Study of switching behavior in bistable twisted nematic liquid crystal displays

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ABSTRACT

We investigate the switching bistability based on the interaction between dynamic flow and director rotation in twisted nematic liquid crystal cells. Numerical calculation shows that there exists a general type of bistable twisted director configurations. Two specific cases are verified experimentally.

Keywords: bistability, twisted nematic, liquid crystal displays, backflow, switching

1. INTRODUCTION

Twisted nematic (TN) and super-twisted nematic (STN) liquid crystal displays (LCD) are used widely in many information display systems. Recently, a bistable TN (BTN) LCD has been demonstrated^{1,2}. This BTN is based on a gross mismatch of the natural twist of the liquid crystal director and the rubbing boundary conditions of the two LC cell surfaces. If the LC cell alignment favors a Φ -twist, then for some value of natural helical pitch P , the LC cell can exist either in the Φ -twist state or the $(\Phi + 2\pi)$ -twist state. Roughly speaking, in the absence of pretilt of the director, the natural twist of the LC cell should be about $\Phi + \pi$ in order for bistability to occur. Hence the d/P ratio, where d is the LC cell thickness, should be about $0.5 + \Phi/2\pi$.

While practical displays have been made using this principle, the switching behavior of such BTN is not well-known. It is evidently related to the hydrodynamics of the twisted nematic liquid crystal cell (TNLCC). There are two parts in the hydrodynamics of TNLCC: dynamic flow and director rotation. The interaction between dynamic flow and director rotation was shown to be responsible in a theoretical explanation of the "bounce" phenomenon observed in the light transmission of TNLCC^{3,4}. More generally, a comparison between the results obtained by including and neglecting the fluid motion showed that under certain circumstances, dynamic flow can play a critical role in governing director rotation.

The purpose of this paper is to investigate the switching bistability that can originate from the flow effect on director rotation in TNLCC. We first give an outline of the physical mechanism underlying the

seemingly "abnormal" behavior of director motion. Our understanding of the mechanism is then used as a guide to seek the switching bistability that can be realized in properly prepared TNLCC's. Several bistable configurations were proposed and verified through the numerical solution of the Ericksen-Leslie equations. The bistable configurations consists of two twist states of twist angles Φ and $\Phi + 2\pi$, respectively, with Φ specified by the relative arrangement of the two substrates with homogeneous alignment conditions.

For a given configuration of $\mathbf{n} \equiv (\sin \theta \cos \phi, \sin \theta \sin \phi, \cos \theta)$, the twist angle is defined as $\int_0^d \partial_z \phi(z) dz$, with the z axis being the substrate normal. We find that the switching bistability can be realized for $-\pi/2 \leq \Phi \leq 0$ in cells with surface alignment pretilt angle $\sim 10^\circ$ as measured from the substrate. In our calculations, we vary the d/P ratio in order to obtain bistability of the final state at the Φ - or the $(\Phi + 2\pi)$ -twist state. We also investigate the driving voltage waveform necessary for switching between the two states. The resulting variation in light transmittance is calculated by using the Jones matrix approach. The predicted switching bistability is confirmed by experiments. However, the observed range of d/P , within which the switching bistability can occur, shows a systematic deviation from the predicted values. Such deviation is observed to increase as the cell thickness decreases, and can be appreciable for $d \leq 7 \mu\text{m}$. Apart from the d/P ratio, quantitative agreement between theory and experiment was obtained in the time profile of light transmission. It should be pointed out that the $\Phi = -\pi/2$ case has been reported recently, but the observation was for wedge shaped cells only and the driving waveform is different from ours⁵, while the $\Phi = 0$ case, reported long ago, was observed in the cells with large cell thickness ($d \sim 50 \mu\text{m}$) and large pretilt angle ($> 35^\circ$)⁶. The results of our study show that the $\Phi = -\pi/2$ and $\Phi = 0$ cases have the same dynamical symmetry and similar flow effect, and can thus be regarded as two specific examples of a general kind of switching bistability phenomenon.

