AERODYNAMIC OPTIMIZATION OF A HIGH SPEED CIVIL TRANSPORT ON PARALLEL COMPUTERS

Anthony A. Giunta, Robert Narducci, Susan Burgee
Bernard Grossman, William H. Mason, and Layne T. Watson
Multidisciplinary Analysis and Design (MAD) Center for Advanced Vehicles
Virginia Polytechnic Institute and State University
Mail Stop 0203, Blacksburg, Virginia 24061
and
Raphael T. Haftka
Department of Aerospace Engineering, Mechanics and Engineering Science,
University of Florida, Gainesville, Florida 32611-6250

ABSTRACT

A design methodology which uses a variable-complexity modeling approach in conjunction with response surface approximation methods has successfully been developed. This approach uses simple models to improve the accuracy of the response surface and reduce the number of analyses based on complex models required for constructing the surface. Simple models are first used to eliminate "nonsense" portions of the design space. Then a response surface based on the simple models is used to reduce the number of unknown coefficients that define the response surface. This approach is applied to an example problem of wing design for a High Speed Civil Transport (HSCT) aircraft involving a subset of four HSCT wing design variables.

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. 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. This variable-complexity technique has been previously applied to the combined aerodynamic-structural optimization of subsonic transport aircraft wings[1] and the aerodynamic-structural optimization of the High Speed Civil Transport (HSCT)[2].

Work on HSCT designs was hindered by convergence difficulties which were encountered in the aerodynamic-structural optimization of the HSCT[3]. The convergence problems were traced to numerical noise in the computation of aerodynamic drag components which inhibited the use of gradient based optimization techniques. To address this problem, response surface models are used to produce smooth approximations for the drag.

In the present work, a variable-complexity modeling approach is adapted for use with response surface approximation techniques. Here, the simple analysis methods are used to evaluate several thousand different HSCT configurations within a prescribed design space. By applying constraints to the design variables and to the objective function data, "nonsense" regions of the design space are excluded. The remaining design points form a ribbon-like domain in which the optimal design is contained. From the several hundred points in the ribbon shaped design space, a small number of points, on the order of fifty to one hundred, are then selected for more detailed analyses. Using the results from these detailed analyses, response surface approximations can be created to model various factors which affect the HSCT design. In the final step of this process, the response surface models are implemented in the HSCT analysis software, and design optimization is carried out. This optimization uses constraints based on both the simple and detailed analyses, along with constraints which limit the design variables to values for which the response surface model is accurate.

This study focuses on applying the response surface approximation methods to a new design problem involving four of the twenty-six design variables used in our previous HSCT design research[2]. Here, the four design variables define the HSCT wing. In this study we minimize the gross takeoff weight of the vehicle within the design space defined by the allowable variations in the four design variables.

2. HSCT DESIGN PROBLEM

We have previously considered an HSCT configuration which was parameterized using twenty-six design variables with the aircraft geometry specified by twenty-three variables and the idealized mission profile by the three remaining variables[2]. A typical optimization problem is to minimize the gross takeoff weight of an HSCT configuration with a range of 5500 nautical miles (n.mi.) and a cruise speed of Mach 2.4 while transporting 250 passengers. A total of sixty-one constraints, including both performance/aerodynamic and geometric constraints, have been employed to prevent the optimizer from creating physically impossible designs.

Our detailed aerodynamic analyses use the Harris program for the supersonic volumetric wave drag, a Carlson Mach-box type method for supersonic drag-due-to-lift, and a vortex-lattice program for landing performance. As part of our variable-complexity modeling approach we also employ simple aerodynamic analysis methods which are typically algebraic relations, and which require at least an order of magnitude less computational time than the associated detailed analysis methods. Details of each calculation are given in Reference 2.

