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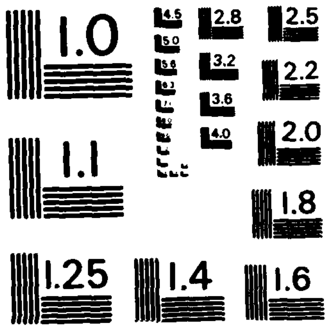

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DAVID W. TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

Bethesda, Maryland 20084

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INFLUENCE OF HULL FORM PARAMETERS
ON ROLL MOTION

by

David A. Walden

and

Paul J. Kopp

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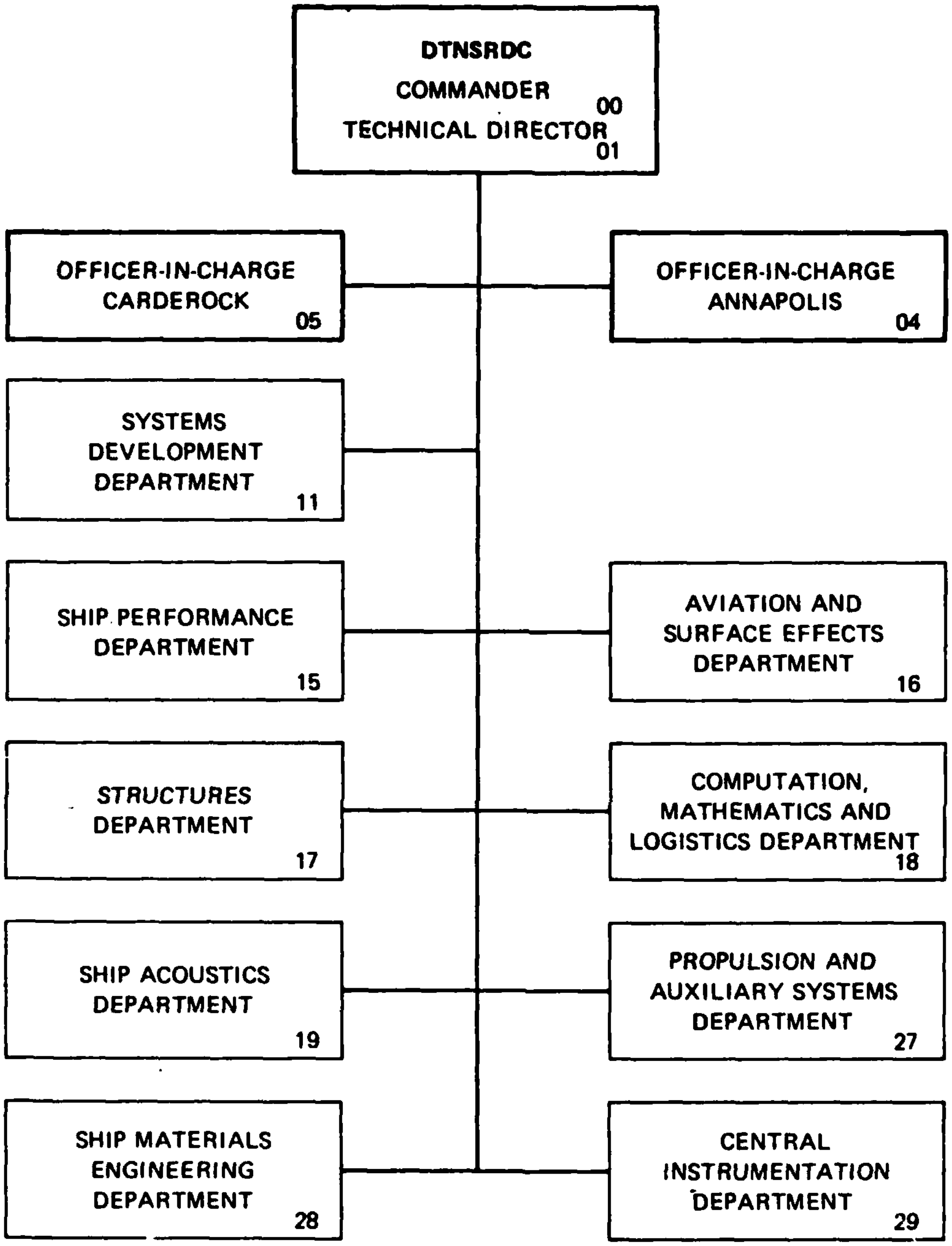

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NOTATION

L	Length between perpendiculars
B	Ship beam
C_p	Prismatic coefficient
C_w	Waterplane coefficient
C_x	Maximum section area coefficient
GM	Metacentric height
KM	Vertical location of metacenter above the baseline
LCF	Longitudinal center of floatation expressed as percentage of L aft of the forward perpendicular
p%	p statistic (expected error, see page 3)
T	Ship draft
VCG	Vertical center of gravity
Δ	Displacement

ABSTRACT

This report describes a statistical analysis of ship roll response as influenced by hull form parameters. A data base of 17 ships is described and regression analyses for the effect of hull form on roll angle are performed for three values of ship heading to wave direction and the maximum observed roll angle. Data for the ships that have antiroll fins are also presented.

ADMINISTRATIVE INFORMATION

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INTRODUCTION

The success of Bales[1*] in quantifying the relation between hull form parameters and seakeeping performance in head seas has led to great interest in extending this work to oblique seas. The most important additional motion introduced by this extension is roll. The present work describes an investigation into the feasibility of developing seakeeping performance estimates based on hull form parameters for roll motion in a manner analogous to Bales' work for head seas.

HULL FORM AND ROLL MOTION DATA BASE

In order to investigate the roll response of surface combatants, a data base of 17 ships was selected. These ships are frigates and destroyers and are a subset of ships used by Bales[1]. Seven of the 17 ships are equipped with antiroll fins and data is presented for these ships with and without antiroll fins.

The principal dimensions and hull form parameters are listed in Table 1.

ROLL MOTION ANALYSIS

Ship motion calculations were carried out using the Navy's Standard Ship Motion Program (SMP81)[2] from which tabulated values of roll angles for long-crested seas were obtained. Roll angle data for ship headings to the wave direction of

*A complete listing of references is given on page 5.

60 (bow), 90 (beam), and 120 (quartering) degrees were extracted from the SMP81 output as well as the maximum observed roll angle.* In all cases, a Bretschneider spectrum with a significant wave height of 3.5 meters and a ship speed of 30 knots was used. These are conditions in which frigates are expected to be fully operational. Table 2 contains a summary of the computed significant single amplitude roll angles.

To analyze the data, several regressions using ship characteristics and roll response were performed. These regressions were done using both multivariable stepwise and single independent variable regression methods.

In order to maintain statistical confidence in a regression with a relatively small sample size, a minimum number of independent variables should be used. To achieve this, two sets of regression calculations were performed. The first set of regressions uses a relatively large number of independent variables, while the second set of regressions use a much smaller number of variables.