2. PHYSICAL MECHANISM OF BACKFLOW EFFECT

Without the inertial terms, the hydrodynamic equations of Ericksen and Leslie have the form

$$\partial_z \sigma'_{zx} = 0, \quad \partial_z \sigma'_{zy} = 0, \quad (1)$$

$$\mathbf{n} \times (\mathbf{h} + \mathbf{h}') = 0, \quad (2)$$

where z axis is perpendicular to the substrate, σ' is the viscous stress tensor, $\mathbf{h}$ the molecular field from elastic distortion and electric field-induced free energy, and $\mathbf{h}'$ the viscous molecular field. Here the spatial dependence of all quantities is noted to vary with z only. The fluid motion is parallel to the substrates, with the two nonzero velocity components v_x and v_y . Explicit expressions for the quantities in Eqs. (1) and

(2) can be found in Ref. ⁷. The boundary conditions are that at the substrates, $\mathbf{v} = 0$ and the directors are time-independent.

The following dynamical symmetries were found numerically and proved to be rigorous analytically. With the directors at the lower and upper substrates denoted by $\mathbf{n}^L$ and $\mathbf{n}^U$, if $n_x^L = n_x^U$, $n_y^L = -n_y^U$, $n_z^L = n_z^U$, then the time-varying directors and velocities obey the relations

$$n_x(z) = n_x(d-z), \quad n_y(z) = -n_y(d-z), \quad n_z(z) = n_z(d-z), \quad (3)$$

together with

$$v_x(z) = -v_x(d-z), \quad v_y(z) = v_y(d-z), \quad (4)$$

provided the initial state has such symmetries. In this paper, the $\Phi = -\pi/2$ case corresponds to $n_x^L \sim \sqrt{2}/2$, $n_y^L \sim \sqrt{2}/2$, $n_z^L > 0$, and the $\Phi = 0$ case corresponds to $n_x^L \sim 1$, $n_y^L \sim 0$, $n_z^L > 0$.

The physical picture of switching dynamics may be described as follows. When a strong electric potential is applied across the cell, the field-induced correlation length can be much smaller than the cell thickness. As a consequence, the directors near the substrates can exhibit large elastic distortions, leaving the directors throughout the central part of the cell (nearly) uniformly vertical. When the large voltage is switched off, the large local elastic distortion energy density near the substrates, and consequently the large molecular field $\mathbf{h}$, can give rise to fast rotation of the directors. The near-substrate rotation of the directors would inevitably induce a flow velocity field due to the coupling between $\mathbf{n}$ and $\mathbf{v}$ through viscous interaction. In the law of friction, the forces are proportional to the fluxes, one of which is just the conventional $\partial_i v_j + \partial_j v_i$ term and the other one is the torque $\mathbf{N} = \dot{\mathbf{n}} - \boldsymbol{\omega} \times \mathbf{n}$ with $\boldsymbol{\omega} = \nabla \times \mathbf{v}/2$. The latter determines the rotational field $\boldsymbol{\omega}$ near the substrates. In all the cases we have studied, it is found that the near-substrate $\dot{\mathbf{n}}$ always induces a local $\boldsymbol{\omega} \times \mathbf{n}$ in the same direction, which means $\boldsymbol{\omega}$ is parallel to $\mathbf{n} \times \dot{\mathbf{n}}$. The knowledge of the near-substrate $\boldsymbol{\omega} = (-\partial_3 v_2, \partial_3 v_1, 0)$, plus the boundary conditions and the dynamical symmetry relations, are sufficient to qualitatively determine the whole velocity field in the cell. The spatial variation of the velocity field near the midplane is therefore completely determined. As the directors throughout the central part of the cell are nearly homogeneous and hence the elastic distortion molecular field is weak, their motion is dominated by the gradient of the flow field. From angular momentum conservation, the initial flow at the midplane has to be opposite to those near the substrates. This is the origin of the so-called "backflow" phenomenon.

3. SWITCHING BISTABILITY

Figure 1: Schematic illustration of the driving voltage waveforms $V_A(t)$, $V_A'(t)$, $V_B(t)$, and $V_B'(t)$.

