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Fuzzy control design of a magnetically actuated optical image stabilizer with hysteresis compensation

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A fuzzy controller (FC) is designed for a magnetically actuated optical image stabilizer (OIS) in order to suppress the vibrations caused by hand shakings and hysteresis. To this end, the dynamic model of the OIS with consideration of hysteresis is first established, along with assuming the hand-shaking vibration as sinusoidal excitations. It is clearly shown that with capability of continuing parameter tuning, the FC is superior to the conventional PID for vibration suppression.

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I. INTRODUCTION

An optical image stabilization (OIS) system is widely implemented into the digital still cameras for mobile devices[1–3] in order to improve blurred images. Previous works[4,5] were devoted to downsize the OIS system using the optimization method, genetic algorithm (GA), while keeping sufficient magnetic actuation force. This leads to nonuniformity resided in magnetic flux density and actuation and a hysteresis relation between the applied voltage to OIS and actuated motions. The OIS inevitably exhibit an hysteretic phenomena while actuated to compensate the external harmoniclike vibration.

A dynamic model considering hysteresis effect to predict the displacement of the lens is first established via Preisach model.[6] A fuzzy controller[7,8] (FC) is next designed to perform precision positioning of the OIS with a feedforward compensation loop to compensate the identified hysteresis and a feedback loop to overcome shaking vibrations. It can be clearly shown based on simulations that with capability of continuing parameter tuning, the FC is superior to the conventional PID for vibration suppression.

II. SYSTEM MODELING

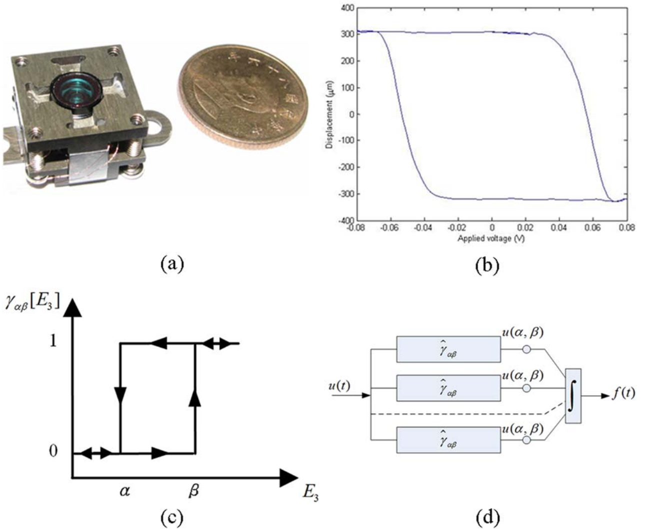
The mechanism of the OIS system is mainly composed of horizontal and vertical positioning platforms carrying image sensor; permanent magnets, yokes, and VCMs for actuation. Figure 1(a) shows the photography of the proposed OIS system. Experiment is conducted first to investigate the actuation performance of the OIS system. It is found that the hysteresis phenomenon, as shown in Fig. 1(b), is mainly caused by nonuniformity of magnetic field distribution and magnetic hysteresis.

A. Preisach model for hysteresis

The Preisach model,[6] is adopted herein to prescribe the force term $f(t)$, which analogies the hysteresis behavior to a force term. The force term $f(t)$ can be expressed as a function of the corresponding applied electric field E by the integral,

$$f(t) = \int\int_{\alpha \geq \beta} \mu(\alpha,\beta)\gamma_{\alpha\beta}[E(t)]d\alpha d\beta, \qquad (1)$$

where $\gamma_{\alpha\beta}$ is the elementary operator as shown in Fig. 1(c), which is also a function depending on the electric field E, a function of applied voltage in OIS. $\gamma_{\alpha\beta}$ varies from 0 to 1, emulating an on-off to distinguish the change in input E either in ascending or descending for reflecting the hysteresis effect. Also seen from Fig. 1(d) is that $\mu(\alpha,\beta)$ is a function



(a) (b)

(c) (d)

FIG. 1. (Color online) (a) Photograph of the proposed OIS. (b) Experimental displacement hysteresis. (c) Preisach model of hysteresis. (d) Elementary hysteresis operator.

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of α and β, so-called the Preisach function, which captures a variety of different hysteresis characteristics with given values of α and β. $\mu(\alpha,\beta)$ is in fact the corresponding switching values of E between ascending and descending processes.

