CONTROL OF A MAGNETICALLY LEVITATED TABLE FOR VIBRATION ISOLATION

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ABSTRACT

This paper experimentally verifies an approach to designing a controller for vibration isolation of a magnetically levitated table. A new subspace-based method for closed-loop system is applied to identifying a state-space model of the system with the measured input/output data. The H_∞ theory is used to design a controller based on the state-space model. This controller aims to isolate the table from any disturbance vibrating the base. The designed H_∞ controller achieves better damping performance than that of the PID controller for almost all frequencies.

INTRODUCTION

Vibration isolation is an important topic in a lot of engineering fields such as manufacturing a semiconductor or micro-scale observation using an electron microscope. Vibration-proof rubber, coil spring, or air bearings are used for passive vibration isolation. However, those passive methods are not yet able to achieve a working environment required by the preceding engineering fields. As an alternative to the passive methods, magnetic bearings are used for active vibration isolation[1-3]. A table is levitated by an active magnetic bearing and isolated from any external vibration. This system is expected to achieve good vibration isolation when compared with the preceding passive methods. Traditional controllers for magnetic bearings are designed to regulate the relative displacement between a levitated object and a base; those bearings are fixed on the base. In order to isolate the table from external disturbance, we have to redesign a controller to regulate the absolute displacement of the levitated table in an inertial coordinate system. Moreover, it would be necessary to obtain a precise model of the controlled system in order to design a good controller. One of the excellent ways to get a precise model would be the one based on the input and output data of the controlled system. From this philosophy, many methods have been developed to the system identification based on the input and output data. In particular, subspace identification methods[4] have been proven to be a valuable alternative to classical prediction-error methods. Unlike the classical methods they do not suffer from such problems as a priori parameterizations, initial estimates and nonlinear optimizations. Subspace methods are used to find a state-space model for the present system from input-output data. Since this system is essentially unstable, we first design a PID controller to levitate the table and then add a random signal to the controller inputs in order to excite the system for a frequency region of interest. So, the system identification is made owing to closed-loop data of the inputs and the outputs.

This paper experimentally verifies an approach to designing a controller for vibration isolation of a magnetically levitated table. A new subspace-based method for closed-loop system is applied to identifying a state-space model of the system with the measured input/output data. Since this system is essentially unstable, a PID controller is first designed to levitate the table using the relative displacement of the table to the gap. A random signal is then added to the controller inputs in order to excite the system for a frequency region of interest. The outputs of acceleration and displacement sensors and the total controller inputs are measured during the excitation tests. The measured data are identified with a state-space model by the subspace-based method. The H infinity theory is used to design another controller based on the state-space model. This controller aims to isolate the table from any disturbance vibrating the base. The absolute displacement of the table is kept being constant by the controller. Experimental results show the designed controller successfully reduces a vibration level of the table to 10 % of that of the laboratory floor.

HARDWARE DESCRIPTION

A table (a rectangular plate) is levitated by electromagnets in order to isolate it from external disturbance such as floor vibration. Here the system configuration is shown in figure 1. The system contains a table to be isolated from any disturbance, three electromagnets, and a base; the base supports those actuators and table and fixed on the floor of our laboratory. The table motion is vertically limited to 0.35 mm, that is, gap width of the electromagnetic actuator. The electromagnetic actuators are able to generate an attractive force upward and downward in order to levitate the table. An eddy-current-type displacement sensor is built in each electromagnetic actuator to measure the relative displacement of the table to the floor, neglecting mechanical flexibility of the base. Moreover, three acceleration sensors are located on the table to measure the table motion in an inertial coordinate system.

Here we present the control system for the preceding sensors and actuators. A digital controller is implemented on a digital signal processor (DSP) built in a PC. All the sensor outputs are amplified, passed through an anti-aliasing filter, and put into the DSP through an analog-to-digital converter (16-bit resolution). The controller input is calculated by the digital controllers and put out of the PC through a digital-to-analogue converter (12-bit resolution). Moreover, the input is passed through a smoothing filter and a Pulse-Width-Modulation (PWM) circuit and converted into an electric current driving the electromagnetic actuator.

IDENTIFICATION SCHEME

Subspace methods are used to find a state-space model for the present system from input-output data. The control system for the levitated table is essentially unstable if it is in open loop, although the clearance of the magnetic bearings would limit the table motion. Since we assume a state-space model should describe the system, input and output data are necessary for the identification such that the table moves not contacting the clearance limits. Thus, we first design a PID controller to levitate the table in that way and then add a random signal to the controller inputs to excite the system for a frequency region of interest. In other words, the system identification is made owing to closed loop data of the inputs and the outputs.

