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ROLE OF OPTIMIZATION IN INTERDISCIPLINARY ANALYSES OF NAVAL STRUCTURES

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ABSTRACT

This paper discusses the need for numerical design optimization of naval structures and illustrates the complexity of problems that arise due to the significant roles played by three major disciplines, i.e., structural mechanics, acoustics, and hydrodynamics. A major computer software effort that has recently begun at the David W. Taylor Naval Ship R&D Center to accommodate large multidisciplinary analyses is also described. In addition to primarily facilitating, via the use of data bases, interdisciplinary analyses for predicting the response of the Navy's ships and related structures, this software effort is expected to provide the analyst with a convenient numerical workbench for performing large numbers of analyses that may be necessary for optimizing the design performance. Finally, an example is included that investigates several aspects of optimizing a typical naval structure from the viewpoints of strength, hydrodynamic form, and acoustic characteristics.

INTRODUCTION

The past two decades have witnessed an unprecedented growth and activity in the field of computer-based numerical solutions to problems of physics. Amongst these, perhaps the most promising and certainly the most popular solution procedure developed and utilized by scientists and engineers has been the method of finite elements. This method, although originally developed for analysis of structural engineering problems, has found applications in several other disciplines of computational physics. The usual objective when analyzing a typical problem in computational physics is to evaluate the performance of a given system or a design, e.g., a specific structural configuration, when subjected to certain service conditions. With the aid of today's large computer programs such as NASTRAN,[1] prediction of stresses, displacements, and frequencies for a large integral structure such as a destroyer with all its discontinuities has become more or less a routine matter. Even though having such computational tools available in the hands of a designer is a substantial step forward, these are often not the most efficient ways of converging to a good design. It appears that some kind of design optimization procedure would be the key to developing an effective design tool. The considerable activity in this field in the past decade is very gratifying and is in fact a clear indication that effective design optimization procedures are no longer relegated to the distant future. The general message that emerges from the current literature on structural design optimization is that the basic technology now exists to efficiently design relatively small structures defined by several hundred design variables under multiple loading conditions and subject to sizing, stress, displacement, buckling, frequency, and flutter constraints.[2,3] This may still be a far cry from designing the structure of a complete ship, but nevertheless it is a definite and encouraging beginning. Another message that comes across from the literature is the absence of an effective technique for shape optimization of large structures, which is of course a very important issue.

A large number of discipines play an important role in ship design, viz. structural mechanics, hydrodynamics, acoustics, and electromagnetics. Thus an efficient ship would be simultaneously lightest and strongest, fastest, quietest, and invisible to electromagnetic sensors. Aside from the optimization problem, which would involve multiple objective functions, even some straight-forward analysis problems become nontrivial when multiple disciplines have to be considered. Often it is necessary to resort to numerical iteration procedures when an efficient coupled procedure is not available. Despite all those complexities, we have made a very modest beginning toward developing computer-based design tools with limited optimization capability. One of these design tools, ASSET (Advanced Surface Ship Evaluation Tool)[4] is an interactive computer program for use in the exploratory and feasibility design phases of monohull surface ships such as frigates, cruisers, and destroyers. ASSET addresses virtually all major technological domains of design that are relevant to such ships, including geometric definition of hull and superstructure, resistance, propulsion, machinery, weight, hydrostatics, seakeeping, cost, and manning. The program features design synthesis capability, database management of design data, and extensive input/output options including interactive graphics. The other design tool, SUBSET, is a similar tool which is being developed for submerged structures. Both ASSET and SUBSET are interactive computer tools which do not, however, address the optimization of detailed ship design. With the rapid advances in individual analysis procedures, computing hardware, and sophisticated software technology, DTNSRDC is becoming greatly interested in developing and/or acquiring an optimization capability for detailed design.

The following sections will discuss the presently ongoing work at DTNSRDC in the area of optimization of detailed design as well as in analysis procedures.

