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Multi-Objective Evolutionary Optimization of Gas Turbine Components

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Berichte aus der Energietechnik

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Abstract

The world-wide increasing demand for energy is one of the key challenges of our century. However, this demand is in conflict to the Kyoto protocols of 1997 and 2001 that contain an international agreement for reducing green house gases. Energy generation concepts involving alternative energy sources and innovative technologies with high thermodynamical efficiencies are needed in order to address these issues.

Gas turbines are one of the key energy producing devices of our generation. Improved designs of gas turbine components are necessary in order to address the increasing demands of high performance and reduced emissions. The design of gas turbine components is a complex and time-consuming engineering task that involves meeting of several design objectives and constraints. This task is usually addressed in an iterative process. Advances in domain knowledge and in areas such as information technology offer the possibility of accelerating and improving this design cycle through automated optimization procedures.

This thesis addresses the key issue of automated optimization by presenting optimization algorithms that are implemented in realistic design processes of gas turbine components. The results of this work include algorithmic advances and the development of new and efficient designs for turbine components. The proposed optimization algorithms are analyzed and enhanced so that they are applicable to the design of compressor blades and burners. The thesis addresses a number of optimization difficulties such as multiple design objectives and constraints, high sensitivity of the objectives, and noise in the evaluation of the objectives.

Automated optimization requires a blend of efficient algorithms and information technology tools from in order to find optimal solutions in limited time frames. We find that it is not sufficient to use existing tools but that extensive, problem specific modifications of the algorithms are required. In this thesis, several new algorithms for single and multi-objective Pareto optimization are presented. The focus is on evolutionary algorithms, as they are robust optimization algorithms suitable for engineering applications where pointwise information is only available. In the context of Pareto optimization, several well known evolutionary algorithms are analyzed with regards to their convergence properties and convergence limits.

Furthermore, the efficiency of certain algorithms is enhanced by defining adaptive mutation and recombination operators based on self-organizing maps. The robustness to noisy objective functions is improved by defining a dominance dependent re-evaluation interval. In the field of single objective optimization, a new optimization algorithm is proposed that is suitable for engineering problems with relatively few decision variables but expensive cost function evaluations. The algorithm relies on the construction of an empirical model of the objective function. The model is then used to predict function values in order to reduce the number of function evaluations.

For the compressor optimization, an optimization procedure is defined that addresses the relevant design objectives and constraints. The procedure comprises a new blade parameterization and tools for the aerodynamical and mechanical analysis. For the aerodynamical analysis, an inexpensive method for estimating off-design behavior is presented. Four compressor blades of adjacent mid-stages of a gas turbine are optimized and the resulting profile shapes are discussed.

The gas turbine burner is optimized in an experimental test-rig. The objectives are to minimize thermo-acoustic pulsations and NO_x emissions. Both objectives are noisy as they result from measurements with limited time averaging. The Pareto optimization results in an approximation of the Pareto set, comprising a number of different trade-off solutions for the two conflicting objectives.

The thesis concludes by identifying a number of open questions and outlines directions for future work.

Zusammenfassung

Der weltweit steigende Bedarf an Energie ist eine der zentralen Herausforderungen unseres Jahrhunderts. Die Bereitstellung der Energie ist schwierig angesichts des in den Kyoto Protokollen von 1997 und 2001 unterzeichneten internationalen Abkommens zur Reduzierung der Treibhausgase. Deshalb werden zur Energiegewinnung alternative Energiequellen und innovative Kraftwerke mit hohem thermodynamischen Wirkungsgrad benötigt.

Gasturbinen sind eine der zentralen Kraftwerkstechnologien unserer Zeit. Kontinuierlich verbesserte Gasturbinenkomponenten werden benötigt um die steigenden Anforderungen an Wirkungsgrad und Emissionen zu erfüllen. Die Entwicklung von Gasturbinenkomponenten ist eine komplexe und zeitintensive Ingenieursaufgabe, die zahlreiche Zielfunktionen und Zwangsbedingungen enthält. Diese Aufgabe wird in der Regel in einem iterativen Prozess gelöst. Fortschritte im Bereich der Physik von Gasturbinen und in Bereichen wie der Informationstechnologie ermöglichen den Entwicklungsprozess zu beschleunigen und durch automatische Optimierungsverfahren zu verbessern.

Die vorliegende Dissertation beschäftigt sich mit diesem zentralen Problem der automatischen Optimierung und präsentiert Optimierungsverfahren, die in reale Entwicklungsprozesse von Gasturbinenkomponenten implementiert werden. Die Ergebnisse dieser Arbeit beinhalten Verbesserungen der Verfahren und die Entwicklung von neuen und effizienten Komponentendesigns. Dabei werden die entwickelten Optimierungsalgorithmen analysiert und verbessert, sodass sie auf die Entwicklung von Kompressorschaukeln und Brenner angewandt werden können. Herausforderungen an die Optimierung sind u.A. die Vielzahl der Zwangsbedingungen und Zielfunktionen, die hohe Sensitivität und das Rauschen in den Zielfunktionen.

