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A Prototype Tool for Multidisciplinary Design Optimization of Ships

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A multidisciplinary design optimization scheme for ships has been developed for use in an integrated ship design environment. Although the system was designed with the intention of using first principle analysis techniques, the containership design examples presented in this paper make use of surrogate parametric analysis modules developed to examine problem formulation issues prior to the availability of the higher fidelity modules. A method of hull shape control based on a barycentric blend of basis hulls is developed. It requires relatively few design variables. In addition to general-purpose geometry, hydrostatic and resistance modules, containership-specific weight, cargo and economics modules were developed. The measure of merit is taken to be the required freight rate. Optimal ship size is found to depend largely on port loading and unloading capabilities. The required freight rate increases and the speed of the optimal ship decreases as voyage length is decreased or fuel cost is increased.

Introduction

The work described in this paper was conducted as part of the FIRST project funded under the U.S. Navy's MARITECH program. The goal of this project was to develop an integrated computational design environment that would enable the ship designer to reduce the time needed to produce and analyze alternative ship designs at a high level of detail. It is envisioned that design calculations be done at a first-principles level, including manufacturing and operational econometrics.

The idea of having hydrostatic, resistance, propulsion, economic, etc. analyses enabled in a common design environment led naturally to the desire to implement a multidisciplinary design optimization (MDO) capability. With MDO, the designer can break out of the traditional design-spiral approach and, what has been called the "stove-pipe" analysis approach.

The design obtained by the design-spiral approach is a valid, balanced solution to a given set of requirements, but it is also a solution that is not unique. By choosing a measure of merit, which can be calculated for a candidate design, the optimization process will attempt to find the design which maximizes (or minimizes) this measure. In the case of the FIRST project, which is aimed at commercial ship design and which is to include first principle economic measures, we have chosen to minimize the required freight rate.

This MDO process also brings to bear the fidelity of first-principle analyses at what would normally be thought of as a preliminary design stage. Typically, basic characteristics (e.g., principal dimensions) are largely determined during the first or second turn around the design spiral. Detailed analyses are not carried out until later in the design process when flexibility to change these general characteristics has been greatly reduced. Decisions that determine these characteristics are generally made based on a single discipline's analysis. By employing the MDO process, all design variables are allowed to be varied based on their effect on the measure of merit and, hopefully, converge to an optimum design as the process progresses.

Two generally popular classes of algorithms for the optimization process are gradient-based and genetic algorithms. In the gradient-based algorithms, sensitivities of the objective function (the measure of merit) to changes in the design variables are calculated and the vector of design variables is adjusted in the direction so indicated. In the genetic algorithms, an initial set of randomly chosen designs is ranked by their objective function values. A second generation of designs is then obtained as more or less random mutations of the better designs of the previous generation. This process continues until little improvement in the objective function is seen from generation to generation.

Since genetic algorithms do not require differentiation of the objective function with respect to the design variables, they handle cases of discrete design variables (such as choice of power plant) more easily than gradient-based algorithms. On the other hand, they usually require a much larger number of objective function evaluations than is necessary for the gradient-based algorithms. Thus, genetic algorithms are practically restricted to parametric analysis methods by the computational time required. Since it is our intention to employ first-principle analysis codes, we have chosen to use gradient-based algorithms in this work. Frank, et al (1) present a further discussion of optimization methods.

Keane, et al (2) present another example of gradient based methods applied to ships. An application of a genetic algorithm to minimizing hull resistance is given by Day and Doctors (3). Sen (4) and Ray and Sha (5) present approaches to the multicriteria optimization problem.

System Overview

The computational code consists of a number of analysis modules, an optimizer and a user interface. The code is written with a target platform of Microsoft Windows NT and uses Microsoft's Component Object Model (COM) framework. This was done so that the MDO system will be compatible with the larger FIRST project design tool into which it will be integrated. In the world of COM, each module acts as an independent server exposing its services to other independent client modules through one or more interfaces. Thus, as long as the interfaces are the same, the modules supplying analysis services may be replaced by another module providing the same service with negligible impact on the rest of the code.

