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Optimal design and experimental verification of a magnetically actuated optical image stabilization system for cameras in mobile phones

Chi-Wei Chiu,[1] Paul C.-P. Chao,[1,a)] Nicholas Y.-Y. Kao,[2] and Fu-Kuan Young[2]
[1]*Department of Electrical and Control Engineering, National Chiao Tung University, Hsinchu 300, Taiwan*
[2]*Department of Mechanical Engineering, Chung Yuan Christian University, Chungli 320, Taiwan*

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A novel miniaturized optical image stabilizer (OIS) is proposed, which is installed inside the limited inner space of a mobile phone. The relation between the VCM electromagnetic force inside the OIS and the applied voltage is first established via an equivalent circuit and further validated by a finite element model. Various dimensions of the VCMs are optimized by a genetic algorithm (GA) to maximize sensitivities and also achieving high uniformity of the magnetic flux intensity. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2839782]

I. INTRODUCTION

Recently, cameras become indispensable features in a mobile phone. One of the important design objectives is to minimize the image blurring caused by the handshaking of users. To this aim, an optical image stabilization (OIS) mechanism,[1,2] is proposed in this study, which is shown in Figs. 1(a) and 1(b). It is aimed to design a miniaturized OIS module with high actuation forces around handshaking frequencies. The magnetic field simulation and analysis performed by the software ANSYS are then conducted to ensure required actuation. An optimization method, the genetic algorithm (GA),[3] is next applied to search for the best dimensions of the mechanism to simultaneously achieve compactness of the OIS and high sensitivity in a satisfied uniformity. Finally, the optimized structure is fabricated to verify the optimal results predicted by the theoretical design.

II. MAGNETIC FIELD ANALYSIS

The lens holder in the OIS module is actively moved by the magnetic force from the VCMs of the OIS module. It is expected that the lens holder is actuated in a uniform and sufficiently strong magnetic field to counteract the handshaking vibrations. To this end, an equivalent magnetic circuit for the VCM is first established to predict the driving electromagnetic forces, which is followed by ANSYS analysis for validation.

The proposed magnetic structure of each VCM, consisting of yoke and a permanent magnet, is shown in Fig. 2(a), along with its generated magnetic field. To derive an equivalent magnetic circuit, the reluctances of the yoke in different dimensions are denoted, respectively, by R_{y1}, R_{y2}, and R_{y3}. On the other hand, R_m denotes the reluctance of a magnet while R_g does the air gap between the magnet and yoke. An equivalent magnetic circuit is then built, as shown in Fig. 2(b), where the reluctances are represented by resistances and the magnet by a voltage source. A yoke reluctance in this equivalent magnetic circuit can be calculated by

$$R_{yi} = \frac{L_i}{\mu A_i}, \quad i = 1,2,3, \tag{1}$$

where L_i is the length of magnetic flux, μ is the permeability of the material, and A_i are the cross sections of the three different parts of the yoke, as shown in Fig. 2(a), with magnetic flux flowing through. Moreover, the reluctance for the air gap between the yoke and permanent magnet could be calculated as

$$R_g = \frac{1}{P_g} = \frac{1}{\mu\left[\frac{wd}{\delta} + 1.04(w+d) + 0.616\delta\right]}, \tag{2}$$

where P_g is the magnetic conductivity of the air, w is the yoke width; d is the yoke length, δ is the thickness of air gap, and μ is the permeability. With all the expressions of the reluctances in hand, the net equivalent reluctance R_{eq}' is obtained based on the basic circuit theory as shown in Fig. 2(b) with

