VARIABLE-COMPLEXITY MULTIDISCIPLINARY DESIGN OPTIMIZATION USING PARALLEL COMPUTERS

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1. INTRODUCTION

The use of multidisciplinary optimization techniques in aerospace vehicle design often is limited because of the significant computational expense incurred in the analysis of the vehicle and its many systems. In response to this difficulty, a variable-complexity modeling approach, involving the use of refined and computationally expensive models together with simple and computationally inexpensive models has been developed [1]. This variable-complexity technique has been previously applied to the combined aerodynamic-structural optimization of subsonic transport aircraft wings and the aerodynamic-structural optimization of the High Speed Civil Transport (HSCT) [2]-[4].

In related research conducted by members of the MAD Center at Virginia Tech, convergence difficulties were encountered in the aerodynamic-structural optimization of the HSCT [5]. The convergence problems were traced to numerical noise in the computation of aerodynamic drag components which inhibited the use of gradient based optimization techniques. An example problem, which involved two design variables, was used to determine the feasibility of using a response surface methodology in conjunction with our existing multidisciplinary analysis tools [5]. The long term goal of this research effort is to apply the response-surface methods to the full HSCT design optimization problem. Such applications of response surface methods to vehicle design have proven successful in previous studies, *e.g.,* [6], [7].

To efficiently use non-derivative-based optimization involving response surface approximation, we have developed a coarse grained parallel implementation of our HSCT analysis codes. In addition, we have produced parallel versions of existing finite-element analysis codes. The aerodynamic and structural analysis codes have been implemented on Virginia Tech's twenty-eight node Intel Paragon parallel computer (a distributed memory architecture with 32 MB of memory at each node).

2. HSCT CONFIGURATION AND MISSION

Successful aircraft configuration optimization requires a simple yet meaningful mathematical characterization of the geometry. We have developed a model that completely defines the wing-body-nacelle configuration, using twenty-eight design variables. The wing planform is described by eight design variables, and the airfoil thickness distribution by an additional five. The nacelles move axially with the trailing-edge of the wing, and two parameters define their spanwise locations. The axisymmetric fuselage requires eight parameters to specify both the axial positions and radii of the four fuselage restraint locations. Two additional variables describe the size of the horizontal and vertical stabilizers. Details of the geometry specification appear in [4] and [8]. While the configuration is defined using this set of parameters, the aircraft geometry is actually stored as a discrete numerical description in the Craidon format [9].

The optimization problem is to minimize the takeoff gross weight of an HSCT configuration with a range of 5500 nautical miles and a cruise speed of Mach 2.4 while transporting 251 passengers. For this mission, in addition to the geometric parameters mentioned above, three variables define the idealized cruise mission. One variable is the mission fuel and the other two are the initial cruise altitude and the constant climb rate used in the range calculation. Sixty-six constraints which include performance/aerodynamic constraints and geometric constraints, such as fuselage volume and tail scrape angle, prevent the optimizer from creating physically improbable designs [8].

3. VARIABLE-COMPLEXITY MODELING

Originally, this methodology was developed for use with a sequential approximate optimization technique whereby the overall design process was composed of a sequence of optimization cycles. At the beginning of each cycle, approximations to the aerodynamic drag components were constructed using either linear, scaled, or global-local approximations [2]-[4], [8]. The scaled approximation method employs a constant scaling function, σ, given as

$$\sigma(x_0) = \frac{f_d(x_0)}{f_s(x_0)}, \tag{1}$$

where f_d represents a detailed model analysis result, and f_s represents a simple model analysis result, both evaluated at a specified design point, x_0, at the beginning of an optimization cycle. During an optimization cycle, the scaled approximate analysis results, $f(x)$, were calculated as

$$f(x) = \sigma(x_0) f_s(x). \tag{2}$$

Move limits then were imposed on the design variables to avoid large errors, and the optimization was performed. At the end of the optimization cycle the scaling function σ was recalculated and the above process was repeated.

When used in conjunction with response surface approximation methods, the variable-complexity modeling approach is implemented differently than with our gradient-based optimization techniques. Here, the simple analysis methods were used to evaluate many different HSCT configurations within the prescribed design space. By then applying the constraints to the objective function data, infeasible regions of the design space were identified. The detailed analysis models were then used to calculate objective function data in the reduced domain and response surface approximations were constructed to the objective function values. Typically the simple analysis methods required at least an order of magnitude less computational time than the associated detailed analysis methods [4]-[8].

Our detailed aerodynamic analysis utilized the Harris program [10] for the supersonic volumetric wave drag, a Mach-box [11]-[13] type method for supersonic drag due to lift, and a vortex-lattice program for landing performance. When compared to the computational costs of current computational fluid dynamics analysis techniques, the aerodynamic analysis methods used in this study are relatively inexpensive. However, when implemented in design optimization, where the same calculation may be repeated thousands of times, the cost associated with these techniques quickly becomes substantial. Therefore, we also employed simple, less computationally intensive aerodynamic analysis methods for this variable-complexity modeling approach [2]-[4], [8].

