SUMMARY of RESEARCH / FINAL REPORT

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"Stochastic Methods for Aircraft Design"

PIs: Richard B. Pelz and Madara Ogot
Mechanical and Aerospace Engineering
Rutgers, The State University of New Jersey

Graduate Students Supported:
Sherif Aly: Masters and Ph.D
Frank Cantelmi: Ph.D.
Zhen Zhao: M.S

Undergraduate Student: Brian Burke

Industrial Sub-contractors:
Frank Marconi and Michael Siclari
Research and Development
Northrop Grumman Corporation

1 Summary

The global stochastic optimization method, simulated annealing (SA), was adapted and applied to various problems in aircraft design. The research was aimed at overcoming the problem of finding an optimal design in a space with multiple minima and roughness ubiquitous to numerically generated nonlinear objective functions. SA was modified to reduce the number of objective function evaluations for an optimal design, historically the main criticism of stochastic methods. SA was applied to many CFD/MDO problems including: low sonic-boom bodies, minimum drag on supersonic fore-bodies, minimum drag on supersonic aeroelastic fore-bodies, minimum drag on HSCT aeroelastic wings, FLOPS preliminary design code, another preliminary aircraft design study with vortex lattice aerodynamics, HSR complete aircraft aerodynamics. In every case, SA provided a simple, robust and reliable optimization method which found optimal designs in order 100 objective function evaluations. Perhaps most importantly, from this academic/industrial project, technology has been successfully transferred; this method is the method of choice for optimization problems at Northrop Grumman.

2   Noisy Objective Functions

In theory, many objective functions associated with aircraft design problems and parameterized geometrical design variables are continuous in those variables. And, gradient-based optimization methods which take advantage of this smoothness are the logical method of choice. In practice, however, objective functions which are formed through the solution of difference equations and iterative procedures will possess roughness on the order of these discretization errors. Not only does this effect produce spurious extrema, but has a magnifying effect on gradients produced by finite-difference.

This fact coupled with the possibility of naturally occuring multiple extrema and nonlinear constraints, make global non-gradient based optimization methods an attractive alternative. Global stochastic methods have been developed to be less inclined to get "stuck" in local extrema than deterministic methods. Our goal in this research was to see how one of these methods, simulated annealing, works on MDO problems related to aircraft design.

Another way that the noise problem has been attacked is through the use of response surfaces (see the final report of the VPI group).

3   Simulated Annealing and Modifications

For this research, modified versions of simulated annealing (SA) were developed and employed to perform the optimizations. Simulated annealing was first introduced by Kirkpatrick et al. (1983) and is analogous to the physical process of annealing solids. By accepting inferior solutions in a controlled fashion, SA is able to jump out of local minima and potentially find a more promising downhill path. Although the global optimal solution is not guaranteed, SA has been found to consistently provide solutions close to it. In addition, because of its probabilistic nature, SA is independent of its initial starting design.

3.1   Discrete SA, SAWI, SADD, ASAP

In the past, one of the main criticisms with the use of stochastic methods for problems in which high fidelity codes were being employed was the relatively large number of evaluations of the objective function and hence large amounts of cpu time required. Consequently numerous modifications were made to the algorithm itself to address this issue. These modifications proved highly effective and reduced the order of most solutions from 1000s of iterations to 100s of iterations.

The first step was to make the continuous design space discrete. This allowed a more uniform sampling of the space and for excursions into nonintuitive parts of the space. The first new algorithm was Simulated Annealing with Iterative Improvement (SAWI). Here, after discrete SA was used with uniform probability, a continuous normal distribution is used about the current best design until convergence. Studies were done to find the problem-independent transition time.

Simulated Annealing with Domain Decay (SADD) was another modification similar SAWI where the actual bounds on the design space shrink slowly around the current best design. This scheme also allows for the design space to start coarse and discrete and move towards fine and continuous.

