Close out and Final report for NASA Glenn Cooperative Agreement NAG3-2869

Multidisciplinary Multiobjective Optimal Design for Turbomachinery Using Evolutionary Algorithm

This report summarizes Dr. Lian's efforts toward developing a robust and efficient tool for multidisciplinary and multi-objective optimal design for turbomachinery using evolutionary algorithms. This work consisted of two stages. The first stage (from July 2003 to June 2004) Dr. Lian focused on building essential capabilities required for the project. More specifically, Dr. Lian worked on two subjects: an enhanced genetic algorithm (GA) and an integrated optimization system with a GA and a surrogate model. The second stage (from July 2004 to February 2005) Dr. Lian formulated aerodynamic optimization and structural optimization into a multi-objective optimization problem and performed multidisciplinary and multi-objective optimizations on a transonic compressor blade based on the proposed model. Dr. Lian's numerical results showed that the proposed approach can effectively reduce the blade weight and increase the stage pressure ratio in an efficient manner. In addition, the new design was structurally safer than the original design. Five conference papers and three journal papers were published on this topic by Dr. Lian.

Introduction

This project aims at conducting multi-objective optimal design for turbomachinery using evolutionary algorithms (EAs). Dr. Lian's goal was to consider both aerodynamic performance and structural requirements in redesign of the turbomachinery. In aerodynamic optimization areas, Oyama et al. (2004) performed an aerodynamic optimization of transonic compressor blades with a GA. In their work, a three-dimensional Navier-Stokes code, TRAF3D, which was developed at NASA Glenn Research Center, was used for aerodynamic analysis of blade design. A real-coded adaptive-range GA was used because its ease of use and global optimization properties. Their work was conducted on a SGI Origin2000 cluster machine. For the rotor67 design, each iteration (generation) takes about seven wall-clock hours with 64 processing elements. With a generation of 200, a total 1,400 wall-clock hours was required. Even if the user can use all the processors 24 hours a day, it still takes about two months to finish a design cycle. This is a serious impediment to any practical application of a GA in aerodynamic design optimizations. Needless to say, it will take longer once we put structural requirement as another objective in the design. It is worthwhile to pause and seek more efficient approaches before we embark on the multi-objective design. This motivates us to improve the performance of a GA to expedite the design cycle. We propose three approaches for this purpose. In the first one, we hybridize a GA with a gradient-based method to improve the local convergence rate. In the second one, we perform data mining to analyze the generated data from genetic computation. By doing this we can recover certain patterns and further improve the existing design with marginal cost. In the third one we apply a GA to optimize a surrogate model in lieu to the computationally expensive functions. We will describe our efforts in the following.

Progress from July 2003–June 2004

Enhanced Genetic Algorithm

In this work we propose an enhanced evolutionary algorithm (EA) to solve computationally expensive design optimization problems. Our strategy is to enhance the performance of EAs by coupling a standard EA with a gradient-based method for multi-objective optimization problems (MOOPs). The gradient-based method is a sequential quadratic programming (SQP) solver. In our approach, an EA is first used to generate a population of data by evaluating the exact model, then surrogate models are constructed based on the generated data. After that, we conduct a local search with a SQP solver based on the surrogate models. These two methods are alternately used under a trust-region framework until an optimum is found. By hybridizing an EA and a gradient-based method under a trust-region framework, the local search and global search properties are maintained. The local search determines a faster convergence. The global search assures that iterates produced by an optimization algorithm working with the approximation models, started at an arbitrary initial value, will converge to a stationary point or local optimum for the original problem. Key elements of this approach include an evolutionary algorithm, a SQP solver, and a surrogate model based on thin plate spline (TPS) interpolation. The coupling is fulfilled with a trust region management. Numerical tests on three problems with different numbers of design variables ranging from 2 to 20 demonstrate that our method can greatly increase the convergence rate and reduce the required CPU time (Lian et al., 2004).

Data Mining with Supervised Learning

Usually evolutionary computation produces enormous amount of data that contains rich information, of which only a tiny fraction is generally utilized throughout the design optimization. Tremendous profit can be taken from the generated data if a systematic analysis of the data is performed. This motivates us to employ the data to the maximum extend possible to help designers to further improve the design or expedite the design process.

