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論文内容要旨

CHAPTER 1 Introduction

In recent years, actively controlled structures have been widely applied in many advanced engineering systems. Due to the introduction of actuators, sensors, and controllers, the whole systems can not only retain shapes or resist external loads, but also behave with some degree of adaptability to the changes of the environment or responsiveness to the commands from human beings and computers. As for optimal designing of an actively controlled structure, obviously, disciplines of both structural and control design are involved. In traditional design practice, the structural and control design are performed separately. First, the structure is designed or optimized and the mathematical model of the final structure is simplified to constitute the plant for control design. Then, the optimal control system is synthesized for the given plant. Such method may not yield the overall optimal solution, since there exist complicated interactions between the structural and control systems and it is possible to further enhance the performance by simultaneous structure-control optimization. Due to more and more stringent performance requirements in advanced applications, simultaneous optimization has been receiving increasing attention from researchers and designers.

The aim of this thesis is to investigate several important issues, i.e., formulations, solving techniques, and practical applications, of simultaneous structure-control optimization, and demonstrate the applicability and effectiveness of the new design method by simulation and experiment. The research work can be divided into two parts according to their contents. In the first part which includes Chapter 2 and 5, and Appendix A, the simultaneous optimizations for vibration control are discussed, while in the second part which includes Chapter 3 and 4, and Appendix B, the simultaneous optimizations for positioning control of flexible robot arms are studied.

CHAPTER 2 Simultaneous Optimization of a Spring-Supported Beam for Vibration Control

A general simultaneous design method for structural vibration control with good applicability and high efficiency is presented. The simultaneous design is formulated as a nonlinear programming problem, in which the overall objective function is optimized over a selected structural and control design parameters, subject to some constraints. To solve the problem, two iterative solving techniques, called "serial" and "parallel", are proposed and compared. In the serial approach, the simultaneous problem is approximated by a sequence of structural and control sub-optimizations where the structural and control design parameters are modified individually. The control parameters are held constant during the structural sub-optimization, and vice versa. In the parallel approach, the control sub-optimization is nested into the main structural optimization. It means that whenever the structural parameters are changed the control parameters will be redesigned. The control parameters can be regarded as functions of structural parameters so that from the level of the main structural optimization they are "invisible". In both serial and parallel approaches, the structural and control design parameters are treated separately; thus existing efficient tools of structural and control design can be used without any difficulty and various control laws can be adopted conveniently in the problem formulation of simultaneous design. As a simple numerical example, the formulation method and solving techniques are applied to the simultaneous design problem of a spring-supported beam for vibration suppression. The beam is modeled using finite element method (FEM) and the cross-sectional dimensions of the beam elements are used as structural design parameters. While for the control system, state feedback is used and the constant gain matrix is adopted as control design variable. The closed-loop H_2 or H_∞ norm of the augmented performance output vector, which includes displacement and control effort, are used as objective function. The optimization problem is solved by both serial and parallel approaches, where sequential quadratic programming (SQP) and linear matrix inequality (LMI) are used respectively to treat structural and control design variables. As the results, the performance of both displacement output and control input is improved significantly after simultaneous optimization and the parallel approach is shown to be more efficient than the serial approach. The effectiveness of the proposed approach and the great potential advantages of simultaneous optimization over traditional design method are shown by the simple example.

CHAPTER 3 Simultaneous Optimization of a One-Link Flexible Robot Arm for Positioning Control

Simultaneous structure-control optimization of a one-link flexible robot arm is investigated. The arm consists of a hub, a flexible link, and a tip mass as payload. The control system is required to drive the arm using the torque produced by hub motor, to reach pre-defined tip position and suppress residual flexural vibrations as quickly as possible, so that both motion and vibration control are involved in this research. The arm is modeled using FEM and the cross-sectional dimensions of the beam elements are used as structural design variables. The overall control system consists of a nonlinear sliding mode controller and a linear optimal stabilizer. A switching logic is used to combine the two feedback terms. First, the nonlinear feedback is applied to make the arm move from its initial position towards the goal position. Then, when the joint angle enters the first neighborhood of the goal, the linear feedback is started and added to the nonlinear feedback, and when the arm moves closer and closer to the goal, the linear feedback plays more and more important role than the nonlinear feedback. Finally, when the joint angle reaches the second neighborhood (more stringent than the first), the nonlinear term is completely removed from the control input and only the linear feedback remains to suppress the residual vibration. Several performance indices, i.e., settling time, overshoot, steady state error, maximum tip deflection, are taken into account and the simultaneous design is formulated as a multi-objective optimization problem. The vector objective function is converted into a scalar one using goal attainment concept. The structural and control parameters are treated equally and optimized simultaneously using float-type genetic algorithm. The designs obtained by simultaneous optimization and traditional method are compared by simulation. The results show that significant reductions in response time and structural weight are achieved by the new design method.

CHAPTER 4 Simultaneous Optimization of a Two-Link Flexible Robot Arm for Positioning Control

Simultaneous optimization of a two-link flexible robot arm for positioning control is carried out. The arm consists of two flexible links, a fixed joint, a moving joint, and a tip load, and is driven by two torque motors at the joints to reach pre-defined goal positions. The same FEM modeling technique is used as in Chapter 3, but the element matrices of the second link and the overall governing dynamic equation are much more complicated. Moreover, similar control method is used to regulate the arm position, but the sliding mode and linear quadratic controller, and the switching logic are augmented and modified to fit the two-output case. The formulation and optimization method of the simultaneous design are also the same but the computation is much more intensive. The performance enhancements of the overall system in response speed and structural weight due to the simultaneous optimization are shown clearly by the simulation results. For motion and vibration control of complicated structural systems, the advantages of the simultaneous design over tradition design are verified again.

