IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received September 5, 2019, accepted September 25, 2019, date of publication October 7, 2019, date of current version October 21, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2945882

Open-Loop Control of Voice Coil Motor With Magnetic Restoring Force Using High-Low Frequency Composite Signals

YU-HAO CHANG[1], CHIEN-SHENG LIU[2], I-WEI CHEN[1], MENG-SHIUN TSAI[3], AND HSIANG-CHUN TSENG[1]

[1]Department of Mechanical Engineering, National Chung Cheng University, Chiayi 62102, Taiwan
[2]Department of Mechanical Engineering, National Cheng Kung University, Tainan 70101, Taiwan
[3]Department of Mechanical Engineering, National Taiwan University, Taipei 10617, Taiwan

Corresponding author: Chien-Sheng Liu (csliu@mail.ncku.edu.tw)

This work was supported by the Ministry of Science and Technology of Taiwan, under Grant MOST 105-2221-E-006-265-MY5 and MOST 107-2218-E-002-071.

ABSTRACT This study proposed an approach to control voice coil motors (VCMs) installed in smartphone modules as autofocus actuators. The VCM developed in this study comprises guide rods. The magnetic field attraction force between guide rods and movable parts serves as lens restoring force. This study did not use feedback elements to avoid the stick-slip phenomenon between VCM guide rods and movable parts. Instead, this study used a high–low frequency composite signal based on the findings from a mathematical model analysis and VCM dynamic attribute analysis, preventing stick-slip and offering the VCM a more favorable positioning precision.

INDEX TERMS Voice coil motor, auto-focusing, open-loop control, stick-slip.

I. INTRODUCTION

Social networks have become a crucial part of people's lives. They rely heavily on smartphones at work and during leisure time. Smartphone camera features are also indispensable. Advancements in smartphone technology have enabled smartphone cameras to evolve from a basic focus to optical zoom, optical image stabilization, and even cameras with dual lens or triple lens. This evolution indicates that smartphone cameras remain a popular feature that major manufacturers strive to develop [1]–[8].

Autofocus is the most fundamental camera feature, whereby the phone moves the lens using an actuator and image processing to produce clear and sharp images [9].The most common actuators are voice coil motor (VCM) [10], [11], stepper motor [12], piezo motor, and liquid lens system [13]–[15]. The existing smartphone camera modules are composed of spring-installed VCM incorporated with open-loop control that actuates the lens. However, this design is known for its weakness in terms of optical axis offset as well as low resistance to elastic fatigue and dropping [16], [17]. This study installed guide rods into the designed VCM to solve the aforementioned drawbacks. However, the friction between the installed guide rods and lens holder led to a stick-slip situation in dynamic behavior, reducing the camera's positioning accuracy [18]. To enhance accuracy, a closed-loop system with feedback elements should be applied [19]. However, to reduce costs and module volume, this study gave up on using feedback elements and proposed a novel open-loop control approach to improve VCM positioning performance. The proposed open-loop control approach used a high-low frequency composite signal to eliminate stick-slip phenomenon between VCM guide rods and movable parts without using a Hall sensor and closed-loop control, to keep the positioning accuracy, and to reduce the cost directly.

The study framework is as follows: Section II describes the design of VCM; Section III introduces the process of building mathematical models; Section IV explains the operational instructions; and Section V presents the experimental results of the designed VCM. The final section addresses the result discussion and conclusion.

The associate editor coordinating the review of this manuscript and approving it for publication was Engang Tian.

II. STRUCTURAL LAYOUT AND PRINCIPLE

Fig. 1 presents the designed VCM, which comprises two parts, namely a movable part and a stationary base structure.