The ASAP project formed the basis for an undergraduate thesis and scholar program. By imagining the discrete design space as a lattice in d dimensions with uniform probability, a logical modification is to increase the probability in certain regions of design space with grid refinement driven by the real-time optimization data. This technique worked by adding new Cartesian grids to the design space periodically as the algorithm worked towards convergence. The frequency of grid production was based on a quantity of function evaluations. These new grids were centered around points with low objective function values. New grids while having the same number of design points are finer and add new points in the area of design space in which the grids are established. This "multi-grid" method allowed a rough sampling of the overall space and as well as a fine sampling of selected regions. The method was tested on a number of simple examples and a suite of supersonic low-drag fore-bodies profiles. Most cases showed a significant decrease (up to 50%) in the number of function evaluations.

4   Case Studies

SA and its modifications were implemented into a number of case studies with a range of computational fidelity, from algebraic analyses of preliminary aircraft design (low fidelity), through problems with vortex lattice analyses and 2-d flow field solutions (medium fidelity), to 3-d supersonic flow field solutions over HSR and HSCT configurations (high fidelity). Disciplines other than fluids were integrated: structural analysis were performed by finite element codes and sonic boom analysis by waveform extrapolation codes.

In each case, SA performed robustly giving reliable optimal designs sometimes at non-obvious points in design space. In the following subsections, these cases are discussed. The modified SA schemes developed under this grant converged faster than genetic algorithms and yielded more reliable global optima than gradient based methods on numerically generated design spaces of real world problems that were currently being pursued by Northrop Grumman.

This methodology was transferred to several other Northrop Grumman programs sponsored by NASA and DARPA: DARPA Smart Wing Project, contract no. F33615-95-C-3202; NASA High Speed Research (HSR) Program, Sonic Boom Softening, subcontract RD-27265-C Task 34; NASA High Speed Research (HSR) Program, Configuration Aerodynamics, Task 32, subcontract RD-27265-C Task 34.

4.1   Minimum Drag on Supersonic Fore-bodies

The goal of this study was to determine the geometry of an axisymmetric fore-body that minimizes aerodynamic drag in supersonic flow. The body geometry was given by radii at discrete stations on the axis and cubic spline interpolation. An Euler flow analysis code

developed at Grumman was used to calculate the drag at Mach 2. Both SAWI and a popular gradient-based optimization code NPSOL were used.

A typical result for a nine variable problem is as follows. From a given initial design, NPSOL converged to a design with a drag coefficient of 120 counts in 262 flow solves. From another, NPSOL gave 178 counts in 266 solves. From the former initial design, SAWI found a design with 110 counts in 198 solves, and from the latter 123 in 217. A decrease to 96 counts occurs when the above designs were used as starting points and either NPSOL or SAWI were used. The total number of solves was about 300.

4.2 A Decoupled Stochastic Approach to the Jig-Shape Aeroelastic Wing Design Problem

A novel approach to the jig-shape aeroelastic wing design problem was investigated. Unlike previous design efforts where the aerodynamic analyses where coupled to the structural analyses throughout the optimization process, this work presents a truly decoupled approach. The developed two - level methodology performs aerodynamic shape optimization at Level I to determine an optimal configuration, followed by structural shape optimization at Level II to find the corresponding jig-shape. During Level II optimization, no aerodynamic analyses are required, resulting in true decoupling. This results in a significant reduction in computation time, making the design of relatively complex wing structures feasible. For this study, high-fidelity codes–ANSYS for the structural analysis and a supersonic Euler code–are used to provide accurate, detailed analyses. A modified simulated annealing algorithm is used as the optimizer. Two examples, a fore-body problem and the design of an HSCT wing, were investigated to demonstrate the efficacy of the methodology.

The developed jig-shape approach completely decouples the aerodynamic and structural analyses of the problem and employs high-fidelity codes for all analyses. In this two level optimization method, the aerodynamic shape optimization problem is completed at the first level. The final loading condition from the first level is then transferred to the structural shape optimization problem at the second level and the optimal jig-shape is solved for. Once the final loading condition is passed to the structural portion of the optimization problem, the aerodynamic analysis module is not called upon again, thus, truly decoupling the problem.

