THE UNIVERSITY OF MICHIGAN
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Final Report

RESEARCH IN RESISTANCE AND PROPULSION

Part IV. Studies on Wave Interference of Mathematical Hull Forms with Large Bow Bulbs

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ABSTRACT

A comprehensive experimental and theoretical study has been made of the wave-resistance characteristics of the cosine hull forms associated with bow bulbs. These hull forms have previously been investigated by Inui in Japan. The current study, which is based on larger models, confirms, in general, results obtained by him. In addition new conditions of hull and bulb shapes have been investigated.

I. INTRODUCTION

A ship hull form, being normally of a rather complex shape, will generally produce a wave pattern which can be broken down into several distinct systems such as bow, stern and shoulder waves. All these systems will be in interference with one another, and the success of a particular hull design can usually be judged by how well the designer has been able to produce a favorable interference (wave cancellation). Over the years a great number of emperical rules have been presented to the naval architects, rules which proclaim to provide them with the means of obtaining optimum hull forms. It is to be realized, however, that the theory of wave-resistance provides the only method by which wave cancellation can be studied in a rational manner.

In addition to the wave interference that exists between the various wave systems produced by the parent hull form itself, further interference can be effected by the introduction of appendages. The bow bulb is the only appendage form that has so far found general usage in practical hull designs. Experimentally, the benefit of bow bulbs was well established by D. W. Taylor. On a theoretical basis, their effects were first studied by Weinblum in Germany and Wigley in England. By applying the linear wave-resistance theory to the problem of wave cancellation, these investigators were able to essentially verify D. W. Taylor's predictions. They did not proceed far enough in their investigations, however, and it was left to Inui and his Japanese colleagues to produce what is now being generally referred to as a "waveless" hull and bulb combination. It will become clear from the formal formulation of the problem, which is reproduced in outline in this report, that complete and exact wave cancellation is not achieved by bulbs. For a given speed, it is possible, however, to reduce the wave-resistance for the hull and bulb combination to a small fraction of that of the hull alone.* Thus the term "waveless" is appropriate for all practical purposes as long as one is referring to a particular speed. It is fortunate that a bulb also proves to be beneficial over a substantial speed range extending both above and below the design speed. This is clearly evidenced by the results of this report.

The failure of the early investigators to realize a "waveless" hull form by means of bulb appendages was apparently due to a lack of computational facility which was necessary to compute the traces of streamlines for the determination of hull forms and also the analysis of wave patterns.

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*For maximum wave cancellation, it is necessary to use both bow and stern bulbs. The bow bulb is by far the most effective and only wave cancellation effects of bow bulbs are included in this report.

The development of new functional relationships of the wave-resistance integral led to the conclusion that for minimum total wave resistance of a hull and bulb combination, it is necessary to have a basic hull form which by itself produces a simple total wave system. The parent hull need not be one of optimum form to obtain a minimum wave resistance of the hull-bulb combination. Stated in a different way, the design of the hull and the bulb must be considered jointly. Thus, it is not surprising that the first studies on "waveless" hull and bulb combination, performed in Japan, were made with the so-called cosine parent hull form . This form has the advantage that it has no shoulder waves, and furthermore, it can be shown that cancellation of bow waves can be almost completely accomplished by means of a single concentrated doublet (spherical bulb). The experimental work described in this report represents in certain aspects a repetition of tests performed in Japan. It was considered important to verify results obtained by Inui with 2.5 m model length by using the somewhat larger model size of 12 ft. The greater part of the experimental work on the cosine hull forms performed at The University of Michigan constitute an extention of investigations performed in Japan.

The most important extention is probably the series of tests with flat bottom models. It has been shown in a previous report (12,p.51) that the depth of the original cosine hulls as obtained from streamline traces is about twice the draft at the bow and stern. The "rocker" bottom produced by these traces have been subject to criticism since it is duly felt that such a bottom can never find any practical application. It was, therefore, essential that tests with flat bottoms be made to determine what effect this feature would have on the overall performance of the hulls and also if a flat bottom would influence the effect of the bow bulb. Results obtained are encouraging, indicating a reduced resistance over certain speed ranges. It should, however, be remembered that both wetted surface and displacement has been materially reduced.

Optimum bulbs have been reported by Inui for particular speeds $\left(\frac{V}{\sqrt{L}} = .87 \text{ for C-101 and } \frac{V}{\sqrt{L}} = .90 \text{ for C-201}\right)$. Other bulbs suitable for different speeds have been designed and tested at The University of Michigan during the past year and available results are reported herein. In our particular case, a modification of a bulb to make it more suitable for the flat bottom of the C-101 proved to improve on the results reported by Inui. In another case, a bulb designed for a speed length ratio of 1.1 was shown to be less effective at design speed than the smaller bulb designed for the speed length ratio of .87. These results point to the fact that, although the linear wave resistance theory will predict possible reductions in wave resistance, it hardly eliminiates model testing as the ultimate mean by which the final determination of design parameters are made.

II. THEORY OF WAVE-INTERFERENCE

Assuming that a ship is moving in the direction of the negative x-axis with the origin located at the bow, the wave pattern of the bow system can for large values of x be defined by

$$\zeta_{w,F}(x,y) \simeq \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} A_F(\theta) \sin[K_o \sec^2 \theta(\overline{x-x_o} \cos \theta + y \sin \theta)]d\theta \qquad (1)$$

where $A_F(\theta)$ is the amplitude function determined from hull geometry and $K_o = \frac{g}{V^2}$. The subscript F refers to the bow wave system.

The corresponding expression for the wave system produced by a bulb located at $(x_o, 0, f)$ is

$$\zeta_{w,D}(x,y) \simeq -\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} B_F(\theta) \sin [K_o \sec^2 \theta(\overline{x-x_o} \cos \theta + y \sin \theta)]d\theta \qquad (2)$$

Superimposing the two wave systems of Equations (1) and (2) we get

$$\zeta_{w,D}(x,y) \simeq \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \{A_F(\theta)-B_F(\theta)\} \text{Sin} [K_o \sec^2 \theta(\overline{x-x_o} \cos \theta + y \sin \theta)]d\theta \qquad (3)$$

The amplitude functions $A(\theta)$ and $B(\theta)$ are described in more detail in Appendix I.

The contribution to the wave-resistance by the bow wave system has been shown (1) to be given by

$$R_{w,F} = \frac{\pi}{2} \rho V^2 \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} [A_F(\theta)]^2 \cos^3 \theta \, d\theta \qquad (4)$$

and it follows directly from Eq. (3) that the wave-resistance due to the bow wave-system and the bulb wave system becomes

$$R_{w,F+D} = \frac{\pi}{2} \rho V^2 \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} [A_F(\theta) - B_F(\theta)]^2 \cos^3 \theta \, d\theta \tag{5}$$

Equation (5) shows that the condition of zero wave-resistance is met if and only if $A_F(\theta) = B_F(\theta)$. It is indeed difficult to imagine, from a physical point of view, that two bodies of completely different shapes can produce wave-systems that are of equal amplitude for all values of θ. From a practical point of view the equality of amplitude functions mentioned above does not have to be fully satisfied, however. As $\theta \to \pm\frac{\pi}{2}$, $\cos \theta \to 0$ and the factor $\cos^3 \theta$ of the integrand of Equations (4) and (5) shows that the contribution to the wave-resistance of the waves associated with the larger values of θ is negligible. In a physical sense this means that wave components which propagate in a direction close to being perpendicular to the direction of motion of the ship have a negligible effect on the wave-resistance.

Assuming that a hull form is properly represented by a distribution of singularities on the center-plane of symmetry, the wave amplitude function can be completely determined from this distribution. In the case of the cosine ship form, the distribution is such that only bow and stern wave systems are produced. Furthermore it can be shown that the resultant wave system is a sine system ($x_o = 0$ in Eq. (1)). It is noted from Eq. (2) that the wave system due to a doublet located at F. P. is an inverse sine system and the condition of inverse phase is satisfied for the particular hull form in question. The inverse phase relationship is of the utmost importance to wave cancellation and is indeed implied in writing Eq. (3) as the sum of Eqs. (1) and (2). It was also implied that x_o = constant. In general this is not so. In fact, the general form of Eq. (1) is

$$\zeta_{w,F}(x,y) \simeq \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} A_F(\theta) \sin [K_o \sec^2 \theta(\overline{x+x_F}(\cos \theta + y \sin \theta)] d\theta \tag{6}$$

where

$$[A_F(\theta)]^2 = S_F^2(\theta) + C_F^2(\theta)$$

and

$$\frac{X_F}{L} = \tan^{-1}\left\{\frac{C_F(\theta)}{S_F(\theta)}\right\} \Big/ K_o L \sec \theta$$

$S_F(\theta)$ and $C_F(\theta)$ are the amplitude functions of the sine and cosine components respectively. It is noted that x_F is a function of both θ and K_0 and it follows therefore that it is not possible to write Eq. (5) for the general case of hull forms, assuming the bulbs to be represented by a single doublet. A bulb represented by a distribution of doublets or even a single doublet may still produce a substantial wave-interference, however, provided it is located properly. If the cosine component of the bow wave system is predominent the center of the bulb should be moved aft, for instance, and the optimum position of its center may actually be aft of the forward perpendicular.

The most desirable main hull form for maximum wave cancellation is one that does not have any shoulder waves and creates a bow wave system that calls for the bulb being located within a practical distance of the forward perpendicular. To accurately determine size, form and location of bulbs, full use must be made of the analysis of wave patterns together with theoretical calculations of the amplitude functions and wave profiles. The University of Michigan does not as yet have the necessary facilities for complete analysis of wave patterns and neither are all the computer programs ready for use. For the analysis of the results obtained with the cosine hull forms it was possible to use computations made previously in Japan by Inui and Takahei. In this way it was possible immediately to continue important research and thus lay the foundation for continued investigation of wave cancellation effects of bulbs.

III. EXPERIMENTAL RESULTS

The experimental results reported here pertain for the greater part to C-101, the narrower of the two cosine hull forms tested. (C-101 and C-201.) Particulars of the hulls are given in Tables I and II. Traced streamlines are shown in Figs. 3 and 4 of Ref. (2) and also in Fig. II-1 in Ref. (12). Figures 1 and 2 show the details of C-101 including bulbs and bottom cut-off. The details of C-201 are similar.

The source distribution representing the cosine hull forms is given by

$$m(\xi) = a \cos\left(\frac{\pi}{2}\xi\right) \tag{7}$$

where the origin is located at the forward perpendicular. The draftwise distribution is uniform. Within the Michell approximation the waterlines are cosine curves with respect to amidships. Because of finite beam the waterlines are not exactly cosine curves however and there is also a slight difference between the forms of the waterlines of C-101 and C-201.

Models were made in wood and so designed that bottoms and bulbs could be easily interchanged. Smooth fairing between bulbs and hull was made in wax. In the designation of individual hull bulb combinations subscripts FK refers to flat keel and F1, F2, etc., identify the bow bulbs. Bulb C-101F1 was designed at The University of Michigan to replace the original bulb C-101F tested in Japan.

Comparisons between tests of bare hull and hull with bulbs are based on the same draft of models, in agreement with the procedures used in Japan. The models were not restrained in trim or heave, however. In Japan the models are customarily restrained from trimming. Preliminary tests at The University of Michigan revealed that the effect of trim is negligible when the amount of trim is small, and it was found that this condition was satisfied in all tests made.

For turbulence stimulation a trip wire of .036 in. diameter was attached to the model at .05L from the bow. In addition, studs of .032 in. diameter and .020 in. length were spaced .5 in. apart in a circle around the head of the bulb (see Figs. 1 and 2). Injection of dye ascertained that the flow around the bulb behind the studs was turbulent for even the lowest speeds of interest.

No blockage correction has been applied to test results. Such corrections would be very small and besides no correstions were used in the analysis of the data obtained at Tokyo University. Blockage ratio (the ratio of model cross-section to tank cross-section) is approximately 1/160 for the model sizes used in the cosine hull form tests for both the Michigan and the Tokyo tanks.

TABLE I

PARTICULARS OF VARIATIONS OF C-101 MODEL (U OF M NO. 938)

	C-101		C-101F1		C_{FK}-101		C_{FK}-101F1		C_{FK}-101F2	
	Model	Ship	Model	Ship	Model	Ship	Model	Ship	Model	Ship
Dimensions										
LWL, ft	12.00	600	12.00	600	12.00	600	12.00	600	12.00	600
LOA, ft	12.00	600	12.72	636	12.00	600	12.72	636	12.97	648
B, ft	1.083	54.2	1.083	54.2	1.083	54.2	1.083	54.2	1.083	54.2
H_F, ft	0.600	30	0.720	36	0.600	30	0.720	36	0.917	45.9
H_A, ft	0.600	30	0.600	30	0.600	30	0.600	30	0.600	30
H_X, ft	1.030	51.5	1.030	51.5	0.720	36	0.720	36	0.720	36
∇, ft^3	6.911	--	7.058	--	5.851	--	5.998	--	6.120	--
Δ, tons	--	24,700	--	25,200	--	20,800	--	21,400	--	21,860
S, ft^2	25.55	63,900	26.678	66,700	23.057	57,650	24.185	60,450	24.739	61,750
$V/\sqrt{L}$ and V, design	--	--	0.85	21 kt	--	--	0.85	21 kt	1.1	27 kt
Coefficients										
B/LWL	0.0904		0.0904		0.0904		0.0904		0.0904	
H_X/LWL	0.0859		0.0859		0.060		0.060		0.060	
C_B	0.515		0.526		0.627		0.642		0.655	
C_X	0.795		0.795		0.913		0.913		0.913	
C_P	0.648		0.663		0.697		0.705		0.719	
LWL/$\nabla^{1/3}$	6.30		6.26		6.66		6.60		6.55	

TABLE II

PARTICULARS OF VARIATIONS OF C-201 MODEL (U OF M NO. 945)

	C-201		C-201F2		C_{FK}-201	
	Model	Ship	Model	Ship	Model	Ship
Dimensions						
LWL, ft	12.00	600	12.00	600	12.00	600
LOA, ft	12.00	600	13.03	652	12.00	600
B, ft	1.446	72.2	1.446	72.2	1.446	72.2
H_F, ft	0.60	30	0.902	45.1	0.60	30
H_A, ft	0.60	30	0.60	30	0.60	30
H_X, ft	1.180	59	1.180	59	0.641	32.1
∇, ft^3	10.320	--	10.685	--	7.312	--
Δ, ton	--	35,900	--	37,100	--	25,400
S, ft^2	28.006	69,500	30.489	76,200	24,850	--
$V/\sqrt{L}$ and V, design	--	--	0.9	22 kt	--	--
Coefficients						
B/LWL	0.1206		0.1206		0.1206	
H_X/LWL	0.0984		0.0984		0.0535	
C_B	0.503		0.524		0.657	
C_X	0.783		0.783		0.946	
C_P	0.643		0.670		0.695	
LWL/$\nabla^{1/3}$	5.52		5.45		6.18	

Although the proportions of the cosine hull forms are not suitable for practical ship designs, it was deemed desirable to calculate the resistance for a hypothetical ship of 600 ft. length based on the model results. In so doing the 1947 ATTC friction extrapolator with a ΔC_f = .0004 was used throughout. Japanese data originally incorporated the Hughes extrapolator with a form factor K. For comparison these data have been re-evaluated on the same friction basis as the Michigan data.

The values of the residuary resistance coefficients are based on the square of the model length. This was done to avoid any ambiguity that might have been introduced if the wetted surface had been used, since the area of this surface varies from model to model.

In summary the results of the C-101 series of tests are shown in Figs. 3-8. Some comments in regard to these figures are in order.

A. C-101

Compared to the Japanese data the larger Michigan model exhibits slightly lower values of C_r throughout the speed range. The difference may have resulted from a too small steepness of the ATTC friction curve at low Reynolds numbers. The constant difference in C_r values supports this point of view. The difference is small, however, and the agreement between results can only be judged to be very good.

B. C-101F1

The bulb F1, which is a modification of the bulb F tested in Japan, produced excellent wave cancellation effects at the design speed of $V/\sqrt{L}$ = .87. The modification was made for the purpose of obtaining a better fit with model C_{FK}-101. The cancellation effect of bulb F1 proved to be superior to that of bulb F even when fitted to the original parent form C-101. This can be easily verified from Fig. 5 and also from the wave profiles shown in Figs. II-2(a-e) of Appendix II. Special attention is called to Fig. II-2(a) showing the wave profile at design speed. Details of the bulb designs are as shown in Table III.

C. C_{FK}-101

The effect of the flat bottom is to increase C_r as shown in Fig. 4(a) and (b). When the data are extrapolated to the 600 ft. ship, however, it is found that the total resistance is approximately the same for both C-101 and C_{FK}-101. The decrease in frictional resistance due to a smaller wetted surface appear to have compensated for the increase in residual resistance.

D. C_{FK}-101F1

Bulb F1 was equally effective as a wave cancelling device in the case of the flat bottom model as when attached to the parent form C-101 (C-101F1).

E. C_{FK}-101F2

The F2 bulb was primarily designed for the hull C-101 to minimize the wave-resistance at a Fronde number of .26($V/\sqrt{L}$ = 1.1). To date it has only been tested with the hull C_{FK}-101, however.

Although the F2 bulb was efective in reducing the wave resistance the smaller F1 bulb was more so even at $V/\sqrt{L}$ = 1.1. It is too early to give a full explanation for these results. Some plausible explanations may be offered at this time, however. The size of the optimized bulb increases rapidly with the design speed (approximately proportional to the cube of the speed). With the larger bulb more fairing is needed to fit it to the main hull. This fairing may change the wave making characteristics of the main hull sufficiently to eliminate some of the wave cancelling effect of the bulb. Another factor, which is described in Appendix I, is that for the case of the cosine hull forms the condition of equal magnitude of the amplitude functions $A(\theta)$ and $B(\theta)$ become rather difficult to satisfy at higher speeds over a significant region of values of θ. The amplitude functions of a variety of bulb shapes do not change materially as a function of θ at various speeds. It follows therefore that it is difficult to accomplish a better wave cancellation by a redesign of the bulb. The course to follow is therefore to design the hull to fit the bulb, and not vice versa. Future studies will be based on this approach.

The characteristics of the F2 bulb are as shown in Table III.

TABLE III

BULB DATA FOR C-101 AND C-201

Bulb	Designed at	Percent					
		a_o/L	$\Delta\nabla/\nabla$	$\Delta S/S$	A_B/A_X	f/L	ℓ/L
C-101F1	UM	2.0	2.13	4.41	21.0	4	4
C-101F	Tokyo Univ.	2.7	3.60	5.80	20.0	4	5
C-101F2	UM	2.8	3.87	6.60	40.5	4.8	5.3
C-201F2	Tokyo Univ.	3.2	4.06	9.96	22.1	5.4	6.0

a_o	radius of a sphere circumscribed by the bulb
L	length of ship
$\Delta\nabla/\nabla$	ratio of bulb volume displacement to that of main hull
$\Delta S/S$	ratio of bulb wetted surface to that of main hull
A_B/A_X	ratio of maximum cross-sectional area of bulb to that of main hull at midship
f	bulb immersion
ℓ	location of bulb center forward of FP in longitudinal direction

Test results on C-201 series is summarized in Figs. 9-14. For these figures the following comments are added:

F. C-201

As can be seen in Fig. 11, small differences exist between the results obtained in Japan and at The University of Michigan.

G. C-201F2

At The University of Michigan, the model with bulb was towed free to trim and heave at different draft. Trim was found to be negligibly small, being less than 0.2 of a degree. These tests are identified as Test Nos. 2, 3 and 4. No appreciable difference was found due to the change of draft although the tested depths of immersion of the bulbs were varied considerably. The following table shows the test conditions indicated in Figs. 9, 11 and 13. For bulb data see Table III.

