学位論文全文の要約

博士の専攻分野の名称　博士（工学）　　氏名　　米沢　安成

学位論文題目

Active Vibration Control Without Using Mathematical Model of Actual Controlled Object
（実制御対象の数理モデルを使用しないアクティブ振動制御）

Vibrations adversely affect mechanical systems, causing noise, worsening comfort, and even resulting in fatal fatigue destruction. To improve safety and the performance, vibration reduction technologies are indispensable to mechanical structures. Vibration reduction technologies can be roughly classified into two types: passive vibration control (PVC) and active vibration control (AVC). AVC systems introduce actuators, sensors, and control theories into vibration control systems and reduce vibrations of controlled objects by actively inputting control forces or changing inherent parameters via external power sources based on feedback signals. A significant virtue of AVC is its control performance: compared with PVC, AVC exhibits much superior performance. In AVC system design, one of the most important points is which feedback control law to use. Controller design of AVC is important not only for control performance but also for implementation aspect such as development cost. To take advantage of the virtue of AVC's good vibration attenuation performance exhibited in various systems, proper selection of control law is indispensable. Excessive complexity of controller design and control system itself imposes huge development costs, diminishing the practicability of AVC.

In general, model-based control (MBC) technique is the dominant technique for advanced AVC systems. The virtue of model-based AVC is that a controller exhibiting good performance can be obtained in a systematic manner using advanced MBC theories proposed since the modern control era. Focusing on such an advantage, many studies targeting model-based AVC have been conducted. However, model-based controller design is costly and burdensome due to the modeling procedure of actual controlled objects. Moreover, a control system based on the model of the actual controlled object is fragile to modeling errors, which always exist between the physical system and the corresponding model, and changes in controlled objects. Note that even model-based robust control and adaptive control sometimes fail due to modeling errors if there are mismatches between the prior uncertainty modeling assumptions and real-word conditions because these methods stand on the assumption (i.e., model) of the uncertainty.

To overcome these problems, several model-free control (MFC) strategies have been examined. Nevertheless, the existing MFC methods have several difficulties such as complicated control system design procedures and lack of systematic approaches to define control actions. Such difficulties cancel out the virtue of MFC, namely, the simplicity of not needing mathematical models of actual controlled objects, significantly reducing its practicability. Therefore, conventional MFC mentioned above essentially cannot solve the problems of MBC and is difficult to implement in practice. For this reason, in the AVC field, conventional MFC is not suitable for replacing MBC.

The main contribution of this study is the development of a simple and practical model-free AVC strategy applicable to various vibration problems in mechanical systems. In this study, an actuator and sensor for obtaining measured outputs are assumed to be mounted directly to a damping point of the actual controlled object. The actuator is assumed to be modeled as a single-degree-of-freedom (SDOF) system. Moreover, upper and lower frequencies of the controlled frequency band, where the vibrations to be reduced occur, are assumed to be known. Note that the controlled frequency band is very important plant information but not a mathematical model of an actual plant. Specifically, the contribution of this study consists of the following consecutive parts:

First, a virtual controlled object (VCO), which is an SDOF structure, is defined between the actuator model and an actual controlled object. The target vibration at the damping point of the actual controlled object is indirectly suppressed by controlling the VCO. The design condition for the VCO is derived to realize the indirect vibration suppression. A state equation to design a model-free vibration controller is obtained by using a 2-DOF system composed of only the actuator and the VCO: this state equation represents a low-order linear time-invariant system. The model-free vibration controller is designed by applying mixed H_2/H_∞ control theory, a traditional model-based robust control theory, to the 2-DOF plant. The model-free AVC based on the VCO (VCO-MFC) has a much simpler design process than conventional MFC schemes because it can employ systematic state-space based MBC theories after the introduction of the VCO. Obviously, VCO-MFC is superior to model-based AVC in that VCO-MFC does not require mathematical models of actual controlled objects. The vibration suppression performance of the proposed method is examined by vibration control simulations and experiments. The experimental results reveal that VCO-MFC has strong robustness to changes in actual controlled objects.

