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Fundamental Study on New Micro Fluidic Drive Method Based on Liquid Crystalline Backflow

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Abstract: In this study, we propose a one-dimensional simple model for predicting the performance of the new micro fluidic drive and then we have a research of the control method based on liquid crystalline backflow by combining the motion of the upper plate of a liquid crystal cell and the flow of a liquid crystal. Comparison of the numerical predictions and the experimental results shows that the proposed model is useful to predict qualitatively the motion the upper plate. The drive efficiency is affected by applied voltage, the frequency, the duty ratio and the gap of the cell. The ideal drive quality can be achieved when the rotation range of the molecules at the center of the cell is controlled within 50-80°.

Keywords: Backflow, Leslie-Ericksen theory, liquid crystal, micro fluidic drive

INTRODUCTION

The molecular arrangement of nematic liquid crystal exhibits a certain degree of order. It results in anisotropy of the mechanical, electrical, magnetic, and optical properties (Beris and Edwards, 1994). These unique characteristics make LC particularly suitable for many applications (Buguin *et al*., 2006; Chandrasekhar, 1992). Until now, the most successful example is LCD. Accompanied by the change in optics, due to the effect of backflow, the flow will be induced by the rotation of the liquid crystalline molecules. In the LCD industry, the flow is suppressed as far as possible because the bad effect to LCD quality. Along with the development of the micro fluidics system, especially the lap-on-chip technology, the liquid crystalline flow in the micro or nano system has aroused the attention of researchers.

In this study, we proposed a new method to drive and control the micro fluid based on liquid crystalline backflow effect. This study covers some important topics on the backflow effect, including theoretical derivations and confirming experimental results. This study work is expected to make important impacts on new application of liquid crystal and to open doors for further research along these topics.

In the former work (Chono and Tsuji, 2008; Chono and Tsuji, 2009; Liu *et al*., 2006), we explained the mechanism of the backflow and the effect factors including the orientation parameters, the gap of the liquid crystalline cell, the applied voltage and etc., and proved the possibility of the liquid crystalline flow to micro fluidic drive and control. It is impossible to achieve continuous driving to micro-fluid through the implosion of the DC electric field, the AC electric field is the best choice, so in this paper, the influence of the AC field such as the voltage, the frequency and the ratio duty were discussed. In order to show the driven characteristics clearly, we have proposed a one-dimensional simple model (Fig. 1) for predicting the performance of liquid crystalline backflow by combining the motion of the upper plate of a liquid crystal cell and the induced flow by the AC electric field.

This study proposes a new micro-fluidic drive and control method, through theoretical and experimental study, the continuous drive can be achieved by applying the AC electric field to the liquid crystal and the object

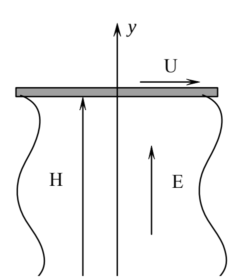

Fig. 1: Computational coordinate

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will be driven to move with oscillating. Moreover, the drive efficiency is affected by the applied voltage, the frequency, the duty ratio and the gap and the high drive quality can be achieved by fix the rotation range of the molecules at the center of the cell within 50-80° when the gap is smaller than 70 μm. The theoretical calculation results agree well with the experimental ones.

NUMERICAL CALCULATION

As to the rigor of the study, three-dimensional model should be selected, but comparing to the gap of two parallel plates, the plate is large enough to ignore the impact of the plate end, so considering the computational efficiency and accuracy, the approximately one-dimensional model was selected. The Leslie-Ericksen (L-E) theory was selected as the constitutive equation of the liquid crystalline backflow (De Gennes and Prost, 1993; Doi and Edwards, 1986).

The liquid crystalline isothermal flow induced by the electric field can be achieved by solving the equations below:

Continuity equation:

$$\nabla \cdot \mathbf{v} = 0 \tag{1}$$

Linear momentum equation:

$$\rho\left\{\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v}\cdot\nabla)\mathbf{v}\right\} = (\varepsilon_{\perp}\mathbf{E} + \Delta\varepsilon\mathbf{n}\cdot\mathbf{E}\mathbf{n})\cdot\nabla\mathbf{E} - \nabla p + \nabla\cdot\boldsymbol{\tau} \tag{2}$$

Linear angular momentum equation:

$$\mathbf{n}\times\left\{\frac{\partial F}{\partial \mathbf{n}} - \nabla\cdot\left(\frac{\partial F}{\partial \nabla\mathbf{n}}\right) - \Delta\varepsilon\cdot\mathbf{E}\mathbf{E} + (\alpha_3-\alpha_2)\mathbf{N} + (\alpha_2+\alpha_3)\mathbf{A}\cdot\mathbf{n}\right\} = 0 \tag{3}$$

