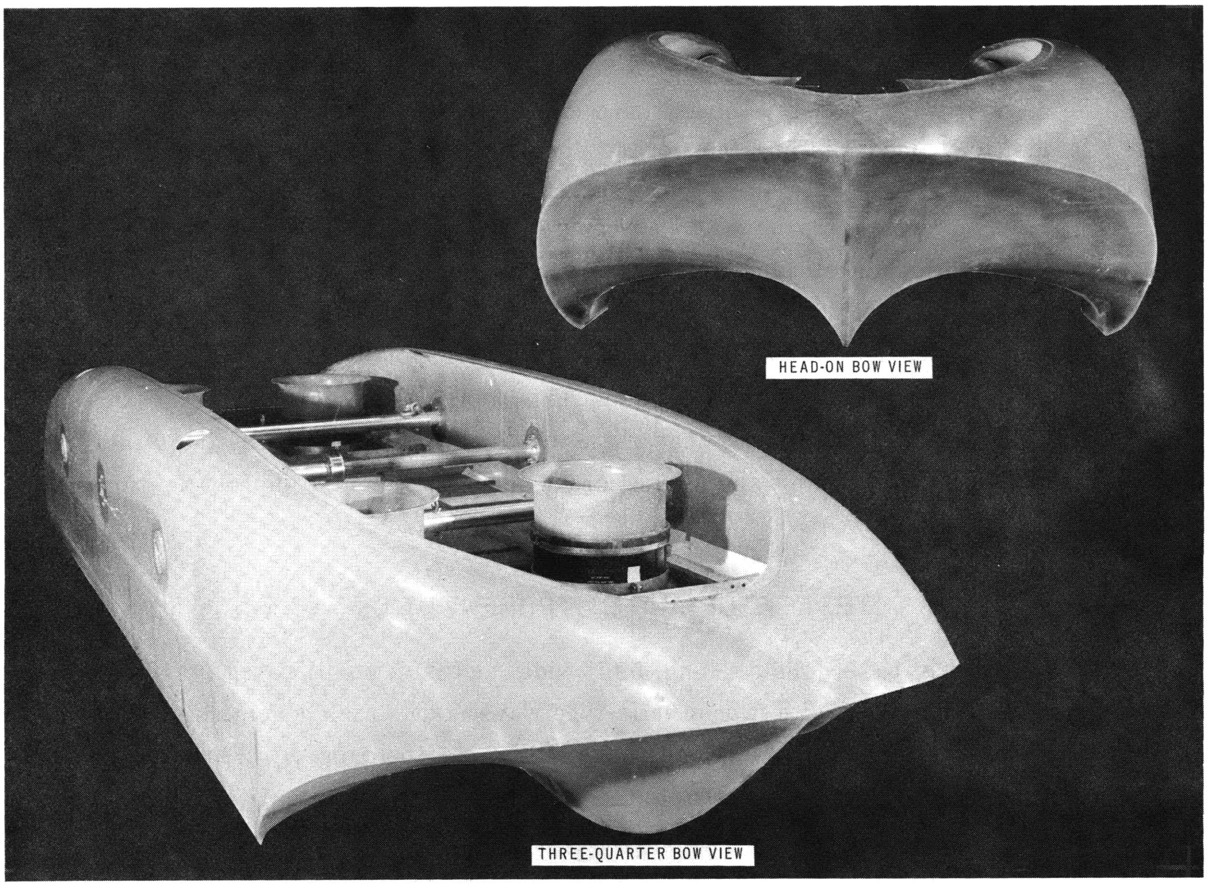

Figure 5 – Three-Quarter Bow View and Head-On Bow View of Hydroskimmer Model

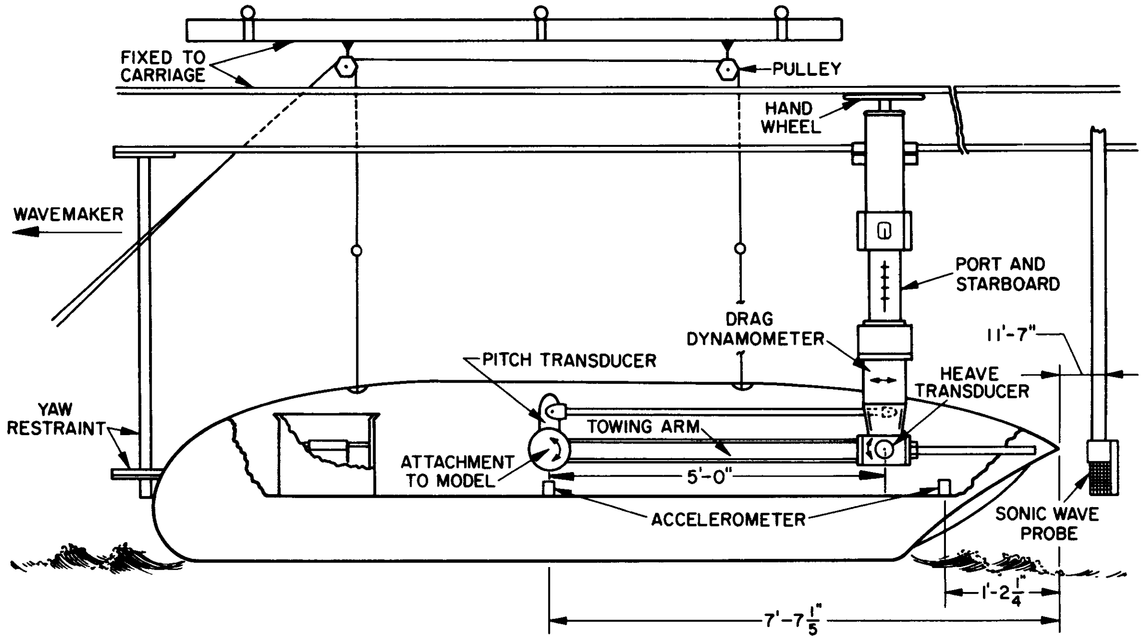

Figure 6 – Towing Gear and Transducer Arrangement

When a model travels normal to the wave crests, the significant motions normally occur in the vertical plane. Therefore, to simplify the towing gear, all motions were restrained except pitch and heave. Surge was restrained, and dynamometers were incorporated in the gear to provide drag measurements.

The various transducers employed are listed below:

Measurement	Transducer
Pitch	Computer Instruments rotary potentiometer
Heave	Shaevitz rotary differential transformer
Drag	TMB modular force gage
Bow acceleration	± 10g Statham accelerometer
Heave acceleration	± 2g Statham accelerometer
Wave height	Sonic wave probe
Model Speed	Slotted disk and induction coils mounted on towing carriage

Heave displacement was determined by measuring the vertical distance moved by the attachment point on the starboard tow arm. This point moved in an arc because of the towing arrangement. However, for the motions that occurred during these tests, the difference between the length of this arc and the length of its chord was less than 1/2 percent.

It was necessary to provide a nonrotating reference for the pitch transducer. This was done by mounting the transducer casing on a plate which made up one side of a parallelogram (the thin tube mounted above the towing arm forms another side). This plate always remains parallel to the fixed, vertical side opposite it.

The cable and pulley system shown in Figure 6 was used to support the model when the fans were not up to the required operating speed. After the model supported itself at the proper standoff, the cables were slackened.

All transducer signals were recorded on Sanborn strip chart recorders. Motion pictures were taken during the model flight down the tank.

TEST PROGRAM

The model tests were carried out over calm water, and regular waves having the dimensions given in Table 2. In this table, λ/L is the ratio of wave length to cushion length. The speeds at which the model was towed are also listed. Froude scaling was used to relate model and prototype speeds. Hovering tests were attempted, but these were discontinued because of the excessive amount of spray impinging on the electrically powered fans and also because model-generated disturbances were reflected back to the model by the tank walls and caused the craft to roll.

The Hydroskimmer performance was to be evaluated at speeds as close to the design speed as possible. Therefore, because of the aforementioned limitation on carriage speed (12 knots when traveling toward the mavemaker, i.e., head seas), the experiments were conducted with the model underway in following seas where a maximum carriage speed of 18 knots (40 knots full scale) could be obtained. The model operated in two regions of the frequency domain. In one region, the waves traveled in the same direction as the craft at higher speeds, and in the other region, the waves traveled in the same direction at lower speeds.