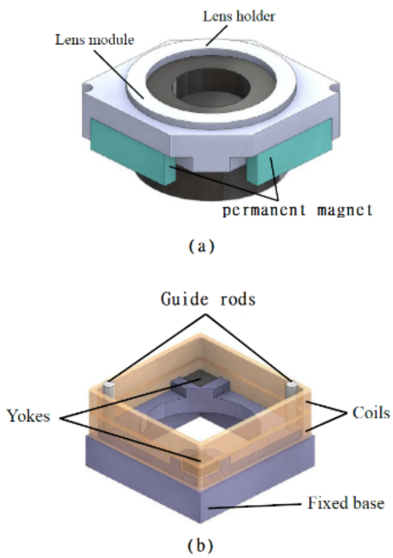


FIGURE 1. VCM actuator with magnetic restoring force (a), movable part, and (b) stationary base structure [22].

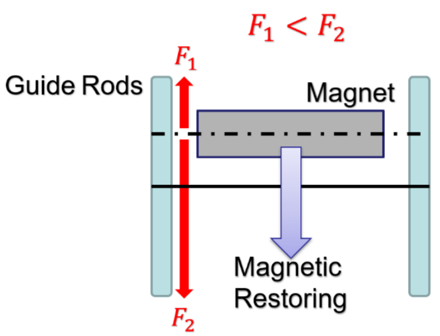


FIGURE 2. Schematic of the magnetic restoring force.

TABLE 1. VCM Parameters.

Specifications	Corresponding value
Size of VCM actuator	8.4×8.4×5 mm
Diameter of lens	M6×2 mm
Rated current	40 mA
Stroke	0.4 mm
Resistance of coil	125 Ω
Inductance of coil	114 mH
Weight of moving part	175.1 mg (without lens)
Weight of lens	121 mg
Maximum thrust	475 mgw (25 mA)

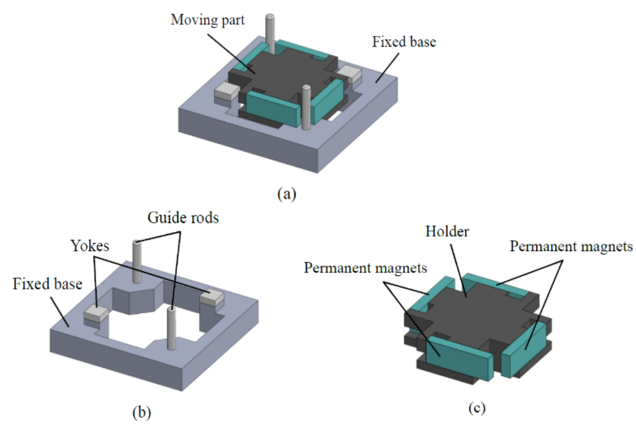


FIGURE 3. Measurement platform of the magnetic restoring force (a), overall structure (b), stationary base structure (c), and movable part.

The stationary structure is composed of a nonpermeable fixed base, two permeable guide rods (AISI 52100), and a set of coils. The movable part contains a lens holder, a lens module, and four permanent magnets. The guide rods designed for said movable part and stationary structure contributed to the considerable endurance of the designed model [20]. The magnets of the movable part create a permanent magnetic field and produce Lorentz force with the coils that pushes the lens, enabling the camera to focus and produce clear images. Furthermore, a magnetic attraction force exists between the magnets and the guide rods in the stationary part, which is referred to as the magnetic restoring force of VCM thereafter. This replaced the mechanism of spring restoring force adopted by spring-installed VCMs [21], [22], as depicted in Fig. 2. The VCM parameters are listed in Table 1.

