Multidisciplinary Analysis and Optimization for Regional Jet Design (リージョナルジェット機設計のための多分野融合解析と最適化)

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論文内容の要旨

Chapter 1 Introduction

In Japan, the New Energy and Industrial Technology Development Organization is supporting the development of an environmentally suitable, highly efficient regional aircraft. Mitsubishi Heavy Industries, Ltd. (MHI) is the prime contractor for the project. The aim of this project is to build a prototype aircraft with advanced technologies, such as low drag wing design, and lightweight composite structures, which are necessary for reduction of environmental burden. In March 2008, MHI has been decided to bring the conceptual aircraft into commercial use. This commercial jet aircraft is named Mitsubishi Regional Jet (MRJ). MHI and Tohoku University have developed the first high-fidelity MDO systems for the wing design under the MRJ project. The objective of the system was to optimize the three-dimensional wing shape for the transonic jet aircraft using evolutionary multi-objective optimization with high-fidelity simulations, such as Reynolds-averaged Navier-Stokes solver for aerodynamics, NASTRAN for structures and aeroelasticity. This MDO system is expected to be applicable to not only the conceptual aircraft design phase, but also the preliminary aircraft design phase in commercial aircraft design. In this system, Adaptive Range Multi-Objective Genetic Algorithm (ARMOGA) was adopted as the optimizer. ARMOGA is an efficient multi-objective evolutionary algorithm designed for aerodynamic optimization and multidisciplinary design optimization problems using high-fidelity CFD solvers with large computational time. As the result of optimization using this MDO system, high-performance wing designs were found, and design knowledge such as trade-offs was obtained. However, 70 Euler and 90 RANS computations were required per generation to evaluate the objective functions, and the population of one generation had to be set to a small value due to the computational cost. Consequently, it took 6 months to finish the optimization using an NEC SX-5. This computational cost is unrealistic for industry with limited computing resources.

Also, two issues were found in terms of shape representation. One was the modified PARSEC to definite the airfoil. This method is used because the number of variables is very small and the variables are directly associated with aerodynamic performance. However, this method often fails to express the detailed shape of the airfoil, especially near the leading edge region. The other issue was that the dynamic surface mesh method for geometrical modification sometimes generated a distorted mesh at the leading edge, and the ranges of the design variables were limited. These two problems led to a narrow design space to be explored.

To solve the problems in the first MDO system, we introduced the RSM to alleviate the computational cost in the optimization process, Non-uniform Rational B-Spline to represent the airfoil, and the geometry generation tool based on the Boolean union to modify the CFD meshes.

The improved MDO system has been applied to more realistic aircraft design problems. Then, high-performance designs have been obtained for aerodynamic and structural performances. Through the optimizations, large data sets composed of the objective function values and the corresponding design variables were obtained. Obtaining the high-performance design and also acquiring design knowledge are very important for designers. Consequently, data mining techniques to extract useful knowledge from the data set are needed in the system.

Also, this improved system has another issue in the accuracy of aeroelastic analysis. The Doublet-Lattice Method (DLM) was used to predict dynamic aeroelastic characteristics of aircraft, such as flutter and dynamic responses. This method, however, has a limitation in the transonic flow condition. The typical flutter boundary of a wing forms concave boundary in transonic speed. In the transonic region, flutter speed decreases markedly due to a shockwave on the wing; this phenomenon is known as the transonic dip, which is one of the most critical issues in aircraft design. DLM cannot predict the transonic dip because of the linear aerodynamic force.

With improvements in computer resources, higher-fidelity Euler/Navier-Stokes CFD was widely used to compute the unsteady nonlinear aerodynamic force. The flutter experiment of AGARD 445.6 standard wing came into widespread use for validation of the flutter analysis code. Many researchers have performed the validation calculation. Furthermore, various coupling methods of aerodynamic and structural equations were also developed at that time. In the 2000s, Kreissl et al. performed unsteady CFD analysis for wing-nacelle configuration using Euler/Navier-Stokes codes. In their study, they concentrated on the unsteady flow mechanism around the configuration, not on the flutter phenomenon. Arizono et al. investigated the flutter mechanism of the wing-nacelle-pylon configuration for the MRJ project. They revealed the coupled flutter of the wing bending and the nacelle pitching. However, the transition of the flutter mode at high Mach number could not be predicted. In addition, they used multi-block structured mesh for CFD. Generally, it takes several months to generate the multi-block structured mesh for the whole configuration by a professional for mesh generation.

