An inverse design procedure for high speed forms

K. Sanoz, A. Kükner & E. Narlı

Faculty of Naval Architecture and Ocean Engineering, Technical University of Istanbul, Istanbul, Turkey

Abstract

Due to modern effective missile and sensor systems high speed small to medium sized corvettes and frigates have become the main force in many navies. These craft are cheap alternatives to larger and more expensive conventional warships. However, being small brings its own problems, particularly in seakeeping performance in rough seas. Due to relative smallness in size these vessels must have superior seakeeping performance characteristics in order to carry out complex missions. In the design of these ships proper selection of main dimensions and hull form parameters will influence the operational effectiveness of the vessel. In order to achieve a balanced design an inverse design methodology is developed and applied to high speed small to medium sized vessels. This methodology is based on a direct search method and employs various hull form generation routines, seakeeping performance prediction programs as well as stability and resistance routines.

Introduction

The primary objective of a ship designer is to obtain the most effective ship that satisfies all requirements of an owner, such as payload, speed, and endurance as well as fulfilling certain safety requirements. Since the hull is the major element of the ship which provides form and structure and contains all other elements of the ship the effectiveness of the design largely depends on the degree of excellency of the hull form design.

The design of a high speed vessel is basically a search for the least cost synthesis capable of delivering a required level of performance. Traditionally, it was considered that the best design was determined more by intuition based on the experience of the designer. However, modern weapon and
sensor systems require more specialised and sophisticated hull form designs. Furthermore, owners are now expecting criteria to be considered which were previously not considered at all.

The basic operational requirement for high speed forms is that they can support a given payload and achieve certain operational criteria in a specified seaway. The operational criteria are dominated by requirements of achieving a maximum speed in calm weather conditions, and excellent seakeeping ability, particularly in head seas, with sustained maintenance of speed and maximum crew and weapon-sensor efficiency.

Traditionally, calm and rough weather performances have been treated separately, and a maximum speed in calm weather is usually of prime concern when discussing the design of a high speed form. However, since only a small part of a high speed form’s total sea time will be spent in calm weather, the ability to maintain speed in a seaway should be considered to be, in operational terms, at least as important as the ability to achieve a specified calm water speed. The calm weather performance can be seen as the trivial case of rough weather performance. Since the design goals for calm water performance may be different than those for rough seas performance measures, some trade-off in design goals may need to be made.

In order to define a design objective which combines both the calm water and rough weather performances an “Average Attainable Speed (AAS)” is defined and used in the design methodology presented in this study. The AAS concept requires the prediction of maximum speed that can be achieved in calm water as well as the voluntary and involuntary speed reductions in rough weather conditions. Therefore, the design objective would be the maximisation of AAS for a given seaway and specified operational conditions. It can be argued that seakeeping considerations related to the efficiency of weapon-sensor systems and crew should also be incorporated into the design objective. However in most cases minimisation of voluntary speed reduction requires the minimisation of vertical plane ship motions as well as the probability of occurrence of extreme effects such as slamming, deck wetness and excessive accelerations.

It is assumed that the random seaway is defined by a wave spectrum, therefore the probability of occurrences of each sea state can statistically be determined. The voluntary and involuntary speed reductions for each sea state can be predicted and therefore an attainable speed envelope for a specified seaway can be determined. Prediction of voluntary speed loss in a seaway requires criteria to be set representing critical seakeeping responses beyond which capability is considered to be degraded. Typical critical values for high speed warships are indicated in Table 1.
Inverse Design Approach

In inverse design approach, the theory is recast in terms of the performance criteria and the output of the process are the values of the parameters corresponding to an optimised design. The basis of inverse analysis is an exploration of the design space to map out the sensitivity of performance to the design parameters. Many different configurations must be analysed to determine even gross sensitivities. This type of search requires a very flexible geometry description. Selection of surface offsets would seem as the natural choice for design parameters however this choice will certainly require a super computer. Furthermore, to ensure that the final form has a fair surface extra geometric constraints would be required.

In order to simplify the problem two different methods can be applied

1. Selection of design curves, i.e. sectional area and design waterline curves as design parameters

2. Selection of form parameters, i.e, block coefficient, $C_B$, longitudinal centre of buoyancy, $LCB$, waterplane area coefficient, $C_{WP}$ and longitudinal centre of flotation, $LCF$ as design parameters

Both methods require the use of linear distortion techniques. Conventional linear distortion methods, e.g Lackenby (1950), allows the variation of $C_B$ and $LCB$ with no control on the geometric characteristics of the design waterline curve. A different approach used by Moor (1970) enables the designer to vary both the sectional area and the design waterline characteristics. This approach can be applied to most conventional ship forms and reduces the number of design parameters to four, i.e., $C_B$, $LCB$, $C_{WP}$ and $LCF$. These parameters are the variables for which the best values are sought.