The configuration of the inputs and the outputs for system identification is shown in Figure 2. If the open-loop plant is given by the state-space realization, $P(z) = C(zI - A)^{-1}B + D$, the system is written in a state-space form:

$$x_{k+1} = Ax_k + Bu_k + w_k, \quad y_k = Cx_k + Du_k + v_k \tag{1}$$

The controller equations are:

$$x^c_{k+1} = A_c x^c_k + B_c y_k, \quad u_k = r_k - C_c x^c_k - D_c y_k \tag{2}$$

where the controller transfer matrix is given by

$$K(z) = D_c + C_c(zI_{n_c} - A_c)^{-1}B_c \tag{3}$$

Here, x_k and x^c_k are an n- and n_c-dimensional state-vector, respectively; r_k is a random signal to be used to excite the levitated table; v_k and w_k are unobserved zero-mean white-noise vector sequence. The problem is now to find the system matrices, A, B, C, and D, from the input and output data, u_k's and y_k's when the system is excited by the random signal r_k.

In general, a control system applied with magnetic bearings are described by

$$x_{k+1} = Ax_k + B(u_k + d) + w_k, \quad y_k = Cx_k + D(u_k + d) + v_k \tag{4}$$

where d is a step disturbance such as the gravity force and the static magnetic force due to the biased electric current. So it would be necessary to eliminate the effects of the step disturbance from equation (4). When a PID controller is used to levitate the table, the disturbance is equivalent to the steady-state controller inputs except for the sign, that is, $u_\infty = -d$. Therefore, once the steady-state controller inputs are measured, the step disturbance is identified with it. Equation (4) is rewritten as

$$x_{k+1} = Ax_k + B\tilde{u}_k + w_k, \quad y_k = Cx_k + D\tilde{u}_k + v_k \tag{5}$$

where $\tilde{u}_k = u_k - u_\infty = u_k + d$. Since equation (5) is equivalent to equation (1), the closed-loop subsystem identification algorithm[8] is then applied to the data set $\{y_k, \tilde{u}_k\}$. The algorithm can be used to find the system order and the system matrices up to within a similarity transformation if the input/output data and the Markov parameters of the controller are given.

CONTROLLER DESIGN

The open-loop plant is identified with a state-space model as described in the preceding section, and the model is used to design an H∞ controller. The plant is augmented as in the standard manner of H∞ control theory:

$$\begin{bmatrix} z \\ y \end{bmatrix} = \begin{bmatrix} W_u u \\ W_y y \\ y \end{bmatrix} = \begin{bmatrix} o & W_u \\ W_y W_d & W_y P \\ W_d & P \end{bmatrix} \begin{bmatrix} d \\ u \end{bmatrix} \tag{6}$$

where W_u, W_y, and W_d are frequency-weighting functions associated with u, y, and d, respectively. An H∞ controller aims to minimize the H∞ norm of the transfer function from d to z. Furthermore, the augmented plant is modified as describe in Reference [9] so that the designed controller is of an integral type.

EXPERIMENTAL RESULT

The subspace method is used to identify the control system for the table levitated by the electromagnetic actuators. The method is implemented in MATLAB, whereas C language is used to write all the programs for controlling the table system. An M-sequence (maximum length null sequence) signal of 15th order is used to excite the table as a random input r_k. This M-sequence signal is generated by a PC and keeps its power spectral density constant up to Hz. When the levitated table is excited by the random signal, the input and output data (3 inputs and 3 outputs) are sampled 9000 times into the PC through an analog-to-digital converter; the sampling rate is 3000 Hz. The closed-loop subspace method is applied to the input/output data. Figure 3 shows some typical transfer functions of the open-loop plant, which are computed by the estimated system matrices; the system order is 13th. The plant contains three unstable poles on the real axis of the complex plane, which corresponds to a feature of linear dynamics of an electromagnet. An H_∞ controller is then designed as described in the preceding section. Figure 4 shows three typical transfer functions of the designed controller; the order of the controller is 22nd. All the controller transfer functions are of an integral type as shown in the figure. In order to evaluate the controller performance, the largest singular-value of the transfer functions between z and d is computed for the two controllers, PID and H_∞. Figure 5 shows frequency responses of the largest singular-value. It is shown in the figure that the designed H_∞ controller achieves better damping performance than that of the PID controller for almost all frequencies.

CONCLUSION

This paper experimentally verifies an approach to designing a controller for vibration isolation of a magnetically levitated table. A new subspace-based method for closed-loop system is applied to identifying a state-space model of the system with the measured input/output data. The H_∞ theory is used to design a controller based on the state-space model. This controller aims to isolate the table from any disturbance vibrating the base. The designed H_∞ controller achieves better damping performance than that of the PID controller for almost all frequencies.