Selection of the variables for the first set of regressions was based on an understanding of ship roll and previous analysis of the data used in this investigation. Ship motion theory indicates that the primary factors that determine roll response are functions of mass distribution (gyradius and the vertical center of mass), hydrodynamic damping (bilge keel area for example), and excitation force (governed by hull form, wave height and slope, and wave encounter frequency). One goal of the study was to determine if roll response could be predicted given the level of detail available at very early design stages. While vertical center of gravity and thus metacentric height is usually not available, it was decided to include metacentric height so that it would be possible to make a comparison of the regressions with and without the metacentric height included. Based on the regressions performed previously, the geometric variables that are considered to be of importance are ship length, beam, draft, prismatic coefficient, waterplane coefficient, and displacement.

The first set of regressions uses GM/B, KM/B, B/T, C_p, C_w and the squares of these variables. Additionally, displacement-length ratio and bilge keel area divided by length square are included. Table 3 shows the results of the single variable regressions for ship headings of 60, 90, and 120 degrees. Table 4 shows

*The convention used in SMP81 is 0 degrees for head seas and 180 degrees for following seas.

the same regression results for the maximum observed roll angle. Results of the multivariable regression for the first selection of variables are not given because the number of variables used in the regression was close to the number of observations, leading to statistical uncertainty in the numeric results. The order in which variables were selected in each step of the regression was, however, used to determine the relative importance of each variable, since selection order is based on the sum of the squares reduced by the addition of a variable in the regression equation.

From the first set of regression results, the coefficient of determination for the single variable regressions and the order of selection for the multivariable regressions are used to reduce the number of variables. For the cases of ship headings of 60, 90, and 120 degrees, the variables that had the highest coefficient of determination and early selection were the same: GM/B, $(KM/B)^2$, $(B/T)^2$, and C_p. Plots of these coefficients versus roll angle at the three headings can be found in Figures 1 through 4. Figure 5 shows the cumulative proportion of the sum square reduced at each step in the multiple regression for beam seas. It can be seen that when GM/B is available, it gives the largest contribution. When GM/B is not used, $(KM/B)^2$ gives the largest contribution, but the fit result is never as good as when GM/B is used. In the case of the maximum observed roll angle, a different set of variables was found to be significant, i.e., $(C_p)^2$, $\Delta/(L/100)^3$, C_w^2 and $(B/T)^2$. Figure 6 shows prismatic coefficient versus maximum expected roll angle. These two sets of variables then become the variables for the second set of regressions.

Tables 5 and 6 give the results for the second set of regressions. Table 5 gives the results for the multivariable regressions with and without GM/B for 60, 90, and 120 degree ship headings. Table 6 gives the results of the regression on the maximum observed roll angle. The coefficient of each variable in the regression equation is the slope of the regression plane in that dimension while the constant is the intercept of the regression plane with the roll angle axis. The standard deviation of the regression will give the range of error of the regression when multiplied by the square root of the number of independent variables. The p% statistic is an indication of the expected error of the standard deviation as compared to the entire population and depends on the number of variables in the regression and the sample size[3,4].

Table 7 shows the roll angles for the ships in the data base separated into groups of three GM/B ranges. The average roll angle for each range is plotted against ship heading in Figure 7. As the ship's heading goes from head to beam and then following seas, the influence of GM/B reverses. This can also be seen in the coefficients of the regression planes shown in Table 5. This agrees with trends shown by Schmitke[5].

Figures 8 and 9 show the roll reduction obtained by using antiroll fins in beam seas and for the heading of maximum roll angle. The average reduction in roll is 64 percent for beam and 66 percent for the heading of maximum roll. Since the primary factors that control roll reduction with fins are the controller system and fin size, no correlation between hull form and roll reduction was observed.

Figure 10 shows the increase in operability for a destroyer hull form due to the addition of antiroll fins. Operability in this case is defined as the percentage of the time that the ship can operate in the winter North Atlantic without exceeding 8 degrees of roll, 3 degrees of pitch, 30 deck wetnesses per hour, 20 slams per hour, and 0.4g vertical acceleration at the bridge.

CONCLUSIONS

It has been shown that the dominant influence on roll response is metacentric height. This makes the estimation of roll response at very early design stages difficult since the location of the VCG is not available. Further, it is not possible to provide guidance on parameters other than GM because change in these parameters can have positive or negative influence on roll motion depending on the value of GM. Since it has been shown in a recent investigation for the Naval Studies Board, that adequately sized antiroll fins can reduce roll to the point where it is not the limiting motion, the recommended procedure for Navy combatants is to develop hull forms to reduce pitch and heave related responses and to provide adequate fins and bilge keels to reduce roll.

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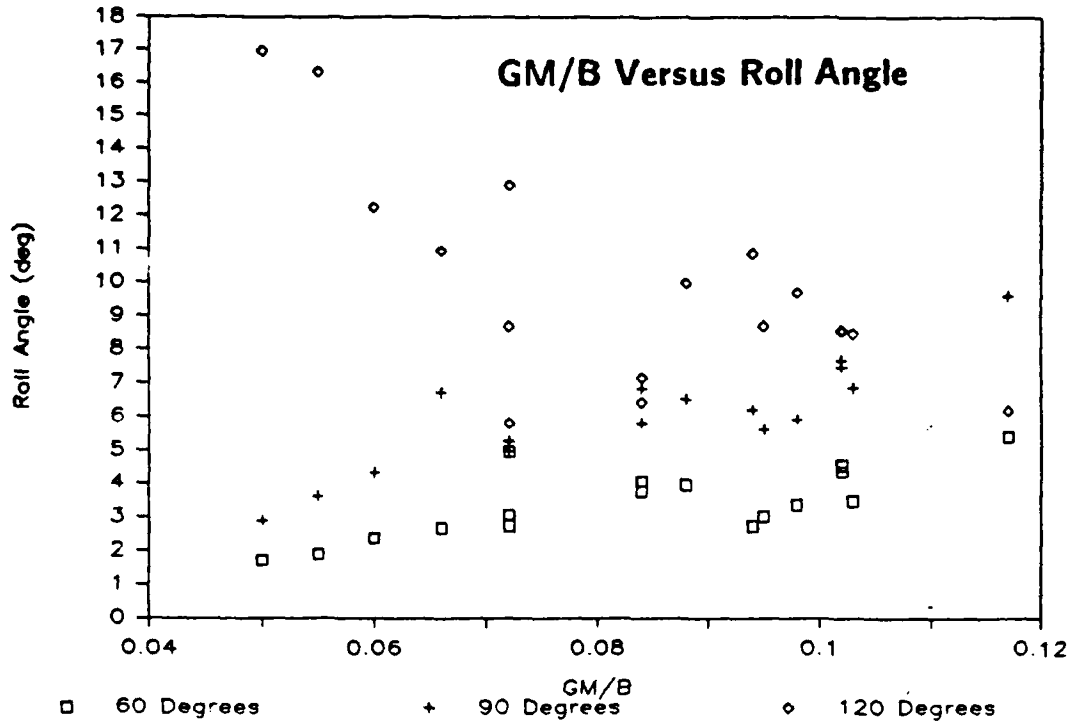

