THE MARIN SYSTEMATIC SERIES FAST DISPLACEMENT HULLS
Geert Kapsenberg - MARIN

Summary
The paper describes the development of a systematic series of high speed displacement hull forms. The series is built around a parent model by varying the length to beam ratio, the beam to draft ratio and the block coefficient. Eventually thirty-three hull forms were built and tested in calm water up to a maximum speed of Froude number 1.14. Twenty-four of these hull forms were also tested in head waves. Regression analysis has been done on the experimental results to allow interpolation for intermediate speeds or intermediate hull forms. All results of the experiments are now made available in the form of a computer program; the program also contains the regression equations to allow interpolation. The use of the program is illustrated by way of a case study.

Introduction
A Joint Industry Project (JIP) on high speed displacement ships was carried out in the period 1979 – 1989 by the Royal Netherlands, US and Australian Navies, Delft University of Technology and MARIN. Western navies were very interested in high speed vessels in the seventies and they studied all sorts of advanced concepts ranging from hydrofoil to air cushion supported vessels and even wing-in-ground effect vehicles. Performance and endurance at high speed in waves was an issue for most of the studied types, so some people believed that also the monohull concept could be a viable alternative. This belief was the starting point of the JIP and it was decided to develop a systematic series around a parent hull form. The main parameters to vary in the series were length over beam ratio, beam over draft ratio and block coefficient and the
speed range to be considered should reach \( Fn = 1 \). Contrary to most existing systematic series, not only resistance characteristics in calm water was to be measured, but also performance in waves. Head seas was considered the most severe wave direction and therefore experiments were restricted to this condition. Most of the models were tested both in calm water and in head seas, the latter at fixed Froude numbers of \( Fn = 0.285, 0.430, 0.570, 0.855 \) and 1.140.

Now, 25 years after closing the project, the results were de-classified by all the partners. It was considered that the results of the project are still valuable today, not only for the naval market, but also for the market of the (mega) yachts. Because of this and with the help of a subsidy of the Dutch Ministry of Economic Affairs (Maritime Innovation Platform) a project was started to make all results available. The format chosen was to make a PC program for numerical results and to write a book on the why, how and what of the project. The PC program contains all the hull forms, the experimental data and the small programs to interpolate in the existing hull forms (geometry) and to predict the hydrodynamic performance for this newly generated hull form. The book will explain in detail the background of the project, how all the work was done and analysed and how the interpolation methods were developed. Some additional topics were also investigated; some of these are mentioned in this paper, all of them are described in the book.

This paper gives an overview of the early phase of the project were the parent hull form was selected, an overview of all the work done and finishes with a case study showing how the results might be used in a design office.

Selection of the parent hull form

The selection of the parent hull form of this systematic series was considered very important and was treated as a separate project. A selection was carried out on the database of hull forms available at Marin; the selection was based on frigate type hull forms tested at high speeds. An average value of the geometrical parameters of the available models was selected at \( L/B = 8; B/T = 4.0 \) and \( c_B = 0.40 \). Sufficient knowledge was considered to be available for the choice of the prismatic coefficient and the longitudinal position of the centre of buoyancy; these coefficients were fixed at \( c_p = 0.63 \) and \( LcB/L_{PP} = 0.052 \); the latter with reference to amidships and positive in a forward direction. Such knowledge was not present for the optimum position of the water plane coefficient \( c_{wp} \) and the optimum position of the centre of floatation \( LcF \). Therefore a subseries was designed with a narrow, medium and wide fore body and similar three different aft bodies; the hull forms are shown in the diagram of Figure 1. The fore and aft bodies could be connected at will and finally six of them were tested in calm water and in head waves. The results of the tests in calm water are shown in Figure 2 and the pitch motion in head seas at a speed of \( Fn = 0.855 \) in Figure 3. The results show that the models with a low resistance, models 3 and 6, have a “narrow” or “medium” width of the aft body and a “wide” fore body. These same models have however the largest pitch motion as shown in Figure 3. The final selection was based on the calm water resistance at a speed of \( Fn = 0.855 \) and a number of seakeeping aspects like heave and pitch motion, relative motion at St 17, vertical acceleration at St 19 and added resistance in waves. Taking the central model, model 2, as a reference, the relative changes to this model were listed in Table 1. The participants of the project all agreed that the wide/wide hull form constituted the best compromise between low resistance in calm water and low
motions in waves. This hull form was therefore selected as the parent of the systematic series. The selection procedure is described in more detail by Blok and Beukelman [1984].

