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A large stroke magnetic fluid deformable mirror for focus control*

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A liquid deformable mirror, which can provide a large stroke deflection more than 100 μm, is proposed for focus control. The deformable mirror utilizes the concept of magnetic fluid deformation shaped with electromagnetic fields to achieve concave or convex surface and to change the optical focus depth of the mirrors. The free surface of the magnetic fluid is coated with a thin layer of metal-liquid-like film (MELLF) prepared from densely packed silver nanoparticles to enhance the reflectance of the deformable mirror. The experimental results on the fabricated prototype magnetic fluid deformable mirror (MFDM) show that the desired concave/convex surface shape can be controlled precisely with a closed-loop adaptive optical system.

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The variable focal location control using a deformable mirror in the imaging system has been studied recently[1-4]. This technology is useful for many imaging applications, such as multi-plane microscopy, fast focus tracking of non-stabilized objects, and axial focus scanning to provide cross-sectional images of vital tissues. The optical focus range of the deformable mirrors is linearly dependent on deflection of the surface. Different actuation schemes have been used to shape the solid mirror surface, including electrostatic, thermal, pneumatic, electromagnetic, and piezoelectric approaches. However, most of the solid deformable mirrors can only provide a small stroke deflection less than 20 μm[5,6]. The main problem of developing a large stroke solid deformable mirror is that the increase of the deformable stroke will make the mirror surface stress exceed the allowable values, thus breaking the mirror surface[7]. In addition, the cost of each actuator channel of the solid deformable mirror is usually high[6].

In this paper, a new kind of liquid deformable mirror based on the magnetic fluid is presented, which can offer a large stroke more than 100 μm with a relatively low cost of each actuator channel. Magnetic fluids (ferrofluids) are stable colloidal suspensions of nano-sized single-domain ferri-/ferromagnetic particles. When subjected to a magnetic field, the suspended particles will affect the variation of the fluid free surface shape, which can be exploited to develop magnetic fluid deformable mirrors (MFDMs). Since ferrofluids have low reflectivity (about 4%), the free surface of the suitable magnetic fluid can be further coated with a thin film called as metal-liquid-like film (MELLF) prepared from silver nanoparticles to enhance the reflectivity of the deformable mirror[8]. The reflective film plays an important role in the deformable mirror system because of its special liquid-like properties. There are a variety of methods to prepare the silver nanometer thin films, such as Langmuir-Blodgett (LB) film method, vapor deposition method and oil-water two-phase interface deposition method[9-12]. In this paper, a self-assembly method is proposed, which is simple and flexible. The MFDMs can provide a large stroke deflection with small power consumption, produce extremely smooth surfaces and offer both cost and performance advantages over the existing deformable mirrors.

The schematic diagram of the proposed MFDM is shown in Fig.1. The strong uniform magnetic field is located around the magnetic fluid. This uniform magnetic field will not cause deflection of the fluid surface, but could help to linearize the surface response to the current input of the miniature coils and significantly amplify the magnitude of the deflection. The container of the MFDM filled with a layer of magnetic fluid is on the top of the miniature coils. The strength of the magnetic field generated by the miniature coils can be controlled by varying the current applied to the coils.

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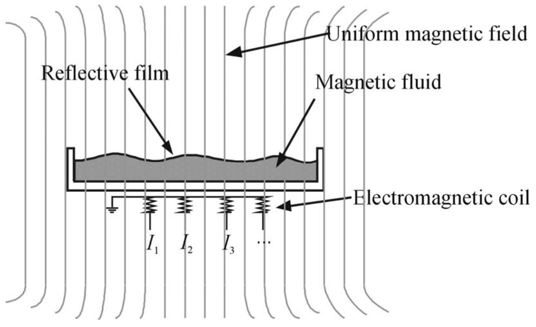