Figure 1 - GM/B versus Roll Angle

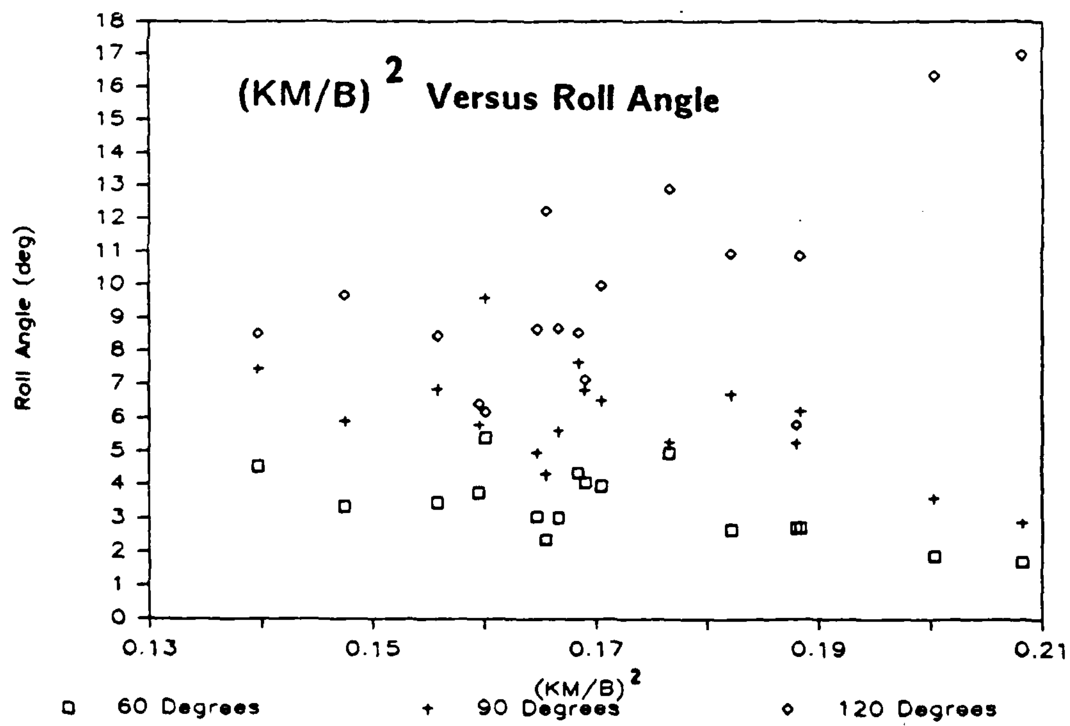

Figure 2 - $(KM/B)^2$ versus Roll Angle

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GM/B= 0.05 - 0.08

GM/B	R60	R90	R105	R120	ship #
0.050	1.71	2.89		16.98	15
0.055	1.89	3.61		16.34	16
0.060	2.38	4.33		12.25	5
0.066	2.68	6.70	21.18	10.94	12
0.072	2.74	5.25	10.54	5.79	13
0.072	4.94	5.27	36.67	12.29	4
0.072	3.06	4.97	13.70	8.67	3
average					
0.064	2.771	4.717	20.523	11.894	

GM/B= 0.08 - 0.10

GM/B	R60	R90	RMAX	R120	ship #
0.084	3.76	5.79	13.52	6.42	6
0.084	4.08	6.85	15.00	7.15	17
0.088	3.97	6.51	19.20	9.97	7
0.094	2.73	6.20	25.65	10.87	11
0.095	3.02	5.61	17.39	8.68	14
0.098	3.37	5.92	19.98	9.68	10
average					
0.091	3.488	6.147	18.457	8.795	

GM/B= 0.10 - 0.12

GM/B	R60	R90	RMAX	R120	ship #
0.102	4.36	7.66	20.67	8.56	2
0.102	4.54	7.46	24.05	8.53	8
0.103	3.49	6.86	19.95	8.46	1
0.117	5.41	9.59	14.58	6.18	9
average					
0.106	4.450	7.893	19.813	7.933	

TABLE 7 - ROLL SEPARATED BY GM/B RANGES AND HEADING

Coefficients:	
Cp^2	103.42720
Disp-L	-0.14628
Cw^2	-59.94104
(B/T)^2	-0.61700
Constant:	10.37530
Cumulative Sum of Squares Reduced:	21%
Standard Deviation:	5.63
p%	40%

TABLE 6 - MULTI-VARIABLE REGRESSION FOR MAXIMUM EXPECTED ROLL ANGLE

60 Degree Heading	GM/B Included In Regression	GM/B Not Included In Regression
Coefficients:		
GM/B	28.61994	- NA -
(KM/B)^2	-16.69558	-37.13960
(B/T)^2	-0.19731	-0.21686
Cp	-0.77042	-2.84692
Constant:	6.33871	13.70484
Cumulative Sum of Squares Reduced:	67%	53%
Standard Deviation:	0.58	0.69
p%	40%	37%

90 Degree Heading	GM/B Included In Regression	GM/B Not Included In Regression
Coefficients:		
GM/B	71.88931	- NA -
(KM/B)^2	-3.71507	-55.06761
(B/T)^2	-0.22251	-0.27163
Cp	2.76008	-2.45580
Constant:	1.12526	19.62796
Cumulative Sum of Squares Reduced:	83%	46%
Standard Deviation:	0.64	1.14
p%	40%	37%

120 Degree Heading	GM/B Included In Regression	GM/B Not Included In Regression
Coefficients:		
GM/B	-76.95155	- NA -
(KM/B)^2	65.04913	120.01780
(B/T)^2	0.57719	0.62976
Cp	-2.28124	3.30193
Constant:	0.83420	-18.97141
Cumulative Sum of Squares Reduced:	63%	53%
Standard Deviation:	1.90	2.15
p%	40%	37%

