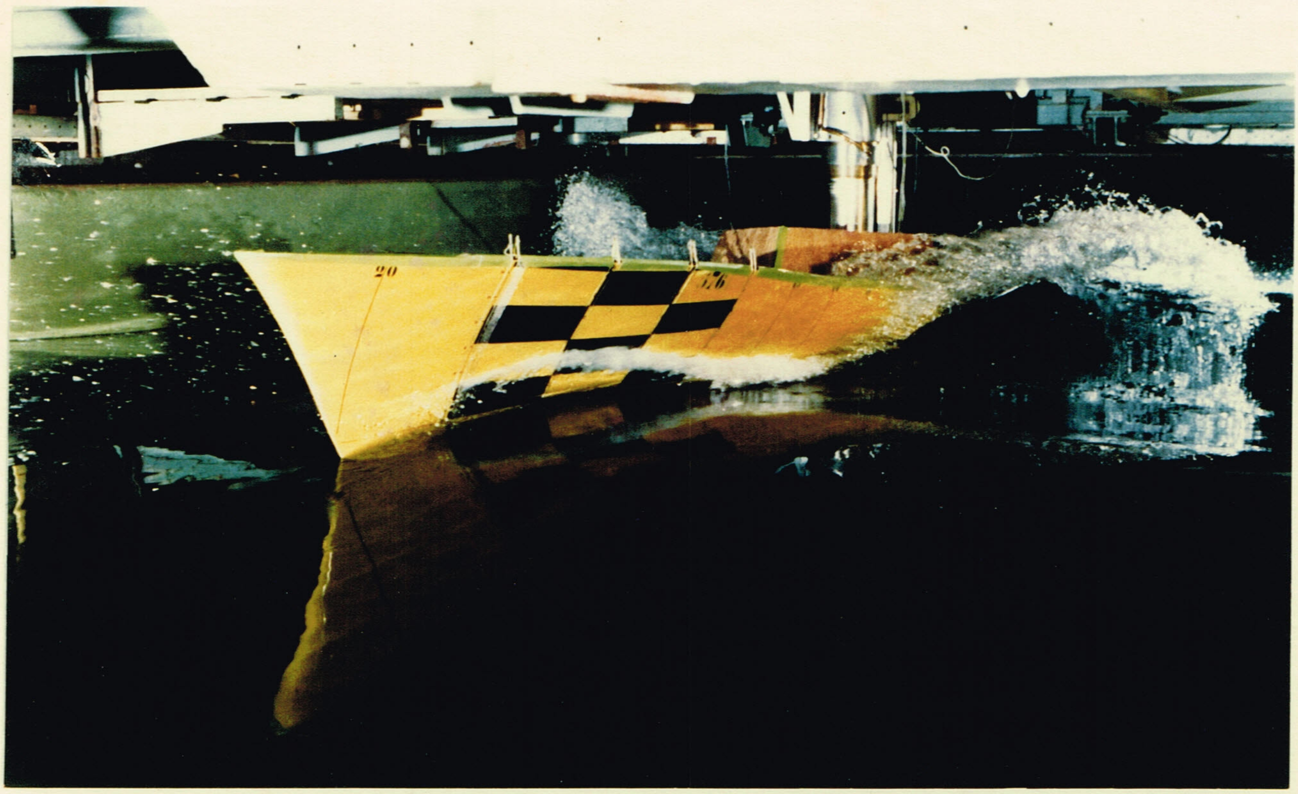

SYSTEMATIC SERIES OF HIGH SPEED DISPLACEMENT HULL FORMS FOR NAVAL COMBATANTS

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SYTEMATIC SERIES OF HIGH SPEED DISPLACEMENT HULL FORMS FOR NAVAL COMBATANTS

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ABSTRACT

The status of a high speed displacement hull form project co-sponsored by the Maritime Research Institute Netherlands, the Royal Dutch Navy, the United States Navy and the Royal Australian Navy is described. The project consists of the experimentation, evaluation and data presentation of a systematic model series of round bilge displacement hull forms suitable for high speed naval combatants which are required to sustain minimum motions in high sea states. Complementary work carried out by the Royal Australian Navy is also described.

NOMENCLATURE

a_a = acceleration amplitude (single)

B_{WL} = ship's breadth on the waterline

b_t = transom stern width

C_A = incremental resistance coefficient for model-ship correlation

C_B = block coefficient

C_{BA} = block coefficent aftbody

C_{BF} = block coefficent forebody

C_C = Distance form the forefoot to aft cut-up

C_{FS} = specific frictional resistance coefficient of ship according to ITTC-57

C_M = midship section coefficient

CG = center of gravity

C_P = horizontal prismatic coefficient

C_{PA} = horizontal prismatic coefficient aftbody

C_{PF} = horizontal prismatic coefficient forebody

C_{RM} = specific residuary resistance coefficient of model

C_{TS} = specific residuary resistance coefficient of ship

C_{VP} = vertical prismatic coefficient

C_{VPA} = vertical prismatic coefficient aftbody

C_{VPF} = vertical prismatic coefficient forebody

C_{WP} = waterplane coefficient

C_{WPA} = waterplane coefficient aftbody

C_{WPF} = waterplane coefficient forebody

F_n = Froude number = $V / \sqrt{g*L}$

$F_{n\nabla}$ = Froude number = $V / \sqrt{g*\nabla^{1/3}}$

g = acceleration due to gravity

i_E = waterline entrance angle relative to centerplane

K = wave number = $2\pi/\lambda$
L_{WL} = ship's length on the waterline
L_{PP} = ship's length between perpendiculars
LCB = longitudinal center of buoyancy
LCF = longitudinal center of flotation
R_B = seakeeping merit figure according to Bales
R_M = seakeeping merit figure according to McCreight
R_{AW} = wave added resistance
R_r = residuary resistance
R_T = total resistance, calm water plus waves
R_{TS} = total resistance in calm water
s_a = relative motion amplitude (single)
s_{17} = relative motion at station 17
T = ship's draft
$\tilde{T}_1$ = average wave period
V = speed
V_s = ship's speed in knots
z_a = heave amplitude (single)
$2\tilde{z}_{a1/3}$ = double significant heave motion
ζ_a = wave amplitude (single)
$\tilde{\zeta}_{a1/3}$ = significant wave height
θ_a = pitch amplitude (single)
$2\tilde{\theta}_{a1/3}$ = double significant pitch angle
λ = wavelength
∇ = displacement volume
ρ = water mass density
γ = specific gravity of water
ε = phase angle relative to the wave crest at C.O.G. of the model
ω = circular frequency

1. INTRODUCTION

The operational expectations of the modern Naval Combatant with its expensive and very capable weapon and sensor system is very high. The modern Naval Combatant must be able to provide a steady and stable working platform despite adverse environmental conditions to enable the weapon, sensor systems and their operators to safely and successfully perform their tasks. Economic factors have also dictated that these Naval Combatants be as small as possible. In general terms, smaller Naval Combatants accommodating more capable weapons systems are now required to be much more seakindly than their predecessors.

In meeting the challenge of designing effective Naval Combatants that can operate in adverse environmental conditions the Naval Architect has had to become more aware of ship performance prediction and optimization in waves. In recent years tools have been developed that can predict with a reasonable degree of accuracy the various degrees of ship motion in a specified sea environment. These tools have proven to be invaluable to the Naval Architect.

There is however still a need to better understand the fundamental design factors which affect the propulsive and motion performance of a ship in waves and that such factors affecting seakeeping and propulsive performance are addressed early in the conceptual design stages of any new Naval combatant. It is also essential that sufficient is known about these factors for trade-off studies when evaluating existing competing designs.

The Directorate of Naval Ship Design of the Australian Department of Defence, in an endeavour to acquire more reliable tools for predicting ship performance in waves is currently supporting a Co-operative Ship Research Project known as the 'High Speed Displacement Hull Form Project'. The other participants in this project are the United States Navy, The Royal Netherlands Navy and the Maritime Research Institute Netherlands. The Delft University of Technology is also involved on a consultative and contracting basis.

The High Speed Displacement Hull Form Project was first set up by the Maritime Research Institute Netherlands (MARIN) in 1979 as a ten year research project concluding in 1989. It was intended that this research project would cover the design and testing of a relatively large series of high speed, round bilge displacement hull forms. The design of this hull form series was to be primarily based on the requirement of maintaining high speed and minimum ship motion in high sea states. The designed calm water speed of the parent hull of the series was established to correspond to 40 knots for a 40 metre ship and 45 knots for a 100 metre ship (F_n= 0.70 to 1.00). The financial support for this project was to be derived from an annual subscription fee paid by each participant with the intention that the research results would be subsequently shared between all participants.

The Royal Australian Navy joined the project in early 1984 after an agreement was reached regarding subscriptions for the years preceeding 1984. The Royal Australian Navy is an active participant in this project and will retain its membership until the project conclusion.

The objectives and direction of the High Speed Displacement Hull Form Project has undergone considerable change since 1979 and will now provide participants with more practical and useable ship design data than was previously thought possible. All of this data will be finally issued in what is hoped to be a very user friendly software package which can be run on available computer hardware. For the Royal Australian Navy this software package will also form part of the 'AUSEVAL' Computer Based Preliminary Ship Design System (1).

The aim of this paper is to discuss the work undertaken for the High Speed Displacement Hull Form Project, provide some research results and to describe how the project findings and outputs will be applied in the design and evaluation of future Royal Australian Navy Surface Combatants.

2. DESIGN OF THE PARENT HULL

In setting up the standard series of hull forms required for the High Speed Displacement Hull Form Project it was essential that a realistic design criteria be established and that the parent hull form not only be derived to meet this criteria but that it be transformable to a large family of realistic hull forms suitable for Naval Combatants ranging in size from Patrol Boats to large Destroyers.

The criteria formulated for the Parent Hull was that it should have good calm water resistance properties and exceptional seakeeping characteristics over a wide range of speeds. In selecting the parent hull it was decided that initially, attention be focused on resistance while propulsion factors were neglected. With regard to seakeeping properties it was decided that attention should be directed towards low motion and acceleration levels, low wave added resistance and a small probability of incurring extreme effects like slamming and shipping of water on the deck.

It was considered that the most critical motions and accelerations would occur in head seas and that maximum wave added resistance would also occur in head seas, so the Parent Hull selection was based on performance in head seas.

In selecting the speed range for the Parent Hull and subsequent series it was important that cruising speeds as well as high speed performance be considered. Taking some various vessels and their typical design speeds as depicted in Table 1 it was evident that the F_n value of interest ranged from 0.40 to 1.10 for the designed maximum speed. Taking into account a cruise speed of 20 knots the lower end of the range was reduced to 0.20. Since the series was generally directed towards high speed frigates of a general length of 120 m pushed to a speed of 45 knots with F_n of 0.70 it was further decided that the Parent Hull should be selected with emphasis on the range of F_n = 0.70 to 1.00. The ultimate speed range for the series was initially taken as F_n = 0.10 to 1.20 with the Parent Hull being optimised for F_n = 0.70.

Before selecting the prime parameters of the Parent Hull it was necessary to first decide upon the fixed parameters and the variable parameter range of the series. Based on current knowledge it was considered that the parameters which effect resistance and seakeeping for which no further experimental research was required were:

prismatic coefficient (C_P)
longitudinal centre of buoyancy (LCB)
midship section coefficient (C_M)

The hull form parameters which were considered to require further experimental research were:

length/beam ratio (L_{wl}/B_{wl})
beam/draft ratio (B_{wl}/T)
block coefficient (C_B)
longitudinal centre of floatation (LCF)
waterplane coefficient (C_{WP})
transom breadth ratio (b_t/B_{wl})
half angle of entrance (1_e)

To reduce the number of models and subsequent experimentation to that permissible in the budget of the project and to still adhere to the prime parameters of direct interest to the designer it was decided to take L_{wl}/B_{wl}; B_{wl}/T; and C_B as the prime variable parameters for the series and to fix all other parameters as established for the Parent Hull.

