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Experimental verification of a real-time tuning method of a model-based controller by perturbations to its poles

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A B S T R A C T

Model-based controllers with adaptive design variables are often used to control an object with time-dependent characteristics. However, the controller's performance is influenced by many factors such as modeling accuracy and fluctuations in the object's characteristics. One method to overcome these negative factors is to tune model-based controllers. Herein we propose an online tuning method to maintain control performance for an object that exhibits time-dependent variations. The proposed method employs the poles of the controller as design variables because the poles significantly impact performance. Specifically, we use the simultaneous perturbation stochastic approximation (SPSA) to optimize a model-based controller with multiple design variables. Moreover, a vibration control experiment of an object with time-dependent characteristics as the temperature is varied demonstrates that the proposed method allows adaptive control and stably maintains the closed-loop characteristics.

1. Introduction

Improved control performance is required to realize smaller and more accurate mechanical systems. Consequently, numerous methods have been developed to actively control performance. One such method is PID control, which is based on accumulated knowledge and model-based control. An advantage of model-based control methods is that they efficiently control performance, but they have limited applicability. This limitation is due to multiple reasons, including model construction, complex theories used to derive the model, modeling accuracy, and practical factors such as reasonable calculation costs and time-dependent characteristics of the controlled object. Over time, these limitations degrade the control property, inhibiting successful deployment of model-based controllers.

Control system tuning theories have been proposed to overcome the aforementioned limitations [1]. These theories are often complex. For example, self-tuning regulators (STRs) automatically classify and tune unknown parameters of an object to refine the control parameters. STRs have employed the minimum variance criterion [2], closed-loop poles [3], and the model reference adaptive control (MRAC). MRAC, which logs errors relative to a reference to adjust the control parameters, has been used to estimate non-modeled hysteresis [4]. The above studies assume that the optimization problem is a parameterization issue between the closed-loop system and the reference model. Although a few studies on simple concepts like PID control do not employ a mathematical model or a complicated theory, simple models are rare for model-based

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controllers. In addition, controller-tuning approaches have been actively investigated in the field of nonlinear system control. Both a neural network controller [5] and a fuzzy controller [6] have been applied to adaptively suppress the vibrations of a flexible robotic manipulator system. An adaptive fuzzy output-feedback control method was presented by combining back-stepping design together with fuzzy systems' universal approximation capability [7]. Boundary control has been employed to control the vibrations in nonlinear systems, including an industrial moving strip system [8], a nonuniform gantry crane [9], and flexible wings of a robotic aircraft [10]. Furthermore, control strategies for nonlinear systems have been developed based on a near-optimal control scheme [11] and a novel iterative two-stage dual heuristic programming [12]. However, from the viewpoint of an adaptive algorithm with a high calculation efficiency implemented in a real-time controller mounted in an actual system, the practicability of the adaptive control approach for time-varying systems has yet to be experimentally validated.

The simultaneous perturbation stochastic approximation (SPSA) algorithm has been employed as an adaptive control method [13–15]. It is applicable to complex optimization problems. The SPSA algorithm is based on a highly efficient gradient approximation, which measures the loss function twice regardless of the number of parameters. Consequently, its algorithm is independent of the number of parameters. SPSA has been used to estimate the parameters in system identification [16–18]. Self-tuning of the PID control parameters [19–21], a neural network [22], and online optimization of NOx soft sensors for the aftertreatment of diesel engines [23]. To implement the adaptive algorithm based on SPSA in a real online control system, the calculation time must be taken into account because SPSA uses an iterative optimization process, even though the calculation efficiency of SPSA is high.

We previously applied the SPSA algorithm to an online adaptive optimization of PID parameters of a PID controller [20], diesel engine control with an adaptive PID controller [21], and an online parameter tuning of a NOx soft sensor used in a diesel engine [23]. Currently, mass production uses gain scheduling of map-based PID control, where each gain is tuned at various operational points. Map calibration has many drawbacks, including time-consuming tuning, difficulty tuning during transient operations, and problems adapting to individual variations in engine characteristics. In [21,23], the effectiveness of SPSA was demonstrated by comparing the results from SPSA to those obtained by a traditional adaptive approach based on map-based gain scheduling with respect to various operational points of the diesel engine. The SPSA adaptive approach is suitable for systems like an automotive engine where the controlled object is a time-varying system with gradual and continuous characteristic variations. Furthermore, other factors, including aging of the mechanical system and environmental condition (e.g., temperature) changes, cause gradual and continuous characteristic variations in the system as well as influence the mechanical properties such as rigidity and elasticity. Consequently, it is important that the controller maintains control performance and stability against these kinds of characteristic variations.

Previously, we simulated vibration control using the finite element method (FEM) to assess the effectiveness of the proposed tuning method for an object with time-dependent characteristics [24]. In this study, we propose an intuitive tuning method where the poles of a model-based controller are refined to maintain the performance. The poles dominate the dynamic characteristics of the controller and deeply influence the performance and the stability of the closed-loop control system [16,25]. The controller is designed using a model of the object. The time-dependent variations are compensated by perturbing the controller's poles to tune the gain and the frequency of the controller. Then SPSA updates the adaptive parameters in real-time. This study experimentally evaluates the fundamental features of the proposed method because experimental verification is important to confirm the practical applicability of the present adaptive control strategy. Specifically, the characteristics of a vibration-controlled object are examined as a function of temperature fluctuations. The proposed method allows adaptive control and stably maintains the closed-loop characteristics.

2. Controller tuning system

2.1. Tuning method

The controller's poles are used as design variables because they influence both the stability and the performance. The real (imaginary) part of the poles governs the gain (frequency) of the controller. The state-space equation used to represent a model-based controller is written as

$$\begin{cases} \dot{\boldsymbol{x}}_c = \boldsymbol{A}_c\boldsymbol{x}_c + \boldsymbol{B}_c\boldsymbol{y}_2 \\ \boldsymbol{u} = \boldsymbol{C}_c\boldsymbol{x}_c + \boldsymbol{D}_c\boldsymbol{y}_2 \end{cases} \tag{1}$$

where $\boldsymbol{y}_2$ is the observed output, $\boldsymbol{x}_c$ is the controller's state variable, and $\boldsymbol{u}$ is the control input. The poles of the transfer function are represented by the corresponding eigenvalues of system matrix $\boldsymbol{A}_c$. Perturbing the elements of matrix $\boldsymbol{A}_c$ tunes the poles. In an nth order system, $\boldsymbol{A}_c$ has $n \times n$ elements. To decrease the calculation costs, the controller state equation is transformed into the diagonal canonical form. In this form, the poles, which are the design variables, are denoted as the diagonal elements of system matrix $\tilde{\boldsymbol{A}}_c$.