Study on phase retardation characteristic of LCVR using dispersion analysis and SVM

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Abstract: To calibrate the phase retardance of a Liquid crystal variable retarder (LCVR), its birefringence dispersion characteristic was analyzed, and the Support vector machines (SVM) algorithm was adopted to establish the prediction model. The obtained SVM decision function was used as a part of LCVR phase retardance, which was generated by the driving voltage. The experimental verification was carried out with a 568 nm laser. The results show that the deviation of the experimental value and the theoretical value is about 0.0061λ. SVM method could be used as an effective method for LCVR phase retardance characteristic calibration.

Key words: liquid crystal variable retarder (LCVR); birefringence dispersion; support vector machines (SVM); phase retardance calibration

1 Introduction

Compared with conventional imaging, the polarization imaging is able to not only obtain the target´s intensity, spectral and spatial information, but also reflect the degree of polarization, polarization azimuth, polarization ellipticity and rotation, which has improved the accuracy of target detection, the target identification rate, wear cloud and penetration fog and so on[1], has become an important research area in remote sensing. With the development of liquid crystal technology, liquid crystal phase variable retarder (LCVR) has been applied in the full polarization imaging technology, and can realize the precise modulation of the full polarization of the light in the visible near infrared band.

The LCVR is one of the phase retardance devices with the operating principle of the electronically controlled birefringence effect. It has the advantages of low driving voltage, low power, easily controlled, fast response, strong anti-interference ability, low cost and small volume[2].Reference[3-4] present two -LCVRs are located before the polarizer for the analysis of the input polarization state. Reference[5-7] present a spectral polarization imaging system based on a Acousto-Optic Tunable Filter (AOTF) and two -LCVRs tuning, the full polarization images of the 4 Stokes parameters are obtained. The advantage of this scheme is it has no moving parts, avoiding the relative observation of the target movement, working stability, and image processing is relatively simple. The defect is the LCVR degrades the measurement quality, and attentions have to be paid on them. One is the interference occurring in the cavity of the LCVR, the other is the temperature influence on the LCVR, which introduces even more complicate errors to the measurement results. For each LCVR, in order to realize the accurate modulation of the light, we must calibrate the function between phase retardance and corresponding drive voltage in different wavelength and environment.

At present, the study of LCVR phase retardance characteristics in the following aspects: Firstly, the specific points ($0.5\pi, \pi, 1.5\pi, 2\pi$) are calibrated by the method of experimental measurement[8-9]. This method is simple, but not universal. When the retardance is about 0.5π, even small shifts in the driving voltage can cause large change of retardance, thus, the error is too large. Secondly, the mathematical formula of LCVR between the emergent light intensity and phase retardance is derived, then the retardance curve can be conducted using the least squares fitting method[10-11]. Thirdly, the liquid crystal birefringence dispersion characteristics is studied[12], the relationship between the driving voltage and phase retardance is obtained, and the curve is obtained by the least squares fitting. The fitting precision of the last two methods are not high.

In order to improve the fitting precision, this paper puts forward the support vector machine (SVM) model to curve fitting analysis for nonlinearity and predict. The intensity of output light in different driving voltage is determined by the setup, which is constructed based on Stokes-Muller theory. Then using MATLAB to calculate the data sample of the phase retardance in corresponding with driving voltage, the function of retardance characteristic is established by SVM decision function, which realizes the prediction of the phase retardance in any driving voltage. At the same time, the feasibility of the method is verified by experiments.

2 Experimental data acquisition principle and device

2.1 Experimental setup and working principle

The intensity modulation method is adopted to measure the retardance of LCVR. Optical setup for calibrating the phase retardance of a LCVR, is shown in Fig.1.