For all tests, the mean standoff of the model side skegs above the undisturbed water surface was approximately 1 in. prior to acceleration up to test speed. This height was

TABLE 2

Test Schedule: Wave Dimensions and Craft Speeds

λ/L	Wavelength, ft		Wave Height, in.		Speed, knots	
	Model	Prototype	Model	Prototype	Model	Prototype
1.0	10	50	1.8, 3.7	9.0, 18.5	2.24	5
1.5	15	75	1.5, 2.1	7.5, 10.5	4.47	10
2.0	20	100	2.9, 4.3	14 5, 21.5	6.71	15
2.5	25	125	2.5, 3.3	12.5, 16.5	8.94	20
3.0	30	150	2.9	14.6	11.18	25
					13.42	30
					15.65	35
					17.89	40

established by moving the forward pivot point of each towing arm vertically (the vertical supporting members telescoped to permit this) so that the skegs were 1 in. above the undisturbed water surface when the arms were horizontal. Before each run, the air output of the fans was adjusted until the model was self-supporting and the towing arms horizontal.

The standoff at test speed was to be determined by measuring the shift between the mean of the oscillatory heave trace obtained while underway and the reference trace obtained at 1-in. hover height prior to acceleration. Because of excessive noise in the recorded signals, it was not possible to obtain this information. It was observed however, that the skegs were usually not visible when the model traveled at high speed over calm water. This indicates that the model flying height decreased as speed increased. The skegs were not actually immersed over most of their length but were riding above the depressed water surface beneath the craft.

PRESENTATION AND DISCUSSION OF TEST RESULTS

PITCH

The pitch data obtained during these experiments are presented in dimensionless form in Figure 7. Maximum wave slope was used as the nondimensionalizing parameter; it is given by $\frac{180\,h}{\lambda}$ in degrees where h is the wave height (distance from crest to trough) and λ is the wave length.

It bears repeating that the tests reported herein were carried out with the model and waves traveling in the same direction. In Figure 7 and subsequent figures, the dashed vertical lines represent the speed of transition from the condition of waves overtaking the craft (to the left of this line) to craft outrunning the waves (to the right of this line). The latter condition is similar to encountering head seas in that the velocity of wave progression relative to the craft is opposite in direction to the absolute velocity of the craft. However, for a given frequency of wave encounter and craft speed, the wave length must be different in following seas from that in head seas. In addition, the water particles comprising the waves have a different velocity relative to the craft than they would have in head seas because the orbital motion of the water particles relative to the craft in following seas is reversed from that in head seas. Thus at a given speed, the forces acting on the Hydroskimmer and its resulting motions will generally not be the same in following and head seas for the same frequency of encounter.

The peak pitch amplitude to wave slope ratios shown in Figure 7 are, in general, appreciably higher than those characteristic of planing and round bottom boats and larger passenger-cargo displacement vessels. Values of ψ/θ for small craft and ships are usually less than 1.0 when the vessel and waves travel in the same direction and less than 2.0 in head seas. Tests conducted by Swaan and Wahab at the Netherlands Ship Model Basin[2] on a model of SKMR-1 reveal that pitch was the greatest in head seas. Thus, there is reason to

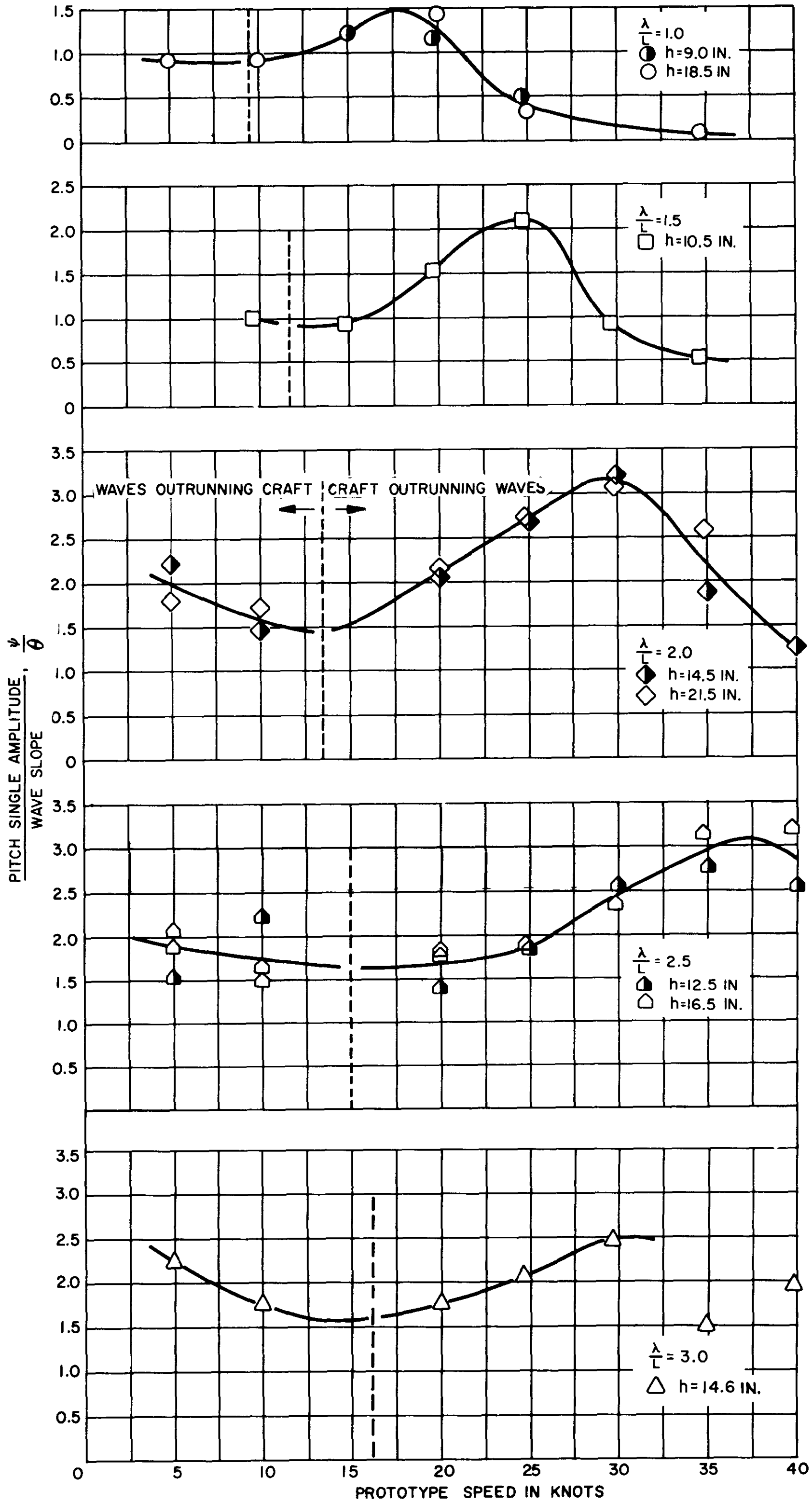

Figure 7 – Variation of Pitch per Unit Wave Slope with Speed

believe that the pitching motions of the Hydroskimmer will be even more severe in head seas than indicated for following seas in Figure 7. Large pitching excursions are not desirable on any craft, but it would appear that full-scale trials at sea are necessary to establish acceptable limits on motions for these novel air cushion vehicles. Until such information is available, the curves presented above are useful principally for comparing the merits of this design with another and not for making absolute judgments on acceptability.

The natural pitch frequency of the Hydroskimmer may be estimated from the data of Figure 7 since the peaks of the curves represent approximately synchronous conditions for a particular wave length. Therefore each wave length (except that for $\lambda/L = 3.0$ where the peak is not clearly defined and the data points for the two highest speeds are questionable), the speed at which the maximum motion occurred was utilized to compute the corresponding frequency of wave encounter. The values obtained range from -1.81 to -1.89 rad/sec with a mean of -1.85 rad/sec. Although natural frequency is somewhat speed dependent, the value of 1.85 rad/sec may be taken as an approximate value of the pitch natural frequency of this vehicle throughout its speed range.

