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Dedicated to the Memory of DR. Meng-Sing Liou (NASA Glenn Research Center:1987-2017)

High-Fidelity Compressor Blade Design Optimization Using Evolutionary Algorithm

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Abstract: This paper reviews Dr. Liou's works on high-fidelity multiobjective and multidisciplinary design optimization method for transonic axial-flow compressor blade design optimization method. This method bases on three-dimensional RANS solver for aerodynamic performance evaluation and finite element analysis for structural performance evaluation. For multiobjective and global optimization, a multiobjective evolutionary algorithm is used. Redesign of NASA rotor 67 shows advantages of the developed method over conventional approaches. Dr. Liou's works have been inspiring many researchers and are still leading researches in this field.

Keywords: Turbomachinery, Compressor, Multiobjective Optimization, Evolutionary Algorithm.

1 Introduction

Compressor is a critical part in developing a new aeroengine because a small improvement in efficiency can result in significant savings in the annual fuel costs of an aircraft fleet. Although today's aeroengine compressors have achieved very high performance, there is an increasing demand for new compressor designs with even higher performance.

When Dr. Meng-Sing Liou and the authors of this paper started research on compressor blade design optimization in 2000, compressor blade design mainly depended on axisymmetric through-flow method. High-fidelity computational fluid dynamics (CFD) such as three-dimensional Reynolds-averaged Navier-Stokes (RANS) computation was also used, but CFD was used only for validation purposes or for evaluating the loss coefficient to be used for the next through-flow calculation. In addition, use of design optimization methods is not common in industry. Therefore, design experts relied on their experience and intuition to optimize the blade design manually through a trial-and-error process.

Based on such background, Dr. Liou launched research on new compressor blade design optimization methodology in 2000 under the Ultra Efficient Engine Technology (UEET) program. His idea was to couple high-fidelity flow computation, i.e., three-dimensional RANS computation and global design optimization method, i.e., evolutionary algorithm (EA) for turbomachinery design to further improve compressor performance. He focused on EA as the design optimization method because (1) EA can find Pareto-optimal designs of a multiobjective design optimization problem simultaneously, (2) EA can find global optimum even if the objective function distribution is multimodal, (3) application of EA to multidisciplinary design optimization problems is straightforward, and (4) EA is suitable to parallel computation environment. We also studied use of response surface methodology for turbomachinery design optimization for quicker turnaround time to get optimal design. This paper reviews Dr. Liou's research on high-fidelity compressor blade design optimization.

2 Development of high-fidelity compressor blade design optimization method

2.1 Transonic Axial-Flow Blade Optimization Using 3D RANS and EA

After confirming feasibility of evolutionary algorithm for turbomachinery design [1-3], a high-fidelity aerodynamic compressor blade design optimization tool based on an EA and a three-dimensional RANS solver was developed [4]. Here, the blade shape represented by profiles at 0%, 31%, 62%, and 100% spanwise stations was optimized so that entropy generation is minimized while maintaining mass flow rate and pressure ratio. Difficulty in using EA for high-fidelity design optimization problem is required number of design candidate evaluations. This optimization required 6,400 three-dimensional RANS computations. To overcome difficulty in computational time, the computation was parallelized on the SGI ORIGIN2000 cluster in Institute of Fluid Science, Tohoku University. Aerodynamic redesign of the NASA rotor 67 blade [5] was demonstrated. Superiority of the proposed method over the conventional design approach was shown, where adiabatic efficiency was increased by 2 percent over the original design, not only at the design condition but over the entire operating range (Fig. 1). Figure 2 compares surface pressure distribution and oil flow pattern on the suction side. While the NASA rotor 67 has strong shock wave from the hub to the tip, the optimized rotor design suppresses the shock wave. As a result, the separated region is significantly reduced. This was a pioneering work in the sense that high-fidelity three-dimensional RANS computation and global design optimization method was used for compressor blade design. This article has been cited by 82 articles by now according to SCOPUS.

