Application of Liquid Crystals to Mechanical Engineering

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ABSTRACT

We introduce the application of liquid crystals to machine elements, such as linear actuators and motors. Due to the high shape adaptability of liquid crystals, these elements exhibit the unique characteristics that are not achieved by conventional machine elements.

1 Introduction

Liquid crystals (LCs) are widely used as display materials, and liquid crystal displays (LCDs) have become the mainstream in the display field. As well-known, the mechanism of LCDs is that the light passing through the liquid crystal cell is switched by controlling the molecular orientation direction of rodlike LC molecules.

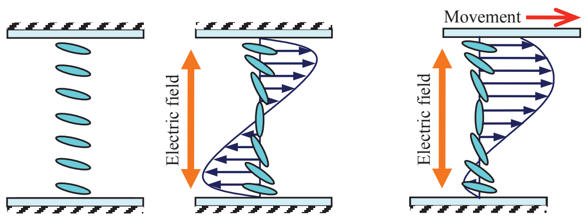
There are some attempts to develop LC devices other than the displays, such as a variable focal lens, an active dumper, a thermometer, and so on. In past decades, we have focused our attention on developing the machine elements using LCs, which are actuators, motors, manipulators, and power generators.

In this study, we introduce some examples of LC machine elements, and discuss the potential of LCs for the future usage in the mechanical engineering field.

2 LC Linear Actuator

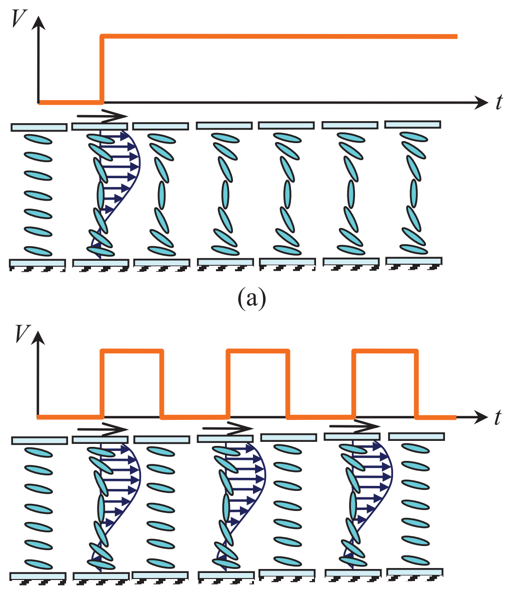
When an electric field is applied to a liquid crystal, the rodlike molecule rotates inducing a velocity gradient around the molecule that results in a bulk flow, called backflow.[1,2] If the liquid crystal is confined between two parallel plates, the induced backflow profile is S shaped (Fig. 1(a)). Because the induced backflow exerts shear stresses on both plates, the upper plate can be driven by the shear stresses if it was free to move in its plane (Fig. 1(b)). This is the principle behind liquid crystal actuators (LC actuators). They have various advantages in comparison with other types of microactuators: simple structure, high shape adaptability, easy downsizing, and low driving voltages.

Recently,[3–8] we investigated experimentally and numerically the velocity profiles of backflow and shear stress at the plate surfaces when a single step-like change in voltage was applied to a liquid crystal (Fig. 2(a)). Indeed, the induced backflow vanishes in a short time because of its viscosity, even though we keep applying an electric field. Therefore, to use LC actuators, in practice, a repeated application of an electric field over an appropriate duration is necessary; that is, we need to return the molecules along the electric field direction to their initial positions by releasing the electric field, and then reapply the electric field (Fig. 2(b)). In this circumstance, frequency and duty ratio also become input parameters. In this study, we describe experiments where, by applying a rectangular wave voltage to a liquid crystal confined between two plates, we are able to drive the free upper plate in its plane.



(a) (b)

Fig. 1 Generation of backflow



(a) (b)

Fig. 2 Application of an electric field

Figure 3 shows an experimental cell used in this study. Whereas the lower glass plate is 20 mm × 20 mm in size, the upper plate is 10 mm × 10 mm in size with a thickness of 0.15 mm and mass of 47 mg. For the lower plate, we sputtered an ITO layer on its upper surface (the side in contact with the liquid crystal), and formed an alignment layer (2.5 wt. % of polyimide dissolved in c-butyrolactone) on the ITO layer. For the upper plate, we sputtered an ITO layer on all surfaces to enable a voltage to be applied easily using a steel rod. An alignment layer was formed only on the lower surface (the liquid crystal side). A number of polystyrene particles were sprayed on the lower plate to keep the two plates parallel and the gap constant.