RECENT ACTIVITY IN OPTIMIZATION

The recent level of activity in detailed optimization at DTNSRDC has been low. In the area of preliminary and conceptual design of ship hulls, the ASSET program previously mentioned is used. Currently, however, the majority of the optimization effort at DTNSRDC is being performed with the COPES/CONMIN[5] computer program in the areas of hydrodynamics and structures. For example, one application involves the minimum surface area design of ship appendages subject to maneuvering constraints. The authors have been using COPES/CONMIN in propeller-related design work, the experiences of which will now be described in some detail.

The purpose of our first experience with COPES/CONMIN was to demonstrate its capability for propeller design. Specifically, our test problem was to minimize the strain energy of a finite element model of a composite propeller subjected to a pressure load. The five design variables were material properties, the purpose of which was to design the effective properties of the composite material. The four constraints involved relationships among the design variables as well as a constraint on the deflection of the propeller tip. The finite element analysis of each new COPES/CONMIN design was to be performed with COSMIC/NASTRAN, hereafter known as NASTRAN. This demonstration was intended to be completed within two weeks.

The problems with our proposed test began early. COPES/CONMIN works most conveniently when the routines needed to analyze a new design can be made part of the COPES/CONMIN program. When that is not possible, as is the case with NASTRAN, two options are available. (1) The first option uses approximate optimization, in which trial designs, with their respective objective and constraint values, must be supplied, after which COPES/CONMIN performs curve-fitting to calculate a new design. Each new design then becomes an additional trial design at the next iteration. Also, since NASTRAN cannot be loaded into the computer's central memory simultaneously with COPES/CONMIN, pre- and post-processors must be developed to transfer information. For example, once a new design is created, a NASTRAN pre-processor must be written to access the COPES/CONMIN design (which is written to a scratch file in our modified version of COPES/CONMIN) and develop the new NASTRAN finite element data. After NASTRAN is run with the new design, a post-processor accesses needed results, computes values of objective and constraints, and modifies the COPES/CONMIN data, after which COPES/CONMIN creates another new design. This looping process through COPES/CONMIN, pre-processor, NASTRAN, and post-processor is set up automatically within the computer's job control language and continues until the pre-processor has determined that convergence has taken place or until a pre-defined number of loops have been executed. (2) The second option uses the standard optimization techniques of CONMIN and sets up the data in such a way that CONMIN can be restarted after NASTRAN has run. The problem with (2) is that gradients of the objective function, design variables, and violated constraints are required for each design. These gradients are computed using finite difference techniques and multiple executions of the analysis routine (NASTRAN). Because such differencing can be very expensive ($6.00 per analysis for our case), we chose (1).

In order to gain confidence in using COPES/CONMIN, we first ran a sample problem from the program's users manual. The problem was to minimize the volume of a cantilevered beam subject to an end load. The design variables were the width B and height H of the beam cross section, with various constraints on stresses and deflection. The correct result is B = 1.818, H = 18.179. The users manual used approximate optimization with the following four trial designs:

	TRIAL			
	1	2	3	4
B	1.	2.	4.	3.
H	15.	20.	10.	12.

COPES/CONMIN gave B = 1.818, H = 18.168 after eight iterations. We ran the same problem with the following ten trial designs:

	TRIAL									
	1	2	3	4	5	6	7	8	9	10
B	2.	1.	3.	4.	5.	15.	5.	4.	3.	2.
H	5.	3.	20.	11.	8.	1.	6.	9.	13.	7.5

After 24 iterations, B = 3.161, H = 18.713. Changing the tenth H value from 7.5 to 18. resulted in B = 1.853, H = 18.219 after 6 iterations, and B = 1.824, H = 18.187 after 24 iterations. At least two conclusions can be drawn from this test. (1) It helps to know the answer before beginning the problem. (2) Too much scattered information may not be useful for approximate optimization, although the program developer has suggested using a random number generator to create the trial designs.

With this information in hand, we proceeded with our composite propeller. With our two-week time limit fast approaching, we used ten trial designs and 50 iterations, which took 12 minutes of CPU time on a CDC CYBER 170/750 computer. While convergence was slow, there was steady improvement in the objective function which gave us some encouragement for future work.

