SEAKEEPING STANDARD SERIES FOR OBLIQUE SEAS

(A SYNOPSIS)

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Abstract - The seakeeping performance in oblique seas for a series of 72 cruiser-stern hull forms has been evaluated analytically and is presented in a systematic way. The hull form series have been created by Loukakis and Chryssostomidis (1975) by extending the principal characteristics of the Series 60 to cover usual shipbuilding practice. In that work, however, only the seakeeping performance in head seas was presented. Recently, the seakeeping performance of the Extended Series 60 was re-evaluated for both head seas and oblique seas. The complete results are presented in tabular and graphical form as a function of the principal characteristics of the ship, the Froude number (including Fn=0, missing in the original series), the non-dimensional modal wave period and the heading angle in a separate NTUA report (Grigoropoulos et al, 1994). In the present paper, the results for one case are given in tabular form accompanied by graphical representation. They include: heave, pitch, bending moment amidships, added resistance, absolute vertical acceleration and relative vertical motion at the bow and the stern regions and relative vertical velocity at stations 2 and 4 where slamming is likely to occur.

Keywords : seakeeping responses, Seakeeping Standard Series, Series 60, oblique seas, strip theory, vertical ship motions, added resistance in waves

NOMENCLATURE

A = wave amplitude

B = beam

C_B = block coefficient

Fn = Froude number, $Fn = V_S / \sqrt{gL_{WL}}$

g = acceleration of gravity, 9.81 m/sec^2

$H_{1/3}$ = significant wave height, in [m]

K_{yy} = longitudinal radius of gyration about LCG

K_{yy}' = longitudinal radius of gyration of the forward part of the ship about LCG_F

L, L_{BP} = length between perpendiculars

L_{WL} = length on design waterline, for the Extended Series 60 $L_{BP} = 0.983\ L_{WL}$

LCB = longitudinal position of centre of buoyancy

LCF = longitudinal position of centre of flotation

LCG = longitudinal position of centre of gravity

LCG_F = distance of the centre of gravity of the forebody from amidships

RAO = Response Amplitude Operator

RMS = Root-Mean-Square value

RM = amplitude of relative bow motion

SSS = Seakeeping Standard Series

t = thrust deduction factor

T = draft

T_P = modal period

T_P' = non-dimensional modal period, $T_P' = T_P / \sqrt{L/g}$

V_S = ship speed

W_F = weight of forward part of ship

W_T = total weight of ship

β = heading angle, β=180° corresponds to head seas

θ = pitch amplitude

κ = wave number

λ = wave length

μ_V = RAO of bending moment, $\mu_V = \dfrac{\text{Bending Moment Amplitude}}{\rho g A B L^2}$

ρ = specific density of sea water

σ_{aw} = RAO of added resistance, $\sigma_{aw} = \dfrac{\text{Mean Added Resistance}}{\rho g A^2 (B^2/L)}$

ω = circular frequency

1. INTRODUCTION

The seakeeping performance of a ship can either be predicted using computer codes or measured in a seakeeping basin. However, during a feasibility study or in the preliminary ship design phase, the hull lines of the vessel are not yet available and hence, neither of the aforementioned methods is applicable. In an attempt to assist the naval architect in predicting the seakeeping behaviour in such cases, Loukakis and Chryssostomidis (1975) presented the Seakeeping Standard Series (SSS) for cruiser-stern ships. In that work the authors extended the principal characteristics of the Series 60 to cover the usual shipbuilding practice and they computed the seakeeping performance of the resulting series analytically. Thus, they generated a set of tables containing the motion characteristics in head seas of 72 Extended Series 60 hull forms. The information was given for a systematic variation of the principal ship geometric parameters i.e. block coefficient C_B, length-to-beam ratio L/B and beam-to-draft ratio B/T. The results were presented in tabular form for various fully developed seas, expressed in terms of significant wave height to length ratio $H_{1/3}/L_{BP}$ and ship speed V_S, expressed as non-dimensional Froude number $Fn = V_S / \sqrt{gL_{WL}}$, where L_{WL} is the length of the vessel at the design waterline.

Since their presentation, the series have been extensively used in naval architecture practice as well as a teaching tool. The usefulness of the series has been appreciated, especially in studies on the effect of hull form parameters on the seakeeping behaviour of ships. In this respect, the papers of Beukelman and Huijser (1977), Schmitke and Murdey (1980), Lee (1983), Pawlowski (1983), Loukakis et al (1983), Grigoropoulos and Loukakis (1988. 1990) and Wilson (1985) should be mentioned. Furthermore, Bhattacharyya (1978) included the series in his book on the dynamics of marine vehicles.

Recently, Townsin et al (1994) recognized the significance of the series and underlined their two strong points, the wide range of hull forms and the number of the seakeeping responses calculated. However, it was pointed out that, the seakeeping performance of the 72 hull forms from the Extended Series 60 has been evaluated analytically only for head seas, while the $H_{1/3}/L_{BP}$ ratio range used, starting from $H_{1/3}/L_{BP} = 0.015$, corresponds to only relatively high sea states for the longer ships of today.

The aforementioned shortcomings of the series have also been noticed by the authors of the original paper. The inconvenient selection of the $H_{1/3}/L_{BP}$ ratios is closely connected to the use of single-parameter modelling of the sea state (fully developed seas), while the two-parameter spectral models are better representations of the actual sea conditions. Since the series refer to vertical motions only, which are linear with respect to the wave height, or to added resistance, which is proportional to the square of the wave height, these shortcomings could be remedied by appropriate scaling of the $H_{1/3}$ for the same modal period T_P. However, it would be more convenient if the results were presented for a range of modal periods and for unity significant wave height.

In addition, the absence of the zero-speed responses from the seakeeping tables, prevented the use of the series in some applications e.g. the design of stationary ship-factories or storage ships. Finally, scant usable information exists in the literature for ship responses in oblique seas, although such knowledge can be useful for ship routing and seakeeping operability studies.

With the above in mind, it was decided to re-evaluate the seakeeping performance of the Extended Series 60 for all headings, using the same seakeeping responses as the initial paper and including a wider range of non-dimensional sea states as well as zero-speed responses. The strip theory of Salvesen, Tuck and Faltinsen (1970) has again been used for the estimation of the ship motions and bending moments. The energy method of Gerritsma and Beukelman (1972), as extended by Loukakis and Sclavounos (1978), has been used for the prediction of added resistance in head to beam seas.

The usage of the same theories for analytical predictions after some twenty three years, underlines the remarkable fact that the simple strip theory continues to give results useful for practical purposes in an efficient computationally manner and it has not been superseded by newer three-dimensional theories, except for the zero-speed case. In this respect, it is interesting to note that in two recent International Conferences on Ship and High Speed Craft Motions & Manoeuvrability, no less than 8 authors were using strip theory for predictions in the absence of other tools, even at very high Fns! For a review of seakeeping theories and their applicability one can refer to Odabasi and Hearn (1977), Hearn and Donati (1980) and to the reports of the Seakeeping Committee of ITTC (1978, 1984, 1993), where the usefulness of strip theory is generally recognized, at least for cruiser stern ships sailing at zero to moderate speeds.

In order to demonstrate the applicability of strip theory to oblique ship responses, the analytical results in regular waves have been compared to the experimental results conducted a long time ago at Wageningen (Vossers et al, 1960 and 1961). Figures 1, 2, 3 and 4 show that for a L_{BP} =120 m, C_B = 0.7, L/B = 7, B/T = 3.0 Series 60 hull form, the predictions for pitching motion, relative bow motion, bending moment and added resistance can be used in practice, with the bending moment and the added resistance results being the weaker predictions (in the case of added resistance, the measured added thrust is approximately converted to added resistance using the measured thrust deduction factor in calm water, t = 0.184). Furthermore, the analytically estimated bow acceleration and added resistance responses in regular waves, for the S-175 containership proposed by the I.T.T.C. for comparison studies, are shown in Figures 5 and 6 with the respective experimental results conducted in the towing tank of the Laboratory for Ship and Marine Hydrodynamics at NTUA (Grekoussis et al, 1986).

The SSS in oblique seas contain, in tabular form and as a function of the principal characteristics of the ship, the Froude number, the non-dimensional modal wave period and the heading angle, the results of the aforementioned computations, Table 1. Due to obvious space limitations, the seakeeping responses for only one case could be accommodated in the present paper in tabular form, accompanied by graphical representation. The complete results, for all 72 cases, are available in a separate technical report accompanied by a PC floppy disk (Grigoropoulos et al, 1994). The results of the Seakeeping Tables can be interpolated for the prediction of the seakeeping performance of cruiser-stern ships not necessarily with Series 60 hull forms.

