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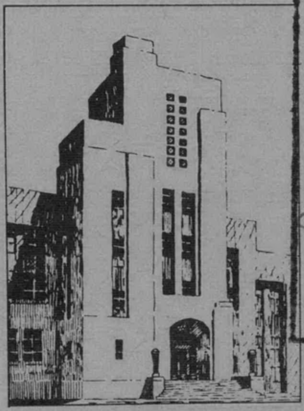
THE EFFECT OF BEAM ON THE SEAWORTHINESS OF ESCORT PATROL CRAFT

by

C.G. Moody



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NOTATION

a	Wave height
B	Beam over-all
C_P	Prismatic coefficient
C_W	Waterplane coefficient
$D.W.L.$	Designed waterline
GM	Metacentric height, center of gravity to metacenter
BM	Center of buoyancy to metacenter
g	Acceleration of gravity
H	Draft
KB	Keel to center of buoyancy
KG	Keel to center of gravity
k_x	Transverse radius of gyration
k_y	Longitudinal radius of gyration
L	Length on waterline
L_{OA}	Length over-all
T	Period in seconds
Z	Heave
γ	Wave slope
λ	Wave length
ψ	Pitch angle in degrees
∇	Displacement in feet^3

NONDIMENSIONAL DATA

	210-Ft	250-Ft	290-Ft
L_{OA}	1.028	1.020	1.026
L	1.000	1.000	1.000
B/L	0.160	0.112	0.862
H/L	0.046	0.046	0.0445
k_y/L	0.23	0.23	0.23
$\dfrac{\nabla}{(L/100)^3}$	357	255	202
C_P	0.58	0.58	0.61
C_W	0.73	0.73	0.78

[redacted]

ABSTRACT

Tests of three models of a proposed 17-knot Escort Patrol Craft were conducted to determine the effect of beam on the speed and behavior of the vessel in waves. Tentative PCE designs having lengths of 210, 250, and 290 ft, and beams of 33, 28, and 25 ft respectively, were prepared for this purpose. It is concluded from the data presented that a reduction of beam has a favorable effect on the performance of the ship in waves of ordinary lengths and heights.

INTRODUCTION

Seaworthiness is a primary consideration in the design of escort patrol craft, which must be able to maintain speed under the rough-water conditions of operational service and must have particularly easy motions if they are to be habitable and of value for military purposes. A study of the possibilities of improving these qualities of seaworthiness by reducing the beam of the vessels is presented in this report, as requested by the Bureau of Ships.[1]

In the past the interest in smooth-water speed has to some extent obscured the importance of sea performance. During the first world war, for example, seven hundred and twenty 80-ft motor launches (ML's) were built to combat submarines. The first consideration in the design of these vessels was a smooth-water speed of 19 knots, and the model was chosen on the basis of this requirement, in preference to one of more seaworthy form that actually showed less resistance for full-scale speeds up to 15 knots, Reference 2. These vessels had well-formed sections, but were excessively fine forward, rather flat aft, and of comparatively shallow draft. They were difficult to steer in following seas and their motions in waves were extremely lively. It is of interest to note, as a consequence, that the emphasis in designing a subsequent class of some four hundred and fifty 110-ft submarine chasers (SC's) was on seaworthiness rather than on speed.

As the proportions of the latter vessels are somewhat similar to those of the proposed PCE designs, References 2, 3, and 4 may be of interest.

On the basis of theoretical considerations D.W. Taylor[5] suggested that a low center of gravity in a vessel of small metacentric height,GM, may tend to give exceptionally good antirolling qualities. Since these characteristics are to some extent obtained in the narrow PCE forms, the beam-sea tests requested by BuShips[1] are of particular interest.

THE PROPOSED PCE DESIGNS

The principal particulars of the three PCE designs that were prepared for this study are given in Table 1. These designs each require about the same power for a speed of 17 knots in smooth water, and are intended for the same service.

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[1] References are listed on page 23.

TABLE 1

Particulars of the PCE Designs

PCE Design	210-Ft	250-Ft	290-Ft
Length, Over-all, ft	216.00	255.00	297.42
Length, Waterline, ft	210.00	250.00	290.00
Beam, Maximum, ft	33.50	28.00	25.00
Beam, Waterline, ft	33.00	28.00	25.00
Draft, ft	9.65	11.50	12.90
Freeboard, Bow, ft	17.85	16.00	21.76
Freeboard, Amidships, ft	7.60	13.00	9.10
Freeboard, Stern, ft	9.10	7.25	10.26
Keel to center of buoyancy, ft	5.92	6.98	7.82
Keel to center of gravity, ft	13.30	12.10	11.30
Metacentric height, GM, ft	3.10	1.30	1.10
Longitudinal Radius of Gyration	0.23 L	0.23 L	0.23 L
Displacement, tons	945	1140	1400
Liquid Ballast, tons	none	120	60
Fixed Ballast, tons	none	none	210
Prismatic Coefficient	0.58	0.58	0.61
Water Plane Coefficient	0.73	0.73	0.78

The first design is of conventional proportions, the second is about 15 percent narrower, and the third is about 25 percent narrower than the first. The table shows that these decreases in beam are attended by relatively large increases in length, draft, and displacement, which are necessitated by the functional requirements of the vessel. The narrow hulls also require ballast at all times for stability.

The 210-ft PCE, Figure 1, has a forecastle deck that extends aft to Station 8. The lines of this design are shown in Figure 4, from Reference 6.

The 250-ft PCE, Figure 2, has a forecastle deck that extends as far aft as Station 14. The lines of this design, see Figure 5 from Reference 7, were developed from those of the 210-ft design by decreasing beam and increasing draft to obtain the required sectional area for the 250-ft hull. Advantage was taken of the greater draft to give the bow a slightly bulbous form.

The 290-ft PCE, Figure 3, was designed with a flush deck and ample sheer to keep the center of gravity low and still provide adequate freeboard forward. The water plane was filled out to increase the BM by making the bow sections V-shaped, and by other changes which necessitated some increase in the prismatic coefficient. The lines of this design, see Figure 6 from Reference 8, consequently represent a considerable departure from the parent form.

