Analysis and Experiment of Encoding Errors for MOEMS Micro Mirror Spectrometer

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Abstract

Micro mirror arrays used in the novel spectrometer to achieve the modulation of Hadamard transformation (HT) and spectrum detection by a single detector can also be considered as a blazed grating. During the modulation, spectrum can not be completely reflected by micro mirror arrays on the “on” state. While on the “off” state, there will be still light incidence into detector, since the way of light modulation by mirror arrays is diffraction rather than reflection. This will then cause encoding errors. To diminish these encoding errors, a blazed grating model for mirror arrays is proposed. In this paper, both encoding error and compensation are analyzed for the algorithm of HT. Firstly, establish a theoretic model of micro mirror arrays modulation, and calculate the light field distribution based on the Fraunhofer diffraction theory. Then use MathCAD software and Matlab software to simulate and correct the HT encoding errors. Finally, some experimental tests have been done on the Micro mirror spectrometer system. The “on” state errors caused by micro mirror can be eliminated by dividing the background or rectifying the HT mask encoding. However, the “off” state errors can only be eliminated by constructing a compensation HT matrix. Both the “on” and “off” state errors are coexisted in the real situation. Experiment not only can reduce the encoding errors, but also increase signal-to-noise ratio.

Keywords: micro mirror; spectrometer; encoding mirror; Hadamard; blazed grating

1. Introduction

With the development of Optical measurement technology, micro mirror spectrometer based on the optical micro electro mechanical system (MOEMS) is focused on the domain of instrument manufacture. Presently, Germany Fraunhofer institute has developed a MEMS scanning grating spectrometer, which scans the spectrum by rotating a grating mirror, so that it can be detected by a single detector. The resolution of this spectrometer mainly depends on the control of the rotating angle. And USA Polychromix Company has pushed out a DTS spectrometer\textsuperscript{[1,2]}. With the
change of the grating, the spectrometer can scan the spectrum in time by the way of diffraction. However, since the modulate way of this spectrometer is to transfer between the intensity of zero order and ±1 orders, there may be errors cause by the control of grating. Both kinds of spectrometer are hard to control, for each wavelength corresponds with a control point.

In this paper, micro mirror can avoid this difficulty. Only change the mirror into +10° or -10° can all the wavelengths be tested by a single detector, while micro mirrors array is employed by the spectrometer. Yet, there will be errors cause by the periodic structure of the micro mirrors array. Aim of decreasing these errors, a blazed grating model for mirror arrays is proposed. Firstly, establish a theoretic model of micro mirror arrays modulation, and calculate the light distribution based on the Fraunhofer diffractions theory. Then simulate it by Mathcad software. Finally, some experimental tests have been done by the Micro mirror spectrometer system, so that an algorithm of compensation can be used to compensate the spectrum.

2. The optical system of micro mirror spectrometer

This optical system of micro mirror spectrometer is showed in Fig 1. Light which comes out from broadband wavelength light source is absorbed by sample. And then it will pass through a slit and incidence into a collimated mirror. A grating is used to disperse the light on different wavelengths, and the light will be focused on the plane of modulator, digital micro mirror device (DMD), whose function is to select wavelength in time. The selected wavelength will be collected by a collimated mirror and detected by a single detector. After the data processing, such as the Hadamard digital transformation, de-noising and calibration, a spectrum of the sample will be tested.

3. The theoretical analysis of error encoding by DMD

DMD used in this system is composed by 1024×768 mirrors (10.8 µm²). To select wavelengths, mirrors will be divided in groups and rotated at ±10° which is used to reflect the light. Each group corresponds with a wavelength showed in fig 2(a). Hence, there are “on” and “off” states which are in accord with “1” and “0” code of HT and the spectrums of both states are complementary. However, there are errors caused by the incomplete “on” state. Each mirrors group can be considered as a blazed grating (99 lines) with 10°blazed angle and the homochromatic image will give way to multi-orders diffracted images. Then, part of the light on “on” state cannot be tested by detector, showed in fig 2(b). This error can be rectified by dividing the background or changing the “0”, “1” code into “0”, “İ”,”0”,”, “İ” is the ratio of the light collected by detector.