TABLE IV

TEST CONDITIONS FOR C-201 (12-FT LWL) AND BULB DATA

Test No.	Test Conditions			
	Model	Draft	∇, ft^3	Wetted Surface, ft^2
1	C-201	Designed	10.320	28.006
2	C-201F2	Designed	10.683	30.489
3	C-201F2	DWL—0.16 in.	10.523 (1% less)	30.165
4	C-201F2	DWL—0.48 in.	10.203 (3% less)	29.519

H. C_{FK}-201

Figures 12 and 14 show the resistance of this model as compared to C-201. It is noted from Fig. 12 that above a speed length ratio of 1.2 the C_r for C_{FK}-201 is less than that of C-201. This is surprising, especially since the coefficients are calculated on the basis of the wetted surface. It appears therefore that the removal of the rocker bottom has had a slight beneficial effect in regard to wave-resistance. This feature needs further investigation from a theoretical point of view.

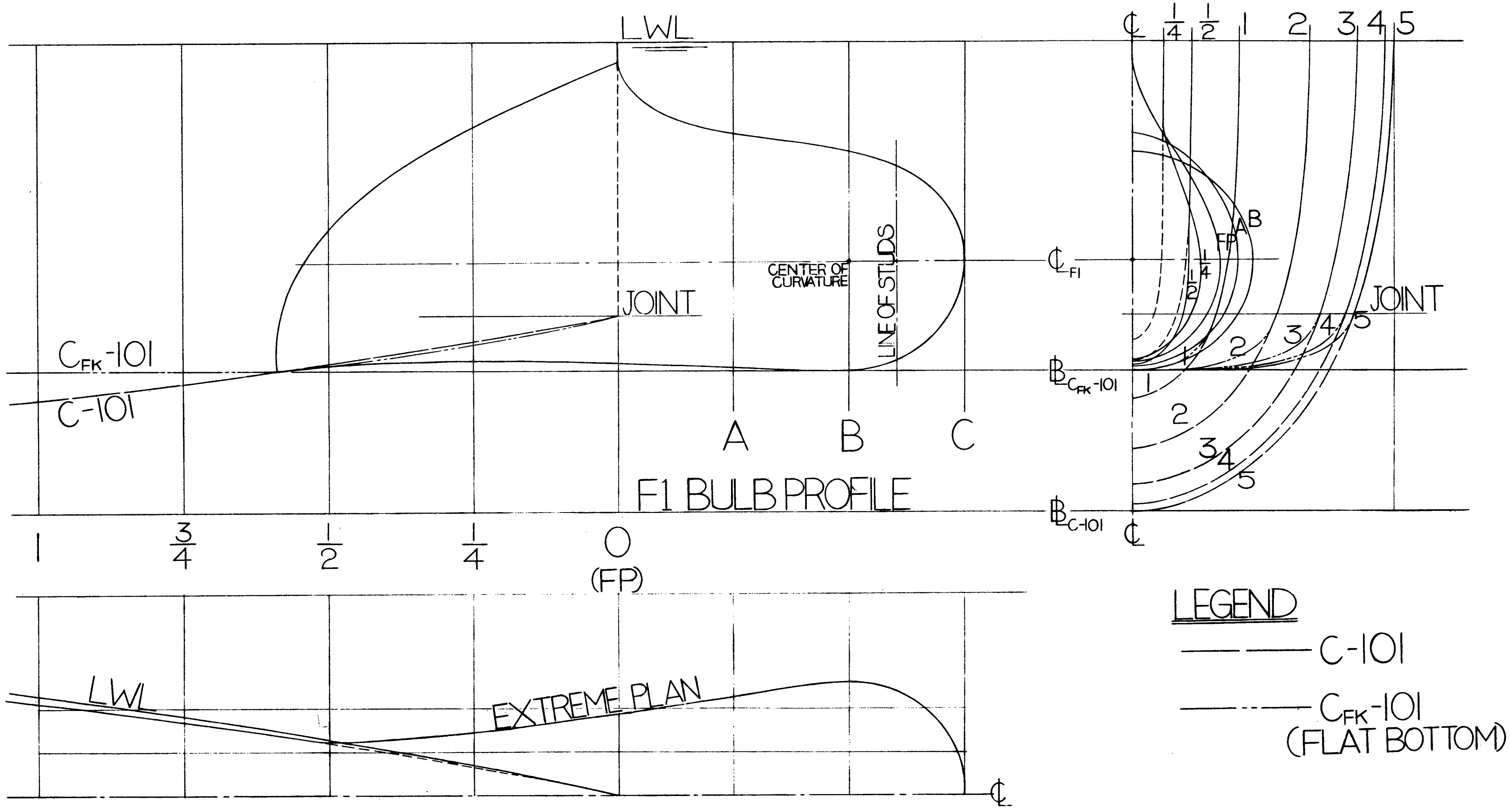

Fig. 1. Details of F1 bulb connection to hull C-101 and C_{FK}-101.

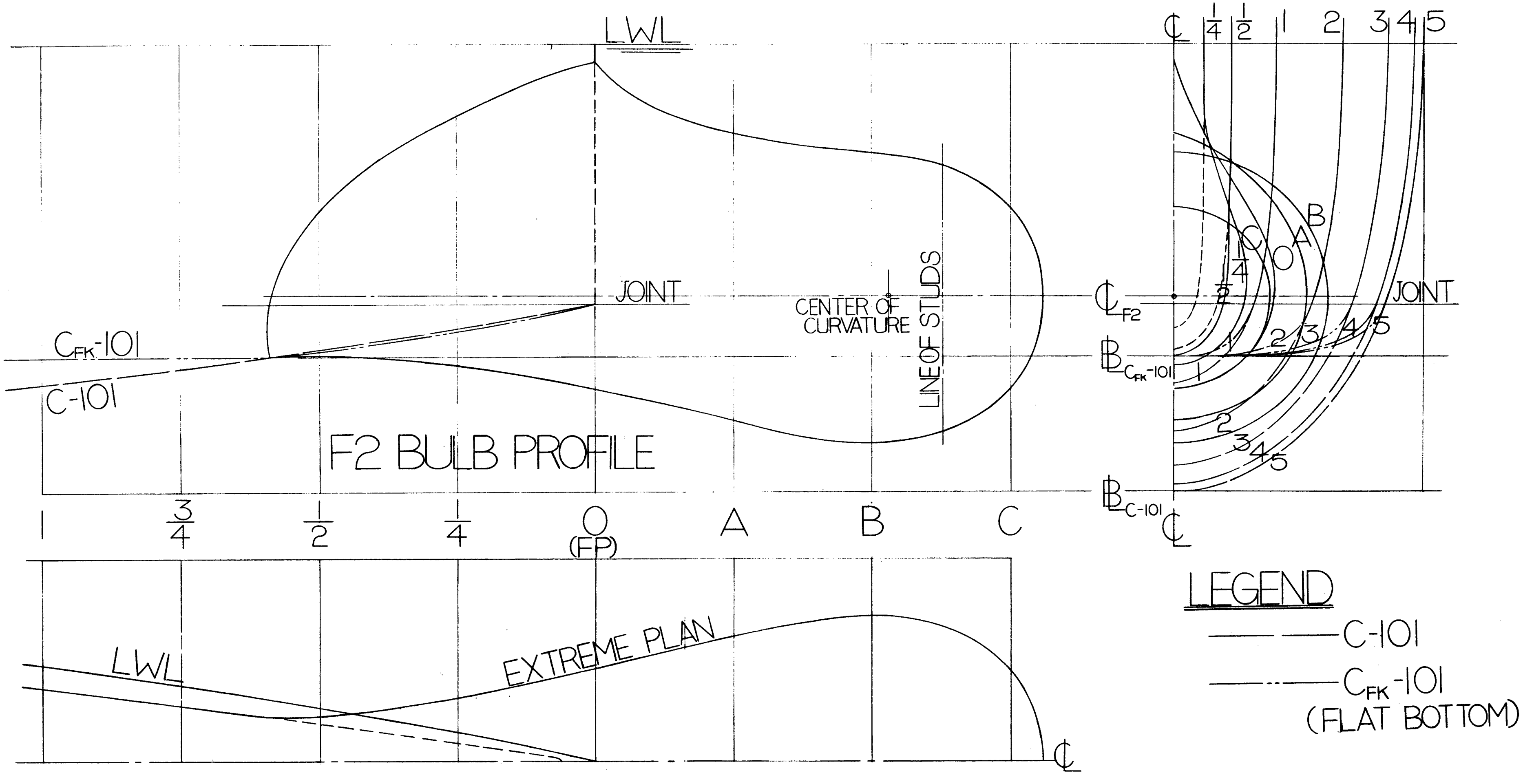

Fig. 2. Details of F2 bulb connection to hull C-101 and C_{FK}-101.

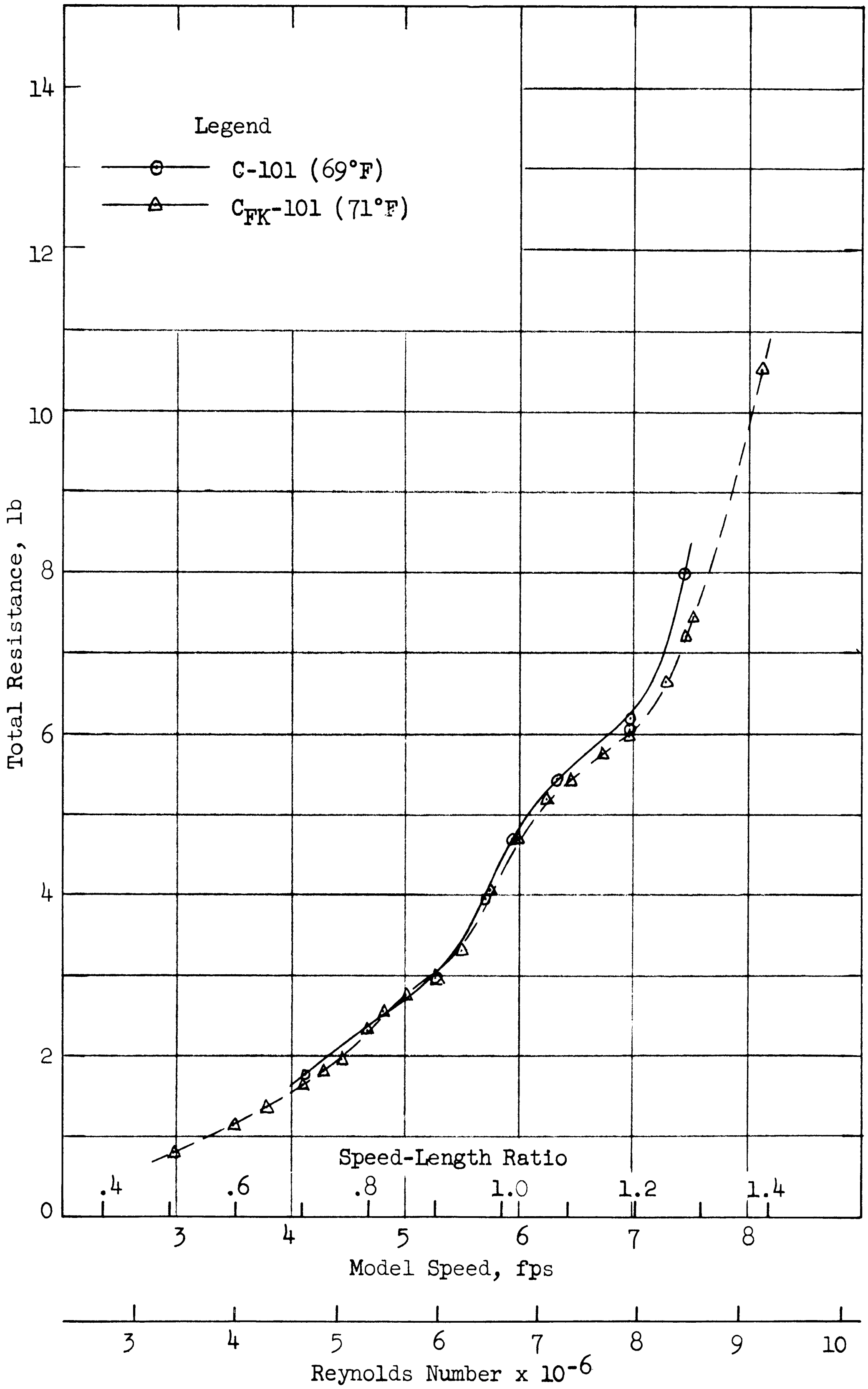

Fig. 3. Total model resistance of C-101 with rocker botton (UM 938) and C_{FK}-101 with flat bottom; 12-ft models.

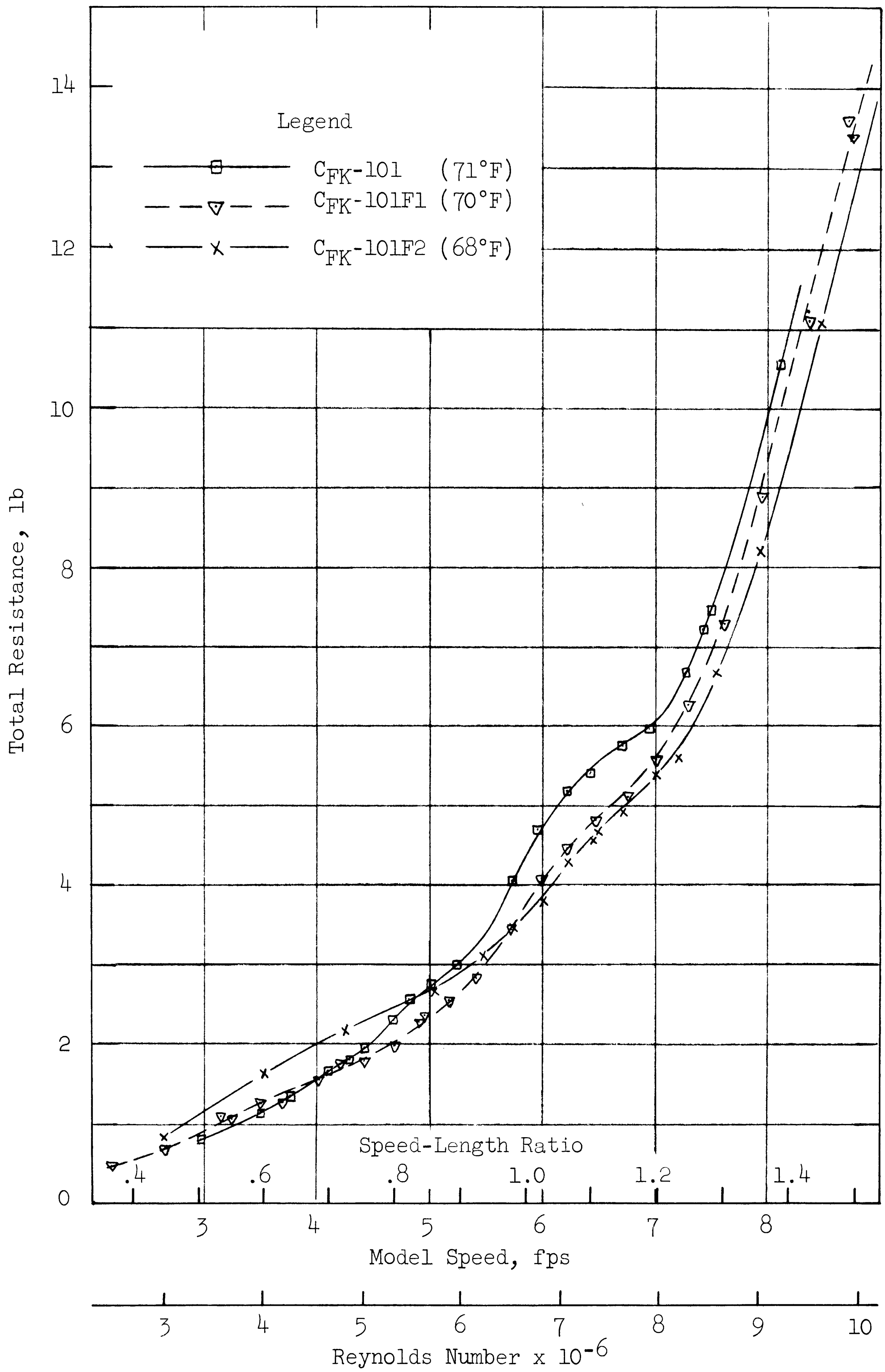

Fig. 4. Total model resistance of C_{FK}-101, C_{FK}-101F1, and C_{FK}-101F2.

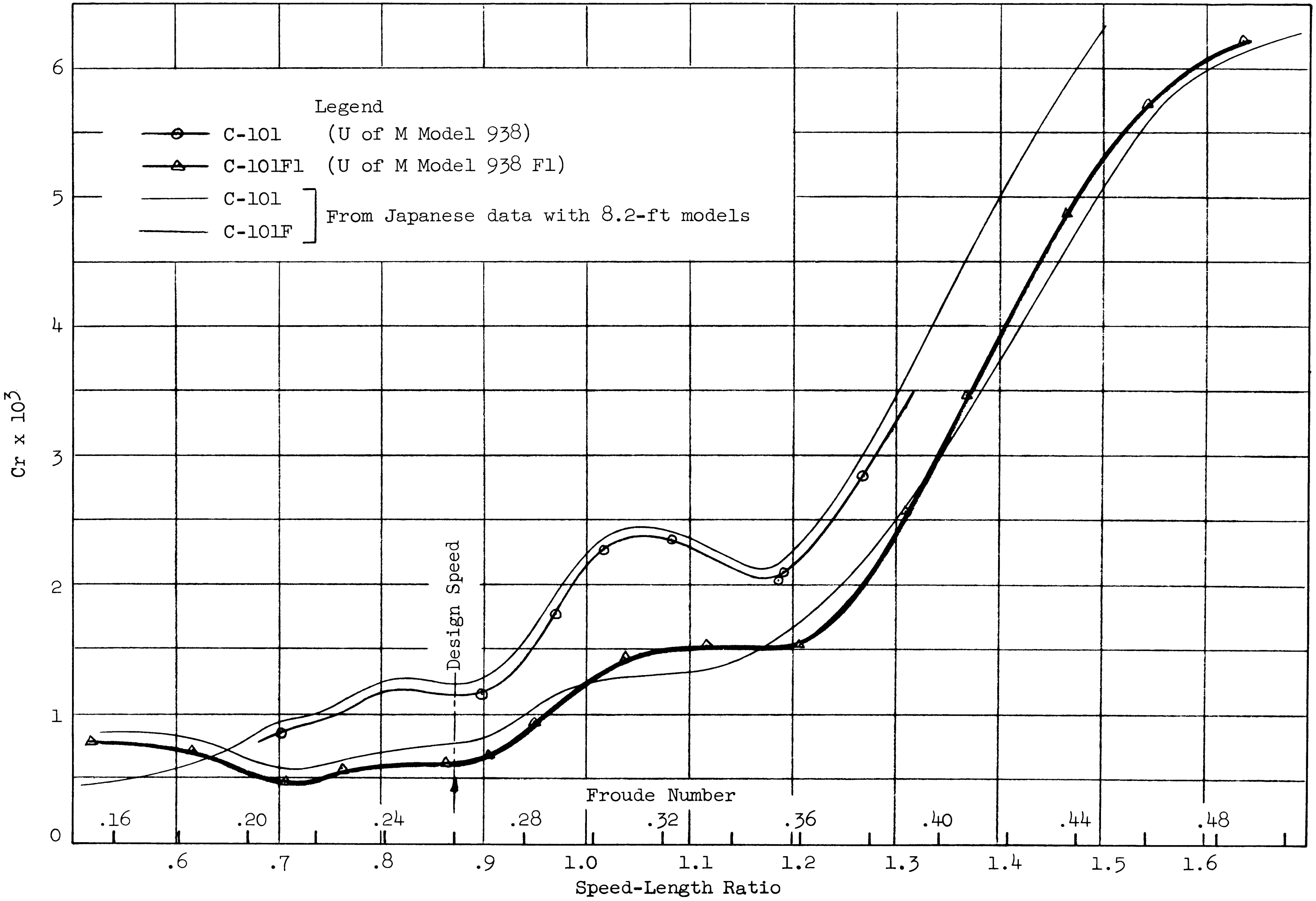

Fig. 5. C_r for cosine from C-101 with rocker bottom and C-101F1.