This feature was important in that both the MDO system and the larger FIRST tool of which it is to be a part, were being developed simultaneously. The higher fidelity analysis tools, which will ultimately be used in this system, were not yet available and thus surrogate analysis modules were written. In order to explore problem formulation issues, these surrogate modules needed to perform in the same general manner as the high fidelity modules and thus simple parametric representations of the analyses were used.

The Design Optimization Tools (DOT) package from Vanderplaats Research and Development, Inc. was chosen as the optimizer. DOT includes the choice of three gradient-based optimization methods, a modified method of feasible directions, sequential linear programming, and sequential quadratic programming. We have created a DOT COM object by writing a C++ wrapper around the DOT FORTRAN source code. Tests have shown that the quickest and most consistently reliable results are obtained using sequential linear programming. It is used for the examples presented below.

Besides the optimization module, the system has modules which perform the following functions: calculate a NURBS (Non-Uniform Rational B-Spline) hull geometry surface, calculate a mesh of offsets on the surface described by the NURBS net, integrate the surface and calculate hydrostatic properties, calculate ship resistance, calculate propulsive efficiency, powering requirements and fuel rate, calculate lightship weight and *CG*, calculate payload weight and *CG,* calculate roll period, minimum *GM* and freeboard, and calculate economic characteristics. Each of these is discussed briefly below.

Immediately obvious is that the weight and economics modules depend on the ship type. A containership design problem was chosen for the construction this prototype MDO system.

The design variables, i.e., those variables that the optimizer manipulates, are chosen to be: the overall length, beam and depth of the hull, the draft, the cruising speed, and a (set of) parameter(s) that controls the hull shape. The hull shape manipulation is discussed in the next section.

Hull Geometry

As a means of controlling the hull shape, the hull is represented as a barycentric blend of basis hulls. This can be represented as

$$\sum C_n \text{ BasisHull}_n = \text{Resultant Ship Hull}$$

where,

$$\sum C_n = 1$$

and,

$$0 \le C_n \le 1,$$
$$n = 1, 2, \ldots, \text{N}.$$

Thus, the hull resulting from this blending process is restricted to being a member of the hull shape space bounded by the basis hulls. Figure 1 illustrates the blending concept for the midship section in a case of only two basis hulls.

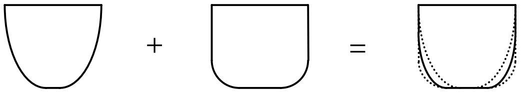

Figure 1. Illustration of geometry blending technique.

The blending coefficients, C_n, are the design variables that adjust the hull shape. Because of the constraint, $\sum C_n = 1$, the number of design variables the optimizer must adjust is N - 1. The blending is applied to the NURBS net points of the basis hulls (which have standard dimensions) and the resulting hull is then scaled to the necessary length, beam and depth.

Hydrostatics

From the NURBS net obtained by the blending and scaling discussed above, a set of unequally spaced points located on the hull surface represented by the NURBS net is calculated. Hull volumes and areas are calculated from this mesh of surface points and the displacement, the hydrostatic coefficients, and the metacentric height are calculated by the hydrostatics module.

Resistance and Propulsion

The ship’s resistance at the current cruising speed is calculated using the Holtrop/Mennen regression formula (6). Additional resistance due to appendages is ignored; however, the effect of a bulbous bow is retained. The propulsion module, at present, simply assumes an overall propulsive efficiency of 0.65. From this a shaft horsepower is obtained and, from a specific fuel consumption that is input as a parameter, a fuel rate is calculated.

Weights

Parametric relationships for lightship weights and centers of gravity were obtained from Benford (7), Taggert (8) and Schneekluth (9). Lightship was broken into three categories: hull steel, outfit and propulsion machinery, each with its own parametric equations for weight and center of gravity. Because the coefficients used in the parametric equations obtained from the above references did not reflect modern design and construction practices, the weight equation coefficients were recomputed based on seven modern containerships ranging in length from 186 to 263 m. A three percent margin was added to the calculated lightship weight and a 0.3 m margin was added to the vertical center of gravity.