It is important to note that *operation at or near the design speed of 70 knots is supercritical* (i.e., frequency of wave encounter greater than the natural pitch frequency of the craft) *for the wave conditions examined here*. For λ/L equal to 1.0, 1.5, and 2.0, ψ/θ decreases rapidly once the speed for peak motions is exceeded. A similar trend can be expected for λ/L equal to 2.5 and 3.0.

For three of the wave lengths (λ/L equal to 1.0, 2.0, and 2.5), data were obtained for two different wave heights. The data points for a given wave length collapse reasonably well, indicating a linear relationship between pitch amplitude and wave height, at least within the range of wave heights tested. If the wave length is equal to the craft length or 1.5 times the craft length, there is a tendency for pitch amplitude to approach the wave slope as the frequency of encounter approaches zero. In longer waves, the ratio of pitch amplitude to wave slope approaches 1.5 at low frequencies. Since the pitching motion right at zero frequency is indeterminate, the faired curves have been broken at the dashed vertical lines which represent the speeds for zero frequency.

A series of experiments was conducted at the Davidson Laboratory of the Stevens Institute of Technology on a 1/15-scale model representing the same Hydroskimmer design involved in the present study. One objective of that program was "…. to study the applicability of superposition theory and spectral analysis techniques in the investigation of GEM motions."[3] The investigators demonstrate that for both pitch and heave, the transfer functions obtained from regular wave tests agree reasonably well with those obtained from spectral analysis of irregular wave experiments. Although the applicability of linear superposition theory to air cushion vehicle motions was not conclusively established, the results were positive. This fact in addition to the indication of a linear pitch-wave height relationship in Figure 7 led the present writers to develop transfer functions and motion spectra where sufficient data were available.

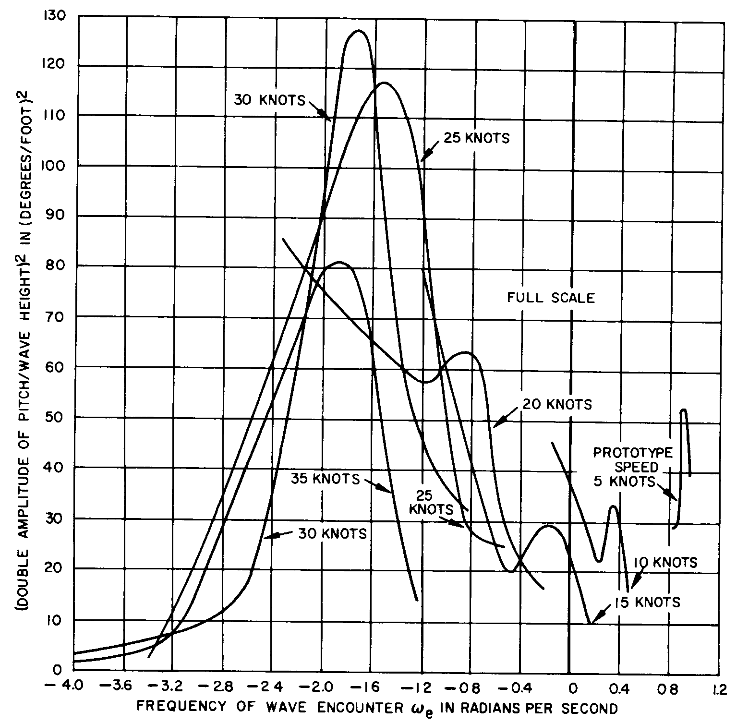

Figure 8 – Pitch Transfer Functions

The pitch transfer functions shown in Figure 8 were cross-plotted from the faired curves in Figure 7. A negative frequency notation has been utilized in the figure following the definition of St. Denis and Pierson.[4] Although negative frequencies do not exist in the physical sense, the term is used to represent the condition in which the craft outraces the waves and the crests appear to be moving from the Hydroskimmer bow toward her stern.

It can be seen from the figure that at lower speeds, the frequency of encounter range is quite small although the wave lengths investigated range from $\lambda/L = 1.0$ to 3.0. The frequency of encounter span at any particular speed depends upon the relative magnitude between the ship speed and the celerity of the wave components in which the ship is traveling. For example, when the ship is traveling with the waves in a wave system whose components have velocities in the range of twice the ship velocity (i.e., relative velocity is close to the ship velocity), small variations in the frequency of encounter result. This condition is best represented by the 5-knot speed in Figure 8. The effect is less pronounced in the 10-, 15-, and 20-knot curves, but only at the higher speeds of 25, 30, and 35 knots are the ship speeds sufficiently far removed from the velocities of the wave components of interest for the spectra of encounter to take on the more familiar shape which is usually obtained in head-sea operation.

It is desired to examine the performance of the Hydroskimmer in a State 3 sea. The Neumann energy density spectrum for a fully developed State 3 sea generated by a 16-knot wind is shown in Figure 9. This seaway has the following characteristics:

Significant (average of the one-third highest) wave height	4.6 ft
Average wave height	2.9 ft
Average of the one-tenth highest wave heights	5.8 ft
Period of maximum energy of the spectrum	6.5 sec
Minimum Fetch } for full development	40 nautical miles
Minimum duration } for full development	6.6 hr

The spectrum is shown in Figure 10 as it would be measured from a craft traveling in the same direction as the waves at 25, 30, 35, and 40 knots. The wave spectrum was not modified for the lower speeds since a fairly wide range of wave components whose velocity is in the neighborhood of twice the ship speed would have converted to approximately the same frequency of encounter (narrow frequency of encounter span). In addition, the Jacobian, a function which modifies the ordinates of the graph in the conversion from wave frequency to frequency of encounter domain, becomes infinitely large at one frequency in this region and the transformed spectra therefore approach infinity at this frequency. The energy in the seaway is proportional to the area under the spectrum. Since practical area-measuring techniques do not enable one to determine the area contributed by an infinite ordinate, an apparent loss of total energy results.

Pitch response spectra in a State 3 sea are shown in Figure 11 for speeds of 25, 30, and 35 knots. These curves were obtained by multiplying the ordinates of curves in Figure 8 by those in Figure 10 for corresponding speeds and frequencies. Since the ship responds to

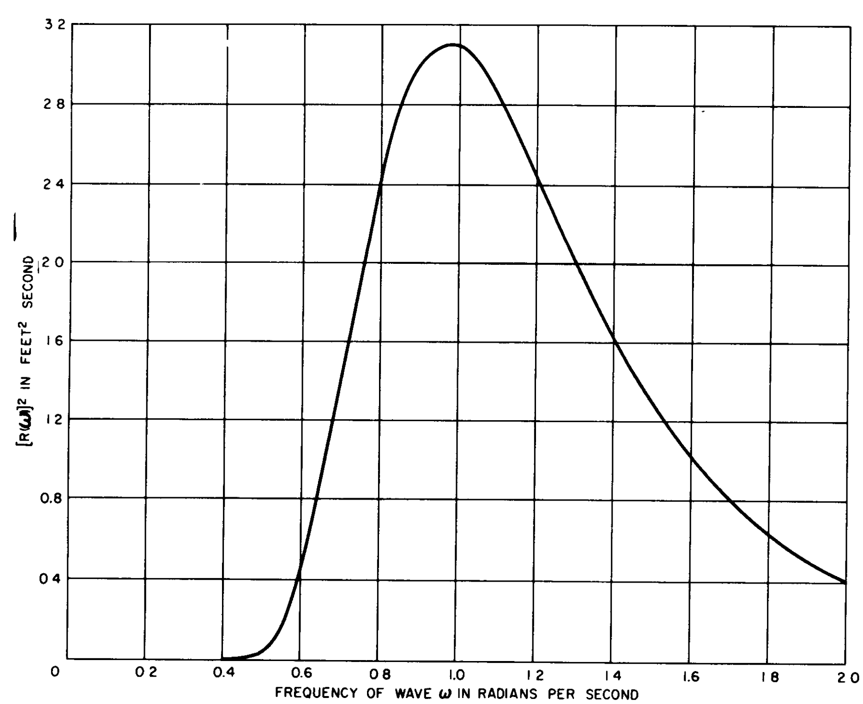

Figure 9 – Neumann Spectrum of a Fully Developed State 3 Sea at Wind Speed of 16 Knots

