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Inverse design of ship hull forms for seakeeping

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ABSTRACT

This paper describes a computational procedure to design seakeeping optimized ship hull forms using optimization techniques. The hull form optimization procedure contains four basic elements; a procedure for representing alternative hull form designs, a procedure for predicting seakeeping performance of a given design, a nonlinear direct search procedure, and a user interface to provide objectives and constraints of the problem. The seakeeping performance of the ship in a specified sea area is expressed as a function of selected hull form parameters. A nonlinear optimization problem is then formulated and solved by using nonlinear direct search techniques. Several alternative objective functions ranging from single response amplitude operators to complex operability indices can be used. The constraints may include both geometric and performance requirements. The methodology is applied for a typical motoryacht form which represents the modern hull form characteristics. First a single-objective optimization problem is formulated and solved to derive optimized hull forms with significantly reduced seakeeping responses. Then a multi-objective optimization problem which takes into account different aspects of seakeeping performance is formulated. The results indicate that complex and conflicting requirements exist between seakeeping characteristics and hull form properties. Despite this complexity, it is shown that, provided that the designer can specify the objectives and constraints of the problem an optimized hull form with improved seakeeping performance can easily be obtained.

1. Introduction

Most ships are designed to operate in an environment, which can be hostile due to winds and waves. Regardless of their type or size the operational effectiveness of ships will be degraded by rough weather and adverse response of ship subsystems to ship motions will restrict the efficiency of the ship system as a whole. Therefore, the technological success of ships hinges upon a good seakeeping design. This is particularly a case for the modern relatively high-speed commercial vessels including container ships, Ro–Ro and Ro-Pax ships, and cruise ships, for which the ability to maintain relatively high speed in adverse environmental conditions is one of the basic design requirements. This implies that direct influence of the winds and waves should be minimized. The direct influence is reflected in an involuntary speed reduction due to added resistance and reduced propulsive efficiency. The indirect influence is reflected by the voluntary speed reduction or change of heading made by the operator to reduce the effects of wave induced responses such as slamming, deck wetness and high levels of accelerations.

The seakeeping performance of a given ship design is closely related to the type, size and form of the ship's hull. Therefore, it is prudent, and crucial to the success of the design to integrate the basic seakeeping design parameters into the conceptual and preliminary design phases where the designer has the most design freedom to properly accommodate them.

Computational tools have been developed that can predict with a reasonable degree of accuracy the various degrees of ship motion in a specified sea environment. Computer-based methods can now be used with confidence to study the effect of variations in the size, proportions and shape of the hull on the major motions (Sarıöz and Sarıöz, 2005 and 2006). However, prediction of seakeeping performance characteristics of a vessel in a specified seaway does not allow the designer to address the problem of how to change the geometric characteristics of the vessel to bring about more desirable seakeeping performance. As a mathematical problem in optimization, design for seakeeping may be considered as the development of a computational algorithm for choosing size, dimensions and hull form characteristics such that seakeeping performance is an optimized subject to constraints on other aspects of design such as the stability and powering.

The use of optimization procedures in design for seakeeping has been appreciated for some years. The first attempt for a seakeeping optimization method is due to Bales (1980). Bales used

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motion data for 20 existing destroyer type hull forms and linear regression analysis techniques to correlate averaged seakeeping performance, in head seas and at various speeds, to certain empirically selected hull form parameters. He then used the resulting optimum combination of these parameters and conventional lines drawing methods to design an *optimum* seakeeping hull form. This hull form was shown to have superior seakeeping performance characteristics compared with similar ships of ordinary design.

Grigoropoulos and Loukakis (1988) developed a computer-based methodology for developing hull forms with optimized seakeeping performance. The parent hull form is defined by a family of four curves; the sectional area curve, waterplane curve, longitudinal profile curve, and the longitudinal distribution curve of the centroids of ship sections. The section forms are obtained using a three parameter Lewis form representation. To obtain variant hull forms from the parent hull, linear transformation methods were used. To reduce the required computer time, only the peak values of the response curves were compared. An optimization problem with the objective being the weighted sum of the peak values of a prescribed set of ship responses in regular waves was stated and solved by using a nonlinear direct search algorithm.

