EXPERIENCES WITH NASTRAN IN A MULTIDISCIPLINARY OPTIMIZATION ENVIRONMENT

Myles M. Hurwitz

David W. Taylor Naval Ship Research and Development Center

SUMMARY

NASTRAN and COPES/CONMIN were used in the early-stage design optimization of a propeller and shaft. The work was undertaken, in part, to assess the performance of these programs for such a task. While the optimization was successful, some drawbacks to the approach surfaced and are discussed.

INTRODUCTION

For almost 25 years, the finite element method (FEM) has been the premier technique used in the field of structural analysis. The FEM has enjoyed this popularity because of its generality, ease of use, and obvious physical relationship with the structure to be analyzed. With the advent of NASTRAN in 1970, engineers had a comprehensive and easily accessible program for taking advantage of this popular technique. NASTRAN and FEM technology, in general, have now had 10-15 years to mature, while users of the FEM have become very sophisticated in their use of such programs. In fact, usage of finite element programs has now extended far beyond structural analyses; heat transfer, aerodynamics, electricity, magnetism, and acoustics are but a few of the disciplines finite element programs now address.

Finite element analyses are now so routine that natural scientific inquiry leads to the question, "Now that I can analyze the structure so easily, can the structure be modified to make it better?" This question leads immediately to another: "What is meant by 'better'?" This question can usually be answered with adjectives such as lighter, cheaper, faster, more efficient, etc. Taking this process a step further, if the analyst (now a designer?) wants a lighter structure, a lighter material may mean larger deflections, which may not be allowable. Therefore, the engineer often has a conflict; he/she has an objective, e.g., the lightest structure possible to do the job, but the situation may call for constraints, e.g., stress, deflection, which conflict with the objective. The goal then is to minimize or maximize some objective function subject to imposed constraints. The subject area which attempts to solve this problem is called "optimization."

The objective of the work was, in part, to assess the performance of NASTRAN for early-stage design optimization. For this paper, the details of the specific structure being optimized are not important, but it should be noted that the optimization was very successful. So, the remainder of the paper will briefly present the optimization problem in mathematical terms and then describe (1) our experiences in attempting to solve an optimization problem which had constraints in fluid mechanics, structural mechanics, and acoustics; and (2) NASTRAN's role in the solution process.

OPTIMIZATION

The general mathematical constrained optimization problem can be described as (reference 1):

$$\text{Minimize:} \quad F(\overline{X})$$

$$\text{Subject to:} \quad G_j\,(\overline{X}) < 0,\ j = 1, \ldots, m$$

$$\text{and } x_i^{\ell} < x_i < x_i^{u},\ i = 1, \ldots, p$$

where

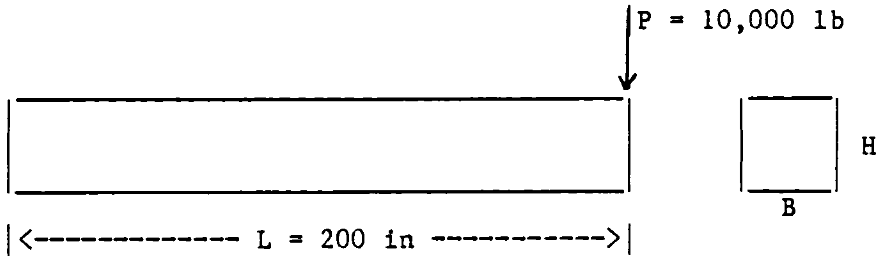
$\overline{X} = [x_1, x_2, \ldots, x_n]^T$ is the vector of design variables, i.e., those parameters in the problem whose values can change in order to achieve a "better structure";

F = the objective function to be minimized;

G_j = the jth constraint on the solution; and,

x_i^{ℓ}, x_i^{u} = lower and upper bounds on the ith design variable.