Finally, it should be noted that only vertical responses have been considered in the seakeeping tables. The lateral ship responses, are highly dependent on the non-linear behaviour of rolling motion, where roll damping is mostly induced by bilge keels, active fins and other anti-rolling devices.

2. CONTENTS OF THE SEAKEEPING TABLES

The seakeeping performance of the 72 Extended Series 60 hull forms has been calculated for all headings and for the same seakeeping responses as the initial paper, that is : heave, pitch, wave bending moment amidships, added resistance, absolute vertical acceleration at stations 2, 4 and 20, relative vertical motion at stations 2, 4 and 20 and relative vertical velocity at stations 2 and 4.

The acceleration and the relative motion have been calculated at three points along the ship, the AP (station 20), 20% aft of FP (station 4) and 10% aft of FP (station 2), while the relative velocity has been computed at the latter two points in the bow region. The above points for the calculation of the relative motions and velocities have been selected so that the random events (propeller emergence, deck wetness and bottom slamming) could be estimated. The vertical acceleration, depending on the wave direction, has its maximum value in the FP and AP regions.

Since vertical ship responses and added resistance vary linearly with the significant wave height $H_{1/3}$ and its square respectively, they have been calculated for sea states following the Bretschneider two-parameter spectral model (Bretschneider, 1959) with $H_{1/3}$ equal to unity. The calculations have been performed for a range of eight modal periods, with non-dimensional values $T_P' = T_P / \sqrt{L_{BP}/g}$ ranging from 1.5 to 5.0 at 0.5 intervals. These values of T_P' correspond to $T_P = 3.4 \div 11.3$ sec for a 50 m vessel, to $T_P = 4.8 \div 16.0$ sec for a 100 m vessel and to $T_P = 6.8 \div 22.6$ sec for a 200 m vessel. Thus, they correspond to sea states appropriate for the determination of the seakeeping responses of different size ships, if the naturally observed relationship between wave height and wave period is taken into account.

The results are in the form of integer values in the range 0 - 9999. In order to restrict the results in this range, the following "non-dimensionalizations" have been used:

Heaving motion = (RMS heave at amidships) * $10^6 / (L_{BP} H_{1/3})$

Pitching motion = (RMS pitch in degrees) * $10^4 / H_{1/3}$

Bending moment = (RMS bending moment at amidships) * $10^9 / (\rho g L_{BP}^4 H_{1/3})$

Added resistance = (mean added resistance) * $10^{10} / (\rho g L_{BP}^3 H_{1/3})$

Relative motion = (RMS relative motion) * $10^6 / (L_{BP} H_{1/3})$

Relative velocity = (RMS relative velocity) * $10^5 / (\sqrt{gL_{BL}}\ H_{1/3})$

Acceleration = (RMS acceleration) * $10^5 / (g H_{1/3})$,

where all results refer to unit significant wave height.

In this fashion, three pages are necessary for the tabular presentation of the results for each hull form and a sample page is shown in Table 1.

The seakeeping responses have been calculated for each of the 72 hull forms of the Extended Series 60 with C_B = 0.55 (0.05) 0.90, L/B = 5.5, 7.0 and 8.5 and B/T = 2.0, 3.0 and 4.0, at four ship speeds corresponding to Froude numbers 0.0, 0.1, 0.2 and 0.3 and for heading angles ranging from head seas (180°) to following seas (0°) at 15° intervals. It should be noted that the radius of gyration K_{yy} has been assumed to be equal to 0.24 L_{BP}, while the weight of the forebody W_F and the distance of the centre of gravity of the forebody LCG_F from amidships are connected to C_B by the following relations:

$$\frac{W_F}{W_T} = 0.20C_B + 0.36 \tag{1}$$

$$\frac{LCG_F}{L_{BP}} = 0.10C_B + 0.13 \tag{2}$$

where W_T is the total weight of the vessel.

Furthermore, the longitudinal radius of gyration for the forebody about the LCG_F of the vessel K_{yy}' has been taken equal to 0.125 L_{BP}.

The justification of these choices has been described in Loukakis and Chryssostomidis (1975).

The three-parameter Extended Lewis-form family, proposed by Athanassoulis and Loukakis (1985) has been used for the representation of the hull forms. Besides to the sectional breadth, draft and area, the sectional KB is used in the conformal mapping of the sections to the unit circle. Thus, the actual longitudinal KB(x) distribution was taken into account during the computations. On the contrary the two-parameter Lewis-form family (Lewis, 1929) has been used for the calculations in the initial paper.

3. DISCUSSION

Seakeeping predictions as a tool for designers of merchant ships is not of paramount importance to the ship design spiral. Merchant ships are primarily designed to carry a given amount of deadweight at a prescribed speed. They have, however, to sail through rough seas and their seakeeping qualities are therefore of some importance, especially in the form of the sustained sea speed. In this situation, the analytical contents of the seakeeping tables do support the practising naval architect in including seakeeping considerations in ship design and operations.

This is true in particular for the case of oblique seas, since most of the reference material pertains to head seas only. This is a void the present series can help to fill, as they pertain to ship responses in all headings in realistic seaways and as strip theory is well known to predict real life with adequate engineering approximation for the hull form and the speeds of the series.

Using the tables, sufficient information can be obtained for a qualitative and quantitative estimation of the seakeeping qualities of any hull form resembling the parent. Furthermore, taking advantage of the quite wide ranges of the C_B coefficient and the L/B and B/T ratios of the data base, conclusions can be drawn on the effect of any variation of these parameters on the seakeeping performance of the ship to be designed. Since, according to usual practice, these parameters are always determined at the preliminary ship design stage, when the hull form is only vaguely defined, the proposed series can support the designer for the creation of a hull form with good seakeeping qualities.

Moreover, the existence of information about seakeeping responses in oblique seas can help the naval architect broaden his understanding about what happens at sea. Using as example the central ship of the series, the following responses are plotted: heave (Fig. 7), pitch (Fig. 8), bending moment (Fig. 9), mean added resistance (Fig. 10), all at Froude number Fn = 0.20 and bow acceleration at Fn = 0.00, 0.10, 0.20 and 0.30 (Figs. 11, 12, 13 and 14).

Obviously, the non-dimensional results are ported to real life, i.e. the ship in real sea states, via the ship length and the wave height. But, nevertheless, the shape of the corresponding curves is interesting per se. Thus, heave resonance occurs around 100° heading angle (Fig. 7) and pitch resonance for the lower sea states (low values of T_P) is not for head seas but for headings close to the 90° minimum, from both directions (Fig. 8).

Similar behaviour pertains for the bending moment (Fig. 9) and even added resistance is not largest for head seas, when in the lower sea states (Fig. 10). For the case of bow acceleration, the results (Figs. 11, 12, 13 and 14) are even more interesting as the resonance is both pronounced and far away, (around beam seas), from head seas at zero speed. Gradually, as speed increases, the situation moves toward the conventional wisdom that head seas induce larger responses, although this is not true for the three lower sea states even at Fn = 0.30.

4. CONCLUSION

The widely recognized usefulness of the seakeeping standard series has been extended by including the zero speed and the oblique seas cases.

The zero-speed and the oblique seas results can be of further use to the designer in the case of special ships, which operate at rest or when oblique seas operation is of importance. Thus, for a given route of the vessel under investigation, the designer, using the tables and the related environmental data, can estimate the operational characteristics of the proposed hull form and decide upon necessary modifications.

However, in addition to the hull form parameters considered in the initial series, additional parameters referring to the waterplane area (C_W and LCF) and the LCB position affect the seakeeping behaviour of ships too. The same is true for the shape of the bow region sections (U or V) as well as for above water characteristics of the hull form (flare, stem angle and others). These parameters can not be examined within the scope of SSS, as they would increase dramatically the number of the hull variants, which is inconsistent with the stated intention of using the Tables during the feasibility study and the preliminary design stage only.

Thus, the selection of main hull form parameters should be accompanied by a subsequent selection of the waterline form parameters C_W and LCF and the longitudinal distribution of KB. The statistical method of Bales (1980) or the direct technique proposed by Grigoropoulos and Loukakis (1988, 1990) could assist the designed in this phase. Both techniques refer to head seas results.

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LABELS OF FIGURES

Fig. 1. Analytically estimated (Salvesen-Tuck-Faltinsen strip theory, 1970) and experimentally measured (Vossers et al, 1960) pitch RAO for a 120-metre Series 60 ship with $C_B = 0.70$, $L/B = 7.0$ and $B/T = 3.0$ at $Fn = 0.20$.

Fig. 2. Analytically estimated (Salvesen-Tuck-Faltinsen strip theory, 1970) and experimentally measured (Vossers et al, 1960) relative bow motion RAO for a 120-metre Series 60 ship with $C_B = 0.70$, $L/B = 7.0$ and $B/T = 3.0$ at $Fn = 0.20$.

