PARALLEL VARIABLE-COMPLEXITY RESPONSE SURFACE STRATEGIES FOR HSCT DESIGN

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1. INTRODUCTION

The use of multidisciplinary optimization (MDO) techniques in aerospace vehicles is often 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 inexpensive models has been developed. This variable-complexity technique has been previously applied to combined aerodynamic-structural optimization of subsonic aircraft wings[1], and the aerodynamic-structural optimization of the High Speed Civil Transport (HSCT)[2,3].

In the present work, the variable-complexity modeling approach has been combined with parallel computing to further reduce the computational demands of aircraft MDO. A response surface methodology is used to construct polynomial approximations to the aerodynamic drag and to the structural weight predicted by structural optimization. Coarse grained parallelization is employed, with each computer node performing a full aerodynamic analysis or a full structural optimization. The work was implemented on Virginia Tech's twenty-eight node Intel Paragon parallel computer.

2. VARIABLE-COMPLEXITY MODELING

We have termed "variable-complexity modeling" the process by which simple, computationally inexpensive analysis techniques are used together with more detailed, expensive techniques in the design optimization process. Originally, this methodology was developed for gradient based optimization techniques in which the overall design process was composed of a sequence of optimization cycles. With this method the detailed analyses were employed at the beginning of each optimization cycle while the simple analyses, scaled to match the initial detailed results, were performed in subsequent calculations during each cycle[2,3].

This variable-complexity modeling approach was adapted for use with response surface based optimization techniques. Here, the simple analysis methods are used to evaluate many different HSCT configurations within a prescribed design space. By applying constraints to the design variables and objective function data, "nonsense" regions of the design space are excluded. The computationally expensive detailed analysis models are then used to more accurately evaluate the remaining configurations. From these objective function data, response surface approximations are created which model the design space. The optimal design is then easily identified using the response surface function. Since we evaluate numerous HSCT configurations in this optimization method, it is particularly advantageous to apply coarse grained parallel computing to both the simple and detailed analyses. Similarly, variable-complexity modeling was implemented in the HSCT structural analysis. Starting with a large number of candidate HSCT configurations, the designs were screened using algebraic weight equations to eliminate impossible design points. Detailed finite element analysis was then applied to selected configurations in the remaining design space to provide a more accurate weight estimation for the HSCT.

In many design problems the designer encounters the *curse of dimensionality* in which the number of required design point analyses greatly increases as the number of design variables becomes large. Statistical techniques known as regression analysis and analysis-of-variance provide methods to identify and remove the less important terms in the response surface polynomial model thereby reducing the number of point analyses needed for later least squares problems. This technique results in the system $Y \approx \mathbf{X}c$, where Y is an $m \times 1$ vector of objective function values and c is a $k \times 1$ vector of coefficients in the response surface fit. The matrix $(\mathbf{X}^T\mathbf{X})^{-1}$ is called the variance-covariance matrix. The k diagonal elements in this matrix are the variance values associated with the k respective coefficients[4]. The standard deviation, σ_k, of each coefficient is the square root of its variance value. Analysis-of-variance involves examining the ratio of the standard deviation value to its respective response surface polynomial coefficient. Terms having large values of this ratio, typically over 0.10, may be discarded without significantly affecting the fidelity of the response surface fit.

3. HSCT DESIGN PROBLEM

The HSCT configuration is parameterized using twenty-eight design variables in which the aircraft geometry is specified with twenty-five variables and the idealized mission profile by the three remaining variables. The structural analysis and optimization requires an additional forty internal structural design variables. Details of the geometry specification appear in Reference 3. 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[5]. A typical 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 250 passengers. A total of sixty-six constraints, including both performance/aerodynamic and geometric constraints, are employed to prevent the optimizer from creating physically impossible designs.

3.1 HSCT Wing Design Problems

Our detailed aerodynamic analysis uses the Harris program[6] for the supersonic volumetric wave drag, a Mach-box[7] type method for supersonic drag-due-to-lift, and a vortex-lattice program for landing performance. The simple aerodynamic analysis methods, typically algebraic relations, require at least an order of magnitude less computational time than the associated detailed analysis methods[3].

In the initial development of the response surface optimization methods we examined a two variable HSCT wing design problem in which we sought to minimize drag-due-to-lift[8]. Figure 1 shows some extreme HSCT configurations created at the design variable limits for this problem. For this sample problem we examined various linear and quadratic response surfaces and several point selection techniques for use in approximating the drag-due-to-lift objective function. In an extension of this work, we evaluated 285 HSCT configurations using the simple analysis methods. After applying the aerodynamic/performance and geometric constraints only ninety-four credible configurations remained (Fig. 2). Since the quadratic response surface polynomial for the two variable problem had only six terms, we elected to examine a design problem with more variables so that the regression analysis methods could be evaluated.