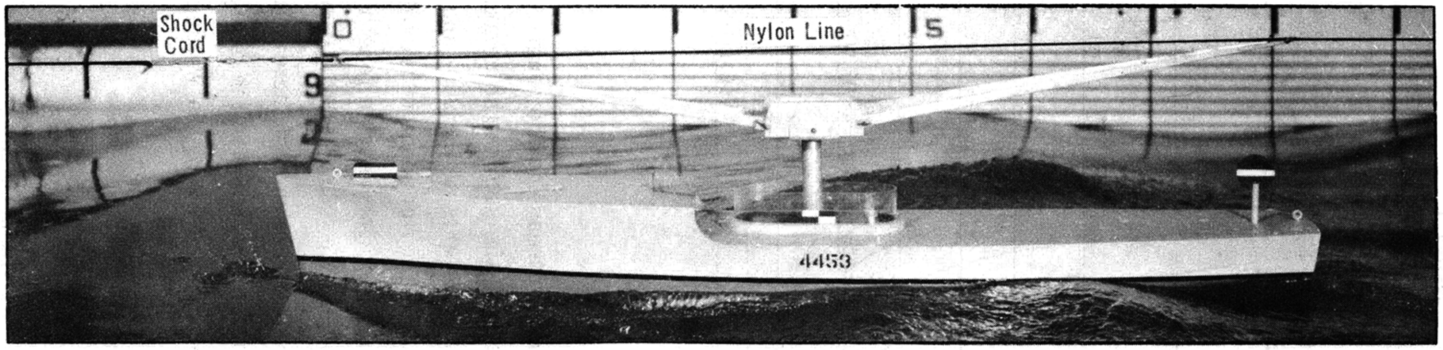

Figure 1 - 210-Foot PCE Model 4453

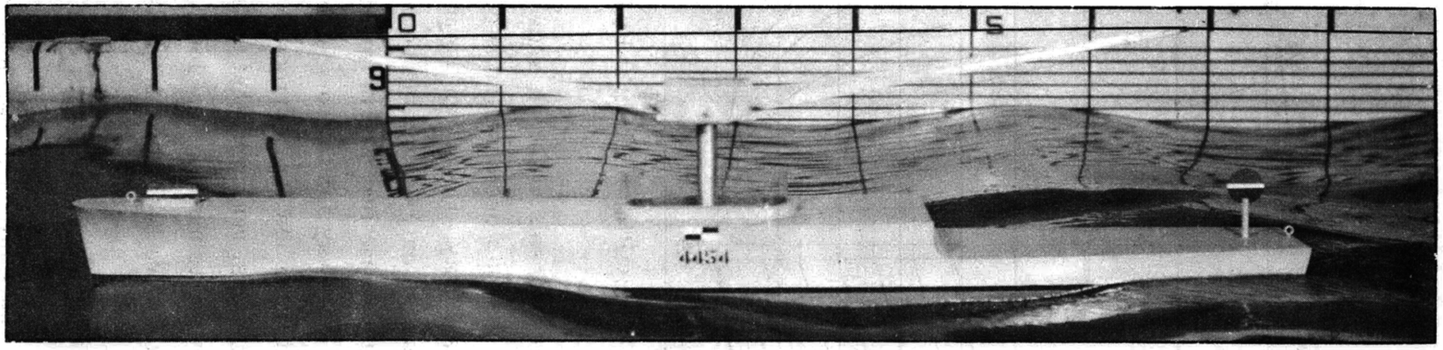

Figure 2 - 250-Foot PCE Model 4454

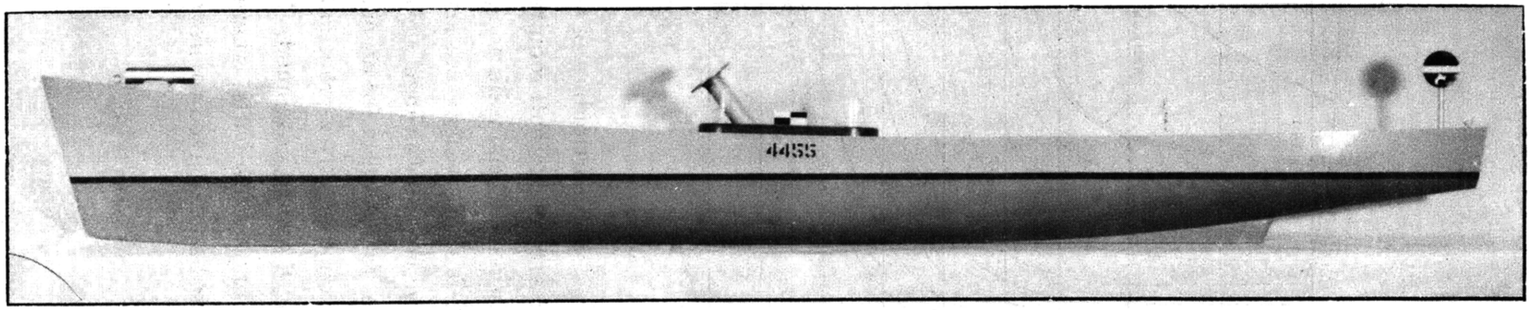

Figure 3 - 290-Foot PCE Model 4455

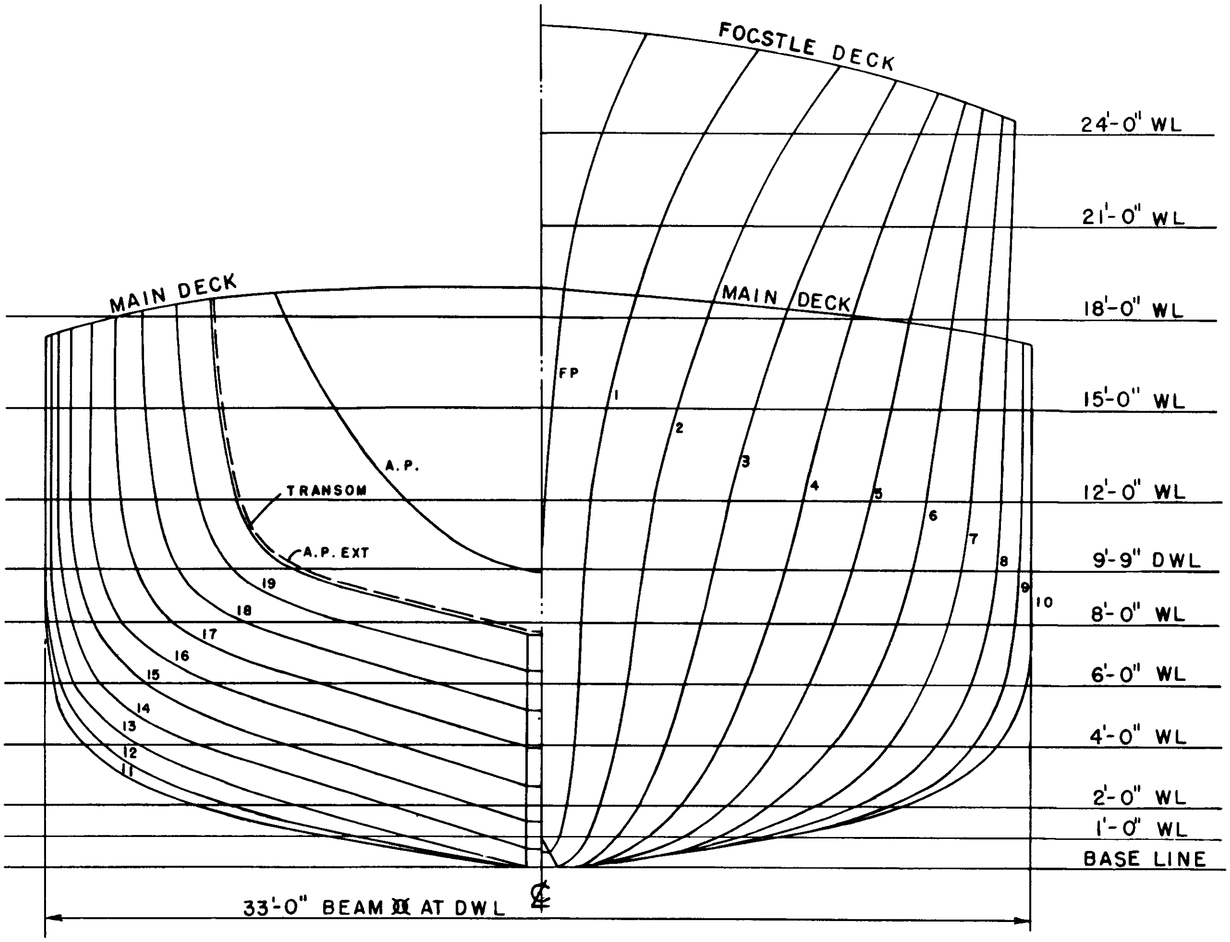

Figure 4 - Body Plan of the 210-Ft PCE Design

The particulars of the three vessels, Table 1, show that each increase in the length and size of the hull requires an absolute decrease in the distance from the keel to the center of gravity to maintain adequate stability. Even then the metacentric heights of the 250- and 290-ft PCE designs are small and are only acceptable because sufficient freeboard is provided to insure a safe range of stability. Some increase in freeboard with each increase in length is also desirable for dryness in a seaway and to provide depth for structural strength. There is consequently a practical limit as to how far the process of decreasing beam and increasing length can be continued. It is obvious, moreover, that freeboard is at a premium in the design of long narrow hulls, where the weights must be kept low for stability, and where the windage must be minimized to prevent excessive heel in beam winds.

THE SHIP MODELS

The models of the 210-ft, the 250-ft, and the 290-ft designs are respectively 5.25 ft, 6.25 ft, and 7.25 ft long. The linear ratio of ship to model is 40, and the longitudinal radius of gyration is 23 percent of the length for all three models. The skegs are the only

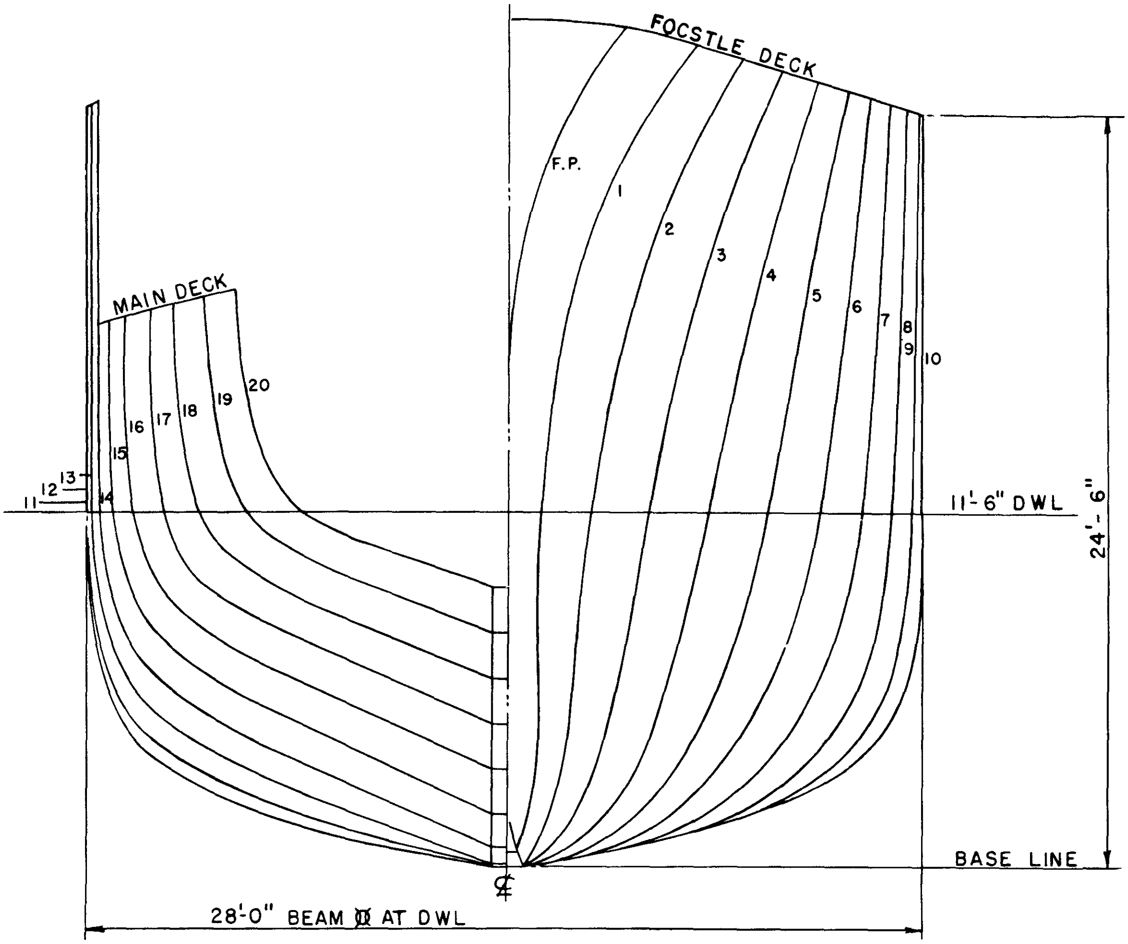

Figure 5 - Body Plan of the 250-Ft PCE Design

appendages on Model 4453 of the 210-ft PCE and on Model 4455 of the 290-ft PCE. Model 4454 of the 250-ft PCE has no appendages.