We first consider cells in which the surface treatment imposes $\mathbf{n}(0) = \mathbf{n}^L$ at the lower substrate and $\mathbf{n}(d) = \pm \mathbf{n}^U$ at the upper substrate. $\mathbf{n}^L$ and $\mathbf{n}^U$ satisfy the symmetry relation (3) for the $\Phi = -\pi/2$ case. We focus on the case of small pretilt angle, i.e., $n_z^L = n_z^U = \sin \psi_p$ with $\psi_p \sim 10^\circ$, which is typical for rubbed polyimide-coated substrates. We numerically find that if $d/P \sim 0.4$, there exists a switching bistability which may be explained from the mechanism of backflow. The two twist states involved in the switching bistability are the $-\pi/2$ - and the $3\pi/2$ -twist states. The $-\pi/2$ -twist state can be switched to the $3\pi/2$ -twist state by applying the driving waveform $V_A(t)$, and the reverse switching process can be realized by applying the driving waveform $V_B(t)$. Both $V_A(t)$ and $V_B(t)$ first jump from zero to a holding voltage V_H that is higher than a threshold value and lasts a certain duration. V_H is switched off suddenly in $V_A(t)$, but gradually in $V_B(t)$. $V_A(t)$ and $V_B(t)$ are schematically illustrated in Fig. 1.

For the $\Phi = 0$ case, we consider cells in which the surface treatment imposes $\mathbf{n}(0) = \mathbf{m}^L$ at the lower substrate and $\mathbf{n}(d) = \pm \mathbf{m}^U$ at the upper substrate. $\mathbf{m}^L$ and $\mathbf{m}^U$ satisfy the symmetry relation (3). Small pretilt angle is assumed. It is found numerically that if $d/P \sim 0.8$, there is a similar switching bistability resulting from the backflow effect. The two twist states involved in the switching bistability are the 0- and the 2π -twist states. The 0-twist state can be switched to the 2π -twist state by applying the driving waveform $V_A'(t)$, and the reverse switching process can be realized by applying the driving waveform $V_B'(t)$. V_A' and V_B' are similar to V_A and V_B , respectively, as shown in Fig. 1, implying a similar underlying mechanism in the two cases. In essence, right after the holding voltage V_H is switched off,

the fast rotation of the directors near the substrates induces the flow velocity pattern which drives the midplane director towards a state with a larger twist angle ($3\pi/2$ and 2π , respectively), in a direction opposite to what the elastic distortion would enforce. Whether the final state can be of larger or smaller twist angle depends on the strength of the viscous molecular field $\mathbf{h}'$ in the initial stage of the relaxation process. The strength of $\mathbf{h}'$ is controlled by the manner with which V_H is switched off, i.e., suddenly or gradually. It is clear that more abruptly V_H is switched off, larger would be the strength of $\mathbf{h}'$.

Experimental results showed that by properly choosing the ratio d/P , the switching bistability can be realized. The two distinct driving waveforms in each case strongly imply that the controlled dynamic flow is responsible for the selection of the final state. The structure of TNLCC comprises a pair of transparent electrodes and polyimide alignment layers on the lower and upper glass substrates separated by a gap d . The cells were filled with a commercial liquid crystal (LC) doped with a chiral additive, leading to a natural helical pitch P . The LC and the chiral additive used are MLC-6218 or MLC-7500-000, and S-811 of Merck. The concentration of S-811 was varied to adjust d/P and an initial twist angle in the uniform cell. The two cases discussed above were prepared and measured for $d = 2.5, 5.0$, and $7.0 \mu\text{m}$. The electro-optical response, depicted in Figs. 2 and 3, was measured by placing the cells between crossed linear polarizers and making the optical axis of the incident light aligned by $\pi/4$ (for $\Phi = -\pi/2$) or parallel (for $\Phi = 0$), respectively, to the rubbing direction of the lower substrate.

Figure 2: Electro-optical response measured for the $\Phi = -\pi/2$ cell sandwiched between crossed linear polarizers. The optical axis of the incident light aligned by $\pi/4$ to the rubbing direction of the lower substrate.

Figure 3: Electro-optical response measured for the $\Phi = 0$ cell sandwiched between crossed linear polarizers. The optical axis of the incident light aligned parallel to the rubbing direction of the lower substrate.