4.3 Design of Wings With a Smart Trailing Edge

In a DARPA sponsored project, a "Smart Trailing Edge" is being developed that can take advantage of optimum performance at a variety of transonic flight conditions. By employing a combination of rotation and translation of its segments to change its shape, the Smart Trailing Edge maintains the smooth upper surface required to reduce shock strength without boundary layer separation. In addition, the actuators are located completely within the contour of the airfoil to further minimize the drag. A new type of electro-magnetically driven smart material linear actuator is completely embedded in the wing structure. A multi-objective, stochastic, SA numerical optimization scheme was used to study the various parametric tradeoffs including the number of flap segments using a full potential flow solver

coupled to an integral boundary layer method. The results of the optimization are checked for validity and flow separation using a Navier-Stokes solver. For all flight conditions, the flap system was shown to reduce drag indicating promise for the concept.

This flap concept was then applied to a configuration being developed in another ongoing program at Northrop Grumman, namely, the Unmanned Combat Air Vehicle (UCAV). In this ongoing DARPA sponsored program, the final flap design will be built and tested in a NASA wind tunnel sometime in the year 2000.

In all cases, SA provided a reliable and robust optimization method which can be "loosely wrapped" around an existing analysis code.

4.4   Design on HSR Aircraft and Low Sonic-Boom Bodies

The stochastic optimization technology developed under this grant was also applied to the NASA High Speed Research (HSR) program. Two areas benefited from this technology, namely, "Sonic Boom Softening" and "Aerodynamic Configuration Optimization".

Because this research is classified, a full summary of results in not appropriate for this document.

In the sonic boom softening program, multidisciplinary optimization was used to coupled the changes in the aircraft surface geometry to sonic booms that are generated and propagate through the atmosphere to the ground and then, ultimately, to noise levels at ground level. After using gradient-based solvers without success, SA routinely found bodies that produced target sonic boom pressure profiles at the ground from a body at Mach 2.4 and 55,000 feet.

In another area, the SA schemes were used to minimize the aerodynamic drag of the TCA concept subject to a whole variety of constraints.

4.5   Aircraft Preliminary Design

The aircraft design process is typically broken into three major phases: conceptual, preliminary and detailed design. Conceptual design involves the analysis of many widely varying designs through the use of computationally inexpensive algebraic models. The preliminary design process improves upon the conceptual design analyses by employing more accurate models of moderate computational expense such as linear aerodynamics. The detailed design process utilizes the highest fidelity analyses to refine the final design.

Unlike the detailed design process, where parameter ranges are reduced to perform local searches of the design space, the preliminary design process often involves relatively large parameter ranges. As a result, major design tradeoffs between disciplines often occur during this stage.

For problems with more than a few design variables, the automated design process presents a systematic means of searching for improved designs. Under ideal circumstances, a gradient based optimizer would provide a computationally efficient means of obtaining improved designs. Unfortunately, the numerical noise often present in engineering analyses

makes it difficult to obtain the accurate sensitivity derivatives required by gradient based optimizers and creates false local minima in the objective function.

There are two basic approaches to overcoming the problems posed by noisy design spaces: modification of the design space to make it amenable to a gradient based optimizer or modification of the optimizer to make it amenable to a noisy design space. The former may be accomplished through the use of response surface modeling, where the design space is approximated locally by a smooth algebraic approximation to the actual objective function. The latter may be accomplished using stochastic optimization techniques such as Simulated Annealing (SA) or Genetic Algorithms (GAs) which do not require smooth or continuous design spaces.

We have demonstrated that stochastic optimization is a viable tool in aircraft preliminary design problems.

- A subsonic transport was analyzed using a full mission module (FLOPS) and optimizations were performed using SA and SAWI. The stochastic methods required about twice as many function evaluations as the gradient-based solvers to produce an optimal design; however, FLOPS contains routines that smooth the objective function.

- A Blended Wing Body was analyzed using a reduced mission module (algebraic) and a vortex lattice code (VORLAX). Changes in the discretization and iteration tolerance caused large discontinuities and spurious extrema to appear in the objective function (see Figure 1). Optimization was performed using SA for several cases, each leading to similar designs (see Figure 2). This work was presented at the 7th AIAA/USAF/NASA/ISSMO Symposium on Multidisciplinary Analysis and Optimization in St. Louis in September 1998.

- Analogs to Entropy and Specific Heat were introduced to help analyze convergence histories for the optimizations and to help determine parameter settings for SA.

5 Academic/Industrial Collaboration: Technology Transfer

While we at Rutgers are continuing to pursue design optimization (there is proposal pending on LaRC's NRA on Airframe Noise) Northrop Grumman has put this technology to good use, as is evident in the case studies. The following paragraph concerns a future NG project in which SA will play a critical role.