TABLE 5 – MULTI-VARIABLE REGRESSIONS FOR 60, 90 AND 120 DEGREE HEADINGS

Maximum Expected Roll Angle	Roll	GM/B	(GM/B)^2	KM/B	(KM/B)^2	B/T	(B/T)^2	AREA/L^2	DISP-L	Cp	Cp^2	Cw	Cw^2
minimum	10.54	0.0498	0.0025	0.3738	0.1397	2.5605	6.5560	0.0066	50.9415	0.5800	0.3364	0.7130	0.5084
maximum	36.67	0.1172	0.0137	0.4563	0.2082	3.7318	13.9261	0.0138	77.7691	0.6700	0.4489	0.8150	0.6642
average	18.67	0.0833	0.0073	0.4133	0.1712	3.1445	9.9713	0.0108	63.0614	0.6194	0.3844	0.7585	0.5761
intercept		14.7046	16.8421	22.5628	20.5448	32.8230	26.0233	14.0995	4.2007	-34.1712	-7.2758	-17.3188	0.8417
slope		47.5585	250.7170	-9.4276	-10.9692	-4.5021	-0.7378	421.4876	0.2294	85.3030	67.4908	47.4445	30.9389
variance of x		0.0004	0.00001	0.0005	0.0003	0.0891	3.5172	0.000003	60.1752	0.0008	0.0012	0.0009	0.0021
variance of y	38.60												
var of regression		40.1309	40.3470	40.9727	40.9754	39.0975	38.9820	40.4372	37.6518	35.1722	35.1934	38.8394	38.8459
correlation coeff		0.1469	0.1277	-0.0326	-0.0315	-0.2163	-0.2227	0.1188	0.2864	0.3775	0.3768	0.2304	0.2300
coef of determination		0.0216	0.0163	0.0011	0.0010	0.0468	0.0496	0.0141	0.0820	0.1425	0.1420	0.0531	0.0529

TABLE 4 - LINEAR REGRESSIONS OF A SINGLE INDEPENDENT VARIABLE ON MAXIMUM EXPECTED ROLL ANGLE

	Roll	GM/B	(GM/B)^2	KM/B	(KM/B)^2	B/T	(B/T)^2	AREA/L^2	DISP-L	Cp	Cp^2	Cw	Cw^2
60 Degreeg Heading													
minimum	1.71	0.0498	0.0025	0.3738	0.1397	2.5605	6.5560	0.0066	50.9415	0.5800	0.3364	0.7130	0.5084
maximum	5.41	0.1172	0.0137	0.4563	0.2082	3.7318	13.9261	0.0138	77.7691	0.6700	0.4489	0.8150	0.6642
average	3.42	0.0833	0.0073	0.4133	0.1712	3.1445	9.9713	0.0108	63.0614	0.6194	0.3844	0.7585	0.5761
intercept		0.1591	1.7239	15.8288	9.6799	6.4341	5.0527	3.5759	3.1384	8.4696	5.8005	6.8875	5.1646
slope		39.1361	233.0150	-30.0261	-36.5609	-0.9587	-0.1638	-14.4390	0.0045	-8.1532	-6.1946	-4.5725	-3.0291
variance of x		0.0004	0.00001	0.0005	0.0003	0.0891	3.5172	0.000003	60.1752	0.0008	0.0012	0.0009	0.0021
variance of y	1.09												
var of regression		0.5555	0.5769	0.7139	0.7018	1.0679	1.0547	1.1543	1.1537	1.1015	1.1059	1.1347	1.1341
correlation coeff		0.7204	0.7074	-0.6179	-0.6263	-0.2745	-0.2946	-0.0243	0.0332	-0.2150	-0.2061	-0.1323	-0.1342
coef of determination		0.5190	0.5005	0.3818	0.3923	0.0753	0.0868	0.0006	0.0011	0.0462	0.0425	0.0175	0.0180
90 Degree Heading													
minimum	2.89	0.0498	0.0025	0.3738	0.1397	2.5605	6.5560	0.0066	50.9415	0.5800	0.3364	0.7130	0.5084
maximum	9.59	0.1172	0.0137	0.4563	0.2082	3.7318	13.9261	0.0138	77.7691	0.6700	0.4489	0.8150	0.6642
average	5.97	0.0833	·0.0073	0.4133	0.1712	3.1445	9.9713	0.0108	63.0614	0.6194	0.3844	0.7585	0.5761
intercept		-0.0250	2.7980	24.1393	15.1473	9.7446	7.9828	5.9106	7.2281	13.0987	9.3815	8.8877	7.4794
slope		71.9496	435.7637	-43.9655	-53.6017	-1.2008	-0.2020	5.3731	-0.0200	-11.5107	-8.8783	-3.8484	-2.6220
variance of x		0.0004	0.00001	0.0005	0.0003	0.0891	3.5172	0.000003	60.1752	0.0008	0.0012	0.0009	0.0021
variance of y	2.53												
var of regression		0.6662	0.6708	1.7468	1.7184	2.5558	2.5399	2.6922	2.6668	2.5859	2.5915	2.6780	2.6767
correlation coeff		0.8675	0.8665	-0.5926	-0.6014	-0.2252	-0.2380	0.0059	-0.0973	-0.1988	-0.1935	-0.0729	-0.0761
coef of determination		0.7526	0.7508	0.3512	0.3617	0.0507	0.0566	.0000	0.0095	0.0395	0.0374	0.0053	0.0058
120 Degree Heading													
minimum	5.79	0.0498	0.0025	0.3738	0.1397	2.5605	6.5560	0.0066	50.9415	0.5800	0.3364	0.7130	0.5084
maximum	16.98	0.1172	0.0137	0.4563	0.2082	3.7318	13.9261	0.0138	77.7691	0.6700	0.4489	0.8150	0.6642
average	9.90	0.0833	0.0073	0.4133	0.1712	3.1445	9.9713	0.0108	63.0614	0.6194	0.3844	0.7585	0.5761
intercept		19.5612	14.6844	-28.8765	-9.7912	0.5111	5.0343	5.3751	3.6621	-3.8082	3.4749	-3.3072	3.4502
slope		-115.916	-656.876	93.8357	115.0225	2.9874	0.4884	418.0454	0.0990	22.1386	16.7276	17.4192	11.2033
variance of x		0.0004	0.00001	0.0005	0.0003	0.0891	3.5172	0.000003	60.1752	0.0008	0.0012	0.0009	0.0021
variance of y	10.46												
var of regression		5.8525	6.5180	6.8045	6.6269	10.2666	10.2199	10.5418	10.4848	10.7178	10.7537	10.8180	10.8268
correlation coeff		-0.6880	-0.6430	0.6226	0.6353	0.2757	0.2833	0.2264	0.2375	0.1882	0.1794	0.1625	0.1600
coef of determination		0.4733	0.4134	0.3876	0.4036	0.0760	0.0802	0.0513	0.0564	0.0354	0.0322	0.0264	0.0256