Table 1  Relative difference (to model 2) of calm water resistance and various seakeeping aspects of the six models at a speed of $F_n = 0.855$

<table>
<thead>
<tr>
<th>model</th>
<th>Calm water resistance</th>
<th>Heave motion</th>
<th>Pitch motion</th>
<th>Rel motion St 17</th>
<th>Vert accel St 19</th>
<th>Raw</th>
<th>Rcalm + Raw</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>+0.1</td>
<td>+7.7</td>
<td>+7.6</td>
<td>+6.2</td>
<td>+3.7</td>
<td>+1.0</td>
<td>-1.0</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>+5.2</td>
<td>0</td>
<td>-10.6</td>
<td>-9.6</td>
<td>-7.4</td>
<td>-13.6</td>
<td>+4.0</td>
</tr>
<tr>
<td>4</td>
<td>-0.4</td>
<td>+2.6</td>
<td>+7.6</td>
<td>+11.9</td>
<td>+3.7</td>
<td>+1.0</td>
<td>+4.0</td>
</tr>
<tr>
<td>5</td>
<td>+1.8</td>
<td>+7.7</td>
<td>+10.6</td>
<td>+4.5</td>
<td>+7.4</td>
<td>-3.9</td>
<td>+1.4</td>
</tr>
<tr>
<td>6</td>
<td>+4.5</td>
<td>+5.2</td>
<td>+4.5</td>
<td>+7.9</td>
<td>0</td>
<td>-9.6</td>
<td>+3.6</td>
</tr>
</tbody>
</table>

Figure 1  Schematic diagram showing the hull forms tested to select the parent hull form.
The systematic series

Once the parent hull form was defined, the systematic series could be developed. The transformation to different values of \( L/B \) and \( B/T \) were quite straightforward since it constituted only a linear factor on the offsets. There was no suitable method for the variation of the block coefficient \( c_B \), so a new method was developed together with Delft University of Technology, [Koops 1985]. The objective was to change the block coefficient while keeping the “character” of the sections. The method transforms the offsets of a particular section by keeping the transverse \( y \)-coordinates the same and adopting a specific rotation for the vertical \( z \)-coordinates:

\[
\begin{align*}
y_{\text{NEW}} &= y_{\text{OLD}} \\
z_{\text{NEW}} &= z_{\text{OLD}} + z_0 + y_{\text{OLD}} \tan \alpha
\end{align*}
\]

In principle a value \( z_0 = 0 \) was used and a non-zero value of \( \alpha \) was determined to create the required submerged sectional area. This method worked well for sections in the fore body, but could result in a negative deadrise for the flat sections in the aft body. This problem was solved by lowering the contour line (the point \( y=0, z_{\text{NEW}} \)) of the section which results in a negative value.
of $z_0$. This last aspect involved some manual intervention of the transformation procedure to arrive at a fair hull form. Figure 4 shows an example of a normal transformation of a section in the fore body and of a section in the aft body where the contour line had to be changed. Figure 4 also shows that the width at the design waterline, especially in the fore body, changes as a function of the block coefficient; this effect was accepted as an unavoidable consequence of the transformation. The main hull form coefficients of 3 models differing in block coefficient are shown in Table 2; the table shows the magnitude of the changes in the parameters for the water line.