The experimental data were modelled by calculating the director time dependence under the various voltage pulses. Using the Jones matrix method, the time-varying light transmittance is calculated from the director configurations. The involved material and optical constants are listed in Appendix. The calculated light transmittance of the cell sandwiched between crossed polarizers is depicted in Fig. 4 for the $\Phi = -\pi/2$ case, and in Fig. 5 for the $\Phi = 0$ case. For the case of $\Phi = -\pi/2$, it is interesting to compare Figs. 2 and 4. Experimentally as well as theoretically, an "optical bounce" is observed in both switching directions. The shape of the transmittance curves, and the rise and fall times are quite well predicted. For the case of $\Phi = 0$, (Figs. 3 and 5), the agreement is also excellent. While there is a bounce in 2π to 0 switching, the opposite switching direction is fast and clean. Both the experimental and theoretical risetime is about 20 msec. Thus the agreement between theory and experiment is remarkable. It should be noted that the calculated results are sensitive to the ordinary and the extraordinary refraction indices, the cell thickness, and the light wavelength, and may exhibit non-monotonic behavior. Thus the quantitative agreement between the calculated and the observed results show that the kinematic behavior of the directors are correctly obtained, in spite of the fact that the experimental d/P value systematically deviates from that predicted theoretically. More recent experimental data show that deviations tend to vanish for thicker cells, implying that the dynamics in thin cells may involve novel physics beyond the conventional theory.

Figure 4: Calculated electro-optical response for the switching from the $-\pi/2$ -twist state to the $3\pi/2$ -twist state (solid line with open squares) and that from the $3\pi/2$ -twist state to the $-\pi/2$ -twist state (dashed line with solid circles), respectively.

Figure 5: Calculated electro-optical response for the switching from the 0-twist state to the 2π -twist state (solid line with open squares) and that from the 2π -twist state to the 0-twist state (dashed line with solid circles), respectively.

4. CONCLUSION

In summary, we have presented a theoretical picture of the switching behavior between the Φ and $\Phi + 2\pi$ states of the BTN. This switching is based on the effect of backflow on the LC director under special conditions of driving voltages. Our theory agrees well with experimental data obtained with sample BTN cells for both the $\Phi = -\pi/2$ and $\Phi = 0$ cases. Further refinement of this theory to include inertial effects of the initial state should allow us to optimize the driving voltage necessary for such switching bistability.

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APPENDIX

Here we give the various material and optical constants used in the present computation. The pretilt angle of substrate alignment is 8° . For the elastic constants K_1 , K_2 , K_3 , and the viscosity coefficients α_i , ($i = 1, \dots, 6$), the respective ratios used in the numerical calculation are listed in Table 1. Since very few measured viscosity coefficients are available, here the ratios of viscosity coefficients are taken from Ref. [4], suitable for MBBA. The ratios of elastic constants for the specific samples in experiments are not available either. Here K_2/K_1 and K_3/K_1 are taken from the respective ratios for MLC-5800-000. These dimensionless material constants, together with the ratio d/P , determine the solution behavior of Eqs. (1) and (2). Various optical parameters in the experiments are directly used in the calculation of light transmission. They are listed in Table 2 for the $\Phi = -\pi/2$ and $\Phi = 0$ cases. The numerical solutions of Eqs. (1) and (2) are obtained by choosing $d/P = 0.425$ for $\Phi = -\pi/2$ and $d/P = 0.85$ for $\Phi = 0$. The time unit is given by $\tau = d^2\alpha_4/K_1$. Comparing the time-varying light transmittance calculated from the numerical solution with the measured electro-optical response yields $\alpha_4/K_1 = 1.56 \times 10^6 \text{cm}^{-2}\text{sec}$ for MLC-6218 and $\alpha_4/K_1 = 2.30 \times 10^6 \text{cm}^{-2}\text{sec}$ for MLC-7500-000.

Table 1: The dimensionless material constants used in the numerical calculation of hydrodynamics.

α_1/α_4	0.07808	α_2/α_4	-0.9315	α_3/α_4	-0.01435
α_5/α_4	0.5565	α_6/α_4	$(\alpha_2 + \alpha_3 + \alpha_5)/\alpha_4$		
K_2/K_1	0.5429	K_3/K_1	1.52		

Table 2: The optical parameters used in the calculation of light transmission. n_e and n_o are, respectively, the extraordinary and ordinary refraction indices of the LC. $\epsilon_{||}$ and $\epsilon_{\perp}$ are the parallel and vertical components of the dielectric tensor of the LC. λ is the wavelength of the laser.

Φ	$-\pi/2$ (material: MLC-6218)	0 (material: MLC-7500-000)
n_e	1.6564	1.5869
n_o	1.4976	1.4830
$\epsilon_{ }$	15.6	14.8
$\epsilon_{\perp}$	4.6	4.6
λ	0.543 μm	0.514 μm
d	7.0 μm	5.0 μm

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