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ANALYTICAL SHIP RESIDUARY RESISTANCE PREDICTION,(U)
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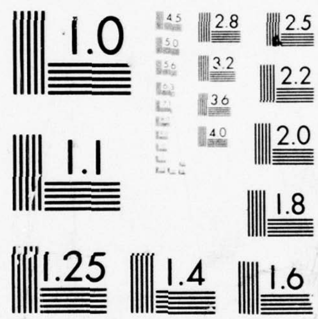

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DAVID W. TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

Bethesda, Md. 20084

ANALYTICAL SHIP

RESIDUARY RESISTANCE PREDICTION

by

Gabor Karafiath

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SHIP PERFORMANCE DEPARTMENT

DEPARTMENTAL REPORT

November 1977 SPD-800-01

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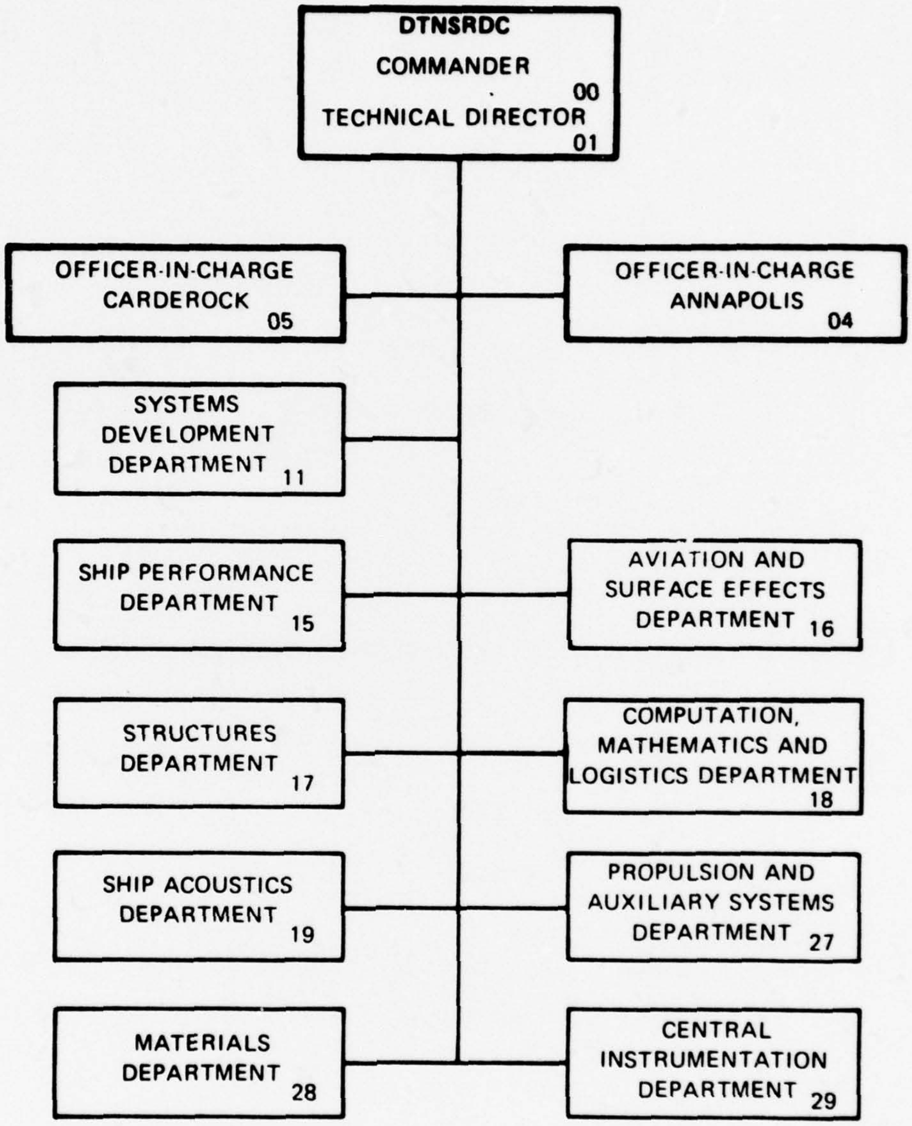

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER SPD-800-01	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) ANALYTICAL SHIP RESIDUARY RESISTANCE PREDICTION		5. TYPE OF REPORT & PERIOD COVERED 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Gabor/Karafiath		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS David W. Taylor Naval Ship R&D Center Bethesda, MD 20084		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Project No. 75568
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Ship Engineering Center Washington, D.C. 20362		12. REPORT DATE November 1977 13. NUMBER OF PAGES 30
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) (12) 38p.		15. SECURITY CLASS. (of this report) UNCLASSIFIED 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

APPROVED FOR PUBLIC RELEASE: DISTRIBUTION UNLIMITED

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Residuary Resistance Coefficient, Wave Resistance Coefficient

C sub R   C sub W

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report attempts to verify the hypothesis that the ratio of the residuary resistance coefficients (C_R) for two sufficiently similar ships is equal to the ratio of their wave resistance coefficients (C_W). Several test cases are constructed using Series 60 and Taylor Standard Series ships. Wave resistance coefficients are obtained from the evaluation of the Mitchel integral by Hsiung's method which, within the limitations inherent in thin ship theory, can be applied to any ship shape. For all the test cases, → over

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S/N 0102-014-6601

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20. Abstract (Continued)

calculated wave resistance coefficients and the residuary resistance coefficients are presented.

In general, predictions based on a known ship whose prismatic coefficient, C_p, volumetric coefficient, C_v, beam-draft ratio, B/T or length-beam ratio, L/B, varied by as much as 25% from the unknown were very poor and predictions based on a known ship whose LCB varied by up to 2% of LBP and had the same C_p, C_v, B/T, and L/B as the unknown ship were also poor and very sensitive to the choice of the predictor model. A better prediction was obtained, within 12% error, in the Froude number range above 0.26 for a test case where only the C_p and C_v were varied by 3%.

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NOTATION

B	Beam
C_B	Block Coefficient
C_p	Prismatic Coefficient
C_R, C_r	Residuary Resistance Coefficient $= \frac{R_R}{\frac{1}{2}\rho V^2 S}$
C_S	Wetted Surface Coefficient $= \frac{S}{\sqrt{\nabla L}}$
C_v	Volumetric Coefficient $= \frac{\nabla}{L^3}$
C_W	Wave Resistance Coefficient $= \frac{R_W}{\frac{1}{2}\rho V^2 S}$
C_{W_1}	Wave Resistance Coefficient $= \frac{R_W}{\left(\frac{8\rho g}{\pi}\right)\left(\frac{B^2 T^2}{L^2}\right)}$
C_{W_2}	Wave Resistance Coefficient $= R_W/\Delta$
C_x	Midship Section Coefficient
F_n	Froude Number $= \frac{V}{\sqrt{gL}}$
L	Length
L_{BP}	Length Between Perpendiculars
LCB	Longitudinal Center of Buoyancy
R_R	Residuary Resistance
R_W	Wave Resistance
S	Wetted Surface Area
T	Draft
V	Velocity

V_k	Velocity in Knots
g	Gravitational Constant
x	Nondimensional Longitudinal Position of Ship Offset
y	Nondimensional Ship Offset
z	Nondimensional Waterline Position of Ship Offset
ρ	Density of Water
π	Pi 3.14159...
Δ	Ship Displacement Weight
∇	Volumetric Ship Displacement

SUBSCRIPTS

P	Proposed Ship
K	Known Ship
4210...4217	Series 60 Model Numbers
I....XI	Taylor Series Ships

ABSTRACT

This report attempts to verify the hypothesis that the ratio of the residuary resistance coefficients (C_R) for two sufficiently similar ships is equal to the ratio of their wave resistance coefficients (C_W). Several test cases are constructed using Series 60 and Taylor Standard Series ships. Wave resistance coefficients are obtained from the evaluation of the Mitchel integral by Hsiung's[1*] method which, within the limitations inherent in thin ship theory, can be applied to any ship shape. For all the test cases, calculated wave resistance coefficients and the residuary resistance coefficients are presented.

In general, predictions based on a known ship whose prismatic coefficient, C_p, volumetric coefficient, C_v, beam-draft ratio, B/T or length-beam ratio, L/B, varied by as much as 25% from the unknown ship were very poor and predictions based on a known ship whose LCB varied by up to 2% of LBP and had the same C_p, C_v, B/T, and L/B as the unknown ship were also poor and very sensitive to the choice of the predictor model. A better prediction was obtained, within 12% error, in the Froude number range above 0.26 for a test case where only the C_p and C_v were varied by 3%.

ADMINISTRATIVE INFORMATION

This report was funded by the Naval Ship Engineering Center, Code 6136. The work was done under Project No. 75568 and Work Unit 1-1524-635.