$$R_{eq} = R_g + R_{y1} + R_{y2} + R_{y3}, \tag{3}$$

$$R_{eq}' = \frac{R_m R_{eq}}{R_m + R_{eq}}. \tag{4}$$

Thus, the net magnetic flux Φ could be obtained as

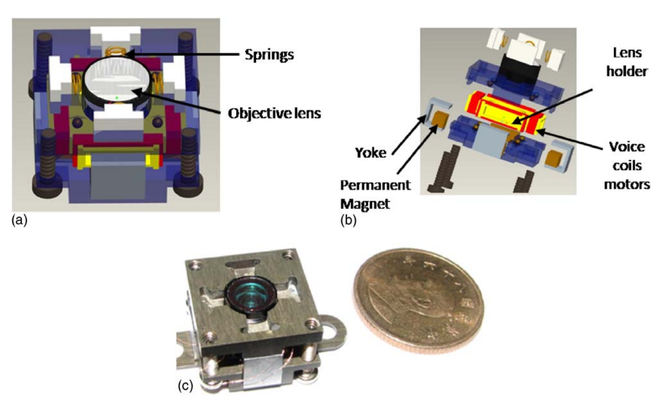

FIG. 1. (Color online) (a) Schematic of the OIS; (b) blown up; (c) photograph of the proposed OIS.

a)Author to whom correspondence should be addressed. Electronic mail: pchao@mail.nctu.edu.tw.

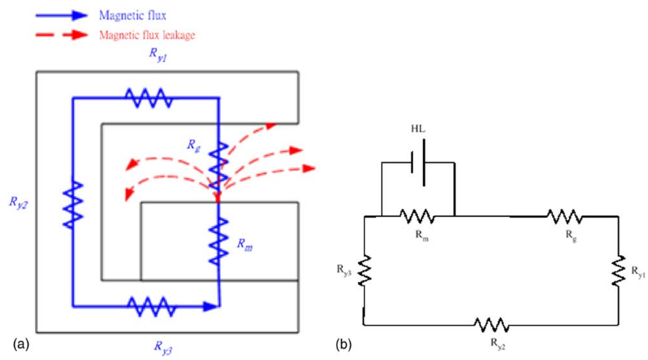

FIG. 2. (Color online) (a) Structure of the magnetic field; (b) equivalent magnetic circuit.

$$\Phi = \frac{F_m}{R_{eq}'}, \tag{5}$$

where $F_m = H_d L_m$; H_d is the field intensity at the operating point obtained from the magnetization curve (or called *B-H* curve) for the magnet and the load line. L_m is the thickness of the magnet. With Eq. (5) in hand, the magnetic flux density between the permanent magnet and yoke, the gap, can be calculated by

$$B_g = \frac{\Phi}{A_g}, \tag{6}$$

where A_g is the cross section area of the gap.

The equivalent magnetic circuit established provides the means to calculate the resulted magnetic flux density with varied VCM structure dimensions. However, the method only gives a bulk value of the flux density instead of a realistic distribution of the magnetic flux density along the air gap width. To validate the effectiveness of the bulk flux density predicted by the previous equivalent magnetic circuit, the commercial simulation software, ANSYS, is utilized to simulate the areal flux density in the air gap. Three basic steps:- preprocessing, solver, and postprocessing, are conducted. The parameters including the relative permeabilities of air, yoke, and magnet are set to be 1, 2000, and 1, respectively. The magnitude of coercive force is set equal to 995 000 for the magnet made of neodymium-iron-boron (NdFeB). The lower-order finite element PLANE13 is constructed for most area and high-order PLANE53 for relatively complicated geometry.

The practical dimensions of the VCM structures built in a typical OIS are used for both analyses of the equivalent magnetic circuit and ANSYS field emission microscopy (FEM). The resulting flux via ANSYS is shown in Fig. 3(a), while Fig. 3(b) does the magnetic field vectors, with which the flux density B_g can be calculated along the air gap. The calculated B_g exhibits the nonlinearity along the gap being only 0.98% (uniformity is 99.02%). It is also resulted that the averaged value of flux density, B_g, calculated by ANSYS is 0.5022 $\mathrm{Wb/m^2}$, which is close to the averaged intensity of 0.5305 $\mathrm{Wb/m^2}$ by equivalent circuitry. The closeness confirms the effectiveness of the proposed equivalent magnetic circuit to be used for subsequent optimization in the next section.