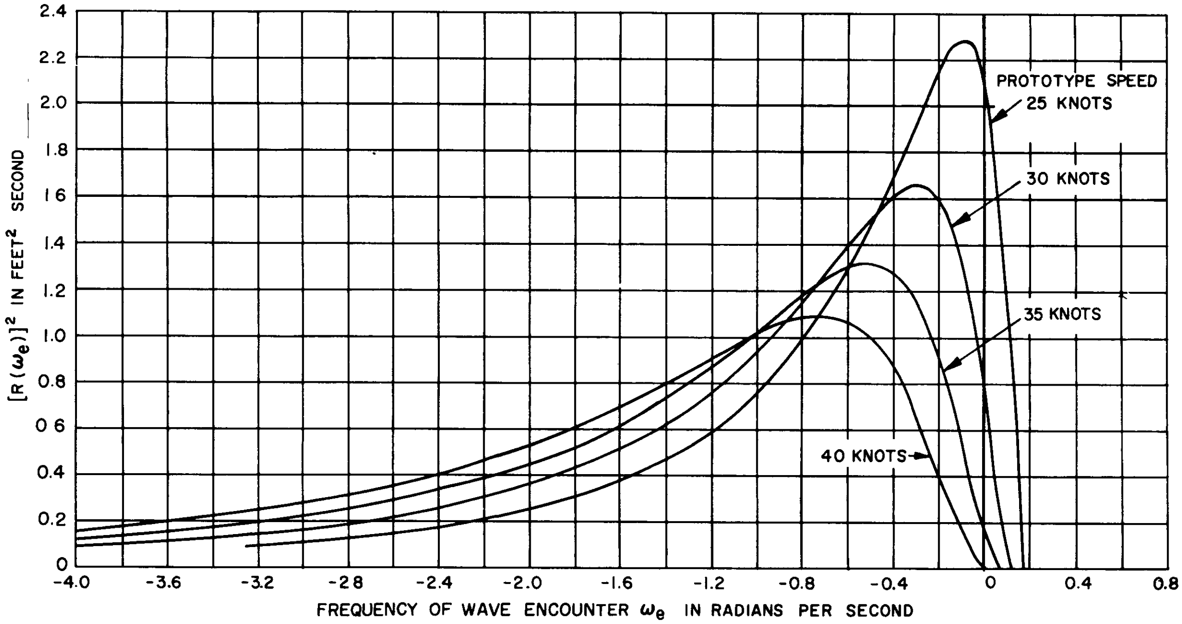

Figure 10 – Neumann Spectra of a Fully Developed State 3 Sea Modified for Craft Traveling with the Waves at Various Speeds

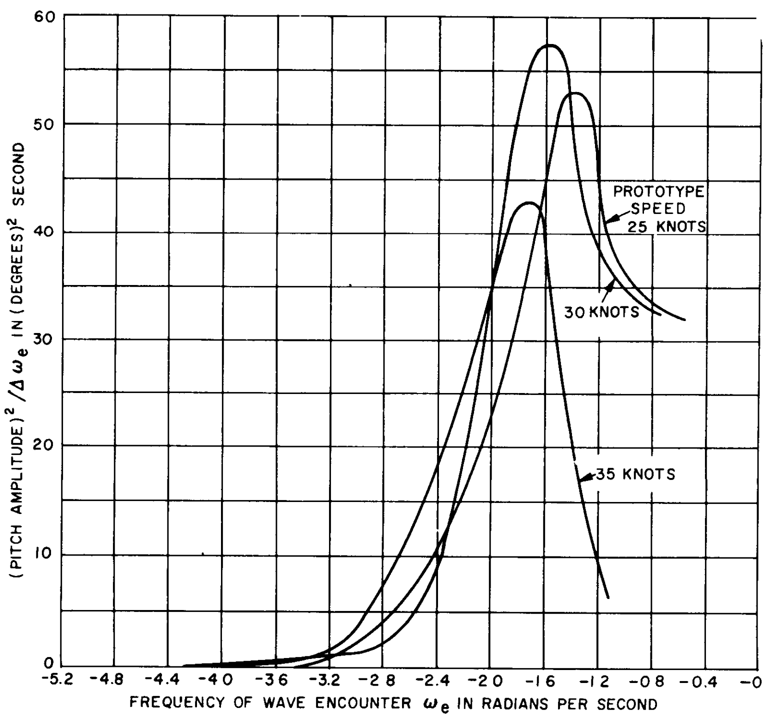

Figure 11 – Pitch Response Spectra in a State 3 Sea for Craft Traveling with the Waves

the seaway at the frequency of wave encounter, these spectra show the actual frequency distribution of pitching energy. Furthermore, as noted, the area under these curves is proportional to the total energy; hence certain statistical properties of the motion amplitudes may be determined. For example:

Average single amplitude oscillation $(\overline{\psi})$ $= 0.885\sqrt{E}$

Average of one-third highest (significant) single amplitude oscillations $(\overline{\psi}_{1/3}) = 1.415\sqrt{E}$

Average of one-tenth highest single amplitude oscillations $(\overline{\psi}_{1/10})$ $= 1.800\sqrt{E}$

where E is the area under the spectrum.

For the lower speeds where the frequency of encounter span is small and the transformation of the Neumann spectrum results in apparent energy loss, the pitch response spectra were not evaluated in the frequency of encounter domain. Instead, transfer functions in the wave frequency domain were obtained and spectra were computed utilizing the Neumann spectrum shown in Figure 9. The spectra obtained in the wave frequency domain are useful for predicting statistical data since the area under each curve is independent of the frequency domain in which it is evaluated. They do not, however, give the true frequency distribution of pitching energy and for this reason they are not presented here. Using the areas under these curves as well as those of the curves shown in Figure 11, the average, significant, and average of the one-tenth highest pitch amplitudes were computed for speeds of 5 to 35 knots. The results are presented in Table 3.

TABLE 3

Statistical Pitch Data (in degrees) for Hydroskimmer in State 3 Sea*

*All values are single amplitude

Prototype Speed knots	$\overline{\psi}$	$\overline{\psi}_{1/3}$	$\overline{\psi}_{1/10}$
5	6.3	10.1	12.8
10	5.5	8.8	11.2
15	6.0	9.5	12.1
20	7.4	11.9	15.1
25	7.1	11.4	14.5
30	8.0	12.8	16.3
35	5.9	9.4	11.9
Craft traveling in same direction as waves.			

HEAVE

Figure 12 is a plot of the basic heave data obtained during the regular wave tests. The values of heave double amplitude to wave height ratio shown for the Hydroskimmer are, for the most part, higher than those obtained for conventional small craft and large displacement vessels in following seas. They are, in fact, comparable to values obtained in head seas for the latter. It is quite possible that this vehicle will undergo more severe heaving motions in head seas than are in evidence for following seas in Figure 12. In addition, the general trend of these graphs (except for λ/L equal to 1.5) suggests that the heaving motion of the Hydroskimmer will continue to increase as speed is increased above 40 knots in following seas. From the location of the peak in the curve for $\lambda/L = 1.5$, the natural heave frequency is estimated to be about 2.70 rad/sec. This indicates that heaving will be supercritical at the design speed of 70 knots.

There is good agreement between the data obtained for different wave heights at a constant wave length. This implies that heave displacement varies linearly with wave height within the range of wave heights employed in these tests. Moreover, just as for pitch, there is a tendency for the curves to reach a minimum at zero frequency of wave encounter.

Heave transfer functions have been derived from the faired curves in Figure 12 and are presented in Figure 13. As discussed previously in the section on pitch, the frequency of encounter span broadens as speed is increased. However, at the higher speeds, unusual behavior occurs in waves of $\lambda/L = 3.0$ as evidenced by the sudden rise of the response curves. It is to be expected that in waves significantly longer than the vessel the motion would tend to follow the waves. This has been found to be the case for conventional displacement-type hulls, and the same trend is shown for this vehicle except at the higher speeds in $\lambda/L = 3.0$. The cause of this phenomenon is not known at present. Further testing with other GEM models will show whether this is characteristic of these vehicles.