INTRODUCTION

The purpose of this report is to test the hypothesis that the residuary resistance coefficient for a proposed ship can be determined from that of a known sufficiently similar design by the following equation:

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* References are listed on page 30

$$C_{RP} = C_{RK} * C_{WP}/C_{WK}$$

where C_{RP} and C_{RK} are the residuary resistance coefficients of the proposed and known ships, respectively, and C_{WP} and C_{WK} are their respective computed wave resistance coefficients. There are two ambiguities associated with the above prediction hypothesis that this report investigates; one is the definition of "sufficiently similar" ships and the other is the choice of wave resistance coefficient, (i.e. selection of non-dimensionalizing parameters). In order to test the validity of the hypothesis, several test cases are set up using Taylor Standard Series ships and Series 60 ships. In all cases the Mitchel integral wave resistance is calculated by the method of Reference 1.

DEFINITION OF "SIMILAR SHIPS"

For the purposes of this report, "similar ships" are ships which are alike in hull-form and have identical or nearly identical hull-form parameters and are not geosyms of each other. The hull-form parameters considered here are:

L	Length - held constant for all comparisons
C_B	Block Coefficient
C_p	Prismatic Coefficient
C_x	Midship Section Coefficient
B/T	Beam-Draft Ratio
L/B	Length-Beam Ratio

LCB Longitudinal Center of Buoyancy

C_v Volumetric Coefficient

y (x,z) Hull Offset at a particular station and waterline

Depending on the restrictiveness of the comparison between two ships, some of the above parameters can be both dependent or independent.

From the basic definitions associated with some of the above hull form coefficients, the identity

$$C_v = \frac{C_x C_p}{(B/T)(L/B)^2}$$

can be derived. This equation is useful for identifying the dependent and independent variables associated with various types of comparisons. For example for constant volume comparisons, the quantity

$$\frac{C_x C_p}{(B/T)(L/B)^2}$$

must be held the same for both ships and preferably two of the four terms, C_x, C_p, B/T, and $(L/B)^2$ will be held constant in order to isolate the effect of the other terms. In the Taylor to Taylor Series comparison and Series 60 to Series 60 comparisons C_x is held constant and the variations shown in Table 1 are performed.

DEFINITION OF WAVE RESISTANCE COEFFICIENT

The hypothesis can be restated as:

$$\frac{C_{RP}}{C_{RK}} = \frac{C_{WP}}{C_{WK}}$$

Form Coefficient Held Constant	Form Coefficient Varied	Rule for Variation	Examples
C_v, C_p, LCB	B/H, L/B	$(B/H)*(L/B)^2$= Const.	Taylor I, II and II Series Taylor V, VI and VII Series
C_v, B/T, LCB	C_p (L/B)	$C_p/(L/B)^2$= Const.	Taylor IV and VI
C_v, L/B, LCB	C_p (B/T)	$C_p/(B/H)$ = Const.	Taylor IV and V (nearly const. L/B)
L/B, B/T, LCB	C_p, C_v	C_p/C_v = Const.	Taylor IX and X, V and I
C_v, C_p, (L/B)(B/T)	LCB	According to Avail. Model Test Data	Series 60 Models

TABLE I - VARIATION OF L/B, B/T, C_v, C_p and LCB

The ratio of C_{WP}/C_{WK} will change slightly depending on the choice of non-dimensionalizing parameter for the wave resistance coefficient and on the parameters that vary between the known and unknown ship. A change in the C_{WP}/C_{WK} ratio will then affect the validity of the hypothesis.

Some common forms of the wave resistance coefficient are:

$$C_W = \frac{R_W}{\frac{1}{2}\rho V^2 S}$$

$$C_{W_1} = \frac{R_W}{(\frac{8\rho g}{\pi})(\frac{B^2T^2}{L})}$$

$$C_{W_2} = \frac{R_W}{\Delta}$$

and they can all be related by the following equation:

$$\frac{R_{WP}}{R_{WK}} = \frac{C_{WP}}{C_{WK}} \cdot \frac{S_P}{S_K} = \frac{C_{WP_1}}{C_{WK_1}} \cdot \frac{\left(\frac{B^2T^2}{L}\right)_P}{\left(\frac{B^2T^2}{L}\right)_K} = \frac{C_{WP_2}}{C_{WK_2}} \cdot \frac{\Delta_P}{\Delta_K}$$

Thus, for identical wave resistance ratio's, one could have at least three different wave resistance coefficient ratios.

A wave resistance coefficient based on L^2 is also common, but was not considered because the ratio $\frac{C_{WP}}{C_{WK}}$ based on L^2 would behave very similarly to the coefficient ratio based on S, since in this study, the wetted surfaces of the "known" and "proposed" ships generally varied within 2%. The first few test cases indicated that the large magnitude of the prediction error could not be eliminated by a 2% wetted surface correction.

In order to deal with wave resistance coefficients of a familiar magnitude the first definition, C_W based on wetted surface, was chosen for all of the test cases. A plot of the ratios

$$\frac{C_{RK}}{C_{RP}} \text{ and } \frac{C_{WK}}{C_{WP}}$$

for a few test cases revealed that in general the prediction could not be significantly improved by selecting ratios of C_{W_1} or C_{W_2} instead of C_W.

WAVE RESISTANCE CALCULATION

The wave resistances for all the test cases were calculated using the following undocumented computer programs, MICHIG, ASTORE, and CRDCALC which use the method of Reference 1. ASTORE and CRDCALC are basically a split-up version of the MICHIG program which permits the storage of the wave resistance matrix and thus significantly reduces the computer time required for calculating the wave resistance of several ships which have common station locations, waterline locations, draft-length ratios, and desired output speeds.

Since ASTORE and CRDCALC are undocumented, several checks on the accuracy of the computation method were performed. The wave resistance of two mathematical ship models, one defined by $y = 1 - x^2$ and the other defined by $y = (1 - x^2)(1 - z^4)$ (in Weinblum's coordinate system*) were calculated and compared to other independent calculations. The doubly parabolic ship was spot checked against results from a computer program written by A.M. Reed (DTNSRDC) and against published values in Reference 1. The wall sided ship model was spot checked using the strut wave making drag prediction program of Reference 2 and the computer calculated and hand calculated values presented in Reference 1. In this process, an error was discovered in Appendix A of Reference 1 in which the published wave resistance coefficients of the wall sided ship are for a ship with a draft-length ratio of 0.10 instead of the 0.05 shown. In general, there was excellent agreement between the wave resistance coefficients calculated by

* Weinblum's coordinate system places the origin on the waterline at midships. x is oriented forwards, y athwartships and z downward in a right handed system. Hsiung's coordinate system, used in MICHIG, ASTORE, and CRDCALC computer programs places the origin at the intersection of the baseline and the bow of the ship with x oriented to the rear, z upward and y athwartships in a right handed system.

ASTORE and CRDCALC with wave resistance coefficients calculated by the other aforementioned independent methods.

The important feature of ASTORE and CRDCALC is that it can calculate quickly the Mitchel integral wave resistance for a ship form defined by offsets at given waterlines and stations.

The sensitivity of the calculated resistance to the number of station and waterlines used to define the hull form has not yet been explored. Thirteen stations and six waterlines were used throughout the calculations in this report. Other calculations have been made with as many as twenty-one stations, however, it is felt that for these initial calculations thirteen stations are enough.

DEFINITION OF PREDICTION ERROR

The definition of error in predicted C_r is given by:

$$\text{Prediction Error} = \frac{C_{r\ \text{predicted}} - C_{r\ \text{measured}}}{C_{r\ \text{measured}}}$$

where $C_{r\ \text{predicted}}$ is the residuary resistance coefficient of the unknown ship predicted by our hypothesis and $C_{r\ \text{measured}}$ is the actual residuary resistance of the unknown ship as derived from model test.

Once a design which is sufficiently close to that of the unknown ship has been found, it becomes desirable to know the error incurred by assuming that the residuary resistance coefficients of the two ships are the same. This error is called "Error Assuming Predictor C_r" and is defined as:

$$\text{"Error Assuming Predictor } C_r\text{"} = \frac{C_{r\ \text{predictor}} - C_{r\ \text{measured}}}{C_{r\ \text{measured}}}$$

where C_r predictor is the C_r as determined from model test of the predictor ship (i.e., the sufficiently close design) and C_r measured is the C_r of the unknown ship as determined from model tests.

If the prediction error is larger than the error incurred by assuming the predictor C_r equal to the unknown ship C_r, then one shouldn't bother with the theoretical wave drag calculations involved in the hypothesis.

PREDICTION TEST CASES

Early Comparisons - Large Variation of B/T, T/L, C_p, C_v with constant LCB

The first test cases were performed on Taylor Series ships (Reference 3). The wave resistance coefficient for seven Taylor ships called Taylor I, Taylor II, etc., were calculated and are presented along with the residuary resistance and some ship geometric characteristics in Table II. Six waterlines and thirteen stations were used to define each Taylor hull.