Automatische Optimierung benötigt eine Auswahl effizienter Algorithmen und Werkzeuge der Informationstechnologie, um optimale Lösungen in vorgeschriebenen Zeitgrenzen zu erhalten. Wir erachten es als unzureichend existierende Optimierungsverfahren zu verwenden, sondern erachten aufwendige und problemspezifische Modifikationen als Grundvoraussetzung für eine erfolgreiche Optimierung. In dieser Arbeit werden mehrere neue Optimierungsalgorithmen für die Ein-

und Mehrkriterienoptimierung vorgestellt. Dabei liegt der Schwerpunkt auf evolutionären Algorithmen, welche sich als robust und effizient in Ingenieursanwendungen erweisen. Im Bereich der Mehrkriterienoptimierung werden Standardalgorithmen bezüglich ihrer Konvergenzeigenschaften und Konvergenzbeschränkungen analysiert. Des Weiteren wird die Effizienz dieser Algorithmen durch die Entwicklung adaptiver Mutations- und Rekombinationsoperatoren auf Basis von selbstorganisierenden Netzwerken verbessert. Die Robustheit der Algorithmen gegenüber verrauschten Zielgrößen wird durch die Definition von dominanzabhängigen Reevaluationsintervallen verbessert. Im Bereich der Einkriterienoptimierung wird ein neuer Optimierungsalgorithmus vorgeschlagen, welcher empirische Modelle der Zielfunktion konstruiert. Dieser Algorithmus eignet sich insbesondere für Optimierungsprobleme mit einer geringen Zahl freier Variablen bei gleichzeitig teuren Funktionsauswertungen. Das Modell wird zur Vorhersage von Funktionswerten verwendet, um die Zahl der Auswertungen zu reduzieren.

Für die Kompressoroptimierung wird eine Prozedur definiert, welche alle relevanten Zielfunktionen und Zwangskriterien eines realistischen Entwurfsprozesses beachtet. Die Prozedur beinhaltet eine neue Schaufelparametrisierung und Berechnungsprogramme für die Aerodynamik und die Mechanik der Schaufel. Für die Bewertung der Aerodynamik ausserhalb des Betriebspunktes wird eine kostengünstige Methode entwickelt. Insgesamt werden vier Kompressorschaukeln aus benachbarten Reihen des mittleren Kompressorbereichs optimiert und die Ergebnisse diskutiert.

Der Gasturbinenbrenner wird in einem experimentellen Aufbau optimiert. Ziel der Optimierung ist die Minimierung der thermoakustischen Pulsationen und der NO_x Emissionen. Beide Zielfunktionen werden durch zeitlich gemittelten Messungen erfasst, welche verrauscht sind. Die Pareto-Optimierung findet eine Approximation der Pareto-Front, welche aus Kompromisslösungen für die beiden widersprüchlichen Zielgrößen besteht.

Diese Dissertation schliesst mit einer Identifikation offener Fragen für zukünftige Forschungsarbeiten.

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Contents

List of Acronyms	VI
List of Symbols	VII
Introduction	XI
I Survey on Optimization Algorithms	1
1 Overview	2
1.1 Multi-Objective Optimization Problem	2
1.1.1 Introduction	2
1.1.2 Definitions	3
1.1.3 Targets	4
1.2 Optimization Algorithms	6
1.2.1 Classification	6
1.2.2 Direct Gradient-Based Methods	7
1.2.3 Evolutionary Algorithms	9
1.2.4 Related Algorithms	10
2 Evolution Strategies for Single Objective Optimization	13
2.1 Introduction	13
2.2 One-Fifth Success Rule	16
2.3 Self-adaptation	18
2.4 Covariance Matrix Adaptation	21
3 Multi-objective Evolutionary Algorithms	24
3.1 Introduction	24
3.2 Selection Operators	26
3.2.1 Independent Sampling	26
3.2.2 Cooperative Population Searches with Dominance Criterion	27

