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学位授与の題目	Robust H∞/ μ Control and Uncertainty Description of Mechatronic Systems （メカトロニクスシステムの不確かさの記述とロバストH∞/ μ制御に関する研究）
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学位論文要旨

Abstract

This thesis is concerned with the robust H_∞/μ control and uncertainty description of mechatronic systems including robot manipulators. We apply the advanced H_∞/μ Control theory to real mechanical systems; a magnetic bearing, an active pantograph system, and robot manipulators. Then I evaluate the performance of the control theme and power of expression of LFT against various forms of uncertainties. And I show that H_∞/μ control theory has a very good framework to treat uncertainties, in order to guarantee robust stability and robust performance.

For the robust control design, the choice of weighting functions which are design parameters plays an important role to decide control performance. I propose some method to quantify the model uncertainties by perturbation of model parameters. From this quantified uncertainties, we decided the weighting functions for design systematically.

Further, I applied this robust control theory to control a robot manipulator in order to show the effectiveness of H_∞/μ control law for nonlinear systems. I design robust control system by three approaches The first approach is μ-synthesis with exact linearization, and the second one is the constant scaled H_∞ control, which is effective

in order to guarantee robust stability for nonlinear uncertainty. The last one is gain scheduling approach with linear parameter varying model representation.

No mathematical system can exactly model a real physical system. For this reason we must be aware of how modeling errors might adversely affect the performance of a control system. The issue of uncertainty is at the main theme of control engineering, since a feedback configuration can significantly affect the sensitivity of the system behavior to uncertainty at the component level. This is the main motivation for the construction of feedback systems, but also the main potential danger as unmodeled effects can. Consequently, to perform good designs, the control engineer must be furnished with rich descriptions of uncertainty and tools to assess their impact in a complex system.

In this thesis, the robust H_∞/μ control and uncertainty description of mechatronic systems including robot manipulators is discussed.

The contribution of this thesis is as follows.

- I develop the H_∞/μ Control technology and apply the advanced H_∞/μ Control theory to real mechanical systems; a magnetic bearing, an active pantograph system, and robot manipulators. Then I evaluate the performance of the control theme and power of expression of LFT against various forms of uncertainties. And I show that H_∞/μ control theory has a very good framework to treat uncertainties, in order to guarantee robust stability and robust performance.

- In robust control design, controller performance depends on choice of weighting function as design parameters. I propose some methods to quantify the model uncertainties by perturbation of model parameters and performance specifications. From this quantified uncertainties, we decided the weighting functions for control system design systematically.

- I apply this robust control theory to control a robot manipulator in order to show the effectiveness of H_∞/μ control law for nonlinear systems. Our three approaches taken here were as follows.

- μ-synthesis with exact linearization of nonlinear plant
- constant scaled H_∞ control to guarantee robust stability for nonlinear uncertainty
- linear parameter varying model representation and gain scheduling approach

Chapter 2

A general robust control problem is descrived in Chapter 2. At first, framework of the robust control was described, especially about modeling, uncertainty, and uncertainty descriptions. Then H_∞ control problem/theory, and μ-analysis and synthesis approach was introduced.

Chapter 3

Chapter 3 is concerned with the robust control of unstable magnetic suspension systems.

Section 3.1

In this section, we evaluate a controller designed by μ-synthesis methodology with an electromagnetic suspension system. We obtain a nominal mathematical model as well as a set of plant models in which the real system is assumed to reside. With this set of the models we design the control system to achieve robust performance objective utilizing μ-synthesis methodology. First, four types of different model structures are derived based on the several idealizing assumptions for the real system. Second, for every model, the nominal value as well as the possible maximum and minimum values of each model parameter is determined by measurements and/or experiments. A nominal model is naturally chosen, this model has the simplest model structure of all four models and makes use of nominal parameter values. Then, model perturbations are defined to account for additive unstructured uncertainties from such as neglected nonlinearities and model parameter errors. Next, we define a family of plant models where the unstructured additive perturbation is employed. The method to model the plant as belonging to a family or set plays a key role for systematic robust control design. Then, we setup robust performance objective as a structured singular value test. For the design, the $D-K$ iteration approach is employed. Finally, the experimental results show that the closed-loop system with the μ-controller achieves not only nominal performance and robust stability, but in addition robust performance.