To develop and test the variable-complexity response surface optimization strategy we decided to construct an example problem involving only a few variables. For this reason, a four variable wing design problem was chosen. Here, two of the original planform variables, root chord and tip chord, were selected along with two new design variables (Fig. 1). The first new design variable is the inboard leading-edge sweep angle. The second new variable is a constant scaling factor, ζ, by which the thickness-to-chord, t/c, ratios from the HSCT baseline were scaled.

The design space for this four variable problem was determined by allowing the root chord and tip chord to vary ± 20 percent from the values on the baseline HSCT. The t/c scaling factor also varied ± 20 percent from a nominal value of unity. The leading-edge sweep was allowed to range only ± 9 percent from its baseline value. Variations in the sweep angle outside of this range produced configurations which were not realistic.

3. RESULTS

3.1 Design Space Reduction

The first stage in the variable-complexity response surface modeling process was to evaluate numerous HSCT designs using simple algebraic analysis methods. This was performed on a $6 \times 6 \times 6 \times 6 = 1296$ uniform coarse grid. At the center of the design space was the baseline HSCT configuration.

Using the constraint data obtained for each of the 1296 HSCT designs, obvious “nonsense” configurations were eliminated from consideration. Here, designs were excluded if any of the aerodynamic/performance constraints were violated by more than twenty percent, and if any geometric constraints were violated by more than five percent. In addition, gross takeoff weight (GTOW) was allowed to vary within ± 20 percent of the baseline GTOW of approximately 650,000 lbs. and range was required to be greater than 5000 n.mi. After applying these constraints, only 157 acceptable HSCT designs remained out of the initial 1296 designs.

3.2 Regression Analysis

With the data from the 157 simple HSCT analyses a fifteen term quadratic polynomial response surface model was fit to the aircraft range data. Using regression analysis, the coefficients of the polynomial and their coefficients of variation for the fifteen terms in the response surface model were calculated (Table 1). Here, the abbreviations ζ, c_r, c_t, and Λ_{LE} correspond to the t/c scaling factor ζ, root chord, tip chord, and leading-edge sweep angle, respectively. As shown, the higher order terms involving c_t have coefficients of variation greater than ten percent and can safely be dropped from the response surface model. Thus, the number of terms in the response surface model has been reduced to eleven and the modeling of the tip chord variable has been simplified from quadratic to linear.

Table 2 shows that the accuracy of the response surface fit is only slightly impaired after removing terms from the polynomial model for which the coefficient of variation is large. Here, the errors are calculated from the difference between the response surface prediction for the range and the actual value for the range at each of the 157 remaining HSCT design points.

From the 157 HSCT designs, fifty were selected on the basis of the D-optimal criterion. The performance and constraint criteria for each of these were then evaluated using the detailed aerodynamic analysis models.

3.3 Optimization

The optimization for the variable complexity response surface approximation method uses constraints based on both the simple and detailed analysis models. For this example problem, this is accomplished by using two constraints on the calculated range.

The approximate constraint uses the original range calculation, i.e., range calculated from the simple analysis of drag components, which must be greater than 5000 n.mi. This is the same constraint used to remove unrealistic design points after the initial 1296 HSCT analyses.

The new range constraint employs the smooth response surface models for the three drag components. This constraint stipulates that the range must be greater than 5500 n.mi. The range based on the response surface models is accurate only for certain regions of the design space defined by the allowable design variable values. One may picture the response surface models as being valid on a four-dimensional spheroid inscribed within a four-dimensional hypercube, where the vertices of the hypercube are defined by the allowable limits on the design variables. Without the approximate range constraint $\geq$ 5000 n.mi., the optimizer invariably moves to a vertex of the hypercube outside of the spheroid on which the response surface models are valid.

The results of the optimization are shown in Table 3 in which the design variables and performance are compared for the initial and optimal HSCT configurations. Figure 2 shows the difference between the baseline HSCT planform from which the optimization was started and the optimal planform. The primary change in the wing design variables occurs for the t/c scale factor which decreased by eight percent. The planform changes for the optimal wing design are most noticeable in the length of the root chord and in the leading-edge sweep angle. However, these differences are relatively modest.