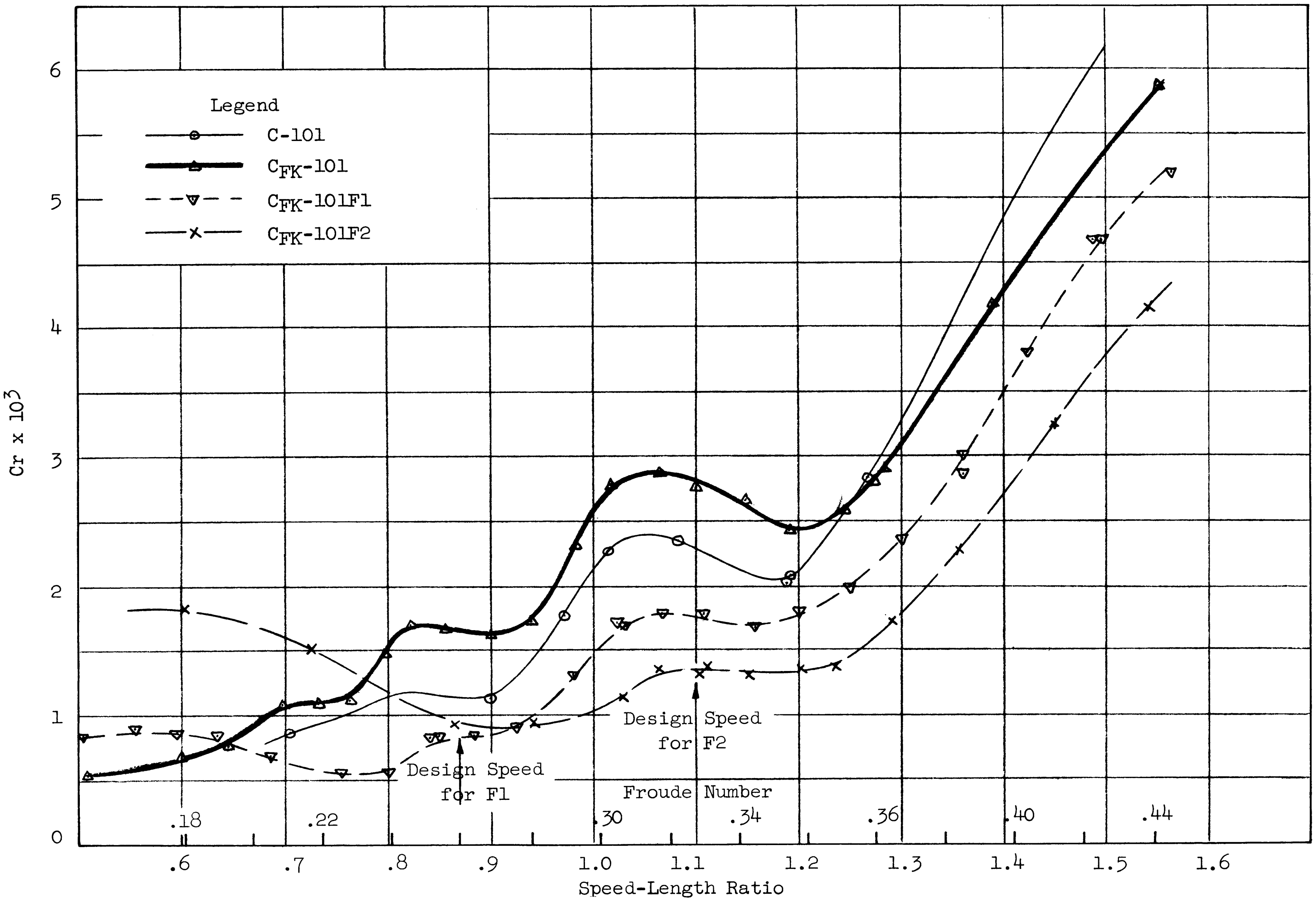

Fig. 6(a). C_r for C-101, C_{FK}-101, C_{FK}-101F1, and C_{FK}-101F2.

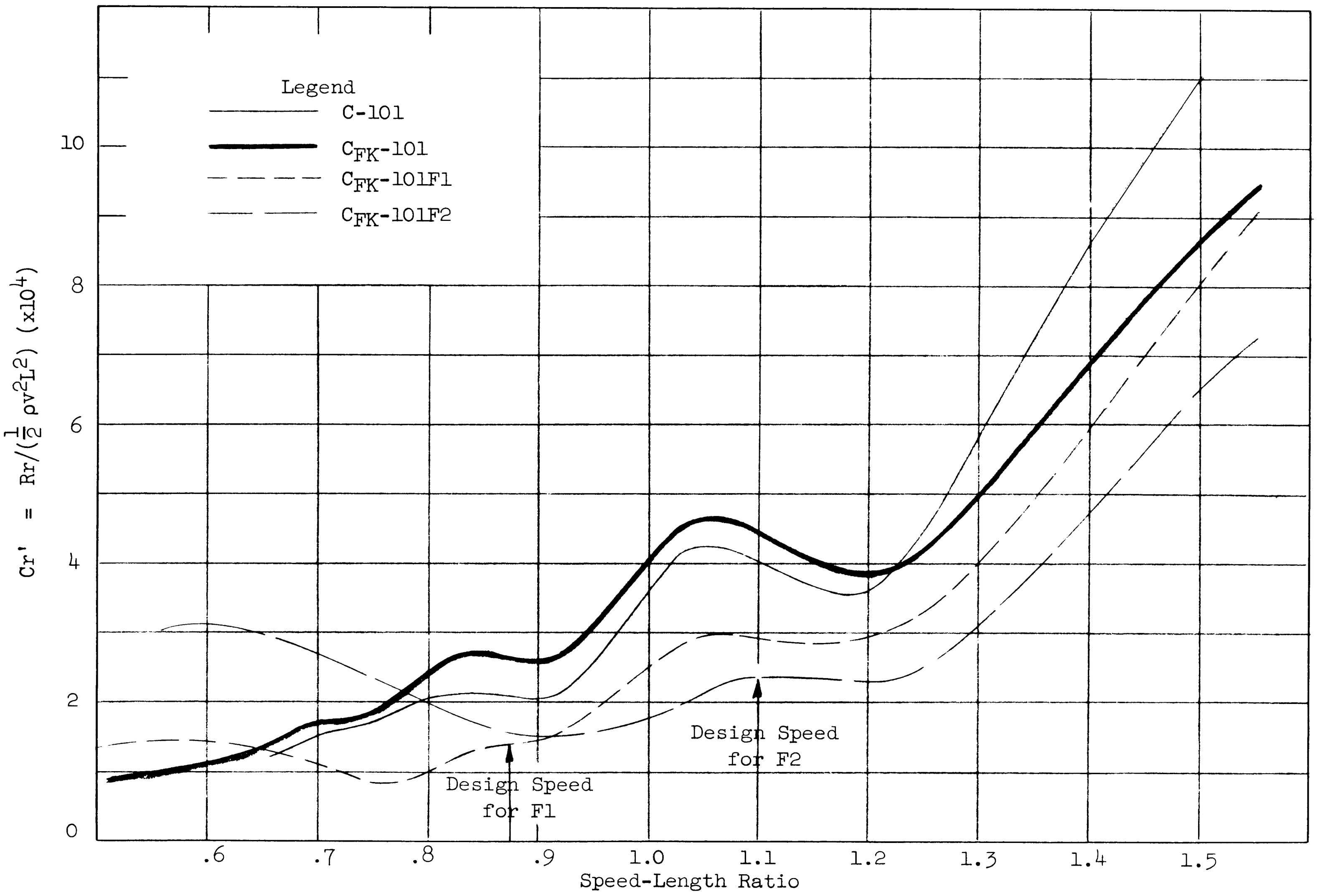

Fig. 6(b). C_r' for C-101, C_{FK}-101, C_{FK}-101F1, and C_{FK}-101F2.

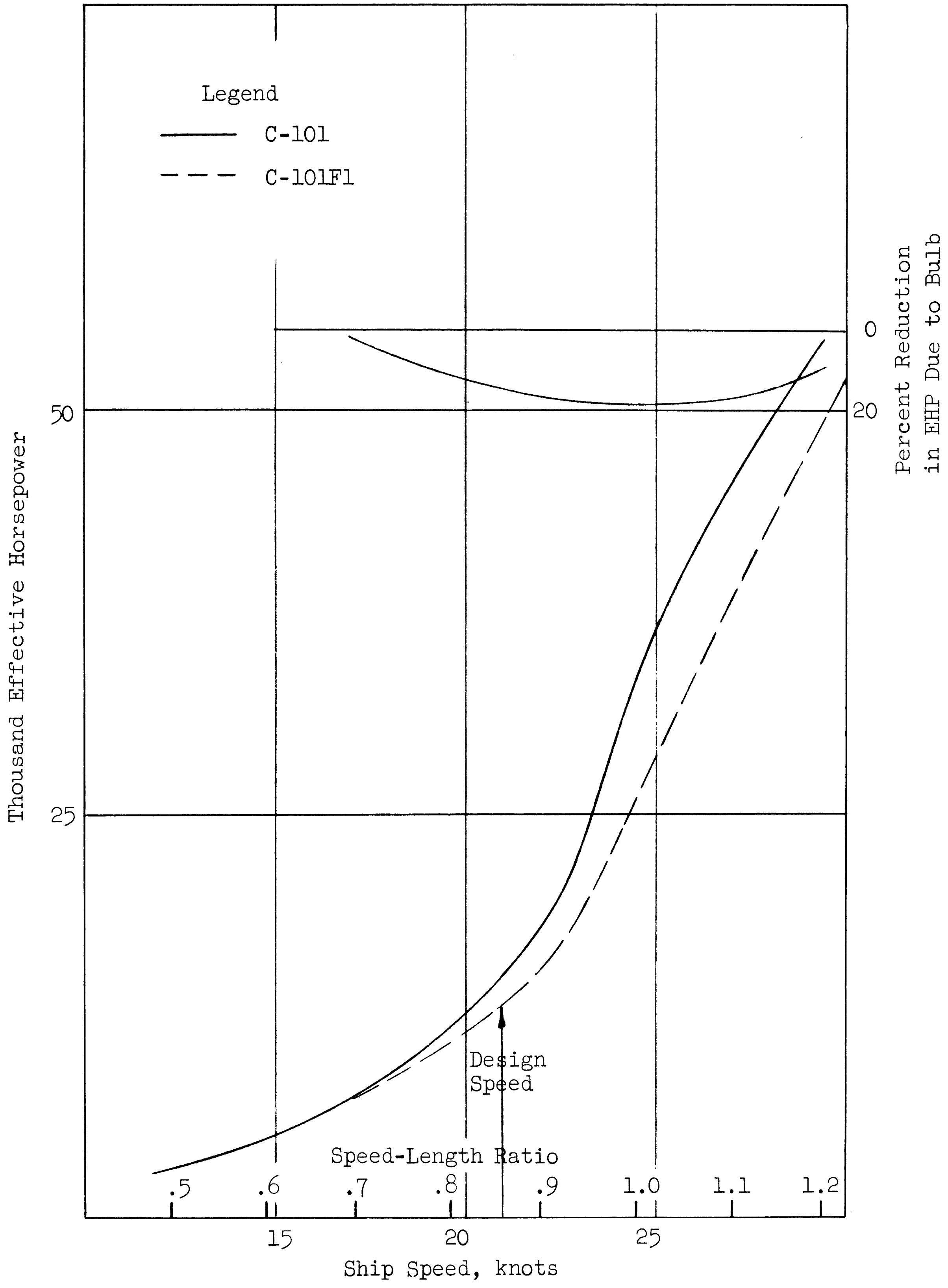

Fig. 7. EHP for C-101 and C-101F1. Ship length = 600 ft.

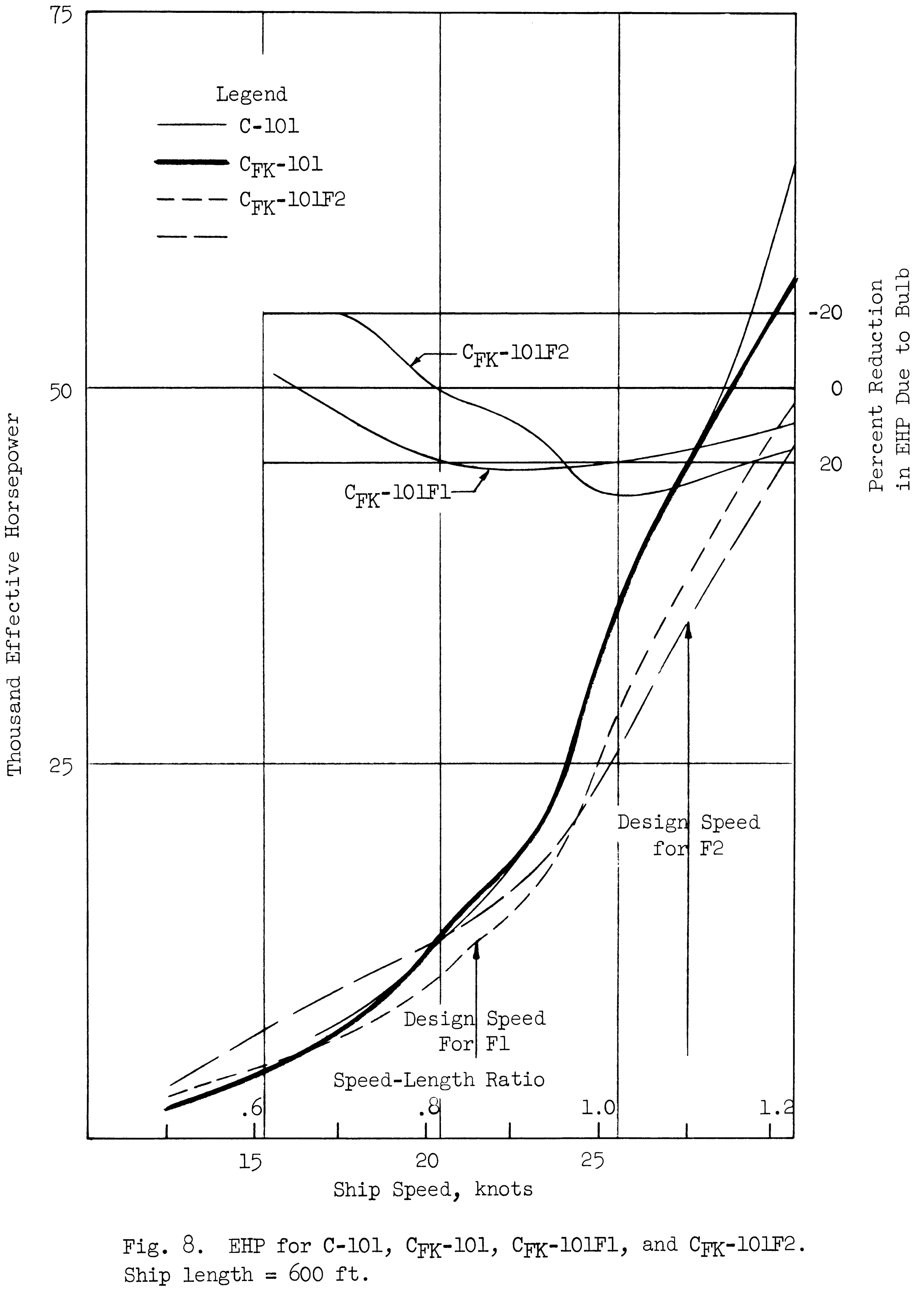

Fig. 8. EHP for C-101, C_{FK}-101, C_{FK}-101F1, and C_{FK}-101F2. Ship length = 600 ft.

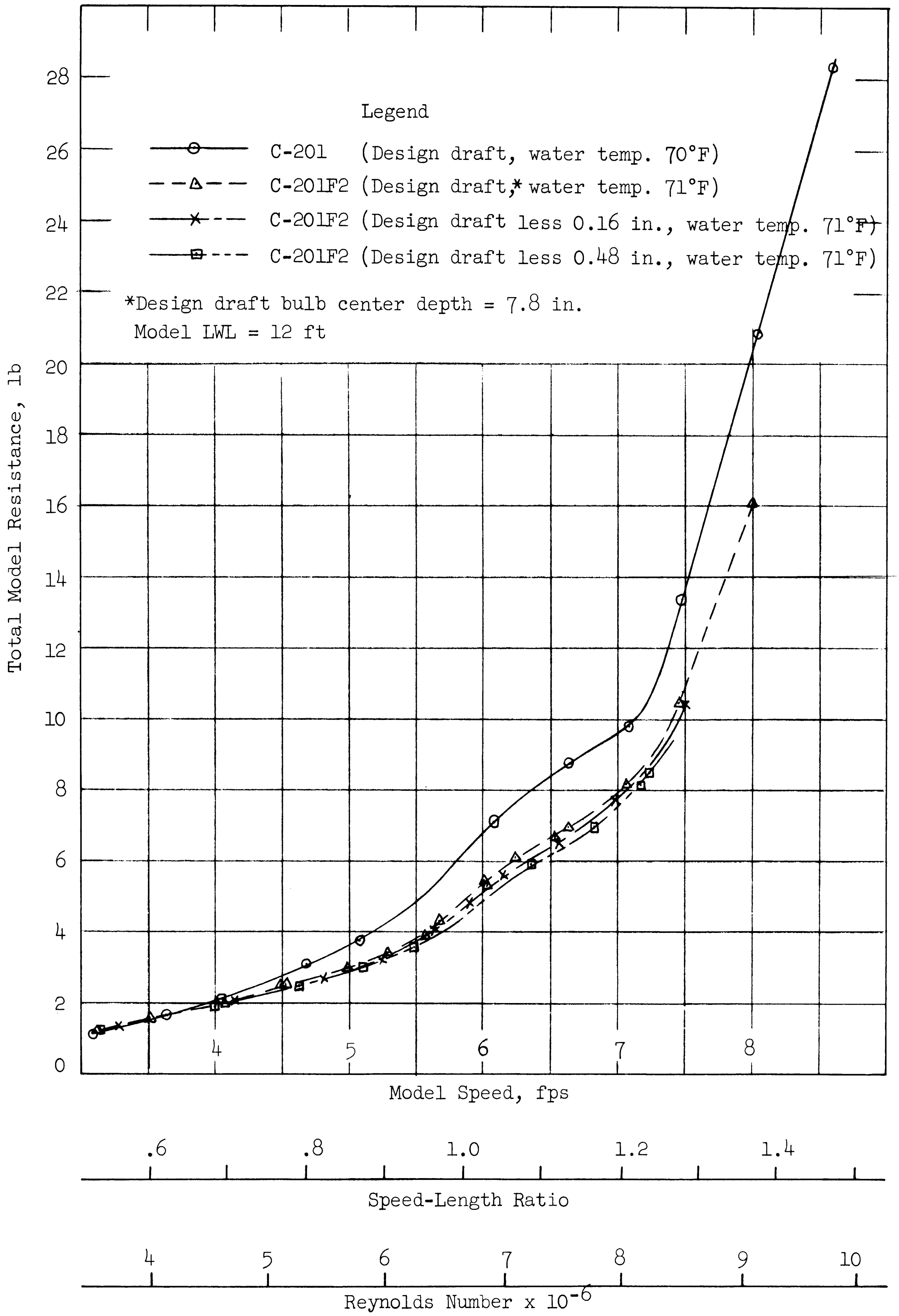

Fig. 9. Total model resistance for C-201 and C-201F2.