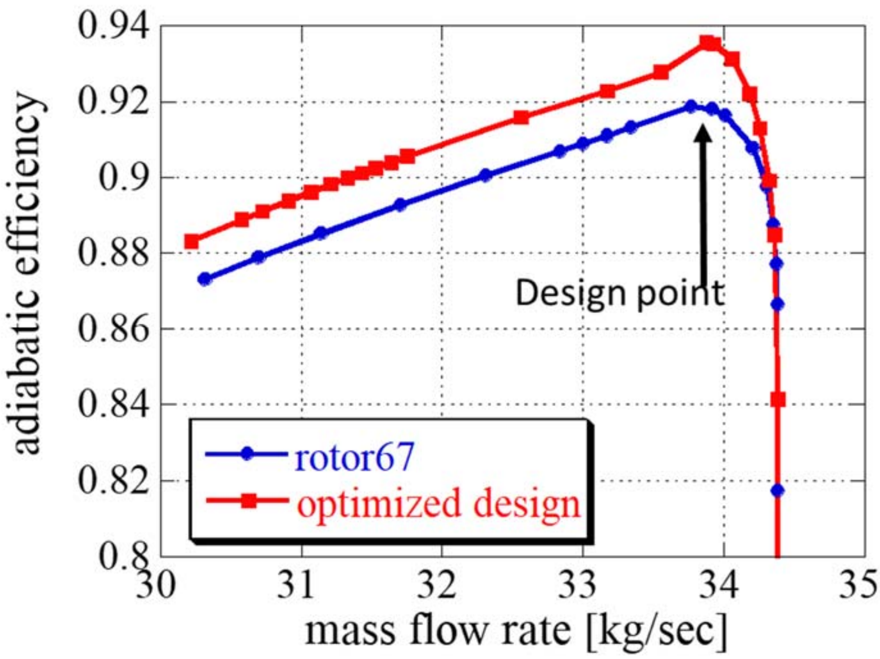


Figure 1: Comparison in adiabatic efficiency.