III. DYNAMIC SIMULATION

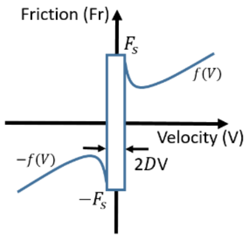
To simulate and analyze the dynamic behavior of the designed VCM, a suitable jig was required to measure the motor parameters in question (Fig. 3). The adopted jig is a simplified VCM movable part, comprising only a magnet base and four permanent magnets. Therefore, the parameters could be measured when the conditions of magnetic field distribution is the same as the original VCM structure. By connecting the movable part with the load cell, this study enabled the magnets to hang in the air. Under such circumstances, the parameters of Lorentz force (F_v) and magnetic restoring force (F_b) could be obtained without being affected by friction. An LCR meter was used to measure the resistance (R) and inductance (L) of the coils. The VCM model was converted into a relation between voltage (V) and current (i), which is represented by Equation (1) as follows:

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

Lorentz force was calculated using Equation (2) as follows:

$$F_v = K_v \cdot i(t) \tag{2}$$

where K_V is the motor coefficient of the VCM. Experimental measurements revealed a proportional relationship between magnetic restoring force and position (P_{os}), as depicted in



$$F_r = \begin{cases} f(V)\cdot sgn(V), & |V| \geq DV \\ F_m, & \begin{cases} if\ V < DV \\ and\ |F_m| \leq F_s \end{cases} \\ F_s \cdot sgn(F_m), & \begin{cases} if\ V < DV \\ and\ |F_m| > F_s \end{cases} \end{cases}$$

FIGURE 4. Friction model [23].

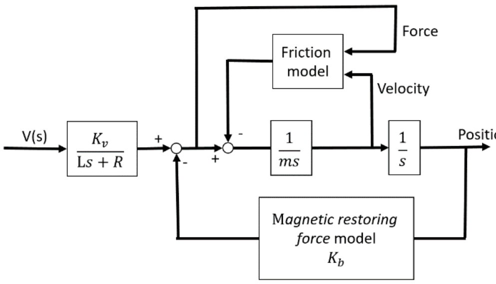


FIGURE 5. Block diagram of the VCM system.

Equation (3):

$$F_b = K_b \cdot Pos(t) \tag{3}$$

where K_b is the magnetic restoring force coefficient of the VCM.

Friction must be applied to said model to develop a complete VCM mathematic model. The Karnopp friction model was adopted to comprehensively present the attributes of dynamic and static friction, as exhibited in Fig. 4 [23].

Curve fitting was conducted on voice coil force and restoring force curves. The results were compared with the experimental data, exhibiting a trend of friction. Subsequently, all simulated and measured VCM parameters were imported into MATLAB/Simulink mathematic model, resulting in a VCM performance curve. Fig. 5 depicts the VCM system.

To ensure the accuracy of said VCM mathematic model, this study compared the simulation data with the experimental data (Fig. 6). Voltage at distinct frequencies was separately imported into the designed VCM. The resulting hysteresis curves were considerably similar to the simulation curves, thus demonstrating the accuracy of the mathematical model in this study.

IV. CONTROL METHOD

A chirp signal was imported into the designed VCM to observe its dynamic performance, formulating a dynamic curve (Fig. 7). As illustrated in Fig. 7, because the VCM was affected by a stick-slip phenomenon, the low-frequency dynamic curve was undesirable, indicating that the movable part only oscillated in one direction. However, when frequency increased, the movable part oscillated in both directions exhibiting a regular and repetitive sliding behavior. The final position also converged at a certain range.

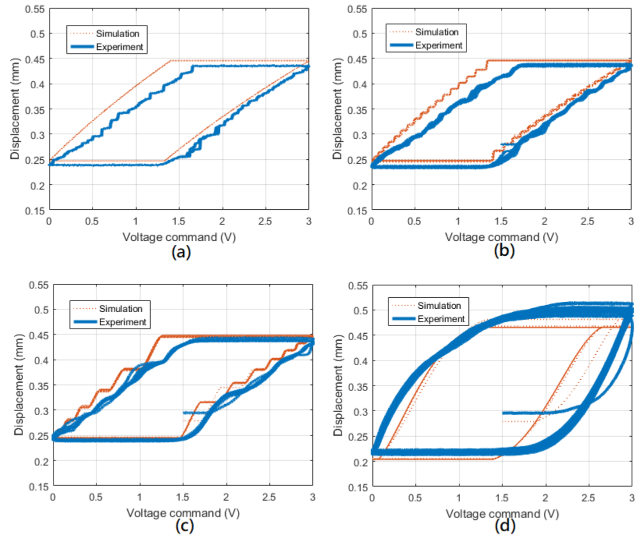


FIGURE 6. Hysteresis curves of VCM under several import frequencies (a) 0.01Hz, (b) 1Hz, (c) 5Hz, and (d) 20Hz.