A simple example from reference 1 will clarify these concepts. Assume that the cantilever beam in the following sketch is to be optimized as follows:



Minimize Volume = B•H•L (design variables are B and H, i.e., $\overline{X} = [B\ H]^T$ subject to the following constraints:

(1) Bending stress $\sigma_b < 20{,}000$ psi

$$\sigma_b = \frac{Mc}{I} = \frac{6PL}{BH^2} < 20{,}000, \text{ or } G_1(\overline{X}) \equiv \frac{6PL}{BH^2} - 20{,}000 < 0$$

where M is the moment, c is the distance from the neutral axis, and I is the moment of inertia of the section.

(2) Shear stress $\upsilon < 10{,}000$ psi

$$\upsilon = \frac{3}{2}\frac{P}{A} = \frac{3P}{2BH} < 10{,}000, \text{ or } G_2(\overline{X}) \equiv \frac{3P}{2BH} - 10{,}000 < 0$$

where A is the cross-sectional area BH.

(3) Deflection $\delta < 1.0$ in.

$$\delta = \frac{PL^3}{3EI} = \frac{4PL^3}{EBH^3} < 1.0, \text{ or } G_3(\overline{X}) \equiv \frac{4PL^3}{EBH^3} - 1.0 < 0$$

where E, Young's Modulus, is assumed to be 30×10^6 lb/in^2.

(4) $0.5 < B < 5.0$

(5) $1.0 < H < 20.0$

(6) $\frac{H}{B} < 10.0$

For a simple two-design variable problem such as this, the constraints and volume contours can be easily represented on a two-dimensional plot as in Figure 1. The cross-hatching of Figure 1 represents the violated sides of constraints. The shaded area represents the region of feasible designs, i.e., the only region which contains acceptable combinations of B and H. This region is enlarged in Figure 2, where the optimum design is at the circled point, which is B = 1.82 in., H = 18.2 in., and VOL = 6608 in^3.

For a problem with many design variables, a numerical, rather than graphical, method is required to obtain the optimal solution. The program used in the present work was the Control Program for Engineering Synthesis/Constrained Minimization (COPES/CONMIN) (references 1 and 2). (The optimization portion of the program has since been succeeded by the code Automated Design Synthesis (ADS), so that the current designation of the complete program is COPES/ADS, reference 3). Along with the numerical optimization program which computes new values of the design variables, and hence develops a new design, a program is needed to analyze the new design. The analysis program must compute the values of the objective function and constraints for the new design. These values are then passed back to the optimization program, which will develop still another design in an attempt to minimize the objective function while satisfying the constraints. This procedure is repeated until convergence has been achieved or until a predetermined number of iterations has been performed.

The analysis program can be linked to COPES/CONMIN in two ways: (1) the analysis program can be a subroutine within COPES/CONMIN, or if that is not possible, (2) the analysis program is kept separate from COPES/CONMIN, but linkage programs between the two must be provided. The second method requires