![Figure 4](image)

*Figure 4  Example of the geometry transformation method for a section in the fore body (left) and a section in the aft body (right) where the contour line was lowered.*

<table>
<thead>
<tr>
<th></th>
<th>Low block</th>
<th>Parent</th>
<th>High block</th>
</tr>
</thead>
<tbody>
<tr>
<td>L/B</td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>B/T</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>$c_B$</td>
<td>0.35</td>
<td>0.40</td>
<td>0.50</td>
</tr>
<tr>
<td>$c_P$</td>
<td>0.63</td>
<td>0.63</td>
<td>0.63</td>
</tr>
<tr>
<td>$c_{WP}$</td>
<td>0.77</td>
<td>0.80</td>
<td>0.82</td>
</tr>
<tr>
<td>LcB</td>
<td>-0.052</td>
<td>-0.052</td>
<td>-0.052</td>
</tr>
<tr>
<td>LcF</td>
<td>-0.092</td>
<td>-0.087</td>
<td>-0.070</td>
</tr>
</tbody>
</table>

Using this method a systematic series of 27 models was built. In order to identify the models, use was made of the fact that just three parameters completely define the shape: L/B, B/T and $c_B$. The hull forms were represented in the so-called “magic cube”, Figure 5, in which each dot indicates a hull form.
Because the project ran for a period of 10 years, inevitably the ideas about interesting “design areas” changed. The initial plan involved three “levels” of $c_B$, but later on a fourth level at $c_B = 0.55$ was added to extend the applicability also to larger destroyer type of hull forms. In a very late stage it was realized that the step from $L/B = 4$ to $L/B = 8$ was a very large one, especially concerning the resistance characteristics. A fourth $L/B$ plane at $L/B = 6$ was added and a series of models was designed, built and tested in calm water; not in waves.

**Experiments**

Experiments in calm water have been carried out on an unappended hull. Turbulence stimulation at the bow has been applied as customary by way of pins. The models were towed at the longitudinal position of the CoG and at a height corresponding to the supposed propulsion drive train. Calm water resistance, trim and sinkage were measured for speeds up to $F_n = 1.14$ unless excessive trim and spray prohibited such high speeds. Propulsion tests were not carried out.

Motions and added resistance in regular head waves were measured using a semi-captive set-up: the model was connected at the CoG to the carriage by way of a gimbaled heave post. Measurements were done at a series of fixed values of the wave length – ship length ratio for a fixed series of speeds: $F_n = 0.285, 0.430, 0.570, 0.855$ and $1.140$. Again the tests in waves could not all be done at the highest speeds due to excessive trim and spray; this was especially the case for the low $L/B$ hull forms.
Interpolation methods

In the final stages of the project the data was further analysed. The idea was to determine the trends on resistance in calm water and on motions in waves based on the 3 hull form parameters and, for the results in waves, also based on the fixed values of the Froude number. This would then allow the prediction of the performance of intermediate hull forms based on the actually measured values.

For the calm water resistance (and the trim and sinkage) it appeared that regression using the three hull form parameters as in the independent variables for a series of fixed values of the Froude-displacement number $F_{Fn}$ gave the most accurate results; an example of the accuracy is given in Figure 6.

For the motions and added resistance in head waves the regression was carried out on the speeds for which the experiments were done. Also fixed values of a non-dimensional wave frequency parameter have been used so that the independent variables of the regression are just the hull form parameters. This approach resulted in reasonably accurate predictions, but the results, motion RAOs or the quadratic added resistance operator, as a function of the wave frequency, are not necessarily smooth lines. An example of the result of the interpolation formulas is shown in Figure 7.

Figure 6 Example of result of regression analysis and original data points for the calm water resistance.

Figure 7 Example of result of regression analysis and original data points for motions in head waves.