Approximately a year after this demonstration, we were asked to assist DTNSRDC's Ship Performance Department in the optimization of a propeller/shaft system. Since the various design aspects of the propeller, such as weight, thrust, torque, etc., affected the shaft, but the design aspects of the shaft, such as cross-sectional area, bearing locations, etc., did not affect the propeller, we decided to perform two separate optimizations within the same computer run.

The first optimization was for the propeller. The hydrodynamic analysis routine for the propeller was small enough to include as part of COPES/CONMIN and therefore standard optimization was used. Various objective functions used were weight, efficiency, tip speed, and weighted normalized sums of these functions. Design variables included propeller diameter, angular velocity, and others. Constraints included hub diameter, thrust, weight, efficiency, tip speed (these latter three when not used as objective functions), and others. COPES/CONMIN gave good, reasonable results in all cases. The number of times that the hydrodynamic analysis routine was executed varied between 50 and 150, depending on the case run. However, since the analysis routine used less than 0.5 CPU seconds on a CDC CYBER 176 computer, costs were small.

The second part of the task was to minimize the shaft weight using various outputs of the propeller optimization, including propeller weight, torque, and steady and unsteady thrusts. The design variables were the inner and outer diameters of the shaft. The constraints included various combinations of static stresses (one NASTRAN run), factor of safety, natural frequencies corresponding to axial and vertical modes (a second NASTRAN run), and acoustic levels computed by another program which uses NASTRAN forced response output (a third NASTRAN run). Because of the NASTRAN analyses required, approximate optimization was used with five trial designs. The computer job control language loop for this second task began with COPES/CONMIN and continued through three separate NASTRAN analyses and an acoustic analysis interspersed with five pre- and post-processors. Ten iterations were performed (@$25.00 per iteration) with good volume reductions and an apparent trend towards a convergent solution. We then decided to remove from these 15 designs (the initial 5 trial designs plus the 10 computed ones) the first 5 trials and continue the iterations. The subsequent designs were significantly lower in volume than any of the first 10 computed designs and still remained feasible.

While our results for the propeller/shaft system were very good, a number of questions remain. What are the true trade-offs between standard optimization and approximate optimization in COPES/CONMIN? Were we saving money initially with approximate optimization by avoiding the finite differencing required to compute gradients, but paying later by not arriving at a better design more quickly? Is the apparent local minimum initially computed more likely to occur with approximate optimization than with standard optimization? Will the cost for such a multi-disciplinary design process become prohibitive for a relatively small number of design variables? How does one convince a sponsor who is not versed in numerical optimization that a significantly better design is worth the funds expended even if it is not the theoretically optimum design?

Finally, we need to mention the development of the pre- and post-processors. While the development of these processors is quite straightforward given a fixed geometry with a known set of design variables, that is not usually the situation in the preliminary ship design process. It takes some time (and iterations) to decide on the design variables (inner and outer diameters of the shaft, bearing locations, bearing stiffness, a combinaton of all these), design parameters (one-section or two-section shaft, shaft length, sand in the shaft or not), and applicable engineering theory (which acoustic analysis, added mass due to fluid effects, etc.). Each time a new approach was considered, the pre- and post-processors were changed (often considerably) to reflect new data and analysis programs. Such code changes can hopefully be minimized with an integrated, database-managed software system. Such systems are currently under development at a number of agencies. In particular, Wright-Patterson Air Force Base is developing an integrated software system for optimization, while DTNSRDC is developing IDEAS (Interdisciplinary Engineering Analysis for Ships), which will be discussed in the next section of the paper.