Heave response in a State 3 sea was computed for speeds up to 30 knots using the same technique as for pitch at the lower speeds. The areas under the spectra were obtained and the statistical quantities $\bar{z}$, $\bar{z}_{1/3}$ and $\bar{z}_{1/10}$ are shown in Table 4.

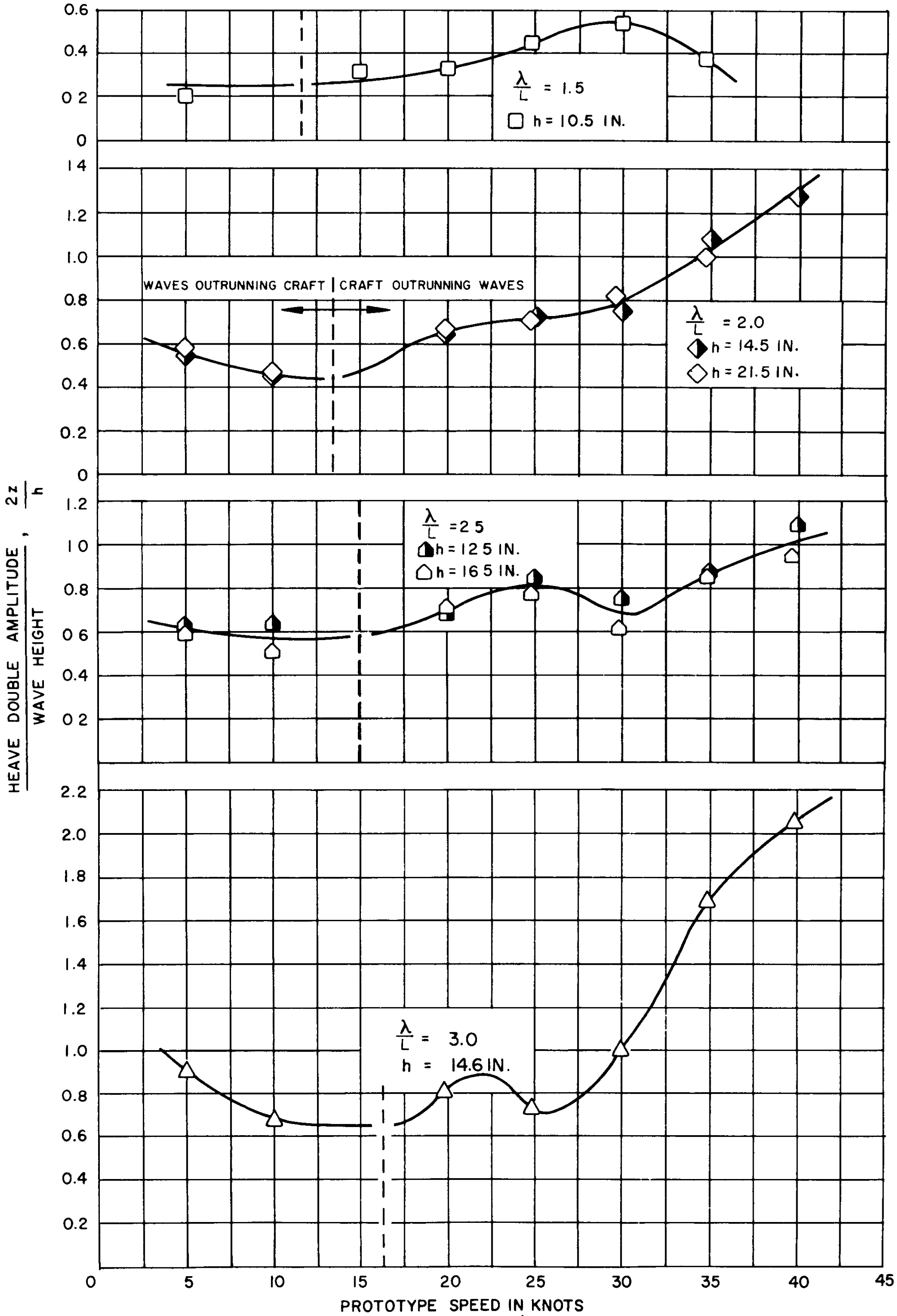

Figure 12 – Variation of Heave per Unit Wave Height with Speed

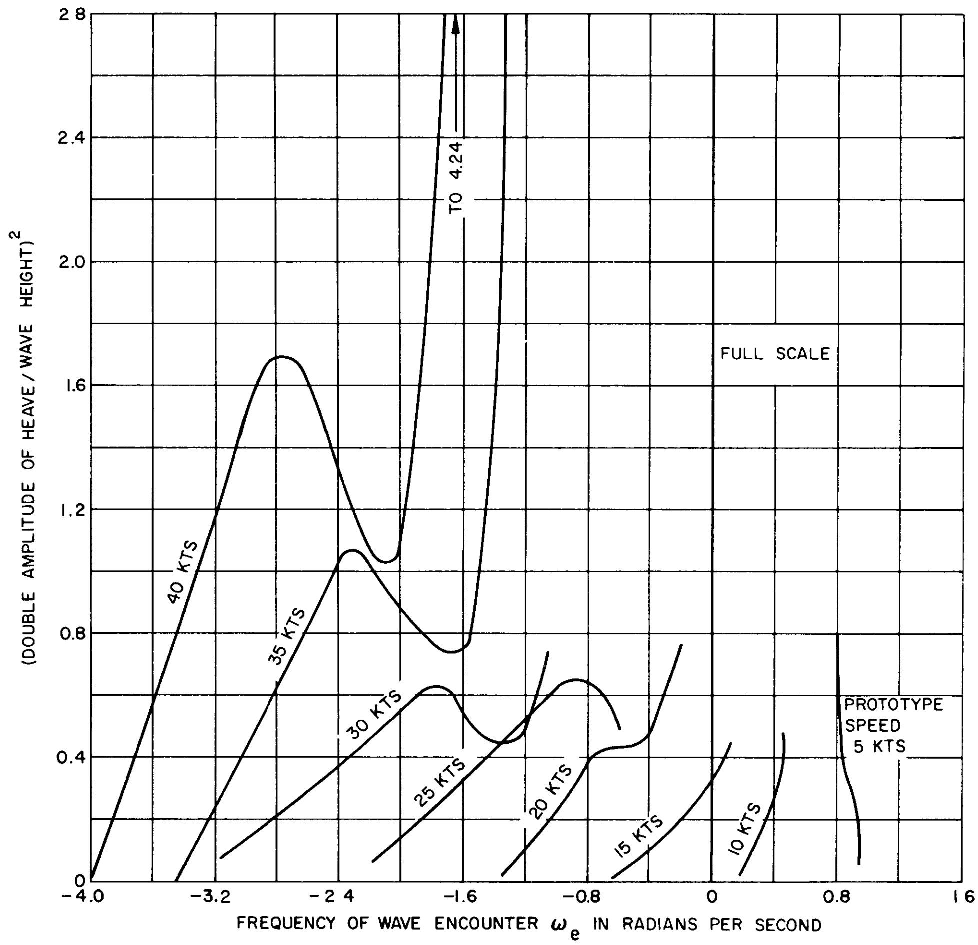

Figure 13 – Heave Transfer Functions

TABLE 4

Statistical Heave Data (in feet) for Hydroskimmer in State 3 Sea*

*All values are single amplitude.

Prototype Speed knots	$\bar{z}$	$\bar{z}_{1/3}$	$\bar{z}_{1/10}$
5	1.1	1.8	2.3
10	1.1	1.7	2.2
15	1.1	1.7	2.2
20	1.1	1.8	2.3
25	1.1	1.8	2.3
30	1.2	1.9	2.5
Craft traveling in same direction as waves.			