The structure of the inverse design approach is illustrated in Figure 1. As shown in the figure this methodology is based on a nonlinear direct search methodology in which the design objective is defined as the average attainable speed in a seaway represented by a one-parameter Pierson-Moskowitz spectrum. In order to predict natural and voluntary speed reductions in waves the well known strip theory and linear spectral analysis techniques are used.

The main difficulty in inverse design procedure is the requirement that each design developed should be analysed for various performance characteristics. This process would require excessive computing time and therefore relatively simple methods of analysis need to be used, e.g. the use of strip theory rather than a full 3-D analysis for seakeeping prediction. Even the strip theory method is further simplified by the use of extended Grim type diagrams for the calculation added mass and damping coefficients. Thus, the inverse design approach may not give excellent correlation with
experiments or full-scale trials. However, it may be shown that this approach can greatly accelerate design decisions in the early stages of ship design.

Application of the Methodology

To illustrate the utilisation of the inverse design methodology a frigate type hull form was re-designed for better AAS values. The parent hull is illustrated in Figure 2. An alternative hull design, shown in Figure 3, was obtained by using the inverse design methodology within the following limits of the design parameters.

\[ 0.44 < C_B < 0.48 \quad 0.72 < C_{WP} < 0.80 \]
\[ 0\% < LCB < 2\%aft \quad 3\%aft < LCF < 6\%aft \]

In this example it was assumed that the main dimensions are fixed due to other design considerations such as building costs and stability requirements. The optimised form has a full forebody with increased waterplane area. Both the centres of buoyancy and flotation moves as forward as allowed. In order to verify the advantages of the optimised design the calm and rough weather performances of the parent and optimised forms were assessed. The basic vertical motions, i.e. heave and pitch amplitudes and added resistance in regular head seas for a top speed of 30 knots are shown in Figures 4, 5 and 6.

### Table 1.

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Limit</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical Acceleration</td>
<td>0.2 g RMS</td>
<td>Lloyd (1989)</td>
</tr>
<tr>
<td>Deck wetness Prob.</td>
<td>120/hour</td>
<td>Lloyd (1989)</td>
</tr>
<tr>
<td>Slamming Probability</td>
<td>90/hour</td>
<td>Lloyd (1989)</td>
</tr>
</tbody>
</table>

It is assumed that a voluntary speed reduction will be required when any of the specified vertical acceleration, deck wetness, and slamming criteria is exceeded. In order to predict the amount of reduction these responses were calculated for six speed and 10 significant wave height values. These are illustrated in Figures 7 through 9 for the parent and optimised forms. Corresponding seakeeping criteria in each graph is indicated by a horizontal line. The voluntary speed reductions for each form then can be read off from these graphs.

Typical results for the parent and the optimised forms are presented in Figures 10 and 11, which show the speeds that are within limits. It can be seen that the major operability restriction varies with the increasing sea state. The first restriction is due to the involuntary speed reduction
which is followed by the vertical acceleration. Deck wetness is restricted to high speed and slamming is not predicted to be a restriction before any of the above limits.

It was estimated that the optimised design would require more power to achieve the specified top calm water speed, however, as shown in Figure 12, as the sea state increases this form is shown to have a better average attainable speed than the parent form.

Concluding Remarks

A method of developing alternative hull designs with better overall speed characteristics for high speed forms is presented. The methodology takes into account of voluntary and involuntary speed reductions in rough seas, as well as the calm water speed. A comparison between a typical parent frigate form and an optimised alternative has shown that although the optimised vessel requires more power to achieve a top calm water speed, it has superior seakeeping performance characteristics and as the sea state increases it will lose less speed and hence will have better overall speed characteristics. The optimised form is also predicted to have better stability characteristics than the parent hull.

Several needs requiring significant upgrades in capability can be identified as; to provide more comprehensive and multi-disciplinary optimisation and the incorporation of these techniques and tools into an integrated design system.

References


Figure 1. Structure of the Inverse Design Procedure.

Figure 2. Parent Hull Form.

Figure 3. Optimised Hull Form.
Figure 4. Heave Comparison at 30 knots.

Figure 5. Pitch Comparison at 30 knots.

Figure 6. Added Resistance Comparison at 30 knots.
Figure 7. RMS Vertical Acceleration for Parent and Optimised Designs.

Figure 8. Deck Wetness Probability for Parent and Optimised Designs.

Figure 9. Slamming Probability for Parent and Optimised Forms.
Figure 10. Speed Reduction Curves for Parent Form.

Figure 11. Speed Reduction Curves for Optimised Form.

Figure 12. Limiting Speed Curves for Parent and Optimised Forms.