Since it was also necessary to have the series cover a diverse range of ship types, it was decided that the following range of the three prime variable parameters were necessary:

L_{wl}/B_{wl}	from 4 to 12
B_{wl}/T	from 2.5 to 5.5
C_B	from 0.35 to 0.50

Putting the Parent Hull into the centre of the 'Magic Cube', which will be explained later, it gave the Parent Hull the following principal characteristics:

$L_{wl}/B_{wl} = 8.0$
$B_{wl}/T = 4.0$
$C_B = 0.40$

The optimum value of Prismatic Coefficient (C_P) was estimated from the results of extensive tests on existing ships by MARIN and from C_P values adopted for other systematic high speed hull form series. The C_P value ultimately adopted for the Parent Hull and resulting series was $C_P = 0.63$.

The optimum value for LCB was also based on research already conducted at MARIN and on other published information. The choice of LCB at a constant position of 5 percent aft of amidships was made and was considered suitable for all models in the series.

From MARIN data it was evident that a good relationship existed between Midship Section Coefficient (C_M) and Block Coefficient (C_B) so C_M for the Parent Hull was taken as 0.633.

To study the influence of the Waterplace Coefficient (C_{WP}), the influence of LCB-LCF separation, the Half Angle of Entrance (1_e) and the influence of the Transom Breadth prior to selecting the parent hull form, an initial subseries (Subseries 1) of three models was tested for Resistance and Seakeeping. Since it was impractical to study the influence of each of these four variables independantly it was decided to design the subseries hull forms as depicted in Fig 1. The three models initially tested indicated that further models were required which were made by cutting up the original three models amidships and rearranging the fore end and aft end configuration.

The detail characteristics of all subsequent six models of subseries 1 tested are provided in Table 2 while general characteristics are depicted in Fig 2. Based on the N.K. Bales (6) seakeeping figure of merit calculations it was considered that three models of the nine point matrix of Fig 2 did not warrant further testing as seakeeping expectations, in comparison with the other models, were lower.

The selection of the Parent Hull Form was based on the comparison of calm water resistance results, added resistance in waves test results, seakeeping test results, and an associated seakeeping figure of merit value. Trade off studies were also necessary between calm water resistance and seakeeping characteristics in headwaves (ISSC Wave Spectrum).

Table 3 depicts the results of the calm water residuary resistance of the models normalised on model 2. With regard to added resistance in waves, it was difficult to establish a meaningful comparison but generally model 3 with the highest C_{VP} value produced the highest added resistance while model 4 with the lowest C_{VP} value produced the lowest added resistance at most speeds. Seakeeping Merit Values R_B for each model are shown in Fig 2. For actual model motion test results the reader is referred to reference 3 where all test results are provided.

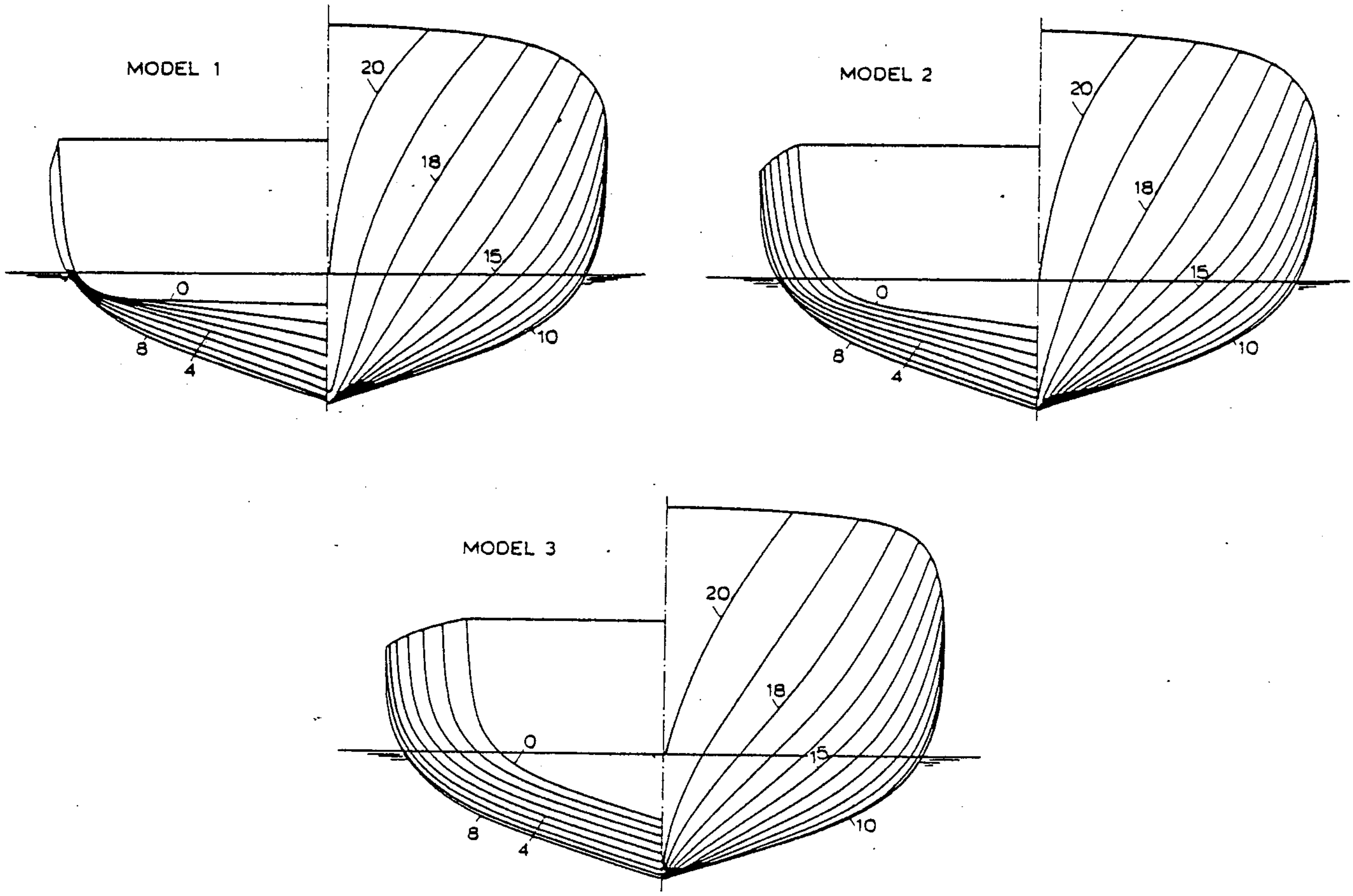


FIGURE 1[3] - BODY PLANS, MODELS 1, 2 & 3 OF SUBSERIES 1.

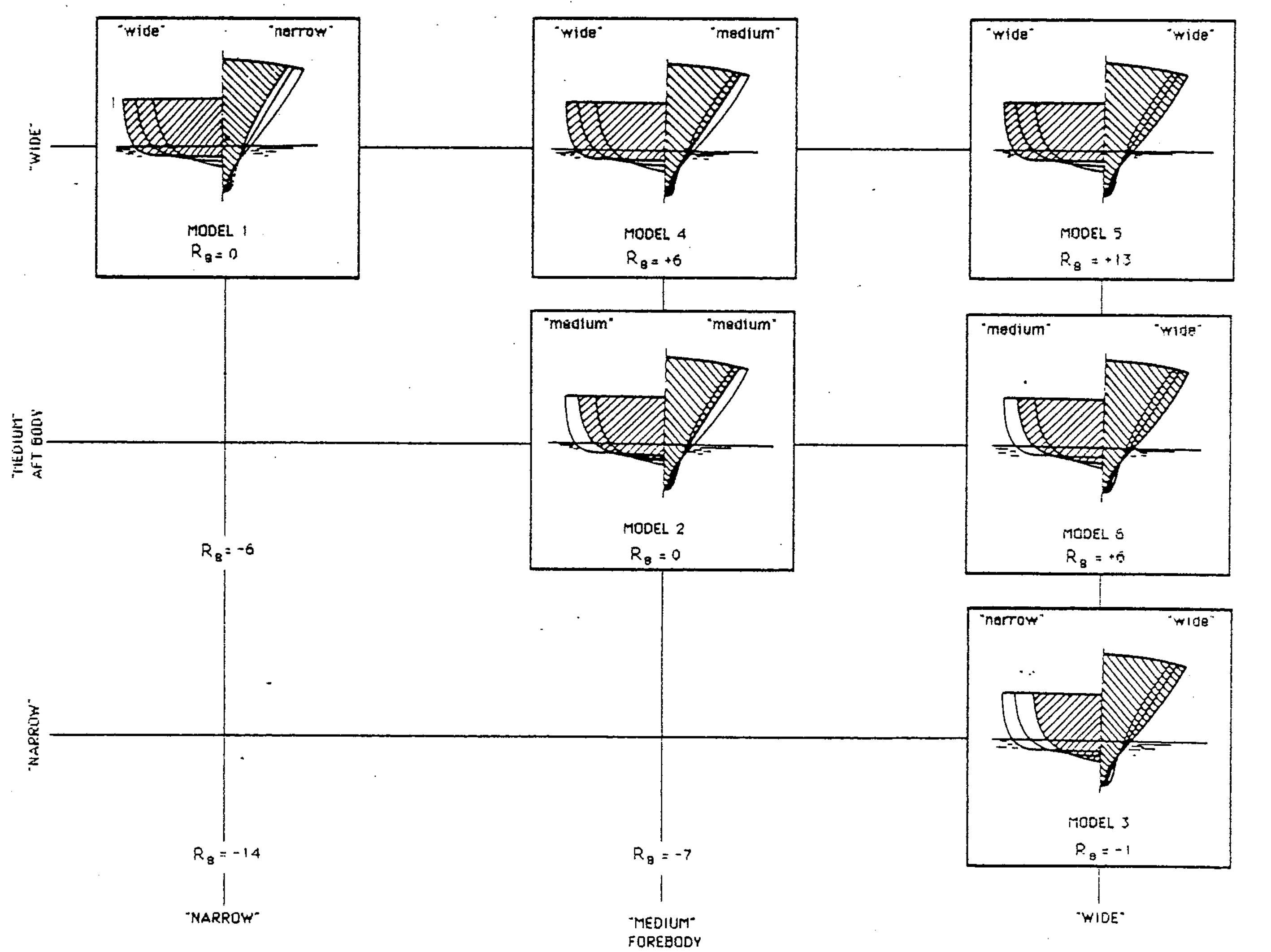


FIGURE 2[3] - SYSTEMATIC SERIES HULL FORMS GENERAL CHARACTERISTICS - SUBSERIES 1.

TYPE OF SHIP	TYPICAL L_{WL}	TYPICAL DISPLACEMENT ∇ (m)^3	DESIGN SPEED (KNOTS)	$F_n = \frac{V}{\sqrt{g * L_{WL}}}$	$F_{n\nabla} = \frac{V}{\sqrt{g * \nabla^{1/3}}}$	$\frac{L_{WL}}{\nabla^{1/3}}$
PATROL BOAT	40	300	40	1.04	2.54	6.00
CORVETTE	85	1800	30	0.53	1.41	7.00
FRIGATE	125	3800	30	0.44	1.25	8.00
DESTROYER	155	7300	35	0.46	1.31	8.00
CRUISER	210	18000	40	0.45	1.28	8.00

TABLE 1[(2)] - TYPICAL CHARACTERISTICS OF NAVAL VESSELS OF INTEREST

Designation	Notation	NSMB Model No.					
		Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
Length/breadth	L_{WL}/B_{WL}	8	8	8	8	8	8
Breadth/draft	B_{WL}/T	4	4	4	4	4	4
Block coefficient:							
total	C_B	0.396	0.396	0.396	0.396	0.396	0.396
forebody	C_{BF}	0.327	0.327	0.327	0.327	0.327	0.327
aftbody	C_{BA}	0.465	0.465	0.465	0.465	0.465	0.465
Midship section coefficient	C_M	0.633	0.633	0.633	0.633	0.633	0.633
Waterplane coefficient:							
total	C_{WP}	0.785	0.768	0.749	0.790	0.796	0.774
forebody	C_{WPF}	0.577	0.588	0.600	0.588	0.600	0.600
aftbody	C_{WPA}	0.992	0.947	0.898	0.992	0.992	0.947
Horizontal prismatic coefficient							
total	C_P	0.626	0.626	0.626	0.626	0.626	0.626
fore	C_{PF}	0.517	0.517	0.517	0.517	0.517	0.517
aft	C_{PA}	0.735	0.735	0.735	0.735	0.735	0.735
Vertical prismatic coefficient							
total	C_{VP}	0.505	0.516	0.528	0.501	0.497	0.512
fore	C_{VPF}	0.567	0.556	0.545	0.556	0.545	0.545
aft	C_{VPA}	0.469	0.491	0.518	0.469	0.469	0.491
Longitudinal center of bouyancy in % L	LCB	-4.97	-5.12	-5.16	-5.02	-5.11	-5.22
Longitudinal center of floatation in % L	LCF	-9.23	-8.11	-6.77	-9.01	-8.68	-7.77
Angle of waterline entrance, degrees	i_e	6.5	9.5	11.0	9.5	11.0	11.0
Breadth transom/breadth	b_t/B	0.89	0.74	0.59	0.89	0.89	0.74

TABLE 2[(3)] - MAIN DESIGN CHARACTERISTICS IN SUB-SERIES 1.