Additional studies

Apart from the experiments as described above some additional work has been carried out:

- A study into the effect of transom stern wedges for a limited series of hull forms.
- A study into the magnitude of the hull roll damping and the effect of bilge keels at these high speeds.
- A check on the choice of the prismatic coefficient by testing two additional hull forms.
- Regression analysis for the resistance of an extended database of high speed displacement hull forms.
Transom stern wedges
The effect of transom stern wedges has been tested on a small series of four models: the parent hull form and the hull forms on the axes of the cube in the low L/B, low B/T and high \( c_B \) directions. Each model was tested with 9 wedges having a length of 1-2-3% of Lpp and a wedge angle of 5, 10 and 15 deg.

As could be expected, the effect of the wedge on the resistance of the L/B = 4 models is quite important due to the fact that these models have a large trim angle at high speed; this is illustrated in Figure 8. The zoom-in shows that the effect on the residual resistance for a speed \( F_{nV} = 2.0 \) is 16%.  

![Figure 8](image_url)  
*Figure 8*  
Residual resistance coefficient for the L/B = 4, B/T = 4, \( c_B = 0.40 \) model with a wedge, length 0.02*Lpp, with different wedge angles (wa). Full speed range (right) and zoom-in (left).

Roll damping
As indicated in the introduction, focus of the experiments was on calm water performance and behaviour in head seas. Nevertheless in the course of the 10-year project attention was paid to the prediction of the roll motion; more specific the prediction of the proper roll damping for these high speeds. Roll is a notorious problem; the damping is usually quite low – much lower than the critical damping. The damping increases significantly for increasing speed; the relatively flat aft body of these designs create lift forces that dominate the roll damping at high speeds. Traditional methods to estimate the roll damping, like the one developed by Ikeda (1978) and Himeno (1981), are based on model experiments with merchant ships. The combination of the frigate type hull forms and the high speeds of this systematic series makes the traditional method very inaccurate.

It was therefore decided to develop a new formula to predict the lift damping. A special series of experiments was designed using an oscillator mechanism to force the model into a roll motion while it was still free in the heave and pitch modes. Experiments were carried out with a series of 13 models covering the B/T range in a band from the low \( c_B \) – low L/B corner to the high \( c_B \) – high L/B corner of the “magic cube”. Most of the models were tested with and without bilge keels; these bilge keels had a length of 25%*Lpp and a height of 1% of Lpp. This work resulted in a new formula for the roll damping which gave much better predictions of the roll motion at high...
speeds as was verified by a series of free running experiments. A detailed description of this work was published by Blok and Aalbers (1991).

Figure 9  Roll response of the parent hull form in beam seas at different speeds. Results of calculations using the new method to estimate the roll damping are shown in lines, experimental results by symbols.

Check on the choice of the prismatic coefficient
The prismatic coefficient has been fixed from the outset at a value of \( c_p = 0.63 \). This value was based on results from existing ships, the results of Series 64, Yeh (1965), the series by Lindgren (1968) and the NPL series, Bailey (1976). Nevertheless it was considered worthwhile to perform a check on the influence of \( c_p \) by developing two variants of the parent hull form at \( L/B = 8 \), \( B/T = 4 \) and \( c_B = 0.39 \). The result of the resistance in calm water is shown in Figure 10; for the higher speeds that are the interest of this series the \( c_p = 0.63 \) hull form is confirmed to be the better choice.

Figure 10  Residual resistance / displacement for the prismatic coefficient sub-series.  
Figure 11  Heave RAO at \( F_n = 0.57 \) for the prismatic coefficient sub-series.
Regression on an extended database of resistance experiments

Regression formulas to interpolate in the data of this systematic series have been developed, but on top of this a regression was made on all available calm water data of high speed displacement hull forms. The database consisted of:

- the NPL High Speed Round Bilge Displacement Hull Series, Bailey (1976), 24 hull forms.
- the David Taylor Research Centre Series 64, Yeh (1965), 27 hull forms.
- the NRC series, Murdey and Simoes Re (1985), 39 hull forms.
- Non-systematic data from the MARIN database, selected for high speed round bilge hull forms, 36 hull forms.
- The MARIN systematic series, 33 hull forms.

