A mobile auto-focus actuator based on a rotary VCM with the zero holding current

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Abstract: In this work, an auto-focus actuator moving lens in mobile phone cameras is developed by applying a rotary VCM (voice coil motor). A novel inclined cam structure is used to convert the rotational motion by the VCM by into the linear motion of the focusing lens. The new focusing design enables the zero holding current required to maintain the lens module in the focusing position as well as the reduction of the module thickness. This paper presents the theoretical analysis and optimal design for the VCM actuator, cam structure and preload spring. We manufacture a prototype module with the size of 9.9×9.9×5.9 mm^3. The experimental results agree with the theoretical predictions and meet the required specifications for mobile camera applications.

OCIS codes: (040.1490) Cameras; (230.2090) Electro-optical devices

References and links

1. K. Tatsuno, “Current trends in digital cameras and camera-phones,” Quarterly review **18**, 35-44 (2006).
2. C.-S. Liu and P. D. Lin, “A miniaturized low-power VCM actuator for auto-focusing applications,” Opt. Express **16**, 2533-2540 (2008).
3. H.-P. Ko, H. Jeong and B. Koc, “Piezoelectric actuator for mobile auto focus camera applications,” J. Electroceram. **20**, (to be published).
4. M.-J. Chung and S.-Y. Son, “Development of compact auto focus actuator for camera phone by applying new electromagnetic configuration,” J. Mech. Sci. Technol. (KSME Int. J.) **20**, 2087-2093 (2006).
5. H. Ren and S. T. Wu, “Variable-focus liquid lens,” Opt. Express **15**, 5931-5936 (2007).
6. S. Kuiper and B. H. W. Hendriks, “Variable-focus liquid lens for miniature cameras,” Appl. Phys. Lett. **85**, 1128-1130 (2004).
7. F. Jorgensen, *The Complete Handbook of Magnetic Recording*, (MacGraw-Hill, 1995).

1. Introduction

The growing market demand for small and slim mobile phone cameras requires the size reduction of the camera module. Consumer also demands image cameras in mobile phones to have similar quality and performance as those of dedicated digital cameras. Therefore, the increase of sensor resolution and the achievement of auto-focus and optical zoom functions in a limited volume are strongly required. The market share of camera phone took only 4.3% of overall mobile phone market in 2002, but it is estimated that more than 90% will have auto-focusing function in 2008 [1].

Currently, the 1/4 inch image sensor is mostly used in mobile phone cameras. The camera module with more than 2 mega pixels needs auto-focus function for a good image quality because of its short focal depth. Furthermore, a small lens group for optical auto focusing needs to be moved in a limited volume, and increasing the power efficiency is also essential in order to conserve the finite battery resources of the mobile phone. Therefore, a compact auto-focus actuator is required to meet the demands for the reduction of both the size and power consumption. Various auto-focus actuators for mobile phones have been considered by many researchers [2-4]. In general, two kinds of auto focusing actuators are mainly used in mobile phone cameras. One is lens-motion-type auto focusing actuation that uses stepper motor,

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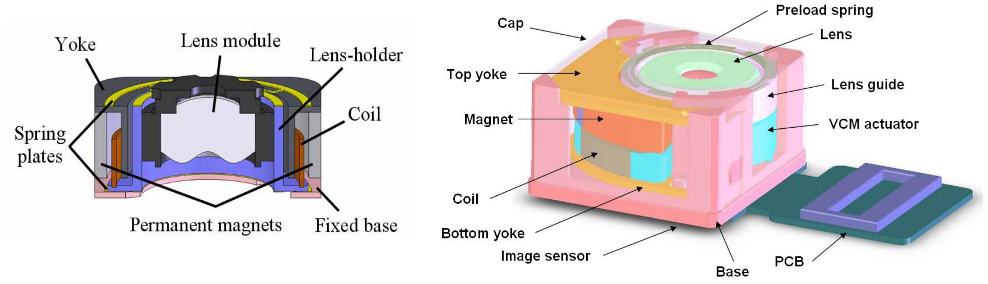
voice coil motor, piezoelectric, EAP(electroactive polymer) and micro-electro-mechanical system (MEMS) technologies. In this method, the precise alignment and motion control of the lens are important for image quality. The other is lens-modification-type auto focus, using liquid lens and solid-state electro-optical devices [5,6]. Lens shape and/or refractive index changes are the key to implementing this type of auto focus.