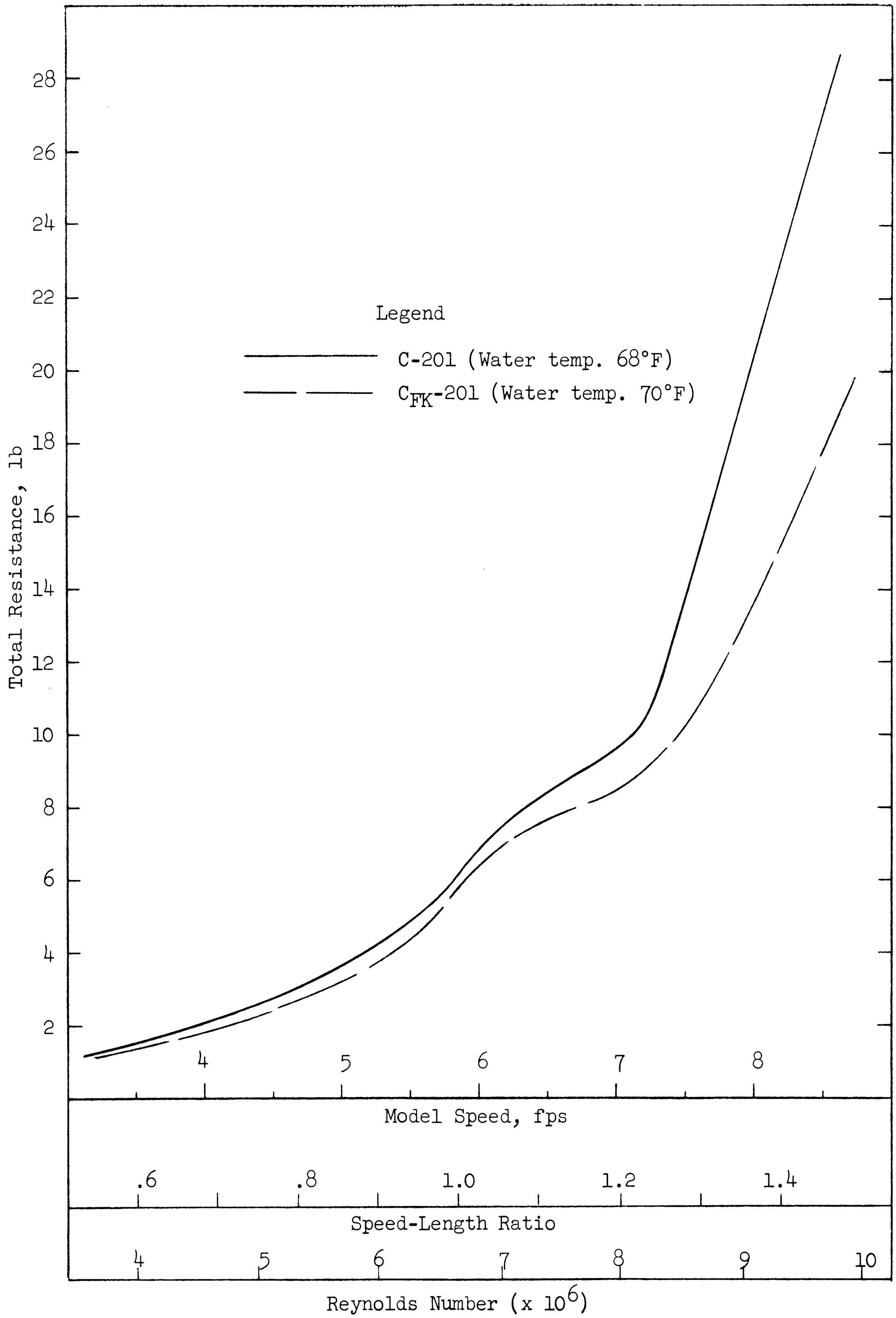

Fig. 10. Total model resistance of C-201 (rocker bottom) and C_{FK}-201 (flat bottom); 12-ft models.

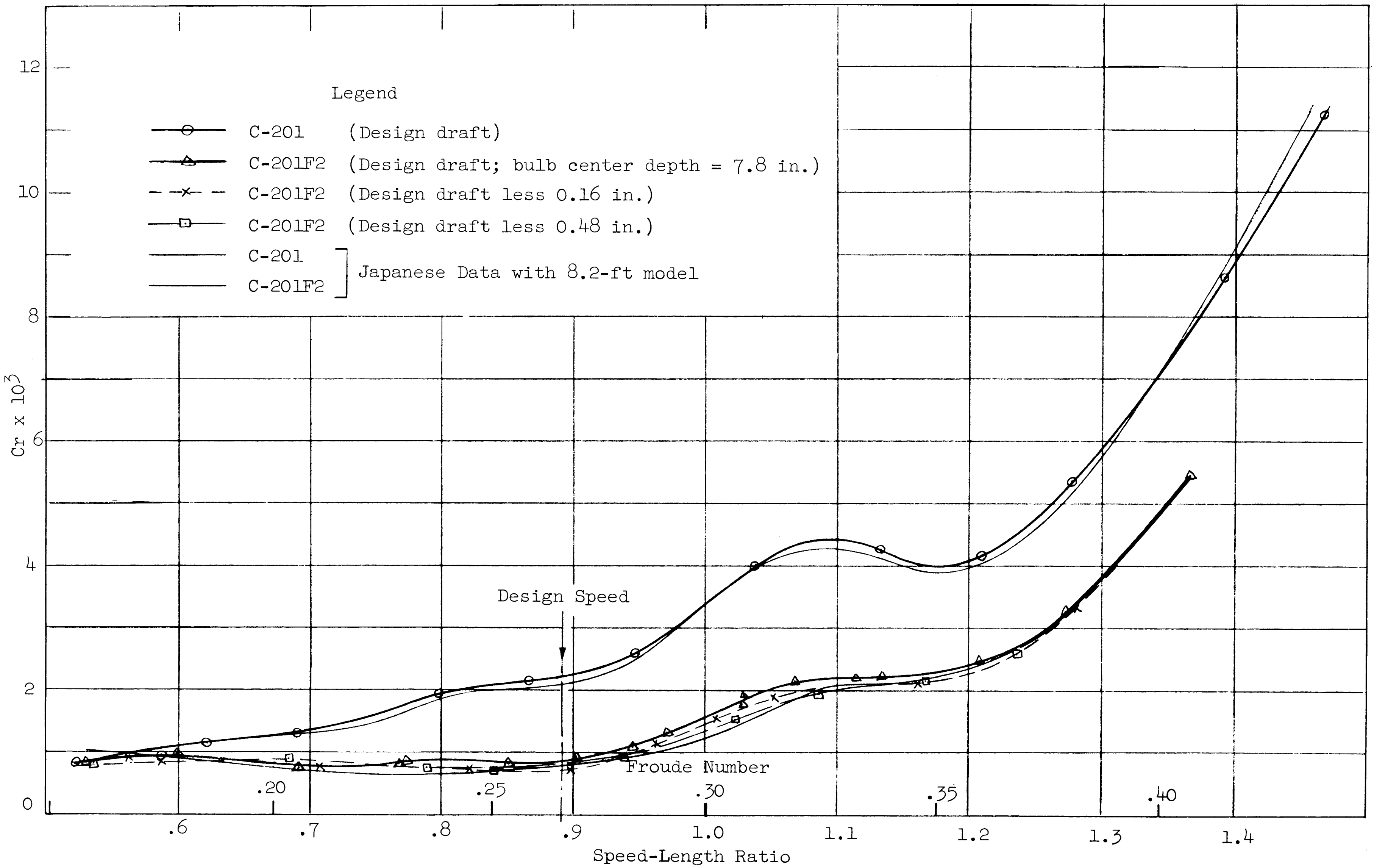

Fig. 11. C_r for C-201 and C-201F2.

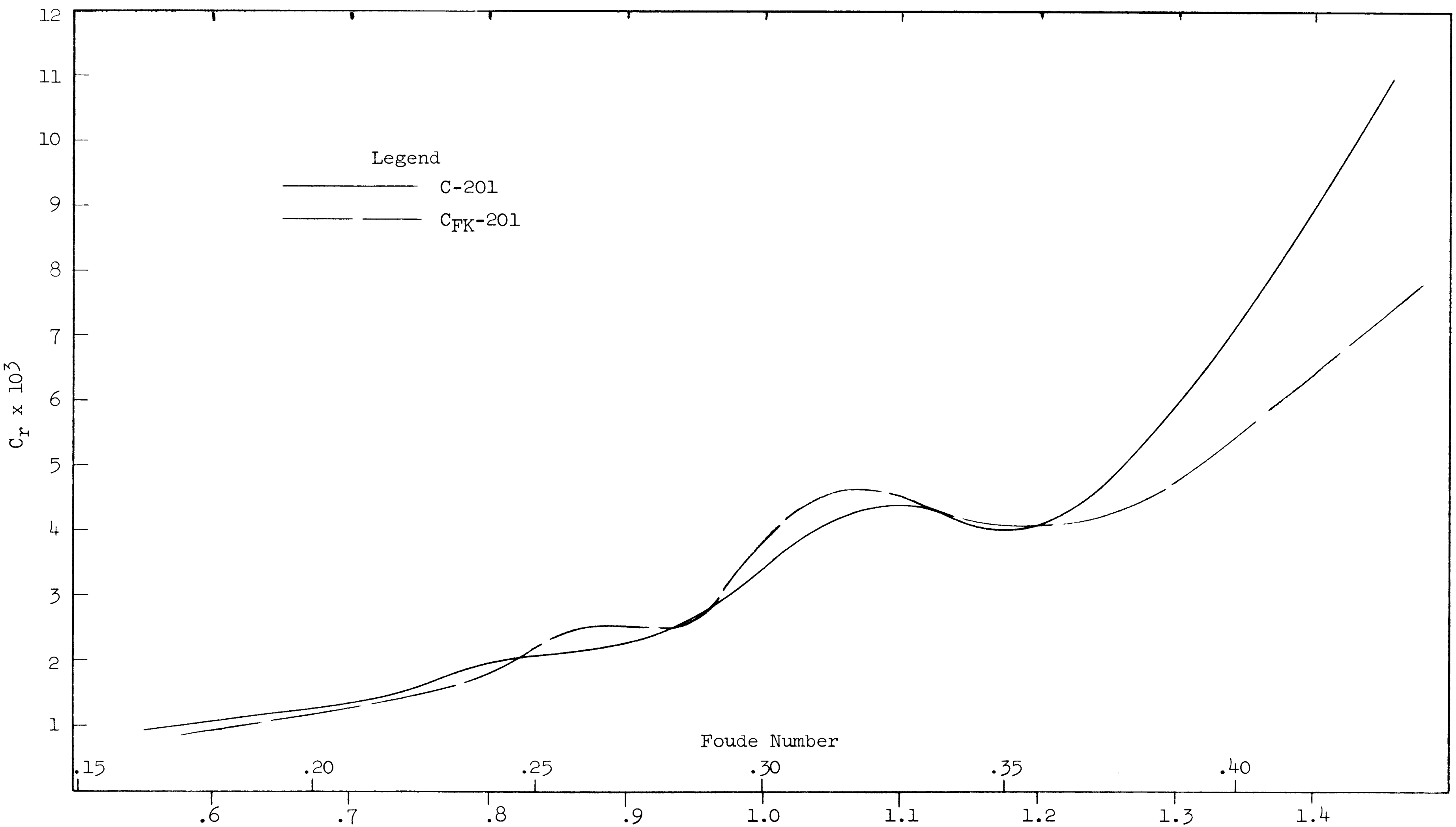

Fig. 12. C_r for C-201 and C_{FK}-201.

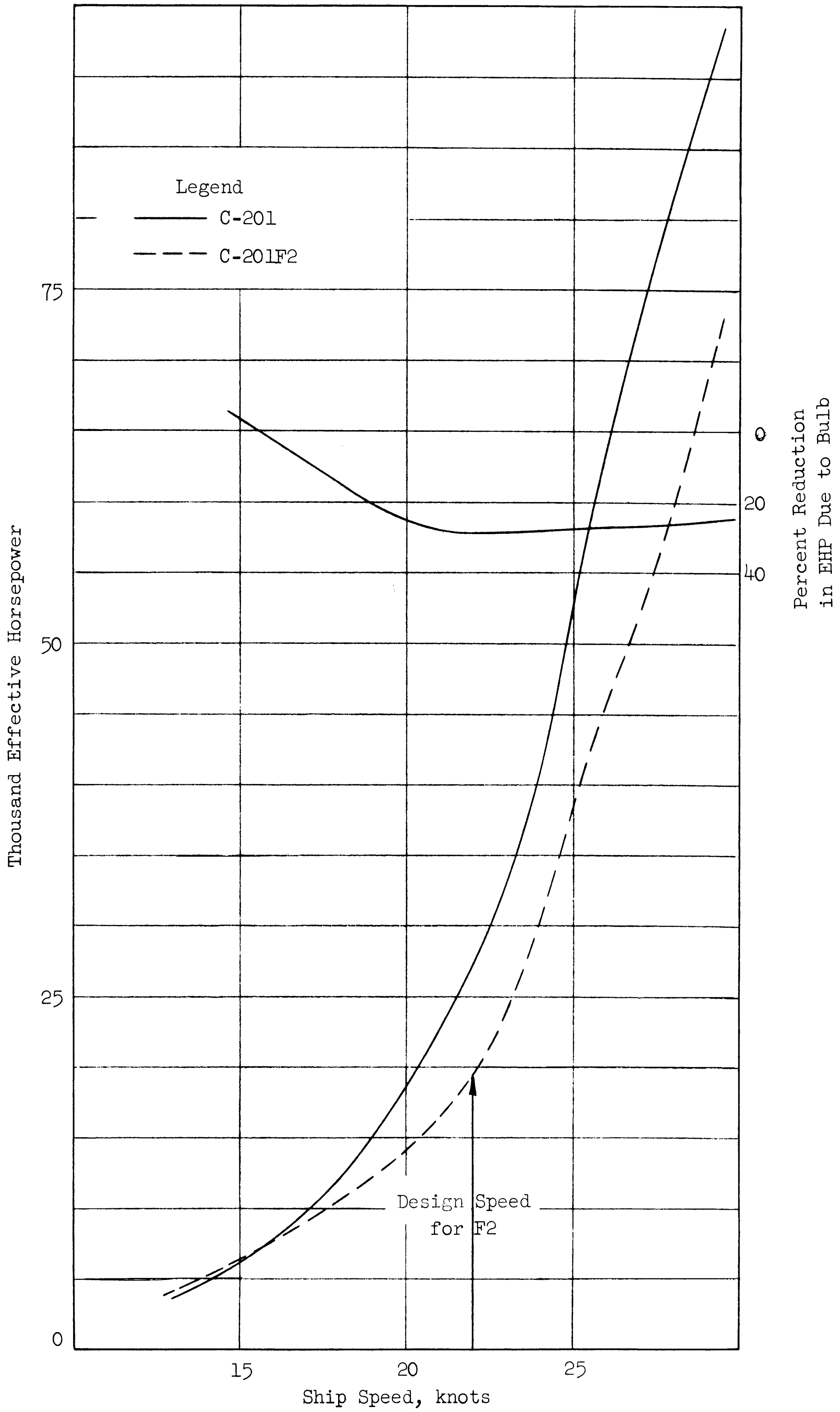

Fig. 13. EHP for C-201 and C-201F2. Ship length = 600 ft.

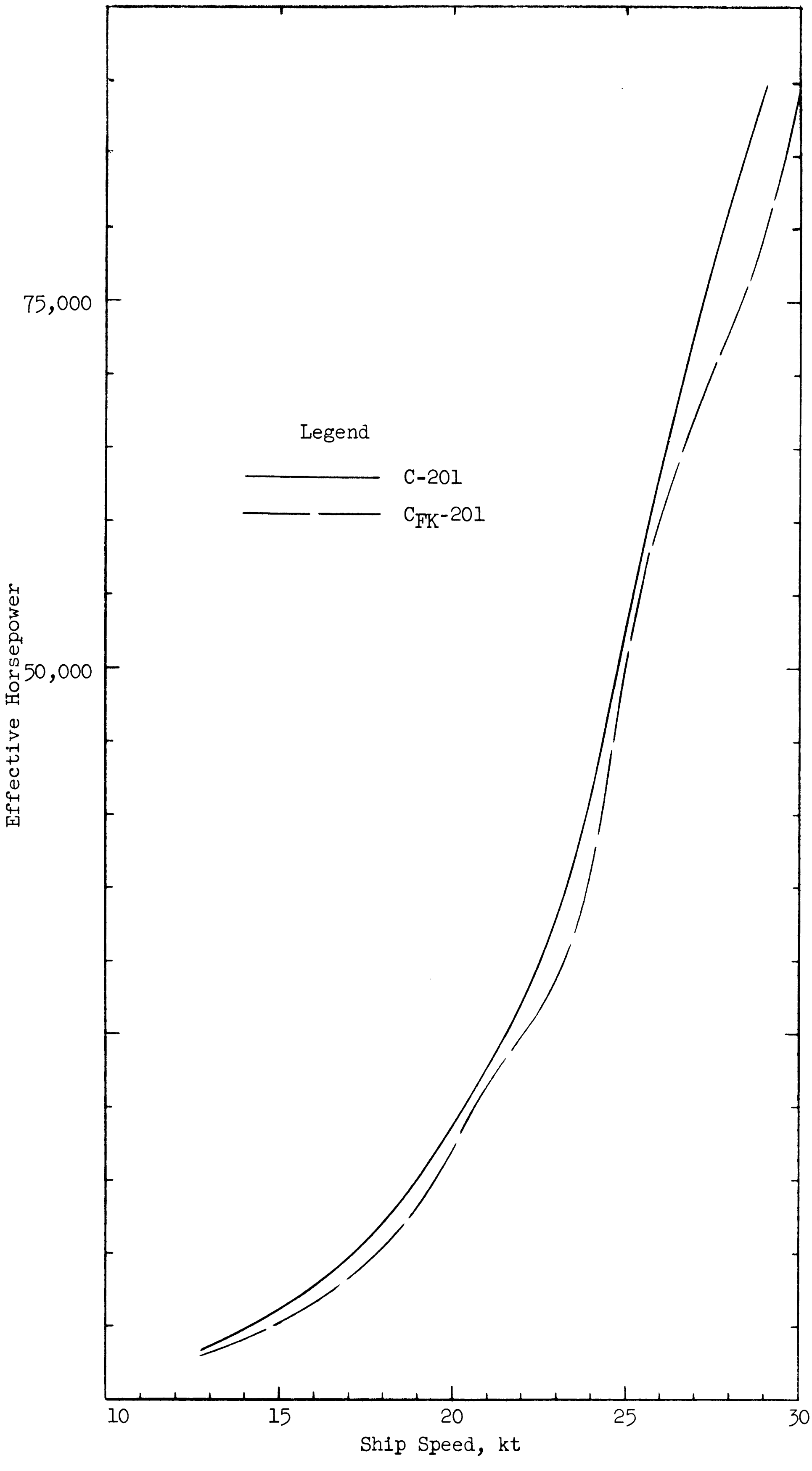

Fig 14. EHP for C-201 and C_{FK}-201. Ship length = 600 ft.

