氏　　　　　名	亀山　正樹（かめやま　まさき）
授　与　学　位	博士（工学）
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学位論文題目	An Efficient Design Approach for Aeroelastic Tailoring and Control of Composite Plate Wings （複合材板翼の空力弾性テーラリング・コントロールのための効率的設計法に関する研究）
論文審査委員	主査　東北大学教授　福永久雄 東北大学教授　中橋和博　　東北大学教授　井上克己 東北大学教授　大林　茂（流体科学研究所）

論　文　内　容　要　旨

Chapter 1.　Introduction

Aeroelastic characteristics, represented by divergence and flutter, have been the one of the most important design factors in aircraft design so far. Up to now, generally, there have been several solutions to improve the aeroelastic characteristics of aircraft structures, such as reinforcement of structures, additional masses, restraint of the rotation degree of freedom of control surfaces and so on. However, these methods have some possibilities to lose their capacities with the increase of structural weight, to deteriorate the flight performance, to increase the operation cost and so on. Hence, it has become one of the important issues in aircraft design to develop the technology in order to improve the aeroelastic characteristics of aircrafts without any deterioration of their performance. At present, the following two technologies have drawn attention: (i) aeroelastic tailoring as passive control, and (ii) aeroelastic control as active control.

The main objective of this dissertation is to propose a simple and effective aeroservoelastic design procedure of composite wing structures. In the present research, a passive and active aeroelastic control technologies are treated one by one for the simplicity. To achieve this goal, it is desirable that the fundamental mechanisms of a passive and active aeroelastic control technology are emphatically reflected in design procedure in order to improve their aeroelastic characteristics, and the following four key issues will be investigated:

(i) To clarify the flutter and divergence characteristics of composite plate wings through the numerical results
(ii) To propose an optimum design method of composite plate wings for the flutter and divergence characteristics
(iii)To clarify the importance of the measurement and control of the torsional vibration mode for flutter

suppression of composite plate wings through the numerical results

(iv) To propose an efficient measurement and control system design method for flutter suppression of composite plate wings focused on the torsional vibration mode.

The first two studies are concerned with the aeroelastic tailoring of composite plate wings, and the latter two studies are concerned with the aeroelastic control of composite plate wings. These four studies correspond to Chapters 2, 3, 4 and 5, respectively. In this study, aeroelastic characteristics, i.e. flutter and divergence velocities and transient response due to an initial deflection, of cantilevered laminated plates in subsonic region are obtained through stability analysis and time response analysis. For this purpose a two-dimensional finite element method and a subsonic unsteady lifting surface theory are employed for structural and aerodynamic analyses, respectively.

Chapter 2. Aeroelastic Characteristics of Composite Plate Wings

In this chapter, the effect of laminate configuration on the flutter and divergence characteristics is investigated for composite plate wings with various sweep angles. As explained in Chapter 1, the most of aeroelastic tailoring parameter studies of composite wing structures have used ply fiber angle of laminates as the design parameters, that is to say, a baseline design, including ply thickness and stacking sequence was defined in advance. As a result, the effects of laminate configuration, especially principal-axis stiffness and bending-torsional coupling, of laminates on the aeroelastic characteristics have not been studied. To examine the effect of laminate configuration, the flutter and divergence characteristics are represented on the lamination parameter plane, instead of using composite fiber angle or the non-dimensional cross-coupling parameter. It is clarified through the contours on the lamination parameter plane that the flutter and divergence characteristics depend heavily on sweep angle and the nature of the first torsional vibration mode of the cantilevered laminate, and the laminate configuration to maximize the critical velocity is an angle-ply laminate, in the case of specially orthotropic laminates without coupling. Besides, it is also clarified that a proper adjustment of bending-torsional coupling can improve the divergence characteristic of forward-swept wings or the flutter characteristic of aft-swept wings and can increase the critical velocity of cantilevered plate wings, however, large bending-torsional coupling decreases the critical velocity as compared with that of a specially orthotropic laminate without coupling for unswept wings. It is found that the contours of critical velocity have a discontinuous change due to the switch of the flutter modes, discontinuous change of the derivative of critical velocity on the boundary between regions of possible flutter and possible divergence, and a complicated shape with multi-peaks due to higher-order mode flutter in the lamination parameter space.