The tests were run with a sand strip on the bow of each model.

TEST APPARATUS

The tests were conducted in the TMB gravity-towing basin, which is 142 ft long and 10 ft wide. The water depth for these tests was 5.44 ft.

In this basin the model is towed by a gravity dynamometer which transmits its power to the model through a continuous nylon line that is stretched over the length of the basin and around a wheel at each end. The model is attached to the tow line by a towing bracket, that is pivoted on ball bearings at the center of gravity of the model, see Figures 1 and 2. An innovation in these tests is the insertion in the towline of a 7-ft length of 1/4-inch diameter rubber shock cord on each side of the towing bracket to provide sufficient elasticity for the model to surge freely in waves while the dynamometer continues to run at nearly constant speed.

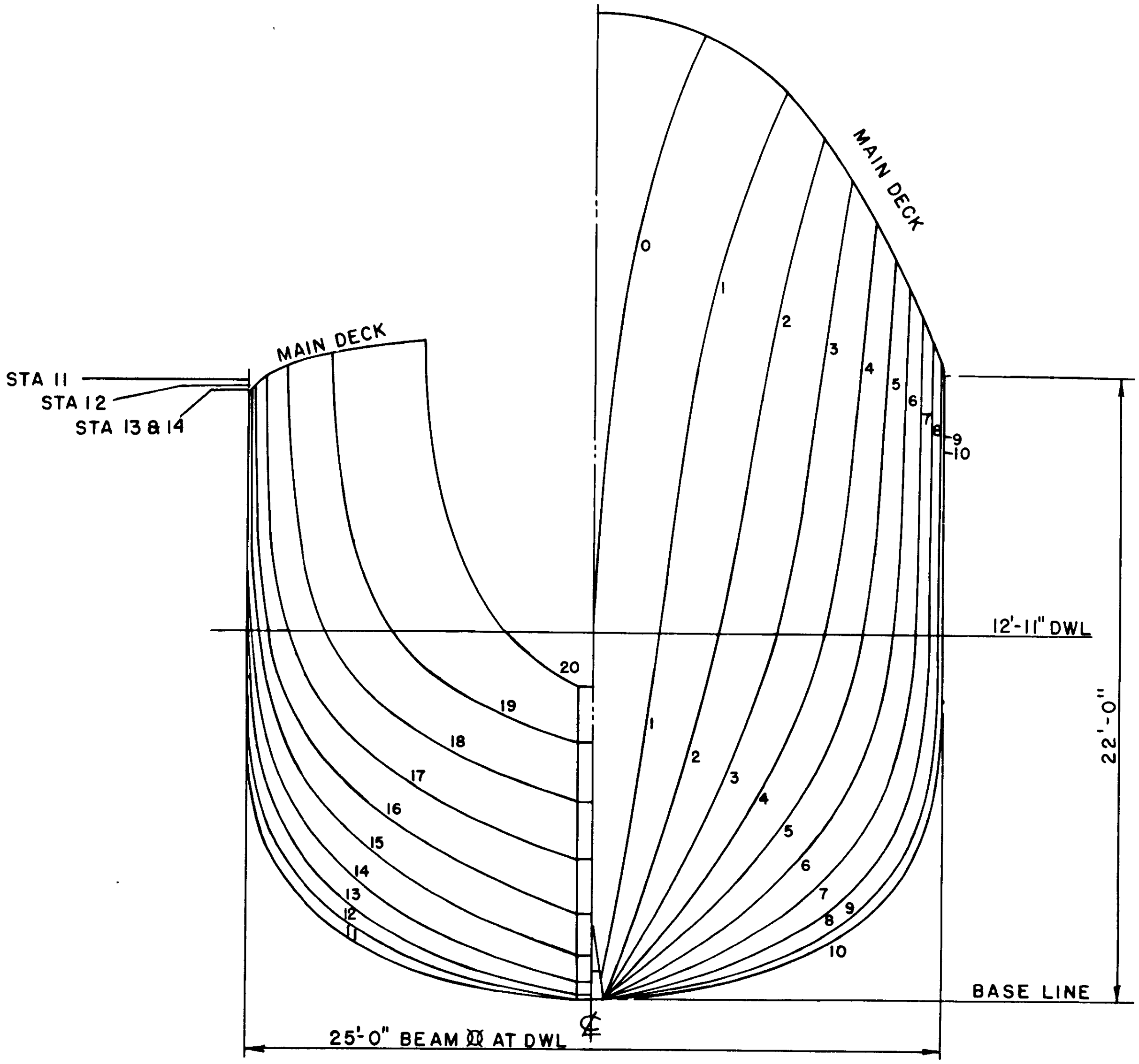

Figure 6 - Body Plan of the 290-Ft PCE Design

The motions of pitch and heave are practically unrestrained by the towing arrangement, as the model in pitching rotates on ball bearings about an axis at its center of gravity, and heaves by displacing the vertical position of the towline. In rolling, the presence of the towline does have a small, but perceptible, influence on the period of roll.

The speed is determined by an electronically operated Potter chronograph with a photoelectric pickup. The model is usually timed over a distance of 20.94 ft.

The motions of the model are recorded by a 35- or 70-mm motion-picture camera which is set with the plane of its image parallel to the vertical centerline plane of the basin. The profile view of the model thus obtained is without perspective in the sense that the same scale applies everywhere in the vertical plane of its motion, although the scale itself is affected by the distance at which the pictures are taken. The pitch and heave motions consequently are readily plotted. This method of analysis is based on the principle of stadia measurements.

TEST PROCEDURE

In tests conducted with a gravity dynamometer, the speed of the model cannot be explicitly set without an experimental determination of the appropriate towing force. For this reason the tests in the 140-ft basin are usually based on the towing force, or resistance. In smooth-water tests the speed is found for discrete increments of resistance; in rough-water tests the variations of speed with wave length are found for a given towing force.

The seaworthiness tests of the proposed escort patrol craft are based on a smooth-water ship speed of 17 knots. The smooth-water resistance of the models at a corresponding Froude speed is given in Table 2. The towing forces for all the tests in waves are constant and equal to these resistances.

TABLE 2

Still-Water Resistance

Ship		Model		
PCE Design	Speed knots	Model	Speed knots	Resistance lb
210-ft	17	4453	2.69	0.542
250-ft	17	4454	2.69	0.526
290-ft	17	4455	2.69	0.575

The dimensions of the full-scale waves represented in the tests, which have heights of 0.55 times the square root of their length, are given in Table 3. These waves are of medium height according to the Bureau of Ships formula 9 which defines the height of heavy seas as 1.1 times the square root of the wave length.

The rolling tests were conducted with an elastic cord attached to each end of the model to keep it in a broadside position to the waves. Still-water rolling periods of 10.4 seconds, 9.0 seconds, and 9.1 seconds were represented for the 210-, 250- and 290-ft ships, respectively. No data on the transverse radii of gyration were given in Reference 1, but the values of the coefficient C obtained from the formula

$$T = \frac{C \cdot B}{\sqrt{GM}}$$

TABLE 3

Full-Scale Wave Conditions Represented in the Tests

Condition	Wave Length ft	Wave Height ft
1	100	5.50
2	150	6.73
3	200	7.78
4	250	8.70
5	300	9.53
6	350	10.29
7	400	11.00

for the 250-, and 290-ft designs are 0.37 and 0.38 respectively, which are of the same order as those given in Table 2 of Reference 10. A more concentrated disposition of weight could not readily be obtained in the tests of the 210-ft design.

The wave conditions for the beam-sea tests were the same as for the head-sea tests.

TEST RESULTS

The results of the model tests in head seas are given in Figures 7 through 12, and the results of the tests in beam seas are given in Figure 13. Design data on the pitch and heave charateristics are given in Figures 14 and 15.

The general-performance characteristics of the vessels are shown in a Taylor Model Basin motion picture.[11]

SPEED IN WAVES

The speeds of the different hull forms in waves of different lengths and moderate heights are shown in Figure 7, the towing force in each case being constant and equal to that required for 17 knots in smooth water. The tests show that the narrow 290-ft hull is the the fastest in waves of ordinary length, up to 270 ft long, but that its superiority is only appreciable in waves that are from 150 to 250 ft long. In waves over 270 ft long, the 210-ft hull is the fastest.

The 250-ft hull is a little slower in comparison with the others than might be expected, but is faster than the 210-ft hull in waves up to 230 ft long.