Northrop Grumman's (NG) close interaction with researchers at Rutgers during this NASA contract has been invaluable in our recent fluidic control work. The NG Blockerless Engine Thrust Reverser (BETR) concept hinges on the ability to divert all the engine by-pass air in the fan duct through a set of cascade vanes in order to reverse engine thrust. In the BETR configuration this is to be done without blocking the fan flow with a door, using instead a small control jet to divert the flow. The design goal is to minimize the mass flow tapped from the engine core to supply the control jet. The design space includes the

variation of control jet location, thickness, pressure ratio and orientation. The only cost effective way to explore the design space completely is to use CFD. Because of numerical inaccuracies due to truncation error and incomplete convergence, the cost function does not vary smoothly over the entire design space. The stochastic optimization scheme SA is ideally suited for this problem. The design optimization resulted in an order of magnitude reduction in the mass flow required to deflect the fan flow through the cascade slot. Details of this work are reported in Ref. 1. Currently "micro mass-less" and macro pulsed jets are being considered for use in controlling flow separation on high incidence wings and in shortened inlets. In all cases the locations and orientations of an array of such jets will be critical design parameters. Here again the design goal will be to magnify the effectiveness of the jet to optimize the control system.

Reference: Marconi, F., Gilbert, B. and Tindell, R., "Computational Fluid Dynamics Support of the Development of a Blockerless Engine Thrust Reverser Concept", AIAA 97-3151, 33rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Seattle, WA, July 1997.

6 List of Publications from this Grant

F. J. Cantelmi, R. B. Pelz and M. M. Ogot "Stochastic Optimization for Aircraft Preliminary Design" AIAA-98-4773, 7th AIAA/USAF/NASA/ISSMO Symposium on Multidisciplinary Analysis and Optimization, September 2-4, 1998.

Aly, S., Ogot, M.M., Pelz, R.B., and Siclari, M., "A Decoupled Stochastic Approach to the Jig-Shape Aeroelastic Wing Design Problem," AIAA Paper No. 98-0906, 36th Aerospace Sciences Meeting, Reno, NV, Jan. 12-15, 1998, 11 pages.

Siclari, M.J., and Austin, F., "Optimization of a Realistic Flap Design for In-Flight Transonic Performance Enhancement," AIAA Paper No. 98-0596, AIAA 36th Aerospace Sciences Meeting and Exhibit, Reno, NV, January 1998.

Pelz, R.B., Ogot, M.M., Aly, S., Cantelmi, F., and Burke, B. "Global Stochastic Methods in MDO/CFD" AIAA Paper No. 97-0352, 35th Aerospace Sciences Meeting, Reno, NV.

Siclari, M.J., Austin, F., Van Nostrand, W., and Volpe, G., "Optimization of Segmented Flaps for In-Flight Transonic Performance Enhancement," AIAA-paper no. 97-0516 AIAA 35th Aerospace Sciences Meeting and Exhibit, Reno, NV, January 1997.

Aly, S. Ogot, M. M., and Pelz, R. B., "Stochastic Approach to Optimal Aerodynamic Shape Design," J. Aircraft, 33(5) 1996, pp. 956-961.

Austin, F., Van Nostrand, W., Siclari, M.J., Aidala, P., and Clifford, R., "Design and Performance Predictions of a Smart Wing for Transonic Cruise," SPIE 1996 Symposium on Smart Structures and Materials, San Diego, CA, Feb. 1996.

Ogot, M. M., Aly, S., Pelz, R. B., Marconi, F. and Siclari, M., "Stochastic Versus Gradient-

based Optimizers for CFD Design," AIAA Paper No. 96-0332, 34th Aerospace Sciences Meeting, Reno, NV.

Siclari, M.J., Van Nostrand, W., and Austin, F., "The Design of Transonic Airfoil Sections for an Adaptive Wing Concept Using a Stochastic Optimization Method," AIAA-paper no. 96-0329 AIAA 34th Aerospace Sciences Meeting and Exhibit, Reno, NV, January 1996.