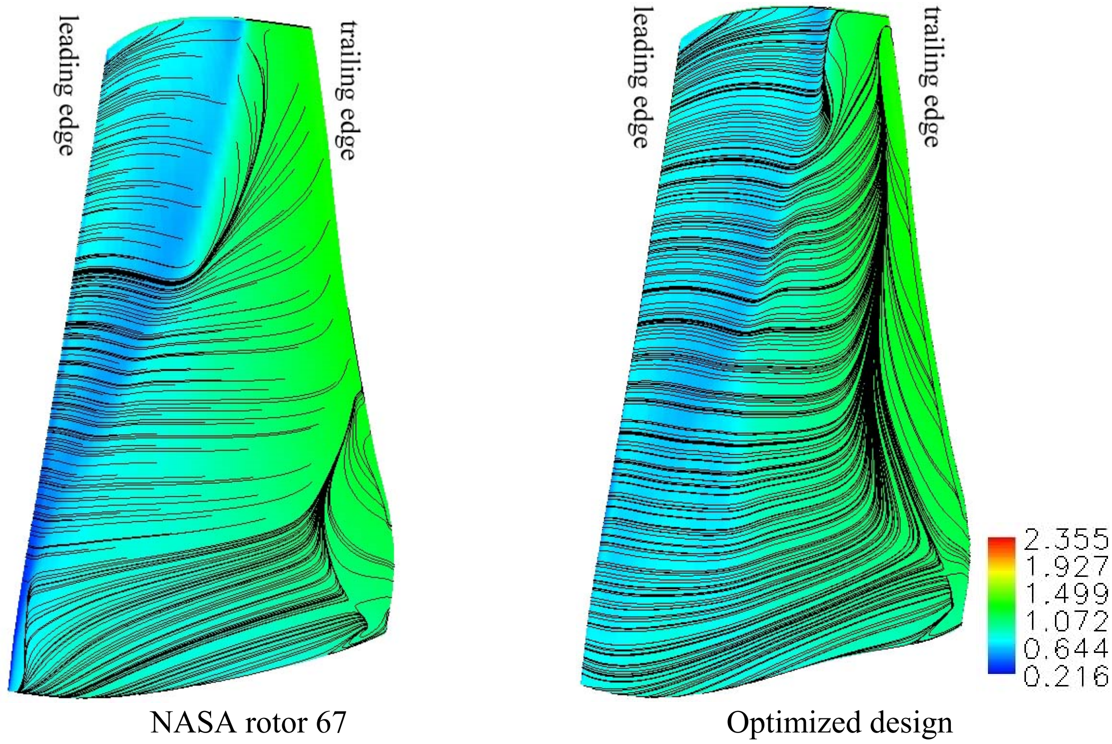


Figure 2: Surface pressure distribution and oil flow pattern on the suction side.

2.3 Swept and Leaned Transonic Axial-Flow Blade Optimization

Next step was to apply the developed method to design optimization of swept and leaned transonic axial-flow blade design [6]. As shown in reference [7], three-dimensional blade design such as blade sweep and lean can improve blade performance. Here, the blade shape is represented by profiles at 0%, 31%, 62%, and 100% spanwise locations, spanwise twist angle distribution, and stacking line. This study gave some insights into design optimization of a swept and leaned rotor blade for axial compressors. The optimized design has more backward sweep near the tip and less backward sweep near the hub (Fig.3). Flow structure around the current design is characterized by the lambda-shaped shock on the suction side, which reduces entropy production due to the shock wave by having two weaker shock waves in the mid-span region (Fig.4). Also, the present study showed that swept blades tend to have smaller operating and maximum mass flow rate (Fig.5).

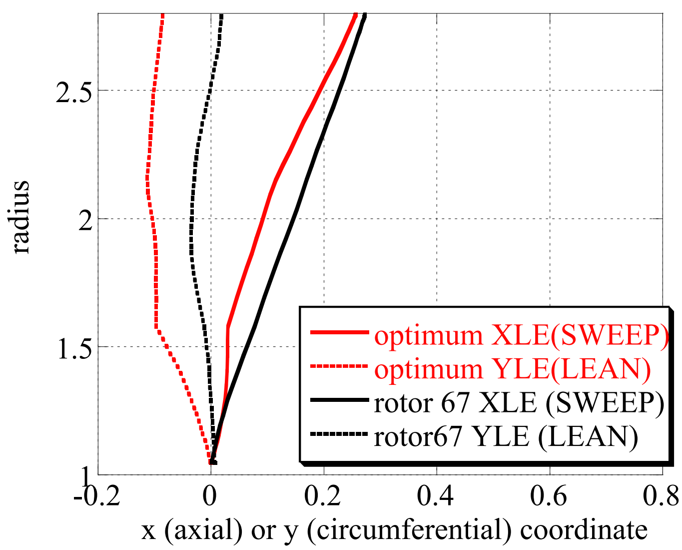


Figure 3: sweep and lean distribution of NASA rotor 67 and the optimized design.