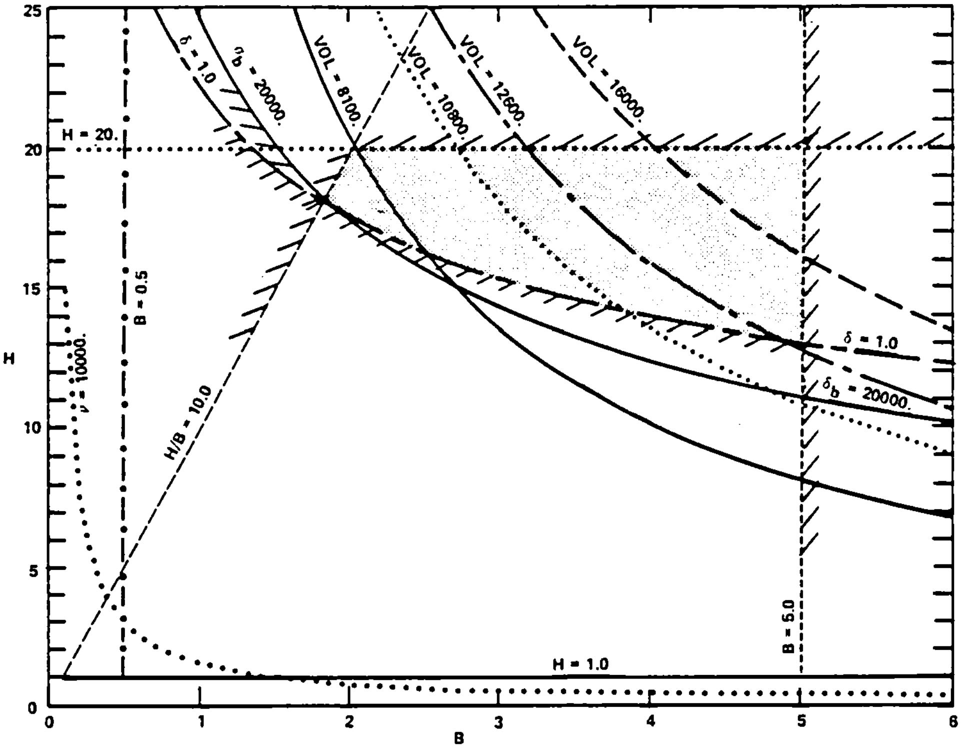


Figure 1 - Two-Dimensional Design Space

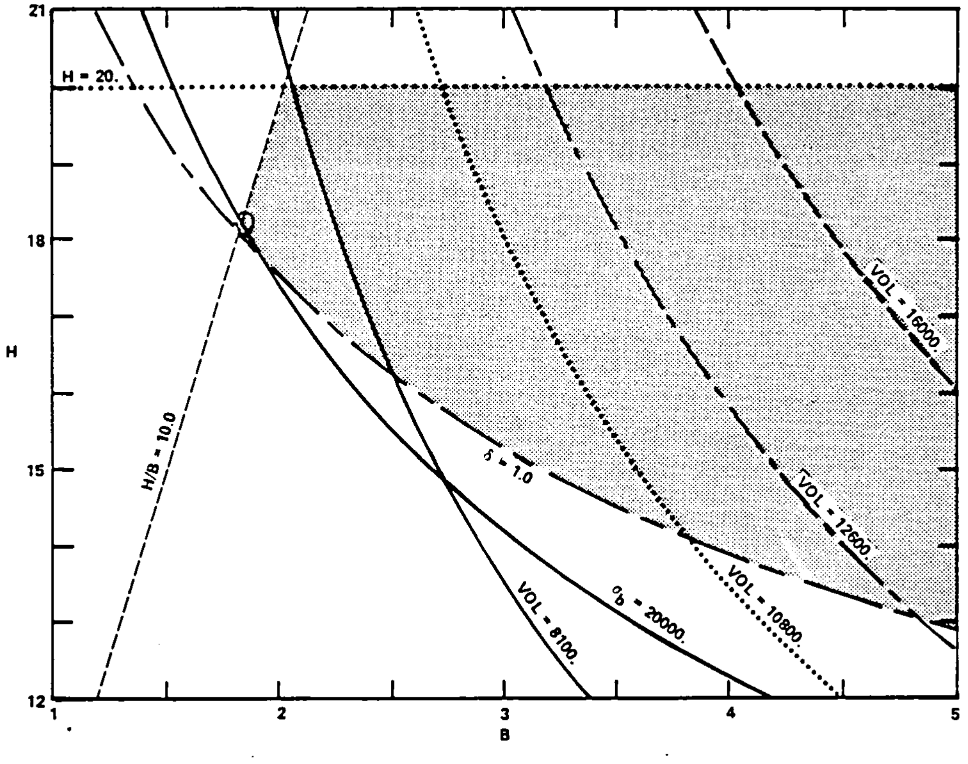


Figure 2 - Two-Dimensional Design Space (Enlarged)

either a special optimization procedure within COPES/CONMIN or a restart procedure, since COPES/CONMIN is not in memory while the analysis program is running. If NASTRAN is the analysis program, then the second method must be used.