3.2.3	Cooperative Population Searches without Dominance Criterion	31
3.3	Recombination and Mutation Operators	32
3.4	Test Problems	33
3.5	Performance Measures	35
4	Optimization Using Fitness Function Models	38
4.1	Introduction	38
4.2	Models in Evolutionary Algorithms	39
4.2.1	Evolution Control	39
4.2.2	Surrogate Approach	41
4.2.3	Empirical Models	41
II	Advances in Evolutionary Algorithms	44
5	Convergence Limits of Multi-objective Selection Operators	45
5.1	Introduction	45
5.2	Analysis of Selection Operators	47
5.2.1	Independent Sampling	47
5.2.2	Cooperative Population Searches with Dominance Criterion	47
5.2.3	Cooperative Population Searches without Dominance Criterion	49
5.3	Experimental Analysis	50
5.3.1	Combining Self-adaptive Mutation with Multi-objective Selection Operators	51
5.3.2	Experimental Results	53
5.4	Conclusions	58
6	Multi-objective Evolutionary Algorithm for Noisy Objective Functions	62
6.1	Introduction	62
6.2	Noise and Noise-tolerant Multi-Objective Evolutionary Algorithms	63
6.2.1	Definition of Noise in Applications	63
6.2.2	Non-Elitist Strength Pareto Evolutionary Algorithm	64
6.2.3	Statistical Strength Pareto Evolutionary Algorithm	64
6.2.4	Estimate Strength Pareto Evolutionary Algorithm	65
6.2.5	Noise-tolerant Strength Pareto Evolutionary Algorithm	67

6.3	Performance Comparison	69
6.3.1	Generation of Noisy Test Functions	69
6.3.2	Experimental Results	71
6.3.3	Discussion of the Heuristic Parameters c_1 , c_2 and κ_{\max} in NT-SPEA	74
6.4	Conclusions	76
7	Growing Self-Organizing Maps for Multi-Objective Optimization	79
7.1	Introduction	80
7.2	Multi-Objective Optimization as Two Step Process	82
7.3	Recombination Operators	82
7.3.1	Standard Recombination Operators from Single Objective Evolutionary Algorithms	83
7.3.2	Recombination Operator based on Self-Organizing Maps	84
7.4	Theoretical Comparison of the Recombination Operators	88
7.4.1	Global Recombination	89
7.4.2	Discrete Recombination	90
7.4.3	Intermediate Recombination	91
7.4.4	Simulated Binary Recombination	91
7.4.5	SOM Recombination Operator	92
7.5	Performance Comparison on Test Problems	95
7.6	Conclusions	101
8	Accelerating Evolutionary Algorithms Using Fitness Function Models	106
8.1	Selected Approach	106
8.2	Gaussian Process Model	107
8.2.1	Optimizing the Hyperparameters	110
8.2.2	Computational Cost	111
8.2.3	Numerical Difficulties	112
8.3	Gaussian Process Optimization Procedure	112
8.3.1	Merit Functions	113
8.3.2	Local Modeling and Local Search	114
8.3.3	Enhancements for Real-World Applications	114
8.4	Performance Analysis	116
8.4.1	Sphere function	117
8.4.2	Schwefel's function	118
8.4.3	Rosenbrock's function	118
8.4.4	Rastrigin's function	118

8.4.5	Summary of the Performance Analysis	120
8.5	Conclusions	121
 III Turbomachinery Design Optimization		124
 9 Gas Turbines for Energy Generation		125
 10 Multi-objective Optimization of Noisy Combustion Processes		127
10.1	Introduction	127
10.2	Atmospheric Test-rig for Gas Turbine Burners	129
10.3	Burner Optimization with Proportional Valves	132
10.3.1	Valve Encoding and Optimization Algorithm	132
10.3.2	Optimization Results	132
10.3.3	Statistical Analysis	134
10.3.4	Noise Analysis	136
10.4	Burner Optimization with Digital Valves	139
10.4.1	Valve Encoding and Optimization Algorithm	139
10.4.2	Optimization Results	139
10.5	Conclusions	143
 11 Optimization of Compressor Profiles and Blades		144
11.1	Compressor Design	144
11.2	Survey on Automated Compressor Optimization	146
11.3	Optimization Approach	147
11.3.1	Parameterization of Compressor Profiles	149
11.3.2	Parameterization of Compressor Blades	150
11.3.3	Mechanical Integrity Analysis	151
11.3.4	Q3D Flow Analysis	152
11.3.5	Objectives and Constraints	152
11.4	Profile Optimization	154
11.4.1	Objective functions	155
11.4.2	Single Objective Optimization	155
11.4.3	Multi-Objective Optimization	159
11.4.4	Discussion of the Optimized Compressor Profiles	163
11.5	Blade Optimization	166
11.5.1	Blade Parameterization	166
11.5.2	Objective Function	167

11.5.3 Optimization Loop	167
11.5.4 Optimization Results	167
11.5.5 Validation of the Blade Optimization by 3D RANS Simulation	171
11.6 Conclusions	173
IV Conclusions and Outlook	176
12 Conclusions	177
13 Outlook and Future Work	180