Currently we are investigating a four variable HSCT wing design problem in which range is maximized. For this problem we initially analyzed 1296 HSCT configurations using the simple analyses.

Of these design points only 112 credible configurations were identified when design constraints were considered. A fifteen term quadratic response surface polynomial then was fit to these design points. Regression analysis was notably successful for this problem in that one variable was identified which could be adequately modeled using only a linear term. This allowed the elimination of four higher order terms involving the particular variable and reduced the response surface polynomial to eleven terms. Research on this four design variable problem is continuing.

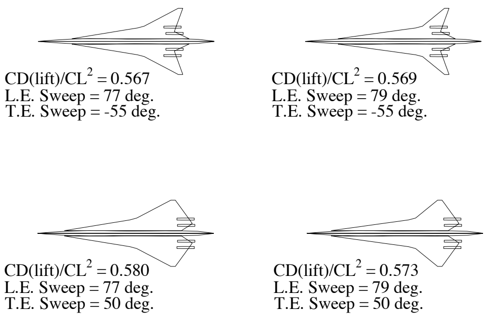

Figure 1. Extreme HSCT configurations at the limits of the two variable design space.

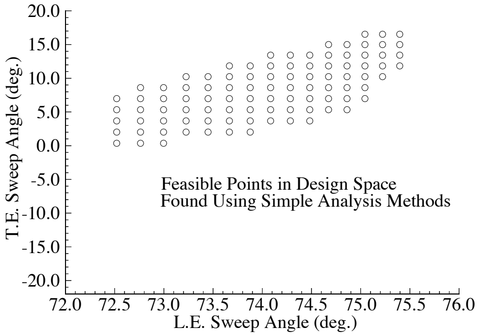

Figure 2. Ninety-four credible points for the two variable design problem.

For the two variable wing design problem both the simple and detailed analysis methods were implemented on the Paragon. Figure 3 shows that nearly ideal speedup was achieved for the detailed analyses. However, the parallel performance of the simple analyses was significantly less than ideal. This is a result of the large amount of serial file input/output (I/O) which occurs during the analysis of each HSCT design point. For the simple analyses the file I/O time is a significant portion of the total execution time, thus limiting speedup.

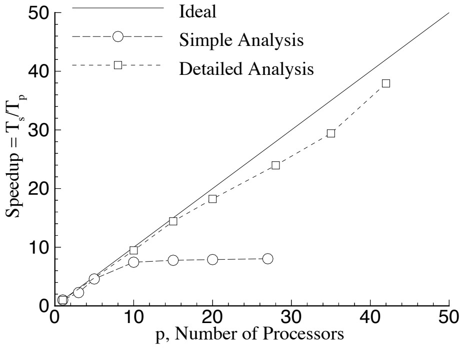

Figure 3. Speedup obtained for the parallel aerodynamic analysis code.

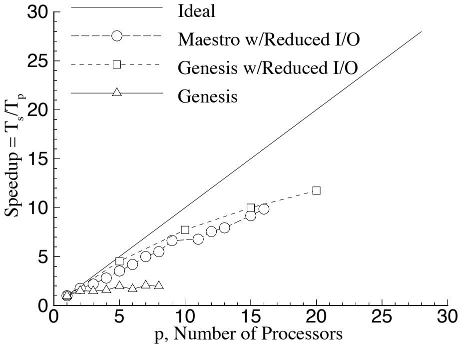

Figure 4. Speedup obtained for the parallel structural analysis codes.

3.2 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. The parallel performance of an original version of Genesis was poor because of its reliance on file I/O. However, a reduced I/O version of Genesis shows a considerable improvement in parallel performance (Fig. 4).

Maestro is a computer program for optimal design of large complex thin-walled structures, extensively used in the ship design industry. Like Genesis, Maestro initially suffered from excessive disk I/O. Figure 4 shows the coarse grained parallel performance of a reduced I/O version of Maestro. Although the parallel performance of Maestro and of Genesis is similar, difficulties in validating Maestro on the Paragon have lead us to choose Genesis for further use.

4. FUTURE RESEARCH DIRECTIONS

Our current research is focused on the four variable HSCT wing design problem to which we are applying our variable-complexity response surface design methodology, coupled with regression analysis to reduce the dimensionality of the design problem. Eventually we will apply this technique to the full HSCT design problem which involves twenty-eight design variables. In addition, we plan to integrate more detailed aerodynamic and structural analysis methods into the HSCT analysis software. The implementation of these more detailed analysis methods will be conducted concurrently with our parallelization efforts.

We plan to apply the coarse grained parallel version of Genesis to variable-complexity structural optimization and to integrate Genesis 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. This 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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