Fig.1 The schematic diagram of the proposed MFDM

According to the working principle of MFDM, the structure of a prototype MFDM is shown in Fig.2, which mainly consists of a Maxwell coil, miniature electromagnetic coils, and a thin layer of magnetic fluid with MELLF. The magnetic fluid body is enclosed by a Maxwell coil which is made up of three separated coils to produce a large uniform magnetic field. The radii of the coils and their vertical positions must follow the ratios as shown in Fig.2. The three separated coils are winding with AWG 25 magnet wires with the turn ratio of 64:49 for the lower and upper coils relative to the middle coil. The middle coil with an inner radius of 110 mm has 1 152 turns. This distinctive design provides a magnetic field which runs parallel to the central axis and is uniform over a significant volume extending around the axis. The container of the MFDM is centrally placed inside the Maxwell coil, so that the central axes of the container and the coil are coincided and aligned with the gravity vector. The inner diameter of the container is 70 mm with a groove diameter of 40 mm and height of 8 mm inside. The container is filled with a 1.5-mm-thick layer of magnetic fluid (EMG 304 from Ferrotec Corp.) and the groove is hexagonally arranged with 37 miniature electromagnetic coils. Each coil with an inner radius of 2 mm consists of 800 turns of AWG 38 magnet wires and has a length of 8 mm. The coils are radically spaced at 4.2 mm from center to center, thus presenting a total active footprint area of approximately 28 mm in diameter. The strength of the magnetic field generated by the miniature coils can be controlled by varying the current applied to the coils, which makes the magnetic fluid surface form an equi-potential one and provides a way to control the shape of the fluid surface.

The silver-liquid-like film formed by silver nanoparticles stacking and spreading on the surface of the magnetic fluid is an important part of the liquid mirror. Preparing dodecanethiol-encapsulated silver nanoparticles in ethyl acetate needs an elaborate procedure as follows.

Firstly, 12 mL solution of silver nanoparticles (300 nm in diameter) was dissociated by centrifugation in low speed centrifuge (TD5A-WS) with a relative centrifugal force (*RCF*) of 1 710 g for 30 min. After centrifugation, two phases of the solutions (dark yellow and transparent) formed. Then the supernatant was removed carefully and ethanol was infused into the tube. This process was repeated four times.

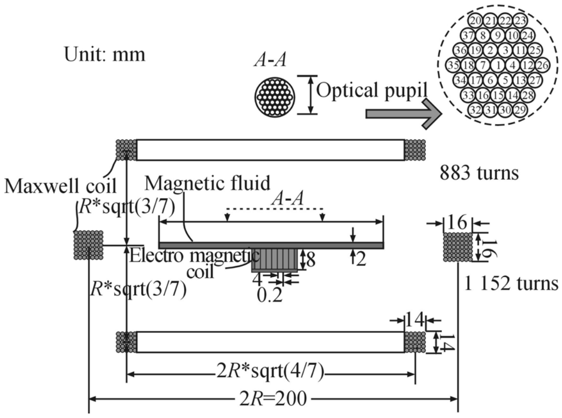


Fig.2 Structure of the prototype MFDM

Secondly, the precipitate of silver nanoparticles was dispersed in the ethanol again with vigorous shaking for 15 min. The dodecanethiol-encapsulated silver particles were prepared by mixing the above prepared ethanol solution of silver nanoparticles with dodecanethiol solution. The typical experimental conditions include mixing 12 mL ethanol solution of silver nanoparticles with 3 mL dodecanethiol (CH_3-$(CH)_{11}$-SH) solution and keeping the mixed solution at room temperature for at least 24 h. The above mixed solution was centrifuged at *RCF* of 1 710 g for 30 min to remove the unreacted materials for four times.

Thirdly, the procedure of centrifugation made the dodecanethiol-encapsulated silver nanoparticles precipitate as a dark spot on the bottom of the tube. The dark spot was dispersed in ethyl acetate with vigorous shaking for 15 min to reach a concentration of 0.1 mg/mL. Then a single-channel adjustable-volume pipette was used to drop the minute droplets of the encapsulated silver particle suspension in ethyl acetate carefully on the surface of the magnetic fluid. After the solvent became a thin layer with the thickness comparable with the particle size, the long-range attractive force between particles induced by the surface tension of the solvent caused the silver particles to coalesce into close-packed arrays on the liquid surface. The final assembly of the liquid mirror is shown in Fig.3.

