Electrorheological fluid-actuated flexible platform

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The design, fabrication, and performance of an electrorheological (ER) fluid-actuated flexible platform integrated on a microfluidic chip are reported in this letter. The digitally regulated ER microvalves control the four diaphragms on which a platform is sustained. With electrical input signals, the platform can perform vibrations at tunable frequencies as well as generate complex leveling modes. The flexible platform can potentially act as a microdamper when its inputs are generated from a sensor, in combination with a feedback control system. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2196847]

In recent years, microfluidic devices have demonstrated their usefulness as research tools as well as in potential applications, such as microchemical preparation devices in life science,[1] microfluidic osmotic device,[2] microtunable optical systems,[3] etc. Microvalves constitute an important component in microfluidic devices, serving the role of actuation. In this work we report the use of electrorheological (ER) fluid microvalves in the design and fabrication of a flexible platform, with potential applications in fast light beam directional control and as a microdamper.[4–7]

ER fluid is a type of colloidal suspension with tunable rheological properties. Its apparent viscosity is continuously variable through the application of an external electric field.[8] With the recent discovery of giant electrorheological (GER) effect, ER fluid can offer high shear stress at relatively low voltages, with response time on the order[9] of 1–10 ms. These properties enable the ER fluid to be an ideal material for micromechanical devices, controllable through applied voltages.[10] We demonstrate that micropolydimethylsiloxane (PDMS) devices actuated by ER fluid valves have many advantages compared to those driven by gas or other fluidic pumps.[11] In particular, ER valves can be integrated in chips, with easily realizable higher frequency operations while retaining significant dynamic range. The latter is an advantage compared with piezoelectric actuators at frequencies below 1 KHz (upper limit due to ER fluid response time).[12]

Figure 1 is a schematic diagram of the system consisting of a multilayered chip, 35 mm in length and 20 mm in width, fabricated with PDMS material (Dow Corning 184). The right upper inset in Fig. 1 shows the various components of the microsystem. The four-layered chip possesses four isolated 500 μm-wide channels, where each channel is connected to an inlet and outlet tube through which the ER fluid is pumped in a closed "U" path. On the arms of U path, two pairs of electrodes (made of PDMS and carbon black composites) were installed, sharing a common ground. The electric fields are applied perpendicular to the channel. A circular diaphragm, 2.75 mm in diameter and 30 μm thick, is placed between each pair of electrodes in the channel. A pillar is mounted on the top side of the diaphragm, sustaining one corner of a silicon platform (8 mm^2 and 0.4 mm thick). Detailed arrangement can be seen in Fig. 1. The ER fluid flow within the channels can be controlled, even stopped, through the application of an external voltage. That is, when increasing electric field across a pair of electrodes, the viscosity of ER fluid would increase accordingly and thus slow down the flow of ER fluid. When an adequate *on-off* dc pulse voltage is applied on one pair of electrodes, e.g., U_1 in Fig. 1 is on and U_2 is off, the discrepancy in flow rates of the ER fluid would lead to pressure accumulation under the diaphragm, causing it to bulge upward. When U_2 is on and U_1 is off, the ER fluid pressure would decrease, causing the diaphragm to be sucked downward. This *up-down* mechanical function could be continuously controlled through either analog or digital electrical signals, thereby changing the level of each platform corner independently and quickly. The response time of the ER microvalve is determined by the ER fluid response time to the electric field, and the time required for pressure buildup. The latter can be adjusted by varying the magnitude of the pressure differential applied to the flow of the ER fluid, as well as by decreasing the size of the system.

As can be seen from Fig. 1, the silicon platform has four diaphragms sustaining the platform, actuated by ER valves. The deformation of each diaphragm (more precisely, the up-down displacement of the membrane) determines the leveling conditions of the platform. This can be realized by sim-

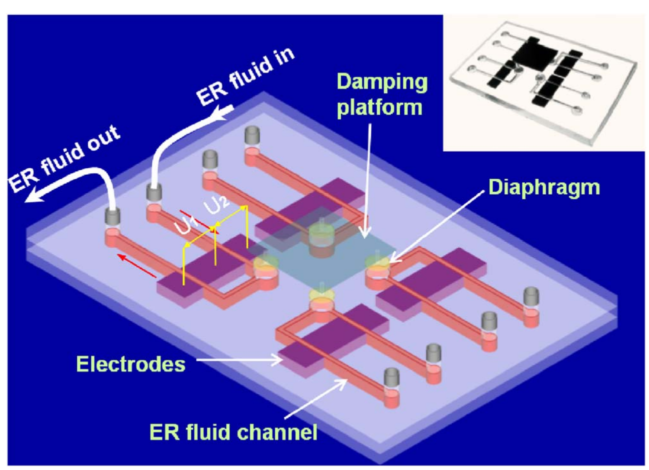

FIG. 1. (Color online) Schematic illustrations of the flexible platform with the microfluidic chip. The left lower inset shows the three-dimensional (3D) structure of the device. The chip actuated by ER valves sustains and controls the platform. The right upper inset shows the fabricated device.