For the trade-off between calm water resistance and seakeeping characteristics in head waves a dimensional numerical design point was selected having the following particulars:

Length	85 m		
Speed	48 knots		
F_n	0.855		
F_{n_∇}	2.49		
Seastate 4	$\bar{\zeta}_{w\ 1/3}$	=	2.50M
	$\bar{T}_i$	=	7.00 sec

Table 4 provides the trade off values between calm water resistance and seakeeping characteristics from which the Parent Hull was selected. Model 2 was arbitrarily set to 100 percent for comparative purposes both for resistance and motion. Numerical values are relative to model 2 as a percentage. The plus sign indicates an improvement while a negative sign means an inferior performance compared to model 2.

On the basis of table 3, model 5 was selected as the Parent Hull as it had good calm water resistance and low overall resistance in waves (although models 3 and 6 were better). Model 5 had superior pitch and acceleration values although the relative motions of model 4 were superior. However it was considered that model 5 could be improved in regard to relative motions with an increase in flare in the above water form.

Considering all aspects, model 5 was selected because of its superior motion characteristics at an expense on approximately 2 percent penalty with added resistance in waves. It is also of interest to note the high value of seakeeping figure of merit R_B.

The final lines of the Parent Hull (Model 5, subseries 1) are depicted in Fig 3.

3. DEVELOPMENT OF SYSTEMATIC SERIES

Having derived the Parent Hull and the prime variable parameters and after consideration of the potentially available budget for model manufacture and testing it was decided that the basic test series could accommodate twenty seven individual models which would be tested at one displacement and trim. The prime variable parameters for the twenty seven models were selected in such a way that a 'Magic Cube' evolved with the Parent Hull at its centre. Figure 4 depicts the 'Magic Cube' showing the parametric space of the basic test series.

The models were initially divided into seven separate series (series 1-7) consisting of the Parent model and fourteen other models representing the central planes of the 'Magic Cube'. It was anticipated at this stage that the corner model results could be extrapolated from series 1-7 models however this was subsequently found to be impractical. Series 8 and 9 were later added to the testing programme to cover the corners of the 'Magic Cube'. Fig 5 depicts the various model series of the basic test series.

The transformation from the parent hull form to all other models introduced some difficulties which were eventually overcome by the development of a new transformation procedure which ensured that the character of the Parent Hull was maintained while transforming over a wide Block Coefficient range.

The transformation from the Parent Hull to series 1 and 2 models which had the same C_B as the Parent Hull was a simple linear transformation for breadth B_{WL} and Draft T since the curve of section area for all models in these two series was the same.

Speed, $F_{n\nabla}$	Model No.					
	1	2	3	4	5	6
1.0	95.2	100	100.0	120.8	96.2	120.6
1.5	97.6	100	91.0	96.0	91.6	88.4
2.0	100.3	100	93.8	99.2	89.4	91.1
2.5	101.2	100	93.2	99.5	94.9	90.9
3.0	104.1	100	89.9	100.0	98.0	88.7
3.5	103.5	100	89.8	101.1	98.0	90.4

TABLE 3[3]– RESIDUARY RESISTANCE COMPARISON NORMALIZED ON MODEL 2 FOR SUBSERIES 1.

	Calm-Water Resistance				Seakeeping Characteristics						
Model No.	$C_{FS}+C_A$ $*10^3$	C_{RM} $*10^3$	C_{TS} $*10^3$	R_{TS} (tonne)	z (m) rms	ϕ (degrees) rms	s_{17} (m) rms	a_{19} (g) rms	R_{AW} (tonne)	R_T (tonne)	R_B
1	1.428	1.168	3.046	88.39	0.36	0.66	1.66	0.26	6.77	95.15	
2	1.428	1.651	3.079	88.44	0.39	0.66	1.77	0.27	6.48	95.28	
3	1.428	1.553	2.981	88.87	0.39	0.73	1.94	0.29	7.77	96.64	
4	1.428	1.593	3.021	88.75	0.39	0.61	1.56	0.26	6.77	95.52	
5	1.428	1.511	2.939	86.85	0.36	0.59	1.69	0.25	7.11	93.96	
6	1.428	1.470	2.898	84.44	0.37	0.63	1.63	0.27	7.50	91.94	
1				+0.1	+7.7	+7.6	+6.2	+3.7	+1.0	-1.0	0
2				0	0	0	0	0	0	0	0
3				+5.2	0	-10.6	-9.6	-7.4	-13.6	+4.0	-1
4				-0.4	+2.6	+7.6	+11.9	+3.7	+1.0	0	+6
5				+1.8	+7.7	+10.6	+4.5	+7.4	-3.9	+1.4	+13
6				+4.5	+5.2	+4.5	+7.9	0	-9.6	+3.6	+6

TABLE 4[3]– TRADE-OFF BETWEEN CALM WATER RESISTANCE & SEAKEEPING CHARACTERISTICS IN HEAD WAVES FOR SUB-SERIES 1.

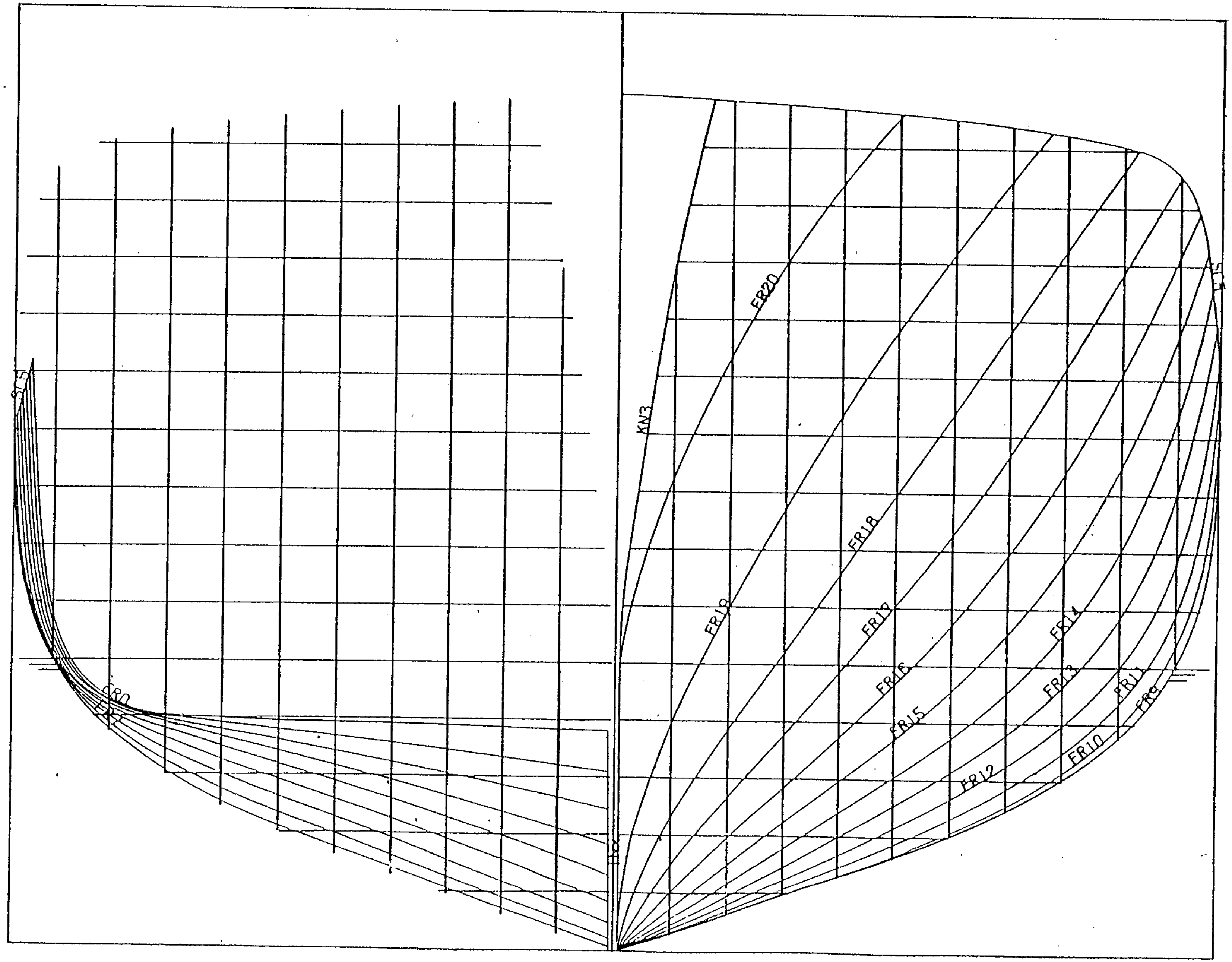


FIGURE 3 - PARENT HULL FORM SELECTED FROM SUB-SERIES 1.

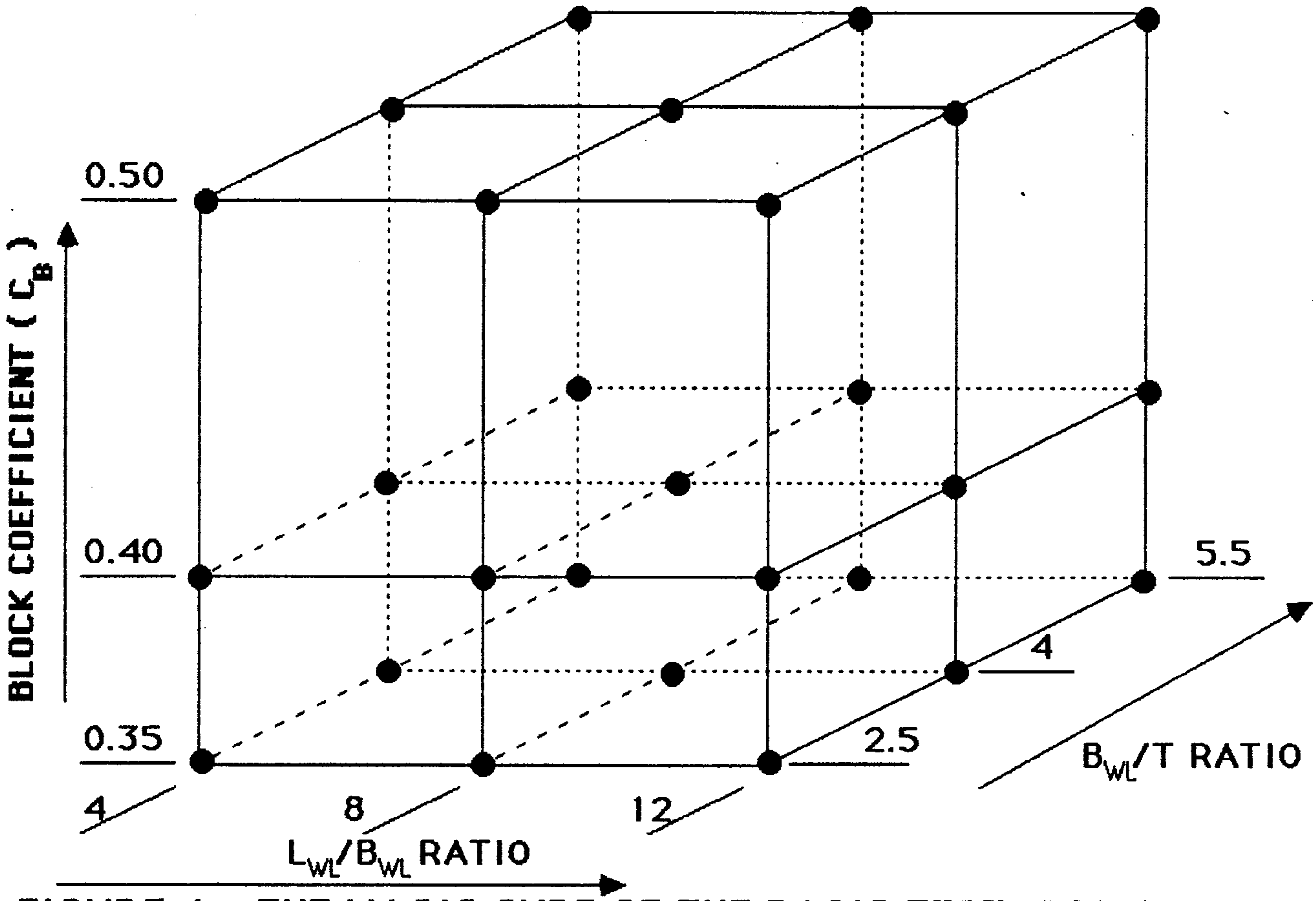


FIGURE 4 - THE MAGIC CUBE OF THE BASIC TEST SERIES.