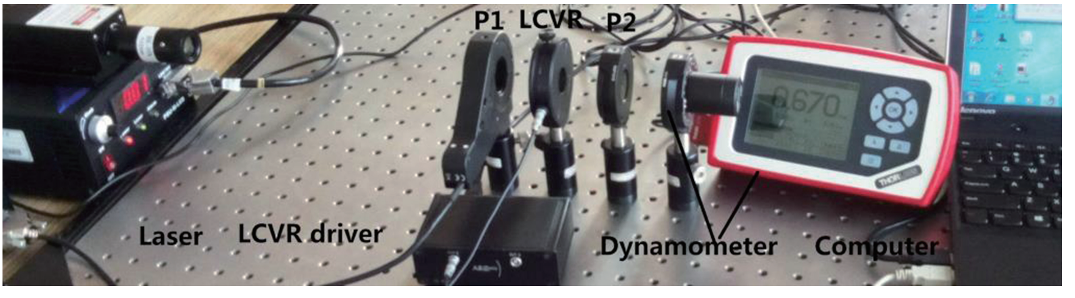


Fig. 1 The experimental Setup of LCVR phase retardance measurement

The LCVR is placed between two crossed polarizers P1 and P2, the extinction ratio is $\varepsilon = 10^{-5}$, the optical aperture is 20mm. A fixed linear polarizer oriented at 0° on the horizontal plane is followed by the LCVR. The orientation of the LCVR's fast axis was kept at the angles of 45°. The wavelength range of the tested LCVR is 350-700 nm, driving voltage (0-8.8V) is controlled by the computer. The output intensity is read by the power meter PM201.

The Mueller matrices of the polarizer ($M_P(\theta_i)$) and the LCVR ($M(\beta,\delta)$) are respectively given by Eqs. (1) and (2).

$$M_P(\theta_i) = \frac{1}{2}\begin{bmatrix} 1 & \cos 2\theta_i & \sin 2\theta_i & 0 \\ \cos 2\theta_i & \cos^2 2\theta_i & \cos 2\theta_i \sin 2\theta_i & 0 \\ \sin 2\theta_i & \cos 2\theta \sin 2\theta_i & \sin^2 2\theta_i & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \quad (1)$$

$$M(\beta,\delta) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos^2 2\beta + \sin^2 2\beta\cos\delta & \cos 2\beta\sin 2\beta(1-\cos\delta) & -\sin 2\beta\sin\delta \\ 0 & \cos 2\beta\sin 2\beta(1-\cos\delta) & \sin^2 2\beta + \cos^2 2\beta\cos\delta & \cos 2\beta\sin\delta \\ 0 & \sin 2\beta\sin\delta & -\cos 2\beta\sin\delta & \cos\delta \end{bmatrix} \quad (2)$$

Where θ_i is the angle of the polarizer between the optical axis and the X axis, δ is the phase retardance of the LCVR. β is arbitrary fast axis orientation. The optical schematic diagram of the setup is shown in Fig.2. S_{in} and S_{out} are the Stokes vector of the input light and the Stokes vector of the output t light respectively.

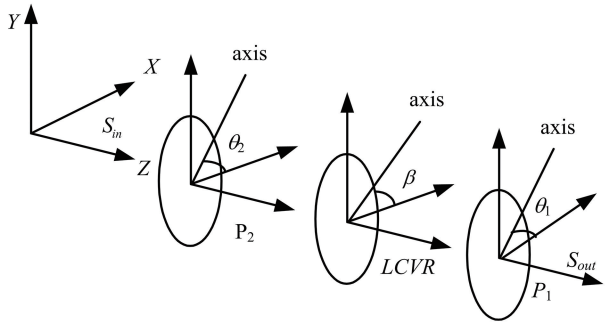


Fig. 2 The optical schematic diagram of the setup

Based on polarization optics theory and Stokes matrix calculus[13], the Stokes parameters of the output light can be calculated by

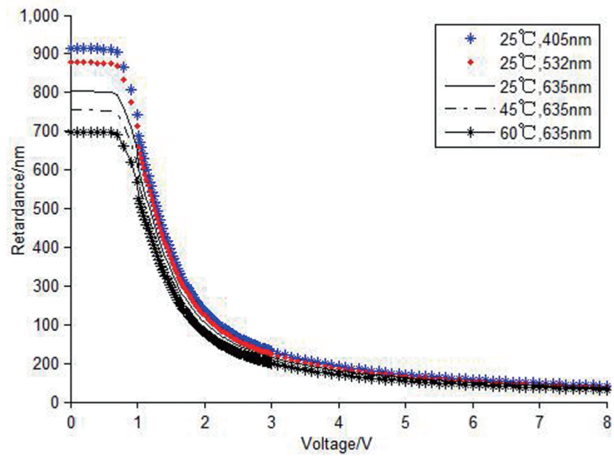
$$S_{out} = M_{P_1}(\theta_1) M(\beta,\delta) M_{P_2}(\theta_2) S_{in} \quad (3)$$

Nevertheless, because the device is based on irradiance modulation, only the first Stokes parameter I is needed to calculate the state of polarization of the incident beam. When $\theta_1 = 0°$, $\theta_2 = 90°$, $\beta = 45°$, the intensity detected by PM 201 is equal to the first terms of the Stokes vector for the output light, after some trigonometric simplification, the parameter I can be expressed as