Additionally, errors can also be caused by the diffraction on the “off” state, showed in fig 2(c). On the “off” state, light can also be regarded as a -10°blazed grating. So that part of light will be diffracted into the detector. And these errors cannot be rectified by dividing the intensity of background. Only if modify the code of HT by changing the encoding “0”, “İ” into “İ”,”, “İ” can these errors be diminish. Actually, mirrors are rotated on an axis tilted in 45°. There are both length difference, and height difference between the two states, which are showed in fig 2(d).
4. The calculation of encoding errors

$I_0$, modulated by DMD and focused on the plane of detector, can be calculated by Eq 1.

$$I(x) = I_0(x) * h_{dmd}(x)$$

$$h_{dmd}(x) = w_1 \sin \left( \frac{x}{\lambda \sqrt{x^2 + f_1^2}} - \xi_1 - \xi_2 \right) \left\{ \sin \left( \frac{N \pi d}{\lambda} \sqrt{x^2 + f_1^2} - \xi_1 \right) \right\}$$

$$I_0(x) \left\{ N \sin \left( \frac{\pi d}{\lambda} \sqrt{x^2 + f_1^2} - \xi_1 \right) \right\}$$

$$\xi_1 = \frac{\sin \theta_0}{\lambda}, \quad \xi_2 = \frac{\tan \theta_b \left( \cos \theta_b + \cos \theta \right)}{\lambda}$$

$I_0$ is the intensity of the light which incidences into DMD; $h_{dmd}$ is the convolution element of the grating diffraction; $w_1$ is the effective length of groove; $\lambda$ is wavelengths; $f_1$ is the focus length of the last lens; $d$ and $N$ are the grating constant and the period number of a fixed grating; $\theta_b$ is the blazed angle of the grating which have two choice, $\pm 10^\circ$; $\theta_0$ and $\theta$ are the angle of the incidence light and diffracted light. When $\theta_b$ is $+10^\circ$, $N$ is 8, $\theta_0$ is $17^\circ$ and the central wavelength is $1350nm$, the intensity of the light in the plane of the detector showed in Fig 3, which is plotted by Mathcad. According to this figure, the position of maximum intensity is not the place of reflection, so the detector position must be changed.

$$\varepsilon = \frac{\int_{-\alpha}^{+\alpha} I(x) dx}{\int_{-\alpha}^{+\alpha} I(x) dx}$$

$\alpha$ is the initial position of the detector; $a$ is the width of the detector in the dispersive direction. When $\theta_b$ is $+10^\circ$, $\varepsilon$ is identical with $\varepsilon_1$, which means the proportion of the light pass thought DMD on the “on” state. And $\varepsilon_2$ also can be calculated by Eq 4 while $\theta_b$ is $-10^\circ$ by means of the proportion of the light on the “off” state which incidences into detector.
Fig 4 the intensity of the light on different pixels (a) On the “on” state (b) On the “off” state

In accordance with the simulation, the relationship between $i$ and pixel number on both states is showed in Fig 4. From these two figures, it is obvious that while on the “on” state, the pixels in the middle of the micro mirrors have higher transmitted rate than the ones on both sides, and on the “off” state, there are still light incidence into detector, especially the ones at long wavelengths. But the modulation by the light source, disperse grating, and air absorption will affect the intensity on both states, so that this theoretical line can not be used for compensation directly.

5. Experiment

The typical experimental set-up showed in fig 5 includes a bromine-tungsten lamp, a D4100-DMD produced by Texas Instrument Company, a lead sulfide single detector and a blazed grating.