Fig. 3. Analytically estimated (Salvesen-Tuck-Faltinsen strip theory, 1970) and experimentally measured (Vossers et al (1960) bending moment RAO for a 120-metre Series 60 ship with $C_B = 0.70$. $L/B = 7.0$ and $B/T = 3.0$ at $Fn = 0.20$.

Fig. 4. Analytically estimated (Loukakis and Sclavounos, 1978) and experimentally derived (Vossers et al 1960) added resistance RAO for a 120-metre Series 60 ship with $C_B = 0.70$, $L/B = 7.0$ and $B/T = 3.0$ at $Fn = 0.20$.

Fig. 5. Comparison of strip theory prediction to experimental results for the vertical acceleration RAO at a position 15% L aft of the F.P of the S-175 standard ship adopted by ITTC. Head seas.

Fig. 6. Comparison of strip theory prediction to experimental results for the added resistance RAO of the S-175 standard ship adopted by ITTC. Head seas.

Fig. 7. Analytically estimated RMS heave for a set of heading angles for the Series 60 central ship at $Fn = 0.20$.

Fig. 8. Analytically estimated RMS pitch for a set of heading angles for the Series 60 central ship at $Fn = 0.20$.

Fig. 9. Analytically estimated RMS bending moment for a set of heading angles for the Series 60 central ship at $Fn = 0.20$.

Fig. 10. Analytically estimated RMS added resistance for a set of heading angles for the Series 60 central ship at Fn = 0.20.

Fig. 11. Analytically estimated RMS vertical acceleration at station 2 (10% aft of FP) for a set of heading angles for the Series 60 central ship at Fn = 0.00.

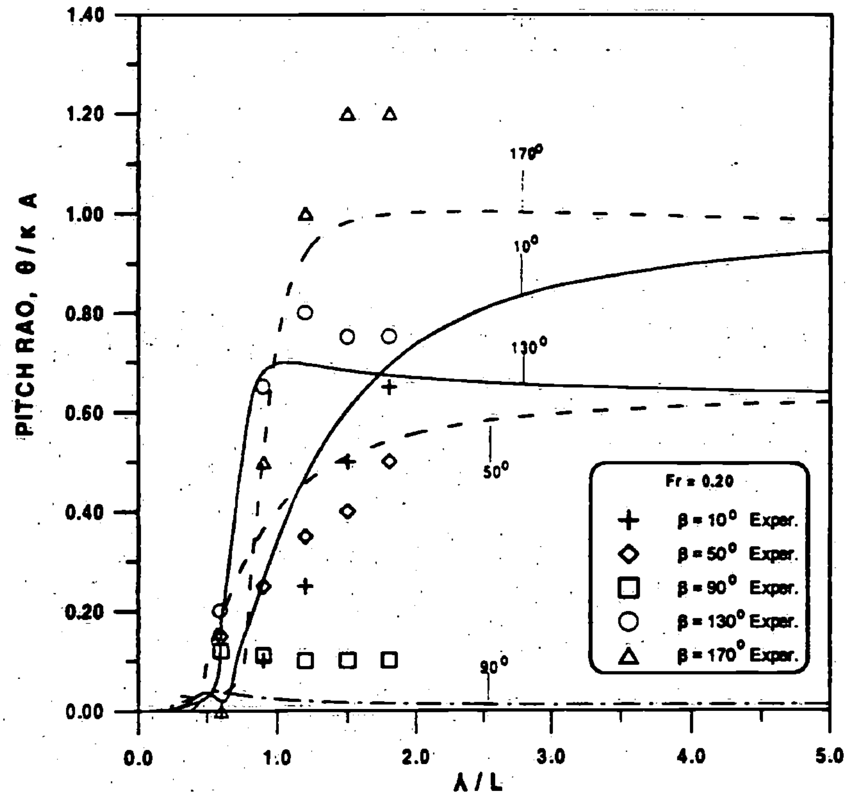
Fig. 12. Analytically estimated RMS vertical acceleration at station 2 (10% aft of FP) for a set of heading angles for the Series 60 central ship at Fn = 0.10.

Fig. 13. Analytically estimated RMS vertical acceleration at station 2 (10% aft of FP) for a set of heading angles for the Series 60 central ship at Fn = 0.20.

Fig. 14. Analytically estimated RMS vertical acceleration at station 2 (10% aft of FP) for a set of heading angles for the Series 60 central ship at Fn = 0.30.

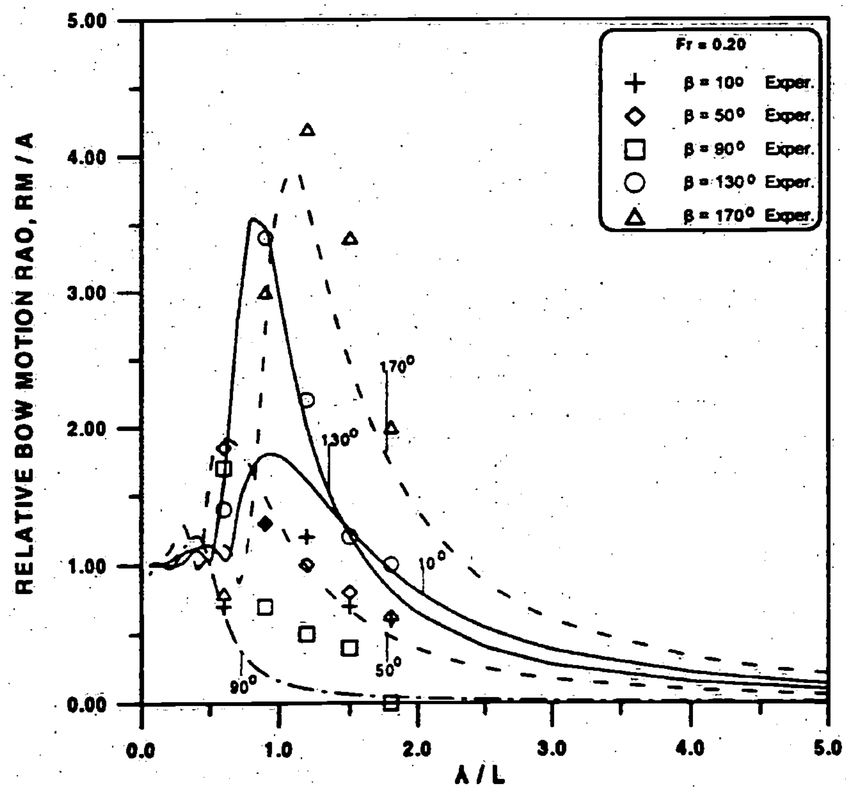
Table 1. Seakeeping responses per meter of $H_{1/3}$ for Series 60 with C_B=0.700, L/B=7.0, B/T=3.0 and LCB=1.0% L