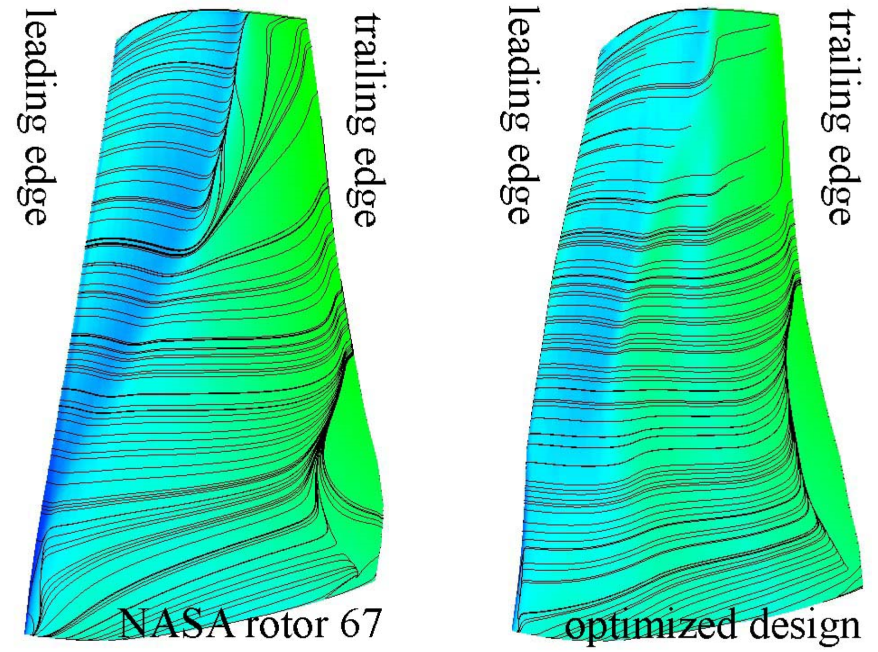


Figure 4: Surface pressure distribution and oil flow pattern on the suction side.

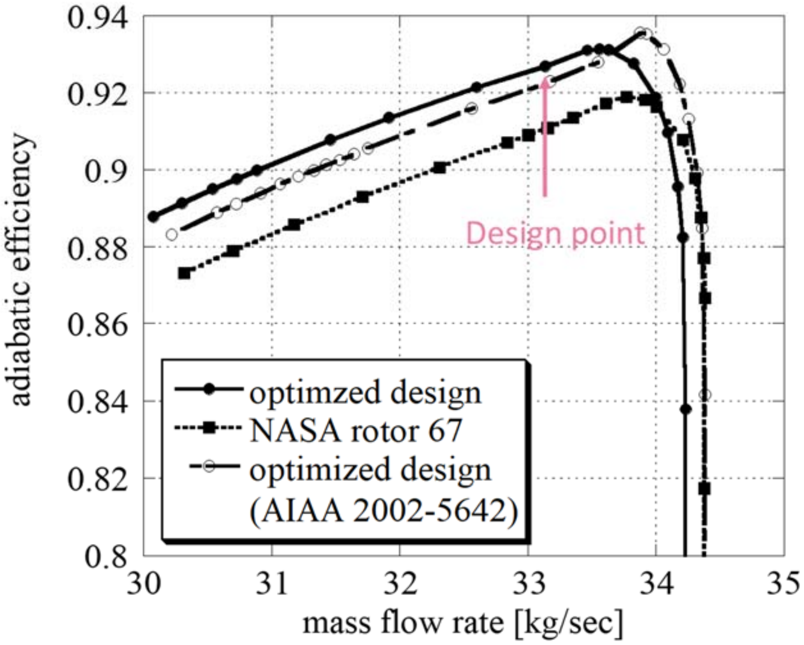


Figure 5: Performance map comparison.

2.3 Multiobjective Optimization of Transonic Axial-Flow Blade

In reference [8], the developed high-fidelity compressor blade design method is applied to the multiobjective design optimization problem of NASA rotor 67. The design objective functions were the entropy generation to be minimized and the stage pressure ratio to be maximized. To obtain Pareto-optimal designs of the multiobjective design optimization problem, a multiobjective evolutionary algorithm (MOEA) was used. Here, design of experiment and response surface method were used to save required computational time. Figure 6 shows performances of the Pareto-optimal designs obtained on the approximated response surface and those verified with three-dimensional RANS solver. This method obtains 7 Pareto-optimal designs that include a design with 1.8% improvement in the pressure ratio and a design with 6.2% reduction in entropy production. Figure 7 shows streamlines close to the blade suction side of NASA rotor 67 and the pressure ratio maximum design. The improvement was partially realized through reducing the separation region near the trailing edge. The developed approach was also coupled with a gradient-based method to enhance convergence of optimization in [9]. This article has been cited by 53 articles by now according to SCOPUS.