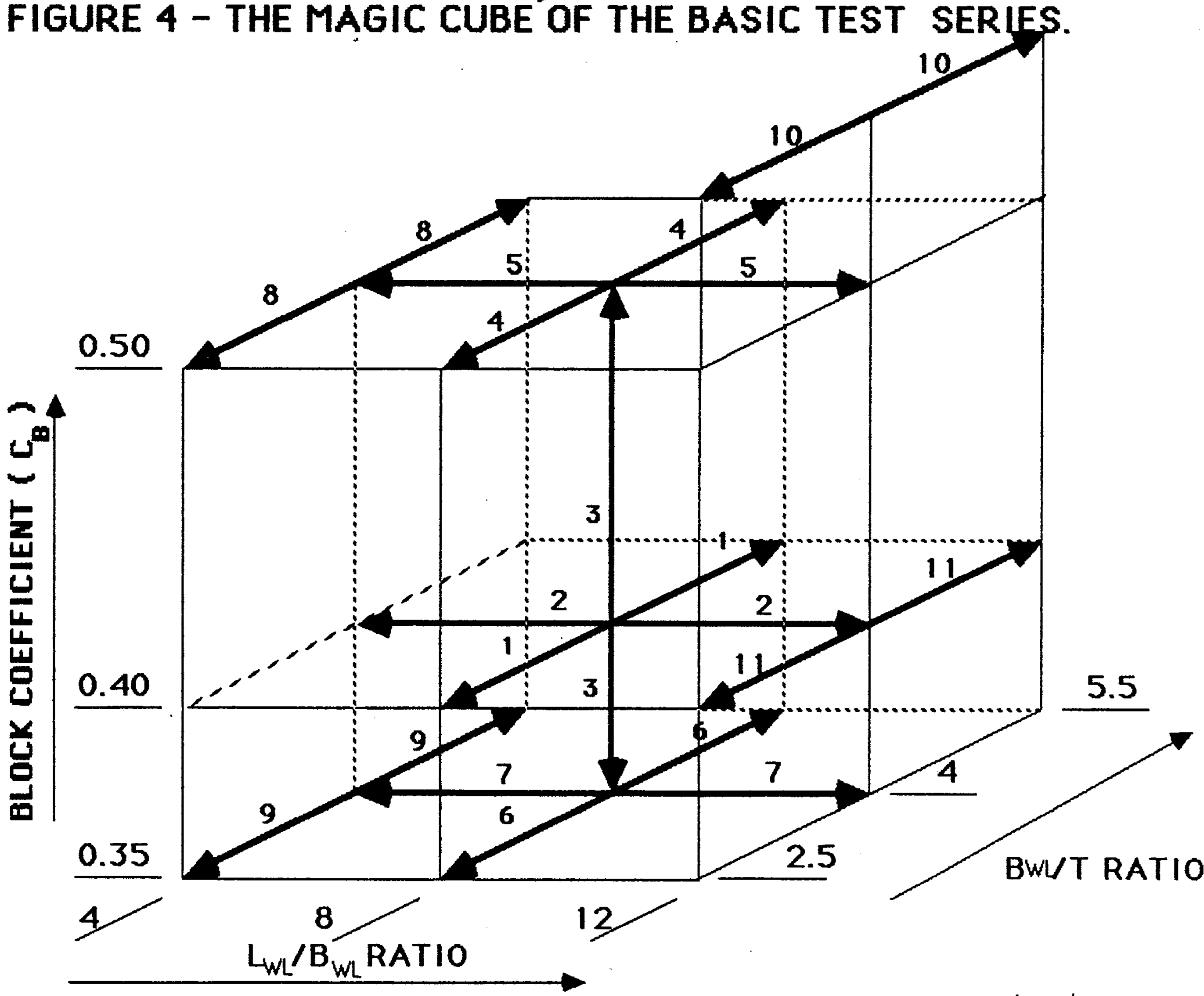


FIGURE 5 - MODEL SERIES IDENTIFICATION

For models with C_B different to the Parent Hull the newly developed transformation procedure commenced by multiplying the ordinates of the section area curve by a constant ratio of the actual C_B/parent hull C_B. This ensured that the C_P and position of LCB was always the same as the Parent Hull. The next step in the transformation procedure was to transform the offsets. The transformation formulas used at any longitudinal station X were:

$$Y_{new} = Y_{parent}$$
$$Z_{new} = Z_{parent} + Z_o + Y\tan\alpha$$

Where
Y = half breadth of section
Z = vertical coordinate (above baseline)
α = angle over which the vertical coordinates are rotated
Z_o = distance over which the profile of the ship at any section is vertically translated.

Fig 6 depicts the transformation of a section shape requiring a decrease in sectional area. Fig 7 depicts the transformation of a section shape requiring an increase in sectional area.

The values of α and Z_o are constant for any section at X. The calculation of α is carried out by first assuming Z_o=0 and then calculating the required value of α to obtain the required sectional area from the transformed sectional area curve. If α is too large leading to a forward section with excessive flare or if α is too small leading to an unacceptable flat deadrise the profile of the ship is altered. Having derived a transformed hull form for each C_B other forms with the same C_B are transformed by the simple linear procedures. By adopting these transformation techniques all twenty seven model hull forms belong to a true geometric family of underwater body forms. The transformed abovewater forms however are not considered to be truely geometric in shape & do not follow modern trends for reduced radar cross section and enhanced stability.

After testing fifteen of the models from the basic test series it was decided in 1984 to check on the validity of the initial C_P value selected for the Parent Hull and thus the entire basic test series. Two additional models were manufactured and tested. These models had the same C_B as the parent hull $L_{wl}/B_{wl}=8$; $B_{wl}/T=4$ and $C_P=0.685$ and 0.561. The Parent Model and these two additional models permitted the determination of the influence of prismatic coefficient on resistance and seakeeping. This new subseries was subsequently identified as the C_P subseries 2.

In 1984 a second subseries was introduced when it was established by a study at DTNRDC (4) that the basic test series produced hulls far superior with respect to seakeeping than other known hull forms in the Frigate-Destroyer size range. Further work at MARIN (5) also indicated that the propulsion factors of the hulls generated from the basic test series were also very favourable. This subseries known as the frigate subseries consisted of a further eight models which constituted that part of the 'Magic Cube' with an extension of C_B to 0.55 and represented the modern frigate and destroyer portion of the 'Magic Cube'. The characteristics of the eight additional models are as depicted in table 5. Unlike the C_P subseries these additional models were still transformations of the parent hull.

Fig 8 depicts the revised 'Magic Cube' to accommodate the C_P and the frigate subseries (subseries 2 and 3).

4. EXPERIMENTAL PROGRAMME

All ship models tested throughout the experimental programme varied in length from 3 to 6 m on the designed waterline. The models had different displacements depending on the major characteristics of the hulls. The Freeboard of the models varied from .06 L_{wl} to .09 L_{wl} at the forward perpendicular but the relative Freeboard along the models length was kept the same for all models. It was however unfortunate that the above water form did

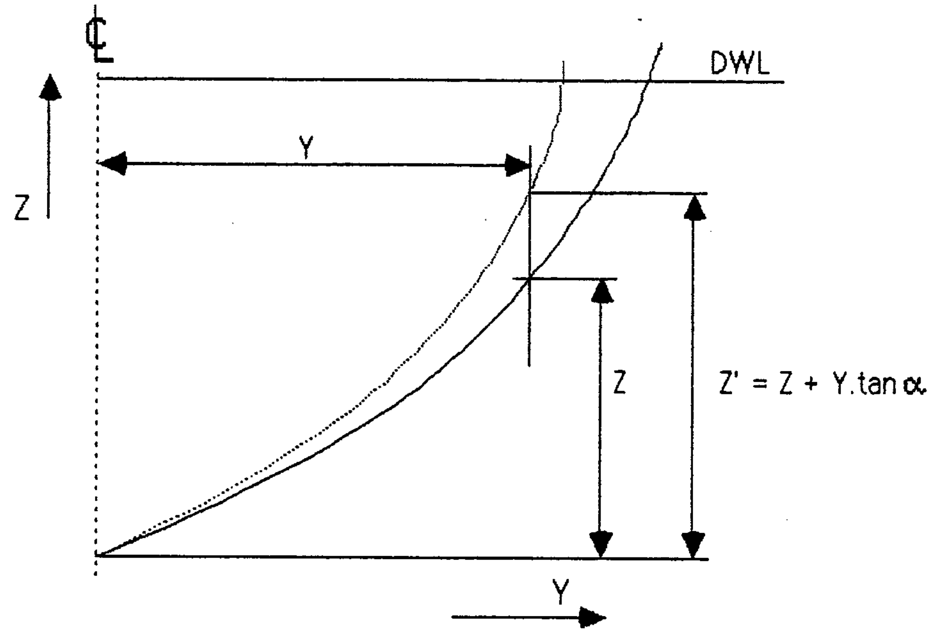


FIGURE 6 - TRANSFORMATION OF SECTION SHAPE REQUIRING A DECREASE IN SECTIONAL AREA, ONLY UTILIZING α.

