Fuzzy Estimator for Gain Scheduling and its Application to Magnetic Suspension

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Abstract

The external force disturbance is the one of the main causes that deteriorate the performance of the magnetic suspension. Thus, this paper develops a fuzzy estimator for gain scheduling control of magnetic suspension systems suffering from the unknown disturbance. The proposed fuzzy estimator computes the disturbance injected to the plant and the gain scheduled controller generates the corresponding stabilizing control input associated with the estimated disturbance. In the simulation results we confirm the novelty of the proposed control scheme comparing with the other method using a feedback linearization.

1. Introduction

The gain scheduled controllers proved to be a successful design methodology have been developed by many researchers [1]-[3]. Furthermore, in order to improve its regulation performance for fast scheduling parameters, [4] and [5] have proposed extended control laws using the derivative information of the time-varying parameter. Nowadays, H_∞ control theory has become an effective design methodology in tracking the problem of stability and performance robustness under plant uncertainties. Thus, many researchers have been interested in the fusion technique of H_∞ synthesis and gain scheduling [6]-[8]. However, since the stabilizing control gains of all the gain scheduled controllers mentioned above are driven by the measured scheduling parameter, these developed controllers become unavailable for the unmeasurable scheduling parameter, which should be estimated and engaged appropriately.

In spite of the high nonlinearity and the unstable dynamics, the magnetic suspension systems have been researched with merits that the absence of contact reduces noise, component wear, vibration, and maintenance costs. It is well known that the external force disturbance and mass uncertainty dominantly deteriorate the quality of system performance. In order to solve such problems, the classical state feedback control with pole-placement has been applied into the linearized model corresponding to a specific operating condition [9]. However, since the operating condition changes according to the disturbance and the uncertainty, the local controller couldn't achieve the satisfactory performance in the global operating points. Nonlinear control schemes have also been reported in the literature such as the gain scheduling [10] and the feedback linearization methodology [11] [12]. However, the force disturbance estimator [10] utilized the exact inverse dynamic of the given plant model using the derivative information of the state vectors. Thus, it was confined to solve the regulation problem only when the exact derivative information of the scheduling parameter is available in the considered plant. Moreover, though the feedback linearization canceled the nonlinear nature in the magnetic suspension, it also had a limitation to tackle the unknown parameter variation and/or disturbance [11] [12]. Most recently, the self-tuning controller was developed for the unknown mass variation and showed improved performance [13]. However, the problem of determining an adequate adaptation rate and combining the cost functions still remained so as to apply to the general nonlinear plants.

The proposed fuzzy-estimated gain scheduled controller in this paper consists of the fuzzy estimator and the gain scheduled controller. The fuzzy estimator tracks the unknown scheduling parameter (external force disturbance) in the closed-loop control system and the stabilizing gains of the gain scheduled controller are appropriately scheduled according to the estimated disturbance. The proposed control scheme has several advantages over the related literature. The developed fuzzy estimator does not require the time derivative of the state vector that induces noise in practice. Moreover, the fuzzy estimator computes the adaptation rate and combine the adaptation laws in the manner of achieving the control objective. Thus, it is applicable to the various nonlinear plants in company with the gain scheduling methodologies.

2. Gain scheduled controller

The single-axis magnetic suspension in Fig. 1 is modeled by the following nonlinear dynamic equation [9]

$$\begin{aligned} \dot{x} &= f(x,u,f_d) = \begin{bmatrix} x_2 \\ -\frac{C}{4m}(\frac{x_3}{x_1})^2 + g + \frac{f_d}{m} \\ \frac{x_2 x_3}{x_1} - \frac{2R}{C}x_1 x_3 + \frac{2x_1}{C}u \end{bmatrix} \\ y &= h(x) = x_1 \end{aligned} \quad (1)$$

with $C = \mu_o A N^2$ where x_1 is the vertical air-gap, x_2 is the vertical velocity, $x_3 = i(t)$ is the magnet current, $u = v(t)$ is the applied voltage, f_d is the external force disturbance, $m = 15kg$ is the total mass, $N = 2000$ is the number of turns of the coil wrapped around the magnet, $A = 0.0012m^2$ is the pole area, $\mu_o = 4\pi \times 10^{-7} H/m$ is the permeability of free space, $R = 8\Omega$ is the coil resistance, $g = 9.8m/sec^2$ is the gravity constant, and r_d is the reference air-gap. Defining the disturbance f_d as the scheduling parameter, the smooth