2. Types and features of auto-focusing actuators

In designing auto-focus actuators for mobile phones, the aim is typically to improve the response, reduce the size, minimize the power consumption and enhance the structural integrity. The major lens-moving mechanisms for focusing use stepping motor, voice coil motor and piezoelectric (or ultrasonic) motor. The stepping motor has the advantages of high reliability and large actuating force, but this method has the disadvantages in the size reduction and cost effectiveness. The ultrasonic motor uses electrically driven mechanical vibration of piezo-ceramic materials, and it uses the accumulation of small displacements at high frequency through frictional contact. This method enables high resolution of displacement, no power consumption when actuator is not moving due to frictional locking. However, it has many mechanical shortcomings such as hysteresis of piezoelectric materials, low reliability by the abrasion of friction parts and low shock resistance by the brittleness of materials.



(a) (b)

Fig. 1. Structures of two types of VCM focusing actuators; (a) conventional structure with the large holding current [2]; (b) Structure of a proposed VCM actuator with zero holding current.

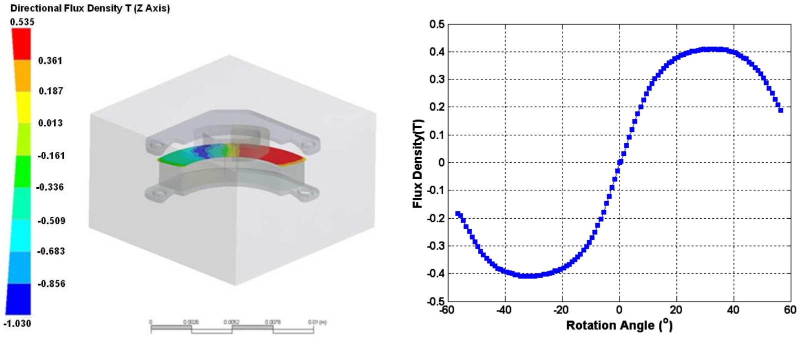
VCM actuators, used as the positioning actuator in the hard disk drives, optical storage devices and precise transport mechanisms, have been mostly used for focusing and zooming motions because of cost effectiveness and high repeatability. It provides the resultant force by the reaction of a magnetic field to the current passing through it. But this method has high power consumption because of a large holding current required to maintain the lens module in the focusing position. Figure 1(a) shows the structure of a conventional VCM focusing actuators for mobile phone cameras. In general, the VCM actuator consists of two parts. The fixed part includes two permanent magnets, a yoke and a base, while the moving part has a lens module, a lens holder and a coil. As shown in Fig. 1(a), the Lorentz force acting on the moving part of the conventional actuator is affected by the resistant force induced by the two spring plates, and the force is to be larger than the sum of the weight of the moving part and the restoring spring force for the focusing actuation. Moreover, the spring resistance is directly to proportional to the vertical displacement of the moving part. Therefore, the holding current for maintaining the lens module in the focusing position, increases with the displacement of the moving part. The continuing power consumption required to remain in the focusing state deteriorates the power efficiency of the mobile device. Recently, in order to reduce the holding current, a new VCM structure was proposed [2].

3. New design of auto-focusing actuator

Unlike the previous researches on VCM focusing actuators for mobile camera phones, we develop a novel focusing actuator having the zero holding current. The low-power VCM actuator is based on a rotary VCM and an inclined cam structure. Figure 1(b) presents the structure of the proposed VCM actuator. The rotary VCM actuator is based on the similar principle to a VCM used as the positioning actuator in the magnetic head of hard disk drives. A lens guide including a novel inclined cam structure, is used to convert the rotational motion by the VCM by into the linear motion of the lens module, the magnetic field produced by driving a current through the coil causes the VCM to react to the magnetic field from a permanent magnet. Thereby the rotational motion of the moving part causes the lens module to moves up and down for focusing.

3.1. VCM actuator

By Fleming's left hand rule, the force by the VCM actuator is proportional to the magnetic flux of permanent magnet, current passing coil and the turn number of coil. The force direction is perpendicular to the directions of magnetic field and current. In order to obtain the operating torque of VCM actuator, the magnetic flux density of magnet in air, coil and yoke are to be calculated. We implement the electromagnetic simulation using a commercial ANSYS program to calculate the magnet flux density distribution, as shown in Fig. 2(a). Here the permanent N48H rare-earth magnet and the yoke using C1018 material are used.



(a) (b)

Fig. 2. (a). Electro-magnetic simulation for the distribution of magnetic flux of air gap between the yoke and magnet; (b). magnetic flux density as a function of rotation angle.

Figure 2(b) shows that the average value of the magnet flux density has about 0.4T. The magnet flux density goes down to the both ends in the radial direction. In order to meet both low torque variation and the geometrical constraint of the auto-focusing module, we set the total rotation angle to 40 degrees. Then, to calculate the torque according to rotation angle, we perform the electromagnetic simulation using J-MAG program, and the simulation results are shown in Fig. 3(a). We also use coil having higher tension and better specific resistance than that of common coils. Here the resistance coefficient is 9.575 Ω/m, the coil diameter is 50 μm and the outer diameter of coil is 67 μm. We also set the required turn number and height of coil. Table 1 shows the input parameters used for the electromagnetic simulation.