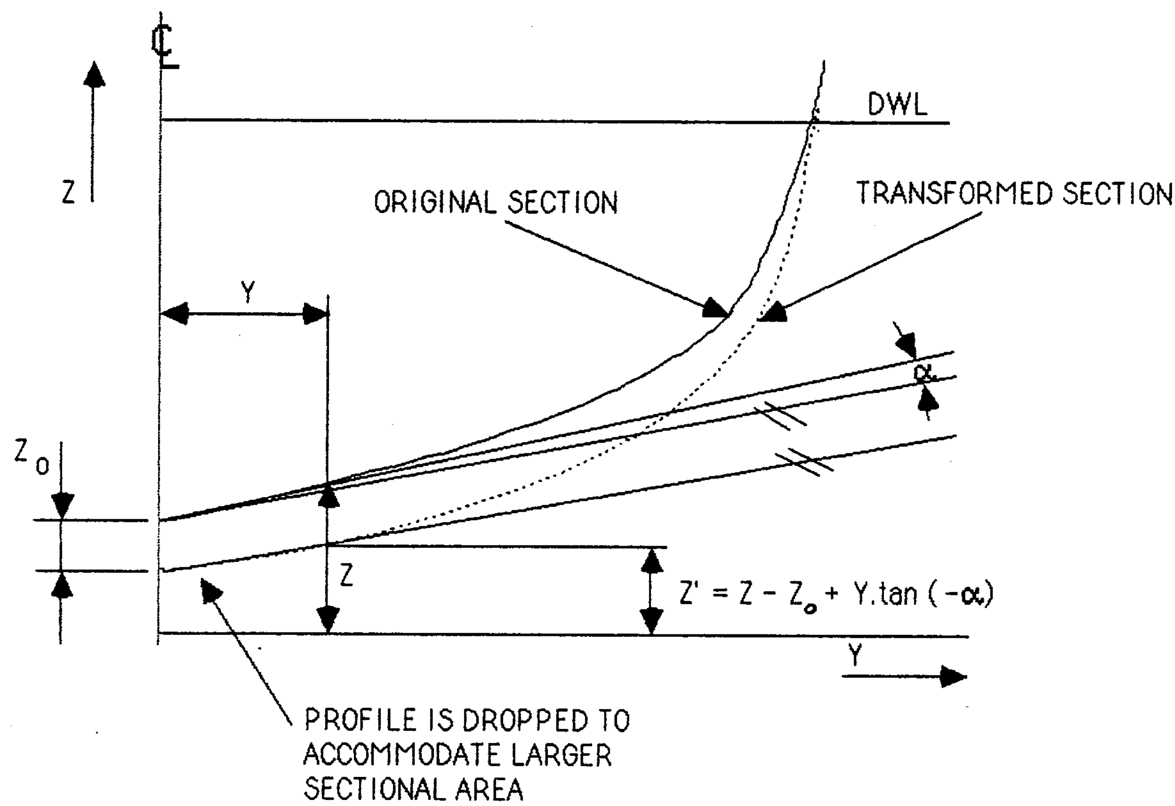
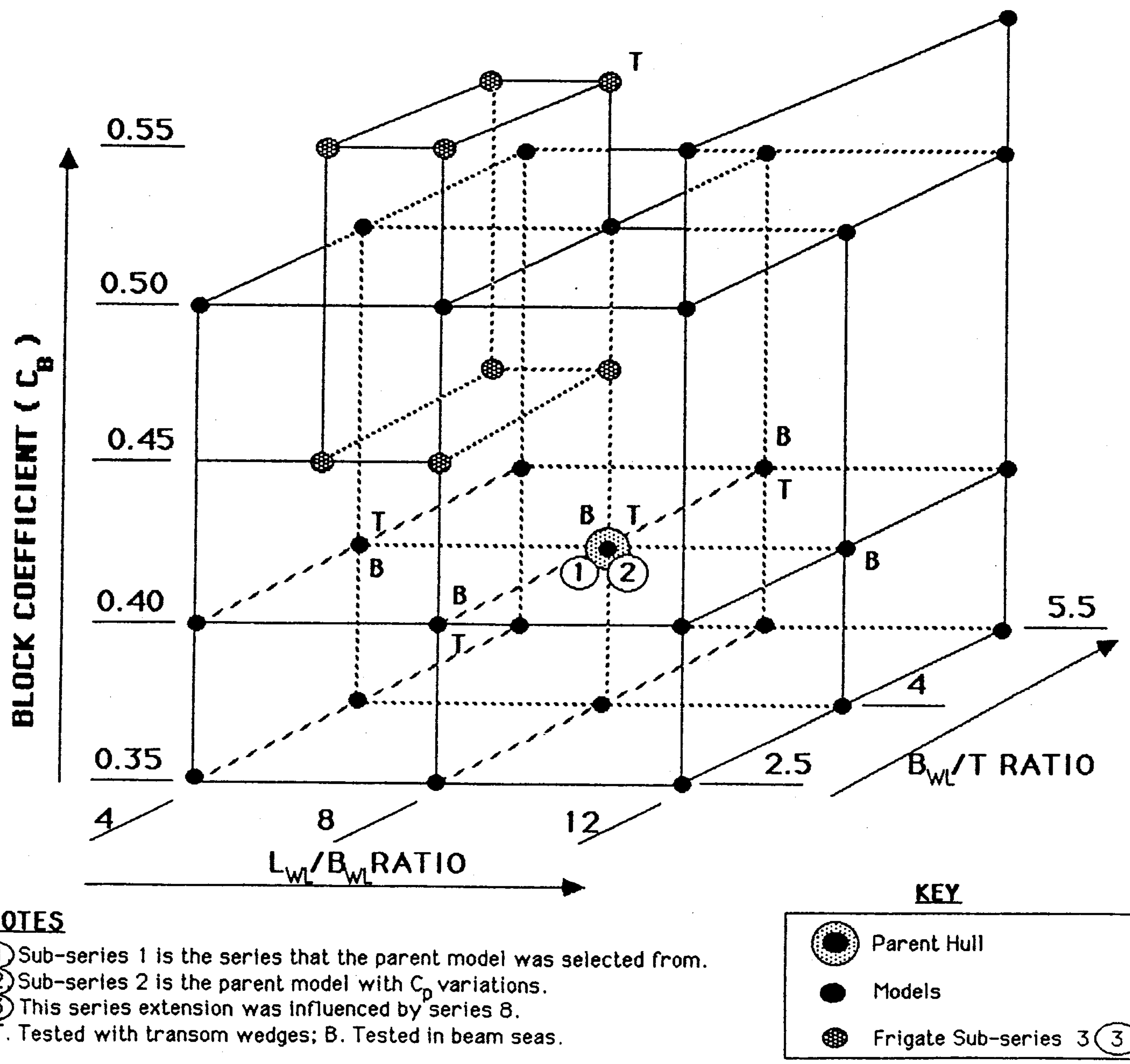


FIGURE 7 - TRANSFORMATION OF SECTION SHAPE REQUIRING AN INCREASE IN SECTIONAL AREA USING BOTH α AND z_0.

L_{WL}/B_{WL}	B_{WL}/T	C_B
6	2.5	0.45
6	2.5	0.55
6	4.0	0.45
6	4.0	0.55
8	2.5	0.45
8	2.5	0.55
8	4.0	0.45
8	4.0	0.55

TABLE 5 - CHARACTERISTICS OF THE FRIGATE SERIES.



NOTES

(1) Sub-series 1 is the series that the parent model was selected from.
(2) Sub-series 2 is the parent model with C_p variations.
(3) This series extension was influenced by series 8.
T. Tested with transom wedges; B. Tested in beam seas.

FIGURE 8 - REVISED MAGIC CUBE

not represent modern trends with regards to ship side splay to reduce radar cross section and enhance the stability characteristics. The Gyradius of the models was kept constant at 0.25 L_{wl} and the vertical centre of gravity was taken as 60 percent of the model depth amidship which was 0.169 m for the 5.0 m models. All models were fitted with sand strips to trip the boundary layer into turbulence. No underwater appendages were attached to the models.

All Calm Water Resistance Tests were conducted in the MARIN Deepwater Towing Tank (250 m x 10.5 m x 5.5m). While the Head Seas Tests were conducted in the MARIN High Speed Towing Tank (220 m x 4.0 m x 3.6 m).

The models were towed from the vertical centre of gravity. For the calm water tests the testing rig allowed for model sinkage and trim. For the head seas tests, the models were restrained in sway, yaw and surge, while pitch, heave and roll were not restricted.

For calm water resistance tests the models were run at a single displacement and trim over a range of F_{n_∇} from 0.25 up to 4.0 where considered appropriate. After deduction of the calculated model frictional resistance according to the two dimensional ITTC 1957 Extrapolation Method the residuary resistance per ton of displacement was determined on the basis of F_{n_∇} and depicted on a standard format for later relative assessment. The measured sinkage at the fore and aft perpendiculars was also measured for each model at each of the model speeds and again represented on a standard format for future comparison. From the sinkage measurements the trim angle and the rise of centre of gravity were derived and also depicted on a standard format for future comparison. Admiralty constants for estimation of effective power were later derived for ship displacements of 10 to 5000M^3.

For tests in waves all models in the series were run in regular and irregular head waves while subseries models were run in regular head waves only. The regular waves had a height of .02 L_{wl} and lengths which varied from .4 to 2.8 L_{wl}. A series of experiments with different wave heights was also conducted to determine the degree of linearity at high speed. The regular waves were supplemented with two irregular sea states mainly to check on linearity and superposition. The seastates represented a low seastate with a comparatively short average period and a high seastate with longer waves. The simulated irregular waves were made to conform as far as possible with the ISSC Spectra following the Pierson-Moskowitz shape, however the Pierson-Moskowitz shape was lost in the high frequency range.

Measurements, notations and definitions adopted for the tests in waves are as shown in Table 6.

For all experiments in head seas the models were run at a single displacement and trim over a wide speed range of F_n from 0.285 to 1.14. Measurements of added resistance, heave, relative motions, vertical accelerations and pitch were converted to transfer functions from regular wave results and to response functions from irregular wave results and presented on a dimensionless base at constant F_n in a standard format for comparative purposes later. Table 7 depicts the selected functions and base parameters used for the presentation of the results.

The linearity and superposition principles were validated when the regular wave results were used to predict the motions in the irregular wave tests.

Initially it was considered that self propulsion tests would be run on selected models to determine the hull propulsion factors, however the selection of standard and appropriate appendages proved to be difficult and the experimentation associated with this requirement was not undertaken. Computational methods will be investigated in lieu of model experimentation.

QUANTITY	NOTATION	DIMENSION	DEFINED POSITIVE	MEASURING DEVICE
HEAVE AT C.G.	z	cm	UPWARD MOTION	POTENTIOMETER
PITCH	ϑ	deg	BOW GOING DOWN	GYRO FITTED WITH POTENTIOMETER
VERTICAL ACCL. AT STATION 19	a	g	UPWARD	ACCELEROMETER
RELATIVE MOTION AT STATIONS 16, 17, 18, & 19.	s	cm	IMMERSION OF MODEL	RESISTANCE TYPE WIRE PROBES
RESISTANCE AT C.G.	R	N	FORWARD SPEED	STRAIN GUAGE TRANDUCER
WAVE HEIGHT 3.5m IN FRONT OF MODEL	ζ	cm	WAVE CREST	SERVO CONTROLLED FOLLOWER DEVICE

TABLE 6 – MEASUREMENTS, NOTATIONS & DEFINITIONS FOR TESTING IN WAVES

	REGULAR WAVES		IRREGULAR WAVES		
MEASUREMENTS	TRANSFER FUNCTION	BASE PARAMETER	RESPONSE FUNCTION	BASE PARAMETER	PHASE ANGLE
ADDED RESISTANCE	$\frac{\Delta R L_{WL}}{\rho g B^2 \zeta_a^2}$	$\sqrt{\frac{L_{WL}}{\lambda}}$, $\frac{\lambda}{L_{WL}}$	$\frac{\Delta R}{\tilde{\zeta}^2_{wl_{1/3}} B}$	$\frac{L_{WL}}{\tilde{\bar{T}}^2}$	
HEAVE	$\frac{z_a}{\zeta_a}$	$\sqrt{\frac{L_{WL}}{\lambda}}$, $\frac{\lambda}{L_{WL}}$	$\frac{2\tilde{Z}_a}{\bar{\zeta}_{wl_{1/3}}}$	$\frac{L_{WL}}{\tilde{\bar{T}}^2}$	✓
RELATIVE MOTION	$\frac{s_a}{\zeta_a}$	$\sqrt{\frac{L_{WL}}{\lambda}}$, $\frac{\lambda}{L_{WL}}$	$\frac{2\xi a_{1/3}}{\bar{\zeta}_{wl_{1/3}}}$	$\frac{L_{WL}}{\tilde{\bar{T}}^2}$	
VERTICAL ACCELERATION	$\frac{a_a L_{WL}}{\zeta_a}$	$\frac{\lambda}{L_{WL}}$	$\frac{2\tilde{a}_{1/3} L_{WL}}{\bar{\zeta}_{wl_{1/3}}}$	$\frac{L_{WL}}{\tilde{\bar{T}}^2}$	
PITCH	$\frac{\theta_a}{k\zeta_a}$	$\sqrt{\frac{L_{WL}}{\lambda}}$, $\frac{\lambda}{L_{WL}}$	$\frac{2\theta_{a_{1/3}} L_{WL}}{\bar{\zeta}_{wl_{1/3}}}$	$\frac{L_{WL}}{\tilde{\bar{T}}^2}$	✓
PITCH	$\frac{\theta_a L_{WL}}{\zeta_a}$	$\sqrt{\frac{L_{WL}}{\lambda}}$			

TABLE 7 – FUNCTIONS FOR TESTS IN HEAD SEAS

A further subseries (subseries 4) was created and tested to investigate the effect of Transom Wedges on performance in calm water and in waves. Existing models from the series were utilized for this purpose.