In total there were 159 hull forms in this database. The regression of the resistance yields a specialized tool for fast displacement ships that is much more general than the regression of the systematic series only.

A case study

In order to illustrate the possibilities using the data and the computer program, a case study is presented. The base design for the case study is a motor yacht with main dimensions as listed in Table 3. The hull form belongs to the FDS family. The basis results of the calm water resistance, powering and motions in head waves are presented in Figure 12.

### Table 3 Main dimensions and hull form ratios of the motor yacht

<table>
<thead>
<tr>
<th>Dim.</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lwl</td>
<td>30.00  m</td>
</tr>
<tr>
<td>B</td>
<td>6.00   m</td>
</tr>
<tr>
<td>T</td>
<td>1.50   m</td>
</tr>
<tr>
<td>V</td>
<td>99.9   m$^3$</td>
</tr>
<tr>
<td>$\Delta$</td>
<td>102.4 ton</td>
</tr>
<tr>
<td>Vs</td>
<td>30     kts</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dim.</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>L/B</td>
<td>5.000</td>
</tr>
<tr>
<td>B/T</td>
<td>4.000</td>
</tr>
<tr>
<td>$C_b$</td>
<td>0.370</td>
</tr>
<tr>
<td>Cwp</td>
<td>0.776</td>
</tr>
<tr>
<td>$F_n$</td>
<td>0.900</td>
</tr>
<tr>
<td>$L/\sqrt{V}$</td>
<td>6.465</td>
</tr>
</tbody>
</table>

Figure 12 shows that the major resistance component is the residual drag for speeds higher than 10 kts. There is a clear hump for speeds 17 – 21 kts after which the relative importance of the residual resistance decreases. Figure 13 shows the heave motion in head seas; the peak of the RAO increases for increasing speed and shifts to lower frequencies. The driving parameter behind this is the heave excitation which increases for longer waves. Those longer waves are being encountered at a higher frequency when the speed increases. Since this higher frequency is closer to heave resonance, the response increases. The wave excitation for pitch has a maximum for a wave length about equal to the ship length (corresponding to a wave frequency of 1.4 rad/s); this is the main reason why the response shows a maximum around this frequency.
Figure 12  Calm water resistance of the motor yacht showing the Total, Frictional, Wave making, Appendage and Wind drag components. The plot on the left gives the absolute values, the plot on the right gives the relative contributions (plotted in a cumulative manner).

Figure 13  Motions in head seas; heave (left) and pitch (right). Results for 10, 20 and 30 kts.

The case study concerns the effect of a variation of the beam and draft while keeping the length and displacement constant. If the beam is changed independently of the draft, the block coefficient has to be changed in order to keep the displacement constant. A matrix can be set up with the B/T ratio on one axis and the $c_B$ on the second axis showing either the beam or the draft, see Table 4 as an example. This table shows that the variation of the beam is quite large and also the draft varies a lot more (from 1.05 to 1.95 m) than might be possible in real life. However limits to the ranges can always be added, even after doing the calculations. Calculations were carried out for a matrix of 100 hull forms, 10 steps on the B/T axis and 10 on the $c_B$ axis. The results considered are the total resistance at the design speed and the significant heave and pitch motion in the “design” sea state with significant wave height $H_s = 2.0$ m and average period $T_1 = 6$ s. The results are shown in Figure 14. The upper left hand graph shows that there is a maximum difference of 24% between the total resistance of the best and the worst.
design. The optimum of the design space is the high block coefficient - low B/T corner. This design has a narrow beam and, since the length is constant, the highest L/B ratio; this design also has the lowest wetted surface, both aspect help in reducing the resistance. The diagram further shows that the penalty in resistance when increasing the B/T ratio is not very large; the total resistance of the \( c_B = 0.55 \), B/T = 5.5 hull form is only 5% higher than that of the optimum hull form.