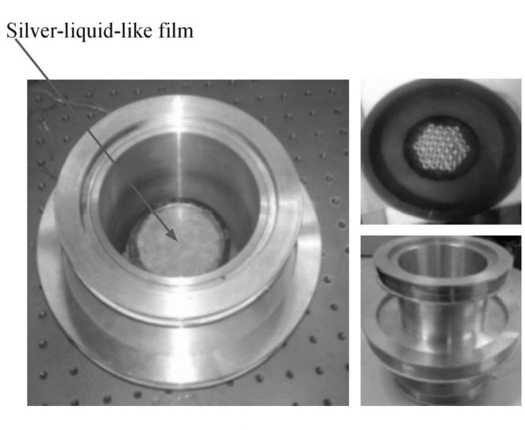


Fig.3 Assembly of the prototype MFDM

The surface deflection respect to different input currents was measured using Polytec OFV 5000/552 and the experimental setup with the Polytec laser measurement system is shown in Fig.4. The Maxwell coil was activated with a 500 mA current input, which produced a 6.8 mT uniform magnetic field inside the Maxwell coil. The linear surface deflections resulting from applying various input currents to the center miniature coil (coil 1 in Fig.1) are shown in Fig.5. Since the resulting deflections of the mirror surface are symmetric about the vertical axis, only 2D surface shapes are shown in Fig.6. It can be seen that the coupling efficiency between the neighbor coils is around 30%.

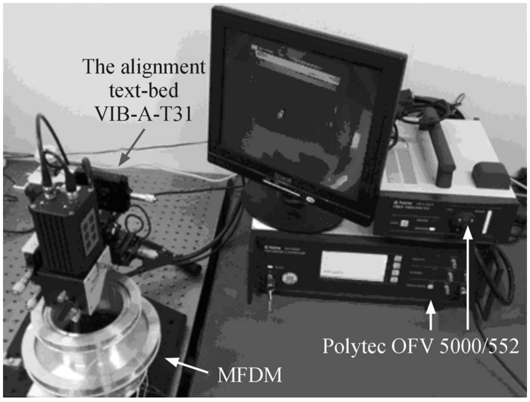


Fig.4 The photo of the experimental setup system

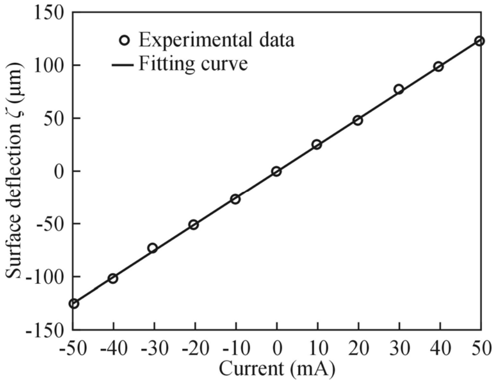


Fig.5 The linear response of the MFDM with active Maxwell coil

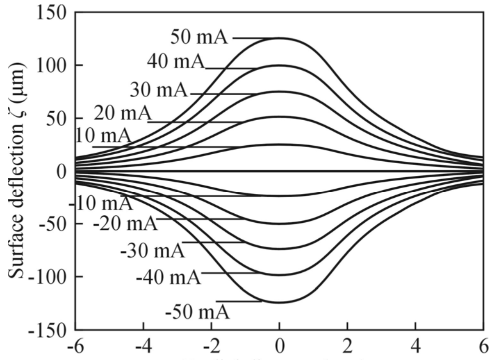


Fig.6 The 2D surface deflection results of the MFDM

In order to produce a desired concave/convex mirror surface for the focus control applications, the surface shape of the mirror was controlled in a closed-loop adaptive optical system. In this paper, the decentralized PID control approach was used. By appropriately choosing the location of the output points on the mirror surface, a decoupling technique using the DC gain (influence function) of the deformable mirror was used to minimize the coupling between different input-output channels. The parameters of the decentralized PID controller can then be properly designed for each decoupled input-output channel[13].

The closed-loop adaptive optical system is shown in Fig.7. A Hartmann optical wavefront sensor WFS150-5C was used to measure the deformation displacement of the mirror surface. The electromagnetic coil was driven by a PC-based system consisting of PCI-type analog voltage output cards (Advantech PCI-1724) with a current protection and amplification circuit. The controller was implemented in a computer under the visual studio 2010 with a developed C program. Fig.8 shows the result of the measured surface shape using the wavefront sensor, where the mirror surface is required to follow a static concave shape defined by the reference shape of $\boldsymbol{r}_0$=[26.7, 22.3, 22.3, 22.3, 22.3, 22.3, 22.3, 13.4, 13.4, 13.4, 13.4, 13.4, 13.4, 13.4, 13.4, 13.4, 13.4, 13.4, 13.4, 4.7, 4.7, 4.7, 4.7, 4.7, 4.7, 4.7, 4.7, 4.7, 4.7, 4.7, 4.7, 4.7, 4.7, 4.7, 4.7, 4.7, 4.7].