A future subseries of existing models is proposed to study Roll Behaviour which will consist of model tests in beam waves and roll decay tests. This will be supplemented with computational methods.

Initially it was also considered appropriate to investigate the effect of Spray Rails but this is still in a state of abeyance in the present testing programme.

The influence of Gyradius on model motions was initially going to be investigated on some of the existing models but this was ultimately investigated by computational methods.

5. CURRENT STATUS OF MODEL TESTING PROGRAMME

Considerable model testing has been undertaken since 1979 to the point where most of the models in the extended 'Magic Cube' have been tested in calm water and in head seas. Fig 9 depicts the current status of the model testing programme. Series 10 calm water testing will be conducted in 1987 while series 11 calm water testing and series 10 testing in waves will be conducted in 1988. Series 11 model testing in waves will be conducted either in 1988 or 1989 depending on the proportioning of available funds. Further series testing of the models remaining in the Magic Cube after series 11 is unlikely but this will be dependent on the outcome of the validation of the regression equation results derived from the models already tested.

All model testing associated with subseries 2 and 3 is complete. It is unlikely that further testing with subseries 4 models (Transom Wedges) will be undertaken in calm water but this will be dependent on the prediction accuracy derived from the yet to be developed regression equations. It is still undecided if further subseries 4 testing in waves will be undertaken.

Beam seas tests will be conducted on series 1 and 2 models during 1987 while roll decay tests on series 1, 2, 4, 5 and 7 will be conducted in 1988. Further testing on some of the existing models fitted with spray rails is also likely.

6. CURRENT STATUS OF SUPPLEMENTARY PROGRAMME

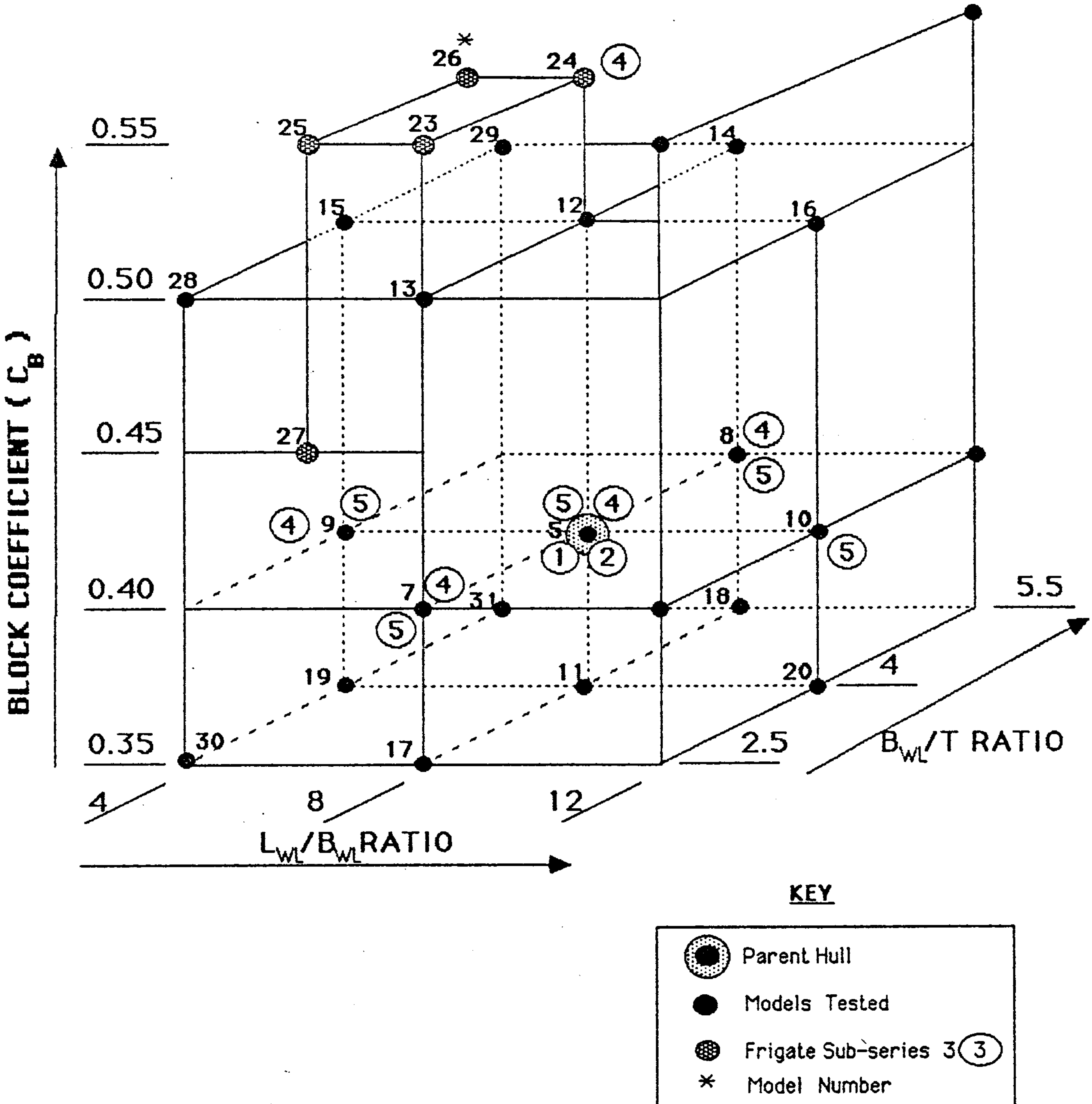
During the timescale that the systematic series model testing was being conducted, the members of the project team were very conscious of the expense and time taken to manufacture and test so many models. To this end they initiated tasks within a supplementary programme which were derived to check by computational methods the results obtained from the model tests and to look at other variables and methods which may ultimately lead to a reduction in the amount of future model testing.

Delft University of Technology was tasked to investigate the relative merits of a Hard Chine version of the Parent Hull form by comparative model testing in calm water and in head seas. Other tasks undertaken by Delft University of Technology were:

a. Computational Validation of Parent Hull subseries 1 model test results in waves.

b. PMM tests on a segmented parent model to investigate restoring heave forces and to measure added mass and damping and to compare results with strip theory predictions.

c. Computational derivation of influence of Gyradius on seakeeping on Parent model.



NOTES

(1) Sub-series 1 is the series that the parent model was selected from.
(2) Sub-series 2 is the parent model with C_p variations.
(3) This series extension was influenced by series 8.
(4) Sub-series 4 Tested with transom wedges
(5) Sub-series 5 Tested in beam seas

FIGURE 9 - STATUS OF MODEL TESTING

d. Computational validation by seakeeping programs 'TRIAL' and 'SERVICE' for model 9.

e. Computational validation by seakeeping program 'TRIAL' of twenty models from the systematic series.

To further complement the model testing programme and to enhance the total software package for the project (described later), investigations have been initiated which will ultimately lead to the computational prediction of the following aspects of the standard series:

a. Appendage Resistance

b. Roll behaviour

c. Propulsion Factors

7. EXPERIMENTAL AND COMPUTATIONAL RESULTS

Although the test results of the systematic series of models tested in waves and in head seas are still being analysed and will ultimately be regressed into useable equations, some interesting trends with the prime variables (C_B, $\frac{L_{wl}}{B_{wl}}$, $\frac{B_{wl}}{T}$) have been revealed. Some of these trends are depicted in Figs 10, 11, 12 and 13.

For the purpose of demonstrating these trends the Bales Seakeeping Merit Values (R_B) (6) have been used rather than the more appropriate merit values derived by McCreight (4) or the actual measured seakeeping values. The Admiralty Coefficient C_ε has been also utilized for demonstration purpose where:

$$C_\varepsilon = \frac{\Delta^{2/3} V^3}{P_e}$$

and Δ = Mass in saltwater in Kg
V = Speed in knots
P_e = Effective horsepower
(1 H.P. = 75 Kgm/Sec^1)

From Fig 10 it can be seen that by increasing Lwl/Bwl both seakeeping and powering properties improve. Fig 11 indicates that by increasing $\frac{Bwl}{T}$ both seakeeping and powering properties improve. From Fig 12 it can be seen that the increase of C_B on seakeeping is only minor. However with powering, an increase in C_B has a favourable influence.

Fig 13 depicts the influence of all three variable parameters and from this figure it can be concluded that the driving hull form parameter with respect to seakeeping is the Length-Draft Ratio while for powering the Length-Beam ratio is most important. Within the context of the variable parameters in the systematic series the Block Coefficient is least important for both seakeeping and powering.

The results indicate that the Short Fat Combatant is generally less favourable than its Long Shallow counterpart. It is interesting to note that if the Length-Draft ratio is the factor driving seakeeping, that a specific seakeeping performance can only be retained for a shorter hull if the draft is decreased in the same proportion that the length is decreased. This is not possible in the context of keeping the specific design displacement when the Block Coefficient is kept the same.

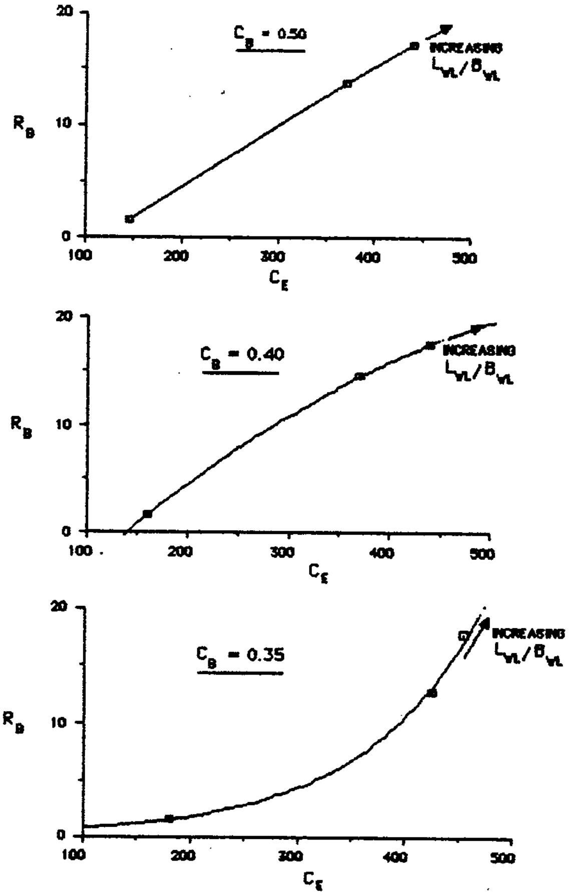


FIGURE 10[2] - INFLUENCE OF $\frac{L_{VL}}{B_{VL}}$ FOR $\frac{B_{VL}}{T}$ =4 & $F_{n\nabla}$ = 1.0

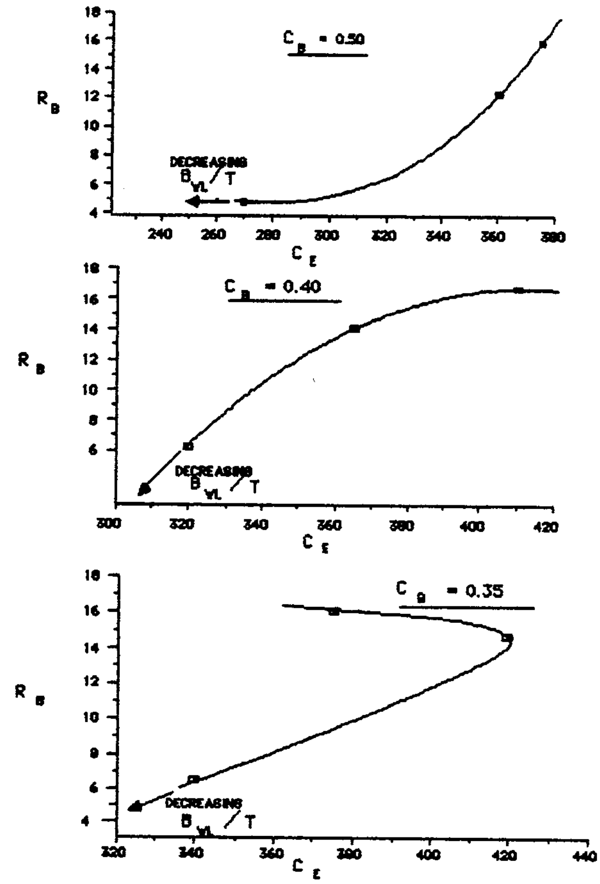


FIGURE 11[2] - INFLUENCE OF $\frac{B_{VL}}{T}$ FOR $\frac{L_{VL}}{B_{VL}}$ = 8 , & $F_{n\nabla}$ = 1.0