Fuel weight was based on the specified ship range, its speed and the calculated fuel rate. A ten percent reserve was added to the fuel weight. Relations for miscellaneous weights, including, crew and provisions, fresh water and lube oil, were obtained from Erichsen (10).

Cargo

It is necessary to calculate the container carrying capacity as the ship's dimensions vary. Two relations were developed, one for containers, in terms of TEU's (Twenty foot Equivalent Unit, 6.1 m x 2.44 m x 2.44 m), below deck and one for TEU's on deck.

For TEU's below deck, the integer number of containers that will fit along each of the length, beam and depth directions is found, allowing for wing tank and double bottom spaces. These integer values are multiplied together to form a block capacity, which is then multiplied by a stowage factor that is a function of block coefficient. The stowage factor was determined from the known capacities of twelve existing ships.

The relation for number of containers above deck is similar to that below deck, except that the number of tiers of containers on deck (not required to be an integer) is substituted for the number that would fit depthwise and a different stowage factor is used.

Cargo weight is simply the total number of containers multiplied by an average container weight. The center of gravity of the containers above deck is calculated considering them to be of uniform density and raised off the deck by a hatch coaming height. The *CG* of the containers below deck is raised from the mid height of the available depth by a factor that depends on block coefficient.

With this scheme, the container capacity, cargo weight, etc., is a discontinuous function of the ship's dimensions (Figure 2). This results in a discontinuous, saw-tooth like objective function (the required freight rate) with many local minima that the optimizer can fall into. Also, the values of the numerically calculated gradients can be significantly in error in the vicinity of the discontinuities, which is a problem for gradient-based methods. To remedy this situation, we have chosen to fit a linear response surface to the discontinuous container capacity function as is illustrated in two dimensions in Figure 2.

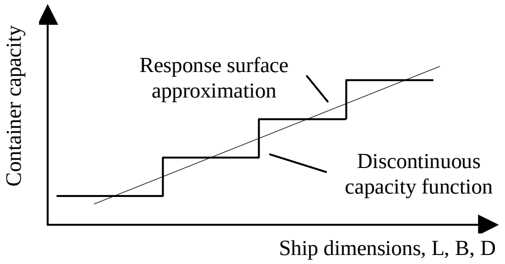

Figure 2. 2-D illustration of container capacity function and linear response surface.

Economics

To calculate the required freight rate, the economics module must find building costs and annual operating costs. These are obtained using the relations of Benford (7) and Erichsen (10).

Building cost is broken into labor and materials costs for each of: hull steel, outfit, hull engineering and propulsion machinery, miscellaneous costs, accommodation costs, overhead costs, yard's profit and owner's expenses. Each of these costs has its own parametric relation that is ultimately based on one or more components of lightship weight, installed horsepower, or number of crew. The building cost is converted to an annual cost by specifying a life of the ship and an interest rate.

To calculate annual operating costs, the number of round trips made annually by the ship must be known. This depends on the cruising speed, to find time spent at sea, and on time spent in port. The port time includes waiting time and time spent loading and unloading the ship. The loading/unloading time depends on the number of cranes being used. The number of cranes can be specified or can be calculated based on length. The annual operating cost is then formed as the sum of individual relations for wages, stores and supplies, insurance, maintenance and repair, port expenses, and fuel cost.

The required freight rate is then expressed as total average annual cost per ton of cargo carried per mile. Important parameters used by the system but not mentioned above include, labor cost, material costs for hull, outfit and engineering, number of containers handled per day per crane, voyage distance and fuel price. No per container cargo handling charges are included since they vary widely from port to port and they do not affect the point in the design space at which the minimum occurs but serve only to boost the value of the required freight rate for all designs.