A common characteristic to all Taylor ships is a midship location of the LCB and the common 0.925 midship section coefficient. The normalized ship hull offsets in the Taylor series are a function of prismatic coefficient, C_p, only and therefore are the same for all Taylor ships having the same C_p. Taylor ships with the same C_p but different B/T, T/L, and C_v's are the same nondimensional shape stretched in different ways.

	TAYLOR I		TAYLOR II		TAYLOR III		TAYLOR IV		TAYLOR V		TAYLOR VI		TAYLOR VII	
L/B	10.33		8.96		8.00		10.01		10.33		8.96		8.00	
B/T	2.25		3.0		3.75		3.0		2.25		3.0		3.75	
T/L	.0430		.0372		.0333		.0333		.0430		.0372		.0333	
C_p	.65		.65		.65		.65		.52		.52		.52	
C_v	$2.5X10^{-3}$		$2.5X10^{-3}$		$2.5X10^{-3}$		$2.0X10^{-3}$		$2.0X10^{-3}$		$2.0X10^{-3}$		$2.0X10^{-3}$	
C_S	2.549		2.530		2.571		2.588		2.566		2.520		2.544	
C_x	.925		.925		.925		.925		.925		.925		.925	
LCB% of L from ⊗	0		0		0		0		0		0		0	
F_n	C_W $X 10^3$	$C_R X10^3$ Meas.	C_W $X 10^3$	$C_r X10^3$ Meas.	C_W $X 10^3$	$C_r X10^3$ Meas.	C_W $X 10^3$	$C_r X10^3$ Meas.	C_W $X 10^3$	$C_r X10^3$ Meas.	C_W $X 10^3$	$C_r X10^3$ Meas.	C_W $X 10^3$	$C_r X10^3$ Meas.
0.15	.362	.31	.431	.42	.478	.55	.340	.39	.338	.25	.410	.33	.460	.41
.25	.540	.65	.597	.80	.628	.80	.446	.72	.147	.32	.174	.60	.193	.57
.35	1.695	2.06	1.849	2.55	1.923	2.70	1.367	2.05	1.707	1.50	1.841	1.53	1.898	1.53
.45	4.812	4.91	5.102	5.40	5.204	5.70	3.700	4.10	4.957	4.82	5.268	5.05	5.374	5.12

TABLE II - SHIP CHARACTERISTICS AND CALCULATED WAVE RESISTANCE COEFFICIENTS AND RESIDUARY RESISTANCE COEFFICIENTS OF SEVEN SELECTED TAYLOR SERIES SHIPS

The first three Taylor ship predictions shown in Table III have the same C_p, and C_v but differenct B/T and T/L ratios. It is significant to note that the prediction errors are relatively large, up to 17% and that there is no discernible trend in the errors. Also, one obtains a significantly different prediction of the Taylor II C_r depending on whether the predictor ship is Taylor I or Taylor III. The other comparisons in Table III also show unacceptably large and random prediction errors.

Although the Taylor to Taylor ship predictions have large errors, it must be remembered that there is a substantial difference, B/T ratios differing by 0.75, in these Taylor ships. Such large differences between the known and unknown ships were probably not envisioned during the formulation of the hypothesis.

Comparison with LCB changed and C_p, C_v, B/T, T/L kept constant

The predictions using the Taylor Series I-VII test cases were poorer than expected. In hopes of obtaining a better prediction, test cases with smaller changes in C_p, C_v, B/T and T/L were sought. The Series 60[4] block coefficient = 0.60, DTNSRDC models (numbers 4215, 4210, 4216 and 4217) were chosen. The characteristics for 400 ft. (121.9 m) versions of these models is in Table IV. Notice that the major difference between these models is the fore and aft distribution in volume reflected in the change in the LCB location and the different values of C_{PE} and C_{PR}. Their C_p, C_v, B/T and T/L are constant.

TAYLOR to TAYLOR Ship Residuary Resistance Predictions

	II PREDICTED FROM I		II PREDICTED FROM III		III PREDICTED FROM I	
F_n	Predicted $C_r \times 10^3$	Prediction Error	Predicted $C_r \times 10^3$	Prediction Error	Predicted $C_r \times 10^3$	Prediction Error
.15	.369	-12%	.495	-17%	.41	-25%
.25	.719	-10%	.760	5%	.76	-5%
.35	2.24	-12%	2.595	2%	2.34	-13%
.45	5.20	-4%	5.58	3%	5.31	-7%

	IV PREDICTED FROM II		IV PREDICTED FROM III		V PREDICTED FROM I	
F_n	Predicted $C_R \times 10^3$	Prediction Error	Predicted $C_R \times 10^3$	Prediction Error	Predicted $C_R \times 10^3$	Prediction Error
.15	.33	-15%	.391	0%	.289	15%
.25	.59	-18%	.568	-21%	.176	-45%
.35	1.88	-8%	1.92	-6%	2.07	38%
.45	3.91	-4%	4.05	-1%	5.05	5%

	VI PREDICTED FROM VII		VI PREDICTED FROM IV	
F_n	Predicted $C_R \times 10^3$	Prediction Error	Predicted $C_R \times 10^3$	Prediction Error
.15	.365	11%	.470	42%
.25	.513	-14%	.280	-53%
.35	1.484	-3%	2.760	80%
.45	5.019	-1%	5.837	15%

$$\text{Prediction Error} = \frac{C_{r\,\text{predicted}} - C_{r\,\text{measured}}}{C_{r\,\text{measured}}}$$

TABLE III - TAYLOR SHIP TO TAYLOR SHIP PREDICTIONS

Model #	4215	4210	4216	4217
L_{BP}	400	400	400	400
L/B	7.5	7.5	7.5	7.5
B/H	2.5	2.5	2.5	2.5
C_B	.60	.60	.60	.60
C_P	.614	.614	.614	.614
C_{PE}	.558	.581	.603	.626
C_{PR}	.671	.646	.624	.602
C_S	2.610	2.611	2.620	2.629
LCB % L_{BP} from midships	2.48 A	1.5 A	.51 A	.52 F

TABLE IV - CHARACTERISTICS OF THE SERIES 60 C_B = .60 SHIP MODELS

The residuary resistance for each of the four Series 60 ships was determined from the tabulated total ship resistance coefficient by subtraction of the sum of the Schoenherr friction coefficient and the correlation coefficient, .0004. The wave resistance coefficient was calculated for the corresponding speeds by using 6 waterlines and 13 stations for inputs to the ASTORE and CRDCALC computer program. Tables V, VI, and Figure 1 show the results. The best prediction among this series of models is the prediction of the C_r of model 4216 from that of model 4217. The prediction is shown in Figure 2 and Table VII.

With reference to Figure 2, notice the "artificial" humps in the prediction at the .625 and .725 speed-length ratios. Also notice that in

F_n	$V_K/\sqrt{L_{BP}}$	Model 4215 $C_R \times 10^3$	Model 4210 $C_R \times 10^3$	Model 4216 $C_R \times 10^3$	Model 4217 $C_R \times 10^3$
.105	.35	.504	.517	.483	.462
.115	.40	.504	.517	.497	.470
.134	.45	.513	.535	.514	.481
.149	.50	.559	.559	.543	.504
.164	.55	.590	.589	.574	.534
.178	.60	.621	.619	.607	.569
.186	.625	.637	.627	.619	.599
.193	.65	.655	.643	.648	.642
.201	.675	.689	.675	.685	.680
.208	.70	.707	.699	.716	.704
.216	.725	.732	.718	.729	.722
.223	.75	.759	.722	.741	.736
.230	.775	.795	.743	.741	.759
.238	.80	.819	.763	.763	.791
.245	.825	.856	.786	.836	.856
.253	.85	.909	.840	.921	1.001
.260	.875	1.061	.986	1.056	1.173
.268	.90	1.295	1.256	1.311	1.451
.275	.925	1.574	1.560	1.690	1.740
.282	.950	1.880	1.856	2.021	2.036
.290	.975	2.119	2.110	2.230	2.290
.297	1.000	2.251	2.275	2.370	2.485
.312	1.05	2.324	2.360	2.500	2.585
.327	1.10	2.320	2.370	2.510	2.581
.342	1.15	2.575	2.638	2.760	2.880
.356	1.20	3.308	3.335	3.300	3.485
	LCB % of L_{BP} from midship	2.48 aft	1.5 aft	.51 aft	.52 fwd