B. Magnetic force

The magnetic force is considered as an external force and will be interacted with the hysteresis force term. The electromagnetic force F_e could be, therefore, obtained by

$$F_e = N \times i \times l_w \times B_g = N \times \frac{VA}{\rho L} \times l_w \times B_g, \tag{2}$$

where N is the number of coil winding, i is the applied current to the voice coil, l_m is the effective length of the voice coil, and B_g is the magnetic flux density. Furthermore, V, A, ρ, and L are the applied voltage, the cross-sectional area of the coil, the electric conductivity of coil, and the total length of the coil, respectively.

C. Dynamic modeling

The structure of OIS actuator in Fig. 1 could be considered as a lumped model, where the lens/holder is integrally considered as a mass and the springs are the stiffness for suspension. Taking the aforementioned hysteresis effects and magnetic force into account, the equation of motion for the OIS actuator can be expressed by

$$\mathbf{M}\ddot{\mathbf{q}} + \mathbf{K}\mathbf{q} = \mathbf{F_e} - \mathbf{f}, \tag{3}$$

where $\mathbf{M}$ and $\mathbf{K}$ are the mass and stiffness matrices, respectively. Furthermore, the vector $\mathbf{q}$ denotes the degrees of freedom (DOFs) of the OIS actuator, which are along vertical and horizontal directions of the lens holder motion. $\mathbf{F_e}$ is a vector, which consists of the magnetic forces as shown in Eq. (2) in two moving directions. $\mathbf{f}$ is the predefined hysteresis force term, which is modeled by Eq. (1). Hence, the equation of motion of OIS actuator in two DOFs of the OIS be formulated as

$$\begin{bmatrix} m & 0 \\ 0 & m \end{bmatrix}\begin{bmatrix} \ddot{x} \\ \ddot{y} \end{bmatrix} + \begin{bmatrix} k_{1x}+k_{2x} & 0 \\ 0 & k_{1y}+k_{2y} \end{bmatrix}\begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} F_{ex} \\ F_{ey} \end{bmatrix} - \begin{bmatrix} f_x \\ f_y \end{bmatrix}, \tag{4}$$

where the m denotes the integral mass of the lens and its holder, k_{1x}, k_{1y}, and k_{2x}, k_{2y} represent the stiffness of the springs that connect the moving platforms and cellphone body in the x and y directions, respectively, F_{ex} and F_{ey} are the electromagnetic forces from the VCMs in the x and y directions, respectively, and the f_x and f_y are the hysteresis force terms. Due to the symmetric mechanism, the dynamic behavior is considered in single axis (DOF) only in this study. Therefore, an experiment through the frequency response is conducted for identifying the unknown parameters. One can obtain the stiffness of the actuator K through the known actuator mass m. In this study, the actuator mass M is 0.926 g and stiffness K is 52 588 N/m. With the two parameters in hands, the transfer function can be expressed by a second order lumped model,

$$G(s) = \frac{1}{0.926 \times 10^{-3}s^2 + 52\,588} + G_n(s), \tag{5}$$

where $G_n(s)$ denotes the system nonlinearity caused by aforementioned hysteresis and nonuniformity embedded in magnetic actuation forces.

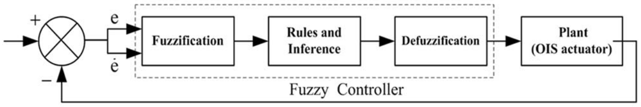

FIG. 2. Block diagram of FC.

III. DESIGN OF FUZZY CONTROLLER

The advantages of FC method herein are using language variables to describe the characteristics of system, thus able to overcome system nonlinearities: hysteresis and nonuniform actuation. The block diagram of applying FC to the OIS actuator is shown in Fig. 2.

A. Fuzzification

Based on the results of measured variables, the controller could then tune the output based on the predetermined fuzzy rules. In this study, the output signal u, input error e, and its differentiation $\dot{e}$ are considered as the variables. The FC system can be described with seven fuzzy values as follows: *NH*, *NM*, *NS*, *O*, *PS*, *PM*, *PH*, and use the same Gaussian membership functions. In this study, the range for output signal u is defined from −3 to 3, the range for input error e is defined from −0.5 to 0.5, and the range for input error differentiation $\dot{e}$ is defined from −1 to 1.

B. Fuzzy rule base and fuzzy inference

Since hand-shaking vibrations as sinusoidal excitations are considered in this study, the fundamental linguistic rules determine that output signal is large as input error or its differentiation is large. For the two inputs and one output in FC system for individual actuation along vertical and horizontal directions, the fuzzy rule base can be designed as shown in Table I, where the 14 fuzzy rules $R_1 \sim R_{14}$ for the actuator in antishake mobile system can be fostered.