The model of the 250-ft design was tested without a skeg, and consequently required careful alignment in towing to attain its proper speed. This model, which has the least bow freeboard of the three, buries its bow in head seas, and it has an abrupt outward flare of the

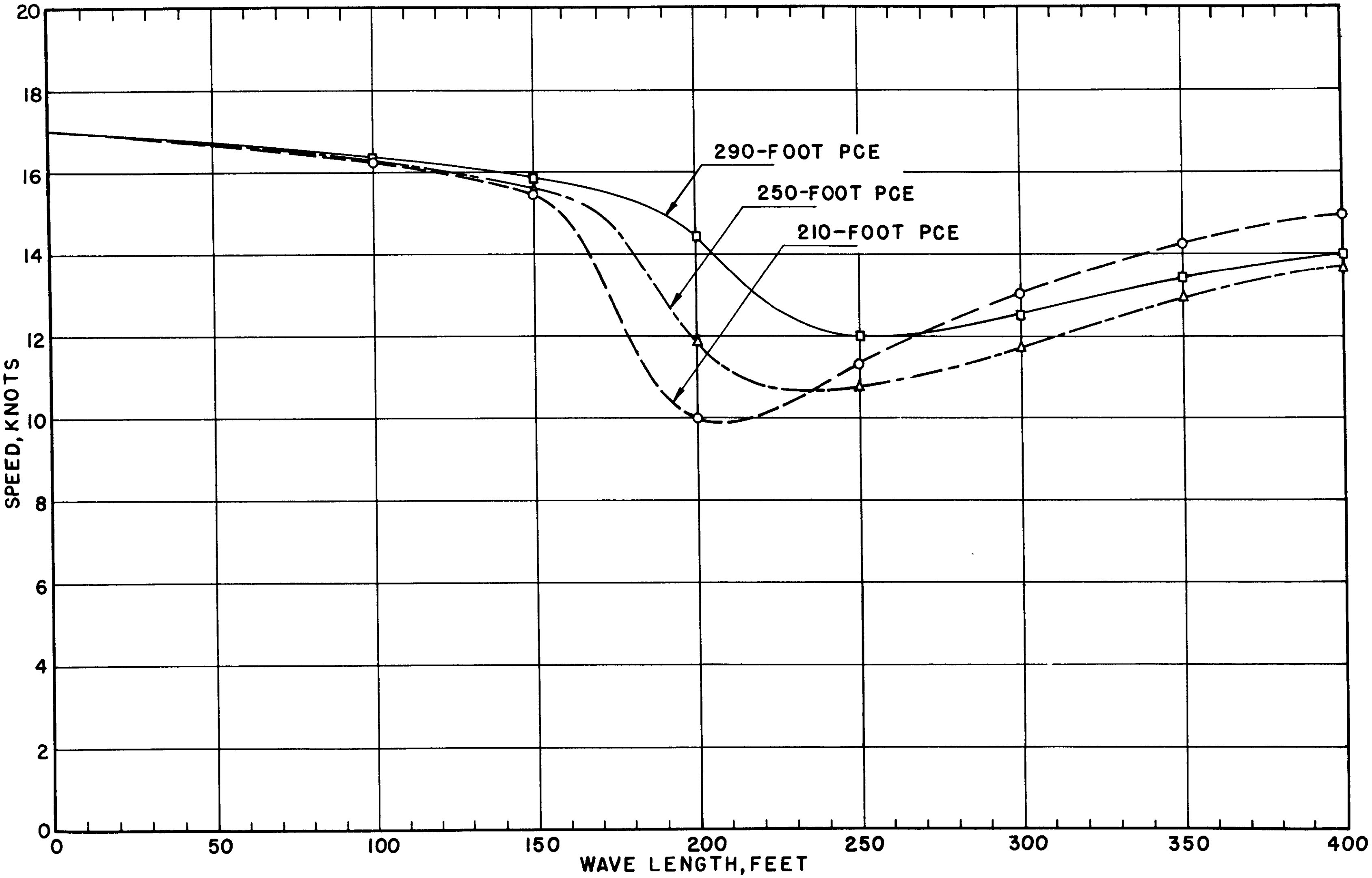

Figure 7 - Variations in Speed with Wave Length for Wave Heights of 0.55 $\sqrt{\text{Wave Length}}$ in Head Seas and for Constant Towing Force

bow near the deck that causes the water to break into spray. It has less resistance at 17 knots than the conventional form, but from the brief tests that were made it does not appear to have the same advantage at 10 knots. These factors – the absence of a skeg, the excessive flare, the low freeboard, and the smaller towing force – combine to cause a reduction of the speed in waves.

In Figures 7 and 14, it should be noted that the wave-height conditions are not as severe in relation to λ/L for the long, narrow hulls as they are for the basic hull. Still the ability of the long, narrow hulls to maintain speed is impressive.

The amplitude of the periodic speed variation for all three hulls in 400-ft waves is about one-fourth of the maximum wave surge, or orbital, velocity.

PITCH AND HEAVE CHARACTERISTICS

Curves of pitch amplitude for the three hull forms are shown in Figures 8, 9, and 10. Inspection of these will show that there is an appreciable difference in the pitching characteristics of the hulls. These curves also show that there are small variations in the amplitude of pitch from wave to wave. The pitch and heave data are shown in Figure 11. Data from both the 35- and 70-mm cameras are given for the 250-ft PCE.

The summary of the pitch and heave data in Figure 11 shows that the 250- and 290-ft hulls have relatively easy motions in comparison with those of the 210-ft hull in head seas of moderate height. In extremely long waves the amplitudes of their motions are large, but the accelerations are small because the periods are long as shown in Figure 12. In all waves of the lengths shown to be critical for pitch and heave, the amplitudes of their motions are comparatively small.

In this comparison, the superiority of the narrow forms is partly due to their greater length and size, and to the fact that the wave slopes decrease with wave length, as the curve of wave slope in Figure 8 shows. The wave conditions, consequently, are less severe for the longer ships.

A nondimensional comparison of the pitch and heave data, Figure 15, indicates that the basic pitching characteristics of the narrow hulls are practically identical.

Figure 11 shows a dip in the amplitude of the heave curve for the 210-ft hull at a wave length of about 350 ft. The tests were not carried far enough to accurately define this hollow, but the curves of Sheet 3, Reference 12, show similar characteristics for large amplitudes of heave.

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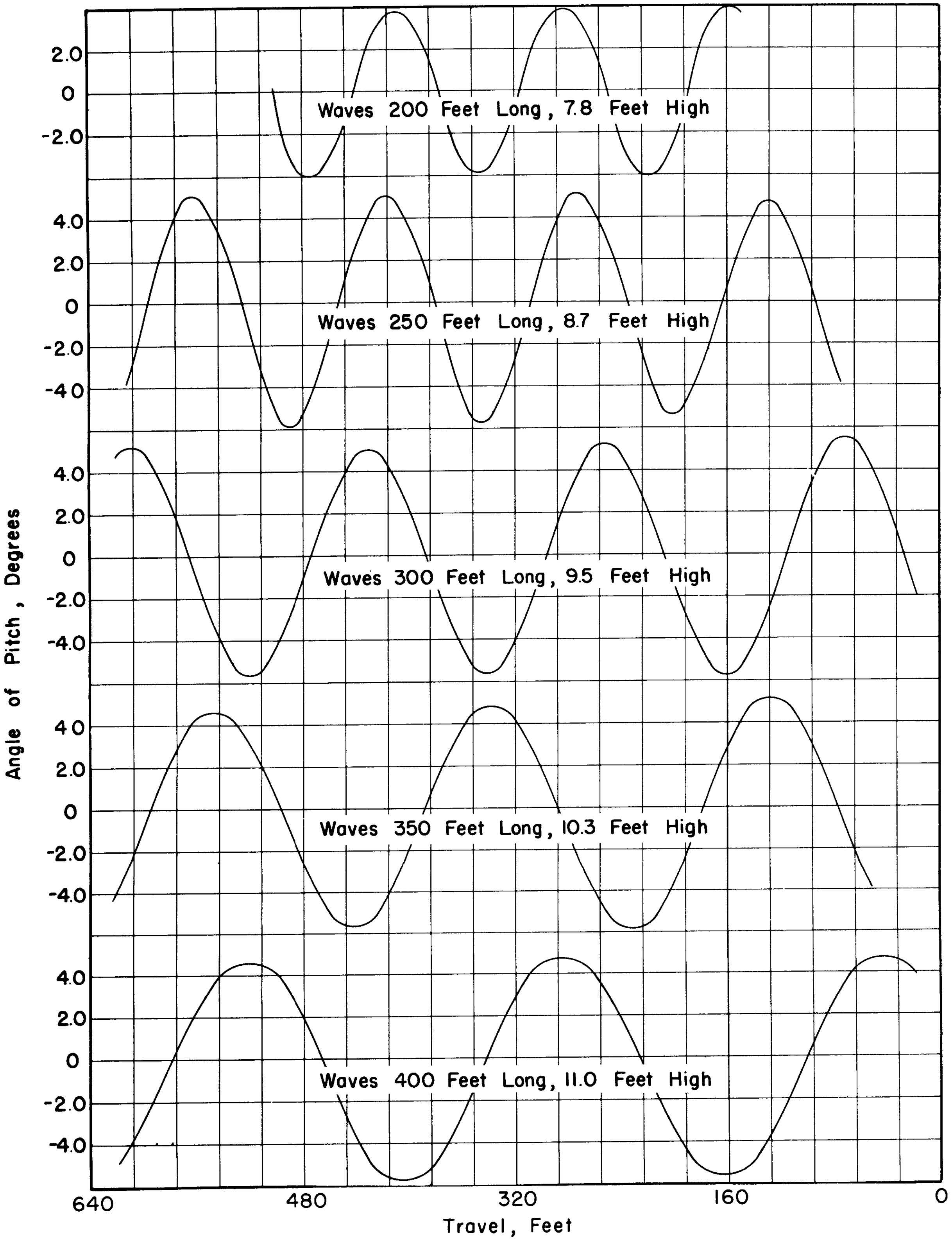