TABLE V - RESIDUARY RESISTANCE COEFFICIENT OF SERIES 60 C_B = .60
MODEL #4215, 4210, 4216 and 4217

$V_K/\sqrt{L_{BP}}$	F_n	Model 4215 $C_W \times 10^3$	Model 4210 $C_W \times 10^3$	Model 4216 $C_W \times 10^3$	Model 4217 $C_W \times 10^3$
.35	.104	.105	.020	.069	.061
.40	.119	.115	.374	.101	.103
.45	.134	.348	1.059	.321	.352
.50	.149	.447	.650	.452	.410
.55	.164	.345	.444	.308	.272
.60	.178	.715	.445	.523	.449
.625	.186	.596	.348	.413	.343
.65	.193	.569	.394	.407	.381
.675	.201	.759	.520	.564	.542
.70	.208	.703	.464	.474	.429
.725	.216	.715	.516	.442	.399
.75	.223	.961	.725	.607	.590
.775	.230	1.123	.806	.677	.677
.80	.238	1.057	.713	.554	.548
.825	.245	1.010	.727	.502	.477
.85	.253	1.129	1.107	.805	.770
.875	.260	1.961	1.855	1.496	1.473
.90	.268	2.834	2.747	2.370	2.378
.925	.275	3.630	3.506	3.145	3.194
.950	.282	4.120	3.927	3.604	3.691
.975	.290	4.247	3.977	3.698	3.814
1.00	.297	4.052	3.722	3.482	3.612
1.05	.312	3.237	2.873	2.672	2.787
1.10	.327	2.688	2.397	2.190	2.253
1.15	.342	2.910	2.745	2.510	2.510
1.20	.357	3.862	3.831	3.567	3.509
LCB % of L_{BP} from ℄		2.48 aft	1.5 aft	.51 aft	.52 fwd

TABLE VI - CALCULATED WAVE RESISTANCE COEFFICIENTS FOR SERIES 60 C_B = .60 MODELS #4215, 4210, 4216 and 4217

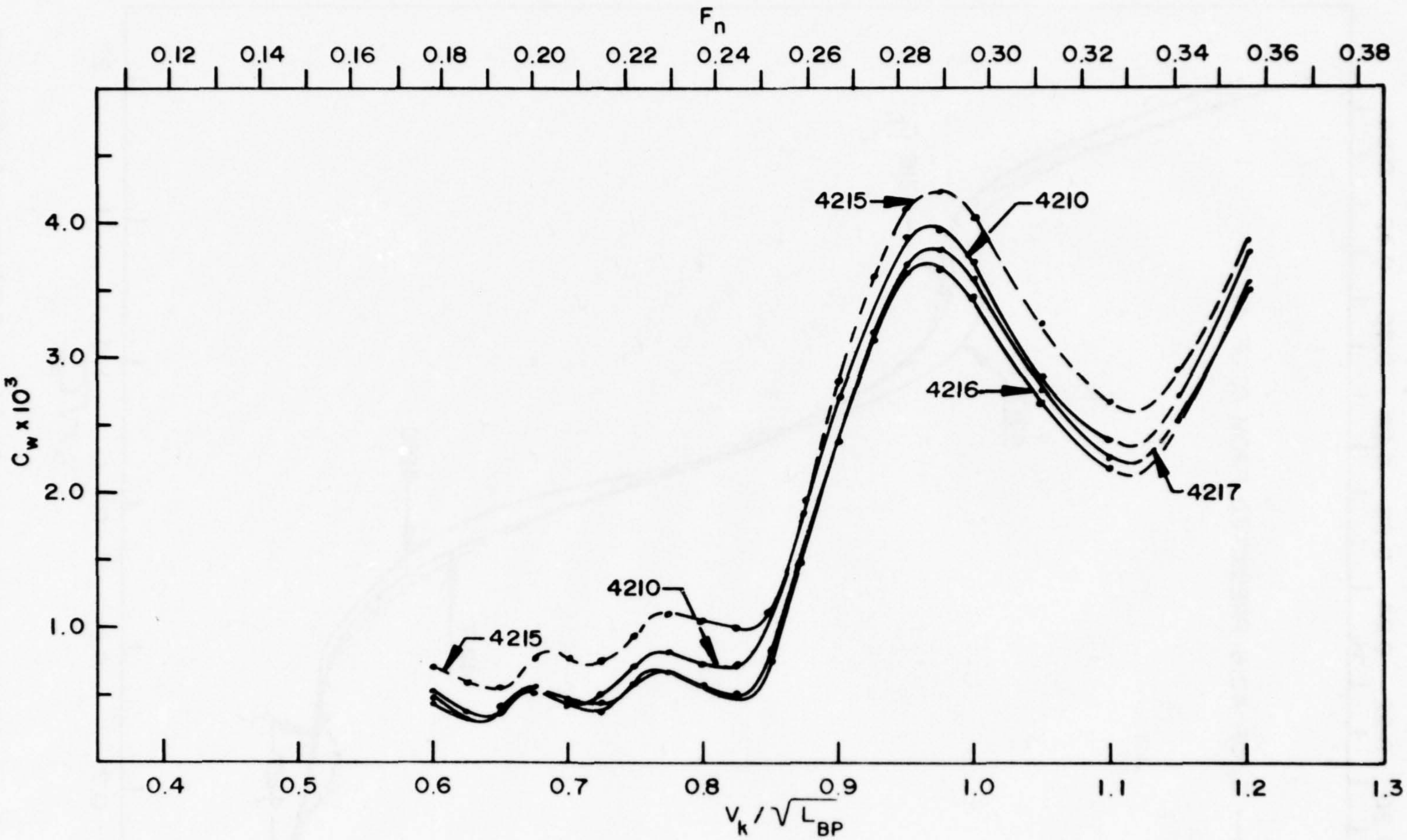

Figure 1 - Calculated C_W of Models 4210, 4215, 4216, and 4217

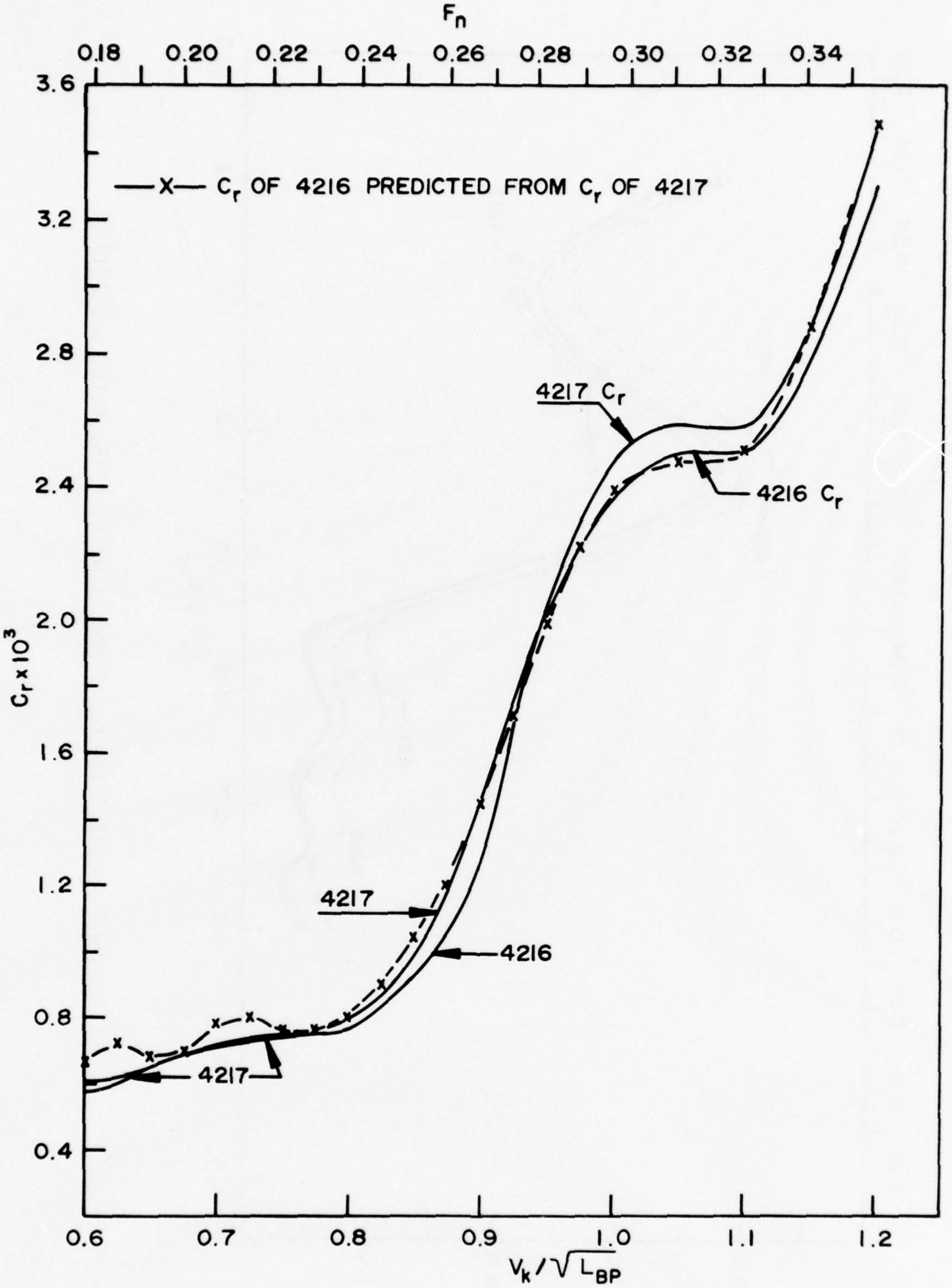

Figure 2 - Predicted and Measured Residuary Resistance Coefficient of Series 60 Model 4216