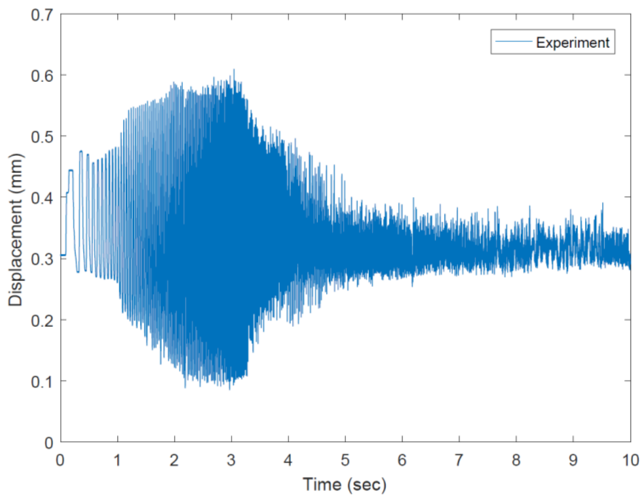


FIGURE 7. Dynamic frequency response of the designed VCM.

Fig. 8 presents the simulation of VCM export response at various home positions. Regardless of the home position, importing high-frequency oscillation signals still maintained the convergence of VCM final position at a certain range. Simply adjusting the voltage enabled the researchers to change and control the VCM export position to one that converged (Fig. 9).

Fig. 10 exhibits the VCM export response under consistent voltage but varying import frequencies. Results indicated that when a low-frequency signal was imported, the export response was quick, and the final convergence range was large. However, an import signal with an excessively high frequency prevented its dynamic behavior from entering a cycle of sliding. Moreover, its reaction was slower than the reaction at a low-frequency signal. As indicated in Fig. 10, export results considerably varied between situations when the same voltage but different frequency signals were imported into

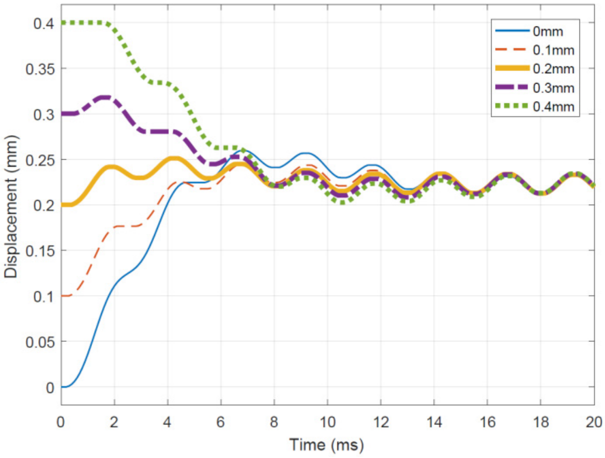


FIGURE 8. Simulation of VCM export response with distinct home positions.

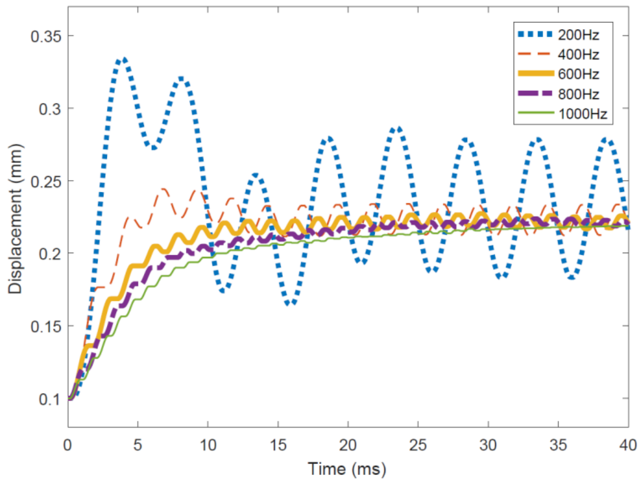


FIGURE 10. Simulation of VCM under various levels of import frequency.