Composition equation:

$$\boldsymbol{\tau} = \alpha_1\mathbf{nnn}\cdot\mathbf{A}\cdot\mathbf{n} + \alpha_2\mathbf{nN} + \alpha_3\mathbf{Nn} + \alpha_4\mathbf{A} + \alpha_5\mathbf{nn}\cdot\mathbf{A} + \alpha_6\mathbf{A}\cdot\mathbf{nn} - \frac{\partial F}{\partial \nabla\mathbf{n}}\cdot(\nabla\mathbf{n})^T \tag{4}$$

v is the velocity vector, ρ the fluid density, p the pressure, τ the extra stress tensor, n the unit vector indicating the average direction of the liquid crystal molecules called the director, E the electric-filed vector, $\varepsilon_{\perp}$ the dielectric constants perpendicular to the director, Δε the anisotropy of the dielectric constants. α_i are the Leslie viscosities. *F* is the free energy density due to spatial distortion of the director, defined as follows according to the Frank theory:

$$2F = K_1(\nabla\cdot\mathbf{n})^2 + K_2(\mathbf{n}\cdot\nabla\times\mathbf{n})^2 + K_3|\mathbf{n}\times\nabla\times\mathbf{n}|^2 \tag{5}$$

Here, K_1, K_2 and K_3 are the elastic constants representing the splay, twist and bend deformations of the director, respectively.

As shown in Fig. 1, the force acting on the upper plate includes driving stress induced by the liquid crystalline flow and the friction between the plate and the liquid crystal molecules. Suppose the mass of the plate as *m*, moving velocity as *U*, the area contacting with the liquid crystal molecules as *A*, the friction coefficient as μ_k, the motion equation of the upper plate is:

$$m\frac{dU}{dt} = \tau_w A - \mathrm{sgn}(U)\mu_k mg \tag{6}$$

τ_w is the stress acting on the upper plate, can be expressed as:

$$\tau_w = \tau_{yx}\Big|_{y=H} \tag{7}$$

It is worth mentioning that the upper plate is stationary when the stress induced by the flow is smaller than the static friction force $\mu_s mg$.

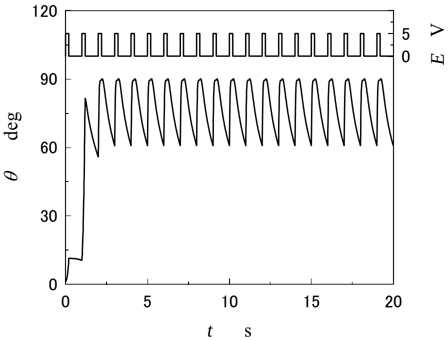
The boundary condition is: velocity is 0 at the lower plate and the orientation state is 0° for twist angle, 5° for tilt angle at two plates.

The finite difference and fourth-order Runge-Kutta methods were used to equation discretization, the mesh size is $\Delta y = H/100$ and the time interval is $\Delta t = 10^{-8}/fs$. The initial values are: the plates and the liquid crystal is stationary, the twist and tilt angle of the liquid crystalline molecules is 0 and 2°, respectively within all the computational area. The switch time of the electric field is supposed to less than $1\,\Delta ts$.

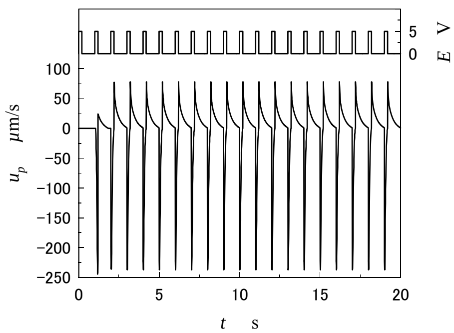
The liquid crystal material we used is 5CB whose material constants are shown in Table 1.

Table 1: Material constants of 5CB (Ericksen, 1960)

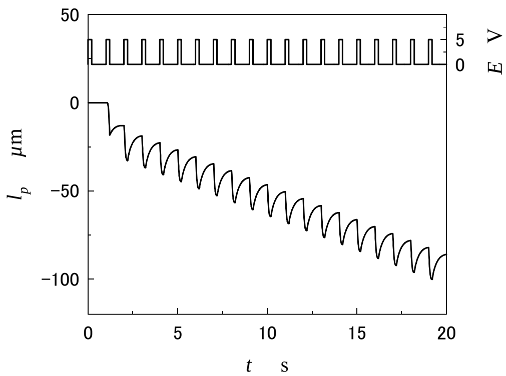
α_1 α_2 α_3 α_4 α_5 α_6 (Pa•S)	K_1 K_2 K_3 (N)	$\varepsilon_{//}$ $\varepsilon_{\perp}$ (F/m)
$\times10^{-2}$	$\times10^{-12}$	$\times10^{-11}$
0 -8.6 -0.4 8.9 5.9 -3.1	6.37 3.81 8.60	15.7 5.7