**Table 4 Table showing the beam of the motor yacht as a function of the B/T ratio and the \( c_B \)**

<table>
<thead>
<tr>
<th>( c_B )</th>
<th>2.5</th>
<th>3.0</th>
<th>3.5</th>
<th>4.0</th>
<th>4.5</th>
<th>5.0</th>
<th>5.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.35</td>
<td>4.877</td>
<td>5.343</td>
<td>5.771</td>
<td>6.169</td>
<td>6.543</td>
<td>6.897</td>
<td>7.234</td>
</tr>
<tr>
<td>0.40</td>
<td>4.562</td>
<td>4.997</td>
<td>5.398</td>
<td>5.771</td>
<td>6.121</td>
<td>6.452</td>
<td>6.767</td>
</tr>
<tr>
<td>0.45</td>
<td>4.301</td>
<td>4.712</td>
<td>5.089</td>
<td>5.441</td>
<td>5.771</td>
<td>6.083</td>
<td>6.380</td>
</tr>
<tr>
<td>0.50</td>
<td>4.080</td>
<td>4.470</td>
<td>4.828</td>
<td>5.161</td>
<td>5.474</td>
<td>5.771</td>
<td>6.052</td>
</tr>
<tr>
<td>0.55</td>
<td>3.891</td>
<td>4.262</td>
<td>4.603</td>
<td>4.921</td>
<td>5.220</td>
<td>5.502</td>
<td>5.771</td>
</tr>
</tbody>
</table>

*Figure 14 Results in calm water and in waves of the case study for the 30 m motor yacht*
The motions in waves and the added resistance are also shown in Figure 14. The optimum is clearly different to the optimum for the calm water resistance. The ship motions show that having a low value of the B/T ratio is not very good for comfort aspects. Unfortunately the corner in the design space having the highest resistance in calm water also has the highest pitch motion! It seems to be a good compromise to aim for a high B/T and a high \(c_B\). The price to pay is the high added resistance in waves, in the design sea state of \(H_S = 2\) m it adds 37% to the calm water resistance. One wonders if this “natural” speed reduction is not a very sensible thing to do anyway in such a seaway...

This case study shows how the PC program can be used; it can quickly show the consequences of quite dramatic changes in the hull form in a very early stage of the design process. It also shows that naval architecture is about making choices, about finding the right balance between conflicting requirements for a particular design. This balance is dependent on the preference of the owner of the yacht, the use of the yacht and about the wave climate in which the yacht has to operate.

**Concluding remarks**

As explained in the introduction, no real results of the project were published because of the confidentiality of the project. Permission was granted for some overview publications: Oossanen (1980), Oossanen and Pieffers (1985) and Robson (1987), and for some publications on specific details of the project: Koops (1981), Blok and Beukelman (1984), Aalbers and Blok (1991), Keuning (1990) and a chapter in the PhD thesis of Keuning (1994).

Now all results will be made available, this concerns the definition of the hull forms, the experimental data and the interpolation routines. Together with the book explaining the details of why and how the experiments and the analysis were carried out, we hope that the maritime community will have a useful database of the hydrodynamic behaviour of high speed displacement hull forms.

**Nomenclature**

- \(B\) \(m\) Maximum beam on the water line
- \(T\) \(m\) Draft amidships
- \(L_{pp}\) \(m\) Length between perpendiculars
- \(LcB\) \(m\) Longitudinal position of the centre of buoyancy forward of St 10
- \(LcF\) \(m\) Longitudinal position of the centre of floatation forward of St 10
- \(CoG\) \(m\) Longitudinal position of the centre of gravity forward of St 10
- \(c_P\) - Prismatic coefficient
- \(c_B\) - Block coefficient
- \(Fn\) - Froude number based on length, \(Fn = \frac{v}{\sqrt{gL_{pp}}}\)
- \(Fn_v\) - Froude number based on displacement \(Fn_v = \frac{v}{\sqrt{gV^{\frac{1}{3}}}}\)
- \(V\) \(m^3\) Displacement volume
References