$V_K/\sqrt{L_{BP}}$	4216 Predicted from 4215		Error Assuming Predictor C_r	4216 Predicted from 4210		Error Assuming Predictor C_r	4216 Predicted from 4217		Error Assuming Predictor C_r
	Predicted			Predicted			Predicted		
	$C_R X10^3$	Error		$C_R X10^3$	Error		$C_R X10^3$	Error	
.35	.331	-.31	.04	1.783	2.69	.07	.522	.08	-.04
.40	.442	-.11	.01	.139	-.72	.04	.479	-.04	-.05
.45	.473	-.8	.00	.162	-.68	.04	.438	-.15	-.06
.50	.565	.04	.03	.388	-.28	.03	.555	.02	-.07
.55	.527	-.08	.03	4.08	-.29	.03	.604	.05	-.07
.60	.454	-.25	.02	.727	-.20	.02	.662	.09	-.06
.625	.441	-.29	.03	.774	.250	.01	.721	.16	-.03
.65	.468	-.28	.01	.664	.02	.01	.685	.06	-.01
.675	.511	-.25	.01	.732	.07	-.01	.707	.03	-.01
.70	.476	-.34	-.01	.714	.00	-.02	.777	.09	-.02
.725	.452	-.38	.00	.615	-.16	-.02	.799	.10	-.01
.75	.479	-.35	.02	.604	-.18	-.03	.757	.02	-.01
.775	. 479	-. 35	.07	.624	-.16	-.00	.759	.02	.02
.80	.429	-.44	.07	.592	-.22	-.00	.799	.05	.04
.825	.425	-.49	.02	.542	-.35	-.06	.900	.08	.02
.85	.648	-.30	-.01	.610	-.34	-.10	1.046	.14	.09
.875	.809	-.23	.00	.795	-.25	-.07	1.191	.13	.11
.90	1.082	-.17	-.01	1.083	-.21	-.04	1.446	.10	.11
.925	1.363	-.19	-.07	1.399	-.17	-.08	1.713	.01	.03
.95	1.644	-.17	-.07	1.703	-.16	-.08	1.988	-.02	.01
.975	1.845	-.17	-.05	1.961	-.12	-.05	2.220	.00	.03
1.000	1.934	-.18	-.05	2.128	-.10	-.04	2.395	.01	.05
1.05	1.918	-.23	-.08	2.194	-.122	-.06	2.478	-.01	.03
1.10	1.890	-.25	-.08	2.165	-.137	-.06	2.508	00	.03
1.20	3.055	-.07	-.00	3.105	-. 06	.01	3.485	.06	.06
LCB as a % of L_{BP} of Predictor Ship	2.48 aft			1.5 aft			.52 fwd		
Predicted Ship	.51 aft			.51 aft			.51 aft		

TABLE VII - PREDICTED RESIDUARY RESISTANCE OF SERIES 60 C_B = .60
MODEL #4216 FROM THREE OTHER MODELS

the range of speed-length ratio from .6 to .9, the wave resistance ratio "corrected" the C_r of model 4217 in the wrong direction, i.e. the predicted C_r instead of being decreased to match the desired C_r of model 4216 was actually increased. The explanation for the incorrect prediction lies in the fact that at a speed length ratio of .825 calculated C_W of model 4217 is lower than that of model 4216 (see Figure 3), but its C_r is substantially higher (see Figure 2).

Some of the problems involved with the prediction method can be readily seen in Figure 4 which shows the oscillating nature of the ratio of wave resistance coefficients and the irregular nature of the C_r ratio. At speeds where the C_W ratio is at a peak, there is a large error in the prediction and at speeds where two curves match, the prediction error is zero. Figure 4 also shows that in this case the choice of the wave resistance coefficient is not significant. In this particular case, the ratio of C_{W_2}'s is 1.003 times the ratio of C_W's, an insignificant difference compared to the magnitude of the prediction error. The major source of prediction error is due to the peaks in the wave resistance ratio curve.

The sensitivity of the prediction method to the choice of predictor model can be seen in Figure 5 which shows the C_r of model 4216 as determined from model test and the predicted C_r's for model 4216 based on three different predictor ships. The prediction based on model 4217 is good at a speed-length ratio above .925, however, without prior knowledge there is no reason to choose model 4217 as the predictor over model 4210 since the LCB of 4210 is 1% forward and the LCB of 4217 is 1% aft of the LCB of 4216. The prediction from model 4210 is extremely poor throughout the speed range.