THE PROBLEM

The structure to be optimized was a propeller and its associated shaft. The problem was to optimize the weight (or some other chosen function) of the system, which was subjected to hydrodynamic, structural, and acoustic constraints. Because the propeller design would influence the shaft design, but not vice versa, the problem was divided into two phases. First, the propeller was optimized; then, with the propeller design in hand, the shaft was optimized.

Propeller Optimization

Several propeller designs were generated corresponding to various objective functions such as weight, efficiency, tip speed, or combinations of these functions. The propeller designs had to meet a number of hydrodynamic and acoustic constraints. Therefore, hydrodynamic and acoustic analysis programs had to be linked to COPES/CONMIN. The relatively small hydrodynamic analysis program could be linked directly with COPES/CONMIN. However, a part of the input to the acoustic analysis program were results from a NASTRAN forced response analysis. Therefore, the acoustic analysis could not be linked directly to COPES/CONMIN, but made use of the second method described in the last section. Because of this complication and because of the strong desire to link the hydrodynamic analysis program to COPES/CONMIN directly, the analyses were separated as follows. An optimized hydrodynamic design was computed first, followed by an acoustic analysis of the optimized design. If the acoustic constraint was not met, tighter hydrodynamic constraints were imposed and the hydrodynamic optimization repeated. The purpose of the tighter hydrodynamic constraints was to modify the design variables so that the acoustic constraint would be met, as would the original hydrodynamic constraints. A flowchart of the process is shown in Figure 3. The linkage program represented in Figure 3 used COPES/CONMIN results to generate a NASTRAN data deck. This process continued until all constraints were met, at which point the shaft optimization was begun.

Shaft Optimization

The shaft optimization involved the design of the inner and outer diameters of two shaft sections. The weight of the shaft was to be minimized subject to various structural constraints; some were static; others, specifically, natural frequencies, were dynamic. Since NASTRAN was used as the analysis program, two NASTRAN runs were necessary: one for statics, another for natural frequencies. A flowchart of the process is shown in Figure 4. Each linkage program used data output from the preceding program to generate input for the following program.

