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論 文 内 容 の 要 旨

Chapter 1　Introduction

Turbomachinery is widely used for exchanging mechanical energy and fluid energy continuously. It can be classified into several categories, i.e., fans, blowers, compressors, turbines, pumps, and water mills, according to the types of fluid media and directions of energy exchange. They are used in various situations in power plants, industrial machines, consumer products, etc. There is increasing social demand for minimizing energy consumption to reduce carbon dioxide emissions and suppress global warming. Therefore, the aerodynamic performance of turbomachinery, particularly aerodynamic efficiency, has to be improved as much as possible. A great deal of effort has been already made to improve the aerodynamic performance of turbomachinery used in power plants and industrial machines, where the amounts of energy consumption are relatively large. In contrast, there have been fewer efforts for turbomachinery used in consumer products. In these products, centrifugal configuration is often used because of its ability to provide higher pressure increases in a more compact body.

One solution for improving the performance is the application of numerical design optimization methods. Design optimization methods for turbomachinery have been investigated since the 1990s. However, there are several problems to apply these existing methods to practical designs in industry, particularly to the designs of centrifugal turbomachinery used for consumer products. One problem is the short design turnaround time. As product life cycles are short and computational resources are limited, it is necessary to develop efficient design optimization methods capable of reducing the design lead time. Another problem arises from uncertainties in practical designs. Designers are often faced with uncertainties in design decisions and design conditions, which cannot be defined deterministically at the start of the designs. The uncertainty in design decisions is defined as freedom of choosing trade-off balance among multiple design objectives. The uncertainty in design conditions is defined as variance in products, such as dimensions and material properties. Practical design optimization methods have to be capable of handling these uncertainties. Another problem is concerned with how to reinforce the design knowledge of designers. Unlike academic applications, industrial designers must repeat and improve design routines. Therefore, it is necessary to develop knowledge-oriented design methods, with which designers can discover design insights such as important design parameters and design rules applicable to subsequent steps in the design process.

Design exploration methods, which combine design optimization and data mining, have been used to facilitate knowledge-oriented design optimization. Thus, the objectives of this research include the proposal and development of practical design exploration methods for centrifugal turbomachinery configurations capable of resolving the problems described above. This research is composed of four stages of developments to achieve this final goal.

Chapter 2 Single-Objective Design Exploration using Simulated Annealing, Neural Network, and Regression Analysis

In the first stage, single-objective design exploration methods were developed. An efficient method for three-dimensional shape parameterization of centrifugal turbomachinery was developed using a minimum set of non-uniform rational B-Spline curves. These curves were assigned only to the enclosed boundaries of the blades consisting of the hub, shroud, leading edge, and trailing edge profiles. In other words, traditional multi-sectional definition of the blade profile was avoided and the number of design variables was reduced. An efficient single-objective global optimization method was developed by combining simulated annealing and artificial neural network. The neural network adaptively learned the simulation results collected by simulated annealing. The trained neural network, as an approximation model, periodically predicted a possible global optimum to shorten optimization lead time. Simulated annealing itself explored the design space independently of the neural network in case the neural network learning failed. This ensured a robust and fully automatic optimization. With these methods, the required design turnaround time was reduced, although the degree of reduction depended on the prediction accuracy of the neural network. As the first step of data mining, the global characteristics of the design space were analyzed using regression analysis. The analysis was attempted to extract useful information such as sensitivity and non-linearity of the design space. The design exploration methods developed in this stage were applied to the design problems of centrifugal impeller and diffuser for a vacuum cleaner. The optimized impeller had a unique S-shaped leading edge profile, which effectively controlled secondary flows and improved the flow uniformity at the impeller exit. The optimized diffuser had a unique bending trailing edge with a wedge-shaped gap, which generated a streamwise vortex and prevented boundary layer separation. The regression analysis revealed important design variables that were related to these unique shapes of the optima.