Constraints

The condition that weight equal displacement is enforced as a constraint. We treat draft as an independent design variable rather than enforce the weight-displacement balance through an internal loop at each design iteration. This has been called an optimization based decomposition approach. Tests have shown that this quickens the calculation over an approach where the design is balanced at each iteration.

The U.S. Coast Guard wind heel criterion for minimum initial stability and the U.S. Coast Guard minimum freeboard requirement are also imposed as constraints.

The user may select constraints on minimum rolling period, maximum displacement, maximum shaft horsepower, and both upper and lower bounds on container capacity. A structural constraint and constraints on the dimension ratios will be implemented in the future.

Two modifications of the constraints were needed to ensure convergence from an infeasible starting point with a negative GM. First, since the natural roll period is undefined for $GM < 0$, it was artificially extended into this region as an even function of GM. Second, the initial stability constraint is formulated as

$$g = 1 - {}^{GM}\!/_{GM_{\min}} \le 0.$$

For $GM << 0$, the derivative of g with respect to beam, ${}^{\partial g}\!/_{\partial B}$, can become positive (due to the dependence of GM_{min} on beam) indicating that the beam should be decreased rather than increased and the optimizer fails to find a feasible solution. To overcome this, we hold GM_{min} equal to its initial value while $GM < 0$.

Example Applications

Several applications are presented below. In each case, the hull shape is adjusted by blending two basis hulls. Only one shape design variable is needed, C_1. Basis hull 1 is finer than basis hull 2. The important parameter values for each case are: ship life = 20 yrs, interest rate = 8%, weight per TEU = 12 mt, and specific fuel consumption = 120 g/BHP/hr. Except in Example 4, the number of cranes loading and unloading is calculated based on one crane every 135 feet over 75% of the ship length. For the 300 m designs that result below, this means 6 cranes. Except in Example 5, voyage distance = 7000 nmi. Except for Example 6, the fuel price used was $80 per mt. In light of the return of fuel prices to considerably higher values in recent months (December 1999), the final example is a repeat of the first with a fuel cost of $120 per mt.

Table 1 gives the initial values of the design variables used for Example 1 along with their upper and lower limits. The upper limits on length, beam, and draft were chosen to roughly coincide with a recently built, large containership. The initial values of the design variables result in an infeasible design with an initial GM of –7.4 m, a weight of 42,000 mt, and a displacement of 33,700 mt. The results for each example are presented in Table 2. Convergence is quick; these examples each converge in 7 – 15 iterations.

	Lower limit	Initial value	Upper limit
LOA	130.0	200.0	300.0
Beam	15.0	28.0	43.0
Depth	10.0	20.0	30.0
Draft	4.0	10.0	13.5
Speed	4.00	19.0	35.00
C_1	0.00	0.5	1.00

Table 1. Design variable bounds and initial values for Example 1.

Example 1 is a minimally constrained case. The only constraints applied, other than the side bounds on the design variables, are weight equals displacement, the stability criterion and the minimum freeboard. The optimizer goes to the maximum length and beam and chooses the fullest possible ship that could result from the blending. The value of C_1 is essentially zero, or the optimum ship is all basis hull 2. It is interesting to note that the required freight rate is relatively insensitive to the value of the blending coefficient. The optimum ship has a B/D = 3.1 and a L/D = 21.6, both very high. This is the result of the absence of a structural constraint. Constraints on these ratios would serve to artificially impose a structural requirement.

Example 2 is the same as Example 1 except that the lower bound on the speed has now been raised to 25 knots. Rather than going for the fullest hull, the optimizer now chooses the finest possible hull; the optimum is all hull 1, C_1 = 1. The ship carries fewer containers but has a larger displacement. This is due, in large part, to the increased engine weight, which also causes a drop in GM and subsequent raise in natural roll period. The required freight rate jumps about 20% with the high speed. Both Examples 1 and 2 have the minimum required freeboard.