Figure 8 - Amplitude of Pitch with 17 Knots Towing Force from Tests of 210-Foot PCE Model 4453

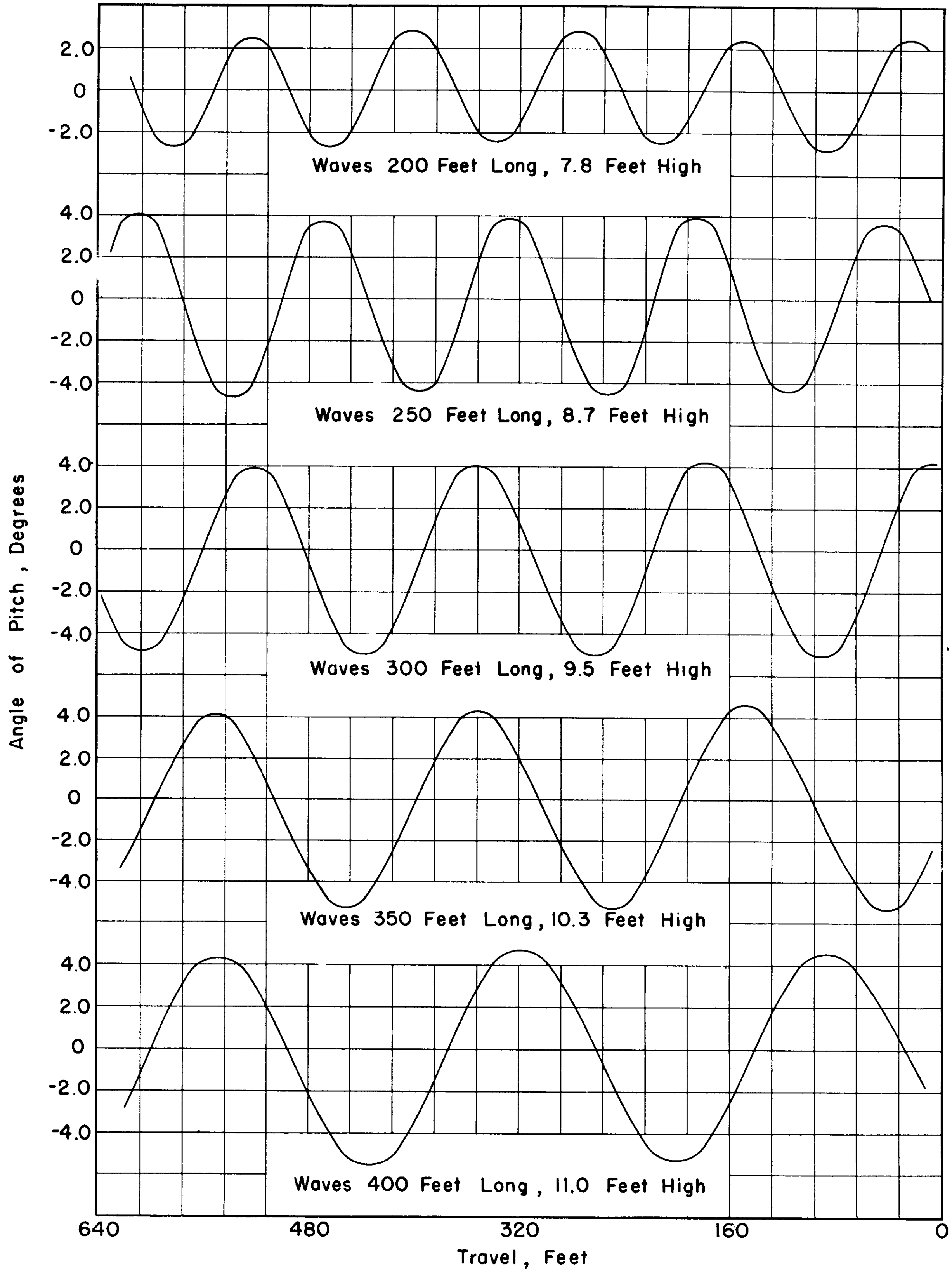

Figure 9 - Amplitude of Pitch with 17-Knots Towing Force from Tests of 250-Foot PCE Model 4454

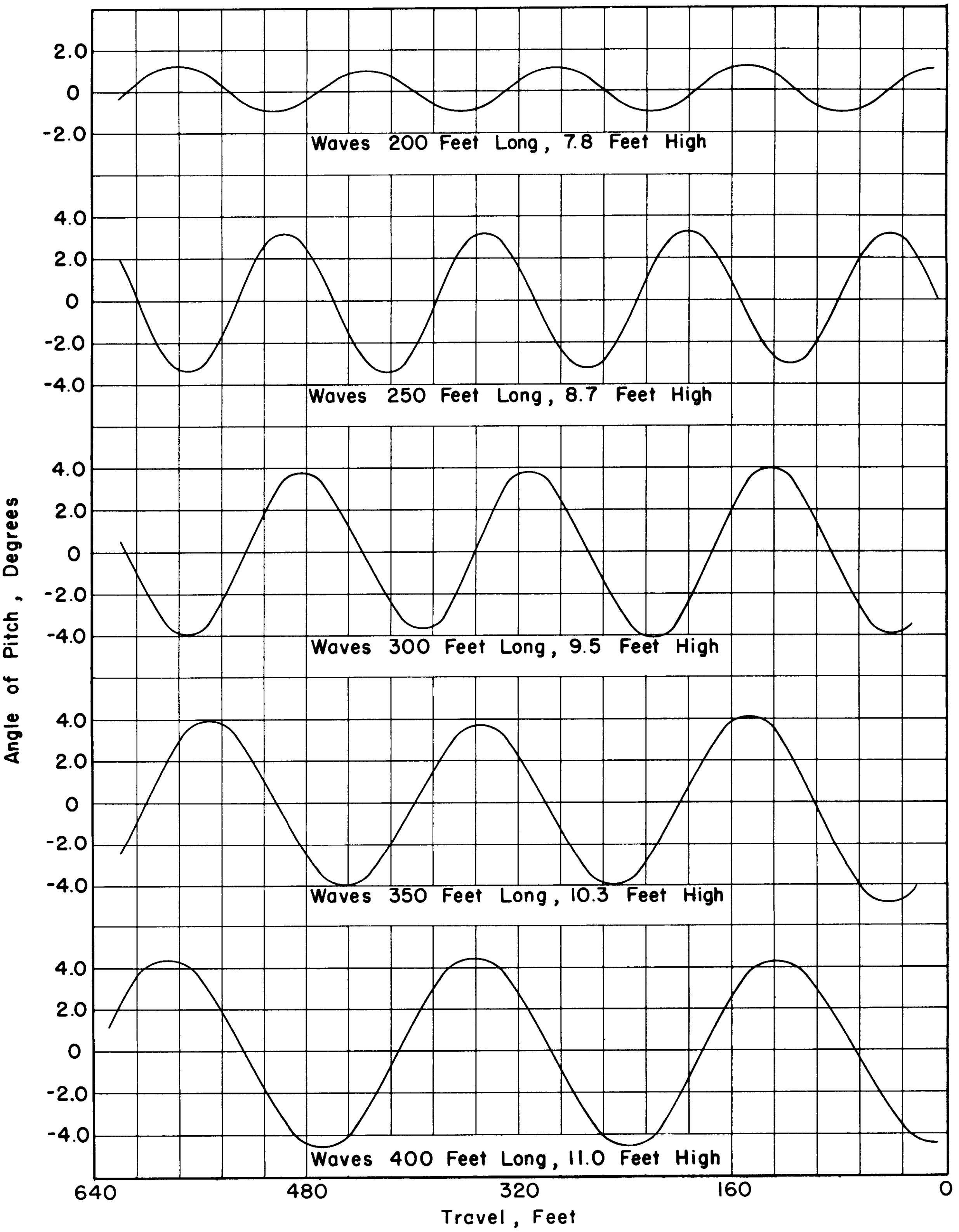

Figure 10 - Amplitude of Pitch with 17-Knots Towing Force from Tests of 290-Foot PCE Model 4455