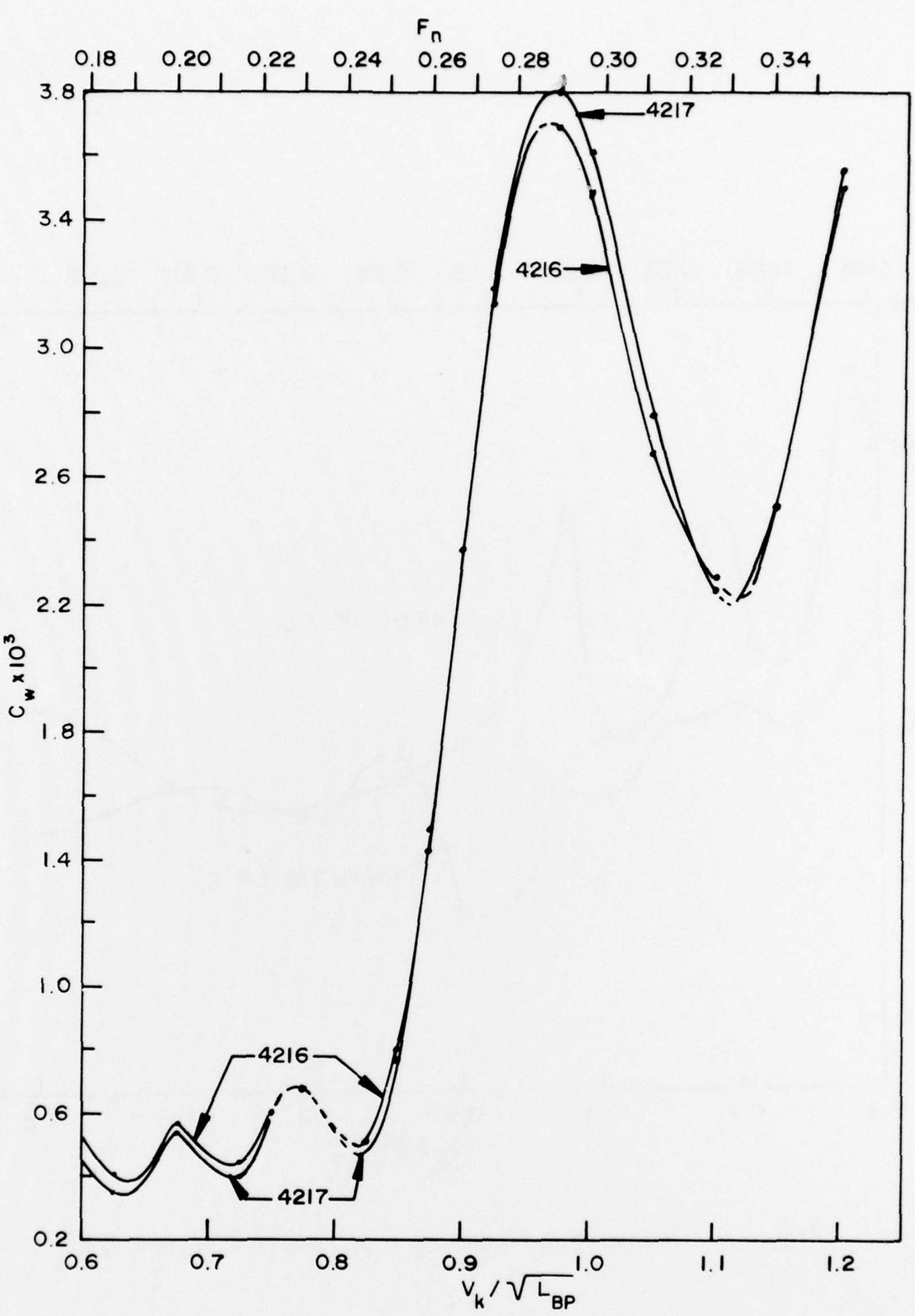

Figure 3 - Wave Resistance Coefficient of Models 4216 and 4217

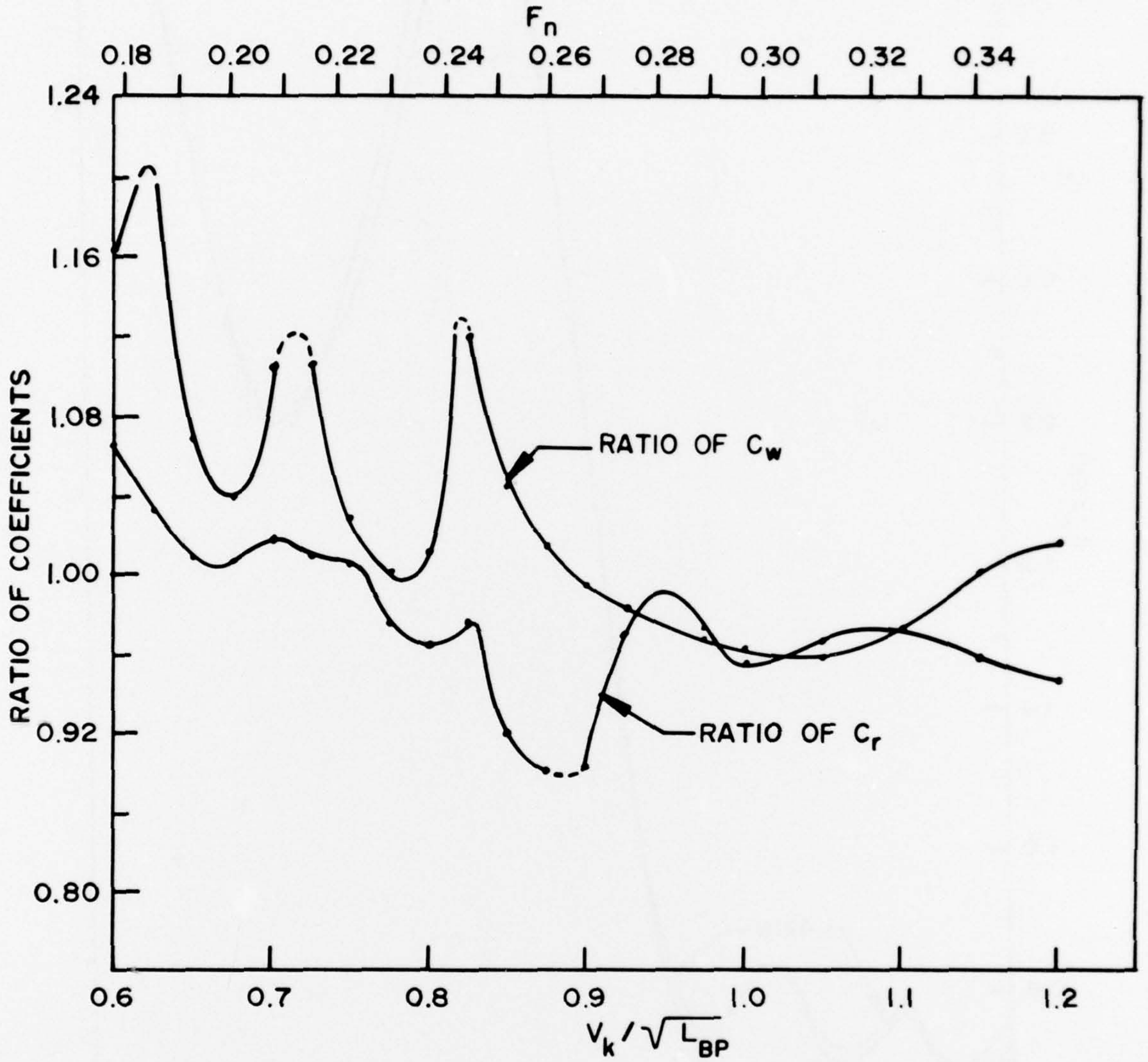

Figure 4 - Ratio of C_R's and C_W's of Models 4216 and 4217

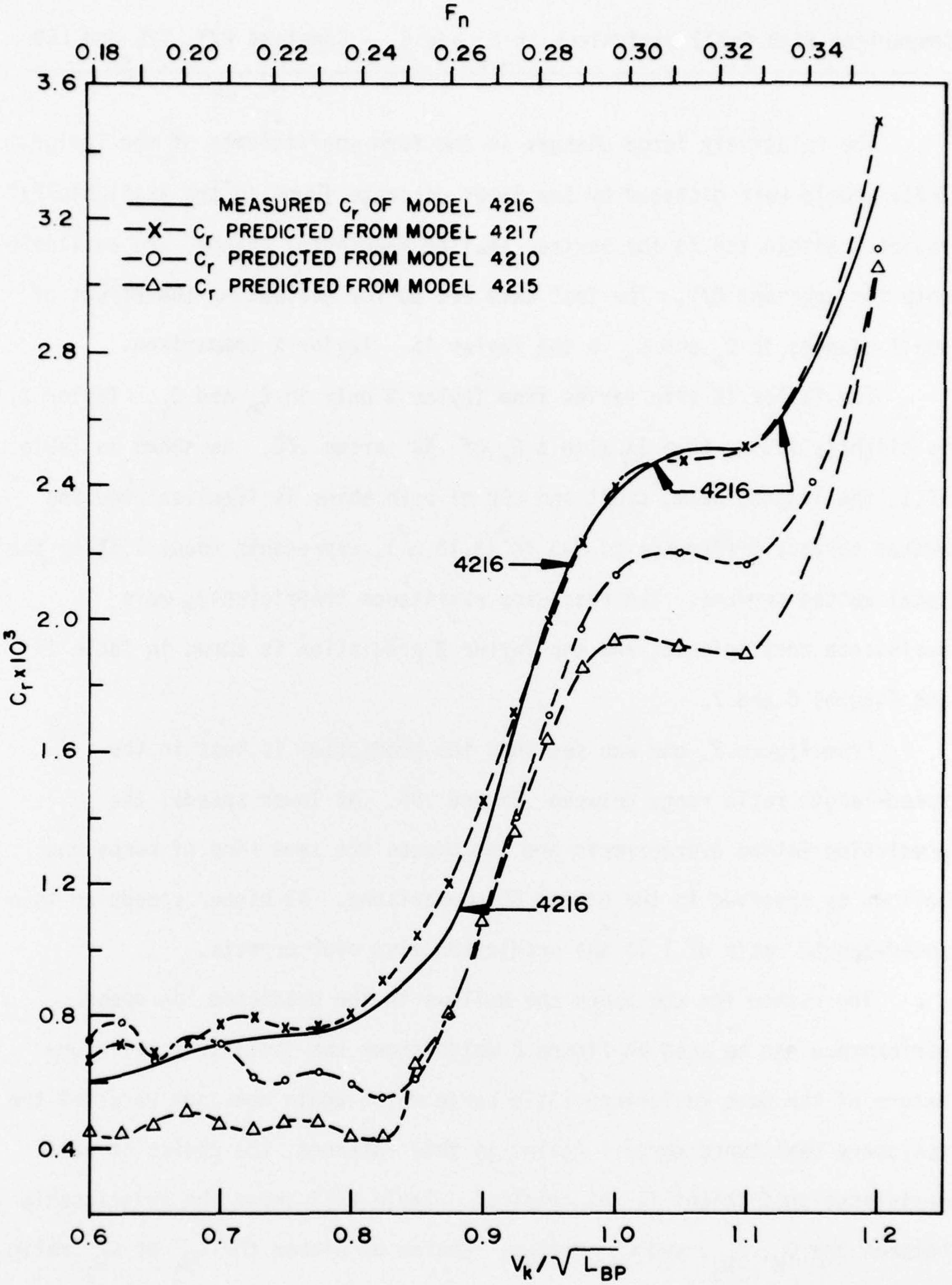

Figure 5 - C_R of Model 4216 Based on Predictions from Three Other Models

Comparison with Small Variations in C_p and C_v - Constant B/T, T/L and LCB

The relatively large changes in the form coefficients of the Taylor I-VII models were dictated by the large discrete jumps in the available B/T ratios. Within the Taylor Series, smaller meaningful changes are available only for constant B/T. The test case set up for evaluating the effect of small changes in C_p and C_v is the Taylor IX - Taylor X comparison.

The Taylor IX ship varies from Taylor X only in C_p and C_v. Taylor X is slightly fuller than IX with a C_p of .62 versus .60. As shown in Table VIII, the length, beam, draft and LCB of both ships is identical and the wetted surface difference of 343 ft^2(3.18 m^2), represents about 1.5% of the total wetted surface. The residuary resistance coefficients, wave resistance coefficients, and the Taylor X prediction is shown in Table IX and Figures 6 and 7.

From Figure 7, one can see that the prediction is best in the speed-length ratio range between .85 and .95. At lower speeds, the prediction method overcorrects and introduces the same kind of humps and hollows as observed in the Series 60 comparisons. At higher speeds up to a speed-length ratio of 1.13 the prediction also overcorrects.