The thinner wing results in a lower wave drag coefficient and thus a lower total drag coefficient. This improvement in aerodynamic efficiency permits the elimination of 18000 lbs. of unneeded fuel. Additional weight savings occur because the optimal wing is smaller. Specifically, the wing area has decreased by 5.5 percent. Although the optimal wing is thinner, and therefore requires a heavier structure, the weight penalty is offset by the decrease in wing size. Thus, the optimal wing design results in a combined weight reduction of approximately 22500 lbs., which is a 3.5 percent decrease in GTOW.

4. PARALLEL COMPUTING

Our efforts at parallel computing involve a twenty-eight node Intel Paragon at Virginia Tech. 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 compare the computational savings for parallel versus serial execution of a code, the term *speedup* is defined as $\frac{T_s}{T_p}$, where T_s is the serial execution time and T_p is the parallel execution time using p processors. Figure 3 shows the speedup results for parallel execution of the HSCT analysis code compared to ideal, linear speedup. The actual results deviate from the ideal due to the file I/O demands of the analysis code which must be executed serially, and due to unavoidable communication overhead in the parallel code. Currently we are examining methods to reduce file I/O and improve the parallel execution of the HSCT analysis code.

5. CONCLUDING REMARKS

The use of response surface modeling for volumetric wave drag and for components of supersonic drag due due to lift has been shown to be an effective technique for alleviating the detrimental effects of numerical noise in design optimization. Further, the coupling of variable-complexity analysis methods with response surface modeling was demonstrated for an HSCT wing design optimization problem involving four design variables.

ACKNOWLEDGMENTS

This research was supported by NASA Grant NAG1-1562 with Dr. P. Newman as contract monitor.

REFERENCES

1 Unger, E. R., Hutchison, M. G., Rais-Rohani, M., Haftka, R. T., and Grossman, B., “Variable-Complexity Design of a Transport Wing,” *Intl. J. Systems Automation: Res. and Appl. (SARA),* No. 2, 1992, pp. 87–113.

2 Hutchison, M. G., Unger, E. R., Mason, W. H., Grossman, B., and Haftka, R. T., “Variable-Complexity Aerodynamic Optimization of an HSCT Wing Using Structural Wing-Weight Equations,” *J. Aircraft,* vol. 31, No. 1, 1994, pp. 110–116.

3 Giunta, A. A., Dudley, J. M., Narducci, R., Grossman, B., Haftka, R. T., Mason, W. H., and Watson, L. T., “Noisy Aerodynamic Response and Smooth Approximations in HSCT Design,” AIAA Paper 94–4376, 1994.

Variable	Coefficient	Std. Dev.	V (%)
$const.$	0.058	0.197	3.416
ζ	-1.200	0.268	0.224
$\mathrm{c_r}$	-0.555	0.206	0.372
$\mathrm{c_t}$	-0.054	0.133	2.443
Λ_{LE}	0.755	0.261	0.346
$\zeta\mathrm{c_r}$	-0.221	0.627	2.835
$\zeta\mathrm{c_t}$	0.009	0.372	40.616
$\zeta\Lambda_{LE}$	0.170	0.848	4.990
$\mathrm{c_r c_t}$	-0.025	0.290	11.621
$\mathrm{c_r}\Lambda_{\mathrm{LE}}$	0.058	0.572	9.907
$\mathrm{c_t}\Lambda_{\mathrm{LE}}$	-0.021	0.358	16.955
ζ^2	-0.095	0.623	6.588
$\mathrm{c_r}^2$	-0.147	0.352	2.399
$\mathrm{c_t}^2$	-0.006	0.234	42.143
$\Lambda_{LE}{}^2$	-0.107	0.700	6.526

Table 1. Regression analysis and ANOVA data for the range response surface model.