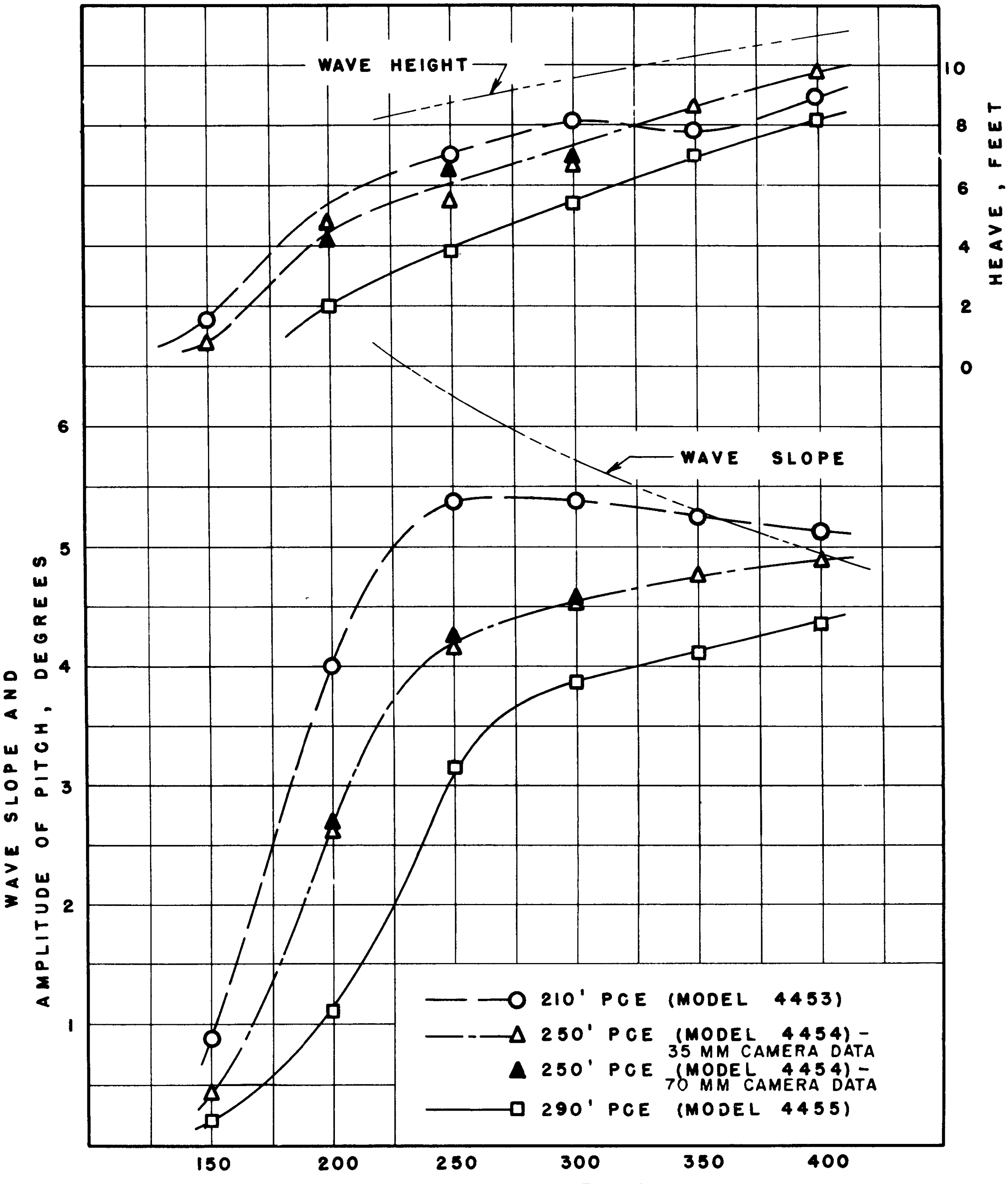

Figure 11 - Variations of Pitch and Heave with Wave Length for Wave Heights of 0.55 $\sqrt{\text{Wave Length}}$

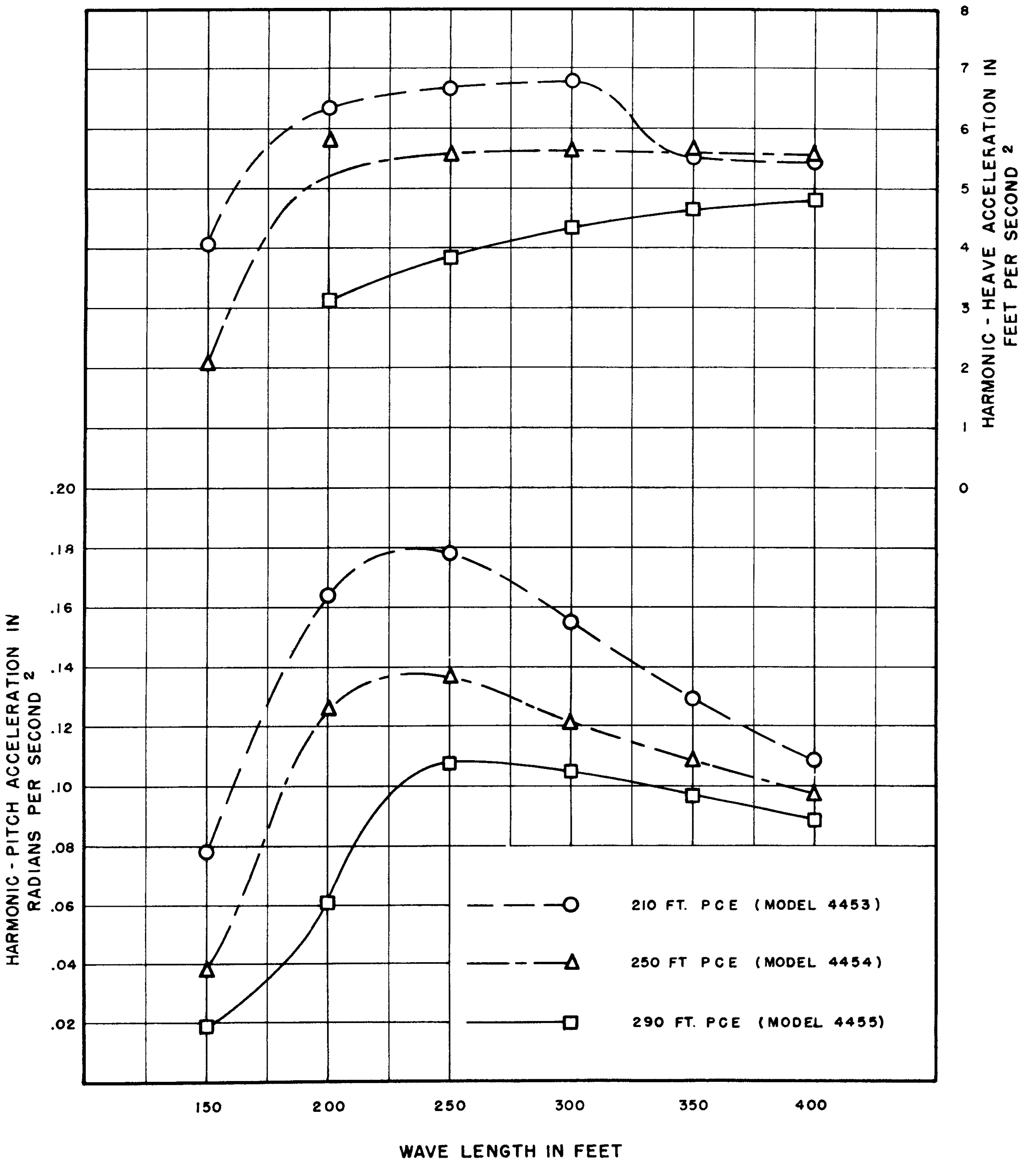

Figure 12 - Pitch and Heave Acceleration for Harmonic Motion of the Observed Amplitude

Based on the curves of Figure 11

WETNESS

The freeboard at the bow of each hull is as follows:

PCE Design	Bow Freeboard ft
210-ft	17.85
250-ft	16.00
290-ft	21.76

The tests indicate that the three designs required about the same freeboard for the same speed in waves of moderate height. The principal characteristics of the performance of the models in waves are shown in the motion pictures, Reference 11.

The model of the 210-ft design is wet in the 200- to 350-ft wave conditions, but a breakwater would keep most of the solid water that comes aboard at the bow from running aft.

The model of the 250-ft design is the wettest of the three, and is quite wet in the 200- to 400-ft wave conditions. The tests and the motion pictures[11] indicate that the freeboard of this design is inadequate for the intended service, and that the slightly excessive bow flare is a source of spray.

The model of the 290-ft design is dry in medium height waves of any length, but as Reference 2 shows, it is only barely dry at times.

ROLLING IN HEAD SEAS

Rolling in head seas was observed in the tests of the 290-ft PCE design in 400-ft waves. This rolling is shown in the motion-picture record, Reference 11.

Rolling in waves dead ahead has been observed in tests of other models at the David Taylor Model Basin. It occurs when the period of encounter of the ship with the waves is in subharmonic resonance with the period of roll. Then the period of encounter is one-half the period of roll, and the vessel is alternately careened to port and to starboard as successive waves are encountered. The action of the waves on the unsymmetrical immersed body of the vessel produces the torque which causes the rolling.

A study of this form of rolling, which is a natural occurence that can be demonstrated with practically any model, is presented in Reference 14.

ROLLING IN BEAM SEAS

In beam seas, there is no outstanding difference in the rolling characteristics of the models without bilge keels. The conventional model has the best roll-damping form, but bilge keels would be particularly effective on the narrow hulls which have low metacentric heights (GM's) and consequently require relatively little energy to stabilize.

Some experimental confirmation of the above conclusion is afforded by tests of submarine models of small metacentric height,[13] which show that the bilge keels contribute greatly to the roll damping of these vessels.

As the model of the 250-ft design has a small metacentric height,[17] its performance in beam seas may be influenced by the fact that it was tested without a skeg.