However, those data are not only massive in volume but also highly multidimensional in space. It is very difficult to analyze and root out distinctive features of the underlying physics. Data mining is a powerful new technology to extract hidden predictive information from large databases with great potential to help designers focus on the most important information in design problems. We propose to use statistical approaches to analyze the generated data from evolutionary computations in our multi-objective optimization problems. Now we are working at (1) providing a robust, automatic, physics-based systematic approach to obtain global optimization to a complex engineering system, and (2) discovering underlying prevalent causal relationships between objective functions and design variables at the end of optimization. In other words, the end result is to provide a capability to yield a better design in much reduced time/cost, by delegating the complex searching process to machine, while freeing scientists and engineers to focus on creative thinking/formulations. The second goal is to gain succinct knowledge for future problems by a systematic analysis of enormous complex data set. The proposed application examples include design of turbo pump used in the space launch vehicle and the technologies derived herein shall have a direct relevance to not only earth-bound but also space-traveling machines. The lessons and tools learned from this project should also provide experience in establishing cause and effect relationships distilled from random, scattered data.

The proposed technique is applied on the optimization of cryogenic rocket engines turbo pumps. Our preliminary results demonstrate that these techniques can greatly expedite the design process, further improve the existing design, and effectively extract the hidden underlying physics (Lian and Liou, 2004a).

Progress from June 2004 to February 2005

Coupled Optimization with RSM and GA

In the work of Oyama and Liou (2002) and Oyama et al. (2004), they use genetic algorithm to sample a population of individuals by evaluating real functions. In the rotor67 optimization, it takes about seven hours to perform one analysis based on Navier-Stokes equations. It takes about two months for one optimization design. Today, powerful parallel computers are increasingly made available in many institutes and universities; however, designers still want to significantly shorten the design cycle for engineering and economic considerations.

Response surface methodology (RSM) provides an efficient tool for this purpose. RSM is a collection of statistical and mathematical techniques useful for developing, improving, and optimizing progresses. It is a popular surrogate model built to approximate computationally expensive simulation codes with low-order polynomials using least-square regression. Instead of solving the problem directly, RSM constructs approximation models for the functional relationships between the performance characteristics and design parameters. A regular optimization procedure is then employed to optimize the constructed approximation model. Usually, the second-order model is widely used in response surface methodology due to its flexibility and easy of use.

Based on this we propose to perform multi-objective optimization using an integrated system coupling RSM with a GA. In this approach, a surrogate model is first constructed based on design of experiment. Then a standard GA is used to optimize the surrogate model. The found optimal solutions are then validated on the real problem. In the turbo pump design, Oyama and Liou (2002) performed 3,600 function evaluations before they terminated the searching; we achieve similar solution with only 233 function evaluations, including 133 to construct the surrogate model and the left 100 to validate. It saves more than 90% CPU time compared to the standard approach (Lian and Liou, 2004b).

Aero-structure Optimization of Rotor67

With the advancement of computational power and computational methods, researchers used optimization techniques to improve the performance of complex system, such as aircraft engine. In this instance, Oyama et al. (2004) minimized the entropy generation of the NASA rotor67 blade, Benini (2004) improved the total pressure ratio and the adiabatic efficiency of the NASA rotor37 blade, Mengistu and Ghaly (2004) performed multi-point design of different compressor rotors to improve their aerodynamic performance, Lian and Liou (2004b) carried out multi-objective optimization of the NASA rotor67 blade. These analyses were focused on a single-discipline response, namely the aerodynamic aspect. However, compressor design is inherently multidisciplinary, and a successful design should involve a combination of a variety of disciplines including aerodynamics, structure dynamics, acoustics and control theory (Chamis, 1999). In addition, the present design procedures are usually based on sequential discipline optimization, which may not be insufficient to provide a satisfactory result. The resulting solution may satisfy some, but not all the requirements. In that case, the coupled multidisciplinary optimization (MDO) design technique is required.

The applications of MDO to compressor designs give rise to considerate challenges. First, the computational expense associated with MDO is usually much higher than the sum of the costs associated with each single-discipline optimization. Secondly, organizational complexity imposes another challenge (Sobieszczanski-Sobieski and Haftka, 1997). For example, different analysis codes may run on different machines at different sites. For these two reasons, a direct coupling of an optimizer with multidisciplinary analysis tools may be practically difficult, especially when a large number of design variables and computationally intensive tools are involved. Thirdly, noisy or jagged response from some disciplines deteriorates the coupling effect and may lead to local optimal design solutions. Lastly, in our multi-objective compressor design problem, the objectives are competing (Lian and Liou, 2004b). Instead of having a single optimal solution, our studied problems have a set of compromised solutions (Pareto-optimal solutions) in which none of the solution is better than the other with respect to all objectives. Traditional optimization methods usually convert such a multi-objective optimization problem into a single objective problem by introducing additional parameters which favor a specific Pareto-optimal solution. To find more Pareto-optimal solutions, we need to start over by changing the values of parameters.

Response surface technique is particularly suitable for MDO. This technique usually approximates the objective and constraint functions with low-order polynomials, which are fitted to a set of preselected design points. With the approximation models, the computational cost is greatly reduced. Moreover, because response surface technique preselects the design points, it provides a simple way to connect different codes from various disciplines (Sobieszczanski-Sobieski and Haftka, 1997). Consequently, this reduces the organizational complexity and facilitates a loose coupling among different modules.