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APPENDIX I

AMPLITUDE FUNCTIONS

The singularity distributions of the "cosine ship" form has the property that both bow and stern free travelling wave systems consists only of the sine wave component throughout the whole speed range, i.e., in Eq. (1), $X_o = 0$. The amplitude function has been shown elsewhere (2, transl. p, 52) to be given by

$$A_F(\theta) = \frac{a_1 L}{\pi} K_o L \frac{V(K_o T, \theta) \sec^2\theta}{(K_o L \sec \theta)^2 - \pi^2} \tag{I-1}$$

where $V(K_o T, \theta) = 1 - \exp(-K_o T \sec^2\theta)$

with $a_1 = 0.4$ for C-101

and $a_1 = 0.6$ for C-201

$A_{F(\theta)}$ increases with speed. This is shown in Fig. I-1 for C-101 for a few values of θ (C-101 identified by U-shape frame lines). For θ varying from zero to about 35°, Eq. (1) refers to the transverse wave component at any location, whereas for $\theta > 35°$, divergent wave components is referred to. In the same figure, the curves identified as the V-shape frame lines show the values of the amplitude function for a main hull form generated by singularities whose lengthwise distribution function $m_1(\xi)$ is the same as that for the C-101. The draftwise distribution function $m_2(\xi)$ is changed from a uniform to a linear function, however, i.e., from $m_2(\xi) = 1$ to $m_2(\xi) = 1 - \zeta/t$. Compared to a U-shape frame line, a V-shape frame line has smaller component

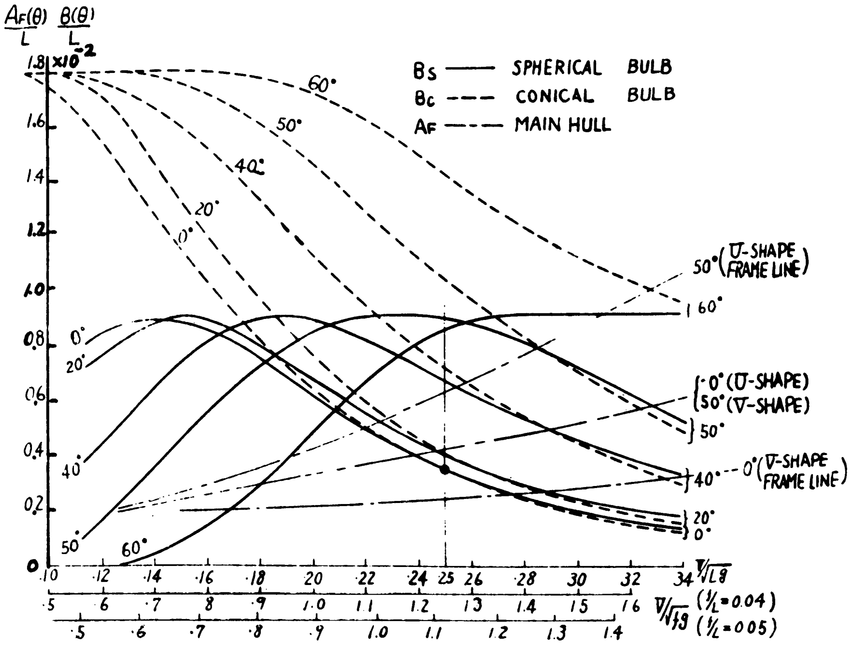


Fig. I-1. Amplitude functions vs. speed for hull C-101 and two bulbs, spherical and conical.

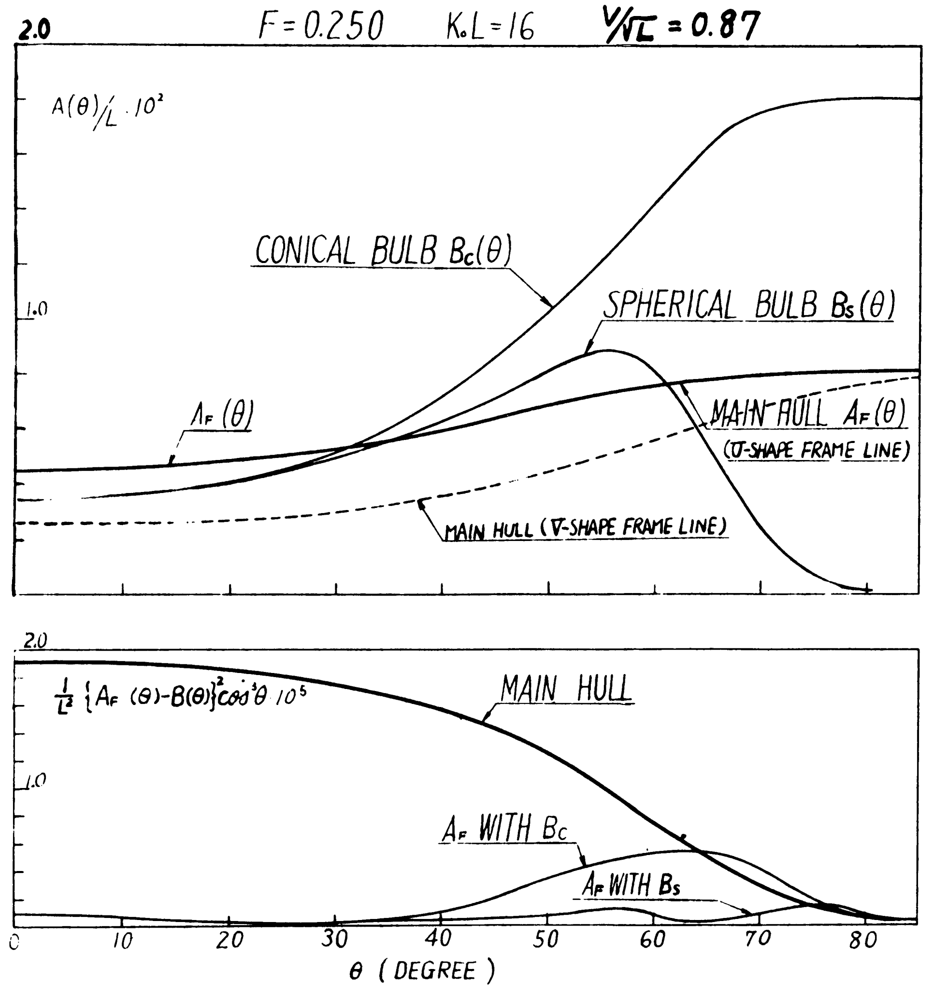


Fig. I-2. Amplitude functions vs. direction angles for hull C-101 and two bulbs, spherical and conical.

in the transverse wave system. The same fact is observed from the upper figure of Fig. I-2. It is also noted that the ratio of the divergent wave component to the transverse component is larger for shallow draft vessels* than for deep draft vessels.

Figs. I-3 and I-4 show the amplitude functions for C-201. Observations similar to those above can also be made in this case.

The free wave pattern to the rear of a doublet with the axis in the direction of advance is described by Eq. (2) in the main text, where the amplitude function is given by

$$B_{F}(\theta) = \frac{MK_o^2}{\pi V} \sec^4\theta \exp(-K_o f \sec^2\theta) \qquad \text{(I-2)}$$

The negative x-axis is in direction of advance, f is the bulb immersion, and M is the strength of the doublet.

For an axisymmetrical three dimensional flow in an infinite media $M = 2\pi a_o^3 V$ corresponds to a sphere of radius a_o. It is, therefore, referred to as "sphere bulb." Figures I-1 and I-3 show the variations of the amplitude function of a sphere bulb with respect to speed changes. From these figures it is noted that the condition of approximately equal magnitudes of $A_{F(\theta)}$ and $B_{F(\theta)}$ over a significant range of θ can only be attained over a narrow speed range since the variations in the amplitudes of these two functions with respect to change in speed are opposite. A distribution of doublets has therefore been investigated for the purpose of comparison with the above-mentioned

*The V-shaped source distribution will produce smaller maximum draft amidships than the uniform draftwise source distribution (U-shape frame line).

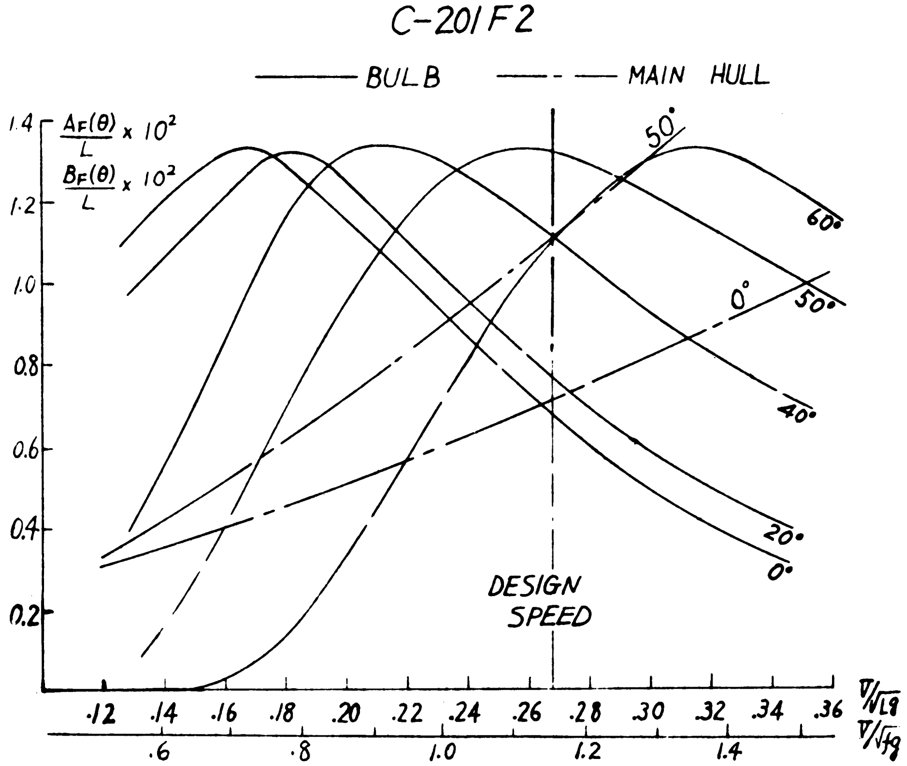


Fig. I-3. Amplitude functions vs. speed for hull C-201 and a bulb (F-201F2).

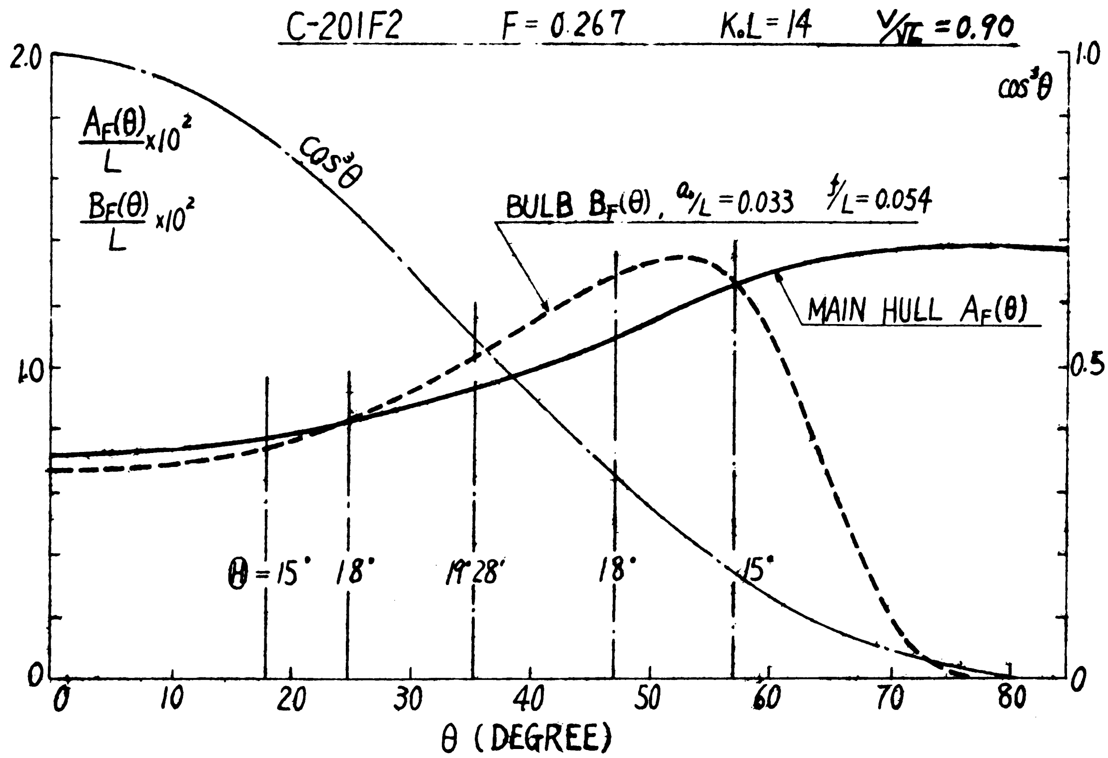


Fig. I-4. Amplitude functions vs. direction angles for hull C-201 and a bulb (C-201F2).

concentrated point doublet. If the doublets are distributed in the vertical direction, the phase of the free travelling wave will be unaltered as compared to that of a point doublet. Therefore, it might be possible to select the following doublet distribution to meet the wave cancellation requirement;

$$\mu(\zeta) = \mu_o \frac{\zeta + f_t}{f_o - f_t} ; \quad -f_o \leq \zeta \leq -f_t \qquad \text{(I-3)}$$

This distribution is shown in Fig. I-5.

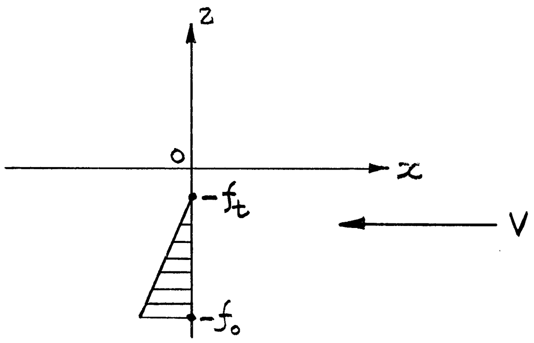


Fig. I-5. Doublet distribution for "conical bulb" investigated.

The amplitude function of such a distribution, which may be called a "conical bulb," is given by:

$$\left[B_{F,C}(\theta)\right]_1 = \frac{K_o \mu_o \sec^2\theta}{\pi V} \left(-e^{-K_o f_o \sec^2\theta} + \frac{e^{-K_o f_o \sec^2\theta} - e^{-K_o f_o \sec^2\theta}}{K(f_o - f_t)\sec^2\theta} \right) \qquad \text{(I-4)}$$

For $f_t = 0$, a linear distribution function extending from the surface down to the depth f_o is obtained, for which we get:

$$\left[B_{F,C}(\theta)\right]_2 = \frac{K_o \mu_o \sec^2\theta}{\pi V} \left(-e^{-K_o f_o \sec^2\theta} + \frac{1 - e^{-K_o f_o \sec^2\theta}}{K_o f_o \sec^2\theta} \right) \qquad \text{I-5)}$$

To compare the characteristics of the amplitude functions of Eqs. (I-2) and (I-5), let us consider the following example.

$$K_oL = 16, \text{ Fronde No.} = 0.25 \text{ or } V/\sqrt{L} = 0.84$$

For the conical bulb $\mu_o = 2\pi a_o^2 V$ is determined so that its amplitude function at $\theta = 0$ is equal to that of a sphere bulb. a_o is the diameter of a cylinder corresponding to a doublet in two-dimensional flow. Under the specified design conditions the bulb sizes become

a. Spherical bulb: $f/L = 0.04$; $a_o/L = 0.024$

b. Conical bulb: $f/L = 0 \quad 0.05$; $a_o/L = 0.021$ at $f_o/L = 0.05$

Amplitude functions are shown in Figs. I-1 and I-2. Wave profiles corresponding to various speeds are shown in Figs. I-6 and I-7.

From these figures it may appear that the amplitude function of the conical source distribution can be made to be in better agreement with the hull amplitude function than that of a sphere bulb, especially at large values of θ. We must remember, however, that the linearized theory is being used and that this theory looses accuracy rapidly for large values of θ owing to the linearization of the free surface conditions. For this reason conclusions reached on the basis of purely mathematical considerations of the linearized theory may not be strictly valid in this region.

An investigation of the wave steepness in the region of large θ reveals that the assumption of a small ratio of wave height to wave length is not well satisfied, and this fact must be taken into consideration in evaluating the significance of a good fit between the hull and bulb amplitude functions. Furthermore, as mentioned before, the weight function $\cos^3\theta$ in the resistance integral reduces substantially the effect of any difference that may exist between the amplitude functions in the region of large θ values.

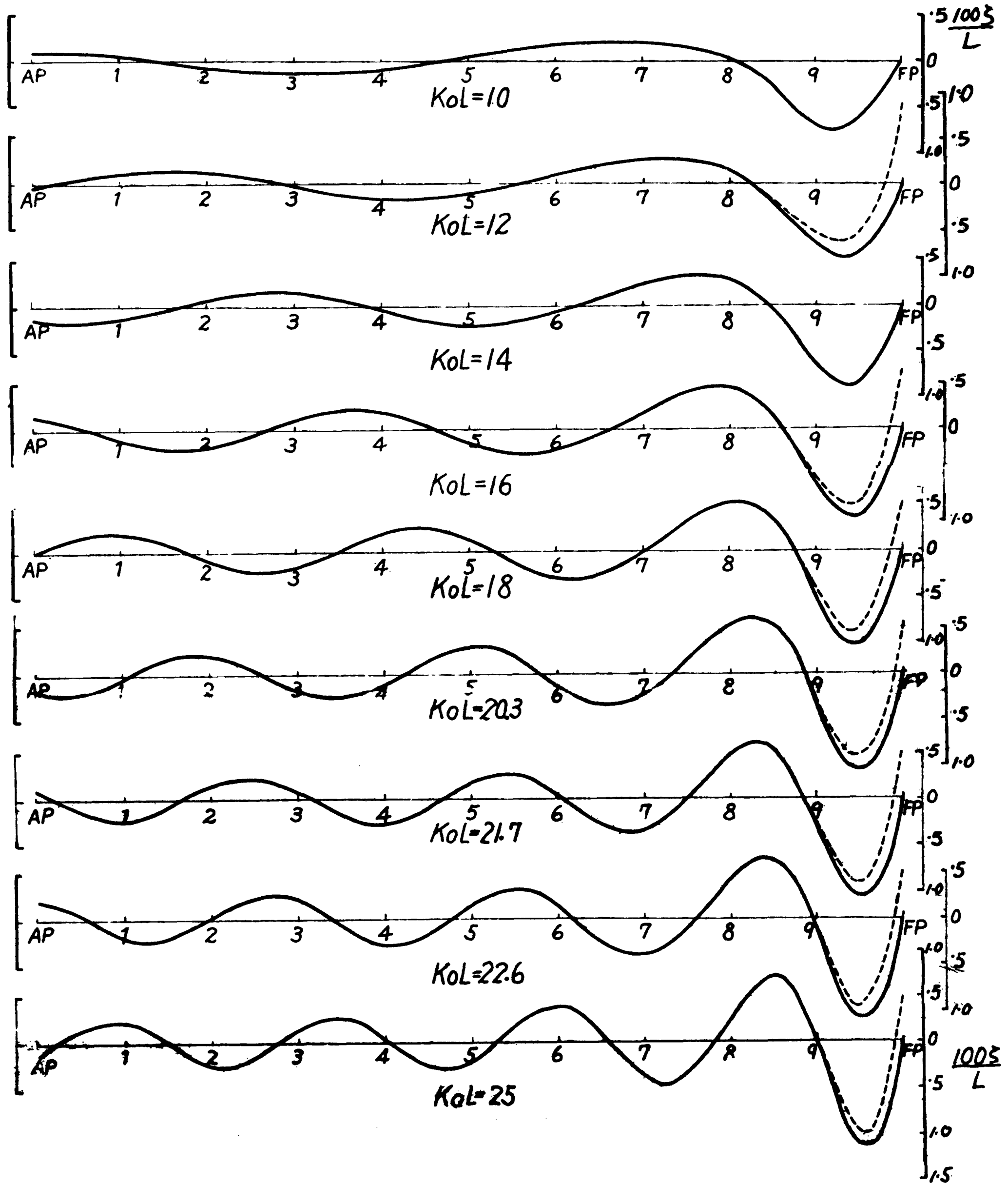


Fig. I-6. Wave profile by sphere: $f/L = 0.04$; $a_o/L = 0.024$.