TABLE 3 - LINEAR REGRESSIONS OF A SINGLE INDEPENDENT VARIABLE ON ROLL ANGLE AT 60, 90, AND 120 DEGREE HEADINGS

Ship Number	Maximum Roll	Heading at Max	60 Degree Heading	90 Degree Heading	120 Degree heading	Maximum Roll With Fins	90 Degree Heading With Fins
1	19.95	105	3.49	6.86	8.46	6.05	3.49
2	20.67	105	4.36	7.66	8.56	9.77	3.51
3	13.70	105	3.06	4.97	8.67	6.41	1.18
4	36.67	105	4.94	5.27	12.90	5.06	0.77
5	12.25	120	2.38	4.33	12.25	7.58	1.67
6	13.52	105	3.76	5.79	6.42		
7	19.20	105	3.97	6.51	9.97		
8	24.05	105	4.54	7.46	8.53		
9	14.58	105	5.41	9.59	6.18		
10	19.98	105	3.37	5.92	9.68	5.74	1.86
11	25.65	105	2.73	6.20	10.87	5.30	1.86
12	21.18	105	2.68	6.70	10.94		
13	10.54	105	2.74	5.25	5.79		
14	17.39	105	3.02	5.61	8.69		
15	16.98	120	1.71	2.89	16.98		
16	16.34	120	1.89	3.61	16.34		
17	15.00	105	4.08	6.85	7.15		
average	18.67		3.42	5.97	9.90		
minimum	10.54		1.71	2.89	5.79		
maximum	36.67		5.41	9.59	16.98		

TABLE 2 - SIGNIFICANT SINGLE AMPLITUDE ROLL ANGLE

Ship Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
L (m)	106.38	131.00	109.73	109.73	119.48	161.24	124.36	126.49	93.88	121.77	106.00	105.00	128.00	142.50	124.00	121.31	108.51
B (m)	13.30	14.79	13.11	12.73	14.33	16.70	13.78	14.26	10.92	14.40	11.98	11.01	13.33	15.29	13.85	15.24	12.80
T (m)	3.78	4.62	4.14	4.51	3.84	5.97	4.52	4.72	3.43	4.27	3.75	4.30	4.80	4.50	4.05	4.75	4.22
Disp (cu. m)	2884	4352	2939	3502	3645	8004	3596	4257	1778	3606	2385	2761	4684	5024	3567	4710	2938
Cw	0.75	0.75	0.72	0.80	0.75	0.74	0.73	0.74	0.77	0.71	0.78	0.81	0.82	0.75	0.75	0.79	0.75
Cx	0.78	0.78	0.80	0.81	0.87	0.84	0.75	0.81	0.83	0.78	0.77	0.80	0.83	0.81	0.82	0.84	0.80
Cp	0.63	0.61	0.60	0.67	0.62	0.58	0.60	0.60	0.59	0.60	0.63	0.67	0.67	0.62	0.61	0.62	0.61
LCF (% L)	0.58	0.55	0.57	0.58	0.54	0.58	0.55	0.57	0.57	0.57	0.59	0.55	0.55	0.55	0.55	0.58	0.56
BK AREA (sq. m)	119	158	116	119	94	267	191	189	110	188	137	105	174	208	212	182	118
AREA/L	1.12	1.21	1.06	1.08	0.79	1.66	1.54	1.49	1.17	1.54	1.29	1.00	1.36	1.46	1.71	1.50	1.09
GM (m)	1.37	1.51	0.94	0.92	0.86	1.41	1.21	1.46	1.28	1.41	1.13	0.73	0.96	1.46	0.69	0.84	1.08
GM/B	0.103	0.102	0.072	0.072	0.060	0.084	0.088	0.102	0.117	0.098	0.094	0.066	0.072	0.095	0.050	0.055	0.084
KG (m)	5.25	6.07	5.32	5.35	5.83	6.67	5.69	5.33	4.37	5.53	5.20	4.70	5.78	6.24	6.32	6.82	5.26
KM/B	0.395	0.410	0.406	0.420	0.407	0.399	0.413	0.374	0.400	0.384	0.434	0.427	0.434	0.408	0.456	0.448	0.411
L/B	8.00	8.86	8.37	8.62	8.34	9.66	9.02	8.87	8.60	8.46	8.85	9.54	9.60	9.32	8.95	7.96	8.48
B/T	3.52	3.20	3.17	2.82	3.73	2.80	3.05	3.02	3.18	3.37	3.19	2.56	2.78	3.40	3.42	3.21	3.03