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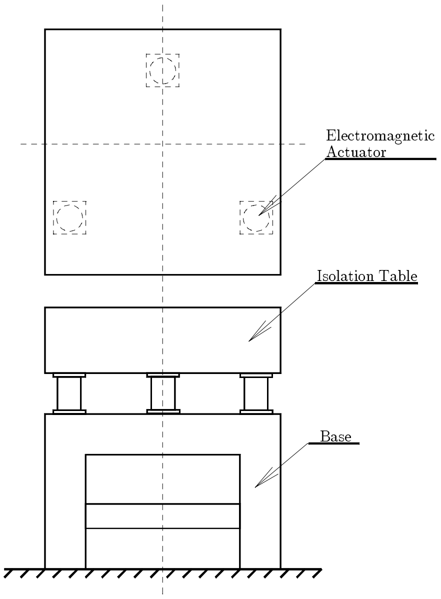


FIGURE 1: Vibration isolation system using electromagnetic actuators

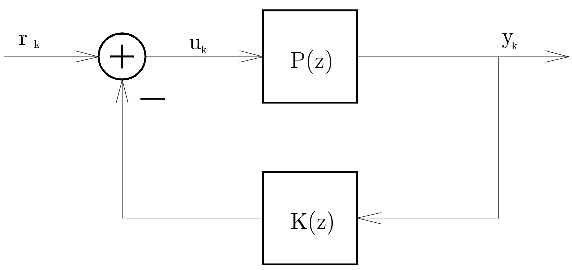
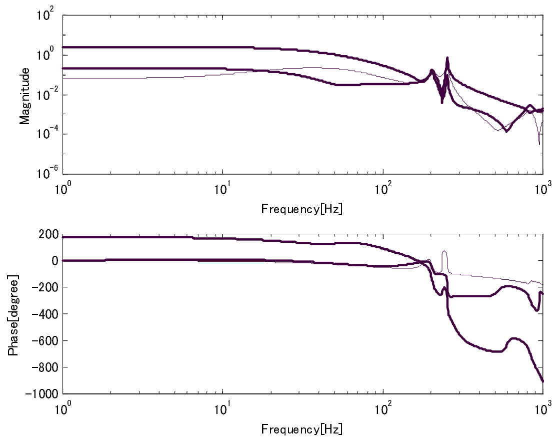


FIGURE 2: Block diagram for identification tests



FGIURE 3: Transfer Functions of the Open-Loop Plant Using the Estimated State-Space Model

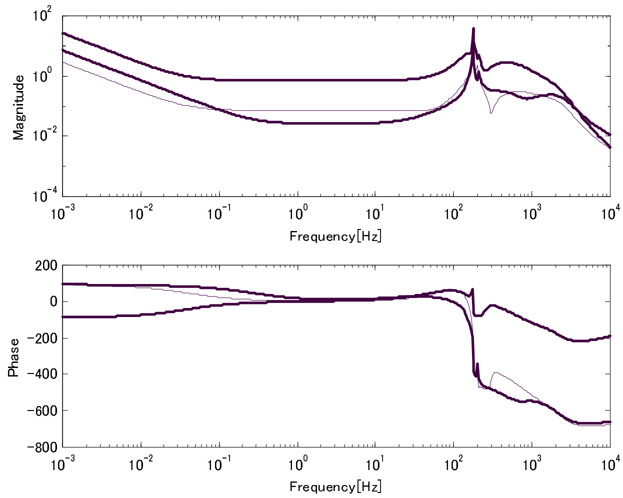


FIGURE 4: Typical Controller Transfer Functions

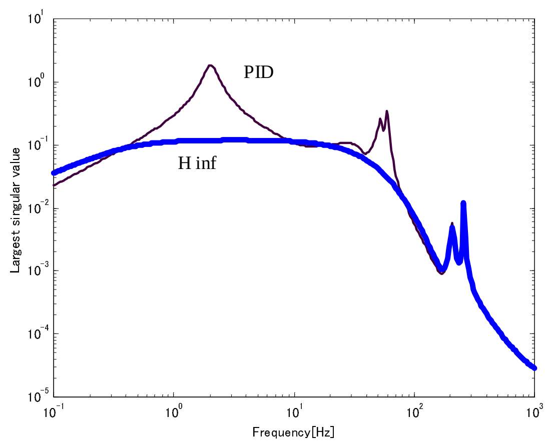


FIGURE 5: Comparison of the largest singular-value between the two controllers