(a) The molecules' rotate angle over time



(b) Velocity of the upper plate



(c) Moved distance of the upper plate

Fig. 2: The change of typical quantities over time

SIMULATION RESULTS

Figure 2 shows the change of rotated angle θ of the liquid crystal molecules at the center of the cell, the velocity and the moved distance of upper plate over time. The applied electric field is AC of 5 V with 1 Hz frequency and 20% duty ratio. The gap of the cell is 50 μm, and the total computational time is 20s. From Fig. 2a we can see that in the first 1s, within the part that the electric field was applied (0-0.2s), the molecules rotated counter-clockwise from 2 to 12°, and within the after 0.8s (0.2-1.0) when the electric field was off, the rotated angle reduced a little. In the 2nd s, the rotated angle increased 70° within the applied 0.2s and reduced 24 to 58° at the end of the 2nd s. From the 3rd s, the rotating motion of the molecules entered a cycling phase and changed within 60 and 90°. The whole changing process is the interaction of electric and viscoelastic force. In the first 2 sec, the spray deformation of the liquid crystal molecues is small, so the resulting viscoelastic restoring stress is smaller than the electric stress. With the increasing of the molecular rotation, the viscoelastic stress reaches the maximum when the rotated angle is 90° and after that the motion of the molecules entered a circling state.

Corresponding to the molecules' rotation, the change of the moving velocity of the upper plate over time was shown in Fig. 2b. At the 1sts, the upper plate was stationary, and from the 2nds, within the appalling 0.2s of the electric, the velocity increased from 0 to max, then decreased, the direction was minux X. When the electric field was off, because the rotation of the molecules turned to clockwise, the velocity of the upper plate increased towards positive X, then decreased. From the 3rd s, the change of the velocity showed a repeated trend. The max value was 230 μm/s of the minux X and 75 μm/s of the positive X.

From the velocity, we could get the moving distance of the upper plate through simple calculation which was shown in Fig. 2c. The plate moved with a average velocity of 3.5 μm/s to the minux X while oscillating.

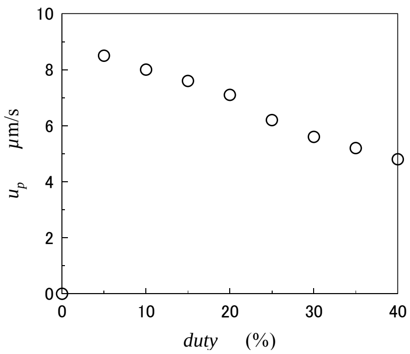


Fig. 3: Effect of the duty on the velocity magnitude

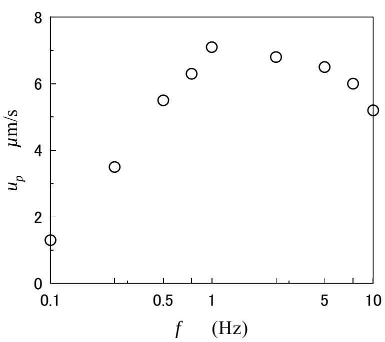


Fig. 4: Effect on the frequency on the velocity magnitude

In order to get the optimal driven effect, the influence of the frequency, duty ratio, the voltage of the implied AC and the gap of the liquid crystal cell. The average speed of the upper plate was treated as the quality standard of the driven effect.

In Fig. 3 and 4, we summarized the effect of the frequency and the duty ratio on the average velocity of the upper plate. The average velocity means the velocity after the upper plate reached steady state (after 3s). From the Fig. 3 we can see with specific frequency of 1 Hz, voltage magnitude of 5 V and gap of 50 μm, the duty ratio of 5% is the best to drive the upper plate, the one that less than 5% could not induce flow and the one more than 5% would create energy waste. On the other hand, when the duty ratio is fixed as 20%, from Fig. 4 it is easy to see that the frequency of 1 Hz is the most proper one. With the parameters of duty ratio 5%, frequency 1 Hz, voltage 5 V and gap 50 μm, the calculated optimal moved distance over time of upper plate was shown in Fig. 5, compared with Fig. 2c, the following conclusion can be obtained that the choice of these parameters suppressed the returning motion of the upper plate, and the average velocity of upper plate was about 8 μm/s to the minux X. By selecting the proper applied and terminated time ratio of the electric field,