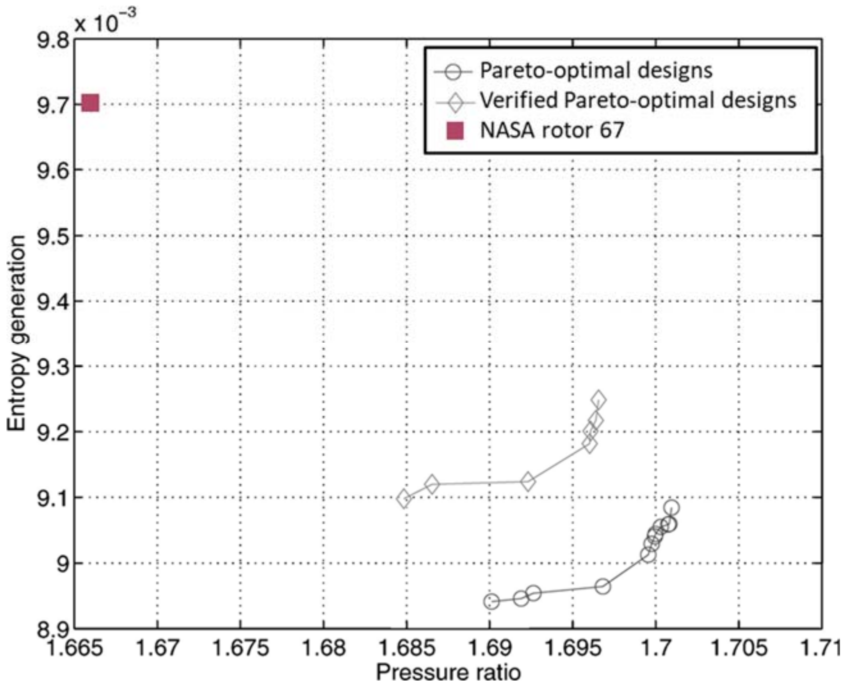
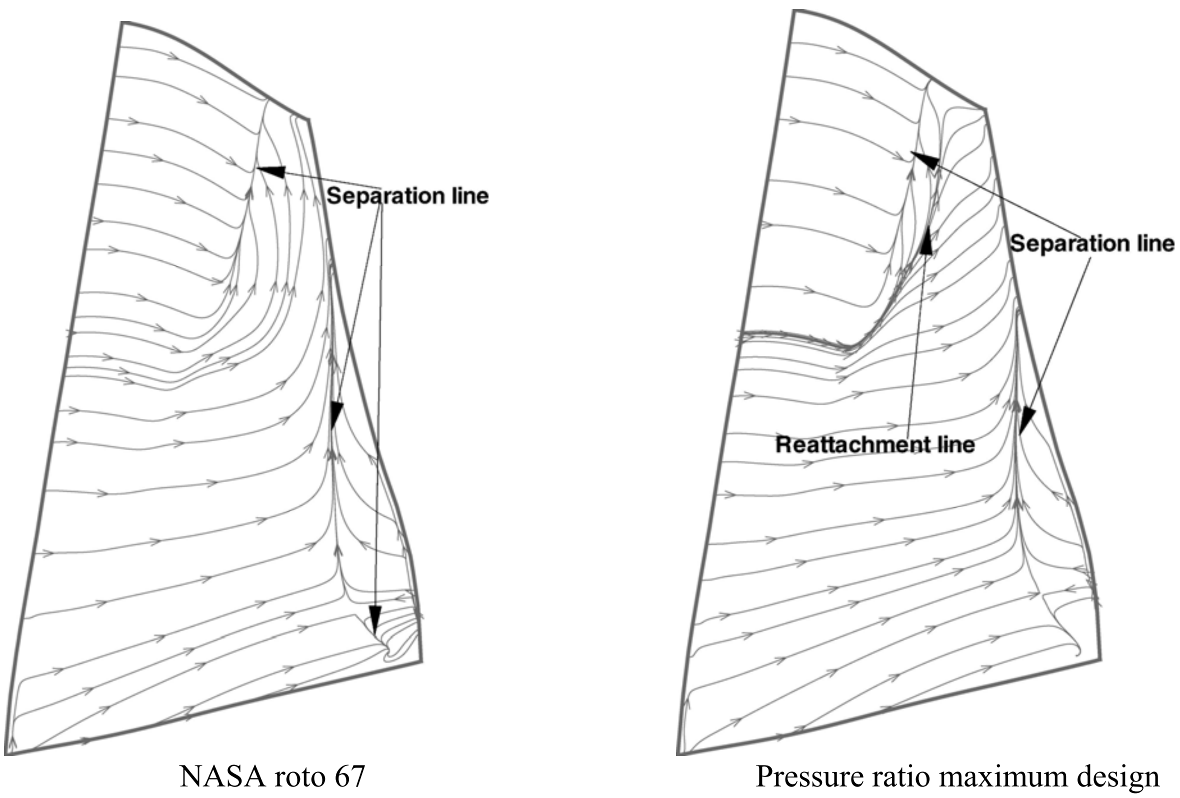