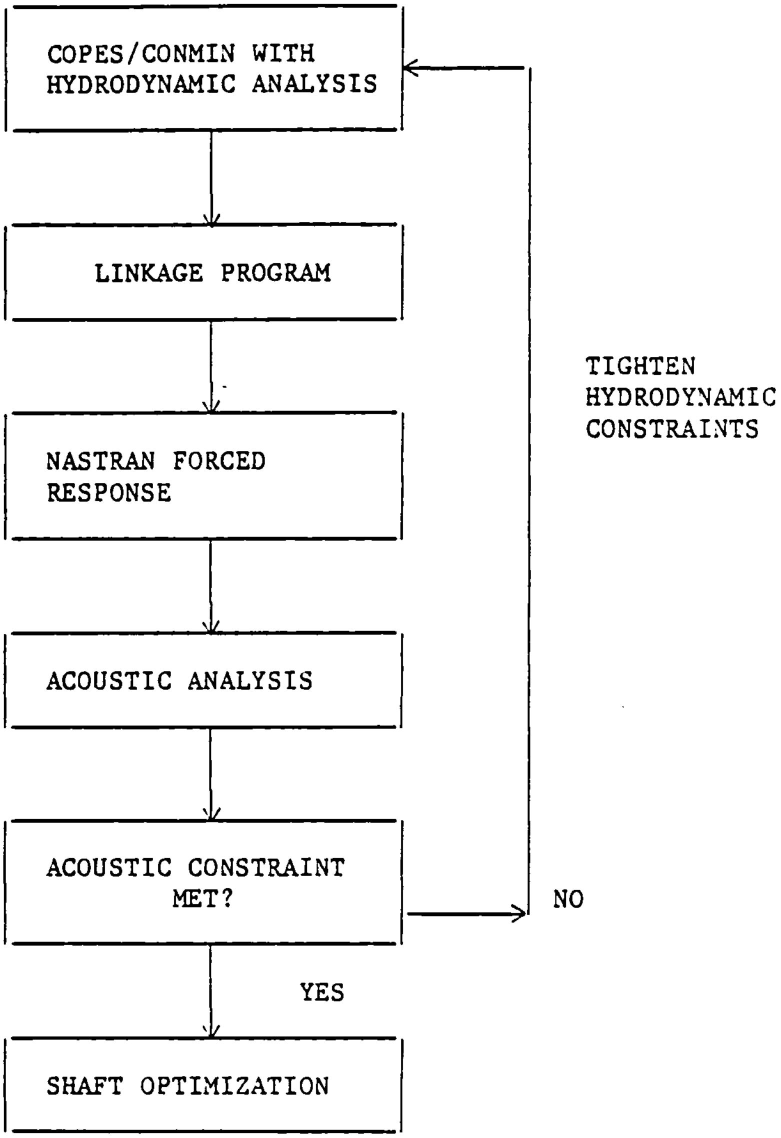


Figure 3 - Propeller Optimization Procedure

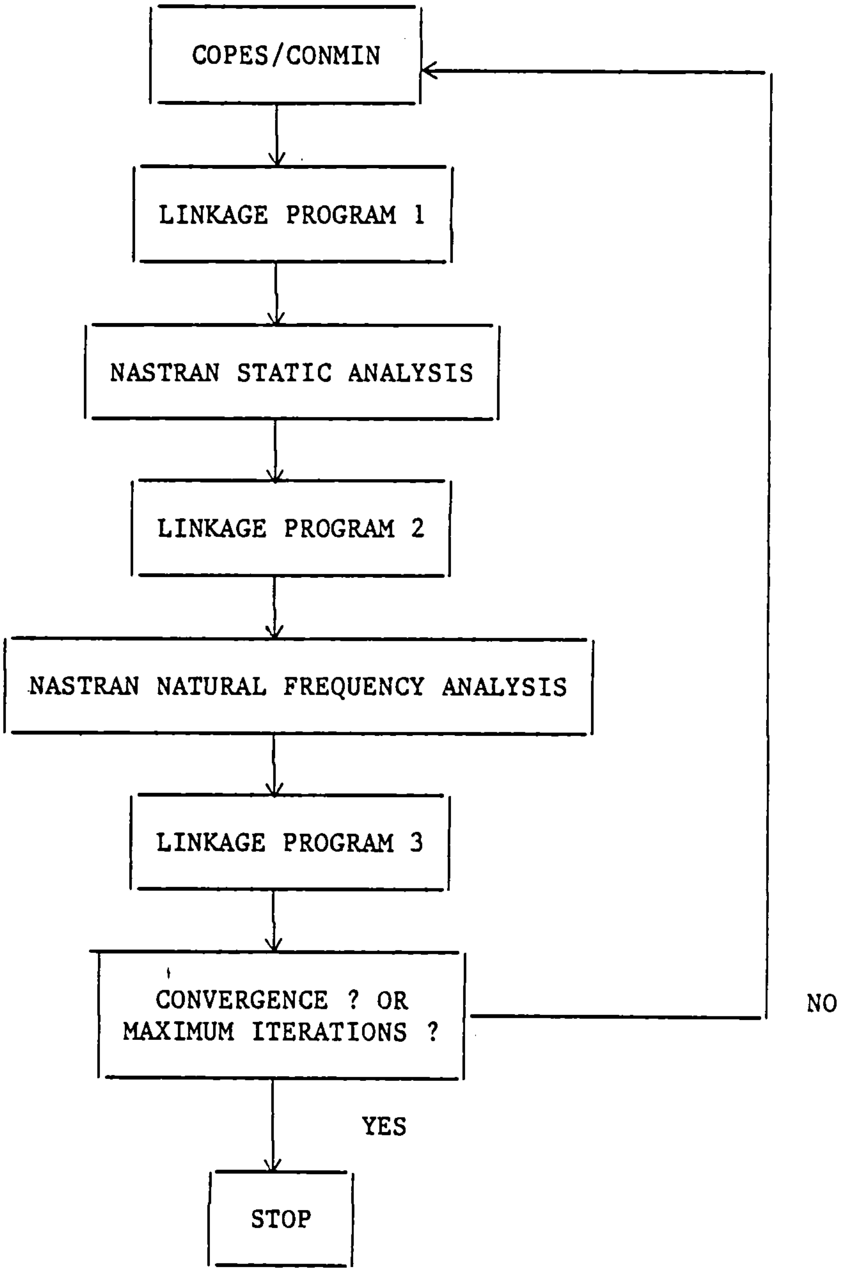


Figure 4 - Shaft Optimization Procedure

DISCUSSION

One of the purposes of this work was to explore the usefulness of NASTRAN in an early-stage design optimization procedure. The conclusions from the study were mixed. NASTRAN was very helpful in that all the required analyses (statics, natural frequencies, and forced response) were available in one program. Also, it was very easy to make changes to the basic structure when needed. However, there were a number of drawbacks to using NASTRAN. First, and perhaps most important, NASTRAN, because of its size, could not be made a subroutine within COPES/CONMIN. This meant that (1) the standard optimization procedures of COPES/CONMIN could not be used, and (2) linkage programs had to be written. Unless linkage programs are written for the very general case, changes to the structure and resulting finite element model require changes to the linkage programs. Since such changes are frequent in early-stage design, much time was spent in modifying the linkage programs. Another drawback was the cost of the optimization-analysis iterations. Although the finite element model was simple (34 CBAR elements, 35 grid points), the cost of one complete iteration was approximately $35.00 on the DTNSRDC computers. For the approximately 30 iterations run, the total cost was $1,000.00. While this is not an exorbitant sum for a large finite element analysis, for those engineers who usually work in early-stage design, $1,000.00 is a significant amount for computer runs. On the other hand, for that sum of funds, a complete, optimized design was achieved <u>for the conditions given</u>. The emphasis of the last phrase was made to indicate that, in early-stage design, conditions can change frequently, which could give rise to a number of optimization runs.