INTERDISCIPLINARY ENGINEERING ANALYSIS FOR SHIPS

The IDEAS (Interdisciplinary Engineering Analysis for Ships) system being developed at DTNSRDC is intended to be an integrated database-managed software system which can significantly smooth the transitions between analyses in different disciplines. For example, suppose that a propeller is to be analyzed for its hydrodynamic, structural, and acoustic characteristics. The hydrodynamic analysis, using finite difference techniques, computes and saves loads. The structural analysis, using finite element techniques, can be performed only after accessing the hydrodynamic loads (the storage scheme for which will differ from program to program), interpolating the loads from the finite difference model to the finite element model, and formatting the loads into those required for the structural analysis program. Similar considerations are required to access the structural deformations for input to an acoustic analysis. In addition to these transformations of data, the development of the two numerical models, finite difference and finite element, usually emanates from drawings shared by the hydrodynamicists and structural analysts, each group separately digitizing the drawings. With an integrated software system such as IDEAS, the data transitions between programs in the system should be very easy. All analysts who need to numerically model a structure will be able to access a common geometrical/mathematical description of the structure without having to locate and digitize drawings. Such a system will allow easy access to the performance characteristics of previous designs, as is often the need in ship and propeller design.

We are planning to use as the basic architecture of IDEAS the Integrated Analysis Capability (IAC)[6] recently developed by NASA's Goddard Space Flight Center. The architecture of the IAC was designed to support an integrated, database-managed system of engineering software and data. It was also designed to allow easy "plug-in" of new analysis progams. Therefore, it is our intention to use the IAC to build an integrated system of DTNSRDC engineering software, including analysis programs such as NASTRAN, and ABAQUS, as well as automatic numerical model generators and other pre- and post-processors usually associated with such analyses. The initial effort for IDEAS was begun in FY84.

OPTIMIZATION OF ANALYSIS PROCEDURES

In addition to the design optimization, DTNSRDC has also been involved in other related optimization efforts which have proven to be very useful.

Since the finite element method is essentially an approximate numerical technique for solving practical differential equations of physics, it has some inherent error associated with it. Knowledge and control of this error are obviously critical to the analysts. A few years ago we began a new effort to evaluate FEARS,[7] a finite element computer program developed by Professor Ivo Babuska at the University of Maryland and based on adaptive meshing and _a posteriori_ error estimation concepts. After each successive iteration this program computes the strain energies in various elements and, based on certain error criteria, makes a decision with regard to further subdivision of individual elements. The computation continues until a certain specified error bound is reached. After initial installation and debugging, the FEARS computer program has been enhanced in several ways. A post-processor has since been developed which computes the stresses more accurately. This post-processor is based on fitting the data to some appropriate analytical expressions that are then used to obtain the desired stresses which are proportional to derivatives of the original data.[8] The program was also modified so that it can now solve some limited plate bending problems.[9] It is now planned to develop a similar error capability without adaptive meshing which would initially be used to compute the error in any given NASTRAN run.

Another effort of DTNSRDC's interest has been to maintain a current version of a post-processor, BANDIT,[10] which is used to resequence the finite element models for minimizing the bandwidth of their stiffness matrices. This program is kept up to date by continuously evaluating and using the newer resequencing algorithms which from time to time keep appearing in the literature. We also maintain a set of test problems which are used to evaluate the effectiveness of these resequencing algorithms. In the near future we are planning to develop a similar resequencing capability for ABAQUS.

At DTNSRDC, we recently developed a NASTRAN-based finite element capability to predict the magnetostatic fields associated with ships and submerged structures. An interactive tool was then developed that can be used to compute the distribution of degaussing coil currents that would minimize the magnetostatic anomaly due to the ship in the Earth's magnetic field. This procedure was based on a simple least squares fit. There are now plans to enhance this capability to include a constrained optimization on the coil currents, taking into account cost, weight, power, capacity, and so forth.

SUMMARY AND CONCLUSIONS

From the foregoing description of various types of activities in the general area of optimization, it is quite evident that DTNSRDC has a positive interest and an urgent need for an effective computer-based capability that would contribute toward improvements in ship design. The problem of optimizing a complete ship from the viewpoints of all the relevant disciplines is clearly a monumental task; nevertheless, a definite beginning has been made in the shape of capabilities for optimizing the exploratory and feasibility designs of ships. Progress is also being made in evaluating and developing and/or modifying existing optimization programs for detailed designs.

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