Section 3.2

In this section, we propose the gain scheduled H_∞ robust control scheme with the free parameter for a magnetic bearing in order to eliminate the unbalance vibration. We treat the changing unbalance vibration caused by varying rotational speed as the known frequency-varying disturbance, and adjust the controller gain according to the rotational speed of the rotor using the free parameter of the H_∞ controller. The obtained controller has high gain at the operating frequency. First, the dynamics of the AMB system is considered and a nominal mathematical model for the system is derived. Next, the conditions for the existence of controllers are derived, and, we design the gain scheduled H_∞ robust controllers using LSDP. It rejects the sinusoidal disturbance of the varying rotor speed. Finally the simulations and experimental results show the effectiveness of this proposed method.

Chapter 4

In this chapter, we improve the control performance of active pantograph system which has very oscillating property, at the resonance frequency by applying μ-synthesis. We consider parametric uncertainty and uncertainty caused by unmodeled dynamics, and measure their quantities, and for these uncertainties, we setup the robust performance problem. And then, we solve the above problem, design a robust controller. Finally, we show several experimental results, and indicate the effectiveness of proposed control system design methodology by comparing conventional H_∞ controller with time and frequency responses.

Chapter 5

In chapter 5, robust control of robot manipulators is discussed.

Section 5.1

In this section, we utilize exact linearization approach and apply μ-synthesis to the obtained linearized robot manipulator. For the design we consider the time delay of the controller implementation. First, we consider a dynamics of the robot manipulator, and derive a linear model as well as the uncertainties for the model. We employ the computed-torque method to obtain a simple linear model for manipulators. Second, we construct the generalized plant which is considered the above uncertainties, and set robust performance objectives as a structured singular value test. We design control systems by $D-K$ iteration approach. Three controllers are designed in consideration of time delay. After that, we carry out a lot of experiments using a DSP. Experimental results show that the effectiveness of the compensation of nonlinearity and the performance of the robust μ controller. Further, we show a control performance depends on time delay of the controller implementation by experiments.

Section 5.2

This section propose a linear robust control scheme for the robotic trajectory tracking based on the H_∞ control theory. We demonstrate the robustness of the proposed scheme by experiments on a parallel link robot manipulator. Taking the actuator dynamics into account, the nominal linear dynamic model of the manipulator is derived. The coupling between joints and the gravity forces are treated as the real structured uncertainties. These uncertainties are nonlinear, but bounded by known constants, hence the constant scaled H_∞ control scheme is employed to achieve robust performance specifications. The controller is designed with consideration of the perturbation of link parameters, which is caused by loads putted on the end of the hand. The experimental results show remarkable robustness of the proposed controller.

Section 5.3

In this section, we apply a linear parameter varying approach to a flexible joint robot control. At first, we introduce the flexible joint robot, and after that derive the LPV form of the nonlinear flexible-link robot manipulator. Then, we review background material on LPV systems, gain scheduling control and μ-synthesis. At last, I show the design procedure, and simulation results for the flexible-link robot manipulator system, and evaluate the effectivenes of the proposed approach.

Chapter 6

Finally, I conclude this thesis.

学位論文の審査結果の要旨

平成８年11月20日に第１回論文審査委員会，平成９年１月13日に第２回論文審査委員会を開催し，提出された論文と資料を検討した。そして２月４日の口頭発表の後，最終審査を行った。なお，口頭発表における質疑を最終試験に代えるものとした。

研究歴と学力：　申請者は，平成６年３月に本研究科システム科学専攻（博士課程）を中退し，同年４月より本学工学部助手として３年間，電気・情報工学，制御工学に関する教育と研究を行ってきた。この間，数々の論文を国の内外で発表している。提出された関係資料および口頭試問により，博士課程修了者と同等の学力を有するものと判断した。

論文：　提出論文は，実際のメカトロニクスシステムに対し，制御対象の数学モデルの不確かさの定量化に対する提案と，$H\infty/\mu$ 制御理論の有効性の検討を行っている。特徴および新規性は以下の３点である。

(1)　従来の $H\infty$ 制御/μ 設計で試行錯誤的に決定していた設計パラメータを繰り返し設計法により，系統的に決定する手法を提案している。(2)　非線形システムであるロボットマニピュレータに対して，$H\infty$ 制御/μ 設計を用いたロバスト制御系設計法を提案している。(3)　複数のメカトロニクスシステムに $H\infty$ 制御/μ 設計を適用し，不確かさの表現能力とロバスト性能に対する有効性を実験的に検証している。

よって，本論文は $H\infty/\mu$ 制御理論の実用化に関して極めて有益な研究である。

したがって本論文は，博士（工学）の学位を受けるに値するものと判定した。