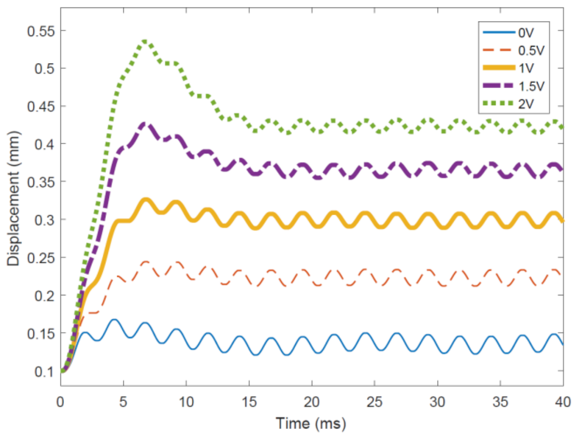


FIGURE 9. Simulation of VCM under distinct levels of import voltage.

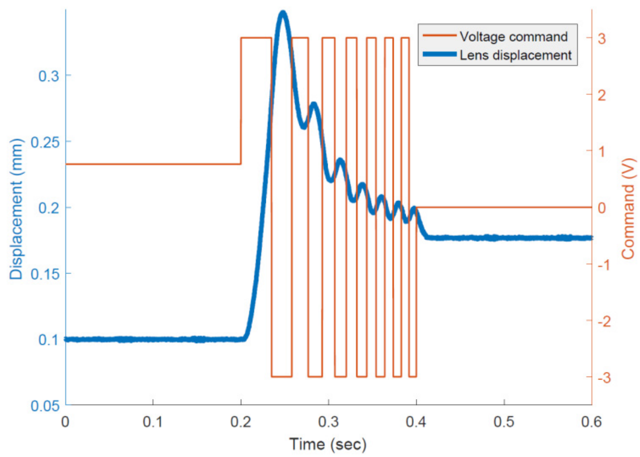


FIGURE 11. Results of a chirp control–positioning experiment.

the designed VCM. This study used such attribute to solve the stick-slip problem faced with a designed guide-rod-installed VCM. By conducting numerous simulations and experiments, this study selected chirp signals to balance the reaction time, displacement, settling time, and positioning accuracy. Moreover, by using attributes such as high and low frequency, researchers imported low frequency (100 Hz) to achieve high displacement. At a later stage, high frequency was selected to enable the signal to enter a sliding cycle, thus reducing the settling time and increasing positioning accuracy, as illustrated in Fig.11.

V. EXPERIMENTAL EQUIPMENT AND RESULTS

Fig. 12 depicts the experimental equipment. A personal computer was connected to the equipment and LabVIEW was run to formulate signals. NI PCI-6221 DAQ Card was installed, serving as the signal export source. Current was exported using a voltage follower, ensuring sufficient current to drive the VCM. A laser displacement sensor was installed to send feedback regarding the VCM positions. In this study, the designed VCM was placed on a rotation stage to simulate the dynamic behaviors of smartphone operations at various angles.

In the experiment, a random voltage setting was imported to the designed VCM with all possible home positions. When the VCM operation stabilized, high-frequency control signals were imported. Finally, the positioning results were recorded. The selected control parameter was chirp with high and low frequency. The initial frequency ranged from 100Hz to 600Hz. The total length of the control signal was 20 ms. The waveform was a square wave with 3-V amplitude (VCM response time = 23 ms).