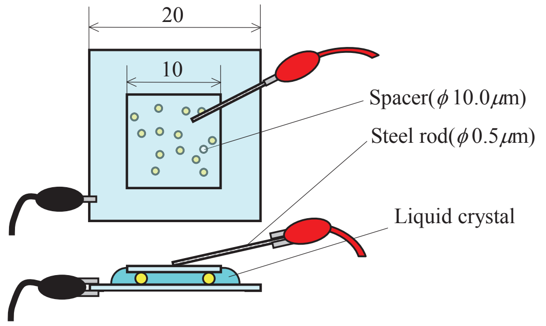


Fig. 3 Experimental cell

We used 4-cyano-4′-pentyl biphenyl (5CB), a low molar-mass nematic liquid crystal in the temperature range of 22.5–35 °C. Under a polarizing microscope, we imaged a small point marked on the upper surface of the upper plate using either a CCD camera (640×480 pixels and 0.75 μm/pixel in space resolution) at 30 frames/s or a high-speed camera (512×512 pixels and 0.80 μm/pixel in space resolution) at 1000–4000 frames/s, saving the video recording to a computer for analysis. The experimental parameters are the applied voltage V=0–10 V, the duty ratio of D=1–50%, the frequency f=1–1000 Hz, and the cell gap (the diameter of the sprayed polystyrene particles) H=1–50 μm.

Figure 4(a) shows the displacement l of the upper plate as a function of the time t when V=10 V, D=5%, H=10 μm, and f=1, 10, and 100 Hz. The upper plate moves as the rectangular wave voltage rises and comes to rest after a short distance. By repeating the voltage signal, the upper plate moves forward in a step-like motion (at f=100 Hz, this motion is not observed in this figure, but is confirmed in video footage using a high-speed camera). For each f, the microscopic displacements l are macroscopically linear with elapsed time t, hence producing macroscopic upper plate speeds that are constant. Similar results were obtained for different frequencies. We take this constant speed as the average speed denoted by U. Figure 4(b) shows the relationship between U and f. At each f, 10 measurements were taken to plot the average value along with its standard deviation. With increasing f, U increases sharply, attains a maximum value of 120 μm/s at f=175 Hz, and then decreases gradually. For lower f, U becomes large with increasing f, because the molecules can respond to the repeating voltage signal. Hence, increasing f corresponds simply to increasing the number of repetitions per unit of time. However, for higher f, the molecules are unable to respond to the change in voltage, so that their rotation cannot induce a satisfactory backflow, and U exhibits a gradual decrease with f.

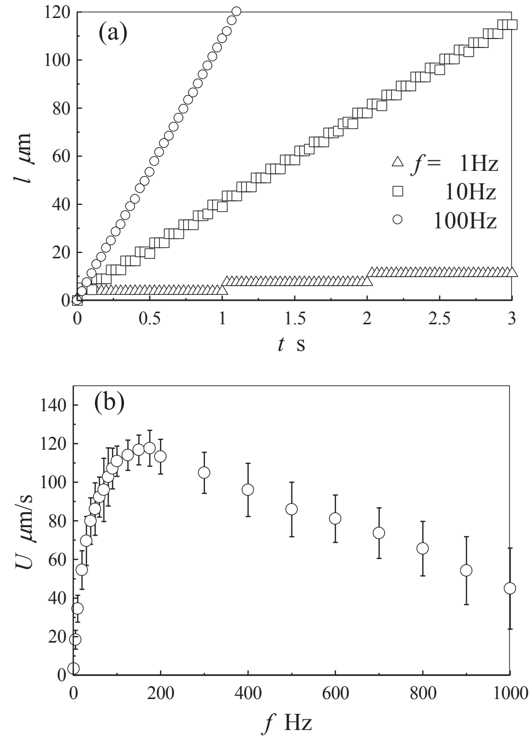


Fig. 4 Experimental results

3 LC Motor

Because of the fluidity of the liquid crystals, there is no restriction on the shape of the objects to be driven, and therefore the driving force acts along the tangential direction of the contact face between the object and the liquid crystal. Hence, if the object has a round shape, then the force produces a rotational motion of the object. We extended the notion further to develop a driving motor of an actuator, aiming to broaden the application of liquid crystal actuators, such as the driving source of MEMS or lab-on-a-chip devices. In this work, we fabricated a micromotor driven by the backflow of liquid crystals and investigated the driving performance in regard to parameters such as the dimensions of the micromotors and the voltage and frequency of the applied electric field.