Figure 13 shows single amplitudes of roll for the ships without bilge keels in 100- to 400-ft waves. It will be noted that the periods at which resonance occurs are shorter than the still-water periods previously given. This difference is attributed to the fact that the resonant periods in waves are for larger amplitudes of roll than the still-water periods. References 15, 16, and 17 show that the rolling periods of ships without bilge keels are usually shorter for large than for small amplitudes of motion. Ships that narrow their waterplanes by emerging one bilge in heeling are exceptions to this rule, as their pro-metacentric heights are smaller than their metacentric heights. The periods of these vessels are longer for large than for small amplitudes of roll; since

$$T = \frac{2\pi k_x}{\sqrt{g \cdot GM}}$$

where T is the period for a complete roll,

k_x is the transverse radius of gyration of the mass of the vessel about the longitudinal axis through the center of gravity,

g is the acceleration of gravity, and

GM is the metacentric height.

The results of the tests in beam seas of the model of the 290-ft design, Figure 13, show that heavy rolling occurs when the period of encounter is one-half the period of roll. In pictures of this rolling the model is upright in the wave hollows and attains the maximum amplitude of roll at the wave crests, where it is heeled first to port and then to starboard in successive waves. Thus the model rolls away from the crest of one wave and toward the crest of the next wave, so that both the front and back slopes of the first wave amplify the motion and both slopes of the second wave oppose the motion.

In considering the amplitude of the motion, Figure 13, it should be noted that the resonant wave slope, Figure 11, is twice as great for the second mode of rolling as for the first.

This form of rolling, which is familiar in theory if not in practice, is discussed in Reference 16.

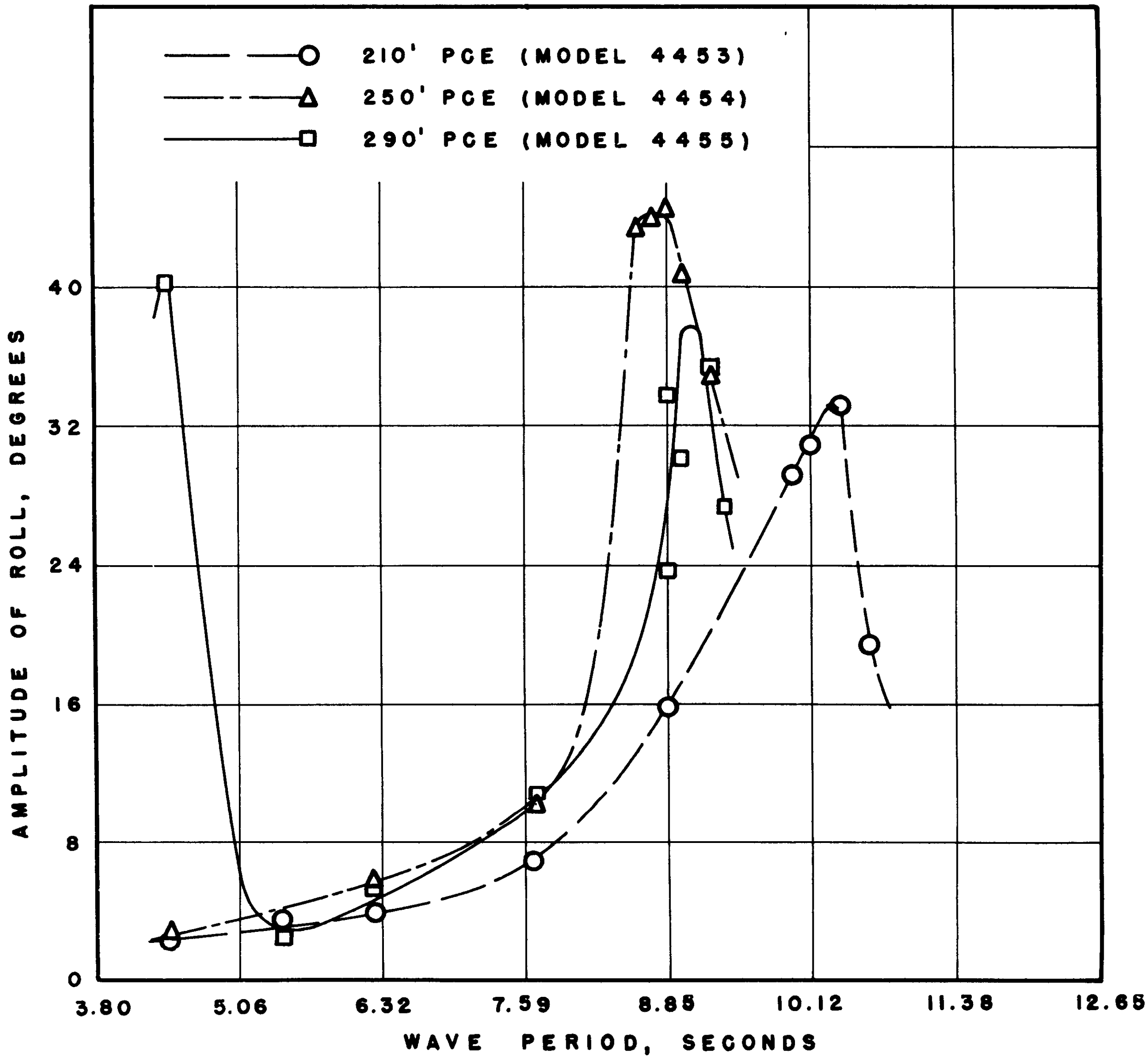

Figure 13 - Amplitude of Forced Rolling in Beam Seas for Wave Heights of 0.55 $\sqrt{\text{Wave Length}}$

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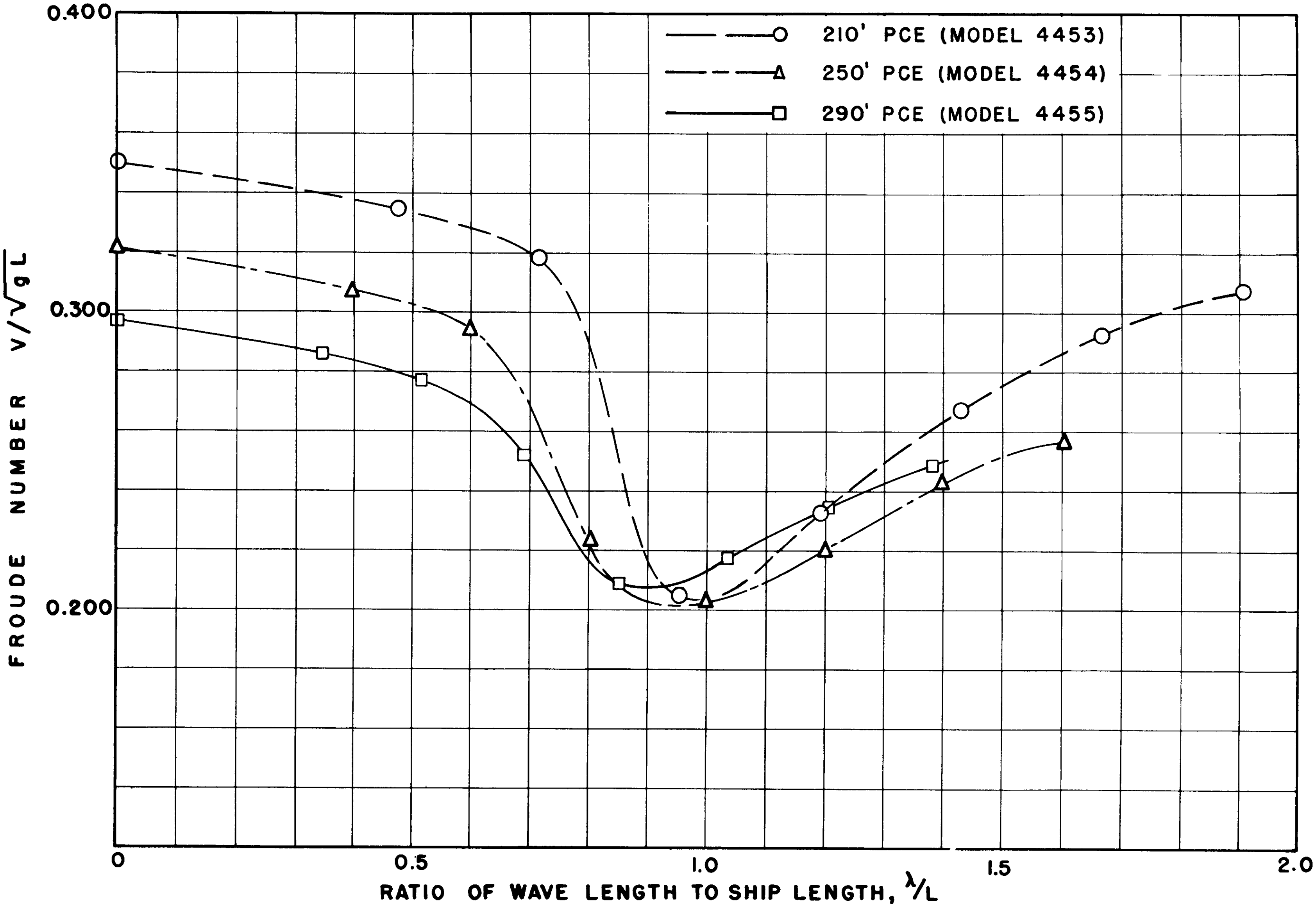

Figure 14 - Variation of Speed with Wave Length for Wave Height of 0.55 $\sqrt{\text{Wave Length}}$, and a Constant Towing Force