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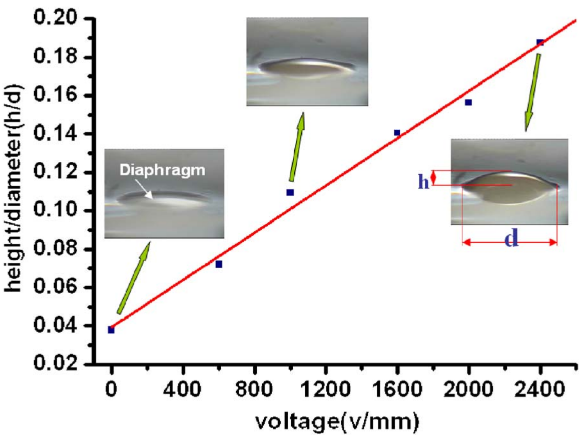

FIG. 2. (Color online) Displacements of diaphragms plotted as a function of applied electric field across the channels. The insets demonstrate the transformations of a diaphragm at specific field intensities.

ply controlling the intensity of the electric field applied to each pair of electrodes for each of the four ER valves. In this particular application of the ER valve, speed and dynamic range (displacement) of the actuation are the critical factors. Below we show the relevant data.

Figure 2 displays the measured diaphragm displacement as a function of the applied electric field (across the channel). For generality, the results are shown as the ratio of diaphragm's height to diameter. Three insets show the deformation characteristics at different field intensities. A linear relationship between the displacement and applied field strength is obtained in the displacement range of 0–400 μm. When the electric field exceeds a critical value (e.g., >2.5 kV/mm), the ER fluid flow can be completely stopped, and the diaphragm would inflate until it breaks.

To test the functionality of flexible platform under different conditions, a digital high-voltage square-wave signal is connected to the electrodes, switching the ER valves. When the four channels are controlled synchronously, the platform acts as a vibrator whose frequency can be adjusted in accordance with the frequency of the electrical signals. In order to monitor the vibration characteristics, an optical sensor (Keyrence trademark, model LB-72) is set right over the platform and connected to an oscilloscope (Phillips, PM3365A). Amplitude variations of the platform are measured in terms of analog signals. After conversion, the vibration amplitudes at different frequencies were obtained. Figure 3(a) shows the displacement of the platform vibrating at 0.5 Hz. Other measurements at higher frequencies were carried out at 1.25, 2.5, and 20 Hz and the results are shown in Figs. 3(b)–3(d), respectively. One can see that the amplitude decreases monotonically when the frequency increases, owing to the time delay in the pressure buildup. Limited by the power of the ER fluid pump, the present experimental limiting frequency is 20 Hz. It is anticipated that by increasing the ER fluid flow rate as well as the electrical signal intensity, the amplitudes can be adjusted to 1 mm or more at 100 Hz.

As the diaphragms are separately controlled, the leveling motion of the platform can be tuned electrically. The electrical signals can be easily programed to generate time-correlated sequences so that any motion sequence of the platform, within the possibilities of up-down motion of each of its four corners, can be achieved. An experiment was designed to demonstrate this controllability. A helium-neon laser beam was irradiated on the platform perpendicularly from the top and reflected to a screen set above the platform. A charge-coupled device (CCD) camera was employed to record the time trace of the reflected laser spot on the screen. As seen in Fig. 4, letters A, B, C, and D located at four corners of each inset indicate the projections of the four pillars underneath the platform. The letters in orange circles indicate the specified pillars to be rising at the time of the spot position, while crosses in pink circles indicate the others to be in the balanced positions at the time of these spot positions. The arrows point out the spot's direction of motion. When no signals are input, the platform is level and the