(Two parenthetical points can be made here. First, had NASTRAN been linked to COPES/CONMIN as a subroutine, the costs probably would have been higher. The reason is that, in that case, the standard optimization of COPES/CONMIN would have been used, necessitating NASTRAN to compute gradients of the constraints and objective function at each iteration, which would have been expensive. Since NASTRAN cannot be so linked to COPES/CONMIN, optimization based on approximation techniques was used, perhaps requiring more iterations but at less cost per iteration. The second point relates to the costs of optimization in early-stage versus detailed design. As was stated, in early-stage design, conditions change frequently, necessitating several optimization runs. In detailed design, where conditions have usually been set, the model is more complex and the number of design variables increases, thereby also increasing computer costs.)

CONCLUDING REMARKS

NASTRAN was used with COPES/CONMIN to, in part, assess the program's performance in early-stage design optimization for ship components. While an optimization of a propeller and shaft was successfully completed, the costs incurred have raised some questions as to the applicability of the approach for early-stage ship design. These costs were primarily due to developing and modifying linkage programs and to running multiple NASTRAN cases. An alternative is to develop special purpose programs which can be linked directly with

COPES/CONMIN, but such development costs would increase with the changing conditions of early-stage design and with the requirement to develop such programs for different structures. These trade-offs will require more study in order to reach "optimal" conclusions for the ship design process.

REFERENCES

1. Madsen, L.E., and G.N. Vanderplaats: COPES - A FORTRAN Control Program for Engineering Synthesis. Naval Postgraduate School, Monterey, California, NPS69-81-003, Mar 1982.

2. Vanderplaats, G.N.: CONMIN - A FORTRAN Program for Constrained Function Minimization, User's Manual. National Aeronautics and Space Administration, NASA Report TMX-62282, Aug 1973.

3. Vanderplaats, G.N.: COPES/ADS - A FORTRAN Control Program for Engineering Synthesis Using the ADS Optimization Program. Naval Postgraduate School, Monterey, California, NPS69-84-009, Jun 1984.