Second, VCO-MFC considering parameter uncertainties of the actuator is proposed. In this study, the stiffness and damping of the actuator are assumed to have uncertainties since exact values are generally far more difficult to obtain than for the mass (large modeling errors and individual differences of the mass of the actuator are quite rare because the mass can be easily measured). The actuator's parameter uncertainty is quantitatively modeled. The effects of the actuator uncertainty are evaluated in the 2-DOF system of the actuator and the VCO from the viewpoint of the small-gain theorem, constructing a generalized plant to design VCO-based MFC with robustness to the actuator uncertainty. A VCO-controller considering the actuator uncertainty is designed using linear H_∞ control theory, one of the most successful robust control theories, and the generalized plant. The robustness to actuator uncertainties and vibration suppression performance of the proposed controller are examined by simulations and experiments. Moreover, to improve the control performance, another VCO-MFC method considering the actuator uncertainty is developed based on sliding mode control (SMC) theory, verifying its superiority to linear H_∞ synthesis based VCO-MFC. The actuator often has the parameter uncertainties due to aging and individual deference. Such uncertainty significantly affects the control performance and closed-loop stability of VCO-MFC since this MFC strategy utilizes the actuator model for model-free controller design, although VCO-MFC does not require mathematical models of actual objects. Accordingly, consideration of the actuator uncertainty in VCO-MFC is indispensable for implementation in practice. The simple state equation for controller design via the VCO-MFC framework enables compensations of the uncertainty based on traditional model-based robust control theories such as H_∞ synthesis and SMC, clearly showing the simple and systematic manner of the design of VCO-MFC.

Third, the controller tuning problem in VCO-MFC is addressed. After the introduction of the VCO, VCO-controllers are designed in the same way as in MBC, implying that there are some tuning parameters to be determined by designers (e.g., constant weighting matrices to design the linear quadratic optimal regulator (LQR)). These tuning parameters are usually determined by trial-and-errors through simulations using exact actual plant models and experiments using the actual plant itself, imposing a heavy burden on designers. Therefore, this study proposes a novel parameter tuning procedure for VCO-MFC. Focusing on the strong robustness of the VCO-MFC system to characteristic changes in the actual controlled object, the proposed method utilizes a designer-defined SDOF structure called a reference controlled object (RCO) instead of mathematical models of actual objects. The RCO is designed so as to share the controlled frequency band with the actual controlled object. An offline iterative tuning procedure is developed based on vibration control simulations with the RCO and the simultaneous perturbation stochastic approximation (SPSA) method. SPSA is an optimization algorithm, and is employed in this study because of its high calculation efficiency. The control performance of the VCO-controller tuned by the proposed method is compared with that tuned by manual trial-and-errors, and exhibits the same performance. The proposed tuning procedure can automatically determine appropriate parameter values for the VCO-controller due to SPSA. Thanks to the RCO, this method does not require mathematical models of actual controlled objects, that is, this tuning procedure is also model-free. Moreover, the vibration control performance due to the VCO-controller tuned by the proposed method is at the same level as ones tuned via conventional trial-and-errors. Consequently, the proposed tuning method is quite simple and can significantly reduce the burden on designers.

Finally, an adaptive VCO-MFC technique is developed by combining the VCO-based LQR with a novel online controller tuning mechanism. Conventional VCO-MFC tuned for some controlled object may not provide the best performance for other controlled objects which is different from the structure for tuning. This is because conventional VCO-MFC is designed without using mathematical models of the actual controlled object; there may be some room for the improvement of control performance for each specific object unless the controller is retuned for each of them (although the RCO- and SPSA-based offline tuning technique can achieve fairly good performance, it is not always the best for actual objects). To overcome this shortcoming, the online self-tuning mechanism is introduced to the VCO-based LQR. The online tuning scheme is based on SPSA and measured outputs from the actual plant. While the control system is working, the online tuning algorithm ongoingly updates the VCO-controller according to the control result (i.e., measured outputs from the actual plant), adapting the controller to each controlled object and improving the vibration suppression performance. The controller fitting the given controlled object is searched online based on SPSA. The proposed self-tuning technique is constructed by utilizing only measured outputs and the SPSA algorithm. Therefore, the resulting adaptive VCO-MFC system is model-free. The measurement-based tuning enables improved control performance according to vibration characteristics of each controlled object. The control performance of the proposed adaptive VCO-MFC scheme is compared with that of conventional

VCO-MFC via vibration control simulations with various controlled objects including time-varying properties, and outperforms the conventional one.

The proposed model-free AVC, namely VCO-MFC, has virtues of both MBC and MFC: it has the clear and systematic controller design of MBC because matured MBC theories can be applied after the introduction of the VCO; it has the quite simple development process and strong robustness to characteristic changes in the actual controlled object because of the model-free framework. Moreover, the practicability of VCO-MFC is enhanced by the offline parameter tuning strategy and the online adaptive self-tuning mechanism. Note that the whole of the proposed control system development in this study is totally model-free. Therefore, the model-free AVC strategies proposed in this study can be applied to various vibration control problems as long as the abovementioned assumptions hold, while the design and implementation are quite easy, simple, and low-cost. Consequently, this study provides a novel and powerful method to solve various vibration problems in mechanical systems.

In addition, the proposed control methodologies also make academic contributions from the viewpoint of not only practicality method but also a control-theoretic perspective. This is because VCO-MFC utilizes MBC theories to design a controller although this method itself is model-free: VCO-MFC can be viewed as a novel control system architecture which bridges the gap between MBC and MFC.