The liquid crystal micromotor is composed of two concentric glass cylinders of different diameters (Fig. 5). As each cylinder rotates relative to the other, the inner cylinder acts as a rotation axis if the outer cylinder is fixed. The gap between the two cylinders is filled with 5CB. The surfaces of the cylinders are coated with an ITO layer to form an electrode pair. On the ITO layers, a horizontal and circumferential orientation layer covers the outer surface of the inner cylinder (if the orientation layer is horizontal and axial, the inner cylinder moves axially). However, for the outer cylinder, because it is difficult to achieve a horizontal orientation layer in the rubbing process, a homeotropic orientation layer is treated on the inner surface. Therefore, when no electric field is applied, the molecular orientation field between the cylinders has a hybrid orientation profile, and the clockwise rotation of the inner cylinder occurs by the backflow when the electric field is applied. The ITO electrode layers on the cylinders are connected to a function generator to create a pulsed electric field in the liquid crystal. The connection between the electrode and the inner cylinder is through an ionic liquid to reduce friction, which inhibits the cylinder's rotation, the motion of which is recorded by a video camera attached to a microscope. The rotation angle is obtained through image analysis. We constructed and tested a liquid crystal motor (the outer and inner diameters of the outer cylinder are 100 and 80 μm, respectively, and the outer diameter, the length and the mass of the inner cylinder are 70 μm, 1.0 mm, and 0.004 mg).

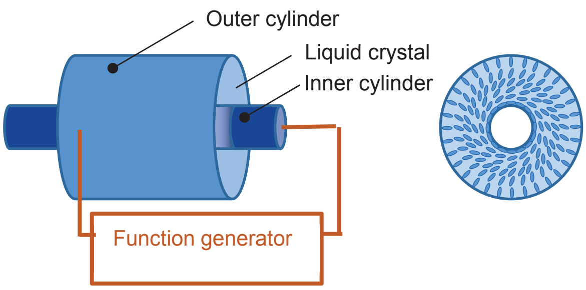


Fig. 5 Schematic and cross section of an LC motor

An image analysis of the time series allows us to evaluate the time dependence of the rotation angle (Fig. 6). With the rotation starting at t = 0 s, the rotation angle monotonically increases linearly with time, resulting in a constant speed of rotation. However, we remark that the time evolution of the angle may be microscopically step-like considering the nature of the applied voltage.

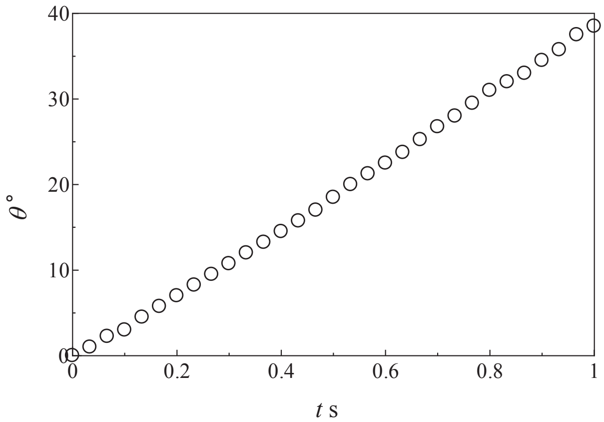


Fig. 6 Evolution of the rotation angle of the inner cylinder

4 Conclusions

In this study, we have introduced and demonstrated the machine elements driven by LCs. Due to the high shape adaptability and low voltage drive of LCs, the LC machine elements might be a strong candidate for the micro mechanical systems, such as MEMS devices and lab-on-a-chip devices.

References

[1] F. Brochard, "Backflow effects in nematic liquid crystals," Mol. Cryst. Liq. Cryst. 23, 51–58 (1973).

[2] D. W. Berreman, "Liquid-crystal twist cell dynamics with backflow," J. Appl. Phys. 46, 3746–3751 (1975).

[3] S. Chono and T. Tsuji, "Proposal of mechanics of liquid crystals and development of liquid crystalline microactuators," Appl. Phys. Lett. 92, 051905 (2008).

[4] A. Sunarso, T. Tsuji, and S. Chono, "Molecular dynamics simulation of backflow generation in nematic liquid crystals," Appl. Phys. Lett. 93, 244106 (2008).

[5] S. Chono and T. Tsuji, "Numerical analysis of characteristics of microactuators driven by liquid crystals," Chem. Eng. Sci. 64, 4625–4631 (2009).

[6] A. Sunarso, T. Tsuji, and S. Chono, "GPU-accelerated molecular dynamics simulation for study of liquid crystalline flows," J. Comput. Phys. 229, 5486–5497 (2010).

[7] A. Sunarso, T. Tsuji, and S. Chono, "Three-dimensional molecular dynamics simulations of re-orientation process and backflow generation in nematic liquid crystals under application of electric fields," J. Appl. Phys. 110, 044911 (2011).

[8] T. Tsuji, S. Chono, and T. Matsumi, "Velocity profiles of electric-field-induced backflows in liquid crystals confined between parallel plates," J. Appl. Phys. 117, 054501 (2015).