PHASE ANGLES FOR PITCH AND HEAVE

The phase between maximum bow up pitch and wave crest at the longitudinal position of the center of gravity (tow point) is given in Figure 14. Since the wave measurements were made 19.2 ft forward of the tow point, it was necessary to shift the wave record by $\frac{360 \times 19.2}{\lambda}$ deg to establish the desired reference. For those cases where the waves traveled faster than the model, the shift was made in the decreasing time direction and conversely. One interesting characteristic of these curves (except for λ/L equal to 1.0) is the sudden transition from maximum bow-up pitch lagging wave crest at the center of gravity to maximum bow-up pitch leading wave crest at the center of gravity at the speed for zero frequency of encounter. This assumes, of course, the usual restriction to angles less than180 deg. That is, rather than consider bow-up pitch leading wave crest by ψ deg (where $\psi > 180$ deg) we consider it lagging by 360-ψ deg.

The phase between maximum upward heave and wave crest at the longitudinal center of gravity is presented in Figure 15. Here the ordinate scale was set up to include angles greater than 180 deg. This was done since data points for a constant wave length and speed fell both above and below 180 deg. The conventional scale usedin Figure 14 would have resulted in an unrealistic scattering of the data points. Although the curves (especially that for λ/L equal to 3.0) fluctuate somewhat, it is clear that for the three longest wave lengths, heave is approximately 180 deg out of phase with the wave throughout the speed range. This is characteristic of the phase response of a lightly damped system being excited at frequencies above its natural frequency. It is considered unusual for two reasons: (1) the GEM tested was quite heavily damped in heave and (2) this situation exists even at frequencies of encounter much smaller than the heave natural frequency.

The phase between maximum bow up pitch and maximum upward heave was obtained by combining the data points shown in Figures 14 and 15. These results are shown in Figure 16. In this graph, the scale of negative angles was extended beyond 180 deg to permit the fairing of a continuous curve. Except for the λ/L equal to 1.0, sudden change in phase occurs at the speed for zero frequency of encounter. This is, of course, a consequence of the pitch-wave phase characteristic. The curve flattens out with further increase in speed and beyond approximately 30 knots, the slope increases again.