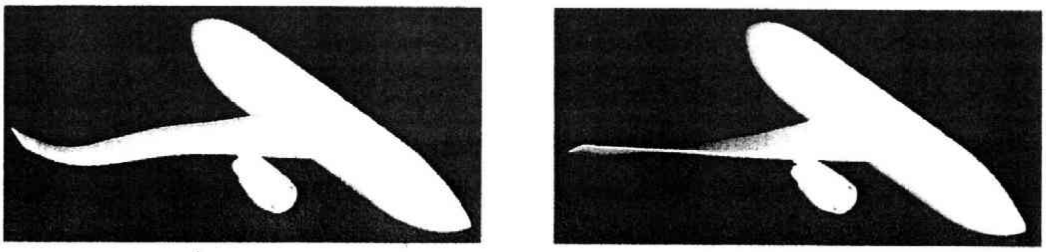
As described above, a nonlinear aeroelastic simulation has been carried out by direct coupling of the CFD and the structural equations and can be used for prediction of transonic flutter. However, in the design phase, various design candidates must be evaluated before the WTT is conducted. Aeroelastic analysis using the unstructured CFD method is a powerful strategy in terms of the cost of mesh generation, but the computational cost is an issue that remains to be solved.

Recently, significant research has been carried out in the development of Reduced-Order Models (ROM) for the rapid evaluation of nonlinear unsteady aerodynamic forces. This concept suggests that the input-output relation of a complex CFD system can be represented by a relatively simple ROM. Various approaches for reduced-order modeling of aerodynamic systems have been reported by several authors, e.g., the use of indicial responses by Ballhaus and Goorjian, pulse transfer-function analysis by Lee-Rausch and Batina, and the use of the Volterra theory as proposed by Silva. ROM based on the Volterra theory is applicable to various fidelity CFD methods or experiments, but there are no guidelines on how to treat the input of ROM system.

Chapter 2 Aeroelastic Analysis Using High-fidelity Unstructured CFD method

In this chapter, to establish the high-fidelity multidisciplinary analysis and optimization methods for regional jet design. These methods should be applicable to the design process of a real aircraft. To achieve these goals, high-fidelity aeroelastic analysis method using unstructured mesh CFD has been developed, also the guideline of the Volterra-theory ROM for the prediction of the aerodynamic force has been established. Moreover, data mining techniques have been integrated in the MDO system. The thesis is consists of following three studies.

First, high-fidelity aeroelastic analysis code based on the nonlinear aerodymamics has been developed to predict the aeroelastic characteristics of the aircraft at transonic speed accurately. The developed code is a fully implicit, unstructured-mesh Euler/Navier-Stokes solver coupled to a linear, second order structural solver. The subiteration algorithm of the fluid equations with three points Euler backward difference is also applied to the structural equations of motion. In the grid modification, the unstructured dynamic mesh method is used because it is able to maintain the grid quality in a complicated geometry. To verify the code, flutter analysis for the AGARD 445.6 standard aeroelastic wing has been performed. The computed results predict well the transonic dip of the flutter boundary found in experiment. Moreover, the present code has been applied to the wind tunnel model of the wing-pylon-nacelle configuration. Figure 1 and figure 2 show the vibration modes of the configuration and unsteady pressure distribution, respectively. The predicted flutter boundary showed a good agreement with the experiment. The present code can accurately predict the transition of flutter mode due to a shock wave. This analysis code has been proven to be useful for an aircraft design.



(a) 2nd wing bending mode (b)1st wing torsion mode

Fig. 1 The vibration modes of the wing-pylon-nacelle configuration

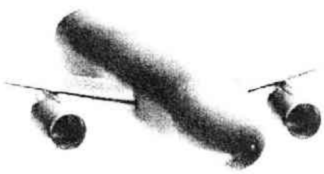


Fig. 2 Unsteady pressure distribution of the the wing-pylon-nacelle configuration