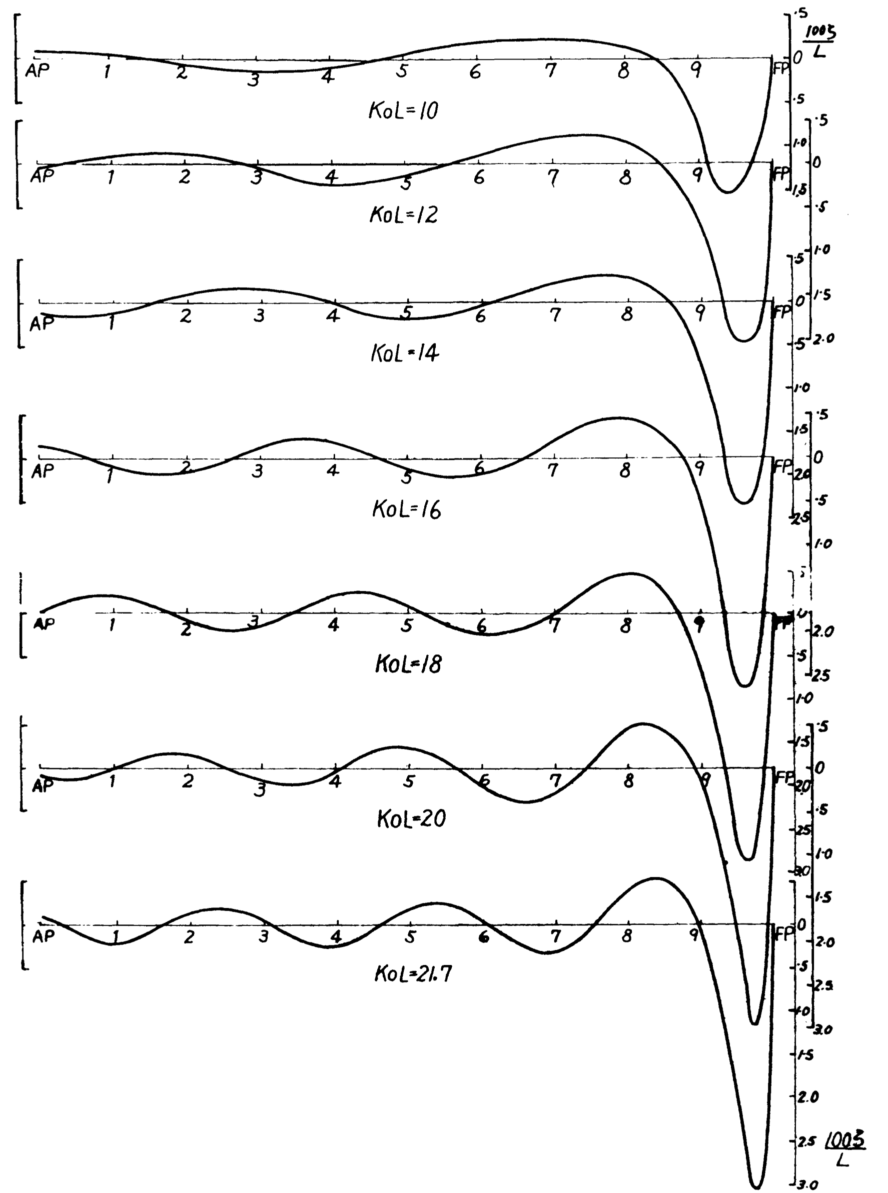


Fig. I-7. Wave profiles (free wave) by conical bulb: $f = 0 \sim L/20$; $a_o/L = 0.021$.

Takahei has tested hull forms fitted with various bulbs in Japan. Some of these bulbs correspond to the cases of so-called conical bulbs. The top of the bulbs were raised up to the waterline, with the shape of the bulb becoming approximately a cone fitted to the main bulb. The test results were rather disappointing, the resistance being considerably greater than predicted by theory, and especially so in the low speed range. The blunt shape of the stem disturbed the water surface sufficiently so that the boundary conditions of the linearized theory were seriously violated. Favorable wave cancellation could and was achieved with the single doublet, or slight modifications thereof, when the top of the bulb was kept at a substantial distance below the water surface, however. For these configurations the linear wave-resistance theory may prove to be valid to a sufficient degree of accuracy. Taking all these facts into account, we believe that the way to achieve the waveless bow is to try to fit the most suitable ship hull form to a sphere bulb, or one modified slightly from it, rather than trying to find a suitable bulb shape for a given ship form.

APPENDIX II

MEASURED WAVE PROFILES AND THEIR ANALYSES

Wave pattern measurements and their analyses have come to play a very important part in the studies of wave-interference phenomena (2,3,4,5,6). The analyses of model and ship waves materially supplements the present linear wave-resistance theory. In particular it can be used in various ways as a means of introducing corrections to the theory due to viscous and nonlinear effects.

The most complete record of the wave-patterns can be obtained by means of stereo-pictures. A more expedient method is offered by the acoustic transducer although it only produces wave profiles along predetermined path lines.

None of these types of equipment are presently available at The University of Michigan. It was therefore necessary to limit the wave pattern analysis to the traces of wave profiles along the model sides as read off from pictures. The measured profiles are compared with the profiles calculated from the singularity distribution function representing the model hull form. For the numerical calculations, tables of wave profile functions prepared in Japan have been used. These tables are not complete and for further analysis of wave patterns extended tables will be greatly needed.

Wave-resistance is caused by the fact that waves are continuously being generated by the ship and that some part of this wave system is propagating away from the ship. This part is referred to as the free travelling wave system. At some distance away from the ship only the free travelling wave system persists. It is therefore the sole contributor to the wave-resistance and thus the object for the wave analysis. The second part of the wave system is referred to as a local disturbance since it attains its maximum value at the ship's boundary and decays exponentially with the distance from it. Although this system is of no direct interest to us it must be included in the wave profile calculations if the profile is to be evaluated along the ship's surface.

Figures II-1(a) through (d) show the wave profiles of C-201 and C201F2. The wave profiles obtained at The University of Michigan are compared with those obtained at Tokyo University with a smaller 8.2-ft model. Wave profiles near both ends of either model were traced with less accuracy than amidships because of curvature of hull surface and splashing water. Taking this fact into account, the agreement between test results is very good. As shown on Fig. II-1(b), the composite wave of the model fitted with the F2 bulb becomes entirely flat at the design speed along the model except near the bow and stern where the local disturbance affects the free-wave profile. This is a direct visual verification of the success of the cancellation of transverse waves by the effect of bulb. Theoretically calculated wave profiles of the main bulb coincide with those measured values although some phase lag between them is noticed. Remembering the discrepancy between measured and calculated values of the wave-making resistance, the confirmed agreement between wave profiles is rather startling.

A careful look at Figs. II-1 and II-2 reveals that the measured bow wave profile leads the calculated bow wave profile in phase by approximately 3-6% of ship length in the speed range of Fronde number less than 0.4. This phase shift is due to the finite draft and does not occur in the case of infinite draft. The reason for this may be due to the neglect of secondary corrections to the perturbation velocity components on the ship's surface.

Since the correct phase relationship between bulb and hull waves is of the utmost importance to the concept of wave cancellation, it is essential that the phase lag mentioned above be correctly determined from the model tests. According to theory the center of the bulbs should have been located exactly at the FP of the C-101 and C-201 models. Actually the centers of the bulbs were located a few percent of the length of the models ahead of FP, as indicated in Table III,* to insure a proper phase relationship and thus satisfactory wave cancellation.

The difference between the wave profiles of the model with bulb and that of the bare hull is expected to be equal to the wave profile of the bulb itself. To investigate if this relationship is properly predicted by the linear theory, the measured differences in wave profiles were compared to the wave profile calculated for a single point doublet. The strength of the doublet was determined from the condition that the volume of an equivalent sphere in a uniform stream was equal to two-thirds of the total increase in model displacement due to bulb and accompanying fillets. Depth of immersion was assumed to be the same as for the bulb. The longitudinal location of the doublet was determined by shifting the calculated wave profile until the fit between it and the measured difference profile was at an optimum. This location was found to be about 5 percent of model length forward of FP in

*See page 10 of this report.

the case of C-201 and the F2 bulb, which we shall call the effective center of the bulb.

Figures II-2(a) through II-2(e) show the wave profiles obtained from C-101 and C-101F1. Figure II-2(a) is the plot of the wave profile measured at the design conditions at which the bow wave is found to be effectively cancelled. The bulb wave profile was calculated on the assumption that the effective center was located 2.5 percent of model length ahead of FP.

The plots of wave profiles clearly show that the bulb wave system can be replaced by a doublet wave system except in the vicinity of the bow and in particular at high speeds. The discrepancies in this region may be partially attributed to a lack of accuracy of measurements but is most likely the result of an interference effect unaccounted for.

Wave analysis has also been applied to C_{FK}-101. A comparison between the wave profiles measured before and after the installation of the flat bottom shows that the change in keel shape does not affect the wave profile materially. Similar results are reported elsewhere (11).

The portion of the original form that was cut off in making the model flat bottomed can be approximately represented by a line distribution of singularities defined as follows:

$$\eta(\xi) = -.03\,\frac{\xi}{\ell}\,; \quad \eta = 0; \quad \xi = -.06L$$

with

$$-.8\ell \leq \xi \leq .8\ell$$

It is noted that this distribution provides sinks in the fore-body and sources in the aft-body. Calculated wave profiles which include the effects of the singularity distribution above are shown in Figs. II-3(a) and II-3(b) as chain lines together with the measured difference profiles.

There remains the problem of actually tracing the streamlines with the singularity distribution $\eta(\xi)$ added to the regular distribution of the cosine hull form. This will be done as a part of a systematic study of the problem of generating ships with flat bottoms.

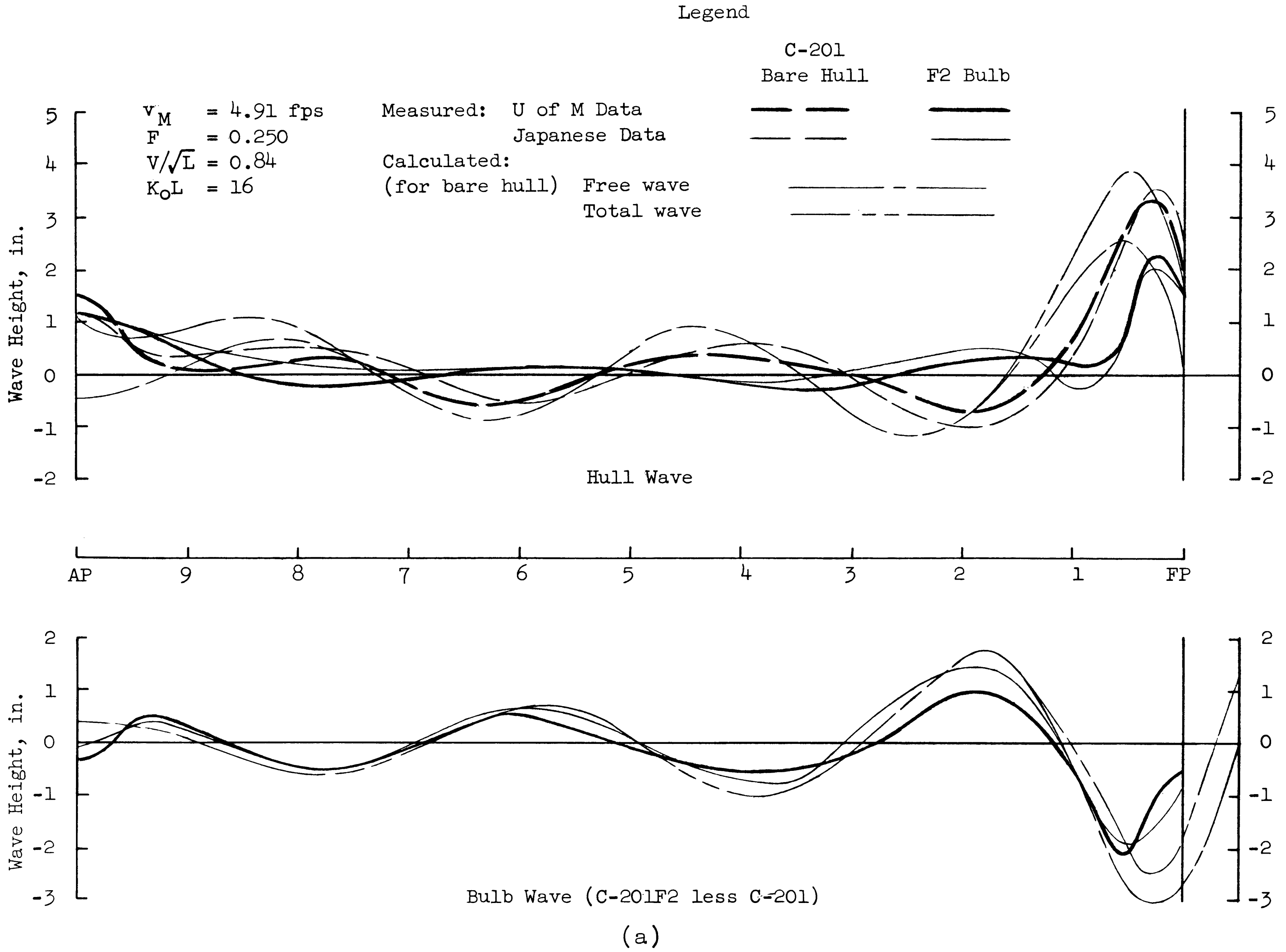
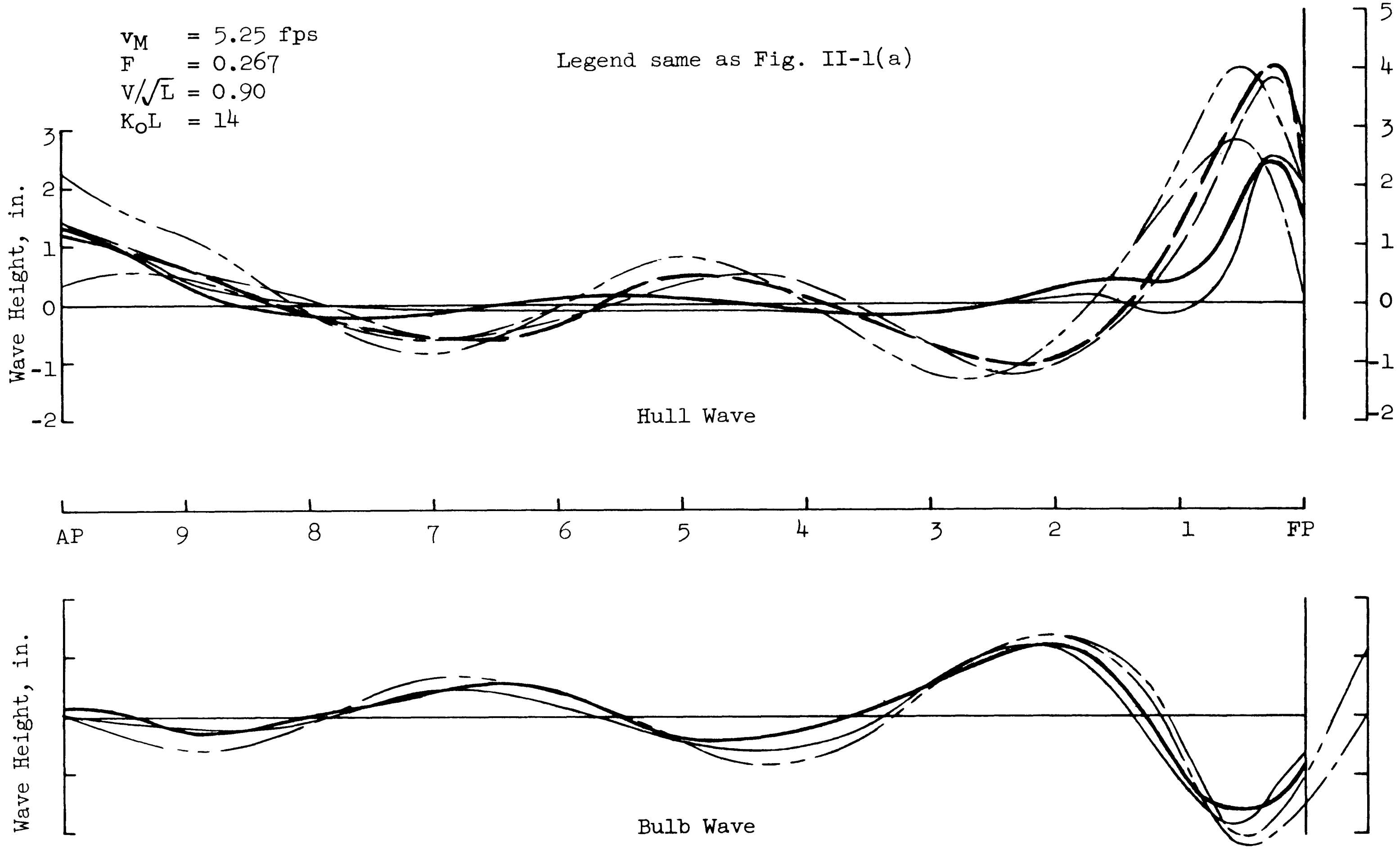
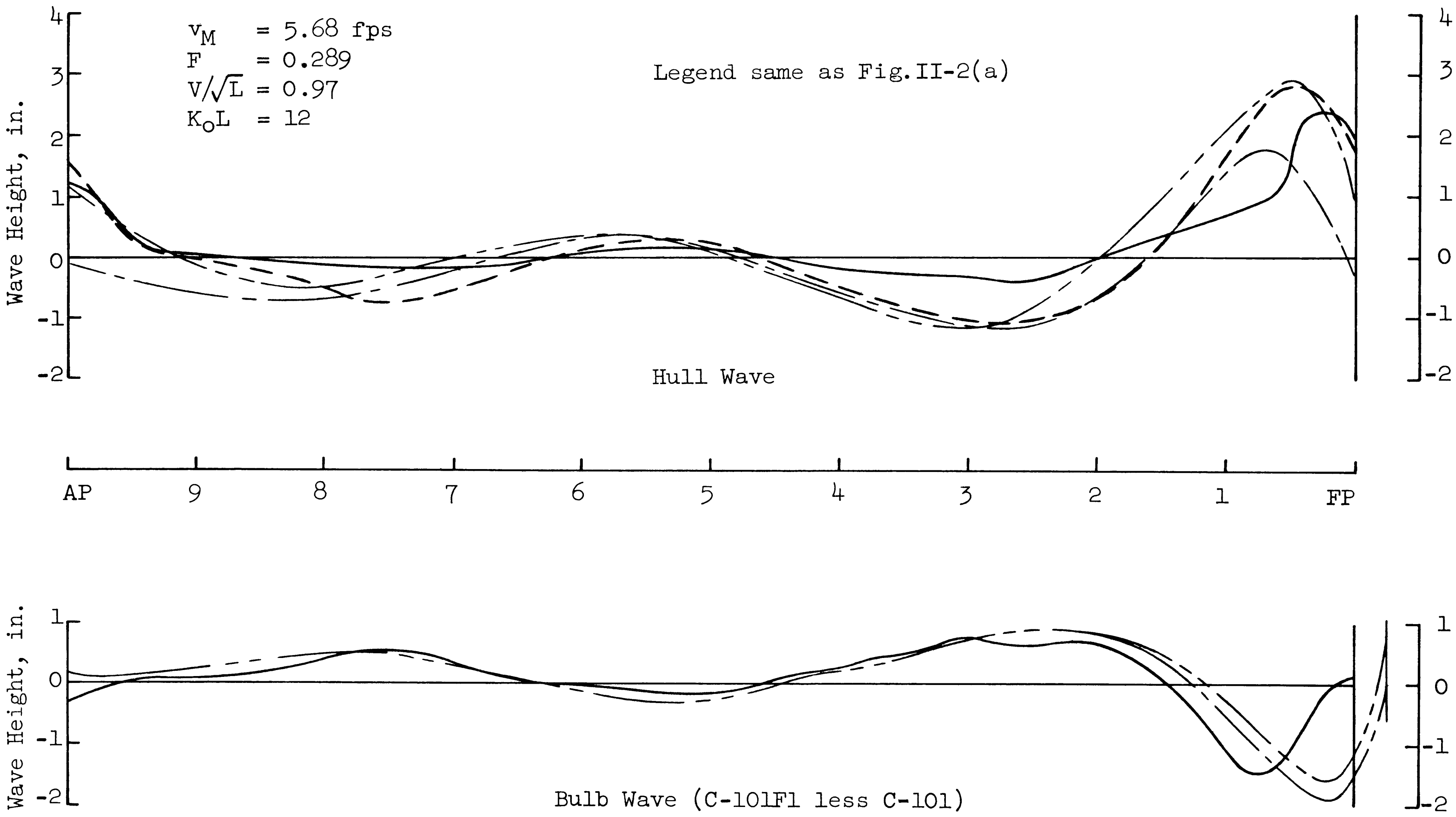


Fig. II-1. Comparisons between measured and calculated wave profiles for C-201 and C-201F2.