Our objectives are to maximize the compressor stage pressure ratio and to minimize the compressor weight of a transonic compressor blade under a set of real-world constraints (Lian and Liou, 2005). To faithfully represent a variety of nonlinear phenomena in the compressor blade study, such as shock waves and boundary layer separation, which are crucial to accurately evaluate the blade aerodynamic performance, we use high-fidelity computational fluid dynamics (CFD) analysis tools. Early aero-structural optimization, mainly due to the availability of computing resources, largely relies on empirical or simple one-dimensional models with a small number of design variables, which is true especially at the conceptual design level and preliminary design level. With the recent advancement in optimization methods and affordable computing power, such rudimentary models need to be improved, and high-fidelity modeling represents the trend in MDO applications. In our work we use a three-dimensional Navier-Stokes solver to analyze the aerodynamic performance of the compressor blade. A commercial software ANSYS is adopted as the computational structure dynamics (CSD) solver to perform static aeroelastic analysis. Each objective function is approximated with a computationally cheap surrogate model. A real-coded genetic algorithm is then applied on the surrogate models for a set of Pareto-optimal solutions. At last, representative solutions are chosen from the Pareto-optimal front and validated by the high-fidelity tools.

Publications

Lian, Y., and Liou, M., "Aero-Structural Optimization of a Transonic Compressor Rotor," AIAA Paper 2005-3634, 41st AIAA/ASME/ASE/ASEE Joint Propulsion Conference and Exhibit, 2005.

Lian, Y., and Liou, M.-S., "Multiobjective Optimization of a Transonic Compressor Blade using Evolutionary Algorithm," AIAA-2005-1816, 46th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, 13th AIAA/ASME/AHS Adaptive Structures Conference 7t, Austin, Texas, April 18–21, 2005.

Lian, Y., and Liou, M.S., "Multiobjective Optimization Using Coupled Response Surface Model and Evolutionary Algorithm," *AIAA Journal,* Vol 43, No. 6, June 2005.

Lian, Y., and Liou, M., "Mining of Data from Evolutionary Algorithms for Improving Design Optimization," CMES, Vol. 8, No. 1, pp. 61–72, 2004.

Lian, Y., Liou, M., and Oyama, A., 2004, "An Enhanced Evolutionary Algorithm with a Surrogate Model," Genetic and Evolutionary Computation Conference, Seattle, Washington, June 2004.

References

Benini, E., 2004, "Three-Dimensional Multi-Objective Design Optimization of a Transonic Compressor Rotor," *Journal of Propulsion and Power*, Vol. 20, pp. 559–565.

Chamis, C.C., 1999, "Coupled Multidisciplinary Optimization of Engine Structural Performance," *Journal of Aircraft*, Vol. 36, pp. 190–199.

Lian, Y., and Liou, M., 2005 "Aero-Structural Optimization of a Transonic Compressor Blade," AIAA Paper 2005-3634, 41st AIAA/ASME/ASE/ASEE Joint Propulsion Conference and Exhibit.

Lian, Y., and Liou, M., 2004a, "Data Mining for Multi-objective Evolutionary Design Optimization," 34th AIAA Fluid Dynamics Conference and Exhibit, June 2004, Portland, Oregon.

Lian, Y., and Liou, M.S., 2004b, "Multiobjective Optimization Using Coupled Response Surface Model and Evolutionary Algorithm," accepted for publication at *AIAA Journal*. Also AIAA Paper 2004-4323.

Lian, Y., Liou, M., and Oyama, A., 2004, "An Enhanced Evolutionary Algorithm with a Surrogate Model," Genetic and Evolutionary Computation Conference, June 2004, Seattle, Washington.

Mengistu, T., and Ghaly, W., 2004, "Single and Multipoint Shape Optimization of Gas Turbine Blade Cascades," AIAA Paper 2004-4446.

Oyama, A., Liou, M., and Obayashi, S., 2004, "Transonic Axial-flow Blade Shape Optimization Using Evolutionary Algorithm and Three-dimensional Navier-Stokes Solver," *Journal of Propulsion and Power*, Vol. 20, pp. 612–619.

Oyama, A., and Liou, M.S., 2002, "Multiobjective Optimization of Rocket Engine Pumps Using Evolution Algorithm," *Journal of Propulsion and Power*, Vol. 18, No. 3, pp. 528–535.

Sobieszczanski-Sobieski, J., and Haftka, R.T., 1997 "Multidisplinary Aerospace Design Optimization: Survey of Recent Development," *Structural Optimization*, Vol. 14, 1997, pp. 1–23.