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Adaptive model-following control for slim voice coil motor type optical image stabilization actuator

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An autofocusing optical image stabilization actuator (AFOISA) will become standard equipment quickly in megapixel resolution mobile phone cameras (MPCs). A slim AFOISA composed of two orthogonal directions has been developed based on magnetic analysis and it is an effective solution to address image quality of a charged coupled device to compensate 10–20 Hz hand jitter in taking photos. However, environmental disturbance often occur irregular shake, such as when a photographer holds a MPC while walking or in a vehicle. Therefore, this paper develops an adaptive model-following control (AMFC) law including two proportional-integral-derivative controllers with position and speed feedback control, which is shown to be able to compensate for irregular shake of MPCs and to obtain fast response. Although irregular environmental shake cause parameter variation, an adaptation mechanism synthesizes an auxiliary input signal to assure that an AFOISA plant exactly behaves as a reference model. The time response by utilizing AMFC includes 30 ms settling time and 5 μm steady state error without any overshoot. Furthermore, a compensatory force can quickly cancel irregular disturbance. As a result, the present slim AFOISA satisfies the optical demands of MPCs. © *2008 American Institute of Physics.* [DOI: 10.1063/1.2835447]

I. INTRODUCTION

Recent advancement in autofocusing optical image stabilization actuators (AFOISAs) has fueled requirements from megapixel resolution mobile phone cameras (MPCs) with characteristics such as minimum power consumption, subminiature dimension, and low cost. No photographer can hold a camera steadily, since 10–20 Hz hand jitter is a biological phenomenon. Due to irregular shake by photographers or environment, lens movement causes focal image to blur. This problem worsens with slow shutter speed. Hence, optical image stabilization which detects movement of a camera body before taking a picture has been presented.[1,2] This structure stabilizes a corrective lens or an image sensor against camera shake in digital still cameras (DSCs). Since this concept appeared, there has been a dramatic increase of related digital products, such as single-lens reflex cameras, video cameras, and telephotolenses.

Digital and optical antishake have been two main approaches to compensating camera shake in DSCs recently.[3,4] Since an AFOISA is not amenable to shrink dimension, antishake technique of MPCs still stay in digital image compensation. Although piezoelectric actuators and shape memory alloy have been adopted[5] to shift an image sensor, they require higher power than a voice coil motor (VCM). Hence, a slim VCM-type AFOISA in a MPC (Refs. 6 and 7) is an effective solution to address focal image quality. MPCs with antishake technique will replace traditional DSCs in several years.

Conventional controllers of industrial motors focus on proportional-integral-derivative (PID). An adaptive model-following control (AMFC) law aims at counteracting system inaccurate modeling and load variation, and a reference model is usually chosen as a linear decoupled model. AMFC method has been adopted to overcome various external loads due to posture change when taking a picture.[8] Therefore, this paper develops an AMFC law including two PID controllers with position and speed feedback control, which is able to overcome irregular shake when taking pictures and improve dynamic performance.

II. MECHANISM OF AUTOFOCUSING OPTICAL IMAGE STABILIZATION ACTUATOR

The AFOISA, as shown in Fig. 1, has been designed with low power consumption and subminiature dimension.[6] Image blur due to hand jitter can be reduced effectively by using the present slim AFOISA mechanism. The mechanical structure of a slim AFOISA is equipped with a stationary
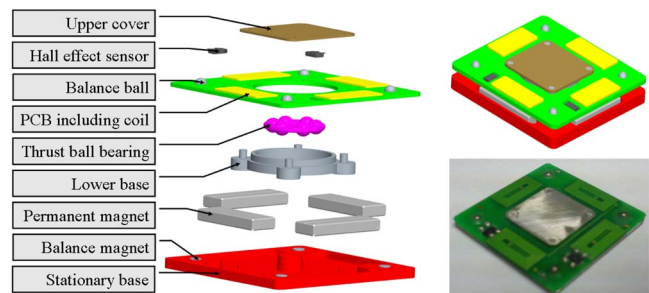

FIG. 1. (Color online) Structure of AFOISA in MPC.

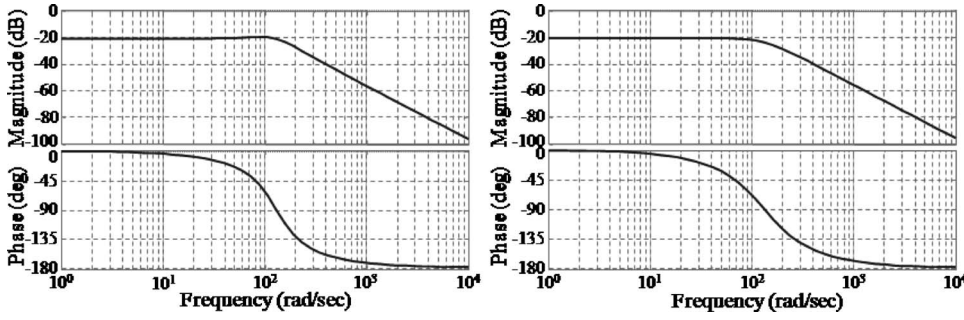a)Author to whom correspondence should be addressed. Electronic mail: hsingchengyu@itri.org.tw.