	SHIP HEADING ANGLE IN DEGREES		HEAD			BEAM				FOLLOW			HEAD		SHIP HEADING ANGLE IN DEGREE		BEAM				FOLLOW								
	Fn	T_p'	180	165	150	135	120	105	90	75	60	45	30	15	0	Fn	T_p'	180	165	150	135	120	105	90	75	60	45	30	15	0
HEAVE	0.0	1.5	238	253	286	286	428	1085	1348	754	320	222	201	186	187	0.1	1.5	123	124	136	224	486	992	1335	877	343	172	131	107	100
		2.0	411	427	471	571	989	1798	2118	1517	845	506	382	335	330		2.0	403	427	534	801	1279	1877	2104	1508	788	437	294	239	223
		2.5	631	662	761	958	1370	2002	2263	1835	1283	915	712	612	584		2.5	770	812	956	1241	1673	2137	2254	1774	1194	842	645	546	516
		3.0	946	980	1087	1279	1605	2046	2235	1954	1555	1253	1060	954	922		3.0	1102	1142	1273	1512	1845	2168	2231	1888	1469	1179	995	893	861
		3.5	1222	1253	1346	1506	1749	2056	2189	2001	1720	1490	1331	1237	1207		3.5	1360	1394	1500	1681	1922	2149	2186	1945	1647	1422	1268	1179	1149
		4.0	1432	1458	1534	1660	1840	2055	2149	2021	1822	1650	1523	1447	1422		4.0	1545	1572	1655	1792	1967	2125	2147	1978	1762	1591	1467	1393	1368
		4.5	1585	1606	1667	1765	1899	2053	2119	2032	1888	1758	1660	1599	1578		4.5	1677	1698	1762	1865	1994	2107	2119	1997	1839	1708	1610	1550	1530
		5.0	1696	1712	1760	1837	1939	2049	2096	2037	1931	1832	1756	1707	1691		5.0	1770	1787	1837	1915	2011	2091	2096	2009	1882	1791	1713	1665	1648
	0.2	1.5	64	68	99	182	389	876	1332	1045	274	121	86	74	70	0.3	1.5	38	41	47	110	275	768	1353	966	245	100	80	77	76
		2.0	555	597	733	1001	1429	1910	2077	1490	722	399	261	205	191		2.0	547	589	725	1002	1434	1941	2046	1387	683	377	249	200	187
		2.5	1177	1226	1373	1631	1958	2242	2230	1711	1122	795	611	518	489		2.5	1437	1490	1647	1877	2156	2341	2199	1625	1076	764	588	500	473
		3.0	1521	1561	1683	1877	2103	2280	2215	1827	1403	1128	954	857	827		3.0	1957	1990	2078	2206	2336	2387	2193	1763	1359	1093	925	832	802
		3.5	1703	1736	1829	1974	2131	2238	2177	1896	1590	1373	1225	1139	1111		3.5	2128	2148	2201	2275	2343	2322	2162	1847	1551	1338	1194	1111	1083
		4.0	1809	1833	1904	2010	2124	2194	2142	1938	1716	1547	1426	1354	1330		4.0	2178	2191	2219	2257	2285	2263	2132	1902	1682	1515	1396	1325	1302
		4.5	1878	1896	1950	2028	2111	2160	2115	1965	1801	1670	1573	1514	1494		4.5	2161	2169	2192	2224	2237	2212	2109	1937	1773	1641	1545	1487	1467
		5.0	1924	1938	1979	2039	2101	2133	2093	1983	1861	1758	1680	1632	1616		5.0	2146	2152	2169	2189	2197	2174	2088	1962	1837	1733	1655	1607	1591
PITCH	0.0	1.5	746	793	840	1088	1901	2030	975	2929	1977	1169	983	834	798	0.1	1.5	442	490	629	948	1519	1713	636	3247	1822	1000	632	517	477
		2.0	1629	1711	1958	2495	3174	2575	1034	3542	3274	2440	1969	1719	1647		2.0	1911	2013	2318	2786	3121	2451	651	3406	2740	1981	1513	1281	1208
		2.5	2540	2605	2794	3096	3304	2397	813	3091	3382	3047	2762	2571	2509		2.5	3122	3195	3379	3565	3441	2350	511	2893	2872	2555	2285	2115	2057
		3.0	2952	2984	3049	3120	3012	2046	606	2517	3068	3088	3020	2946	2917		3.0	3537	3563	3609	3568	3191	2227	382	2356	2564	2667	2596	2529	2503
		3.5	3002	2999	2979	2903	2639	1718	459	2050	2681	2882	2958	2976	2977		3.5	3514	3505	3452	3271	2795	1706	290	1923	2368	2545	2607	2621	2621
		4.0	2867	2848	2775	2617	2285	1442	362	1691	2315	2604	2761	2831	2851		4.0	3284	3256	3152	2917	2415	1439	227	1577	2077	2337	2476	2538	2556
		4.5	2657	2627	2526	2333	1980	1211	273	1390	2002	2323	2516	2616	2646		4.5	2996	2959	2832	2572	2087	1216	171	1283	1815	2111	2287	2378	2405
		5.0	2429	2393	2280	2075	1713	1013	186	1125	1731	2066	2273	2386	2422		5.0	2706	2665	2529	2268	1809	1024	117	1034	1583	1897	2088	2192	2225
	0.2	1.5	268	294	400	596	1112	1505	366	3146	1424	689	415	333	303	0.3	1.5	141	155	217	371	773	1382	335	2743	1220	571	365	373	382
		2.0	1796	1888	2162	2585	2953	2455	399	3151	2315	1662	1267	1071	1009		2.0	1463	1548	1820	2279	2775	2580	449	2849	2111	1500	1173	1059	1045
		2.5	3347	3407	3561	3676	3481	2415	332	2669	2524	2245	2010	1866	1816		2.5	3271	3340	3515	3672	3561	2608	397	2473	2354	2077	1879	1790	1772
		3.0	3917	3924	3915	3764	3303	2087	260	2193	2399	2400	2338	2283	2262		3.0	4075	4079	4054	3913	3427	2268	317	2063	2267	2250	2203	2181	2179
		3.5	3897	3870	3768	3498	2898	1760	203	1803	2168	2328	2386	2402	2404		3.5	4116	4083	3957	3672	3051	1887	251	1714	2066	2202	2263	2298	2312
		4.0	3630	3585	3432	3105	2513	1471	159	1475	1924	2163	2292	2352	2370		4.0	3871	3813	3621	3268	2629	1572	201	1419	1844	2060	2185	2257	2281
		4.5	3290	3238	3066	2732	2166	1247	125	1204	1697	1972	2137	2223	2250		4.5	3487	3428	3241	2877	2262	1325	162	1173	1634	1888	2047	2139	2171
		5.0	2950	2896	2724	2403	1877	1055	96	990	1492	1785	1965	2064	2095		5.0	3124	3063	2873	2518	1961	1121	130	974	1444	1715	1889	1992	2026
BEND.MOMENT	0.0	1.5	1183	1254	1675	2289	2808	1882	2071	2245	2625	1997	1503	1283	1230	0.1	1.5	1382	1388	1638	2137	2232	1679	2168	2495	3150	2455	1785	1394	1295
		2.0	3246	3300	3545	3814	3592	2197	2039	1961	3005	3261	3202	3087	3060		2.0	3676	3739	3893	3957	3420	2224	2146	2189	3578	3801	3604	3394	3318
		2.5	4228	4202	4150	3954	3303	1924	1614	1608	2742	3440	3791	3934	3980		2.5	4799	4776	4669	4312	3397	2046	1696	1768	3152	3837	4095	4172	4187
		3.0	4229	4153	3938	3523	2755	1538	1222	1277	2310	3115	3635	3910	4001		3.0	4748	4676	4426	3905	2930	1670	1283	1368	2585	3375	3830	4059	4130
		3.5	3825	3731	3458	2988	2251	1220	936	1006	1901	2671	3218	3533	3639		3.5	4268	4175	3872	3307	2406	1339	982	1051	2094	2844	3338	3619	3711
		4.0	3333	3236	2957	2502	1834	983	727	780	1564	2254	2768	3077	3181		4.0	3687	3591	3294	2772	1979	1076	765	819	1695	2373	2844	3126	3219
		4.5	2867	2777	2515	2097	1500	803	562	622	1280	1900	2364	2648	2745		4.5	3154	3064	2789	2318	1632	886	589	656	1368	1984	2414	2675	2763
		5.0	2464	2382	2144	1758	1223	650	424	516	1040	1604	2022	2277	2363		5.0	2699	2617	2371	1950	1348	730	440	534	1098	1655	2052	2291	2371
	0.2	1.5	1375	1419	1480	1904	1975	1564	2118	3136	4255	3039	2096	1565	1404	0.3	1.5	1390	1444	1509	1899	1902	1687	1949	4731	5646	3997	2711	1982	1744
		2.0	3724	3780	3881	3932	3423	2200	2042	2706	4561	4404	3876	3487	3349		2.0	3593	3656	3807	3929	3525	2271	1781	3846	5980	5517	4575	3924	3690
		2.5	5357	5323	5150	4700	3654	2100	1605	2109	3852	4272	4241	4146	4102		2.5	5606	5588	5470	5040	3976	2176	1382	2867	4988	5231	4838	4467	4333
		3.0	5513	5414	5076	4392	3230	1755	1214	1595	3070	3660	3882	3960	3981		3.0	6139	6032	5663	4904	3589	1826	1045	2125	3934	4420	4350	4185	4114
		3.5	5005	4884	4502	3800	2686	1414	928	1206	2439	3030	3335	3489	3537		3.5	5728	5585	5131	4309	3041	1466	800	1575	3098	3621	3696	3648	3631
		4.0	4337	4214	3834	3172	2220	1141	723	929	1941	2497	2811	2988	3045		4.0	5057	4907	4437	3638	2505	1187	620	1148	2445	2958	3091	3101	3094
		4.5	3705	3593	3248	2656	1833	941	555	715	1529	2065	2368	2541	2598		4.5	4315	4177	3763	3061	2074	976	475	826	1904	2421	2583	2621	2629
		5.0	3156	3055	2748	2234	1525	781	413	542	1186	1698	1999	2164	2219		5.0	3690	3566	3195	2576	1729	808	356	603	1451	1971	2158	2218	2233
ADDED RES.	0.0	1.5	1441	1411	1617	1862	1866	1376	0	•	•	•	•	•	•	0.1	1.5	487	498	651	987	1280	1129	0	•	•	•	•	•	•
		2.0	1645	1581	1548	1538	1503	1179	0	•	•	•	•	•	•		2.0	1123	1127	1222	1453	1612	1176	0	•	•	•	•	•	•
		2.5	1265	1198	1091	998	933	726	0	•	•	•	•	•	•		2.5	1285	1267	1262	1295	1233	792	0	•	•	•	•	•	•
		3.0	839	787	686	594	538	414	0	•	•	•	•	•	•		3.0	1024	998	953	908	790	471	0	•	•	•	•	•	•
		3.5	533	498	421	348	309	238	0	•	•	•	•	•	•		3.5	726	701	642	578	484	281	0	•	•	•	•	•	•
		4.0	338	314	260	206	178	139	0	•	•	•	•	•	•		4.0	490	471	427	372	297	168	0	•	•	•	•	•	•
		4.5	214	198	161	122	103	80	0	•	•	•	•	•	•		4.5	331	317	283	241	188	102	0	•	•	•	•	•	•
		5.0	135	125	98	72	59	43	0	•	•	•	•	•	•		5.0	227	216	191	159	119	60	0	•	•	•	•	•	•
	0.2	1.5	149	160	220	514	847	882	0	•	•	•	•	•	•	0.3	1.5	42	46	86	202	415	698	0	•	•	•	•	•	•
		2.0	865	909	1072	1413	1616	1123	0	•	•	•	•	•	•		2.0	542	585	750	1069	1352	1039	0	•	•	•	•	•	•
		2.5	1751	1765	1796	1794	1524	830	0	•	•	•	•	•	•		2.5	1837	1873	1951	1947	1618	831	0	•	•	•	•	•	•
		3.0	1743	1713	1619	1433	1079	517	0	•	•	•	•	•	•		3.0	2310	2266	2111	1801	1245	542	0	•	•	•	•	•	•
		3.5	1364	1325	1209	998	684	315	0	•	•	•	•	•	•		3.5	1976	1908	1698	1350	849	334	0	•	•	•	•	•	•
		4.0	966	930	826	661	441	192	0	•	•	•	•	•	•		4.0	1507	1435	1225	925	555	207	0	•	•	•	•	•	•
		4.5	678	650	569	442	286	120	0	•	•	•	•	•	•		4.5	1059	1008	864	638	367	132	0	•	•	•	•	•	•
		5.0	474	453	393	303	191	74	0	•	•	•	•	•	•		5.0	759	719	608	440	251	84	0	•	•	•	•	•	•