TABLE 1 - HULL FORM CHARACTERISTICS

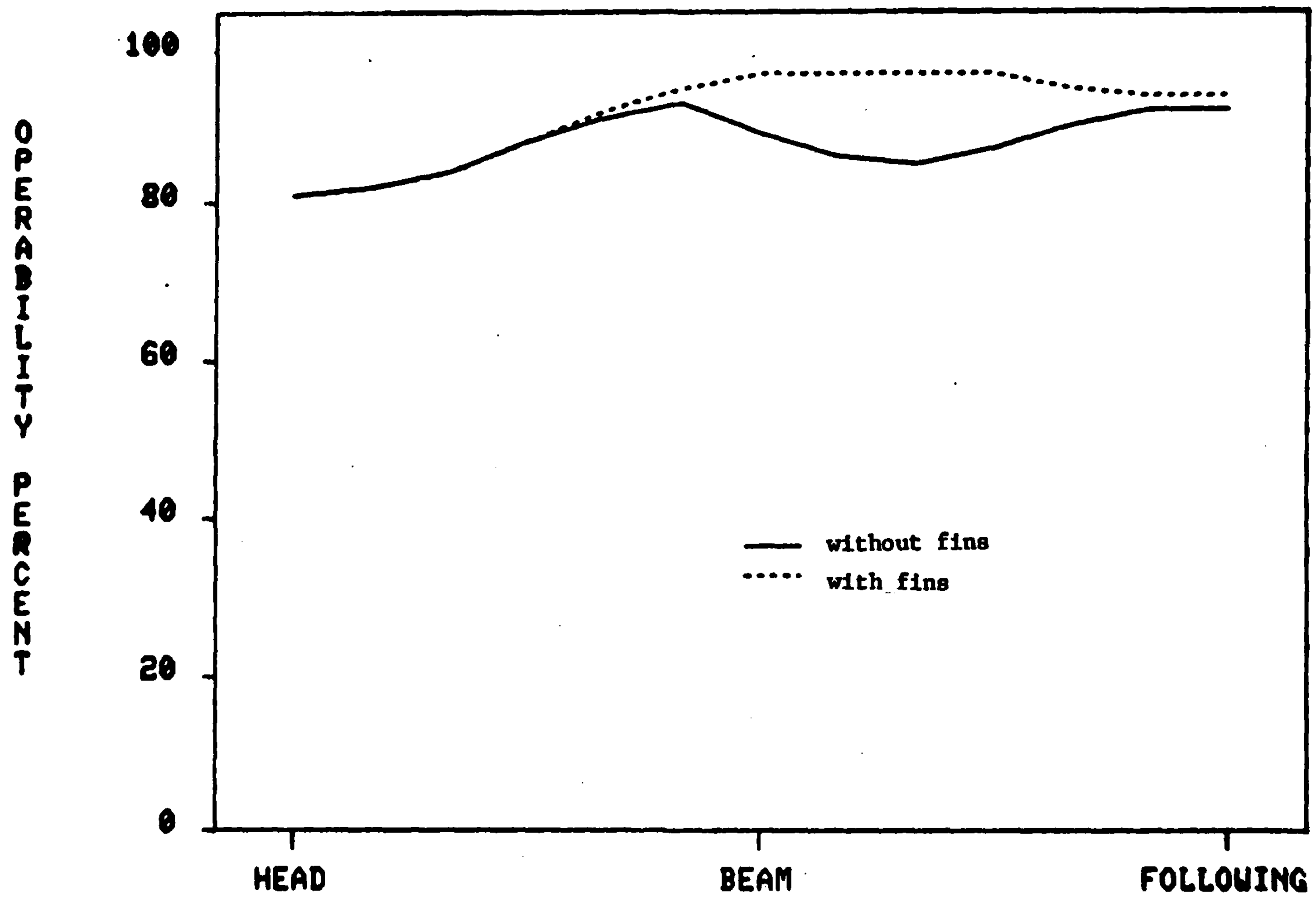

Figure 10 - Operability With and Without Anti-Roll Fins on a Destroyer Hull Form

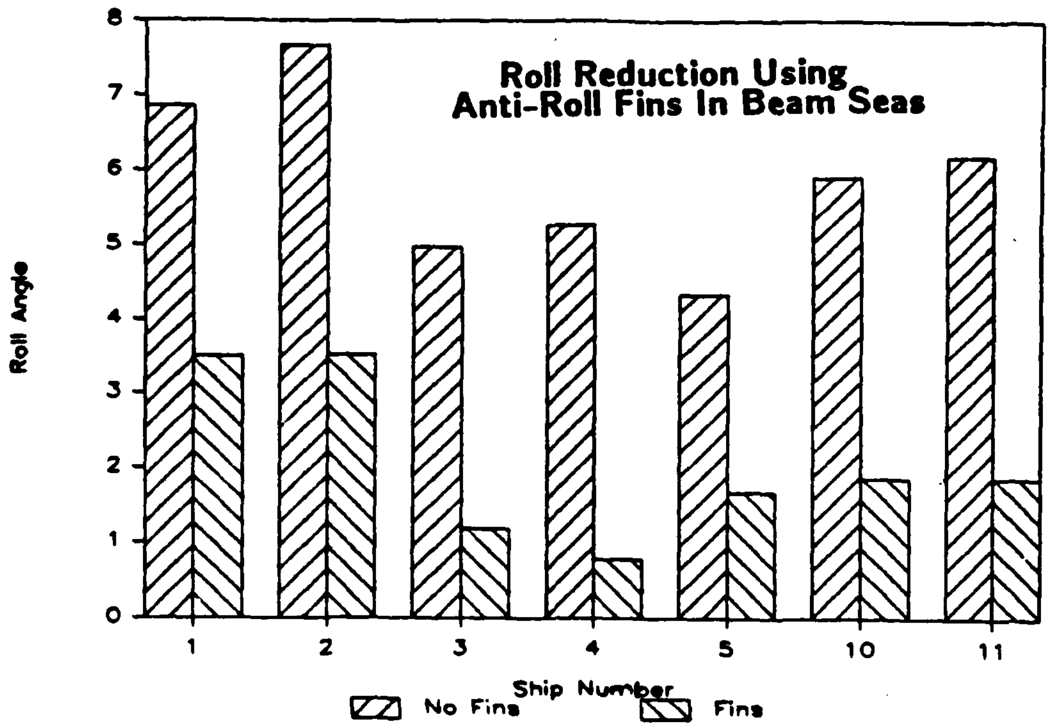

Figure 8 - Roll Reducting Using Anti-Roll Fins in Beam Seas

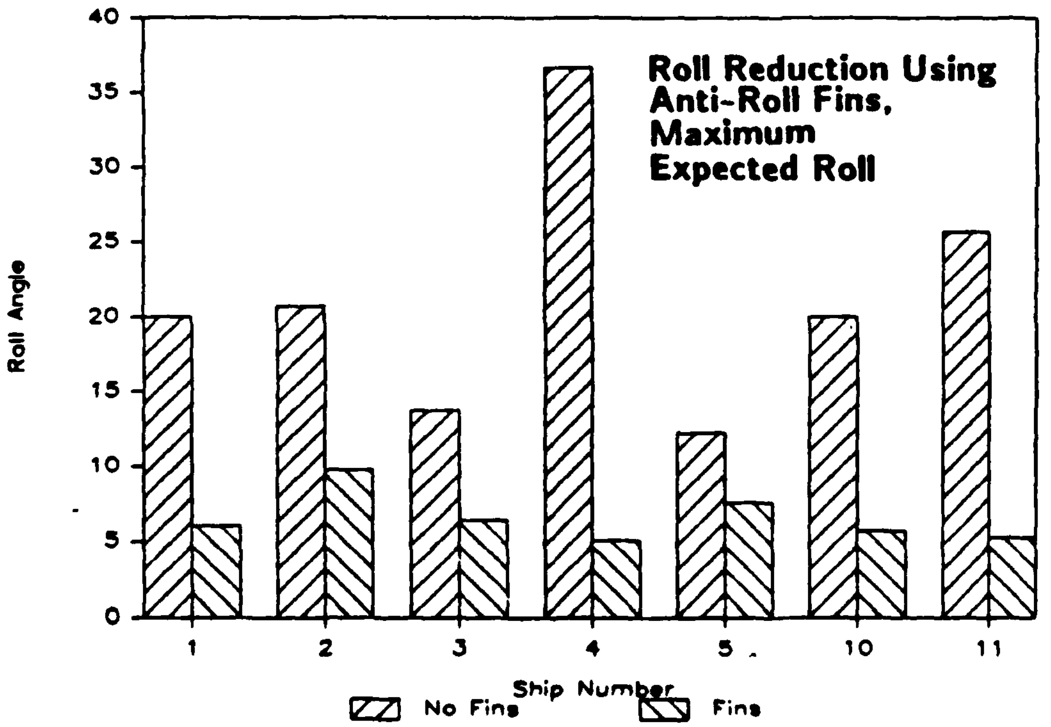