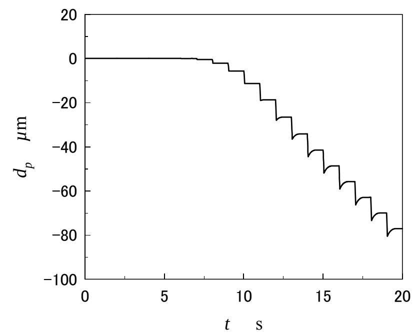


Fig. 5: Moved distance of the upper plate

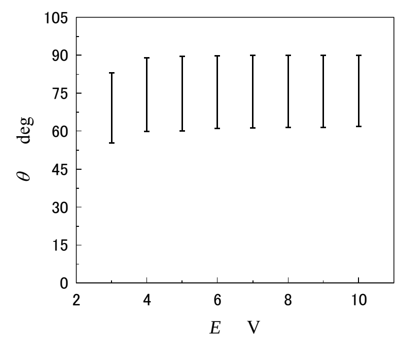


Fig. 6: Effect of applied voltage on the rotate angle range

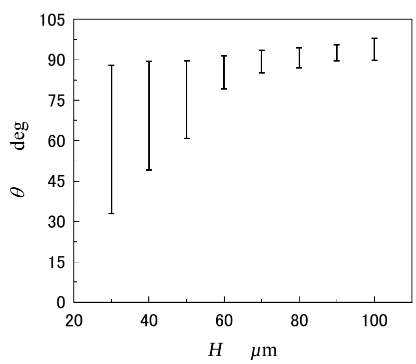


Fig. 7: Effect of the gap on the rotated angle range

the rotated range of the molecules can be controlled and that is the key factor to affect the motion state of upper plate (equal to drive quality). The rotated range corresponding to Fig. 5 is 50-80°, and within this range, the electric force can get the highest work efficiency overcoming the viscoelastic resistance of the molecules. As same as to control the frequency and ratio duty of the applied voltage, we can also control the drive quality by controlling the magnitude of the voltage and the size of the cell. As the magnitude, it is easy to see in Fig. 6 that the magnitude of the voltage could only make effect on the rotate angular velocity, not the rotate range of the molecules. As the gap, because the existence of the effect of the anchoring condition, it is necessary to discuss it in detail. From the calculation results of upper plate moving velocity calculated with parameters of same applied electric filed intensity of 1 V/10 μm and different gap of 40-90 μm, it can be see that with the increasing of the gap, the motion state of upper plate changed, so it can be speculated that the rotated range of the molecues changed. The speculation was confirmed by Fig. 7, the rotate angle range of the molecules at the center of the liquid crystal cell. We can see that when the gap was larger than 70 μm, the rotated angle exceeded 90° and along with the increase of the gap, the exceeded angle increased. When the gap is small, the effect of the anchoring condition can reach the center of the cell, when the electric field is off, under the effect of the anchoring, the director can return to initial state, so with the same frequency and ratio duty, it is easy for smaller gap to keep the rotated range. As the gap reach a certain level, the effect of the anchoring condition becomes weak. When the electric field switched off, because of the coupling between molecules rotation and hydrodynamic motion, fluid flow is induced and the fluid motion results in a counterclockwise rotation of the molecules at the center to over 90°.

EXPERIMENT AND RESULTS

We also did the experiment to verify the simulation results, the parameters were shown in Table 2.

Contrast of the simulation and experiment results was shown in Fig. 8, both simulation and experiment were done under same initial conditions of AC 10 V with 1 Hz frequency and 20% duty ratio, we can see that the simulation result is in well agreement with the experimental result.

Table 2: Experimental parameters

Voltage (V)	Gap (μm)	Twist angle (°)	Tilt angle (°)
10	110±5	0	1~5

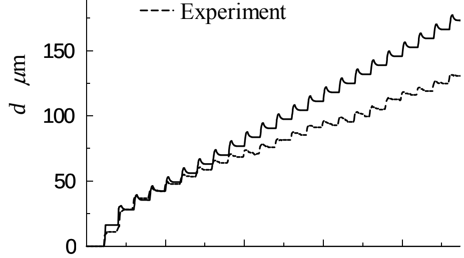


Fig. 8: Contrast of the simulation and experiment results

CONCLUSION

This article proposed a new micro-fluidic drive and control method, through theoretical and experimental study, the conclusions below can be achieved:

- Continuous drive can be achieved by applying the AC electric field to the liquid crystal.
- The object will be driven to move with oscillating.
- The drive efficiency is affected by the applied voltage, the frequency, the duty ratio and the gap.
- The high drive quality can be achieved by fix the rotation range of the molecules at the center of the cell within 50-80° when the gap is smaller than 70 μm.
- The theoretical calculation results agree well with the experimental ones.

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