1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
PITCH RAO, θ / κ A
0.0
1.0
2.0
3.0
4.0
5.0
λ / L
170°
10°
130°
50°
90°
Fr = 0.20
β = 10° Exper.
β = 50° Exper.
β = 90° Exper.
β = 130° Exper.
β = 170° Exper.

Fig. 1



5.00
4.00
3.00
2.00
1.00
0.00
RELATIVE BOW MOTION RAO, RM / A
0.0
1.0
2.0
3.0
4.0
5.0
λ / L
Fr = 0.20
β = 10° Exper.
β = 50° Exper.
β = 90° Exper.
β = 130° Exper.
β = 170° Exper.
170°
130°
10°
50°
90°

Fig. 2

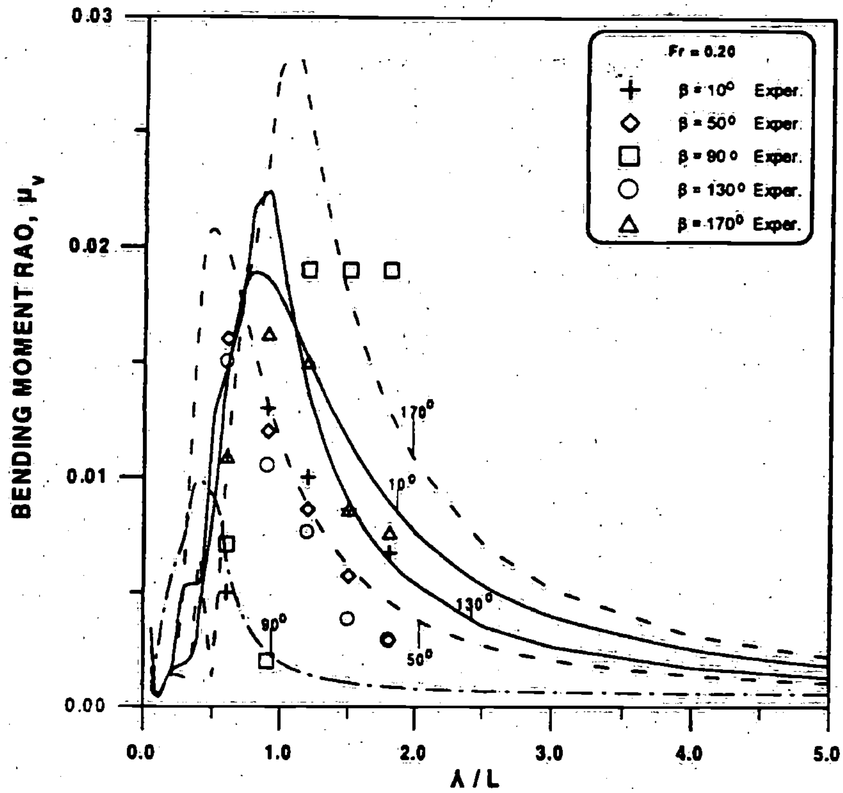

Fr = 0.20
β = 10° Exper.
β = 50° Exper.
β = 90° Exper.
β = 130° Exper.
β = 170° Exper.
BENDING MOMENT RAO, μv
λ / L
0.03
0.02
0.01
0.00
0.0
1.0
2.0
3.0
4.0
5.0
170°
10°
130°
90°
50°

Fig. 3

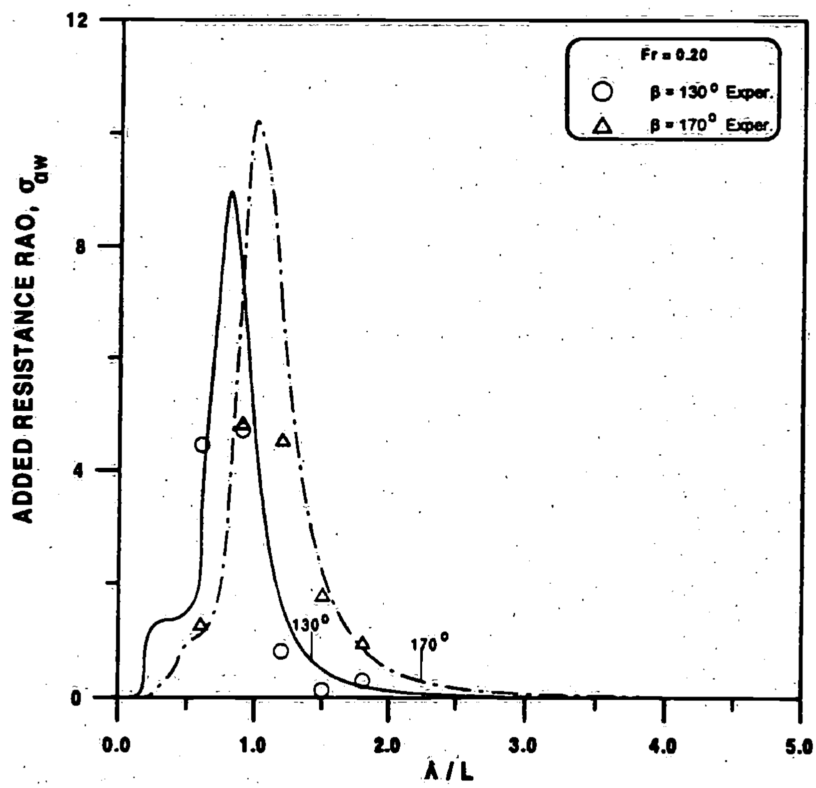

Fr = 0.20
β = 130° Exper.
β = 170° Exper.
ADDED RESISTANCE RAO, σaw
λ / L
12
8
4
0
0.0
1.0
2.0
3.0
4.0
5.0
130°
170°