FIG. 2. Frequency responses of X and Y axes, respectively.

base and a moving part. Four permanent magnets are assembled on a stationary base to generate magnetic flux. A moving part consists of an upper cover, a printed circuit board (PCB) including four coils, a thrust ball bearing, and a lower base. Two opposite coils laid out on a PCB are connected in series to be a set. A slim AFOISA contains two coils and four permanent magnets to actuate a moving part in two orthogonal directions. To do so, two Hall effect sensors are utilized to track and to control the position of a moving part by detecting magnetic field magnitude. A slim AFOISA can be integrated in a subminiature dimension tightly and work together for precise position control of antishake in a MPC. The dimensions of the present slim AFOISA are 23.1 mm long $\times$ 23.1 mm wide $\times$ 3.1 mm high, and the net weight of the moving part is 1.12 g.

The movement range required by the present slim AFOISA depends on the system optics, which leads to 0.6 mm. Moreover, an equilibrium system includes four balance balls inserted in a PCB and four balance magnets mounted on a stationary base for maintaining an equilibrium position to avoid a maximum static friction at initial movement. Furthermore, a thrust ball bearing is installed between an upper cover and a lower base so that a moving part can move with respect to a stationary part without significant friction. A corrective lens or an image sensor can be mounted on an upper cover of the moving part. When photographers snap a shot, two angular rate sensors, also called gyrosensors, with low noise and high sensitivity detect pitch and yaw motion of a slim AFOISA in a MPC. Moreover, a corrective lens moves in vertical and horizontal directions to counteract hand jitter or environmental shake. While a driving current is applied to coils of a PCB, two coils generate Lorentz forces in two orthogonal directions. The driving current less than 5 mA is enough to actuate a moving part in a MPC. Therefore, the present slim AFOISA satisfies subminiature dimension and low power consumption requirements for adoption in a MPC.

III. MATHEMATICAL MODEL AND ADAPATIVE MODEL-FOLLOWING CONTROL

Two orthogonal directions are required in a slim AFOISA system and both axes are controlled separately. The dynamic characteristics of a VCM-type AFOISA satisfy Kirchhoff's voltage law and mechanical equation[9]

$$V(t) = i(t)R + L\frac{di(t)}{dt} + K_e v(t), \tag{1}$$

$$J\frac{dv(t)}{dt} + Bv(t) = F_e - F_L = K_t i(t) - F_L, \tag{2}$$

where $V(t)$ is the supplied voltage, $i(t)$ is the driving current, $R = 12.75\ \Omega$ is the coil resistance, $L = 9$ mH is the coil inductance, $v(t)$ is the linear speed, $J = 1.12$ g is the inertia of moving part, $B = 0.01$ N s/m is the damping constant, F_e is the electric force, F_L is the load force, K_e is the voltage constant, and K_t is the force constant. In meter-kilogram-second unit, $K_e = K_t = 0.3$ N m/A. Laplace transform of Eqs. (1) and (2) yields the single axis transfer function

$$G_P(s) = \frac{K_t}{sL + R}\frac{1}{sJ + B}. \tag{3}$$

The mathematical model of the designed slim AFOISA system can also be obtained based on system identification experiments. Input various voltages into a slim AFOISA and velocity variation outputs can be measured. Figure 2 shows frequency responses of dual axes, and their identified transfer functions of both axes are formulated as

$$G_{P_x}(s) = \frac{1474.63}{s^2 + 131.2s + 1.72 \times 10^4},$$

$$G_{P_y}(s) = \frac{1619.39}{s^2 + 193.4s + 1.76 \times 10^4}. \tag{4}$$

Angular movements of a MPC detected from two gyrosensors are very small, so they can be regarded as linear motion. An AMFC law[10,11] aims at counteracting system inaccurate modeling and load variation, and its reference model is usually chosen as a linear decoupled model. This controller does not require an on-line computation of the dynamic model, even though partial compensation of model nonlinearities is possible to decrease control effort. Hence, the proposed AMFC law comprising two PID controllers with position and speed feedback control is illustrated in Fig. 3. The PID controllers in Fig. 3 can be expressed by