After conducting experiments on the designed VCM with various attitudes, the final positioning data are summarized in Fig. 13. This figure demonstrates that importing a specified high–low frequency composite chirp can effectively solve the stick-slip problem and guarantee favorable positioning performance according to the VCM attitude in question.

The experiment results show that the stick-slip could be eliminated effectively by using the proposed high-low frequency composite signals approach. Furthermore, due to lack of a Hall senor, the proposed approach has the advantage

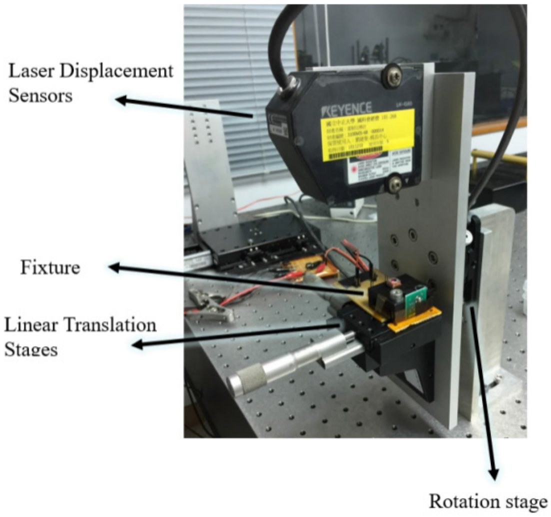


FIGURE 12. Experimental structure.

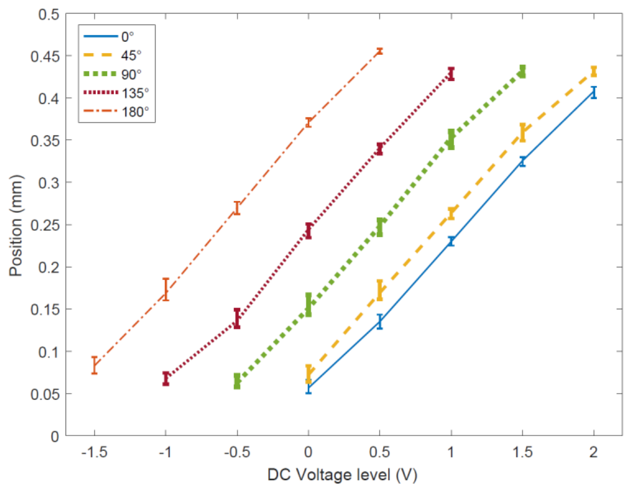


FIGURE 13. Positioning performance of VCM under various attitudes.

of low cost, low assembly procedure and high positioning accuracy when compared to a closed-loop VCM.

VI. CONCLUSION

This study proposed an open-loop control approach and the use of the high–low frequency attribute of chirps to solve the stick-slip problem caused by VCMs equipped with guide rods. The proposed high–low frequency composite signals control method used different frequency to reducing the settling time and increasing positioning accuracy. In addition, it makes the guide-rod-equipped VCM has the advantages of low cost, low assembly procedure and high positioning accuracy. The experimental results indicated that the proposed approach produced a positive reaction rate and repetitiveness. By adopting said approach, a guide-rod-equipped VCM can fulfil the general autofocus requirements.

REFERENCES

[1] Y.-H. Chang, C.-C. Hu, C.-L. Hsieh, and C.-S. Liu, "Design of VCM actuator for optical zooming smartphone cameras," *Microsyst. Technol.*, vol. 25, no. 1, pp. 277–281, 2019.

[2] C.-L. Hsieh, Y.-H. Chang, Y.-T. Chen, and C.-S. Liu, "Design of VCM actuator with L-shape coil for smartphone cameras," *Microsyst. Technol.*, vol. 24, no. 2, pp. 1033–1040, 2018.