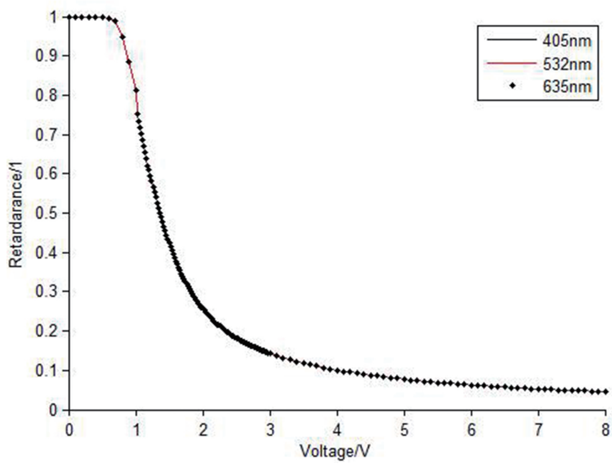
$$I = 0.5 I_{max}(1 - \cos\delta) \quad (4)$$

2.2 Data acquisition

The phase retardance of LCVR is mainly dependent on the applied voltage in LCVR, incident light wavelength and temperature. The experimental data can be measured by the above experimental apparatus in the following circumstances: ① 25℃, 405nm \532\635nm, ②635nm, 25℃\45℃\60℃. For each applied voltage from 0 to 8 V, the corresponding intensity is obtained. Averaging is carried out for each applied voltage in order to reduce the noise in estimating the intensity. Then the values of retardance are calculated using Eq. (4) by MATLAB, and the graph of retardance versus voltage is established. The 256 phase retardance values are obtained, which is shown in Fig.3.



(a) The original data samples



(b) The normalized data samples

Fig. 3 256 set of data samples

Fig.3(a) shows the measured retardance of the LCVR is related to temperature and wavelength. When temperature is certain, the retardance is increasing with wavelength decreasing. For fixed wavelength, the retardance is falling with temperature rising, according to the LCVR data tables, the decline rate is 0.4%/℃. So, each set of sample must be measured at constant temperature. The overall trend of the data distribution shows that the threshold voltage starting to drive the LCVR is around 1.1 V. In the range from 1.1 V to 2.6V the retardance of the LCVR decreases quickly with increasing the voltage. When the change rate of the retardance becomes slow since the voltage is over than 2.6 V. In the end, it tends to an extreme value.

Fig.3 (b) shows that the normalization data have nothing to do with the wavelength of incident light and the ambient temperature.

3 LCVR birefringence dispersion theory

The working principle of the LCVR is based on the theory that the liquid crystal can electronically control birefringence effect. When $U \leqslant U_{th}$ (U is the driving voltage, U_{th} is the threshold voltage), the liquid crystal molecules are arranged in parallel, its phase retardance is largest, when $U > U_{th}$, the liquid crystal molecules are turned over, the tilt angle for the long axis of the molecules is θ, at the time, o light and e light components of refraction rate are shown in Fig.4.

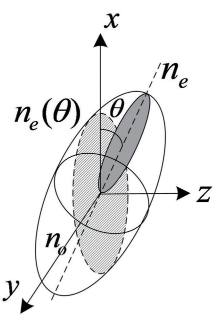


Fig. 4 $U > U_{th}$ for LCVR index ellipsoid

o light refractive index n_o remains unchanged, and e light refractive index n_e changes, the approximate formula is[14]:

$$\Delta n = n_{e(\theta)} - n_o = (n_e - n_o)\cos^2\theta \quad (5)$$

For the LCVR with thickness of d, according to Eq. (5), the phase retardance produced by e and o light is:

$$\delta = \frac{2\pi d \Delta n}{\lambda} = \frac{2\pi d}{\lambda}(n_e - n_o)\cos^2\theta \quad (6)$$

The phase retardance can be obtained in terms of the function relation of the phase retardance, the wavelength and the thickness. Optical axis Angle θ is decided by U, and U is one-to-one correspondence with θ. Normalized δ to [0, 1], the normalized phase retardance is expressed as.

$$\delta_i^* = \frac{\delta_i - \delta_{\min}}{\delta_{\max} - \delta_{\min}} = \cos^2\theta \quad (7)$$

where, δ, δ_i are respectively the value before and after the normalization, δ_{max}, δ_{min} are respectively the maximum and minimum of the data samples. Eq. (7) indicates that the normalized LCVR phase retardance is independent of the wavelength of the incident light, and is only related to U, Fig. 3 (b) is also verified the conclusion.