Figure 6: Obtained Pareto-optimal designs.



NASA roto 67 Pressure ratio maximum design

Figure 7: Streamlines close to the blade suction side.

2.4 Aero-structural Optimization of a Transonic Compressor rotor

Reference [10] presented a framework for multi-objective and multidisciplinary design optimization using high-fidelity analysis tools and a MOEA. Here, structure dynamics was computed using commercial finite element analysis software (ANSYS) while the aerodynamic performance was computed by a three-dimensional RANS solver (TRAF3D). The response surface method was used to save the required computational time. Here, redesign of NASA rotor 67 was demonstrated where objective functions are stage pressure ratio to be maximized and compressor weight to be minimized. As shown in Fig. 8, the proposed method successfully obtained Pareto-optimal designs that outperform NASA rotor 67 in both pressure ratio and mass. This article has been cited by 17 articles by now according to SCOPUS.

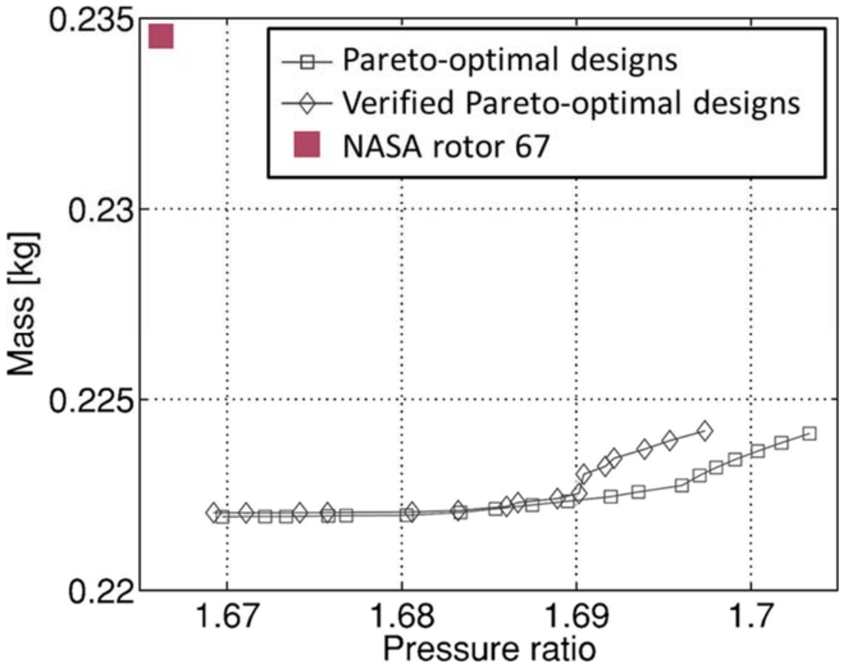


Figure 8: Distribution of the obtained Pareto-optimal designs.

3 Concluding remarks

Through the series of researches, high-fidelity multiobjective and multidisciplinary design optimization method for transonic axial-flow compressor blade design optimization method has been developed. The developed method bases on three-dimensional RANS solver for aerodynamic performance evaluation and finite element analysis for structural performance evaluation. For multiobjective and global optimization, a multiobjective evolutionary algorithm is used. Redesign of NASA rotor 67 shows advantages of the developed method over conventional approaches. Lian and Liou also studied approaches for data mining and knowledge discovery from obtained Pareto-optimal designs [11].