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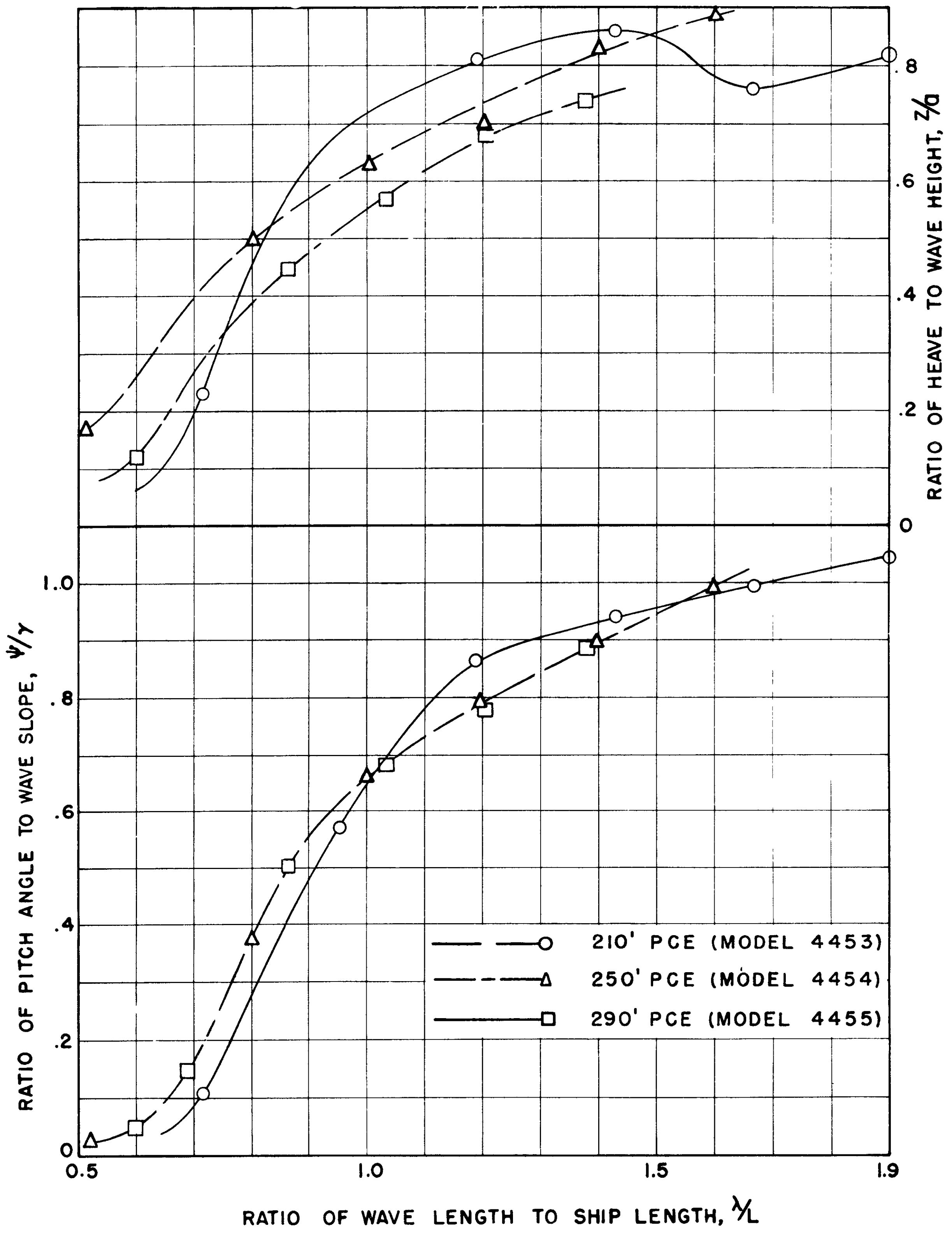

Figure 15 - Nondimensional Pitch and Heave Data

DISCUSSION

Although the waves in these tests are considered to be of moderate height, the short waves, in accordance with the formula

$$\text{Wave Height} = 0.55\sqrt{\text{Wave Length}}$$

are particularly steep. There is consequently, as Figure 4 shows, an unusual reduction in the speed of the vessels in waves less than 150 ft long. Waves of this length with the proportions of the longer waves would have very little effect.

The long narrow hull is the fastest in the wave conditions that are most commonly encountered in operational service at sea. It is even more significant, though, that this form of hull can maintain a sea speed of 12 knots in medium-height waves of all lengths, whereas the conventional 210-ft PCE form can only maintain a speed of 10 knots. Since sea speed is a highly critical factor in the design of a small vessel for escort service this difference is of considerable consequence.

The principal reduction in the speed of an escort patrol craft is in waves that have little effect on the speed of larger convoyed ships. The small vessel, however, can ride up and down the slopes of waves that are of critical length for larger ships without difficulty and maintain a high rate of speed in them, as Figure 7 indicates. Performance in relatively short waves, between 150 and 300 ft long, therefore determines the ability of an escort patrol craft to keep station in a convoy.

The vessels experience the most violent pitching motions in 200- to 300-ft waves which, according to References 18 and 19, are frequently encountered at sea. Hence, it is of interest to find that large reductions in the amplitudes of the pitch and heave motions can be obtained in these waves by reducing the beam and increasing the length of the hull. This reduction of motion would enable the vessel to participate in more extensive and arduous operations, and would materially improve its performance. The sharp sections of the narrow hull, moreover, would make the motions especially smooth and easy.

For the reasons previously given, it is concluded that bilge keels may be particularly effective in stabilizing the narrow PCE hulls. Further tests of the models, however, should be conducted to show the extent of the stabilization and the changes in the character of the rolling with bilge keels.

The conclusion that the subharmonic resonance of beam seas does not produce heavy rolling[16] should be re-examined in the light of the present tests. Several aspects of this rolling are of interest. It is obvious from the tests and from theoretical considerations, for example, that waves with an apparent period of one-half the roll period can cause heavy rolling very suddenly; but it has not been demonstrated that this can occur unless the vessel has a small mass radius of gyration about the axis of roll, or is inadequately damped so that the rolling is largely unresisted. Rolling tests of the models with bilge keels would afford a basis for evaluating this phenomenon. The effect of the variations in displacement and metacentric height which are caused by heaving should be considered also in this connection.

In waves of moderate height there is little difference in the wetness of the three hull forms. Hence, the tendency of the 250-ft vessel to ship seas and throw spray is not attributed to the general proportions of the hull, but to the low freeboard and excessive flare of the bow.

No investigation of heavy sea conditions was conducted. But such tests would be of interest, for the dynamic reactions of the 250- and 290-ft hulls in pitching are slower than those of the 210-ft hull, and they may be wet for this reason in high steep seas. This is one instance in which tests under severe, and even unrealistically extreme, conditions would serve a useful purpose.

It should be noted that these tests are concerned with vessels of moderate speed that do not heel excessively in turns, and consequently can be designed with small metacentric heights. Model tests should be conducted, nevertheless, to assess the yaw-heel effect of quartering seas, which is somewhat analogous to that of turning with the added effect of heave on displacement and metacentric height.

The 290-ft design may be too extreme for most practical purposes, but the 250-ft design could be used as the basic concept of an actual ship. It would be of interest, consequently, to test an improved model of this vessel, and at the same time to test a model with slightly more beam and finer ends, so that the effect of beam on the speed in waves could be more fully determined.

Since these tests have proven of value in providing data of basic and general interest, it is proposed to continue the seaworthiness study of escort patrol craft. Other tests of the effect of beam on seaworthiness should be conducted, as indicated in the above discussion. Of course, there are other factors beside length, beam, and draft which influence the rough-water speed of a ship. Weight, for example, may be an asset in waves where the way of the vessel is maintained by her momentum. The longitudinal radius of gyration has a pronounced effect on the speed in waves, according to References 20 and 21. A vessel, moreover, may be appreciably faster in waves with a cruiser stern than with a transom stern, as shown in Reference 22.

Waves with heights of 0.55 times the square root of their length provide significant test conditions over a wide range of wave lengths, and as the vessels can negotiate these waves with full power, the required data are obtained with a minimum number of runs. This procedure therefore is very satisfactory in conducting tests for a specific purpose. It is important to note as a general consideration, however, that the data cannot be satisfactorily nondimensionalized.

CONCLUSION

The tests show that a reduction of beam has a favorable effect on the performance of Escort Patrol Craft under the rough-water conditions most frequently encountered in operational service, but that the improvement is attained only at the expense of building a longer and larger ship that would require ballast at all times for stability.

The tests also show that an extremely narrow hull without bilge keels may have undesirable rolling characteristics.

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THE EFFECT OF BEAM ON THE SEAWORTHINESS OF ESCORT PATROL CRAFT, by C.G. Moody. September 1954.
iv, 25 p. incl. tables, figs., refs. CONFIDENTIAL

Tests of three models of a proposed 17-knot Escort Patrol Craft were conducted to determine the effect of beam on the speed and behavior of the vessel in waves. Tentative PCE designs having lengths of 210, 250 and 290 ft, and beams of 33, 28, and 25 ft respectively, were prepared for this purpose. It is concluded from the data presented that a reduction of beam has a favorable effect on the performance of the ship in waves of ordinary lengths and heights.

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2. Patrol craft - Models
3. Patrol craft - Rolling, pitching and heaving
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