TABLE I. Fuzzy rule base of FC system.

	e	u		$\dot{e}$	u
R_1	*NH*	*NH*	R_8	*NH*	*NH*
R_2	*NM*	*NM*	R_9	*NM*	*NM*
R_3	*NS*	*NS*	R_{10}	*NS*	*NS*
R_4	*O*	*O*	R_{11}	*O*	*O*
R_5	*PS*	*PS*	R_{12}	*PS*	*PS*
R_6	*PM*	*PM*	R_{13}	*PM*	*PM*
R_7	*PH*	*PH*	R_{14}	*PH*	*PH*

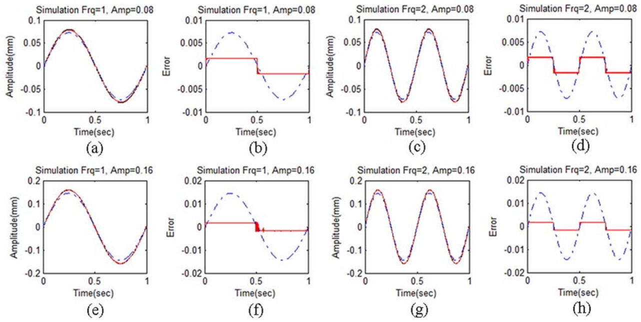

FIG. 3. (Color online) (a) The simulation results with Freq. = 1, Amp. = 0.08. (b) The error of results in (a). (c) The simulation results with Freq. = 1, Amp. = 0.16. (d) The error of results in (c). (e) The simulation results with Freq. = 2, Amp. = 0.08. (f) The error of results in (e). (g) The simulation results with Freq. = 2, Amp. = 0.16. (h) The error of results in (g).

C. Defuzzification

Having forged fuzzy reasonings, linguistic output variables need to be converted into numerical values. The subsequent defuzzification is an inverse transformation, which maps the output from the fuzzy domain back into the numerical domain. The center-of-area method is chosen to complete the job, which is often referred to as the center-of-gravity method because it computes the centroid of the composite area representing the output fuzzy variables.

IV. SIMULATION RESULTS

The hand-shake excitation is assumed harmoniclike due to the tilt angle range of ±2° caused by human holding hands while shooting pictures. Considering the effective focal length of a commercial lens is 4.84 mm, the compensation distance expected from OIS can easily be computed as 0.169 mm, which is obtained by the multiplication of focal length and tangential of tilt angle. Four kinds of periodic waves in sinusoids are considered as the desired compensation movement to eliminate the hand shaking.

Four simulations results are shown in Fig. 3. In Fig. 3(a), the red curve is the simulated result using FC, which is in the frequency of 1 Hz and designates 0.08 mm for the desired displacement amplitude. The blue line is the similar results using PID control. The error between sine wave and simulation line was shown in Fig. 3(b), which are 0.0017 and 0.0046 by using FC and PID control, respectively. Figure 3(c) shows the results with 0.15 mm for the desired displacement, while Fig. 3(d) shows the resulted errors. In terms of controller performance, the error should approach zeros to achieve a satisfactory vibration suppression. Note that the FC owns the superiority in terms of low displacement error. The areas of peak amplitude represent those close to the two edges of the OIS mechanism, where the lowest magnetic force occurs and hysteresis effect plays a role. This shows the significantly better improvement by the designed FC over PID for overcoming the nonuniformity of magnetic force between the yoke and VCM. Figure 3(e)–3(h) shows the same findings while the frequency of the desired displacement is increased to 2 Hz. The results also show the good expectation of magnetic hysteresis compensation. Table II summarizes the resulted errors by FC and PID where the superiority of FC is clearly seen.

TABLE II. Simulation errors by using FC and PID.

Frequency	Amplitude	Error of FC	Error of PID
1	0.08	0.0017	0.0046
1	0.16	0.0017	0.0092
2	0.08	0.0017	0.0046
2	0.16	0.0017	0.0091

V. CONCLUSIONS

In this study, the nonlinear phenomenon of hysteresis effect and the nonuniformity of magnetic force in the VCM for OIS are improved by a newly designed FC. It is found that the FC is superior to the PID in terms of eliminating the magnetic hysteresis phenomenon.

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