The reason for the humps and hollows in the predicted low speed performance can be seen in Figure 8 which shows the familiar oscillatory nature of the wave resistance ratio curve which again does not parallel the residuary resistance curve. Again, in this instance, the choice of wave resistance coefficient is not critical. Table VIII shows the relationship between the C_W, C_{W_1}, and C_{W_2} ratios. Choice of either the C_{W_1} or C_{W_2} ratio would have affected the prediction less than 2%.

	TAYLOR IX	TAYLOR X
L	400 ft (121.9 m)	400 ft (121.9 m)
C_p	.60	.62
C_v	3.0×10^{-3}	3.1×10^{-3}
L/B	9.0676	9.0676
T/L	.0490	.0490
B/T	2.25	2.25
C_S	.555	.574
C_x	.925	.925
LCB	at ⊗	at ⊗
Wetted Surface	22,373 ft^2 (207.8 m^2)	22,716 ft^2 (211.0 m^2)

$$\frac{(C_{W_1})_X}{(C_{W_1})_{IX}} = 1.0153 \frac{(C_W)_X}{(C_W)_{IX}}$$

$$\frac{(C_{W_2})_X}{(C_{W_2})_{IX}} = .9825 \frac{(C_W)_X}{(C_W)_{IX}}$$

TABLE VIII - TAYLOR IX AND X SHIP CHARACTERISTICS AND WAVE RESISTANCE COEFFICIENT RELATIONSHIPS

		Measured $C_r \times 10^3$		Calculated $C_W \times 10^3$		X Predicted by IX	
F_N	$V_k/\sqrt{L_{BP}}$	IX	X	IX	X	$C_r \times 10^3$	Error in Predicted C_R
.178	.60	.34	.35	.463	.512	.38	.086
.186	.625	.34	.35	.393	.438	.38	.086
.193	.65	.33	.35	.345	.399	.38	.086
.201	.675	.34	.36	.465	.575	.42	.167
.208	.70	.35	.37	.396	.495	.44	.189
.216	.725	.37	.40	.343	.420	.45	.125
.223	.75	.39	.43	.448	.551	.48	.116
.230	.775	.42	.47	.524	.659	.53	.128
.238	.80	.46	.52	.452	.579	.59	.135
.245	.825	.51	.58	.377	.476	.64	.103
.253	.85	.58	.66	.490	.592	.70	.061
.260	.875	.67	.77	.807	.977	.81	.052
.268	.90	.79	.91	1.299	1.612	.98	.077
.275	.925	.92	1.10	1.691	2.150	1.17	.064
.282	.95	1.12	1.37	1.938	2.527	1.46	.066
.290	.975	1.32	1.63	1.997	2.685	1.78	.092
.297	1.00	1.45	1.80	1.888	2.606	2.00	.111
.312	1.05	1.53	1.92	1.446	2.075	2.20	.146
.327	1.10	1.54	1.90	1.224	1.647	2.07	.089
.342	1.15	1.69	2.01	1.498	1.708	1.93	-.040
.356	1.20	2.10	2.37	2.158	2.215	2.15	-.024