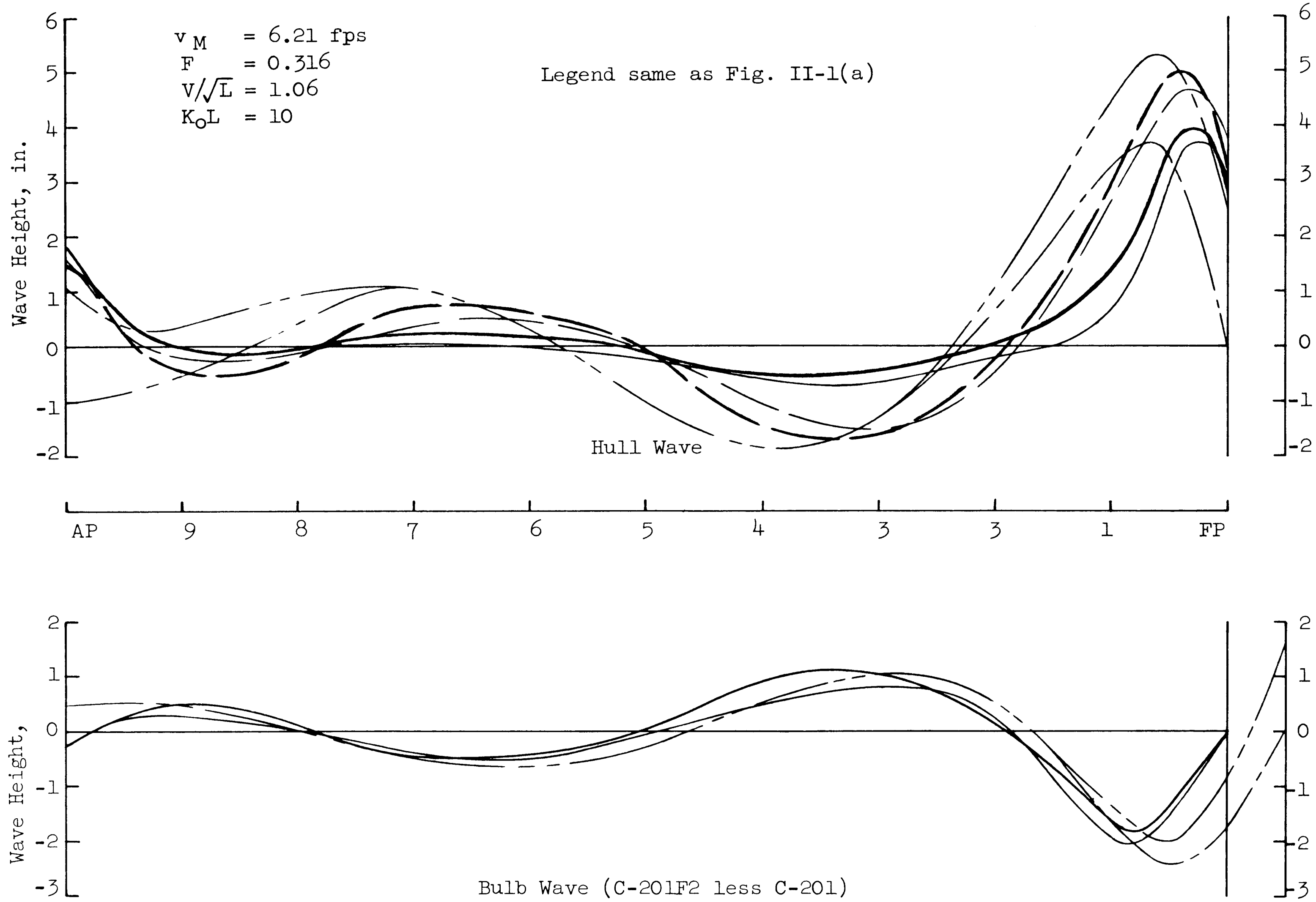
(b)

Fig. II-1. (Continued).



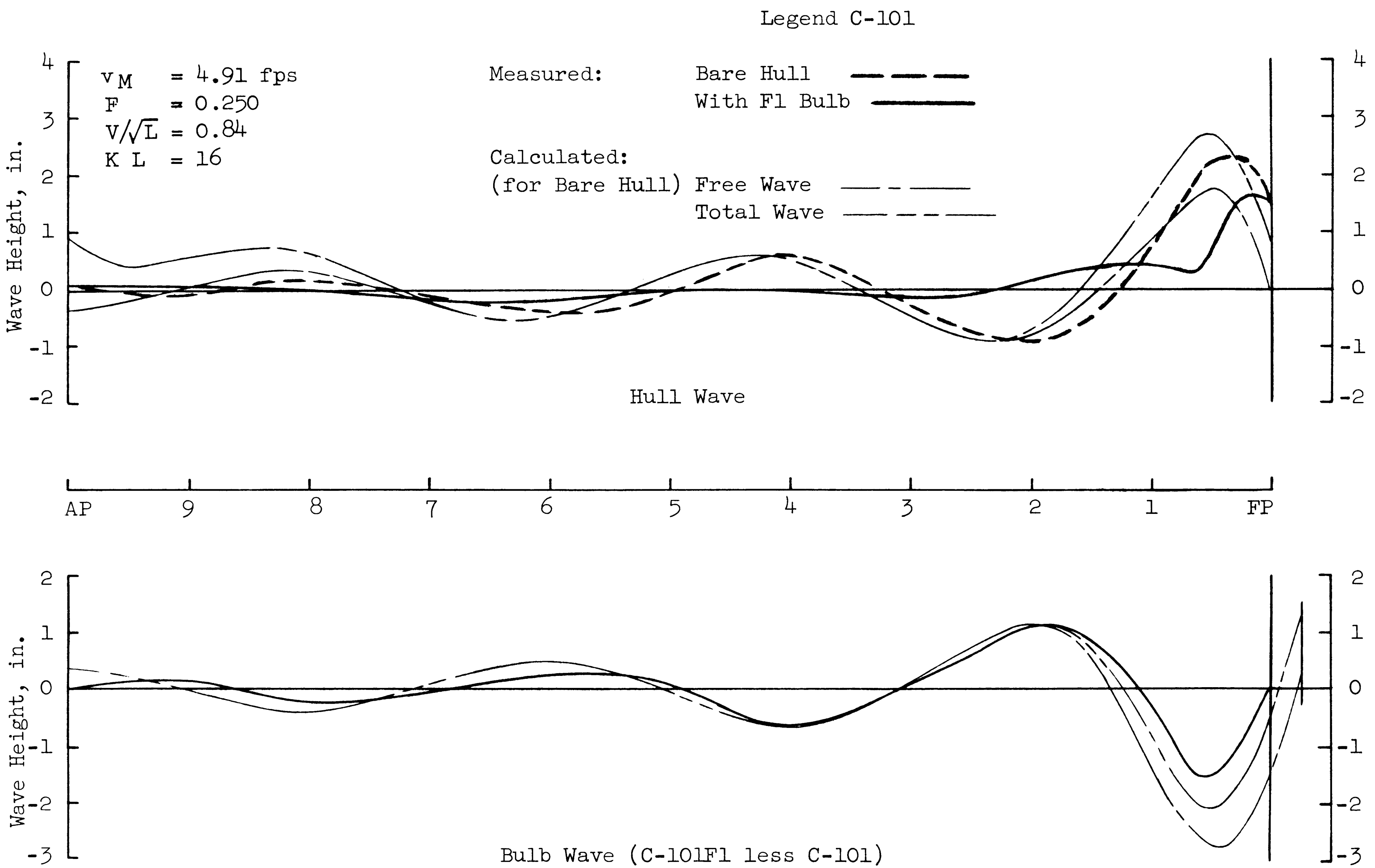
(c)

Fig. II-1. (Continued).



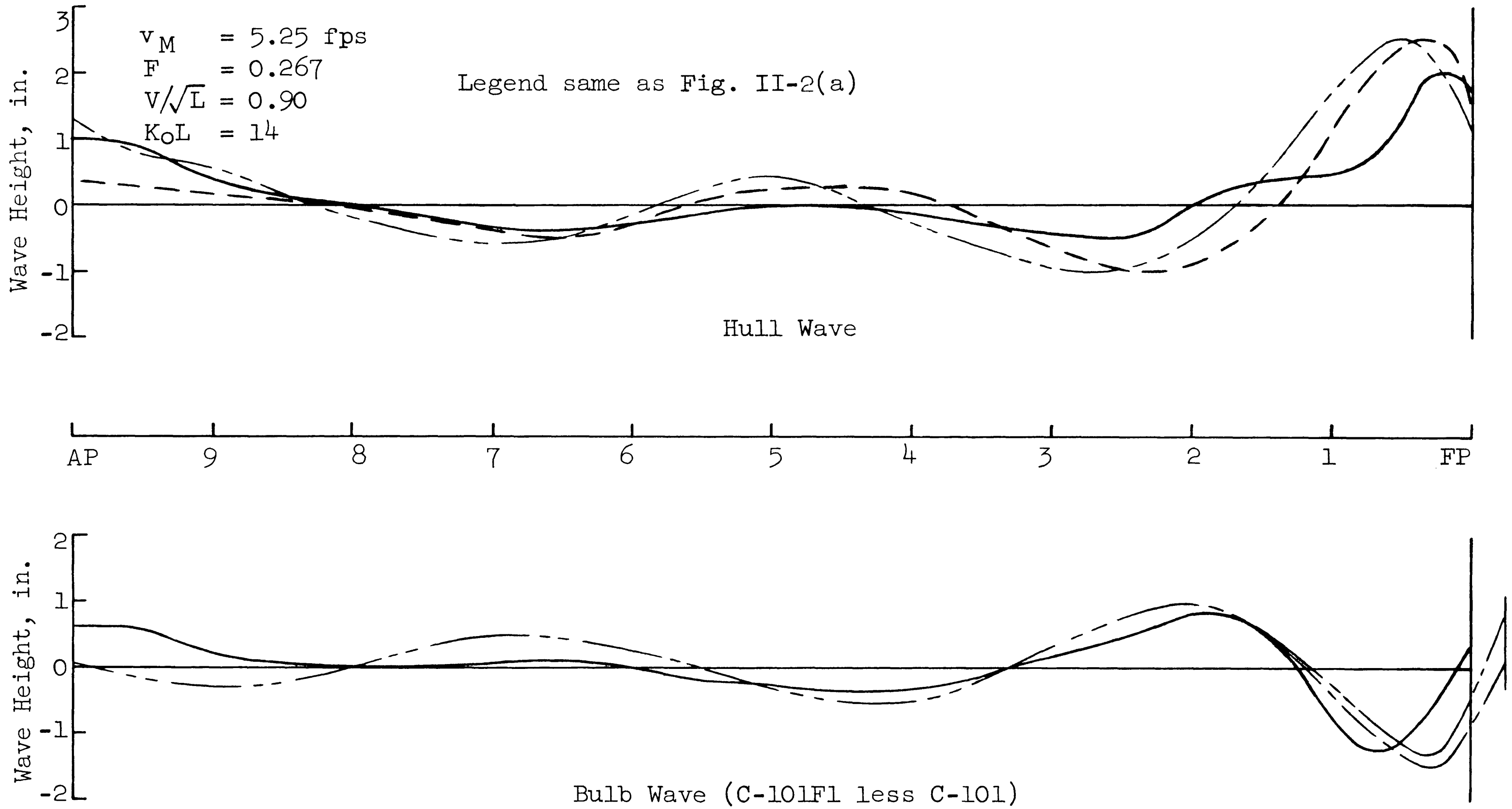
(d)

Fig. II-1. (Concluded).



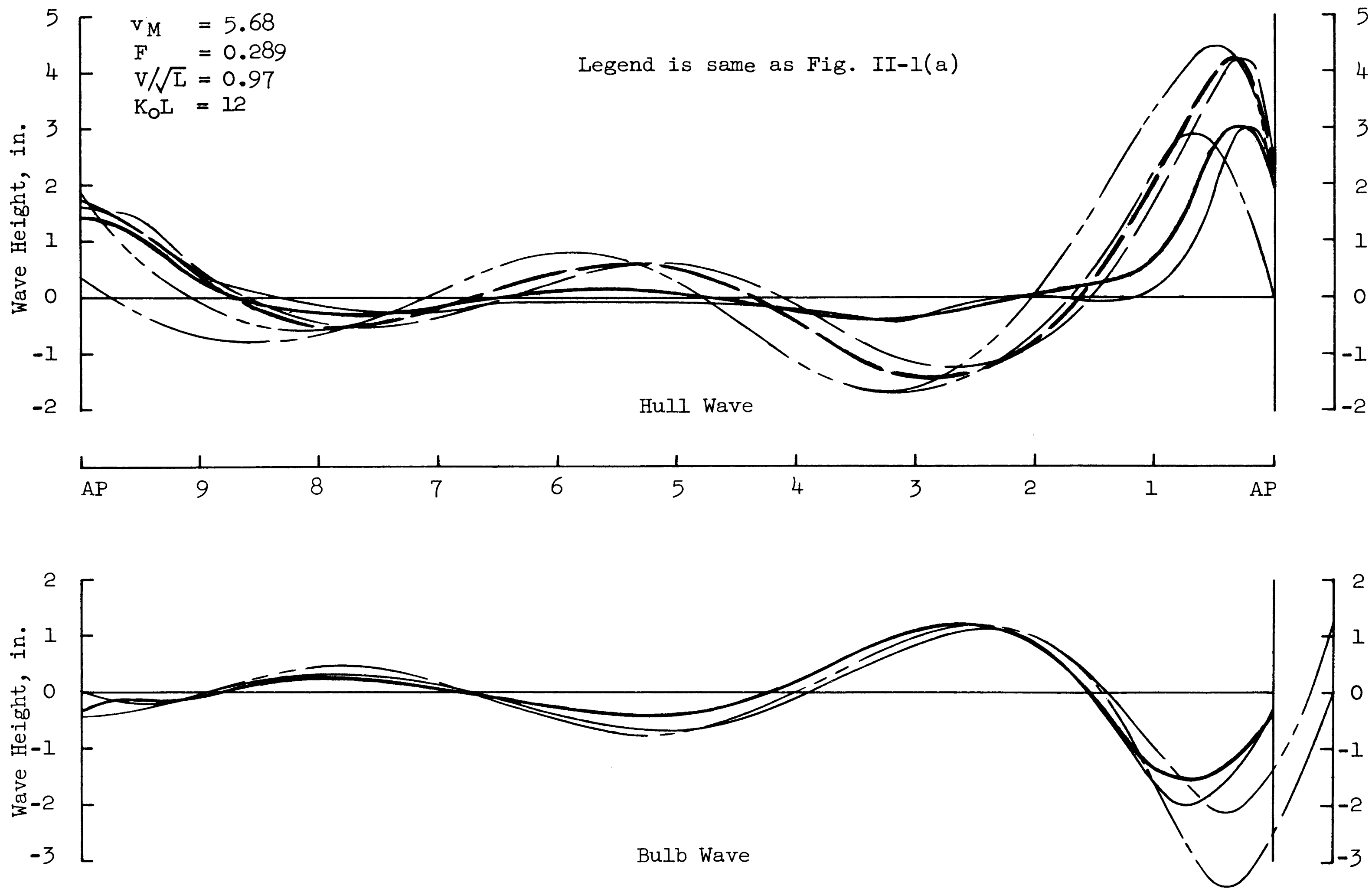
(a)

Fig. II-2. Comparisons between measured and calculated wave profiles for C-101 and C-101F1.



(b)

Fig. II-2. (Continued).



(c)

Fig. II-2. (Continued).