Aly, S., Marconi, F., Ogot, M.M., Pelz, R.B. and Siclari, M, "Stochastic Optimization Applied to CFD Design," AIAA 95-1647, 12th AIAA CFD Conference, San Diego, June 1995.

Aly, S., Ogot, M.M. and Pelz, R.B., "An improved Simulated Annealing Algorithm," Proceeding of the 21th ASME Design Automation Conference, Boston, September 1995.

Siclari, M.J., "Sonic Boom Prediction and Minimization of the Douglas Reference OPT5 Configuration," NASA High-Speed Research: Sonic Boom Workshop, NASA CDCP-1003, 1995, Sept 1995.
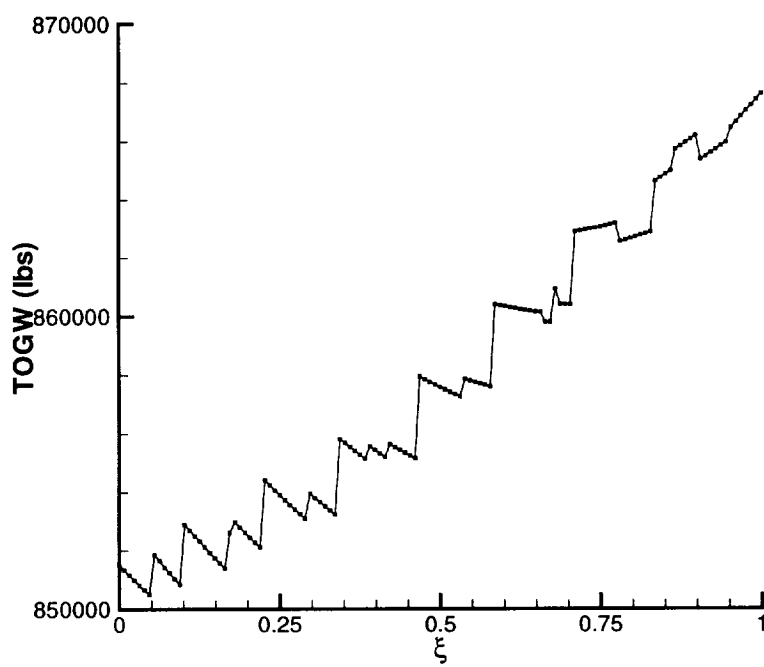
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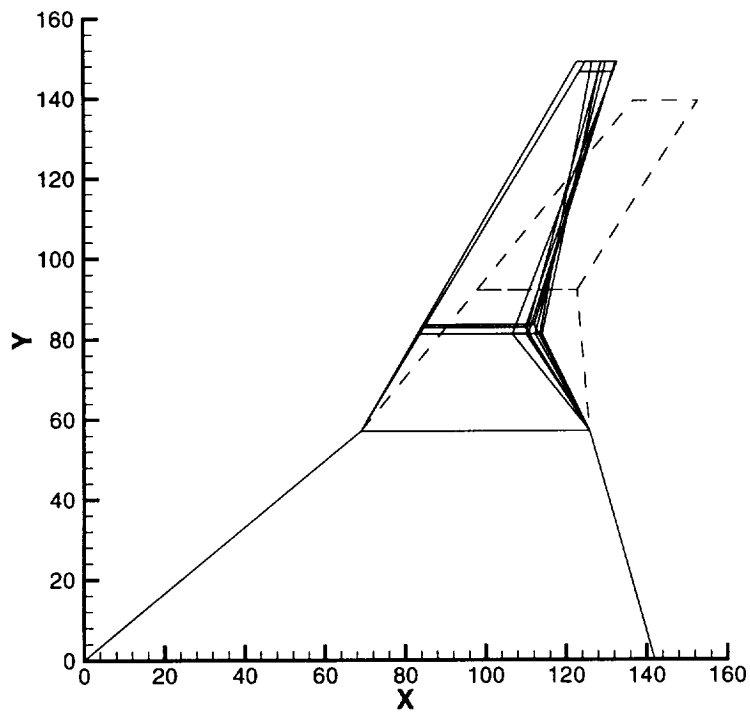Figure 1: Takeoff Gross Weight Variation over Tailing Edge Break Location Range.

Figure 2: Initial (solid) and Optimal Wing Geometries for Cases 1-10.