TABLE IX - RESIDUARY RESISTANCE, WAVE RESISTANCE AND PREDICTED RESISTANCE FOR TAYLOR SHIPS IX AND X

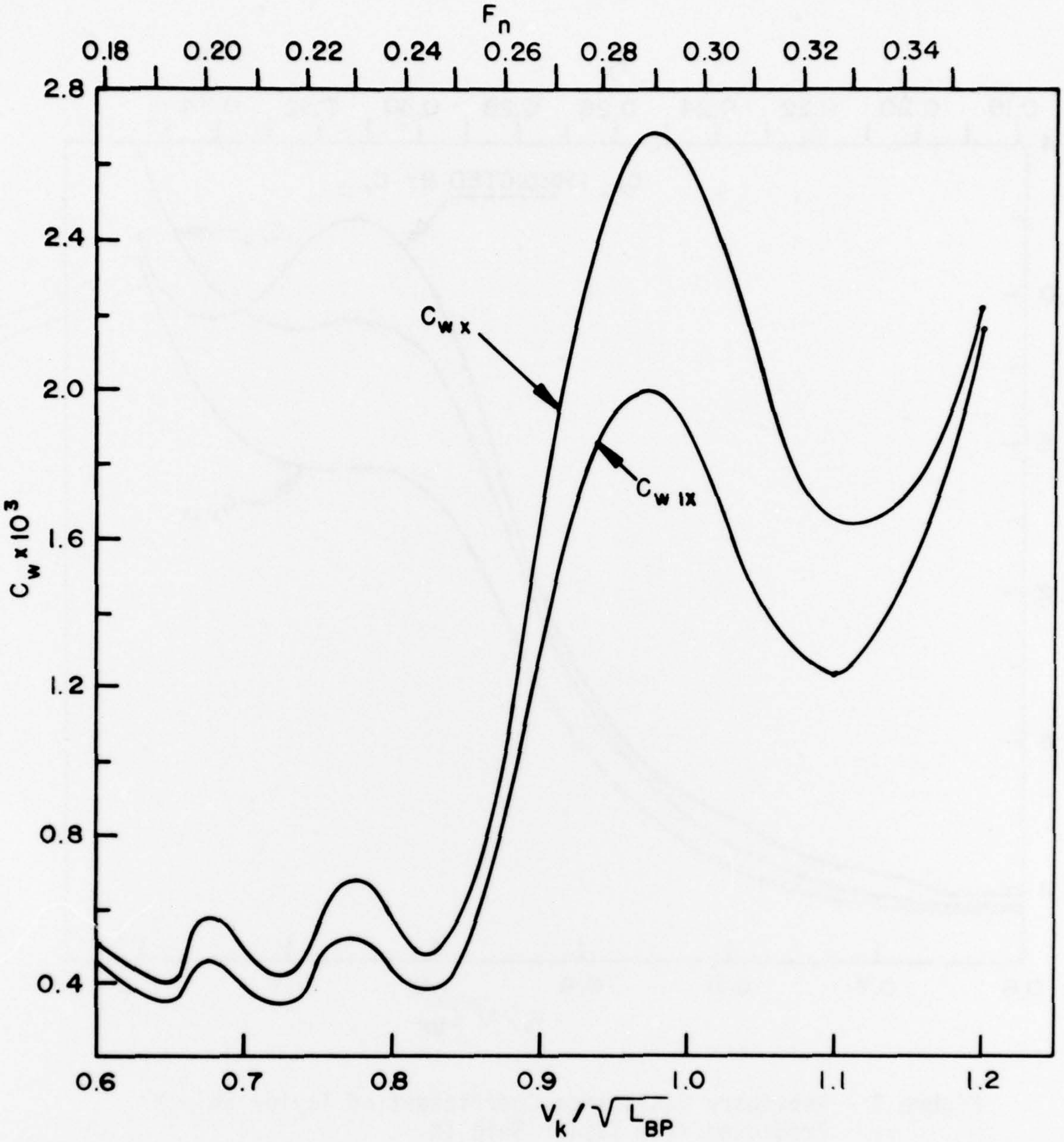

Figure 6 - Wave Resistance Coefficient for Taylor Ship IX and X

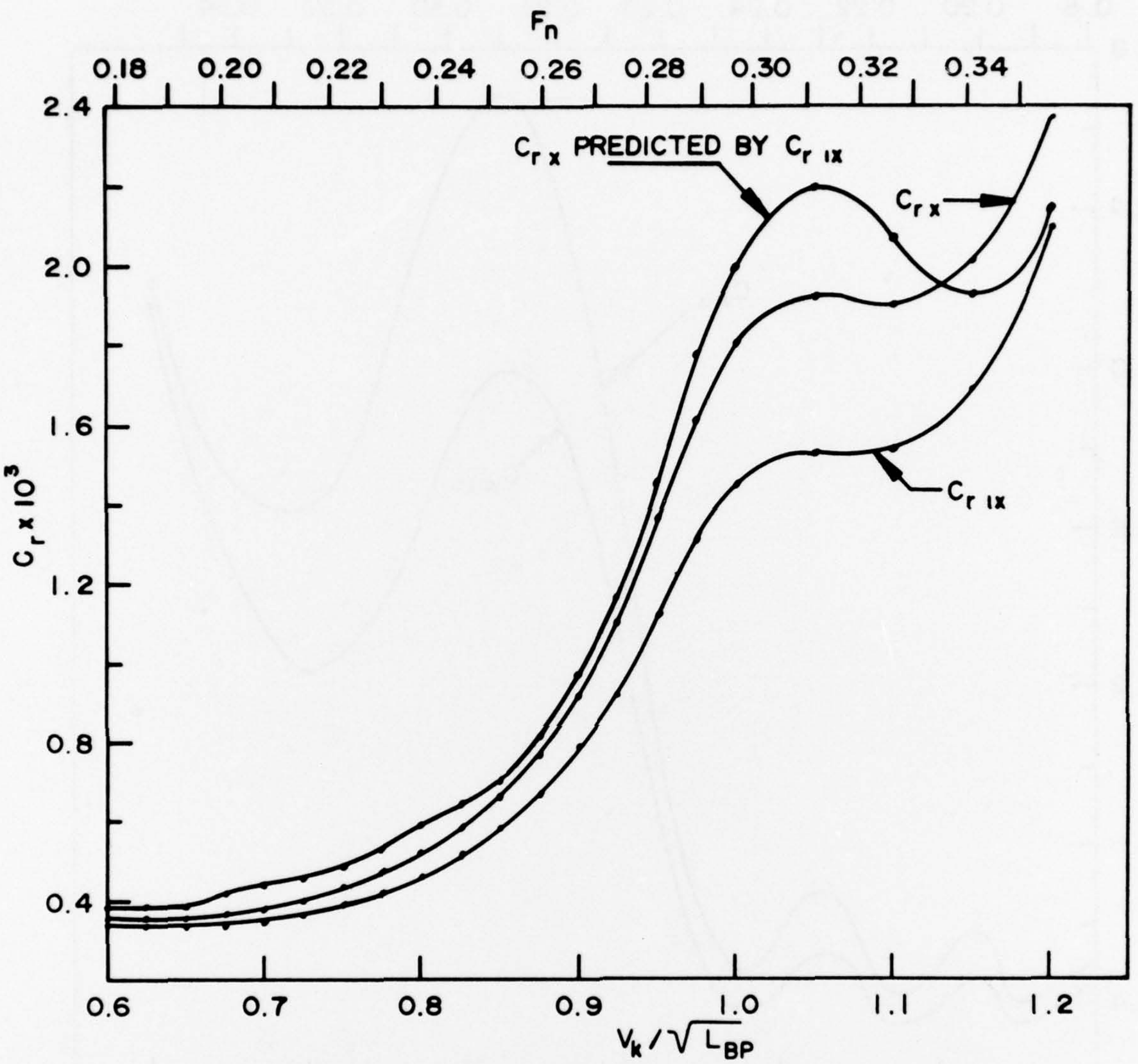

Figure 7 - Residuary Resistance Coefficient of Taylor Ship X
Predicted from Taylor Ship IX

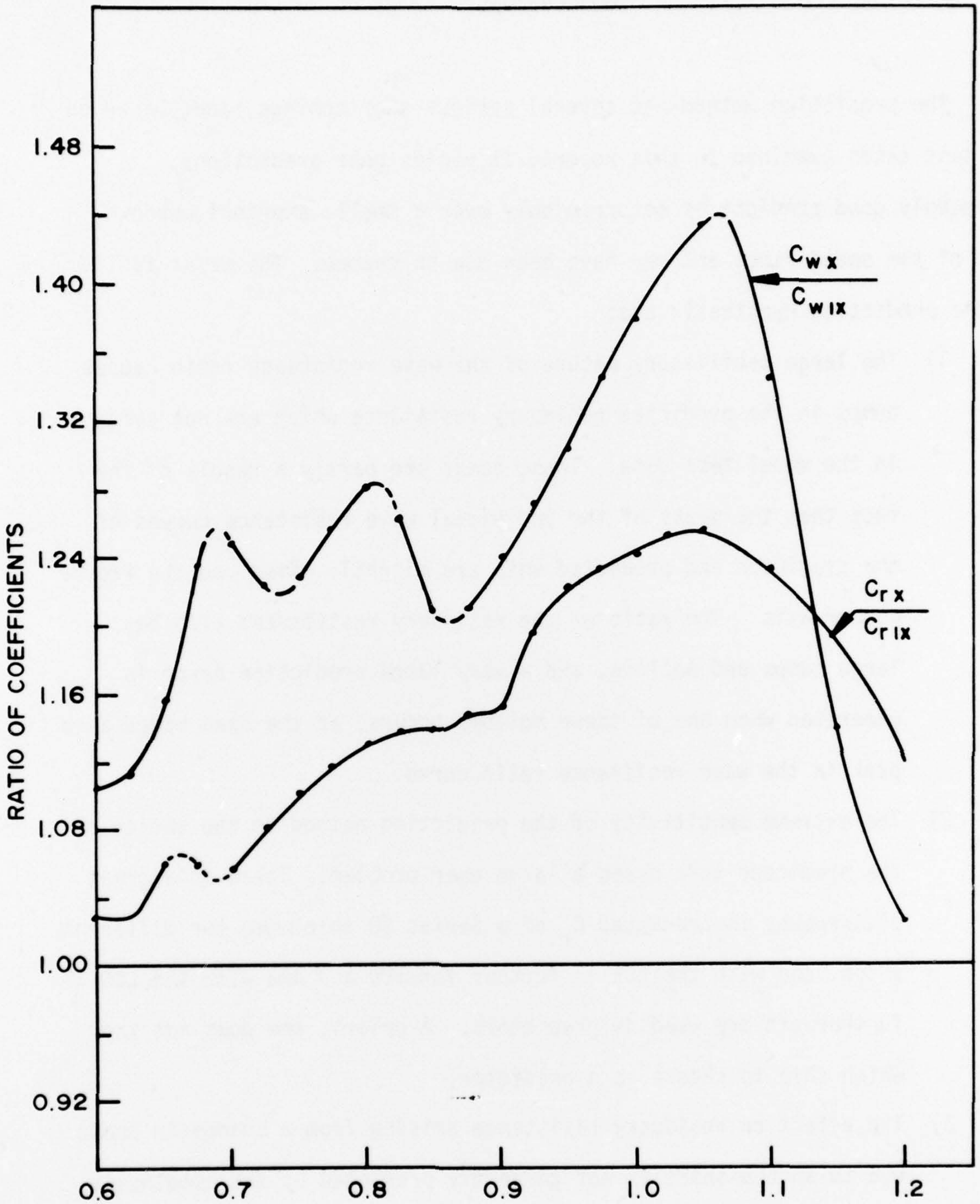

Figure 8 - Ratio of C_R's and C_W's of Taylor Ships IX and X

CONCLUSIONS

The prediction method has several serious shortcomings, and, based on the test cases examined in this report, it yields poor predictions. Reasonably good predictions occurred only over a small, a priori unknown part of the speed range and may have been due to chance. The major faults of the prediction hypothesis are;

1) The large oscillatory nature of the wave resistance ratio causes humps in the predicted residuary resistance which are not evident in the model test data. These humps are partly a result of the fact that the peaks of the individual wave resistance curves of the predictor and predicted ship are slightly offset on the Froude number axis. The ratio of the residuary resistances also has large humps and hollows, and a very large prediction error is generated when one of these hollows occurs at the same speed as a peak in the wave resistance ratio curve.
2) The extreme sensitivity of the prediction method to the choice of the predictor ship poses a large user problem. There is a great discrepancy in predicted C_r of a Series 60 ship when two different ships, one with the LCB 1% further forward and one with the LCB 1% further aft are used as predictors. A priori, one does not know which ship to choose as a predictor.
3) The effect on residuary resistance arising from a change in shape due to an LCB shift is not correctly predicted by the hypothesis.

SUGGESTIONS

The poor prediction results obtained in this report can be due to one of three causes, error in the model tests, error in the wave resistance prediction, or the invalidity of the prediction hypothesis. The magnitude and oscillatory nature of the prediction errors for both Taylor Standard Series and Series 60 test cases indicate that the primary source of error is probably not in the model test results. On the other hand, an error in the prediction hypothesis can not be checked without a 100% accurate wave resistance prediction method.

The prediction hypothesis of this report should be tested using the following two wave resistance theories in place of the Mitchel integral:

1) Low Froude number approximation - calculation by Baba and Hara, Reference 5. Compared with the Mitchel integral wave resistance, this method predicts a much smoother and more accurate wave resistance curve up to a Froude number of 0.22 for the Wigley parabolic form. Comparison of Baba's wave resistance calculation to conventional ship residuary resistance also shows good agreement and a definite attenuation of the low speed humps and hollows normally generated by the Mitchel integral.

2) Guilloton's modified thin ship theory method should be tried. The modifications involve a representation of the hull shape by a series of wedges and they are expected to better predict the effect of thickness on wave resistance. References 6, 7, and 8 provide detailed information on Guilloton's method.

In addition to trying other wave resistance prediction methods, the resistance prediction hypothesis could be modified to include additional terms on the right hand side so that the new hypothesis would have the form:

$$C_{RP} = C_{RK} \cdot \left[\frac{C_{WP}}{C_{WK}} + \text{Additional Terms} \right]$$

The mathematical formulation of the additional terms would be the subject of a future study, however it is anticipated that changes in the geometric characteristics of length, beam, draft, volume and wetted surface between the known and proposed ship would be included.

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