Chapter 3 Multi-Objective Design Exploration using Multi-objective Genetic Algorithm, Decision Tree Analysis, and Rough Set Theory

In the second stage, multi-objective design exploration methods were developed. A multi-objective optimization approach was taken to handle the uncertainty in design decisions, i.e., the variety in trade-off balance among objective functions. A multi-objective genetic algorithm was employed with enhancements of convergence to widespread non-dominated solutions. It enabled the acquisition of multiple design candidates with different trade-off balance, from which the best design candidate can be chosen according to the requirement specified afterward. This method was applied to the design of a low-specific-speed centrifugal impeller with a vaned diffuser for a vacuum cleaner. The design objectives were set to improve both aerodynamic efficiency and aerodynamic stability. Computational fluid dynamics were conducted for a combined model of blade-to-blade regions of an impeller and a diffuser. A time-averaged and spatially distributed flow was modeled at the mixing plane to evaluate the flow uniformity, which affected aerodynamic stability. Seven non-dominated solutions were obtained, and the improvements in both design objectives were confirmed by experiments with a selected non-dominated solution. Data mining methods, namely decision tree analysis and rough set theory, were applied to extract quantitative design rules for improving each of the objective functions to the maximum limit. The obtained rules indicated that dimensions such as inlet blade angle, vane-less diffuser height, and blade load balance were important for the extreme designs, helping designers correlate important design variables with underlying flow physics. It was also clarified that decision tree analysis generally extracts a single rule of necessary condition, while rough set theory mines multiple rules of sufficient conditions. Decision tree analysis extracts a single but yet simple rule, while rough set theory extracts multiple but yet complicated rules.

Chapter 4 Multi-objective Robust Design Exploration using Kriging Model, Self-organizing Map, and Association Rule

In the third stage, multi-objective robust design exploration (MORDE) methods were developed. The previously developed method was extended to a multi-objective robust optimization method to handle the uncertainty in design conditions, i.e., the variance in product's properties. Probabilistic representations of design parameters were introduced to the multi-objective genetic algorithm to model these variances. The parameter representation was generalized in such a way that it was compatible with that in the Taguchi method. Kriging models were adopted as approximation models to conduct large number of response calculation among design parameters swiftly. Data mining methods, namely Self-organizing maps and association rules, were used to clarify the design rules for achieving certain trade-off balance among multiple objective functions. The combined use of the association rule with an aspiration vector, which specified the desired trade-off balance, was proposed to analyze multi-objective design space. The MORDE was applied to a centrifugal fan design problem of a washer-dryer. This design was aimed toward improving the means and standard deviations of the resultant statistical distributions of fan efficiency and turbulence noise level. The variances were assumed to exist in the fan's dimensions due to mass production. It was demonstrated that designers could obtain the best design candidate and quantitative rules that met with the required trade-off balance. It was also demonstrated that traditional non-robust optimal design as well as quality-weighted design such as the Taguchi method were simultaneously accomplished with the MORDE. It was clarified that association rule generally reveals multiple and quantitative design rules, while it is difficult to perform the same analysis with Self-organizing map. Association rules can be either necessary or sufficient conditions according to the control parameters for rule extraction. The design turn around time necessary for this fan design was only two weeks and was considered to be practical. Based on these investigations, it was concluded that practical design exploration methods were established with the MORDE, with which knowledge-oriented design optimization under the uncertainties became feasible within short design turnaround time.

Chapter 5 A New Design Method based on Cooperative Data Mining from Multi-objective Design Space

In the final stage, another practical design exploration method was further developed. Because design rules represent key structures in multi-objective design space, they were considered to be useful in determining the optimum setup of design variables. Therefore, a new rule-based multi-objective parameter design method was proposed. This method utilized a database of design rules obtained by the following data mining methods, namely analysis of variance, Self-organizing maps, decision tree analysis, rough set theory, and association rule. Comparative studies of these methods revealed the strengths and weaknesses of each method, and a systematic procedure was developed for applying these methods in a complementary way. Firstly, analysis of variance was applied to determine dominant main and interaction effects of design variables, which were used in the latter process of data mining. Self-organizing maps or alternative visualization methods were used to find qualitative low-order correlations, particularly trade-off relationships between objective functions. Then, design rule extraction methods were applied to obtain quantitative rule sets. Decision tree analysis could be applied to extract an easy-to-understand rule. However, decision tree analysis could be skipped because the rule could not distinguish main and interaction effects. Both rough set theory and association rule were applied to extract multiple design rules that distinguished main and interaction effects. While rules from rough set theory were only sufficient conditions, association rules could be either of sufficient or necessary conditions. However, rough set theory had an advantage in capability of automatic finding the minimum rule length, which had to be specified manually in the case of association rule. Therefore, the usage of association rule, after obtaining the proper rule length by rough set theory, was recommended. Once the design rule database was obtained, the proposed method first used predominant main effects of different design variables for optimizing different objective functions. Then, it used predominant interaction effects to resolve any remaining trade-off conflicts. The capability of this method was demonstrated using the same design optimization problem of a washer-dryer's fan. It was confirmed that this method was superior to the Taguchi method in its capability of performing multi-objective design.