Fig. 4

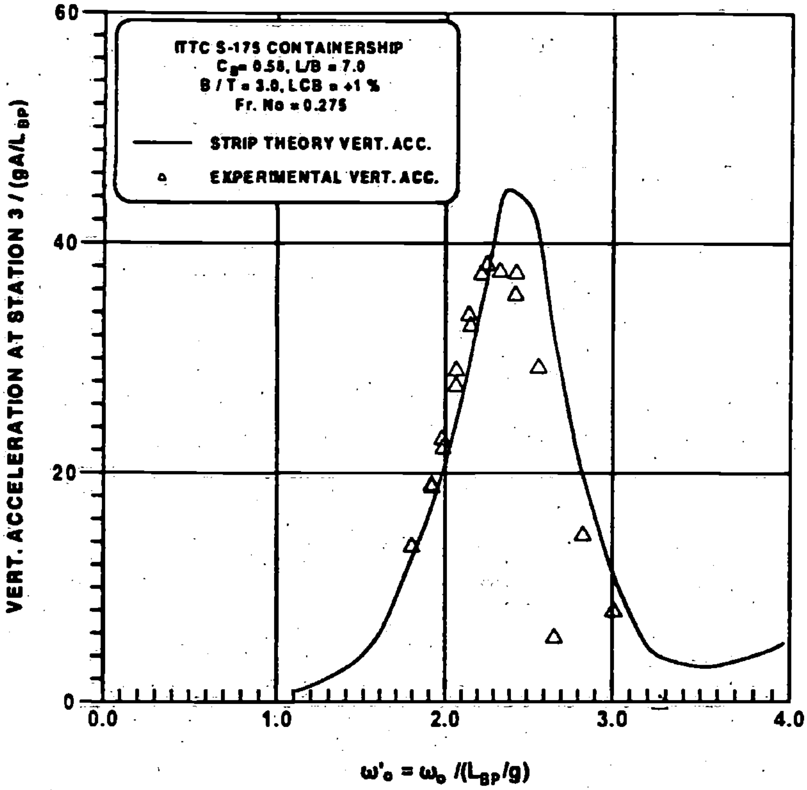

ITTC S-175 CONTAINERSHIP
C_B = 0.58, L/B = 7.0
B / T = 3.0, LCB = +1 %
Fr. No = 0.275
STRIP THEORY VERT. ACC.
EXPERIMENTAL VERT. ACC.
VERT. ACCELERATION AT STATION 3 / (gA/L_{BP})
$\omega'_o = \omega_o /(L_{BP}/g)$
0
20
40
60
0.0
1.0
2.0
3.0
4.0

Fig. 5

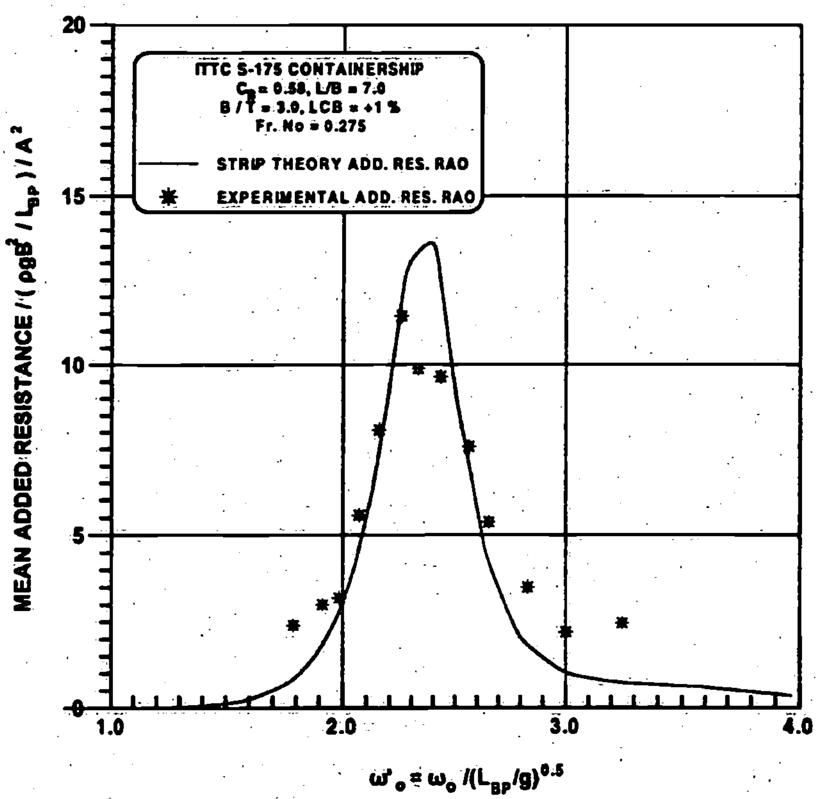
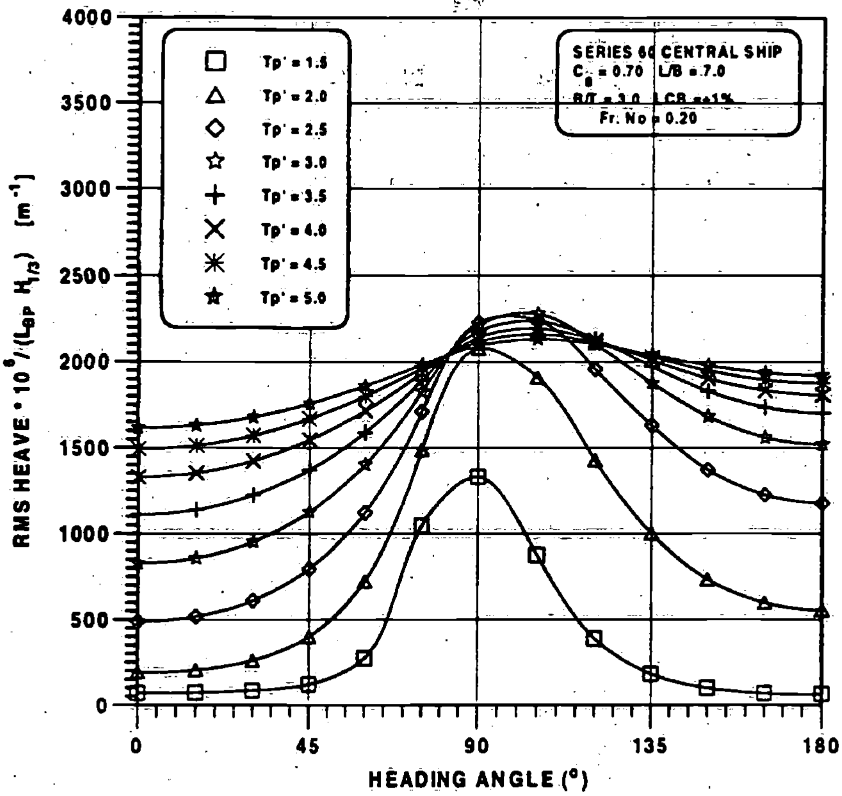
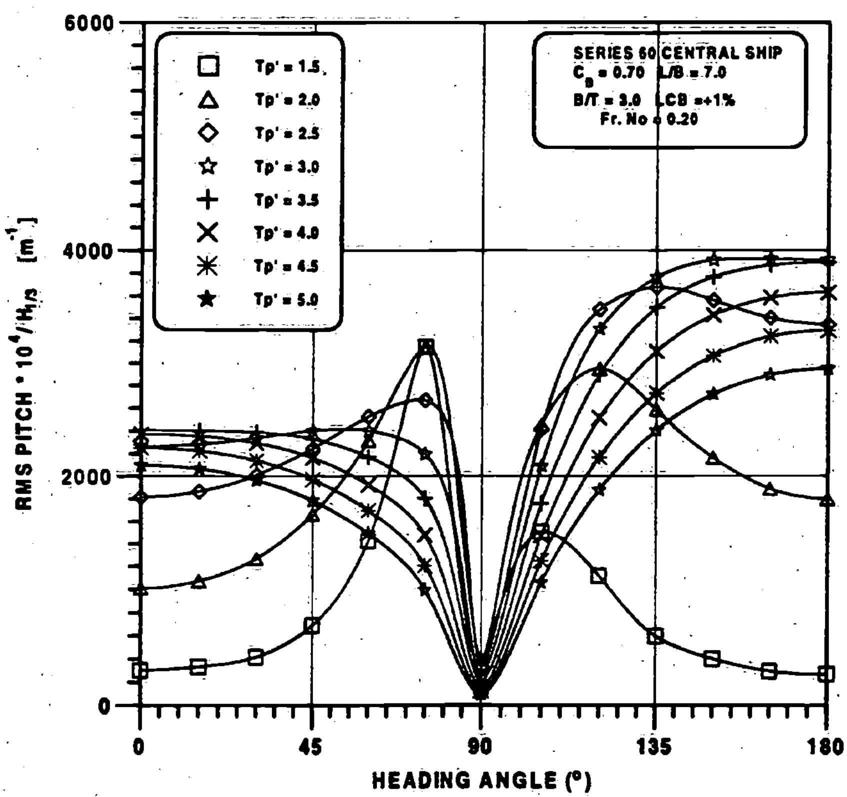

ITTC S-175 CONTAINERSHIP
C_B = 0.58, L/B = 7.0
B / T = 3.0, LCB = +1 %
Fr. No = 0.275
STRIP THEORY ADD. RES. RAO
EXPERIMENTAL ADD. RES. RAO
MEAN ADDED RESISTANCE / ($\rho g B^2 / L_{BP}$) / A^2
$\omega'_o = \omega_o /(L_{BP}/g)^{0.5}$
0
5
10
15
20
1.0
2.0
3.0
4.0