Example 3 is the same as Example 1 except with the additional constraint of a 25 second natural roll period. By using several starting points, the optimizer found two solutions to this problem that give approximately the same required freight rate. These are shown as 3a and 3b in Table 2. Solution 3a uses a smaller beam, smaller depth, and less freeboard than does solution 3b. It consequently carries fewer containers but requires less SHP for about the same speed and so the required freight rates are similar. This illustrates that the optimizer finds local rather than global optima. The larger roll period costs about 5% in required freight rate.

The fourth example illustrates the effect of port time on the optimum design. This example is, again, the same as Example 1 but with only one crane being used to load and unload the ship. The increase in time spent in port reduces the benefit of investment in a larger, faster ship. The result is a much smaller, slower ship than was obtained in Example 1. The required freight rate has increased 41%.

For the fifth example, the voyage distance was halved to 3500 nmi but otherwise, the conditions were the same as for Example 1. It was thought that changes in the optimum ship in the same direction as was seen in Example 4 would be obtained since the time in port relative to that at sea was again increased; however, what was found was a very similar, only slightly slower ship with a 20% higher required freight rate shown as Example 5a. The voyage distance was then cut to 1000 nmi. The result, shown as Example 5b, was again, a very similar, but slower ship. It appears that if the cranes are available, it is worth building a large ship, assuming of course that the market exists for the large capacity.

Example 6 looks at the effect of raising the fuel cost from $80/mt to $120/mt. Except for this change, the input is the same as for Example 1. The optimum ship is nearly identical to the one in Example 1 with the exception of a slower speed and the consequent smaller SHP and displacement. The fuel cost was also raised in Example 2, where a 25 kn speed is required; a nearly

	Ex. 1	Ex. 2	Ex. 3a	Ex. 3b	Ex. 4	Ex. 5a	Ex. 5b	Ex. 6
Loa (m)	300.0	300.0	300.0	300.0	209.0	300.0	299.8	300.0
Beam (m)	43.0	43.0	36.1	39.2	43.0	43.0	43.0	43.0
Depth (m)	13.9	16.6	14.7	16.6	11.7	13.8	13.7	13.9
Draft (m)	9.14	11.9	9.44	10.1	8.29	9.06	8.96	9.10
Speed (kn)	17.1	25.0	17.5	17.8	15.1	16.8	15.3	15.9
C_1	0.0	1.00	0.003	.012	0.008	0.008	0.013	0.0
Displ.(mt)	85,030	88,370	73,320	83,780	54,400	83,960	82,900	84,520
# TEU's	5203	5049	4427	4996	3393	5183	5165	5195
SHP	22,040	72,650	20,700	23,050	11,970	20,790	15,110	17,260
Roll per. (s)	11.2	17.8	25.0	25.0	9.32	11.2	11.2	11.2
C_b	0.714	0.568	0.710	0.703	0.722	0.712	0.712	.713
RFR ($/t/nmi)	.00106	.00126	.00111	.00111	.00149	.00124	.00212	.00115

Table 2. Design variable values and various ship characteristics at the optimum point for each example.

identical ship was obtained but its required freight rate went up by 18% to 0.00149 $/t/nmi.

Conclusions

A prototype MDO tool for ship design has been developed based on Microsoft's COM framework. With this design, the analysis modules can be replaced with a minimum of programming effort. Surrogate parametric analysis modules have been developed for the purpose of exploring problem formulation issues while higher fidelity analysis modules are being developed. A geometric shape manipulation scheme was developed in which the hull was formed by blending a set of basis hulls.

The MDO system was exercised on a set of containership design problems with the objective being to minimize the required freight rate. It was found that without being otherwise constrained, the optimizer sought the largest allowed length and beam. In the absence of a structural constraint, the optimizer seeks a design with a high *B/D* ratio.

The MDO system generally behaves as expected. Test exercises have shown that if the loading/unloading time is constrained, investment in larger, faster ships is not beneficial. Required freight rate decreases with increasing voyage distance but vessel size is determined by how fast it can be turned around in port. The limited study performed indicates that fuel cost affects the required freight rate and optimum speed but not the principal dimensions of the ship.

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