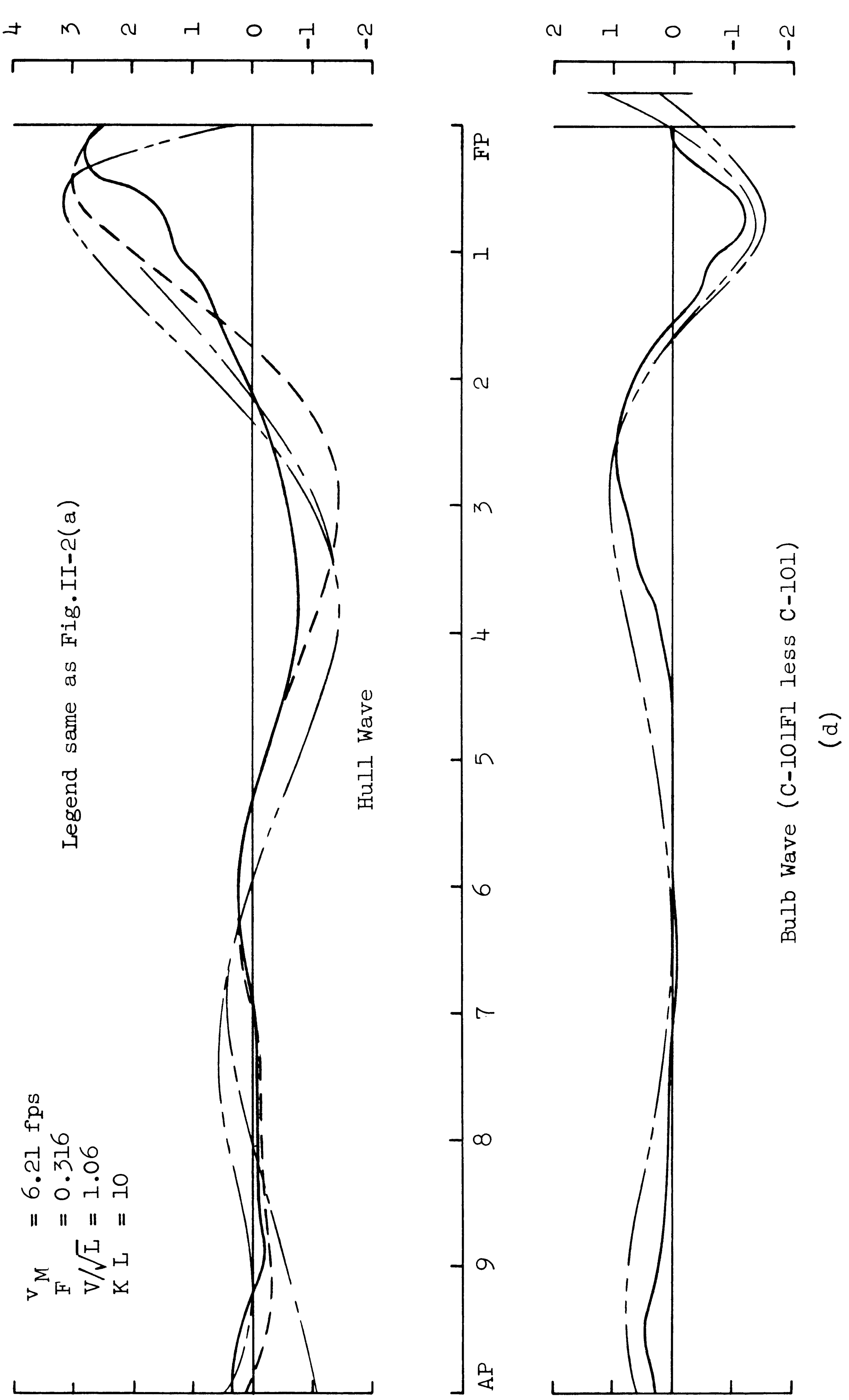
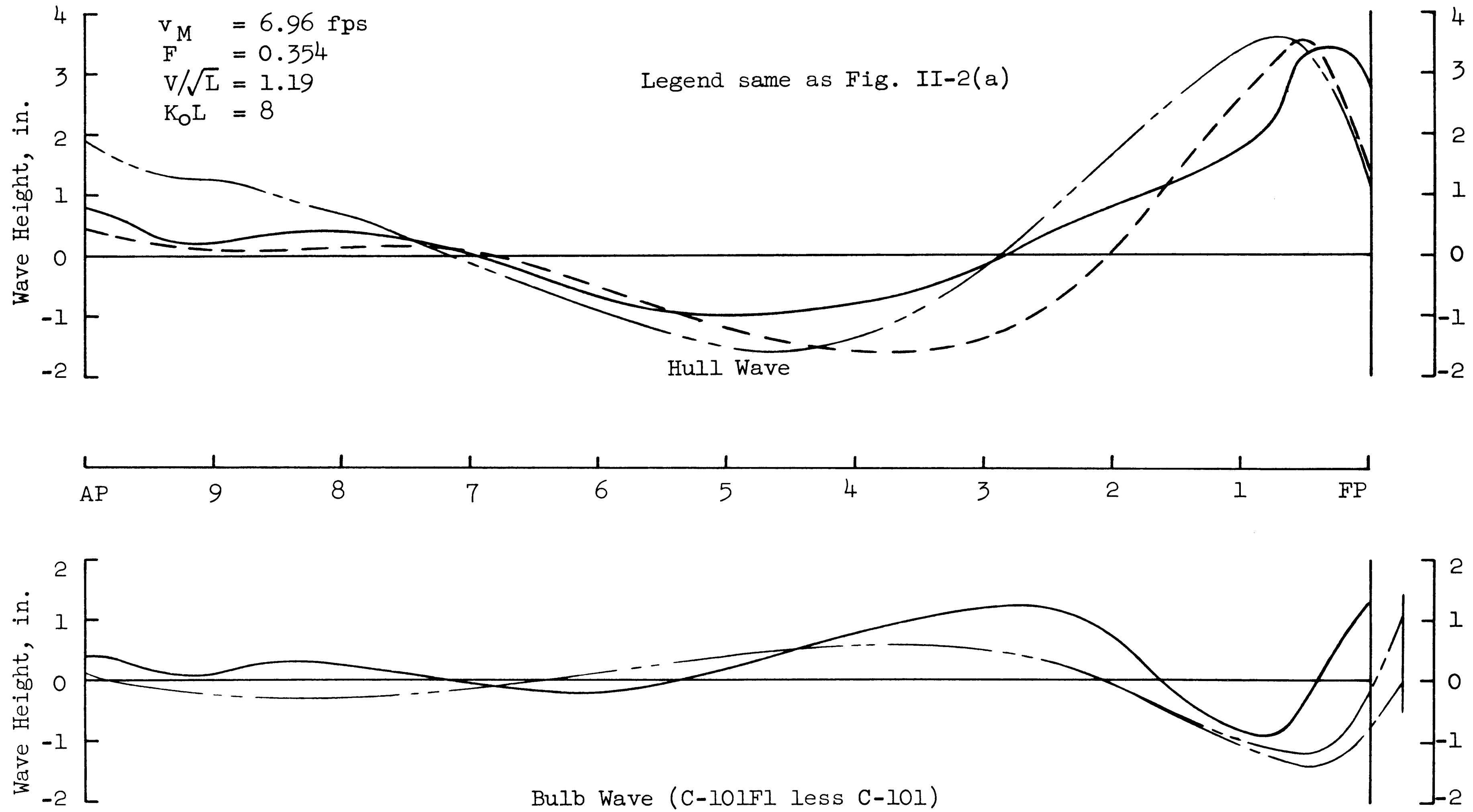
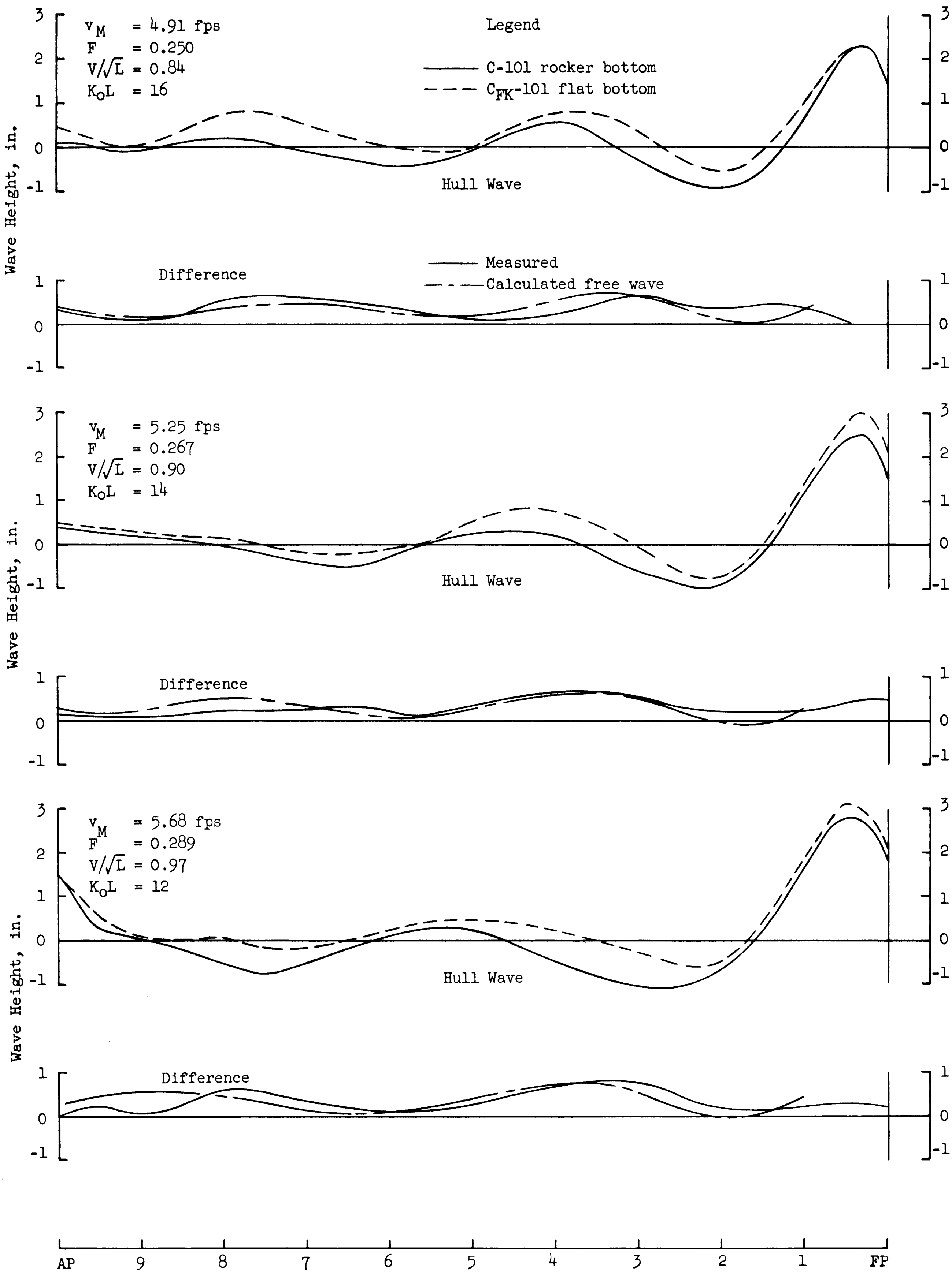


Fig. II-2. (Continued).



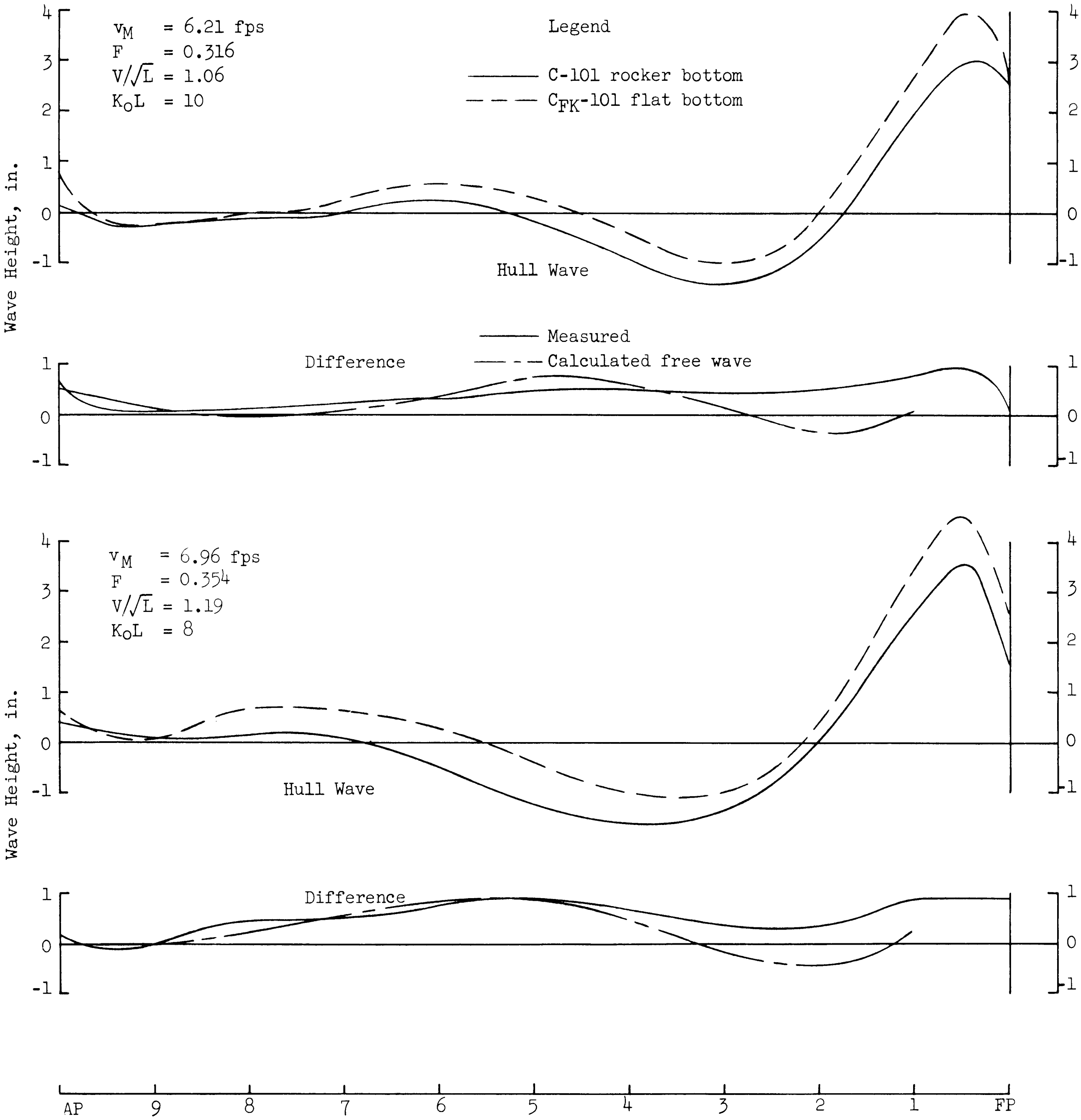
(e)

Fig. II-2. (Concluded).



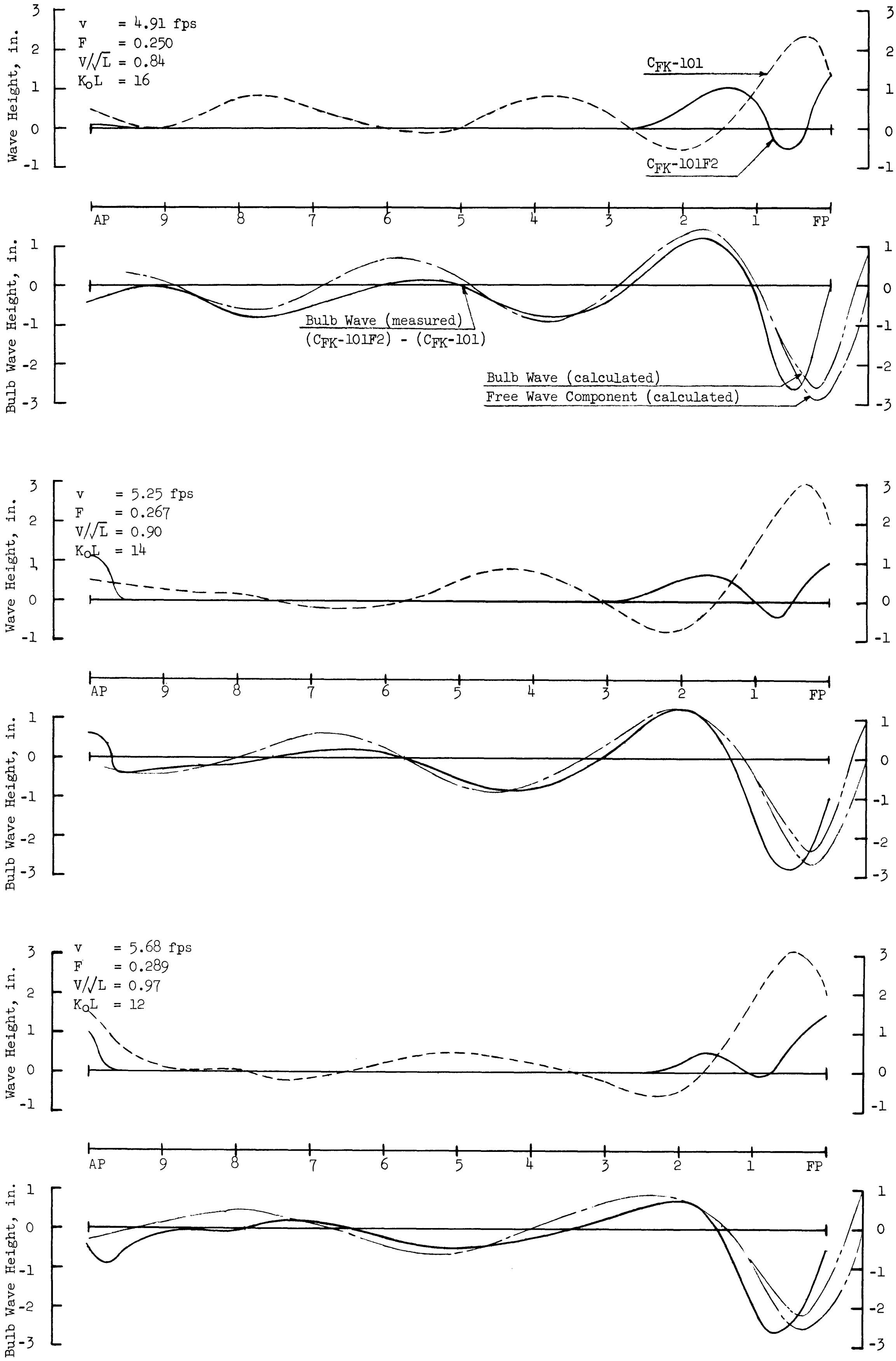
(a)

Fig. II-3. Effect due to modifying the bottom flat for C_{FK}-101F1.



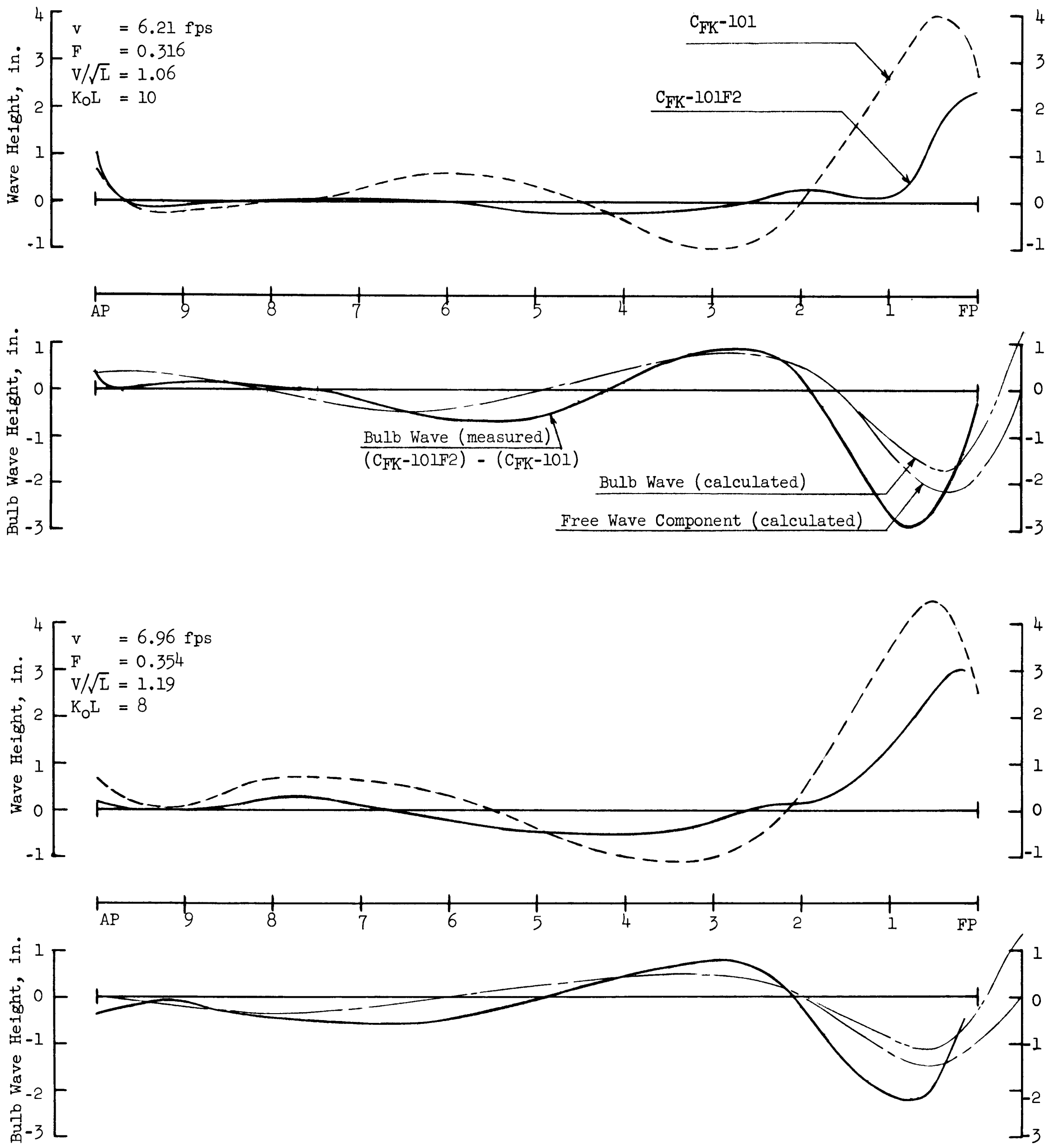
(b)

Fig. II-3. (Concluded).



(a)

Fig. II-4. Comparison between C_{FK}-101 and C_{FK}-101F2.



(b)

Fig. II-4. (Concluded).