Fig. 6



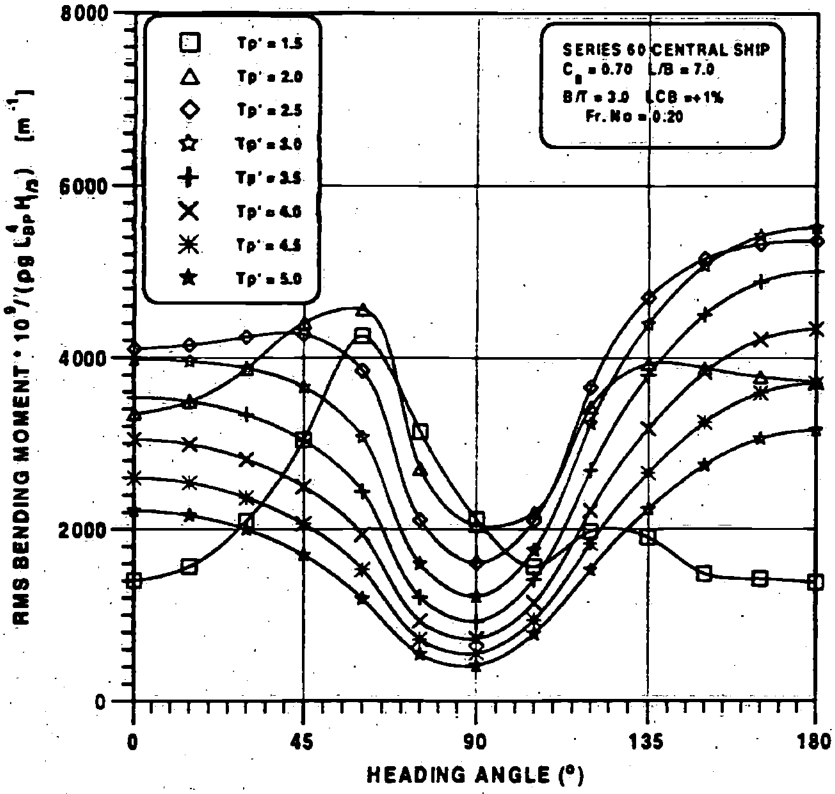
Tp' = 1.5
Tp' = 2.0
Tp' = 2.5
Tp' = 3.0
Tp' = 3.5
Tp' = 4.0
Tp' = 4.5
Tp' = 5.0
SERIES 60 CENTRAL SHIP
Fr. No = 0.20
RMS HEAVE * 10^6/(L_BP H_1/3) [m^-1]
HEADING ANGLE (°)
0
45
90
135
180
0
500
1000
1500
2000
2500
3000
3500
4000

Fig. 7



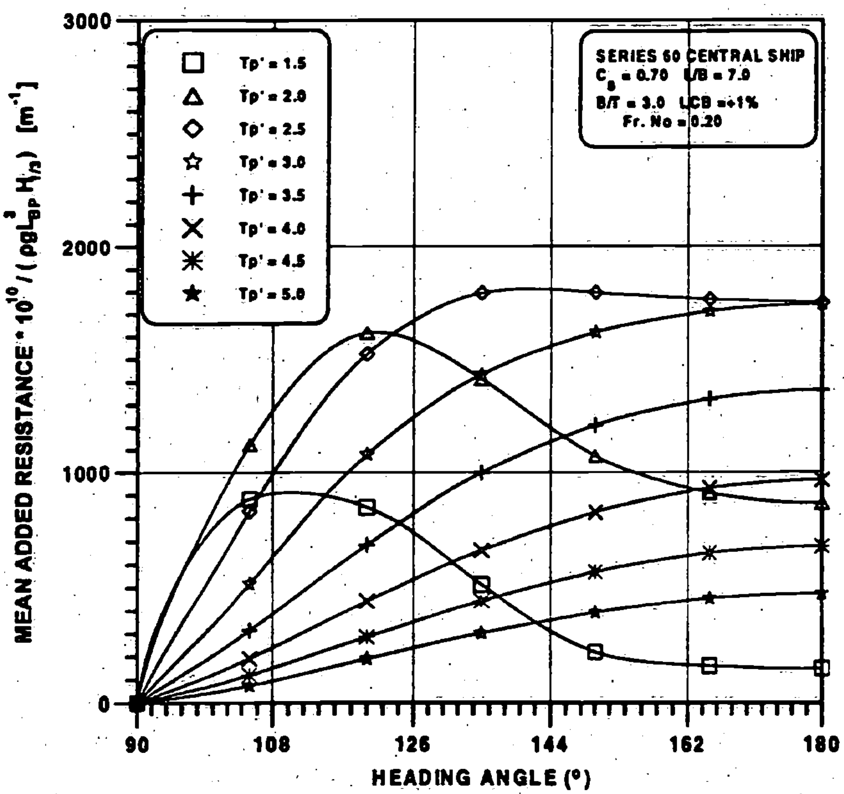
Tp' = 1.5
Tp' = 2.0
Tp' = 2.5
Tp' = 3.0
Tp' = 3.5
Tp' = 4.0
Tp' = 4.5
Tp' = 5.0
SERIES 60 CENTRAL SHIP
C_B = 0.70 L/B = 7.0
B/T = 3.0 LCB = +1%
Fr. No = 0.20
RMS PITCH * 10^4/H_1/3 [m^-1]
HEADING ANGLE (°)
0
45
90
135
180
0
2000
4000
6000

Fig 8



RMS BENDING MOMENT * 10^9 / (ρg L_BP^4 H_1/3) [m^-1]
HEADING ANGLE (°)
Tp' = 1.5
Tp' = 2.0
Tp' = 2.5
Tp' = 3.0
Tp' = 3.5
Tp' = 4.0
Tp' = 4.5
Tp' = 5.0
SERIES 60 CENTRAL SHIP
C_B = 0.70 L/B = 7.0
B/T = 3.0 LCB = +1%
Fr. No = 0.20

Fig. 9



MEAN ADDED RESISTANCE * 10^10 / (ρg L_BP^3 H_1/3) [m^-1]
HEADING ANGLE (°)
Tp' = 1.5
Tp' = 2.0
Tp' = 2.5
Tp' = 3.0
Tp' = 3.5
Tp' = 4.0
Tp' = 4.5
Tp' = 5.0
SERIES 60 CENTRAL SHIP
C_B = 0.70 L/B = 7.0
B/T = 3.0 LCB = +1%
Fr. No = 0.20

Fig. 10

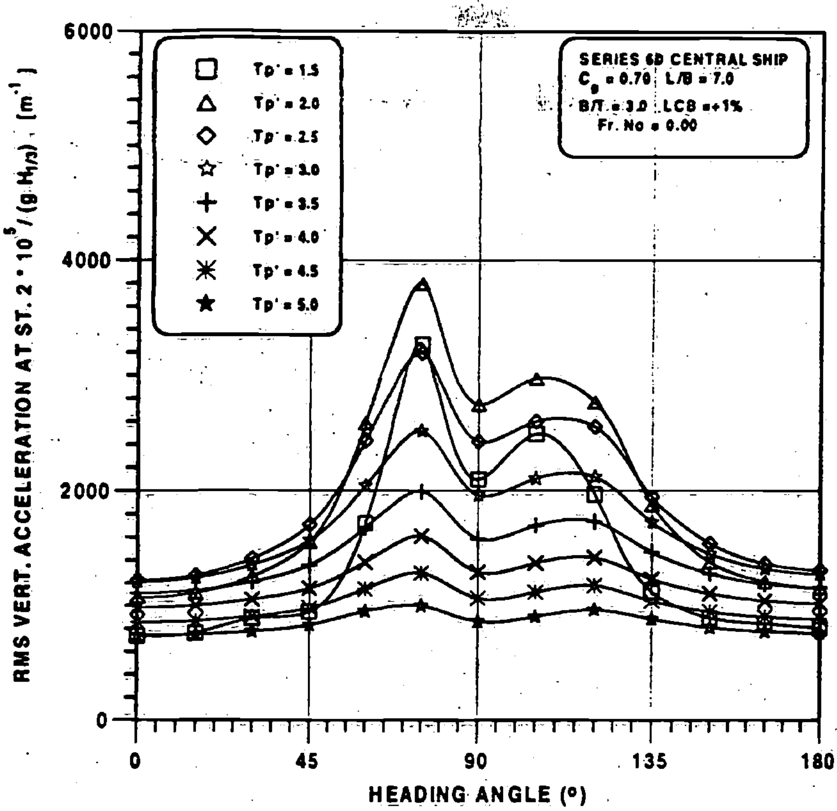

Tp' = 1.5
Tp' = 2.0
Tp' = 2.5
Tp' = 3.0
Tp' = 3.5
Tp' = 4.0
Tp' = 4.5
Tp' = 5.0
SERIES 60 CENTRAL SHIP
C_B = 0.70 L/B = 7.0
B/T = 3.0 LCB = +1%
Fr. No = 0.00
RMS VERT. ACCELERATION AT ST. 2 * 10^5 / (g $H_{1/3}$) (m^{-1})
HEADING ANGLE (°)
0
2000
4000
6000
0
45
90
135
180