Chapter 3. Optimum Design of Composite Plate Wings for Aeroelastic Characteristics

The investigation in Chapter 2 shows that proper choice of the stiffness components, especially the bending-torsional coupling stiffness components, in accordance with the sweep angle can effectively improve the flutter and divergence characteristics of composite plate wings. It is also shown that flutter velocity changes discontinuously with respect to the design variables in flutter analysis because of the switch between two flutter modes. The knowledge mentioned above indicates that it is necessary to apply the optimization procedure that does not depend on the flutter velocity derivative with respect to the design variables in aeroelastic tailoring. In this chapter, a minimum weight design of composite plate wings subjected to the constraints on the flutter and divergence velocities is conducted by using a distributed genetic algorithm. To obtain the global optimum, lamination parameters are used as design variables instead of ply angle and ply thicknesses. The effectiveness of aeroelastic tailoring is also demonstrated through the optimization results. It is clarified through the optimization results for unswept wings and swept wings with forward and aft sweep angles of 30 degrees that the optimal laminate configurations mainly consist of two different fiber angles and different types of flutter and/or divergence occur at almost the same free stream velocity for the optimal structure obtained from the present formulation of the optimization problem. It is also clarified that the structural weight can be remarkably reduced by a lay-up optimization, and the bending-torsional coupling determines the extent of the reduction of structural weight by a lay-up optimization for a design of forward-swept or aft-swept wing, respectively.

Chapter 4. Critical Measured and Controlled Modes for Flutter Suppression of Composite Plate Wings

Fundamental mechanism of flutter suppression has been considered for a two-dimensional airfoil with control surfaces by several researchers as mentioned in Chapter 1. In this chapter, the importance of the measurement and control of the torsional vibration mode is investigated through the dynamic aeroelastic response characteristics for composite plate wings with segmented piezoelectric sensors and actuators. Piezoelectric sensors are used as a modal transducer for measurement of the specific modal displacement, which is constructed by optimizing the sensor gain distribution. Piezoelectric actuators are used as actuators for flutter suppression, which apply the modal control force to the specific modes, like a modal actuator, with the pseudo-optimal output feedback control law based on the LQR control theory. It is clarified through the results of flutter suppression for $[0_2/90]_s$ and $[+45_2/0]_s$ cantilevered laminated plates that the measurement and control of the torsional vibration mode is essential for flutter suppression of composite plate wings, and a feedback control based on the first torsional vibration mode can suppress the divergent vibration efficiently for single vibration mode feedback control scheme. It is also clarified that the present controller has a dominant and significant effect on the increase of the damping of the controlled mode of laminate, and consequently, about 10% increase of the flutter velocity can be achieved by the present control scheme. Moreover, the divergent vibration can also be suppressed by pseudo-optimal output feedback control based on the measurement and control of the second bending vibration mode for single vibration mode feedback control scheme, although the control cost becomes larger than that of flutter suppression based on the first torsional mode, in the case of a $[+45_2/0]_s$ cantilevered laminated plate.

Chapter 5. Flutter Suppression of Composite Plate Wings based on the Optimal Placement of Sensors and Actuators

In Chapter 4, fundamental mechanisms of the flutter suppression of composite plate wings based on the measurement and control of the torsional vibration mode have been discussed through the numerical results. A modal transducer constructed by the optimization of sensor gain distribution has been adopted as a measurement system for the modal displacement of the specific vibration mode, and a feedback control system has been designed to apply modal control force to the specific vibration mode. In this chapter, flutter suppression of composite plate wings based on the measurement and control of torsional vibration with a limited number of sensors and actuators is examined. Locations of sensors and actuators are optimized based on the minimization criteria of observation and control spillovers. It is clarified through the results of flutter suppression for a $[0_2/90]_s$ cantilevered laminated plate that the optimal placement of sensors and actuators to suppress the observation and control spillovers, respectively, are indispensable to the flutter suppression for suppressing spillover instability of the control loop due to the higher residual modes. It is also clarified that the present method can realize the flutter suppression based on the measurement and control of the first torsional vibration mode by using a limited number of segmented piezoelectric sensors and actuators.

Chapter 6. Conclusions

This dissertation has dealt with flutter and divergence instability problems as a part of aeroelastic phenomena for cantilevered laminated plates. First, a minimum weight design of composite plate wings based on the lay-up optimization subject to the constraints on the flutter and divergence velocities has been conducted by using genetic algorithms and lamination parameters as intermediate design variables. Next, a design for active flutter suppression of composite plate wings with a limited number of segmented piezoelectric sensors and actuators has also been conducted based on the optimal placement of sensors and actuators.