These researches were state of the art at that time and referred by many of subsequent studies. For example, Chen et al [12] studied blade parameterization techniques for aerodynamic design optimization of a three-dimensional compressor rotor using three-dimensional RANS solver, response surface method, and a gradient-based method. Wang et al [13] developed aerodynamic design optimization method of compressor blade based on three-dimensional RANS computation and an adjoint method and showed that the optimized design outperforms existing rotors. In [14], Ellbrant et al also developed design optimization method for aerodynamic compressor blade design and studied response surface method by comparing several different response surface models. In [15], Myoren et al developed multiobjective optimization method for transonic compressor blade design.

Dr. Liou's works have been inspiring many researchers and are still leading researches in this field.

References

[1] A. Oyama and M.-S. Liou. Multiobjective Optimization of Rocket Engine Pumps Using Evolutionary Algorithm. AIAA J. Propulsion Power, 18, 3:528-535, 2002.

[2] A. Oyama and M.-S. Liou. Multiobjective Optimization of a Multi-Stage Compressor Using Evolutionary Algorithm. AIAA-2002-3535, 38th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Indianapolis, Indiana, July 7-10, 2002.

[3] A. Oyama and M.-S. Liou. Design Optimizations of Turbomachines Using Evolutionary Algorithm. Transactions Aeronautical Astronautical Society Republic of China, 34, 2:528-535, 2002.

[4] A. Oyama, M.-S. Liou and S. Obayashi. Transonic Axial-Flow Blade Optimization Using Evolutionary Algorithms and a Three-Dimensional Navier-Stokes Solver. AIAA J. Propulsion Power, 20, 4:612-619, 2004.

[5] A. J. Strazisar, J. R. Wood, M. D. Hathaway and K. L. Suder. Laser Anemometer Measurements in a Transonic Axial-Flow Fan Rotor. NASA Technical Paper 2879, November 1989.

[6] A. Oyama, M.-S. Liou and S. Obayashi. High-Fidelity Swept and Leaned Rotor Blade Design Optimization Using Evolutionary Algorithm. AIAA-2003-4091, 16th AIAA Computational Fluid Dynamics Conference, Orlando, Florida, June 23-26, 2003.

[7] J. D. Denton. The effects of lean and sweep on transonic fan performance: a computational study. Task Quarterly Vol.6, No.1, pp.7-23, 2002.

[8] Y. Lian, and M.-S. Liou. Multiobjective Optimization Using Coupled Response Surface Model and Evolutionary Algorithm. AIAA J., Vol.43, No.6, 2005.

[9] Y. Lian and M.-S. Liou. Multiobjective Optimization of a Transonic Compressor Rotor using Evolutionary Algorithm. J. Propulsion Power, 21, 6:979-987, 2005.

[10] Y. Lian and M.-S. Liou. Aerostructural Optimization of a Transonic Compressor rotor. J. Propulsion Power, 22:880-888, 2006.

[11] Y. Lian and M.-S. Liou. Mining of Data from Evolutionary Algorithms for Improving Design Optimization. Computer Modeling Engineering Sciences, 8, 1:61-72, 2005.

[12] N. Chen, H. Zhang, Y. Xu and W. Huang. Blade Parameterization and Aerodynamic Design Optimization for a 3D Transonic Compressor Rotor. J. of Thermal Science, Vol. 16, No. 2, pp. 105-114, 2007.

[13] D. X. Wang, L. He, Y. S. Li and R. G. Wells. Adjoint Aerodynamic Design Optimization for Blades in Multistage Turbomachines – Part II: Validation and Application. J. of Turbomachinery, Vol. 132, 2010.

[14] L. Ellbrant, L.-E. Eriksson and H. Martensson. CFD Optimization of a Transonic Compressor Using Multiobjective GA and Metamodels. ICAS2012, 2012.

[15] C. Myoren, Y. Takahashi and Y. Kato. Multi-Objective Optimization of Three-Dimensional Blade Shape for an Axial Compressor Rotor in Transonic Stage. International J. of Gas Turbine, Propulsion and Power Systems, Vol. 5, No.1, 2013.