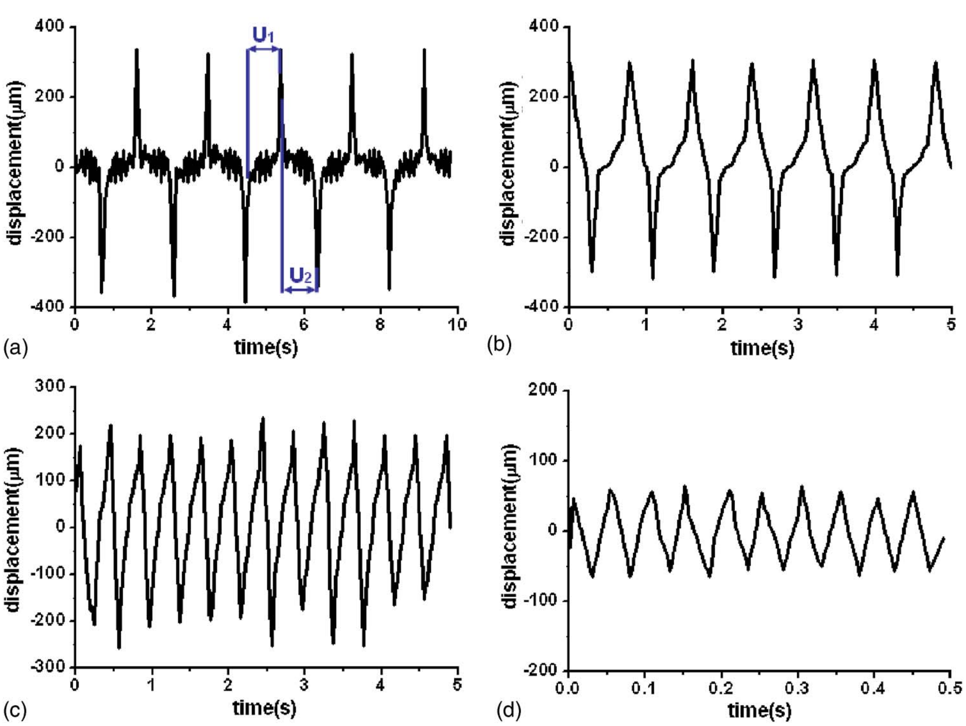

FIG. 3. (Color online) Vertical vibrations of the platform when four diaphragms move synchronously. Vibrations at 0.5, 1.25, 2.5, and 20 Hz are shown in (a)–(d), respectively.

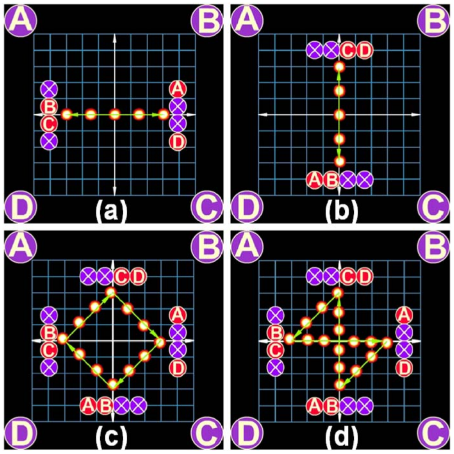

FIG. 4. (Color online) The time traces of a laser spot reflected from the platform are shown on a screen with coordinates. Digitally programed electrical signals to the four ER valves generate complex leveling modes of the platform to direct the laser spot. (a) and (b) show the horizontal and vertical time traces, respectively. The square and "butterfly" time traces are demonstrated in (c) and (d), respectively.

spot is at the origin. Figure 4(a) shows the oscillatory horizontal motion of the reflected beam spot when two opposite pairs of pillars (A with D and B with C) rose alternately. Figure 4(b) shows the case when A and B as a pair and C and D as a pair work alternately to display an oscillatory vertical spot motion. More complex modes are demonstrated in Figs. 4(c) and 4(d). In Fig. 4(c), the motion of the spot forms a clockwise square on the screen when the programed signals follow the input orders according to the arrows, i.e., AD to AB to BC to CD. The spot could also form a "butterfly" trace that crosses the origin, as shown in Fig. 4(d). All traces can be easily reversed. The speed of the trace is tunable with the signal frequency, and the scale of the traced patterns is also controllable to some degree via the voltage signal intensity.

From the above discussions, the flexible platform is seen to have potential application in the fast directional control of reflected light beam. If the system is equipped with a sensor-feedback system, the flexibility demonstrated by the platform can be used to minimize the overall vibration amplitude caused by external sources. Applications in microassembling and microalignment systems, such as optical scanning, inspection systems, etc are also envisioned.

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