Figure 9 - Roll Reduction Using Anti-Roll Fins, Maximum Expected Roll

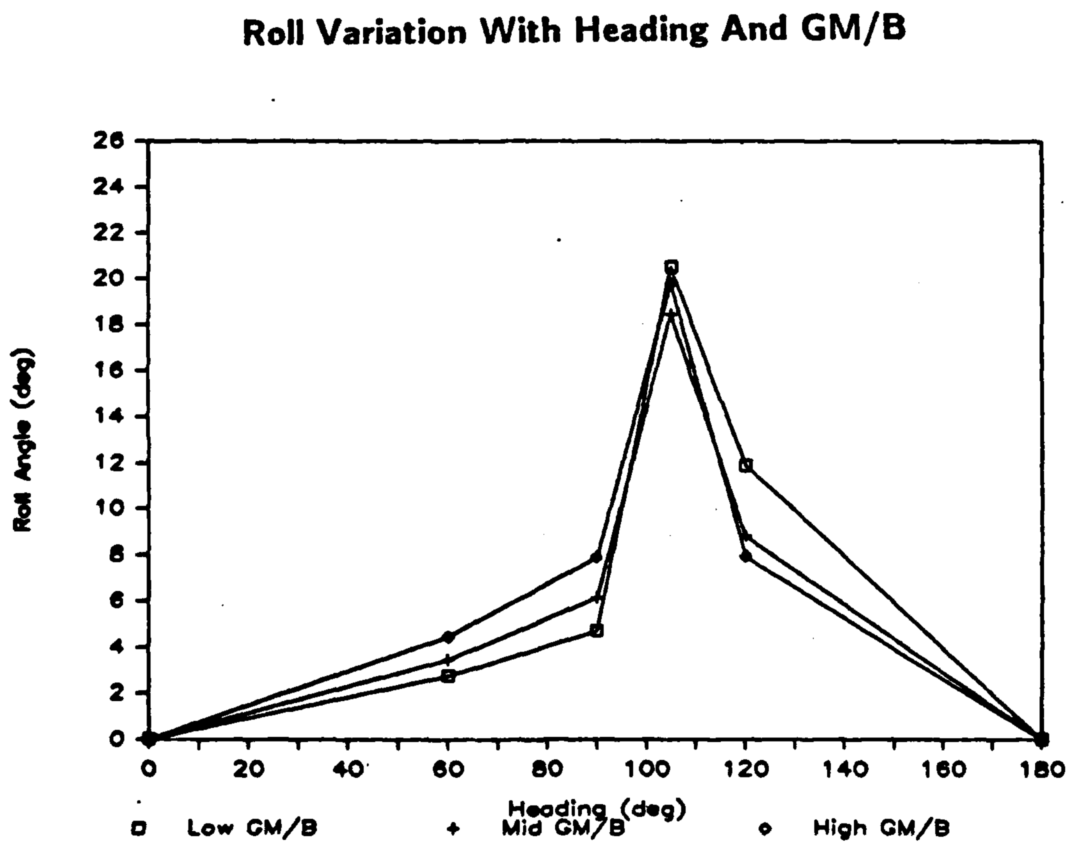

Figure 7 - Roll Variation with Heading and GM/B

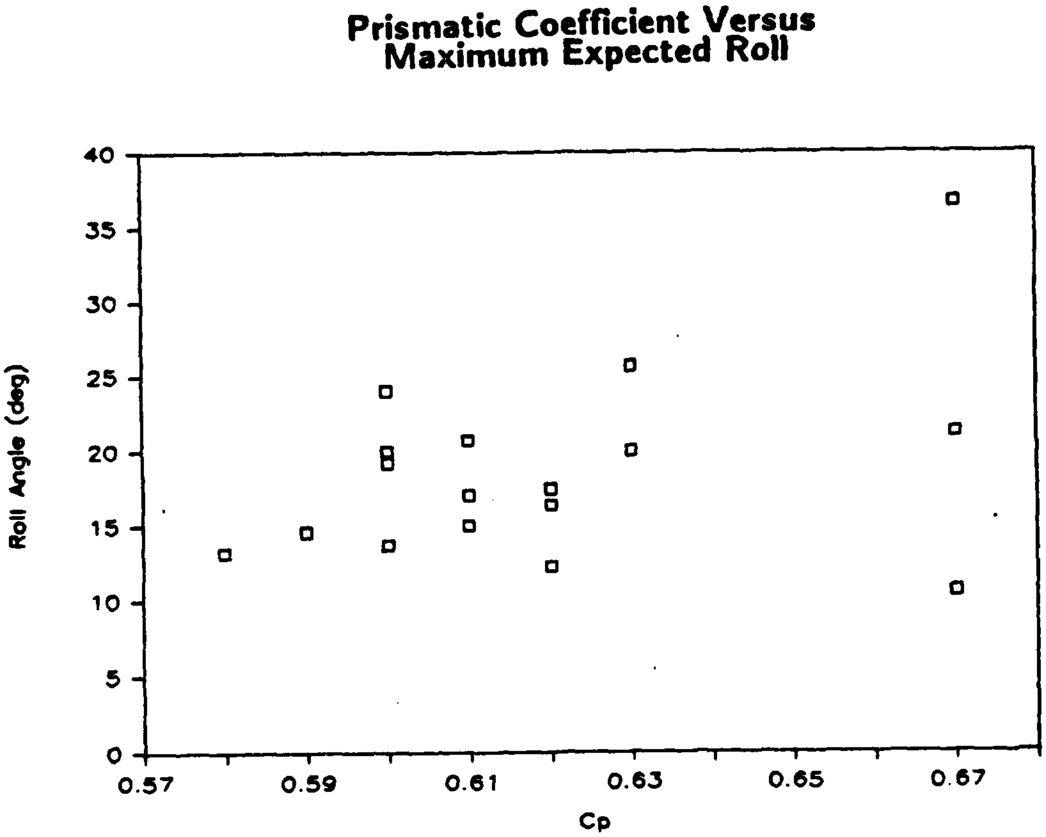

Figure 6 - Prismatic Coefficient versus Maximum Expected Roll

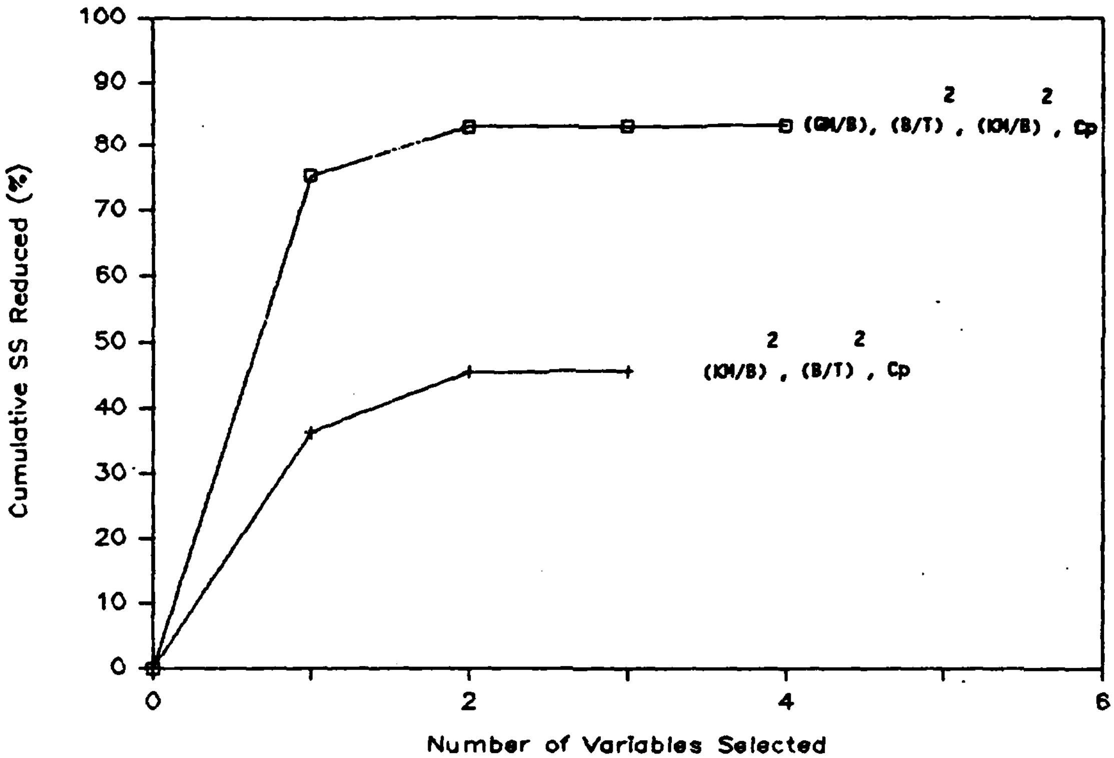