The Cauchy experience dispersion formula shows that e and o light birefringence dispersion is:

$$n_e - n_o = a + \frac{b}{\lambda^2} + \frac{c}{\lambda^4} \quad (8)$$

Where a, b, c are the Cauchy dispersion coefficient associated with the liquid crystal.

According to Eqs. (6), (7) and (8), Eq.(9) can be obtained.

$$\delta = \left(A + \frac{B}{\lambda^2} + \frac{C}{\lambda^4}\right)\frac{2\pi}{\lambda}\cos^2\theta \quad (9)$$

For Eq.(9), where $A=ad$, $B=bd$, $C=cd$, for each identified LCVR, we can find that the phase retardance $\delta(\lambda, U)$ can be expressed as a function of incident light wavelength λ and the driving voltage U, namely

$$\delta(\lambda, \mathrm{U}) = \frac{2\pi}{\lambda}\delta(\lambda)\delta_i^* \quad (10)$$

Where $\delta(\lambda) = \left(A + \frac{B}{\lambda^2} + \frac{C}{\lambda^4}\right)$ is the dispersion expression, that only relates to incident light wavelength, following the Cauchy dispersion relation, and $\delta(\lambda)$, δ_i^* are independent. When $U \leqslant U_{th}\theta = 0°$, $\delta_i^* = 1$, the retardance is the maximum, the function is:

$$\delta(\lambda) = \left(A + \frac{B}{\lambda^2} + \frac{C}{\lambda^4}\right) \quad (11)$$

Thus, only to test the maximum retardance under three different wavelengths, the Cauchy dispersion coefficient A, B, C can be calculated, thus, the dispersion expression $\delta(\lambda)$ of the other wavelength can be achieved, It also proves that the dispersion characteristics of the LCVR is introduced in the maximum retardance. The maximum retardance of three wavelength obtained by the above built setup are shown in table 1.

Table 1 The three maximum retardance of the LCVR

λ /nm	405	532	635
Retardance/nm	914	878.6	803.4

The data in Table 1 are brought into the Eq.(11), and three coefficients (C, B and A) are calculated , thus, the dispersion function $\delta(\lambda)$ is obtained for any wavelength:

$$\delta(\lambda) = 486.8 + 1.6715 \times 10^8/\lambda^2 - 1.5923 \times 10^{13}/\lambda^4 \quad (12)$$

4 LCVR calibration

According to Eqs.(10) and (12), when the dispersion expression $\delta(\lambda)$ is determined, the phase retardance $\delta(\lambda, U)$ is also calculated. The support vector machine (SVM) method is used to fit the curve of the dispersion expression $\delta(\lambda)$ between the normalized phase retardance δ^* and the driving voltage U.

4.1 SVM forecast modeling method

SVM is the approximate implementation of the structural risk minimization, has good nonlinear mappingability, and can overcome the inherent problems of neural network "dimension disaster". Even in the case of small-sample database, SVM could still be adopted in classification and regression analysis with preferable generalizing performance [15-17], so that it has been extensively applied to tackle many real-world problems in various fields.

Support vector machine (SVM) modeling process, the input of SVM is the driving voltage U, and the output is the normalized phase retardances δ^*. On the Matlab platform, ε-SVM and nu-SVM algorithms are used to model, kernel function is the radial basis function (RBF), the cross-validation grid search algorithm is used to select the appropriate parameters(penalty parameter c, the span coefficient of the RBF function g).The SVM decision function $f(x) = \sum_{i=1}^{n} W_i K(x, x_i) + b$ is looked as the final normalization retardance expression δ^*, where W_i are support vector coefficients, x_i are support vectors, x are the inspected samples, and n is the number of support vectors, b is constant, $K(x, x_i)$ is the radial basis kernel function computed as $K(x, x_i) = \exp(-g \| x - x_i \|^2)$ $(g > 0)$. The fitting curve is shown in Fig.5.