Fig. 11

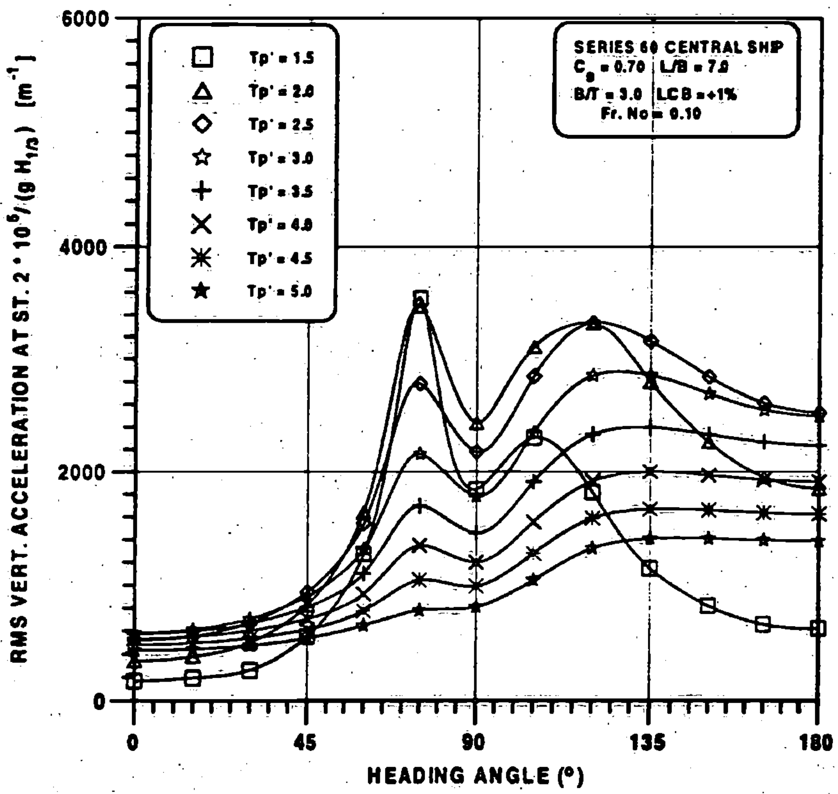
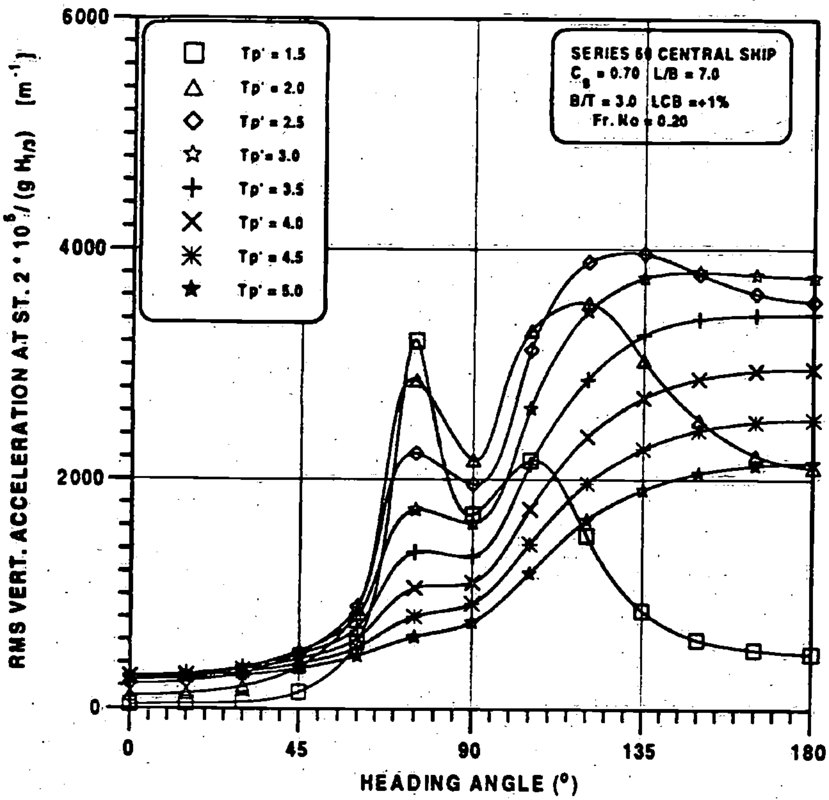
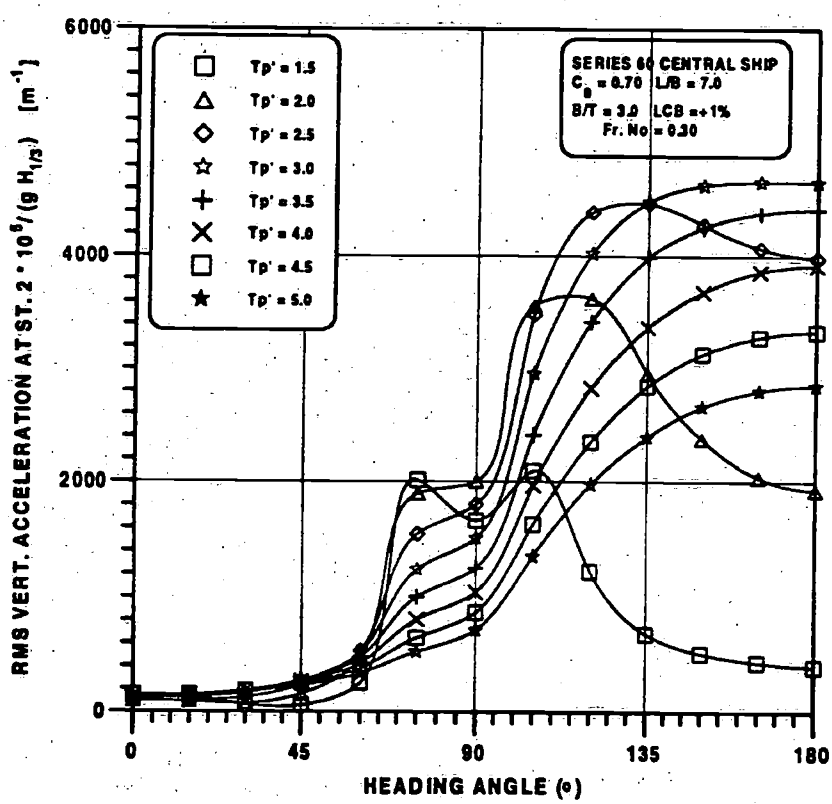

Tp' = 1.5
Tp' = 2.0
Tp' = 2.5
Tp' = 3.0
Tp' = 3.5
Tp' = 4.0
Tp' = 4.5
Tp' = 5.0
SERIES 60 CENTRAL SHIP
C_B = 0.70 L/B = 7.0
B/T = 3.0 LCB = +1%
Fr. No = 0.10
RMS VERT. ACCELERATION AT ST. 2 * 10^5 / (g $H_{1/3}$) (m^{-1})
HEADING ANGLE (°)
0
2000
4000
6000
0
45
90
135
180

Fig. 12



6000
4000
2000
0
0
45
90
135
180
HEADING ANGLE (°)
RMS VERT. ACCELERATION AT ST. 2 * 10⁵/(g H1/3) [m⁻¹]
Tp' = 1.5
Tp' = 2.0
Tp' = 2.5
Tp' = 3.0
Tp' = 3.5
Tp' = 4.0
Tp' = 4.5
Tp' = 5.0
SERIES 60 CENTRAL SHIP
CB = 0.70 L/B = 7.0
B/T = 3.0 LCB =+1%
Fr. No = 0.20

Fig. 13



6000
4000
2000
0
0
45
90
135
180
HEADING ANGLE (°)
RMS VERT. ACCELERATION AT ST. 2 * 10⁵/(g H1/3) [m⁻¹]
Tp' = 1.5
Tp' = 2.0
Tp' = 2.5
Tp' = 3.0
Tp' = 3.5
Tp' = 4.0
Tp' = 4.5
Tp' = 5.0
SERIES 60 CENTRAL SHIP
CB = 0.70 L/B = 7.0
B/T = 3.0 LCB =+1%
Fr. No = 0.30

Fig. 14