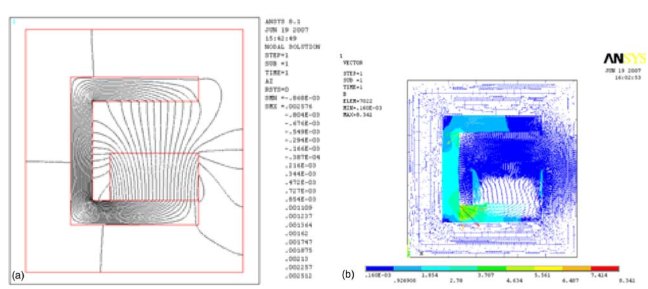

FIG. 3. (Color online) (a) Magnetic flux from ANSYS; (b) magnetic flux vector from ANSYS.

III. GENETIC ALGORITHM FOR OPTIMAL DESIGN

In order to be installed inside the limited inner space of a mobile phone with the market acceptable size of $15 \times 15 \times 9\ \mathrm{mm}^2$, the OIS is minimized herein to have as a small size as possible. An optimization is performed to determine the final sizes of OIS parts without sacrificing the performance by the VCM actuation force. This optimization is accomplished by GA,[3] which starts with defining 14 varied dimensions of the OIS as design variables, and also determining their corresponding constraints that resulted from the limited space for the OIS to be installed in a mobile phone. Note that the major dimensions of the OIS components to be optimized are the total length, width, and thickness of the OIS; the varied dimensions of the yoke; and the gap between the yoke and magnet. The second step is to assign the sensitivity of a VCM as the fitness function to maximize, with the aim to minimize traveling time of lens holders. The sensitivity is then defined as the ratio of square of lens holder acceleration, *G*, over the applied power by VCM; i.e.,

$$S = \frac{G^2}{P} = \frac{\left(\dfrac{F_e - f_{fri} - kx - mg}{m}\right)^2}{\dfrac{V^2}{R}}, \tag{7}$$

where P is the power; F_e represents the electromagnetic actuation force from the VCM; f_{fri} is the friction force of the lens holder; k is the net stiffness constant of the spring as shown in Fig. 1(a); x is the displacement of the lens holder; m is the total mass of the moving parts which consists of a lens holder, lens module, and voice coil motors; V is the applied voltage; while R denotes the resistance of the voice coil. The electromagnetic force could be obtained by

$$F_e = N i l_w B_g = N \frac{VA}{\rho L} l_w B_g, \tag{8}$$

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; B_g is the magnetic flux density; and V, A, ρ, and L are the applied voltage, the cross section area of the coil, the electric conductivity of coil, and total length of the coil, respectively. Note that the derivation of Eq. (8) is based on the negligence of back emf of VCM due to the much slower motion of the moving lens holder than the dynamics of VCM electricity.

TABLE I. GA optimization results.

No.	The values to represent	Design variables for GA optimum program	Constraints	Optima
1	Total length of OIS	$l_{\_sub}$	$0.013 \leqslant l_{\_sub} \leqslant 0.015$	0.015
2	Total wide of OIS	$w_{\_sub}$	$0.013 \leqslant w_{\_sub} \leqslant 0.015$	0.015
3	Total thickness of OIS	$h_{\_sub}$	$0.008 \leqslant h_{\_sub} \leqslant 0.009$	0.009
4	Total thickness of OIS	T	$0.000\,06 \leqslant T \leqslant 0.000\,42$	0.042
5	The electromagnetic force	F_e	$0.0371 \leqslant F_e$	0.011 146
6	Thickness of the yoke	$h_{\_yoke}$	$0.0008 \leqslant h_{\_yoke} \leqslant 0.001$	0.000 8
7	The air gap	$d_{\_yoke}$	$0.001 \leqslant d_{\_yoke} \leqslant 0.0012$	0.001
8	Length of the yoke	$l_{\_yoke}$	$0.004 \leqslant l_{\_yoke} \leqslant 0.005$	0.005

With design variables, constraints, and fitness function in hands, the optimization is performed by the GA,[3] which is widely applied for searching optimal values in complicated optimization problems. A GA program is constructed with setting population size to be 1000 for each parameter, the crossover and mutation rate to be 0.9 and 0.008, respectively, and entire program runs for 2000 generations to find optimum dimensions of the OIS module. Table I lists the optimization results by the built GA, where it is seen that the major dimensions are determined with the resulted electromagnetic force larger than the minimum required 0.0371 to overcome the friction induced by lens holder movement.