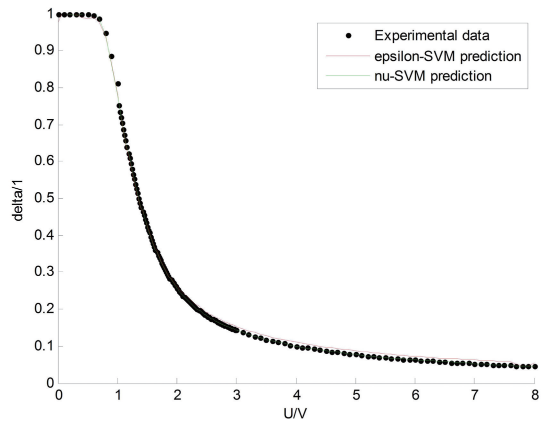


Fig. 5 Phase retardance fitting curve based on different models

The fitting curves show that the fitting accuracy and predictive validity are remarkable, According to the liquid crystal dispersion theory, when $U \leqslant 1.1$V, the liquid crystal molecules do not turn over, its phase retardance is constant. So, the big deviation samples predicted results are no application value, whose effect can be ignored.

4.2 Performance comparison

Experimenting repeatedly, when the forecast effect is best, the performances of the two SVM modeling methods are shown in table 2, the optimum parameters (c and g), mean square error (MSE), Maximum wavelength deviation (Δλ) , and the running time (t) are listed.

Table 2 Performance comparison of various methods

Performance indicators	SVM type	optimal parameters	MSE	Δλ(λ)	t(s)
Modeling Method	epsilon-SVR	c=0.707107 g=5.65685	0.0042	0.0061	4.279614
	nu-SVR	c=2.2974 g = 4	0.0034	0.0061	0.747737

Table 2 shows that the best fitting effect can be achieved by epsilon-SVR algorithm (C = 0.707107, g=5.65685) and nu-SVR algorithm (C = 2.2974, g = 4), MSE is almost the same and Δλ is about 0.0061λ, epsilon-SVR running time is 6 times as much as that of nu-SVR. Comprehensive comparison shows that two SVM modeling method can meet the practical application requirements, the training accuracy and generalization ability are also considered together.

4.3 Experimental verification

To verify this method, when the incident laser source wavelength is changed to 568nm, the experimental data is measured. The obtained SVM decision function and the wavelength 568nm are taken into Eqs. (10), (12), thus, the verification data under different modeling methods is calculated. It is shown in Fig.6.

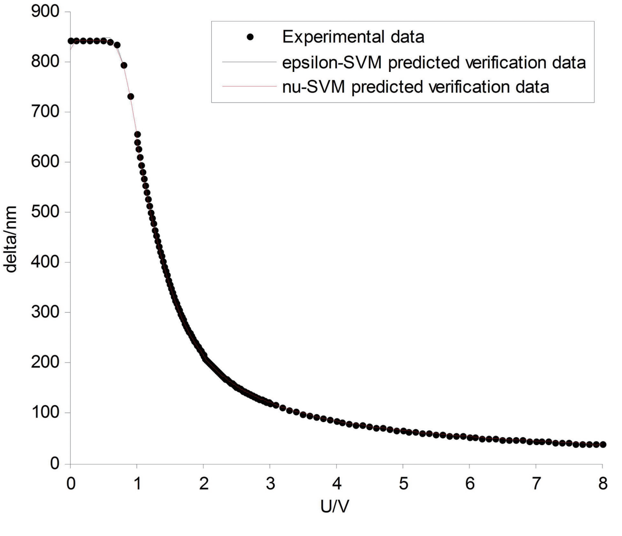


Fig. 6 568nm verify data curve

By comparing the experimental data and the verification data, the maximum deviation of the two SVM modeling method is 0.0061λ, therefore, it is very effective to use SVM as a method for predicting the LCVR phase retardance characteristic.

5 Conclusions

This work describes the techniques for calibrating the phase retardance of an LCVR. One of the key important parts of the method is data samples collection. An optical experimental setup was built, in which, the output intensity is read by the power meter, and the phase is calculated by MATLAB, thus the data samples are obtained. Another important aspect was the regression modeling method. A calibration curve for voltage versus retardance for the LCVR was built by adopting SVM regression algorithm (epsilon-SVR and nu-SVR). Through comparative study and repeated experiments, the calibration curve for voltage versus retardance for LCVR was obtained. Compared with the least square method, the fitting accuracy is greatly improved, the maximum wavelength deviation (Δλ) reaches 0.0061λ, and mean square error (MSE) is ranging within several thousandths, and the shortest running time is only 0.7477s. Finally, the feasibility of the method was demonstrated by the experiment. The exact voltage could be found when the phase retardance which has been set was needed.

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