Table 1. Input parameters for VCM electromagnetic simulation

Input voltage (V)	Input current (A)	Coil diameter (mm)	Outer diameter (mm)	Coil turns	Coil height (mm)
3	0.075	0.05	0.067	207	1.33

3.2. Preload spring

When the lens module moves up and down along the cam structure by the rotating motion of the VCM actuator without preload spring, it causes lens tilt, backlash and defocus by external impacts and hand shaking etc. Therefore, the optimal design of preload spring is essential for

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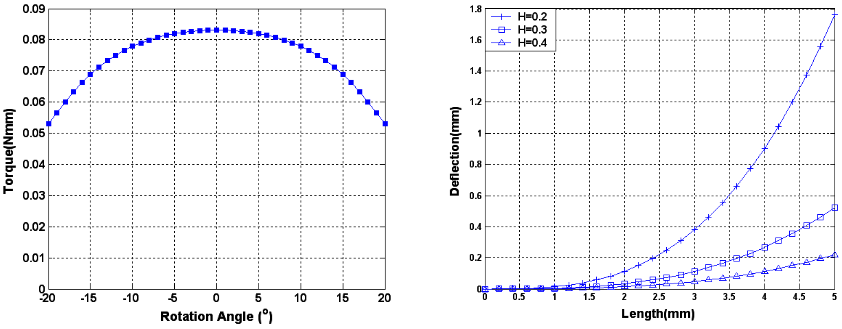
the auto-focusing module to reduce the optical errors. By considering the torque induced by the VCM actuator, we set the preload of spring as 0.049 N. The preload spring is designed to move 0.4 mm in the working range of the VCM actuator and it is made by SUS303 material. In general, the deflection of a cantilever beam is given by $\delta = Fl^3/3EI$. Here $E = 1.93 \times 10^8 N/m^2$ is Young's modulus and l is the length of preload spring. Also, $I = bh^3/12$ denotes the moment of inertia, b and h are the width and thickness of preload spring.

The minimum thickness considering the available manufacturing process is 0.03 mm. Thus, we perform the optimal design by fixing the thickness of preload spring among design parameters. Figure 3(b) shows deflections according to various widths and lengths of the preload spring. Because the deflection required for the auto-focusing module is 0.4 mm, the design parameters satisfying this deflection condition have two cases in Fig. 3(b). One is that width is 0.3 mm and length is 4.6 mm. The other is that width is 0.2 mm and length is 3.1 mm. By considering manufacturing feasibility, we choose the width of 0.3 mm. In order to verify the deflection by the optimally designed preload spring, we perform a structural simulation using the ANSYS program. The simulation results in Fig. 4 show that the maximum deflection is 0.441 mm, almost corresponds with the theoretical prediction.



(a) (b)

Fig. 3. (a). Torque of VCM actuator; (b) the deflection at various lengths and widths

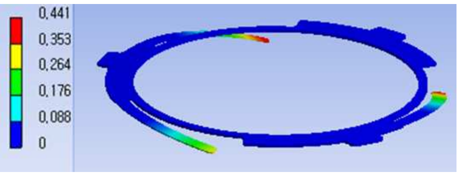


Fig. 4. Simulation result of spring deflection

3.3. Cam design

The rotational motion of the proposed VCM actuator causes the linear motion of the lens module by an inclined cam structure. Figure 5 shows the force diagram of the cam structure. Tangential and axial forces become

$$\sum F_t = q - n(f \cdot \cos\lambda + \sin\lambda) = 0, \quad \sum F_a = w - n(f \cdot \sin\lambda - \cos\lambda) = 0 \tag{2}$$

Here λ denotes lead angle, L is lead, d_m is the average diameter of thread, f is friction factor, q is friction force, w is weight and n is normal force. The minimal torque of the VCM actuator in order to move the lens module is calculated by considering the lead angle of cam and the preload of spring. We choose the rotation angle and lead as 40 degree and 0.4 mm by considering auto-focusing module size. Then, the minimum torques required for moving up and down the lens module are given by

$$T_u = \frac{Fd_m}{2}\left(\frac{L + \frac{2\pi}{9} f \cdot d_m}{\frac{2\pi}{9} d_m - fL}\right) \qquad T_d = \frac{Fd_m}{2}\left(\frac{\frac{2\pi}{9} f \cdot d_m - L}{\frac{2\pi}{9} d_m + fL}\right) \tag{3}$$

We calculate the torques for the up-down motion by substituting the design parameters in Table 2, such as $T_u = 0..043$ Nmm and $T_d = 0.01$ Nmm, respectively. Thus, the torque for the upward motion becomes the minimum torque required for the focusing operation.