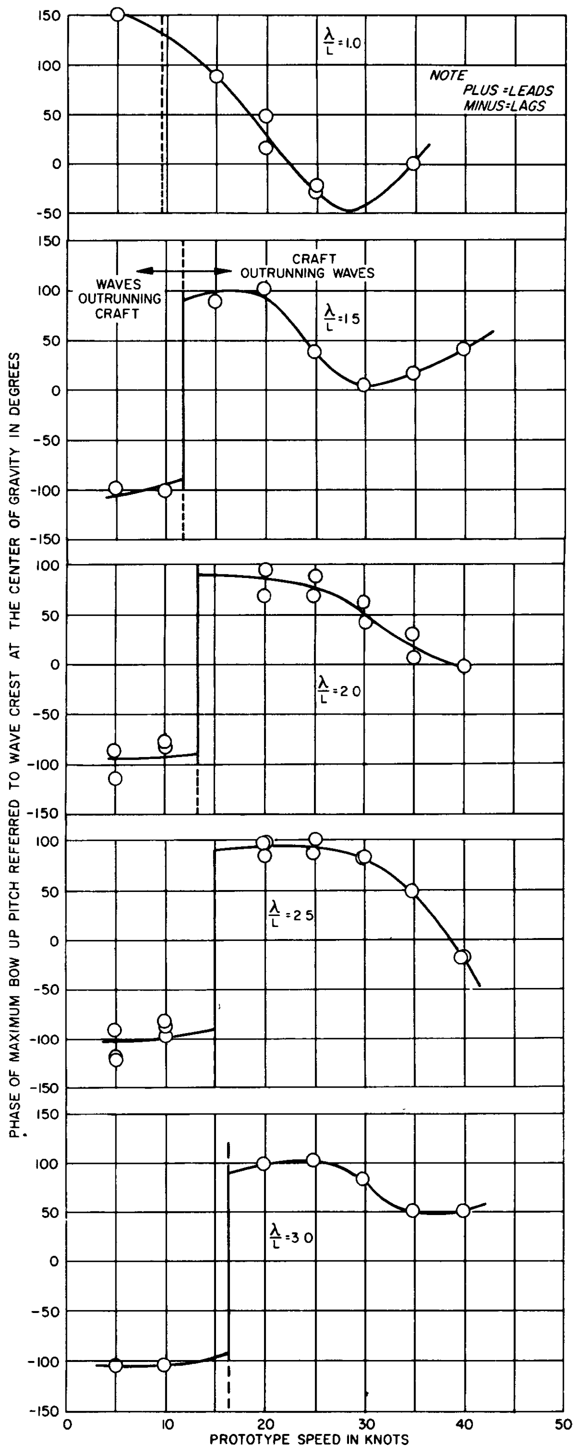

Figure 14 – Phase of Maximum Bow Up Pitch as a Function of Speed

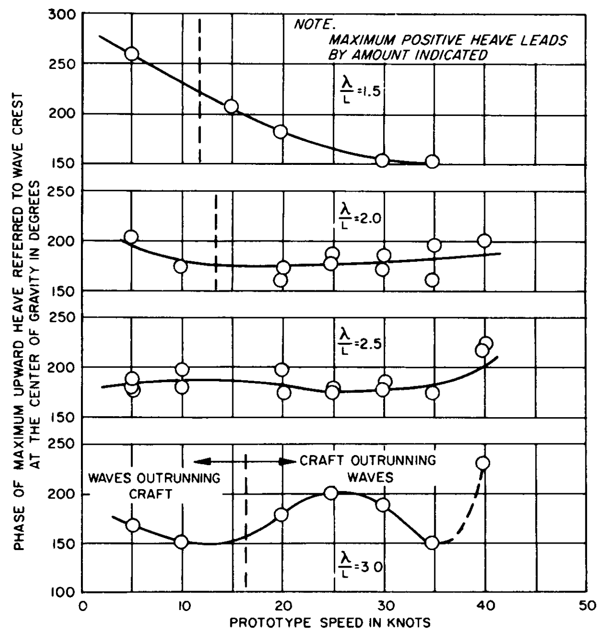

Figure 15 – Phase of Maximum Upward Heave as a Function of Speed

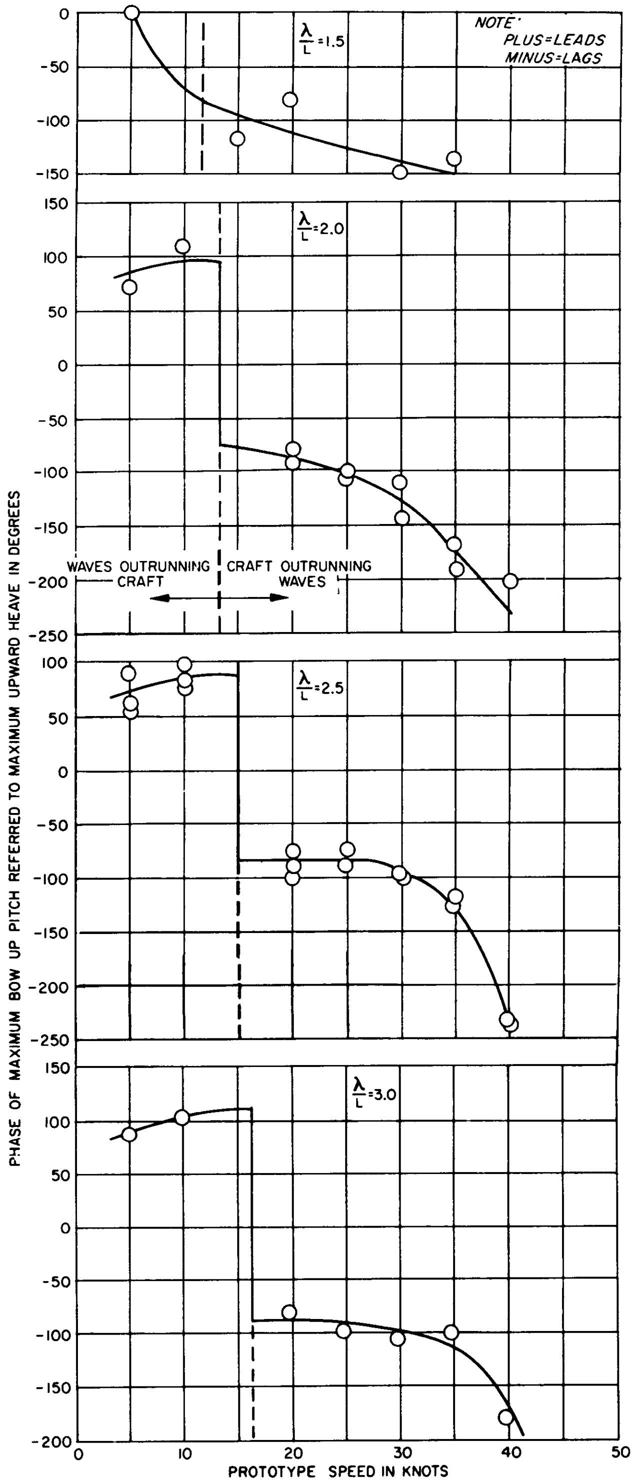

Figure 16 – Phase between Maximum Bow Up Pitch and Maximum Upward Heave

HEAVE ACCELERATION

Vibration was induced in the model hull by the fan motors and by the flow of air into the plenum chambers. Because of this, the signal-to-noise ratio on the heave acceleration traces obtained from the output of the $\pm 2g$ accelerometer was extremely low. Filtering of the noise was attempted but did not prove successful. It was therefore not possible to obtain direct measurements of heave acceleration.

As an alternate approach, heave acceleration data were derived from the faired values of heave displacement per unit wave height in Figure 12. It was assumed that the heaving motion is simple harmonic. This is a good approximation to the true motion because for the wave heights used in these tests, the water surface elevation at a given point (forcing function) varies essentially sinusoidally with time. Since, as mentioned above, the heave-wave height relationship is linear, heave displacement should also vary approximately sinusoidally with time.

The variation of heave acceleration per unit wave height with speed is represented by the derived curves in Figure 17. The curves go to zero at zero frequency of wave encounter. For all wave lengths except that equal to 1.5 times the cushion length, the acceleration curves increase monotonically from the speed for zero frequency of encounter to 40 knots. Thus at speeds above 40 knots, the heave acceleration may be appreciably higher than the maximum values shown on these graphs.

BOW ACCELERATION

The rigid body vertical acceleration measured at a point approximately 6 ft (full scale) aft of the extreme forward end of the Hydroskimmer is presented in Figure 18. Unfortunately, data could not be obtained for all speeds and wave conditions because, as for heave acceleration, the signal-to-noise ratio was very low. It is indicated in the data for λ/L equal to 1.0 that the bow acceleration also varies linearly with respect to wave height. However, because of the high noise level in the Sanborn records, these data should be taken as approximate.

SURGING FORCE

The surging force acting on the model when it travels over waves was obtained from the drag records and is presented in Figure 19. These graphs reveal that surging force is proportional to wave height for the range of wave heights utilized in these tests. For the design speed of 70 knots, operation in waves whose lengths are equal to $1.5L$ and $2.0L$ should be supercritical.

CALM WATER DRAG

The calm water drag shown in Figure 20 is comprised of (1) wave drag, (2) momentum drag due to a change in momentum of the air entering the fan intakes, (3) aerodynamic drag,