[3] C.-L. Hsieh, H.-Y. Wang, Y.-H. Chang, and C.-S. Liu, "Design of VCM actuator with the chamfered edge magnet for cellphone," *Microsyst. Technol.*, vol. 23, no. 12, pp. 5293–5302, 2017.

[4] S.-W. Chen and Y.-Q. Chen, "Double-camera imaging device," U.S. Patent 10 178 285, Jan. 8, 2019.

[5] H. Chu, P.-J. Wang, X.-H. Zhu, and H. Hong, "Antenna-in-package design and robust test for the link between wireless ingestible capsule and smart phone," *IEEE Access*, vol. 7, pp. 35231–35241, 2019.

[6] Y. Tokudaiji, D. Miura, Y. Hattori, K. Murasato, Y. Bu, and T. Mizuno, "AC resistance reduction of a flexible wireless power transmission coil using magnetic path control technology at 13.56 MHz," *IEEE Trans. Magn.*, vol. 55, no. 7, Jul. 2019, Art. no. 8401407.

[7] A. Heya, K. Hirata, and N. Niguchi, "Dynamic modeling and control of three-degree-of-freedom electromagnetic actuator for image stabilization," *IEEE Trans. Magn.*, vol. 54, no. 11, Nov. 2018, Art. no. 8207905.

[8] P. Wang, X. Chen, F. Ye, and Z. Sun, "A smart automated signature extraction scheme for mobile phone number in human-centered smart home systems," *IEEE Access*, vol. 6, pp. 30483–30490, 2018.

[9] S.-M. Sohn, S.-H. Yang, S.-W. Kim, K.-H. Baek, and W.-H. Paik, "SoC design of an auto-focus driving image signal processor for mobile camera applications," *IEEE Trans. Consum. Electron.*, vol. 52, no. 1, pp. 10–16, Feb. 2006.

[10] S. Manabu and Y. Morimasa, "Lens drive device," JP Patent 2002 365 514, 2002.

[11] C.-S. Liu, P.-D. Lin, P.-H. Lin, S.-S. Ke, Y.-H. Chang, and J.-B. Horng, "Design and characterization of miniature auto-focusing voice coil motor actuator for cell phone camera applications," *IEEE Trans. Magn.*, vol. 45, no. 1, pp. 155–159, Jan. 2009.

[12] B.-L. Kuo, B.-W. Huang, and M.-L. Ye, "An analysis on vibration of a micro stepping motor system," *J. Adv. Eng.*, vol. 4, no. 2, p. 113117, 2009.

[13] H.-P. Ko, H. Jeong, and B. Koc, "Piezoelectric actuator for mobile auto focus camera applications," *J. Electroceramics*, vol. 23, pp. 530–535, Oct. 2009.

[14] L. Li, Q.-H. Wang, and W. Jiang, "Liquid lens with double tunable surfaces for large power tunability and improved optical performance," *J. Opt.*, vol. 13, no. 11, 2011, Art. no. 115503.

[15] D. Wang, C. Liu, and Q.-H. Wang, "Holographic zoom system having controllable light intensity without undesirable light based on multifunctional liquid device," *IEEE Access*, vol. 7, pp. 99900–99906, 2019.

[16] Y.-H. Chang, C.-J. Lu, C.-S. Liu, D.-S. Liu, S.-H. Chen, T.-W. Liao, W.-Y. Peng, and C.-H. Lin, "Design of miniaturized optical image stabilization and autofocusing camera module for cellphones," *Sensors Mater.*, vol. 29, no. 7, pp. 989–995, 2017.

[17] K.-H. Kim, S.-Y. Lee, and S. Kim, "A mobile auto-focus actuator based on a rotary VCM with the zero holding current," *Opt. Express*, vol. 17, no. 7, pp. 5892–5896, 2009.

[18] Z. Jinjiang, C. Xinglin, W. Changhong, and F. Rupeng , "Study on criterion about overcoming low-speed stick-slip of simulator," *J. Syst. Eng. Electron.* , vol. 10, no. 2, pp. 29–38, Jun. 1999.