Chapter 6 Concluding Remarks

Based on the developments of design optimization and data mining methods described above, design exploration for centrifugal turbomachinery configurations has become practical for industrial applications. The methods were successfully applied to actual products of a vacuum cleaner and a washer-dryer in Hitachi Ltd., which suggested the methods' capabilities in real-world applications.

論 文 審 査 結 果 の 要 旨

ターボ機械は、機械と流体の間のエネルギー変換器として様々な用途に用いられている。近年の地球温暖化問題を受け、効率に代表される性能諸元の一層の改善が望まれている。そのために設計最適化技術の研究が進められてきたが、民生品に多用される遠心型ターボ機械に対して設計最適化を実施するのには、次のような課題がある。それは、製品のライフサイクルが短いことから来る設計期間の短さ、開発段階における製品仕様の曖昧さ、量産品特有の性能ばらつきの存在、設計改善を促すための設計者の知識強化手段の不足である。これらの課題を解決するためには、設計情報が不確実な中でも、効率良く最適化を実施し、かつ検討結果から設計知識を抽出して設計者に提示できるような実用的な設計最適化技術の開発が必要である。そこで本研究では、最適化とデータマイニングを融合させた「設計探査」というアプローチに着目し、その実用化のための技術開発と、産業界における実設計問題への適用を行っている。本論文は、これらの研究成果をまとめたものであり、全編6章からなる。

第1章は緒言であり、本研究の背景、課題、目的を述べている。

第2章では、最小限のパラメータ曲線を用いた遠心型ターボ機械向けの効率的な形状表現法を確立している。焼き鈍し法とニューラルネットワークをハイブリッド化した効率的な単目的最適化アルゴリズムを開発し、回帰分析による設計空間構造の特徴分析も可能としている。遠心羽根車とディフューザの設計に適用し、設計期間の短縮を確認すると共に、従来にない革新的な形状を発見している。これは大変に有益な成果である。

第3章では、目標とすべき製品仕様が曖昧な場合でも設計できるように、遺伝的アルゴリズムを用いた多目的最適化手法を開発し、予め製品仕様を定める必要がない設計法を確立している。また、個別性能の極限化を達成するための条件を明らかにするため、決定木やラフ集合という設計法則抽出を適用している。開発手法を掃除機用遠心ブロアの設計に適用し、効率の改善と空力安定性の確保を両立できることを実験的に検証するとともに、性能極限化に支配的な因子を明らかにすることにも成功している。これは有効かつ非常に重要な成果である。

第4章では、量産ばらつきがある場合でも合理的に設計ができるように、第3章で開発した多目的最適化手法に統計モデルを導入するとともに、統計応答計算を高速で実施できるクリギングモデルを導入することによって、多目的ロバスト最適化手法へと拡張している。また第3章で示した個別性能の極限設計のみでなく、複数性能間の任意のトレードオフバランスを実現するための条件を明らかにするため、相関ルールと希求ベクトル法を用いた新しい設計法則抽出法を提案している。開発手法を洗濯乾燥機用遠心ファンの設計に適用し、量産による寸法ばらつきを考慮した上で、効率と騒音の歩留まりを考慮した最適化が2週間という短期間で実施可能であることを示している。これは設計探査手法の実用化を達成した非常に重要な成果である。

第5章では、各種データマイニング手法の比較検討を実施し、各々の手法の特徴を明らかにするとともに、手法間の連携法について考察し、多目的設計空間からの設計知識抽出のプロセスとして体系化している。さらに本プロセスの実践により、設計変数の主効果と交互作用を分離した形式での設計法則の同定と、この設計法則を再利用する新しい多目的パラメータ設計法を提案している。本設計法はタグチメソッド等の既存のパラメータ設計法にない利点を持つもので、実用的な設計探査手法の新しい局面を切り開くという点で重要な成果である。

第6章は結論であり、本論文を総括している。

以上要するに本論文は、設計期間が短く設計情報が不確実という現実的な設計環境において、効率的な最適化と設計知識抽出を可能とする実用的な設計探査手法を開発するとともに、産業設計事例に応用したという点において、システム情報科学及び機械工学の発展に寄与するところが少なくない。

よって、本論文は博士(情報科学)の学位論文として合格と認める。