CHAPTER 5 Simultaneous Optimization of a Steering Wheel for Vibration Control

Both computational and experimental investigations into a simultaneous design problem of a steering wheel and its control system for vibration suppression are performed. The research in this chapter can be divided into two halves. In the first half, the basic concept and solution approach of simultaneous structure-control optimization developed in Chapter 2 are applied to the steering wheel which has more complicated geometry and is more challenging than the spring-supported beam studied in Chapter 2. The H_∞ norm of the closed loop transfer function is adopted as the objective function for the simultaneous design. The selected physical parameters of the structure and the system matrices of the H_∞ output feedback controller are modified iteratively to minimize the objective function subject to several design constraints. Compared with the base system obtained by traditional design method, the closed-loop H_∞ performance of the simultaneously optimized structure is improved significantly. It is confirmed by the simulation results that, for practical and complicated structural vibration control problems, more desirable design can be achieved by the simultaneous structure-control optimization. In the second half, the performances of the base and optimized wheel are evaluated and compared by experiment. First, the FEM models of the two wheels are refined according to the results of vibration test. Then, the controllers are redesigned for the two wheels using μ synthesis method due to its capability to consider the effect of plant uncertainty and improve the robust performance. Finally, the μ controllers are implemented using DSP system and the experiments of vibration control are carried out. The experimental results show that the magnitudes of the closed-loop peak frequency responses decrease considerably. Moreover, when the time responses at the resonant frequencies are considered, compared with the base system, the optimized system has less convergence time, requires smaller steady-state control input, and has lower steady-state vibration level.

CHAPTER 6 Discussion and Conclusion

The results and achievements of the whole research work are summarized.

Appendix A Vibration Control of a Steering Wheel Using Piezoelectric Actuators

Appendix A can be regarded as a preparation work for Chapter 5. Its main purpose is to verify the effectiveness of the necessary numerical and experimental techniques involved in the vibration control problem of the steering wheel, since such techniques will be used again in the second half of Chapter 5 to evaluate the design obtained from simultaneous optimization. In Appendix A, a numerical model of the wheel is derived from FEM structural analysis and then modified according to the experimental data. First six natural vibration modes of the wheel constitute the state space plant for control design while the higher modes are neglected. The control system is designed using μ synthesis. Multi-layer piezoelectric actuators are bonded to spokes of the wheel to actively suppress the vibration caused by environmental disturbance. Displacement measured by a photonic sensor is used as feedback signal. The digitalized controller is realized on a PC with A/D, D/A converters. Both simulation and experimental results show that the vibration level is successfully reduced.

Appendix B Float-Type Genetic Algorithm for Parametric Optimization

The major procedures of the float-type genetic algorithm used in Chapter 3 and 4, including individual representation, initialization, selection function, crossover and mutation operators are listed and explained briefly.

審査結果の要旨

制御系を含む構造系の設計法として、従来は、設計された構造物に制御系を設計し付加することが行われていた。しかし、最近では、構造物の軽量化と高性能化の進展に伴い、構造と制御の同時最適設計が必要になってきた。本論文では一般的な非線形最適化法と現代制御理論に基づき、効率的な汎用性のある同時最適化法を提案し、構造物の振動制御問題に適用し、その有効性を確認している。また、遺伝アルゴリズムと多目的最適化法を用いて、弾性ロボットアームの位置決め制御の同時最適設計を行い、アームの高速化と軽量化を実現できることを示している。本論文は、これらの研究成果をまとめたもので全文6章よりなる。

第1章は序論であり、本研究の背景及び目的を述べている。

第2章では、一般的な非線形最適化法と現代制御理論に基づき、効率的な汎用性のある同時最適化法を提案し、ばね支持はりの振動制御問題に適用し、その有効性を計算で示している。これは優れた成果である。

第3章では、遺伝アルゴリズムと多目的最適化法を用い、1リンク弾性ロボットアームの位置決め制御の同時最適設計を試みている。その結果、従来の設計方法と比べ、アームの重さと応答時間が同時最適化により大幅に減少されることを示している。これは重要な知見である。

第4章では、3章で用いられた方法を拡張し、2リンク弾性ロボットアームの位置決め制御問題に適用し、複雑な問題に対してその有効性を明らかにしている。

第5章では、自動車ステアリングホイールの振動制御のための同時最適設計及びその実験による検証を行っている。提案した方法を用いてホイールを最適化し、その改善を計算で確認している。さらに、同時最適化したホイールと同時最適化してないホイールに対し、μシンセシスと圧電アクチュエータを用いて振動制御実験を行い、その性能を比較し、同時最適設計の有効性と必要性を示している。これらは重要な成果である。

第6章は結論である。

以上要するに本論文は、構造と制御の同時最適設計の定式化及び解く方法を提案し、構造物の振動制御と弾性ロボットアームの位置決め制御に適用して、その有効性と必要性を明らかにし、機械及び制御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。