Chapter 3 Reduced-Order Aerodynamic Model for Efficient Aeroelastic Analysis

In this chapter, the reduced-order model approach for the evaluation of nonlinear generalized aerodynamic forces based on CFD has been presented. To investigate the numerical procedures of the ROM kernel identification, the validation test case of the AGARD 445.6 wing's heaving motion has been performed. It was found difficult to identify correctly the system's kernel from the impulse responses. The step-type ROM resulted in very good prediction of the forced-harmonic response. The choices of input amplitude and time step were proven to be less sensitive to the step response compared to the impulse response .Appropriate time step was found to be 1/1000-order time step of the cycle. Compared to the time step, the step input amplitude was found sensitive and thus to be chosen carefully. Furthermore, generalized aerodynamic force of the elastic AGARD 445.6 wing at 0.96 Mach number has been also predicted by the step-type ROM. From these results, the guideline for the kernel identification has been established. Furthermore, the flutter prediction by the step-type ROM has been preformed. The prediction point by the ROM agreed with that by the direct simulation. The computational cost by the ROM can be reduced by up to 90% for the linear kernel ROM, and reduced by up to 80% for the first-order kernel of the second-order ROM compared to the direct simulation. The flutter prediction using the Volterra-theory ROM has been proven to be very effective for reduction of the computational cost.

Chapter 4 Multidisciplinary Optimization of Regional Jet Wing

In this chapter, the MDO system has been extended to an engine-airframe integration problem and applied to the wing-nacelle-pylon design problem that considers the aerodynamic and structural performance simultaneously. Figure 3 shows the CFD and CSD meshes to analysis the performances. Through the optimization, a lot of data set composed of the objective function values and the design variables have been obtained. To extract the useful knowledge from the data set, data mining techniques, SOM and ANOVA, have been introduced. SOM has revealed the sweet spot in the design space (Fig. 4) and the airfoil parameters effective for improving objective function values and determining trade-offs. Furthermore, ANOVA has revealed important airfoil parameters for the objectives quantitatively. Data Mining using SOM and ANOVA provides valuable information regarding the design space structure and trade-offs, and will facilitate extraction of hidden information about the design space from optimization. The improved MDO system integrated with the data mining has been proven to be applicable to the design process of a real aircraft.

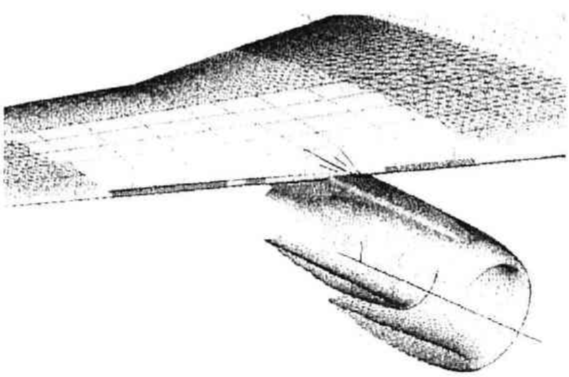
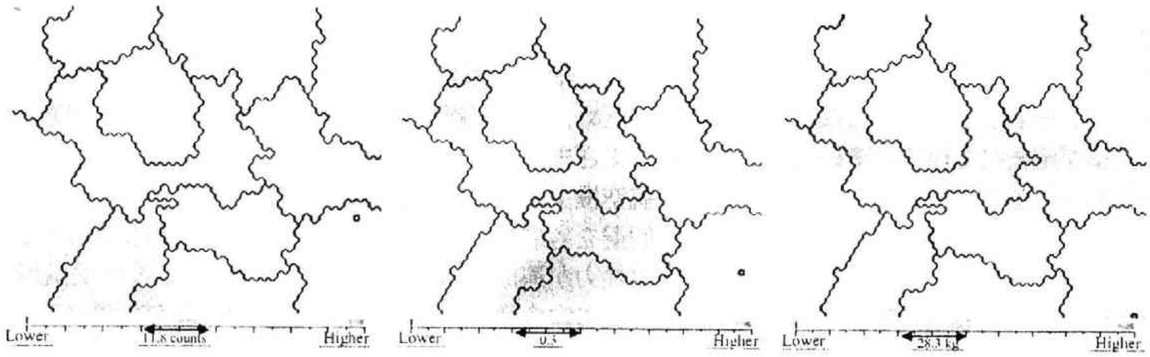


Fig. 3 CFD and CSM meshes



(a) Drag (b) Shock wave (c) Wing weight

Fig. 4 Visualization of the design space using SOM

Chapter 5 Conclusions

Consequently, it is demonstrated that the methods developed in this study contributed to the design process of a real aircraft. The achievements in this thesis will open the possibility of high-fidelity multidisciplinary analysis and optimization for further detailed aircraft design.