Figure 5 - Summary of Stepwise Regression for Beam Seas

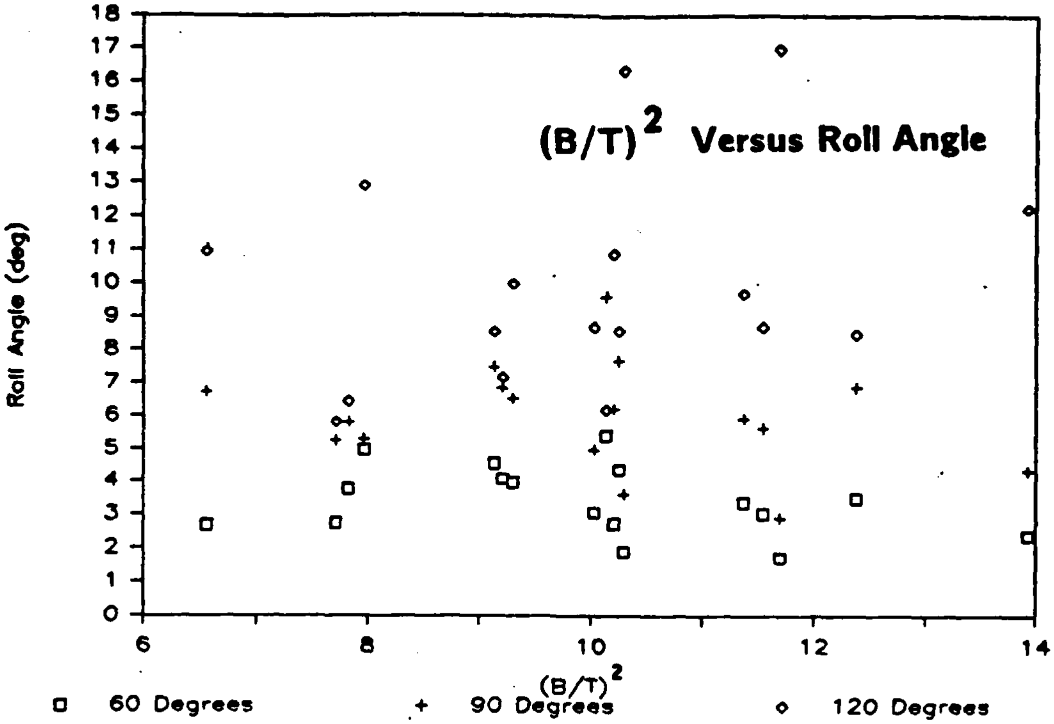

Figure 3 - $(B/T)^2$ versus Roll Angle

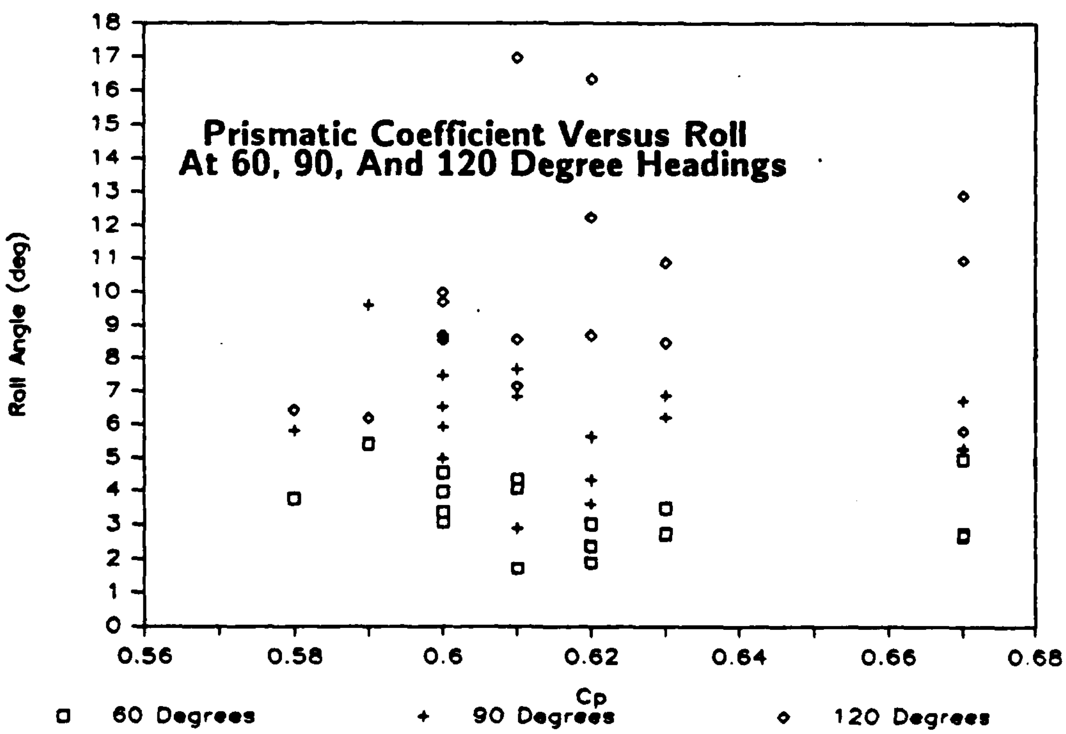

Figure 4 - Prismatic Coefficient versus Roll at 60, 90, and 120 Degree Headings

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