Smith et al. (1990) developed a random search procedure to design destroyer type ship hull forms with reduced vertical motions. The objective function is a single, head seas only response to be minimized. A strip theory based procedure is used to calculate the transfer functions and the hydrodynamic coefficients are calculated using Lewis form approach. The optimization process is shown to improve seakeeping performance by making heave, pitch and roll natural periods shorter. Generally the optimized destroyer type hull forms were as long and wide as possible, with draft being on the low end of the range. The displacement is typically very close to the maximum allowed. The waterplane are very full, with the aft being very wide all the way to the transom. The volume is moved forward. These waterplane and volume distributions produce wide V-shaped sections forward and flat shallow sections aft.

Lloyd (1991) developed a computer aided optimization procedure which automatically creates a destroyer type hull form to achieve a specified seakeeping performance. The objective of optimization process is defined as to design a hull form having the closest match between the given probabilistic criteria and their corresponding target values. The optimal values of specified hull form parameters are obtained by searching a database consisting of regression equations for each response in terms of the selected form parameters. Having determined the optimal form parameters, the optimal lines plan is obtained by using polynomial representation.

Hearn et al. (1991) developed an inverse design procedure to develop seakeeping optimized hull forms based on a nonlinear direct search process. It was assumed that an initial hull form satisfying the basic design requirements is available and the main dimensions and displacement of the parent form are fixed. The number of design variables was significantly reduced by the use of linear distortion techniques which enabled to generate alternative hull forms for specific values of longitudinal center of buoyancy (LCB), waterplane area coefficient (CWP) and longitudinal center of flotation (LCF). It was shown that even when the displacement and main dimensions are fixed the seakeeping performance could be improved by changing the hull form characteristics. It was also concluded that trends which lead to improvements in one ship type or form may not be applicable to another and generalized empirical relationships could be misleading.

Peacock et al. (1997) developed a mathematical model for the preliminary hydrodynamic design of displacement monohulls based on multi-objective goal programming technique. The underwater shape of the hull form is represented by 23 design variables. These variables were used to generate the two-dimensional hull from sections using B-spline curves. Both geometric and motion related constraints were used to define the feasible design space. The objective function was based on a number of goals defining the critical ship response and sea conditions. The ship motion transfer functions were estimated in accordance with the strip theory method. The model was based on one speed and five discrete headings due to the excessive computation required for the seakeeping analyses. A case study based on a high-speed patrol vessel was considered to demonstrate the developed model. The results indicated that, for a given design scenario, significant reductions in motion levels can be obtained by changing hull form parameters.

In recent years, inverse design of ship hull forms for improved hydrodynamic performance has been a popular research subject. The solution of the formulated inverse design problem is achieved by using two different approaches; namely the conventional method based on nonlinear direct search techniques and a novel approach based on neural network analysis. Both methods have been widely used for the solution of hydrodynamic optimization problems by Eefsen et al. (2004), Grigoropoulos (2004) and Koh et al. (2005).

In this paper an analytical procedure is developed by means of a normalization of the governing equations of linear ship motion theory for obtaining the shape of a vessel which minimizes specified motions in a random sea. To accomplish this task, linear ship motion theory is recast in terms of geometric form parameters which become the variables of the optimization procedure. It should be noted that the current design procedure is restricted to the minimization of vertical plane motions and roll is not included for the following reasons:

- the sensitivity of roll motion to weight distribution characteristics which are generally not available at the early stages of design;
- difficulties in predicting nonlinear roll damping;
- the fact that excessive roll can always be reduced by changing heading to head or bow seas.

Firstly, the dependence of hull form design parameters on seakeeping performance is presented. These hull form parameters form the basis of optimization variables in the inverse design procedure.

Next, it is shown that provided the design variables, objective function and the constraints of the problem are clearly defined, a multi-objective nonlinear optimization problem in terms of specified hull form design parameters can be formulated. The details of the formulation of the inverse design problem are given in Section 3.

In order to illustrate the developed inverse design procedure a modern motoryacht design is considered. Depending on the number of seakeeping responses included in the objective function single-objective and multi-objective optimization problems are formulated and solved to generate seakeeping optimized alternative hull form designs. The applications are presented in Sections 4 and 5. Finally, the conclusions are drawn.

2. Seakeeping and hull form dependence

Linear superposition principle applied to random seas by St. Denis and Pierson (1953) assumes that a random seaway can be represented as a sum of regular waves each having its height and a random phase. According to this principle, the motions of a