[19] H.-C. Yu, T.-C. Chen, and C.-S. Liu, "Adaptive fuzzy logic proportional-integral-derivative control for a miniature autofocus voice coil motor actuator with retaining force," *IEEE Trans. Magn.*, vol. 50, no. 11, Nov. 2014, Art. no. 8203204.

[20] C.-S. Liu and S.-S. Ko, "Miniature auto-focusing voice coil motor actuator with excellent shock resistance," *Adv. Sci. Lett.*, vol. 8, no. 1, pp. 83–88, 2012.

[21] C.-S. Liu and H.-F. Li, "Design and experimental validation of novel force sensor," *IEEE Sensors J.*, vol. 15, no. 8, pp. 4402–4408, Aug. 2015.

[22] C.-S. Liu, B.-J. Tsai, and Y.-H. Chang, "A compact low-cost camera module with modied magnetic restoring force," *J. Mech.*, vol. 33, no. 4, pp. 475–482, 2017.

[23] D. Karnopp, "Computer simulation of stick-slip friction in mechanical dynamic systems," *J. Dyn. Syst., Meas., Control*, vol. 107, no. 1, pp. 100–103, Mar. 1985.

YU-HAO CHANG received the M.S. degree from the Department of Mechanical Engineering, National Chung Cheng University,Chiayi, Taiwan, in 2015, where he is currently pursuing the doctorate degree with the Department of Mechanical Engineering. His current research interests include applications of FSM and voice coil motors.

CHIEN-SHENG LIU received the B.S. and M.S. degrees from the Department of Power Mechanical Engineering, National Tsing Hua University, Hsinchu, Taiwan, in 1996 and 1999, respectively, and the Ph.D. degree from the Department of Mechanical Engineering, National Cheng Kung University, Tainan, Taiwan, in 2010. He was with the Industrial Technology Research Institute (ITRI), Taiwan, as a Mechanical Design Engineer, from 2003 to 2011. He was an Assistant Professor with the Department of Mechanical Engineering, National Central University, Jhongli, Taiwan, from 2011 to 2012, and joined the Mechanical Department, National Chung-Cheng University, Chiayi, Taiwan, in 2012. He is currently a Professor with the Department of Mechanical Engineering, National Cheng Kung University, since 2018. His current research interests include applications of force sensors, voice coil motors, precision measurement, laser-based auto-focusing module, and opto-electronics sensing.

I-WEI CHEN received the B.S. degree from the Department of Electrical Engineering, Tunghai University, Taichung, Taiwan, in 2016, and the M.S. degree from the Department of Mechanical Engineering, National Chung Cheng University, Chiayi, Taiwan, in 2018. His research interests include digital control, virtual mechanism, and voice coil motors.

MENG-SHIUN TSAI received the B.S. degree from the Department of Mechanical Engineering, National Taiwan University, Taipei, in 1988. After the military service and the two year working experiences, he went to Penn State University, where he received the master's and Ph.D. degrees in 1994, and 1998, respectively. He joined the Mechanical Department as an Assistant Professor at National Chung-Cheng University, Chiayi, Taiwan, in 1998. He was promoted to be a Distinguished Professor in 2018. Then, he was recruited to the Mechanical Engineering Department of National Taiwan University, in 2018, and was promoted to be Distinguished Professor, in 2019. His current research interests include CNC motion control, structural dynamics control, ultrasonic motor, smart structure, and intelligent machinery.

HSIANG-CHUN TSENG received the B.S. degree from the Department of Mechanical Engineering, National Chung Cheng University, Chiayi, Taiwan, in 2012, where he is currently pursuing the doctor's degree with the Department of Mechanical Engineering. His research interests are focused on electromechanical integration, machine dynamic, motion control, cyber-physical systems (CPS), and intelligent application of machine tool.