Avg. Error	RMS Error	Max. Error
15 Term Polynomial		
0.034395	0.044025	0.126625
11 Term Polynomial		
0.035187	0.045363	0.113389

Table 2. Errors for the fifteen and eleven term polynomial response surface models.

	Initial Design	Optimal Design
root chord	174.0 ft.	171.1 ft.
tip chord	8.1 ft.	7.8 ft.
LE sweep	71.88°	72.44°
t/c scale	1.00	0.92
Exact Range	5577 n.mi.	5510 n.mi.
R.S. Range	5546 n.mi.	5519 n.mi.
Landing AOA	12.28°	12.33°
C_{Dwave}	0.0017	0.0015
C_{Dtotal}	0.0053	0.0052
Wing Weight	107410 lbs.	103123 lbs.
Fuel Weight	328044 lbs.	310750 lbs.
Fuel/Gross	50.99 %	50.05 %
GTOW	643393 lbs.	620876 lbs.

Table 3. HSCT performance data for the initial and optimal HSCT designs.

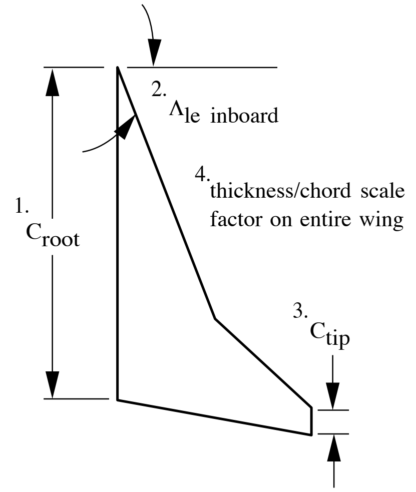

Figure 1. Wing design variable definition for the four variable problem.

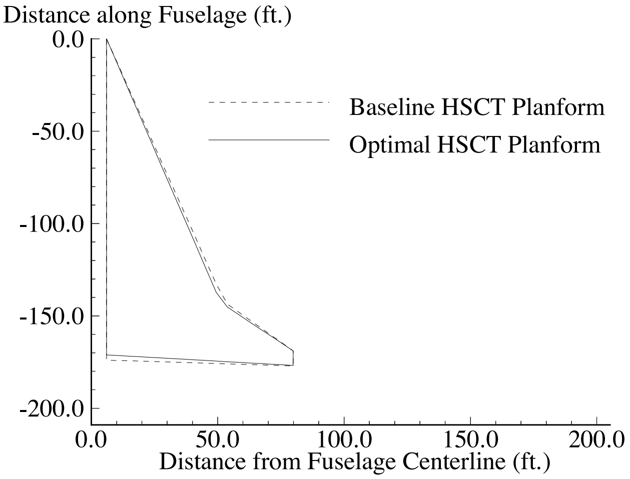

Figure 2. Baseline vs. optimal HSCT planforms.

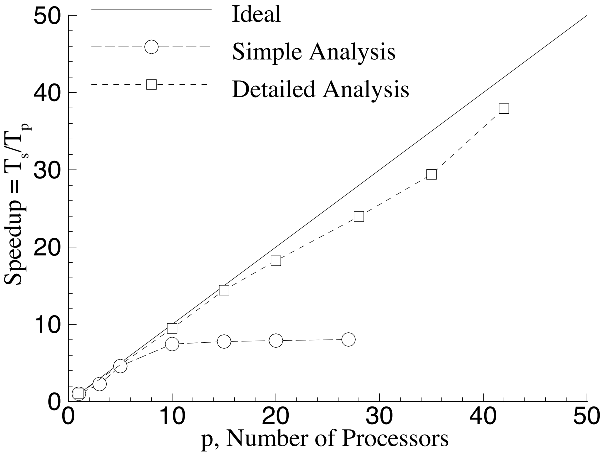

Figure 3. Ideal versus actual speedup for parallel execution of the HSCT analysis code.