IV. EXPERIMENTAL RESULTS

A practical OIS module is fabricated in this study, as shown in Fig. 1(c). The major dimensions of this module are those optima listed in Table I. Figure 4 shows the comparison of the computed magnetic flux density along the gap between those from ANSYS, equivalent magnetic circuit, and measurements. It is shown from this figure that in the actuation range, which is approximately from 6 to 13 mm of lens holder traveling distance, three sets of resulted flux densities are close to each other. However, as considering broader

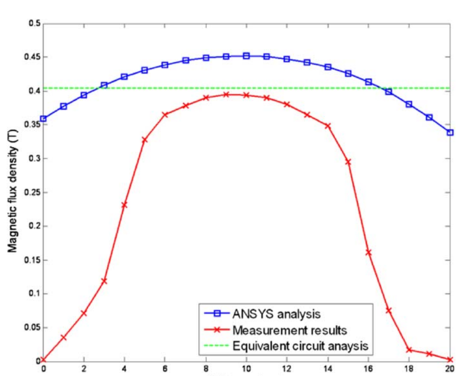

FIG. 4. (Color online) Comparison of the magnetic flux density between ANSYS, equivalent circuit analysis, and experimental results.

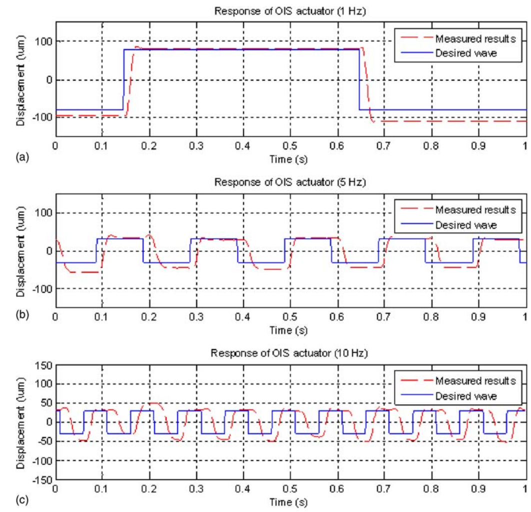

FIG. 5. (Color online) Responses of the OIS system for square waves in three driving frequencies: (a) 1, (b) 5, and (c) 10 Hz.

ranges of the traveling distance, ANSYS renders larger density than the experimental counterparts and an averaged value close to that from equivalent magnetic circuit. To test the response of the actuator, experiments are conducted to measure the motions of the lens holder in the proposed OIS system by a laser displacement sensor under the applied periodic voltage. Figure 5 shows the measured results for square wave commands under three different driving frequencies: 1, 5, and 10 Hz. It is shown from this figure that the OIS is actuated by the input signal in satisfactory responses. Note that the tracking performance of the OIS system could be easily improved to the error less than 0.5% if a closed-loop control scheme is applied in the future.

V. CONCLUSIONS

A novel miniaturized OIS module for a camera phone is successfully proposed, optimized, and manufactured in this study. The analysis of the magnetic field for the VCMs in the OIS is conducted by using the equivalent magnetic circuit and then verified by commercial software, ANSYS, and experimental data. A good agreement with error less than 6.1% in the actuation range of the lens holder in the OIS is present. The established and verified equivalent circuit model is then successfully adopted for GA optimization to minimize the overall size of the OIS and at the same time maximizes the sensitivity of the VCM actuator under a high uniform magnetic field. Finally, a prototype OIS system is fabricated with the dimensions resulted from the GA optimization with satisfactory experimental performance.

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