Title	構造的な不確かさを考慮した磁気軸受のロバスト性解析・設計に関する研究
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Citation	
Issue Date	1999-03
Type	Thesis or Dissertation
Text version	author
URL	http://hdl.handle.net/10119/1225
Rights	
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Robustness Analysis and Synthesis of a Magnetic Bearing with Structured Uncertainty

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February 15, 1999

Keywords: magnetic bearing, modeling, structured uncertainty, robust control, μ-analysis.

This paper is concerned with robustness analysis and synthesis of a 4-axis controlled horizontal shaft magnetic bearing considering structured uncertainty. We propose a model of the magnetic bearing with structured uncertainty. Moreover we analyze and simulate with regard to the model, and examine whether the model is valid or not for robustness analysis and synthesis.

Magnetic bearings are bearings where the suspension forces are generated magnetically without any contact. Around the rotor, several pairs of electromagnets are arranged by the active control of magnetic forces. Magnetic bearings have excellent advantages compared with conventional mechanical bearings, for example, no friction or frictional wear, being able to rotate superspeed rotation, no vibration or noise, oil free and so on. On the other hand, magnetic bearings have some faults that increase in price or feel uneasy mentally. However magnetic bearings have been drawing much attention of the industrial fields, for example, turbomolecular pumps and flywheels for artificial satellites are made practicable. But stabilizing magnetic bearings using feedback control is indispensable because of its essential instability. Furthermore feedback control is able to set up characteristics of compliance or attenuation of bearings.

For application of feedback control to the magnetic bearing, we need a mathematical model that describe the actual magnetic bearing. It is desirable that the mathematical model represent information of control object well. Usually, however, we do some idealization or simplification when we make the mathematical model of control object. Therefore, it is difficult for us to represent behavior of control object completely on the mathematical model, the model uncertainty exists as a error between the mathematical model and the actual system. Generally there are parametric uncertainty, neglected nonlinearity, unmodelled dynamics and uncertainty involved in application of control contrivance, e.g. sensor noise, and so on. In addition, in the case of magnetic bearings, there are a changes of the rotational speed and the load under running. A control system is robust if it is insensitive to such differences between the actual system and the model of the system which was used to design the controller, recently, many researches is being done about robust control. In terms of magnetic bearings, there are many applications of robust control, such as $\mathcal{H}_\infty$ control theory. In robust control theory, a controller design is made considering the model uncertainty explicitly, it is very important problem how represent the uncertainty between the actual system and the mathematical model.

So far the uncertainty is almost represented as unstructured uncertainty using complex perturbations. Using complex perturbations, we are able to describe the unmodelled dynamics at high frequencies especially and to develop the general analytic method easily. However the unstructured description of uncertainty is conservative because it gets miscellaneous uncertainties together. The conservative description may cause the conservative analytic result as well. Whereas we describe the uncertainty as it is as much as possible using the structured uncertainty, it is expected that we are able to reduce the conservativeness. A structured singular value μ is used in robustness analysis against the model considering the structured uncertainty. It is difficult to analyze the closed loop system considering the structured uncertainty. However, recently many researches about computation of μ have been done. Also the computer aided design have developed, the structured uncertainty is dealt fair easily. Under such situations, we did as follows.

First, in order to propose the model of the magnetic bearing with uncertainty, we derived the mathematical model to represent the actual system. For examination of the uncertainty of the magnetic bearing, we also have to examine in terms of deriving the mathematical model sufficiently. The mathematical model derived here has the information of a gyroscopic effect dependent on rotational speed of rotor. When the rotor is at a standhill, i.e. the rotational speed is zero, the magnetic bearing has no gyroscopic effect and regards 4-input 4-output system as two 2-input 2-output parallel system. Therefore we adopt the nominal plant at this case. Then we examine the uncertainty for this nominal plant. In the case of single-input single-output magnetic suspension system, there is a previous research that the uncertainty is described as the structured uncertainty. Although the magnetic bearing is similar to the magnetic suspension system, the magnetic bearing is multi-input multi-output system. Hence we have to take account of a coupling of plural degrees of freedom. In this paper, we consider the changes of the load and the rotational speed as the parametric uncertainty, the linearization error of the characteristic of electromagnetic attractive force as the uncertainty dependent on linearization and the unmodelled dynamics with regard to the electromagnets with the complex dynamics. From the above argument, we propose a model of the magnetic bearing with the structured uncertainty.

Next, we make the closed loop system from the model with structured uncertainty and controllers, and analyze the robustness using the real/complex mixed structured singular value μ. This analysis carry out using MATLAB, μ-Analysis and Synthesis Toolbox. The controllers using this analysis are designed by μ-synthesis with respect to the model with unstructured uncertainty. In this analysis, we examined the conservativeness for the robust stability and the robust performance when we describe the uncertainty as the unstructured uncertainty. From this results, we found out the robust stability and the robust performance are guaranteed in larger uncertainty than that of guaranteed when the controllers was designed. We conclude that the robustness analysis against the model with the structured uncertainty is less conservertive than that with the structured uncertainty. In addition, we examined how did several uncertain factors effect against the magnetic bearing respectively.

Finally, we carry out the levitated simulation of the magnetic bearing if the proposed model and the analytic result are available or not. From simulated result, we confirmed that the results of robustness analysis is available. Also we confirmed that the unstructured uncertainty description is conservativeness. However, with respect to robust stability analysis, the closed loop system is still stable for the perturbation resulting unstable by μ-analysis. Thus We need to reduce still more the consevativeness of the robustness analysis. Perhaps we might need the model represented the behavior of the actual system better. If the model is able to represented the behavior of the actual system better, it is possible that the simulation is substituted for the experiment.

We discuss the uncertainty of the 4-axis controlled horizontal shaft magnetic bearing and propose a model considering structured uncertainty. Then we conclude that the uncertain model with structured uncertainty reduces the conservativeness on robustness analysis compared with the model with unstructured uncertainty. In addition, we confirmed the proposed uncertain model is available for the robustness analysis. However we need to make another attempt representing the uncertain model and also to make the uncertain model suitable for controller synthesis.