$$u(t) = K_P e(t) + K_I \int e(t)dt + K_D \frac{de(t)}{dt}, \tag{5}$$

where $u(t)$ are the outputs of position controller $v^*(t)$ or velocity controller $V_v(t)$, respectively, K_P, K_I, and K_D are control gains, and $e(t)$ are the displacement error $e_d(t)$ or the velocity error $e_v(t)$, respectively. Furthermore, feed forward and feedback parameters are constants and are designed by treating a plant as a reference model. To examine performance when parameter variation occurs, an adaptive loop is
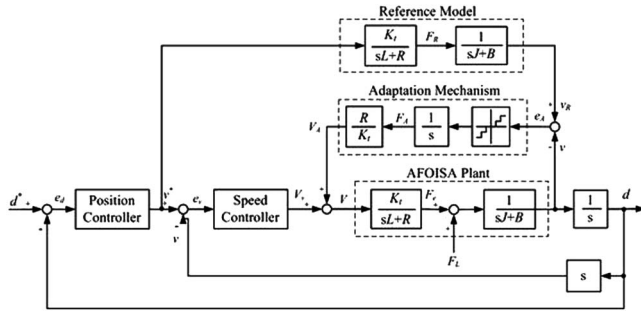
FIG. 3. Control block diagram of AMFC for single axis.

FIG. 5. (a) Load error between compensatory and external variation. (b) Time response of AMFC in the presence of load after 100 ms.

F_L of 20 mN mean and 5 mN variance exists after 100 ms, the compensatory force F_A can quickly approach F_L within 40 ms, as shown in Fig. 5(a). Figure 5(b) shows the transient and steady-state responses for target position at 0.5 mm. It depicts 30 ms settling time, 5 μm steady state error, and without any overshoot. Furthermore, the designed slim AFOISA in a MPC is manufactured with low power consumption and subminiature dimension.

IV. EXPERIMENTS

The hardware block diagram of an AFOISA system in a MPC is depicted in Fig. 4. A personal computer (PC)-based implementation of an AMFC law including two PID controllers has been achieved. First, position and angular signals generated from Hall effect sensors and gyrosensors pass through active low-pass filters and amplifiers before entering four-channel analog/digital converters on a data acquisition card. Next, an AMFC algorithm written in C language is executed on a PC to obtain fast dynamic performance. Additionally, the reference model of the AMFC can be formularized as a linear equation according to some AFOISA driving tests with various supplied voltage inputs. Hence, a PC calculates velocity v_R of a reference model by adapting this linear model equation.

Irregular hand jitter or environmental shake F_L occurs when a photographer holds a MPC during walking or in a vehicle. While F_L causes parameter variation of a slim AFOISA system, an adaptation mechanism synthesizes an auxiliary input signal to assure that the controlled AFOISA plant exactly behaves as the reference model. An adaptive control loop is then added to preserve the same control performance as that of a constant load case. The velocity error signal e_A can be obtained from velocity v of a moving part and the reference model velocity v_R. Hence, the compensatory force F_A can be calculated from the adaption mechanism. Additionally, F_A is factored by R/K_t to determine compensatory voltage V_A that will cancel F_L. When random load
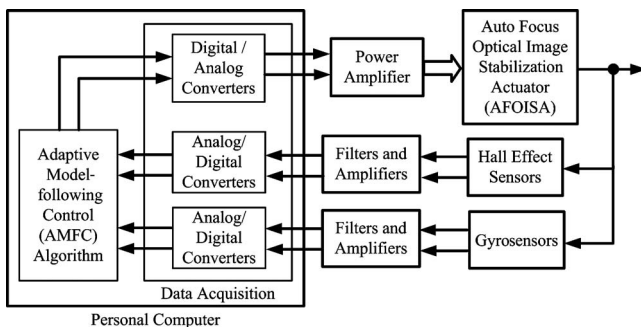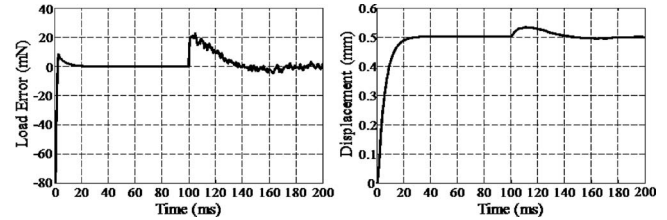
V. CONCLUSIONS

In this paper, an AMFC law including two PID controllers with position and speed feedback control is adopted to compensate irregular hand jitter or environmental shake of MPCs and to obtain fast response when a photographer holds a MPC during walking or in a vehicle. Although hand jitter or environmental shake cause various parameters of a slim AFOISA, an adaptation mechanism synthesizes an auxiliary input signal to assure that a slim AFOISA plant exactly behaves as a reference model. When the target position is at 0.5 mm, the time response by adoption AMFC includes 30 ms settling time and 5 μm steady state error without any overshoot. Furthermore, a compensatory force can quickly cancel irregular disturbance within 40 ms. As a result, the characteristics of the slim AFOISA satisfy the optical demands of MPCs.

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FIG. 4. Hardware block diagram of an AFOISA system.