Similarly, variable-complexity modeling was implemented in the HSCT structural analysis as well. Starting with a large number of candidate HSCT configurations, the designs were screened using algebraic weight equations to eliminate infeasible design points. Detailed finite element analysis was then applied to selected configurations in the feasible design space to provide a more accurate weight estimation for the HSCT.

4. RESPONSE SURFACE METHODS

The goal of response surface approximation is to model the objective function for either the entire design space or portions of it using smooth functions, typically polynomials. Since the topography of a multidimensional objective function generally is unknown and may have many local minima, the smooth functions are selected so that the prominent features of the objective function are retained. Thus, in the optimization process, the region where the global minimum exists may be readily found while spurious local minima may be avoided.

As described in our previous work [5], our noisy analysis models produced a jagged design space which inhibited the use of gradient based optimization. To approximate the noisy analysis results we investigated response surfaces obtained from quadratic polynomials, quadratic-linear tensor products, and biquadratic tensor products. For these functions, the quadratic polynomial in two variables has the form

$$f(x,y) = a_1x^2 + a_2xy + a_3x + a_4y^2 + a_5y + a_6. \tag{3}$$

The quadratic-linear tensor product has the form

$$f(x,y) = \big(a_1x^2 + a_2x + a_3\big)\big(a_4y + a_5\big) \tag{4}$$

and the biquadratic tensor product is defined as

$$f(x,y) = \big(a_1x^2 + a_2x + a_3\big)\big(a_4y^2 + a_5y + a_6\big). \tag{5}$$

In addition to polynomial models, we investigated rational functions as well. However, these produced response surfaces similar to those obtained from the polynomial models but at a higher cost. Therefore, we do not plan further use of rational functions.

The construction of a response surface from a polynomial with k coefficients requires a minimum of k function evaluations. Typically, $1.5k$ analyses are used to smooth out noise and local minima.

5. AERODYNAMIC ANALYSIS

Example Design Problem

To develop our variable-complexity response surface design methods, we created an example design problem with two of the eight design variables used to model the HSCT wing planform – the leading-edge and trailing-edge break locations of the wing. These two parameters determine the leading-edge and trailing-edge sweep angles and thus have a considerable effect on aerodynamic performance. From our past experience we knew that the analysis methods for estimating supersonic drag due to lift were particularly sensitive to changes in planform geometry. This sensitivity was demonstrated when we plotted the calculated drag values against the two design variables and found that the design space had many minima. We then applied our variable-complexity response surface approximation strategy to locate the planform geometry with the minimum drag due to lift.

Using this example problem we investigated several polynomial response surface functions for modeling the design space. Further, we examined the number of function analyses used to construct the response surfaces. Our research confirmed that approximately $1.5k$ function analyses were required to produce response surfaces which accurately approximated the global trends of the objective function data. However, the choice of points selected for evaluation of the objective function is of great importance to the accuracy of the response surface. Thus, we also examined several methods for distributing analysis points in the design space. Of the three methods we considered, the D-optimal point selection technique [14] was superior. Response surfaces formed from the D-optimal points provided significantly higher accuracy than the other methods for a given number of k function analyses [5].

Parallel Computation

The coarse grained parallelization of the aerodynamic analysis modules within the full HSCT analysis code makes use of a master-slave paradigm on the Paragon whereby one designated master node controls the data transfer and file input/output (I/O) of the remaining slave nodes. This coarse grained approach is used for the numerous independent analyses required for response surface construction.

To initiate the parallel multipoint analyses, a group of predetermined analysis points is input to the master node. The master node then computes the subset of the points which each slave node will analyze and sends that information to the appropriate slave. Both the master and slave nodes then analyze their respective subsets of the selected points and store the results in an array local to each node. When each slave has finished its portion of the analyses, it sends the array of analysis values to the master node for output.

Speedup and efficiency results have shown improvement since our initial attempt at parallelization. This improvement was a result of the following modifications to the aerodynamics code: incorporating input data directly into the analysis code, removing unnecessary output, and sending necessary output from the slave nodes to the master node for output. As evident in Figure 1, for a relatively small number of nodes (less than ten), reasonable speedup was obtained from the coarse grained parallelization. When the number of nodes was increased, speedup leveled off as a result of the large amount of temporary file I/O occurring during the analysis of each HSCT design point. Further, at the beginning and end of the aerodynamic analyses there is a portion of the HSCT code which must be executed serially. This also contributed to the deviation from ideal linear speedup as the number of processors increased.

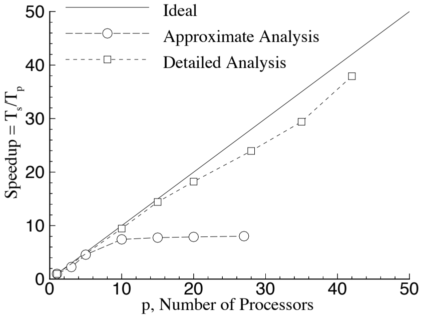

Figure 1. Speedup obtained for the parallel aerodynamic analysis code.