In Chapter 2, the effect of laminate configuration on the flutter and divergence characteristics has been investigated for composite plate wings with various sweep angles. Some useful information on the flutter and divergence characteristics of composite wing structures has been given in this chapter.

In Chapter 3, a minimum weight design of composite plate wings subjected to the constraints on the flutter and divergence velocities has been conducted by using a real-coded distributed genetic algorithm. It is shown in this chapter that an optimization method based on the concept of lamination parameters and genetic algorithms is applicable to the minimum weight design problem of composite wing structures under the constraints on flutter and divergence velocities.

In Chapter 4, an active flutter suppression of composite plate wing with segmented piezoelectric sensors and actuators has been studied. Some important information on a design has been given in this chapter through the study on fundamental mechanisms of active flutter suppression of composite wing structures with piezoelectric sensors and actuators.

In Chapter 5, flutter suppression methodology of cantilevered laminated plates with a limited number of segmented piezoelectric sensors and actuators has been studied. It is shown in this chapter that a design of measurement and control systems based on the optimal placement of sensors and actuators is applicable to an active flutter suppression problem for composite wing structures with piezoelectric sensors and actuators based on the first torsional vibration mode.

This research has given some important information on an aeroservoelastic design, which has been widely accepted as a key role related to these issues, from the viewpoints of a structural and control design. When a crucial optimum design procedure considering multidisciplinary problems including aeroelasticity is established based on a simultaneous structural and control optimization for composite smart wing structures, together with a progress in materials for structures, sensors and actuators, a high performance aircraft or a progressive aircraft, like a morphing aircraft, will be realized in future.

論文審査結果の要旨

航空機構造設計において、空力弾性特性、特にフラッタ・ダイバージェンス特性は航空機の安全性および信頼性の観点から最も重要とされる設計基準の1つである。近年の航空機の高性能化に伴い、機体構造重量を増加させることなく空力弾性特性を改善する技術に関する研究が極めて重要となっており、翼構造部材に複合材を適用しその異方性を積極的に利用する空力弾性テーラリング技術、およびセンサ・アクチュエータを利用し空力弾性特性を能動的に制御する空力弾性コントロール技術に期待が寄せられている。本論文は、複合材板翼を対象として、フラッタ・ダイバージェンス特性を考慮した積層構成最適化に基づく最小重量設計、および圧電素子を用いた能動フラッタ制御のための計測・制御系設計の効率化に関する研究成果をまとめたものである。

論文は全6章で構成されている。

第1章は序論であり、本研究の背景および目的を述べている。

第2章では、種々の前進・後退角を有する片持対称積層板の積層構成がフラッタ・ダイバージェンス特性におよぼす影響に関して、積層パラメータに基づく剛性特性表示を導入することにより詳細な検討を行っている。この成果は、複合材翼構造のフラッタ・ダイバージェンス設計における異方性の扱いに関する新たな知見であり、複合材翼構造の最小重量設計において有益である。

第3章では、第2章において得られた成果に基づき、中間的設計変数として積層パラメータを用いることによるフラッタ・ダイバージェンス特性を考慮した片持対称積層板の最小重量設計法を提案し、最適化手法として実数値分散遺伝的アルゴリズムを適用することにより、指定されたフラッタ・ダイバージェンス速度制約を満足する積層構成および板厚分布を得ている。これは重要な成果である。

第4章では、小型のPVDF圧電センサおよびPZT圧電アクチュエータを用いた片持対称積層板の能動フラッタ制御に関して、ねじり振動の計測・制御に基づいた能動フラッタ制御法を提示し、その有効性について詳細な検討を行っている。この成果は、圧電素子を用いた複合材翼構造の能動フラッタ制御の基本メカニズムに関する新たな知見であり、能動フラッタ制御のための計測・制御系設計において有用である。

第5章では、第4章において得られた成果に基づき、小型かつ少数のPVDF圧電センサ・PZT圧電アクチュエータを用いた片持対称積層板の能動フラッタ制御に関して、センサ・アクチュエータの最適配置に基づいた計測・制御系設計法を提案し、フラッタ速度の10%向上を実現するセンサ・アクチュエータ配置箇所を得ている。これは重要な成果である。

第6章は結論であり、各章の成果をまとめている。

以上要するに本論文は、フラッタ・ダイバージェンス特性を考慮した航空機複合材翼構造の構造・制御系設計において簡便かつ有効な設計方法を確立し、数値解析を行うことによりフラッタ・ダイバージェンス特性の改善において有用な成果を得たものであり、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（工学）の学位論文として合格と認める。