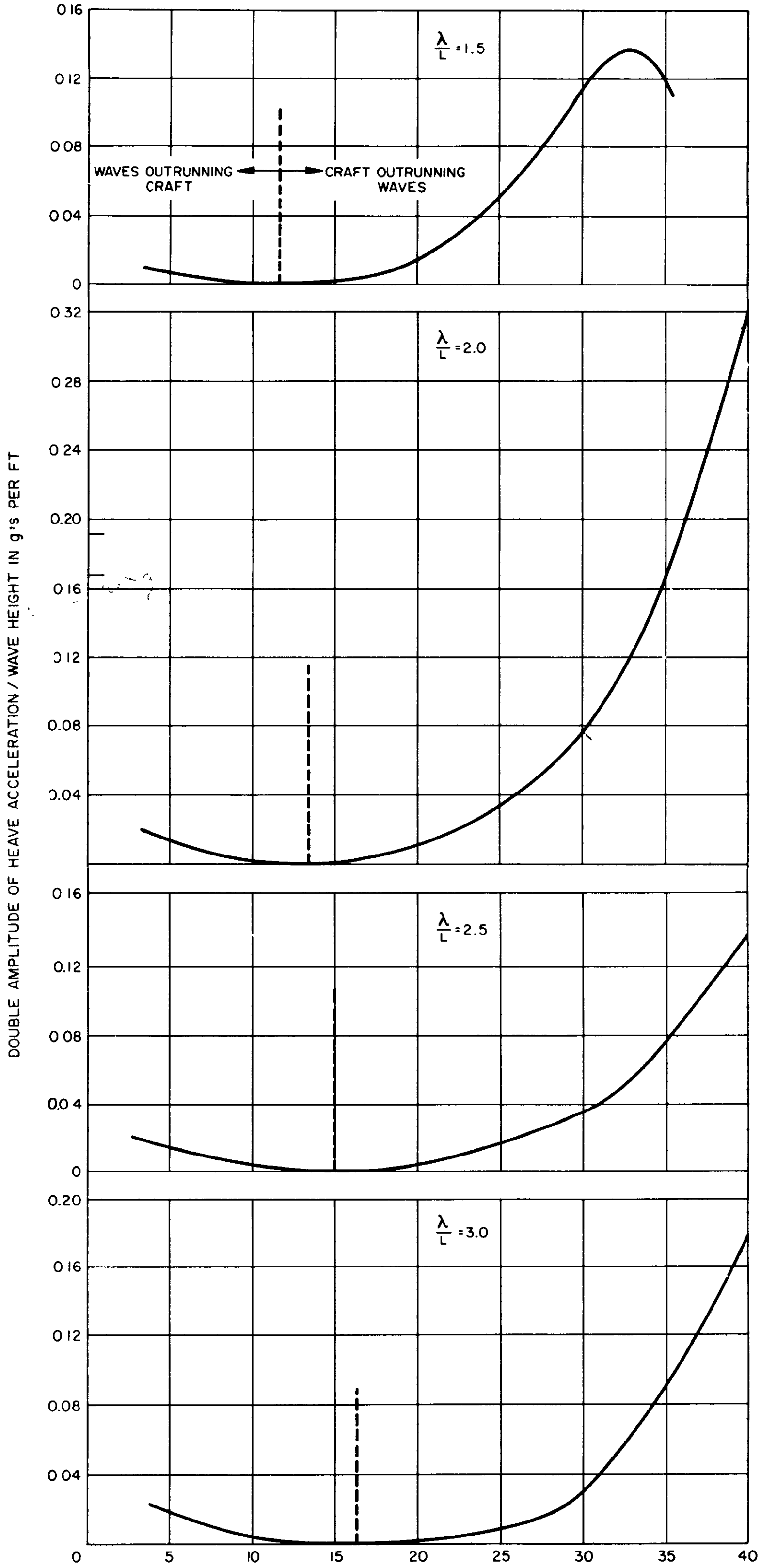

Figure 17 – Variation of Heave Acceleration per Unit Wave Height with Speed

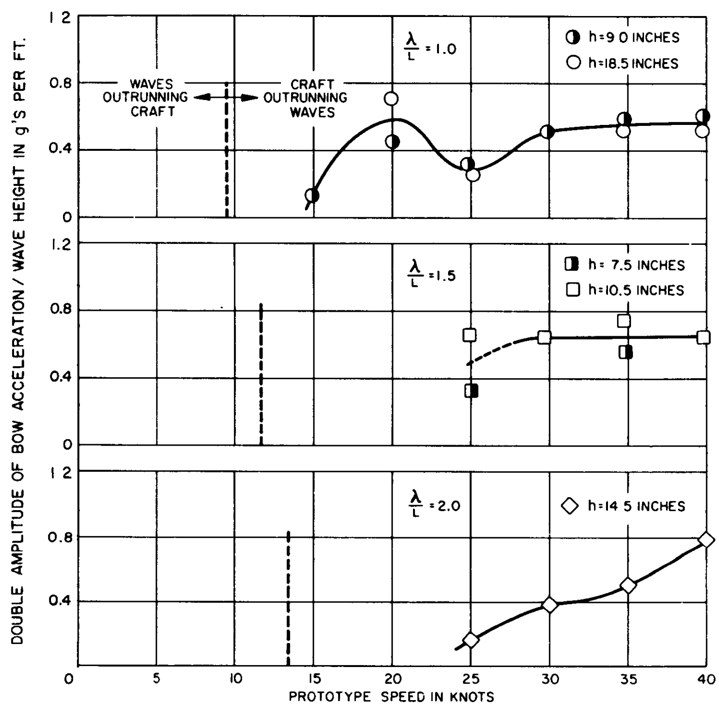

Figure 18 – Vertical Acceleration at the Bow

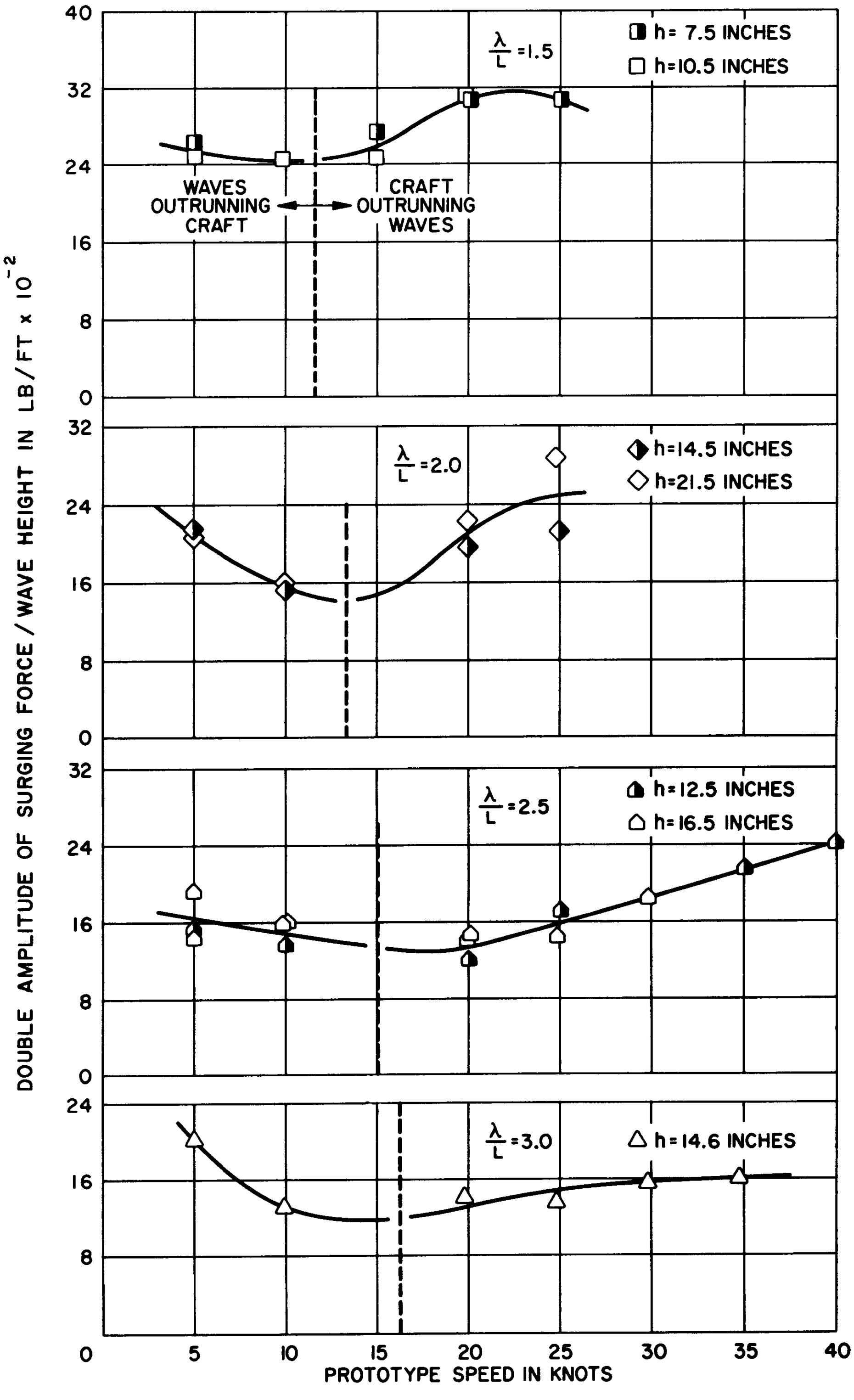

Figure 19 – Surging Force as a Function of Speed

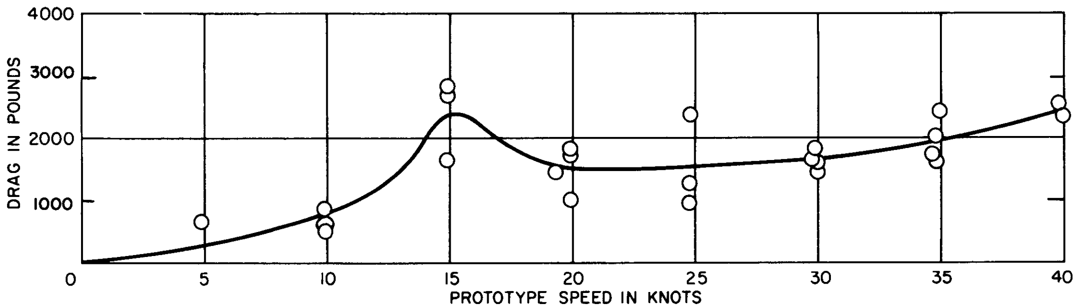

Figure 20 – Drag over Calm Water versus Speed

(4) viscous drag of the skegs since they were generally submerged near the stern, and (5) drag due to spray generation. The faired curve represents a best estimate, based on average values, of the drag acting throughout the speed range. It indicates that the hump speed is approximately 15 knots.

MOTION PICTURE RECORDS

Motion pictures were taken of the model while it operated over both calm water and waves. Selected sequences have been combined into a short film as an addemdum to this report (TMB Film No. M2051).

CONCLUSIONS

The following conclusions apply to operation of the Bureau of Ships preliminary design concept of a 20-ton Hydroskimmer in following seas. Some of these statements (especially those regarding linearity of motions) may be applicable to ground effect machines in general.

1. The pitch amplitude per unit wave slope reaches significantly higher peak values than are normally associated with small craft and ships. However, for all wave lengths considered, operation at the design speed will be beyond the region of maximum pitching (supercritical).
2. The natural frequency in pitch is approximately 1.85 rad/sec (full scale).
3. For the speeds investigated, the heave amplitude per unit wave height is, in general, greater than the heaving response characteristic of both small craft and ships. For waves whose lengths are equal to or greater than twice the cushion length, heave increases as speed is increased from 30 to 40 knots. It is therefore to be expected that even larger heaving motions will be experienced at the normal cruising speeds of this craft.
4. Based on the natural heave frequency of approximately 2.70 rad/sec (full scale), operation at the design speed will be supercritical with regard to heave for all wave lengths considered.

5. Pitch, heave, and surging force are proportional to wave height for the range of wave heights used in these tests. Additional model tests on other configurations are needed, however, to establish this as a basic characteristic of the GEM.

6. For waves whose lengths are equal to or greater than twice the cushion length, the heave acceleration increases monotonically at speeds above that for zero frequency of encounter.

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The data reveal that at speeds up to 40 knots, the pitching motion per unit wave height of the GEM is generally more severe than that experienced by conventional small craft and large oceangoing ships. The heaving motion per unit wave height of the GEM is also greater than the characteristic heaving motion of more conventional vessels. It was also determined that pitch and heave motions and surge force are linearly related to wave height throughout the range utilized in these tests. Wave steepnesses (h/λ) as great as 1/32 were investigated.

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