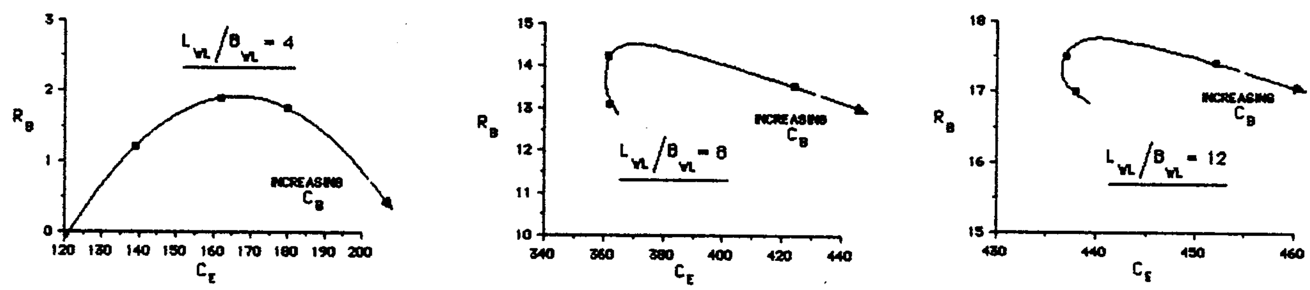


FIGURE 12[2] - INFLUENCE OF C_B FOR $\frac{B_{VL}}{T}$ = 4 & $F_{n\nabla}$ = 1.0

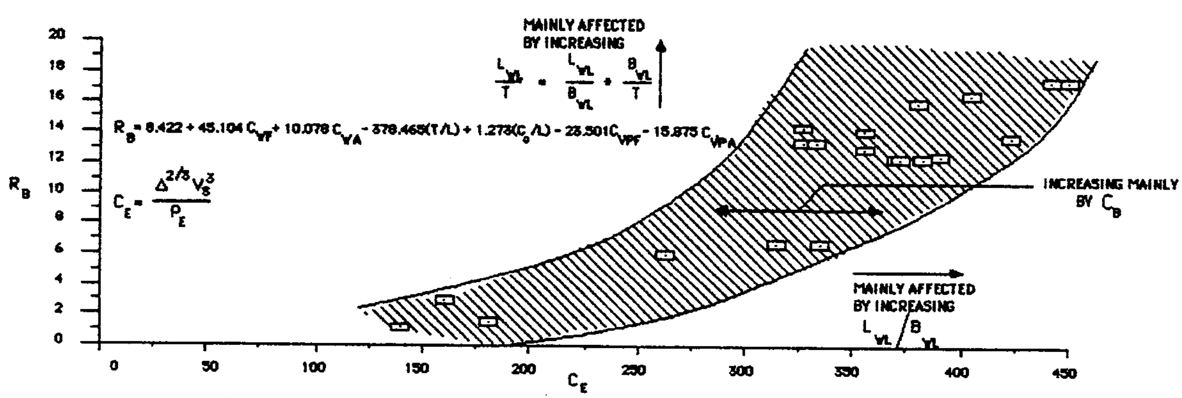


FIGURE 13[2] - MAIN TRENDS FOR THE SYSTEMATIC SERIES FOR $F_{n\nabla}$ = 1.0

It was established during the subseries 2 model testing programme that over the entire speed range the model with the highest Prismatic Coefficient (C_P=0.685) had the highest resistance while the model with the lowest Prismatic Coefficient (C_P=0.561) had a lower resistance than the Parent Model (C_P=0.626) in the speed range up to F_{n_∇} = 1.3 and beyond F_{n_∇} = 3.3. It was apparent that the optimum C_P for calm water resistance for the specific combination of main dimensions and displacement is very close to the value selected for the parent hull providing speeds around the main hump speed are considered. Fig 14 clearly demonstrates this point.

The effect of Prismatic Coefficient variations on motions in waves was very small with the small differences being attributed to secondary effects such as model geometry variation rather than the Prismatic Coefficient variation. This again validated the C_P selection for the Parent Hull.

With regard to the influence of Transom Wedges (subseries 4) it was established that their influence was very moderate below the hump speed F_{n_∇}= 1.2-1.4, but for speeds in the hump region 1.2-1.4 $< F_{n_\nabla} <$ 2.0-2.2, a reduction in residual resistance of more than 10 percent was realised. At very high speeds $F_{n_\nabla} >$ 2.6 the positive influence of transom wedges disappears and gives an increase in resistance at speeds $F_{n_\nabla} >$ 3.4. The transom wedges tested had almost no effect on seakeeping behaviour. However it was observed that spray generation increased as the trim angle reduced. No further testing in waves will be carried out.

Computational investigations into the influence of the Gyradius from .22 to .28 L_{bp} indicated that the effect on motions was very small, the influence on heave motion being slightly more noticeable than the influence on pitch motion. All motions and added resistance in waves were reduced as the Gyradius decreased, a percentage reduction of added resistance in waves was also evident which was almost speed independent.

The conclusion reached by Delft Institute of Technology concerning their comparative model tests with the parent hull form and an equivalent chine form was that there was no advantage to be gained from using a chine on the parent hull and that decrease in resistance of the chine form could only be expected when considerable changes were made to the original hull form.

The computations carried out by Delft University of Technology to validate their ship motion programs with model test results produced a surprise. The results indicated that the simplest program using Lewis Forms and Strip Theory gave the best validation for the parent model and model 9 at all F_n values. This program confirmed that validation on a further twenty models was reasonable with strip theory prediction with pitch being better than heave. For hulls with the same L_{wl}/B_{wl}, better results were obtained for higher values of B_{wl}/T. For hulls with the same B_{wl}/T better results were obtained for higher L_{wl}/B_{wl} values. It was also established that the main errors in the strip theory was its tendency to predict lower than measured response functions at resonance. However it was generally concluded that strip theory provided a good preliminary design tool which could be used on forms like those constituting the systematic series of the High Speed Displacement Hull Form Project for motions other than relative motions and added resistance in waves at much higher values of F_n than was previously thought possible.

As a practical demonstration of the value of the work already done in the project the Directorate of Naval Ship Design undertook two 'in house' studies which ultimately proved that superior seakeeping performance ships could be derived from the standard series. The first study looked at the seakeeping merit of a number of existing modern frigate designs and compared them with a frigate which was designed from the series and which is currently under construction in Europe. Fig 15 tells the complete story. The second study involved redesigning the RAN FFG utilizing the Parent Hull Form. In this study the revised FFG Design had the same waterline length as the

RESIDUARY RESISTANCE PER TON OF DISPLACEMENT R_R / ∇

SUB-SERIES 2

SHIP MODEL	6406	F5607A/A5609	6407
L_{WL}/B_{WL}	8.0	8.0	8.0
B_{WL}/T	4.0	4.0	4.0
C_B	0.40	0.40	0.40
C_P	0.685	0.626	0.561

R_R = Residual Resistance in tons of 1000 Kg f.
∇ = Displacement in fresh water
V = Ship Speed in Knots
Δ = Displacement Volume in m^3
g = 9.81 m/sec ^{2}

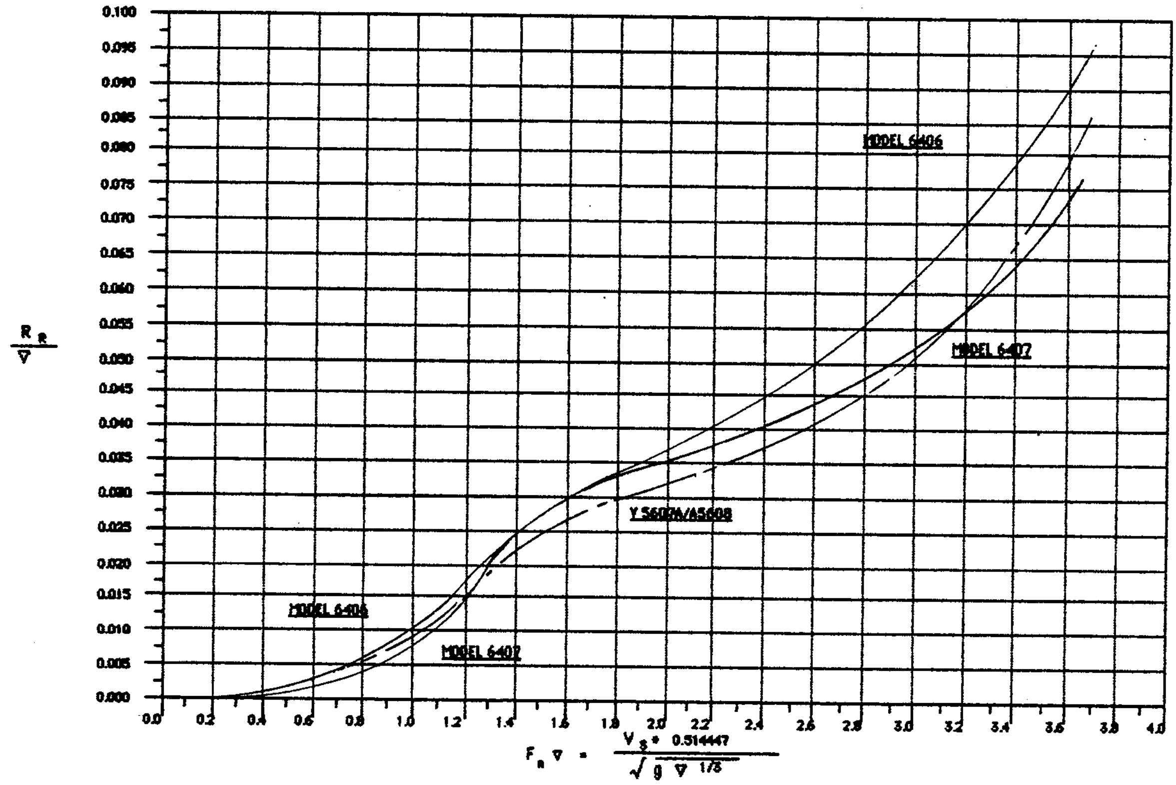


FIGURE 14 - SUBSERIES 2 C_p VARIATION. CALM WATER TEST RESULTS

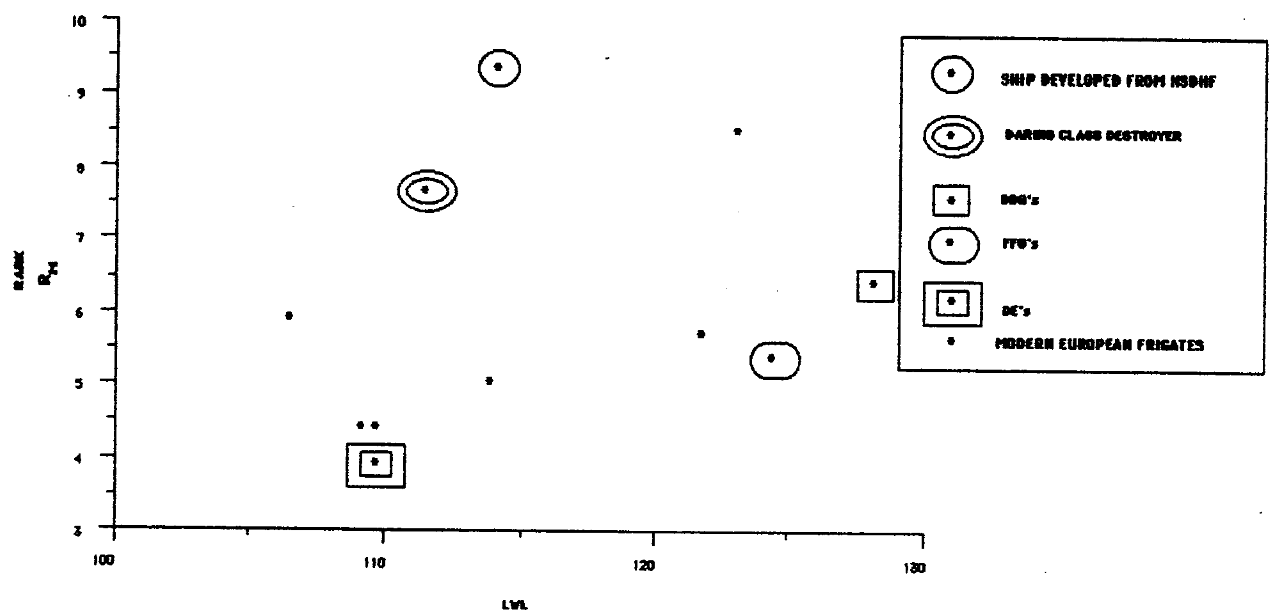


FIGURE 15 - MODERN FRIGATES SEAKEEPING PERFORMANCE

existing FFG, the Hull Form was that of the Parent Hull Form of the series with comparable beam and draft and the displacement was slightly reduced. The results from this study showed that the redesigned FFG could be expected to sustain helecopter operations up to one seastate higher than is possible with the existing FFGs.