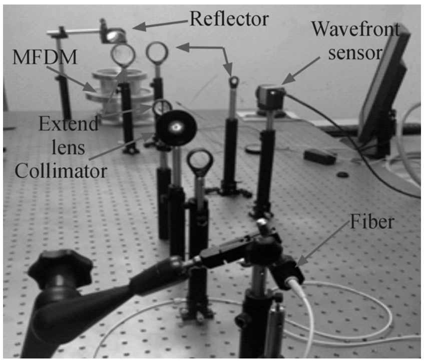


Fig.7 Photo of the adaptive optical system

Fig.9(a) shows the wavefront shape measurement results at selected locations (# 1, # 2, # 8 and # 20), where the corresponding reference wavefront signals are shown as dashed lines. The control inputs determined by the designed controller are given in Fig.9(b). The surface control performance is also evaluated using the root mean square (RMS) error of 37 tracking points. The formula of RMS error is presented as $\sigma=\sqrt{\frac{1}{37}\sum_{k=1}^{37}(y_k\text{-}\bar{y}_k)^2}$, where y_k is the measured wavefront shape of the kth point and $\bar{y}_k$ is the corresponding reference displacement. The RMS error of the wavefront shape computed for the 37 channels is given in Fig.10. The experimental results show that the measured surface shape converges successfully to the desired reference shape in less than 1.5 s and the RMS error asymptotically drops below 20 nm, thus the desired concave surface shape can be obtained.

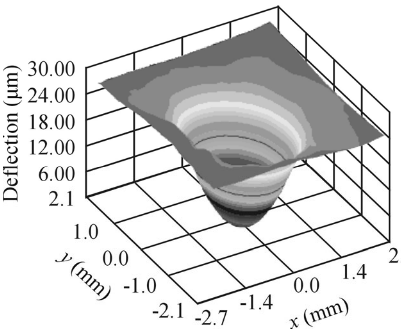
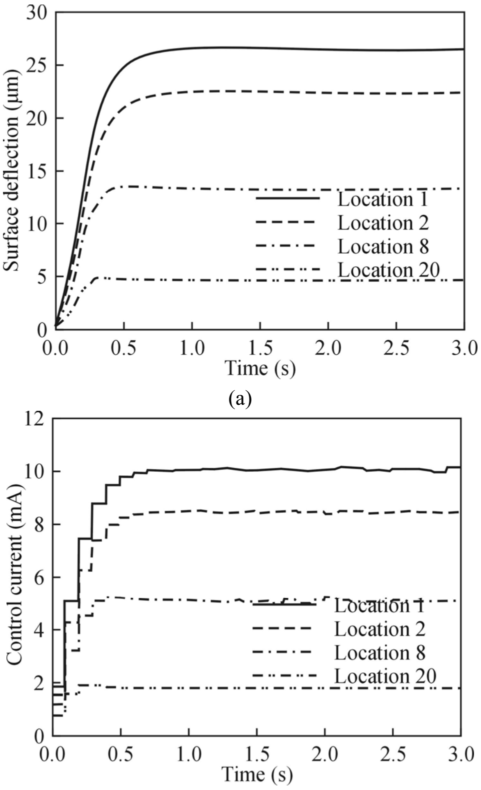


Fig.8 The measured surface shape of MFDM



(a)

(b)

Fig.9 The variations of the measured outputs of selected points using the decentralized PID controller: (a) Surface deflection; (b) Control current

In this paper, a magnetic fluid based liquid deformable mirror is proposed for the optical focus control. The magnetic fluid deformable mirror (MFDM) can supply a large stroke more than 100 μm with a good linearity of the surface deflection response to the applied control current. A thin layer of MELLF was prepared from densely packed silver nanoparticles using the self-assembly method to enhance the reflectivity of the deformable mirror. Experimental results based on the designed prototype MFDM with a closed-loop adaptive optical system show that the MFDM can precisely form the desired concave shape and be used to produce the variable focus depth for different applications.

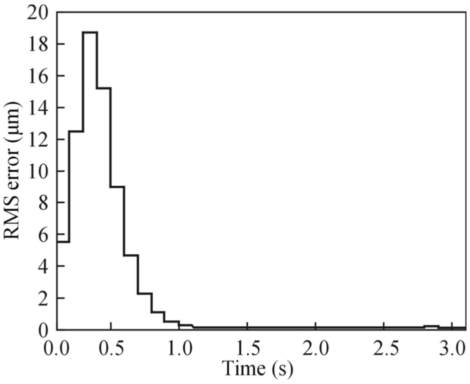


Fig.10 The RMS error of the tracked surface shape

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