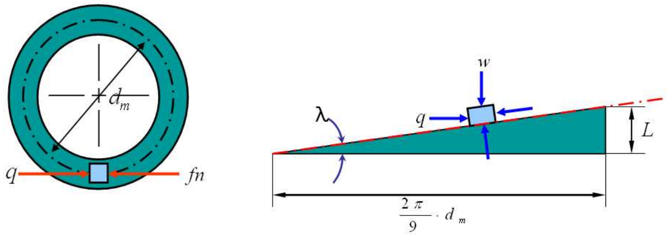


Fig. 5. Force diagrams by the cam structure

Table 2. Input parameters of the minimum torque

Rotation angle (°)	Lens module (N)	Diameter (mm)	Lead (mm)	Friction factor	Preload (N)
40	0.00294	7	0.4	0.2	0.049

3.4. Self-locking condition

For the auto-focusing actuator using the inclined cam, the self-locking condition maintaining the lens module in the focusing position is to be ensued when the current turns off. The minimum torque for the down motion (Eq. 2) should be positive to satisfy the self-locking condition, such as

$$\frac{2\pi}{9} f \cdot d_m > L \tag{3}$$

We can check that the developed auto-focusing module satisfies self-locking condition (0.977 > 0.4) of Eq. 3. It means that lens module is fixed in position satisfying the focusing status, if it is not changed equivalent condition by outside shock. Therefore, the developed auto-focusing module needs not continuously supply the voltage to keep the lens focusing position. The result, it can save dramatically power consumption than current method.

(a) (b) (c)

Fig. 6. (a). Photograph of the proposed auto-focusing actuator; (b) operation test - initial condition; (b) lens moving by input voltage.

4. Experimental results

4.1. Operation test

Figure 6(a) shows the actual size of a prototype of the optimally designed auto-focusing module. The dimensions of the auto-focusing module is 9.9×9.9×5.9 mm^3 including PCB thickness. By reducing the total height of the module less than 6 mm, the VCM actuator meets the size constraint for mobile phone cameras. Figures 6(b) and 6(c) present the operation test of the manufactured actuator. Figure 6(b) is an initial state without input current and Fig. 6(c) shows that the lens module moves upward by 0.4 mm with input voltage and current of 3V and 75mA. The lens module comes back to the initial state by giving reverse current

4.2. Auto-focusing function test

Auto-focusing systems determine correct focus by performing passive analysis of the image that is entering the optical system. Auto-focusing can be achieved by phase detection or contrast measurement. We use the hill-climb search method which is a typical contrast-measuring method. Contrast measurement is achieved by measuring contrast within a sensor field, through the lens. The intensity difference between adjacent pixels of the sensor naturally increases with correct image focus. In order to apply the auto-focusing algorithm to the prototype module, we have designed a focusing control algorithm including the asymmetric effect of preload spring when the lens guide moves up and down.

Figure 7(a) shows a prototype of the auto-focusing module including image processor. Here we use a 1/4 inch CMOS sensor (OmniVision OV9650) having the functions of auto exposure, auto white-balance and color processing. The image signal processing board (Mtekvision MV9315) has the logic of contrast calculation for the auto-focusing algorithm. We perform experiments to test the focusing performance. Since the VCM actuator has the resolution of 11.5 μm and the total stroke is 400 μm at 35 steps. To evaluate the auto-focusing performance quality, we perform experiments using a sector star image as shown in Fig. 7(b) and (c). The image quality is significantly improved when the auto-focus function is activated.

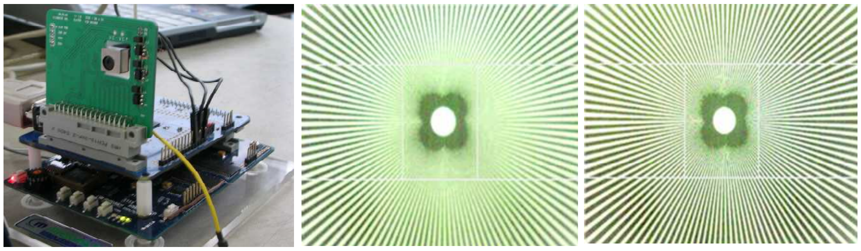


Fig. 7. (a). Experimental set-up for testing auto-focusing performance; (b) auto-focusing performance test using a sector star target without auto-focus; (c) with auto-focus

5. Conclusions

This paper has presented a low-power auto-focus actuator based on a rotary VCM with an inclined cam structure. The novel cam structure is used to convert the rotational motion by the VCM by into the linear motion of the focusing lens. Since the proposed actuator has the zero holding current, there is no power consumption when actuator is not moving due to frictional locking. Various experiments have been implemented to test the auto-focusing performance using a prototype module with the size of 9.9×9.9×5.9 mm^3. Experimental results confirm the potential of the proposed actuator for commercial mobile phone cameras.

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