8. SOFTWARE DEVELOPMENT

With such a project as the High Speed Displacement Hull Form Project it was perceived early on that a vast amount of experimental data would be collected and the task of presenting this data in a useable form for the ship designer could be a task equal in magnitude to that of the experimental program itself. The project members pursued the line that if the results were not easy to access in the way of a total software package the potential of the project findings would not be fully realised. The development of the software package therefore is unique to the High Speed Displacement Hull Form Project.

Having agreed upon the need for a complete software package with its main objective being to assist the ship designer in hydrodynamic evaluation and the design of a high speed displacement vessel, the following tasks evolved:

a. Design a specific hull form based on main dimensions and form coefficients within the parametric space of the systematic series and predict from regressed experimental data the resistance and seakeeping characteristics of the vessel.

b. Evaluate an existing design or a proposed design through a comparison with a comparable design derived from the systematic series.

c. Create a user friendly environment in terms of a well structured and easy to use interactive computer system to perform the above tasks.

In meeting the above objective it is intended that the following application programs be included in the software package:

a. Lines Generation and Hydrostatics of any hull within the parametric space of the series.

b. Resistance prediction from regressed experimental results.

c. Resistance and Powering predictions based on a general frigate methodology.

d. Influence of Transom Wedges.

e. Seakeeping Prediction from regressed experimental results.

f. Seakeeping prediction based on a general strip theory method, for vertical motions and a method based on the 'Ikeda' theory for lateral motions.

As well as the above it is envisaged that application programs for Appendage Resistance, Propulsive Factors, and the effect of Bilge Keels and Fin Stabilizers will be included in the software package.

The software executive system of the environment in which the application programs run will consist of:

a. A database management system to store and retrieve data.

b. A user interface manager to communicate between user and application programs.

c. A graphics system to illustrate the calculations.

d. A compare function to compare present calculations with previous derived data.

e. Input and Stowage of foreign designs.

f. A help system to assist new users.

In order to organise the vast amount of experimental data into a useable form for the software package it is the intention to regress this information into polynomial equations. To date, regressional formulas have been derived for wetted surface and for residuary resistance and trim angles at a number of speeds, but results for residuary resistance have been disappointing and the equations need further investigation. Regression investigation for the seakeeping data is still in the preliminary phase.

Generally, there is still considerable effort required to regress the experimental data but other aspects of the software package development are proceeding in parallel on the assumption that by the end of 1988 all regression work will be satisfactorily concluded.

One of the recognised drawbacks of the software system described above is its general limitation to the hull forms and parametric range of the high speed displacement hull form series of models. With such considerable effort being applied to the development of this software package it was subsequently decided that additional effort should be applied to overcome this restriction with the use of available mathematical models in the form of additional computer programs for the independent prediction of the resistance and seakeeping phenomena. Two different situations were envisaged which could benefit by an enhancement to the general software package. One situation was a high speed displacement hull form with main parameters outside the parametric range of the series and the second was a 'FOREIGN' hull form which had to be evaluated.

With respect to seakeeping the program 'Trial' of the Delft University of Technology has proven its worth and may be included in the software package. For resistance predictions, use may be made of either the Taylor Series, the Hamburg 'C' Series, or the NPL Series. Such programs can be used to expand the applicability of the computer system. The High Speed Displacement Hull Form Series are then used to update the prediction of the calculation process.

Given a ship design which can be stored in the system, performance can be calculated using the above program. The next nearest possible high speed displacement hull form is selected and its performance is calculated by using these same programs. The performance is also calculated using the regression equations produced for the series. From the differences between the two results a correction factor can be determined. This correction factor can then be used to update the results of the required design. Fig 16 depicts this procedure which will considerably enhance the software in extending its applicability and for independent evaluation of Foreign designs.

A perceived limitation in the software package is its inability to select automatically with multiple objectives an optimised design from within the bounds of the 'Magic Cube'. It is intended that this capability may be incorporated in the package by the Directorate of Naval Ship Design using the Auseval programme.

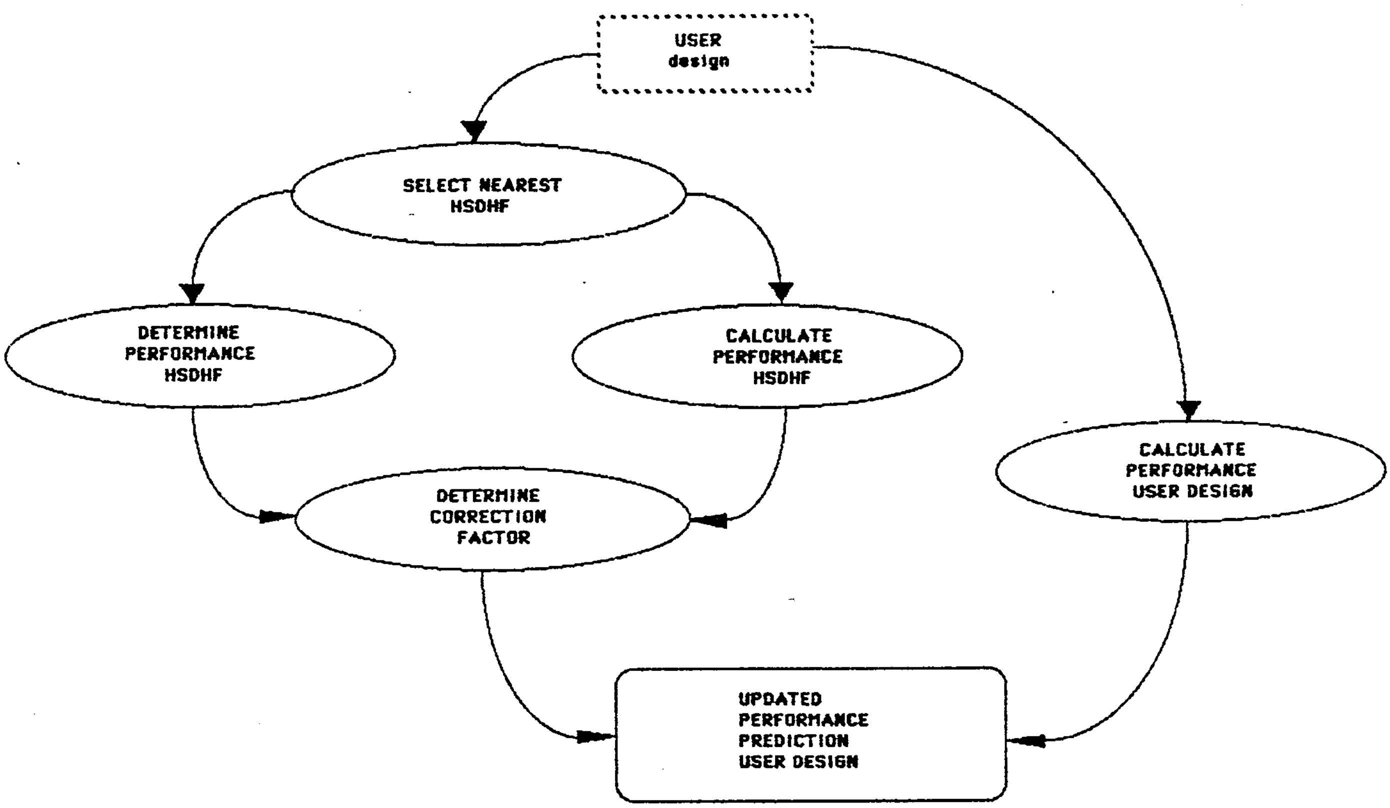


FIGURE 16 - SCHEME FOR EXTENDED APPLICABILITY

9. FUTURE APPLICATION

It is envisaged that the results obtained from the High Speed Displacement Hull Form Project will be used during the conceptual and preliminary design phases for future Frigates and Patrol Boats for the Royal Australian Navy. It will be possible to investigate the effects of each of the independent hull form parameters of alternate designs within the parametric bounds of the 'Magic Cube' on calm water resistance, added resistance in waves, pitch, heave, relative motions and acceleration so that an optimal compromise selection can be made in the early stages of a design that will ultimately lead to a design which will achieve the desired seakeeping characteristics.

It is also envisaged that the results obtained from the project will enable the establishment of a benchmark against which foreign competing designs can be evaluated.

The completed software package described in the paper will be set up on the Directorate of Naval Ship Design 'Shipcalc II' Hewlett Packard computer system either as a stand alone package, or it will form part of the 'AUSEVAL' computer based ship design system currently being developed by the Directorate.

With the inclusion of the additional independent programs for calculating ship resistance and motions the software package will further enhance the fast growing library of computer programs already available in the Directorate of Naval Ship Design. The test results from the project have already been utilized to validate the ship motion programs currently being used in the Directorate. In this case validation applies only to model and computation predictions, full scale trials validation is still uncertain.

Once the software package is set up, further uses will be found for it and overall it will provide a very valuable ship design tool to the Australian Department of Defence.

10. CONCLUSIONS

The High Speed Displacement Hull Form Project is certainly an innovative approach to researching the effect of hull form parameters on naval ship performance in waves. The co-operative approach to this kind of research has certainly worked well as each participating organization has had access to research results which would otherwise have cost a fourfold amount to obtain individually. The opportunity to have Australian Naval Architects involved in such a project has been most worthwhile not only with the management of the project itself but with the association and dialogue that normally occurs when naval architects of different nationalties work together. All participants, I believe, have obtained a better insight into the factors which effect ship performance in waves and hopefully by the application of the described software package during the conceptual and preliminary design of future naval combatants the ultimate user navies will obtain a better ship which will permit the prosecution of its missions in a much safer and reliable manner in more demanding environmental conditions. There is no doubt that we could have done more research to extend our knowledge even further, but research can go on forever. The big plus for this project is that its end product will be a tool that practical ship designers can use. This was a conscious objective right from the very start of the project.

Most of the experimental work is now complete and software development is still in the early stages, but with the talent that is being applied to the software development the project will most definitely come to a satisfactory conclusion at the end of 1989.

11. ACKNOWLEDGEMENTS

The High Speed Displacement Hull Form Project is sponsored equally by the United States Navy (monitored by DTNSRDC), the Royal Australian Navy (monitored by the Director of Naval Ship Design), the Royal Netherlands Navy (co-ordinated by the Research and Development Bureau of the Shipbuilding Department) and by the Netherlands Ship Model Basin. The input from each of these organizations has been considerable. Permission to publish this paper is gratefully acknowledged. The supplementary work conducted by the Delft University of Technology (Laboratory of Ship Hydromechanics) is also gratefully acknowledged.

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