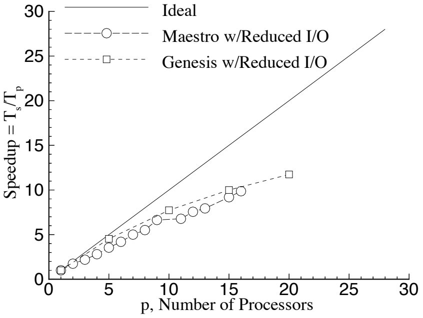

Figure 2. Speedup obtained from parallelization of the structural analysis codes.

6. STRUCTURAL OPTIMIZATION

Structural optimization acutely requires parallelization because it is repeated many times within the overall HSCT optimization. The first step in the application of parallel computing to the HSCT structural analysis was to choose a finite element program that could be efficiently run on the Paragon. Two software packages were considered: Genesis, and Maestro.

Genesis is a finite element structural optimization code developed and supported by Vanderplaats, Miura and Associates, Inc. An attempt was made to develop a coarse grained parallel version of this code. However, because Genesis relies on disk I/O, its parallel performance on the Paragon is somewhat limited (Fig. 2). Our current efforts are directed toward reducing the amount of I/O in Genesis which should improve the performance on the Paragon.

Maestro is a computer program for optimum design of large complex thin-walled structures. This program is used extensively for ship design. Like Genesis, Maestro suffers from excessive disk I/O. However, we developed a coarse grained parallel version of Maestro by replacing disk I/O with memory usage. As shown in Figure 2, the parallel performance of Maestro is particularly promising and should improve as the parallel code is refined.

The results from the coarse grained parallel versions of Genesis and Maestro will be compared to results obtained from a serial version of the NASTRAN code, the de facto standard in structural analysis. To facilitate this comparison, several geometry translators have been developed to allow the HSCT geometry in the Craidon format to be easily transferred to either Genesis, Maestro, or NASTRAN.

7. FUTURE RESEARCH DIRECTIONS

Aerodynamic Analysis

We have completed a design problem involving two design variables in which the response surface approximation methods were demonstrated. Currently we are investigating design problems with four to eight design variables to further validate this methodology. In addition, we are implementing several dimensionality-reducing strategies. After we have used the inexpensive analysis methods in our variable-complexity modeling approach to identify the feasible regions of the design space, we then apply principal component analysis [15] to identify the design variables which have the most impact on the overall HSCT design. Those variables having the most effect will be modeled using higher order response surface functions while those having less effect will be modeled using lower order functions. We illustrate this in Figure 3 for the two design variable problem. The circles represent feasible points in the design space and the directions Y_1 and Y_2 are found from principal component analysis. The response surface fit involving Y_1 and Y_2 shows improvement over the fit in the original design space.

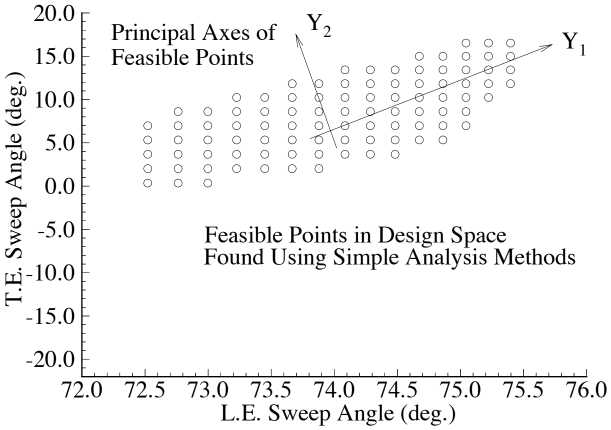

Figure 3. Principal component axes found for
the feasible points of a two variable design problem.

Eventually we will apply this variable-complexity response surface design methodology to the full HSCT design problem which involves twenty-eight variables. In addition, we plan to integrate more detailed aerodynamic and structural analysis methods into the HSCT analysis software. We have begun initial evaluation of an Euler/Navier-Stokes solver for use with our HSCT design methodology and the development of parallel versions of Genesis and Maestro is ongoing. The implementation of these more detailed analysis methods will be conducted concurrently with our parallelization efforts.

Structural Analysis

We plan to apply a coarse grained parallel version of either Genesis or Maestro to variable-complexity structural optimization and to integrate one of these programs into the HSCT design process. In particular, we plan to develop a response surface approximation for the ratio of wing structural weight obtained from weight equations to the weight obtained from structural optimization.

Using coarse grained parallelization, structural optimization will be performed with a finite element program to estimate structural weight at a large number of points in the design domain. Candidate points will first be screened using a weight equation to eliminate infeasible points. The D-optimal criterion will then be applied to select points for refined analysis from the set of feasible candidate points. Principal component analysis will also be used to reduce the dimensionality of the design space. The approximation will provide a means of assessing the effects of aerodynamic changes on both structural weight and aircraft performance in our aerodynamic optimization process.

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