論文審査結果の要旨

航空機の設計開発では空気力学・構造力学・推進工学・制御工学など多分野が連成する問題や、多分野間の性能のトレードオフを考慮しなければならないため、多分野融合解析技術、及び多分野融合最適設計システムの構築が望まれている。そのため欧米でもさまざまなアプローチが提案されているが、我が国では進化型計算法を用いる多目的最適化法が開発され、航空機主翼の多分野融合最適設計に適用されている。この最適設計システムでは、拘束条件としてフラッタ回避を考慮している。空力と構造の代表的な連成現象である翼のフラッタは、翼にかかる空気力、弾性力、慣性力が連成する動的不安定現象であり、いったん生じると機体に致命的な破壊を引き起こすことから、航空機の安全性に非常に重要であるが、既存の設計システムでは線形空気力を用いているために、フラッタ予測精度が悪い。また、設計者の知識強化には、最適計算結果から設計空間全体の構造を把握することが重要であるが、従来の進化型最適化手法ではそのための十分な質のデータが得られないことや、膨大な多次元データを理解しやすい形で可視化することが困難なことなどから、設計者に有益な知識を得ることは容易ではなかった。

本論文は、航空機の多分野融合解析・最適設計技術の高度化を目指し、新しい空力弾性解析コードの開発、及びその低コスト化を行い、フラッタ予測の精度を上げて計算コストを下げるとともに、設計空間全体像を表現する近似モデルと多次元データを有効に可視化するデータマイニング手法を組み合わせることにより、設計に有用な知識を提示する方法を提案している。本論文は、これらの研究成果をまとめたものであり、全編5章からなる。

第1章は緒論であり、本研究の背景及び目的を述べている。

第2章では、圧縮性 Euler/Navier-Stokes 方程式に基づく3次元非構造格子流体解析とモード法による構造解析を連成させた空力弾性解析コードの開発・検証を行い、実用的なエンジンナセル付き主翼に適用している。検証計算では提案手法が線形空気力解析ではとらえることできない遷音速ディップを正確に予測し、風洞試験結果と非常に良い一致を与えることを確認している。またエンジンナセル付き主翼の計算では、風洞試験で観測された不連続なフラッタ境界を予測することに成功しており、本手法が有効であることを確認している。本成果のような複雑形状のフラッタ現象を数値計算により詳細に解明した例はこれまでなく、今後の航空機設計にとって非常に重要な成果である。

第3章では、上記空力弾性解析コードに低次元化空力モデルを導入し、モデル化に際して必要となる計算上の知見について論じている。翼にかかる非定常空気力をモデル化するため、インパルス型・ステップ型入力による Volterra モデルを適用し、その有用性を検証している。翼の剛体運動と弾性運動の二つの検証例に対して非定常空気力のモデル化を行い、入力の時間ステップや変位などモデル化に必要なパラメータに関する知見を明らかにしている。ここで得られた結果では、従来の高次物理モデル用いた空力弾性解析に比べて精度を維持したまま計算コストを90%削減することに成功しており、今後の空力弾性解析にとって非常に有用な成果である。

第4章では、多分野融合最適設計システムにデータマイニング手法を組み込み、設計者に有益な設計知識を発見する方法を提案している。データマイニング手法として自己組織化マップ、及び分散分析法を適用している。検証例として、推進系を統合した主翼の実用的な多分野融合最適化問題に対してデータマイニングを行い、その結果を議論している。応答曲面法による近似モデルから得られるデータを利用することや、設計上重要な翼型パラメータを用い設計空間を可視化することにより、設計者にわかりやすい形で設計知識を提示することを可能としている。本成果は、国産旅客機の開発に利用されており、多分野融合最適設計システムの有用性を高める重要な成果である。

第5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、低コストかつ高精度の空力弾性解析コードの開発、および主翼設計に適したデータマイニング法の組み込みにより航空機の多分野融合最適設計システムの高度化を行い、さらに実設計問題に適用することでその有用性を検証したもので、システム情報科学および航空宇宙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。