Fig 5 the typical experimental set-up

Fig 6 (a) the spectrum of the 1063.8nm filter modulated by Hadamard Template (b) Hadamard template compensated by background

To diminish the effect of the errors caused by the “on” state, a 1063.8nm band-pass filter was tested. The intensity of the spectrum modulated by Hadamard template is showed in Fig6 (a). e contain “on” state error $e_{1i}$ and “off” state error $e_{2j}$.

$$e = \begin{bmatrix} e_{i_1} & \cdots & e_{i_{N-1}} & e_{i_N} & e_{2_1} & \cdots & e_{2_{N-1}} & e_{2_N} \end{bmatrix}$$

(5)

$$H_{cprn} = H \times \text{diag}(e_{i_1} \quad e_{i_2} \quad \cdots \quad e_{i_N})$$

(6)

$$Y_{samp} = H_{cprn}^{-1} \times Y$$

(7)

Supposed the influence of the “off” state is so small that the influence of these error can be ignored, a Hadamard template $H_{cprn}$ which is compensated by background is showed in Fig6 (b).

H is the template of Hadamard transforms. According to this figure, transitive efficiency of the pixels in the middle of DMD is higher than the ones on both sides. After the compensation, the intensity of both sides can be enhanced. The comparison showed in Fig 7 is among the reference spectrum (dotted line), the spectrum of inverse HT with compensation (green line) and the one without compensation (black line). It is clear that the compensated spectrum is close to the reference. But, for the noise of the background, there are still errors in this spectrum.
1000 1100 1200 1300 1400 1500 1600 1700 1800
0 0.2 0.4 0.6 0.8 1

Fig 7 the comparison among reference spectrum, the spectrum of inverse transform of Hadamard with compensation and the one without compensation

On the purpose of reducing both states errors, the second experiment was done. This experiment was not tested by HT, for the intensity of the background modulated by Hadamard template is too high to test. Hence, single line scanning is tested. Aim of calculate the errors, 2N equations are constructed by the test of background. At first, post a board in front of DMD to keep the light off DMD and Move the board. Test the background spectrum one time while move the board at one pixel’s length. N spectrums of the background are tested by detector showed in Fig 8(a). Use these spectrums to construct equation group. Choose the intensity of i point and i+1 point from i spectrum except the last spectrum, while in the last spectrum, choose 1 point and N point. A matrix H is constructed by the way above which is showed in Fig 8(b) and the intensity chosen is Y.

\[ e = H^{-1} \times Y \]  \hspace{1cm} (8)

According to these equations, compensated coefficients can be solved. The rectified matrix is H1, and the compensated spectrum can be calculated by Eq 10.

\[
H1 = \begin{bmatrix}
1 & 0 & \cdots & 0 \\
0 & 1 & \cdots & 0 \\
0 & 0 & \ddots & 0 \\
0 & 0 & \cdots & 1
\end{bmatrix}
\quad \text{diag} \left[ \varepsilon_{11}, \cdots, \varepsilon_{1N-1}, \varepsilon_{1N} \right] +
\begin{bmatrix}
0 & 1 & \cdots & 1 \\
1 & 0 & \cdots & 1 \\
1 & 1 & \ddots & 1 \\
1 & 1 & \cdots & 0
\end{bmatrix}
\quad \text{diag} \left[ \varepsilon_{21}, \cdots, \varepsilon_{2N-1}, \varepsilon_{2N} \right]
\]  \hspace{1cm} (9)

\[ X = H1^{-1} \times Y_{\text{samp}} \]  \hspace{1cm} (10)

\( Y_{\text{samp}} \) is the original spectrum showed by Fig 8(c), and Fig 8(d) is the compensated spectrum. From the comparison of these two spectrums, the pixels in the middle and long wavelengths are enhanced. The compensated spectrum is slightly closer to the reference than the original one, and the intensity of the compensated spectrum is nearly 10 times more than the original one. So in the test of the signal with low signal noise ratio, it will benefit a lot from the compensation. But there are still errors in the spectrum, even though it had compensated by the background, since the condition of the experiment is still limited, the changing background can not be test precisely.

6. Conclusion

The errors of the micro mirrors array influence the resolution and accuracy of the spectrometer. A blazed model of DMD has been found. According to the simulation, while on the “on” state, the transmit rates of the pixels in the middle of micro mirrors are higher than the ones on both sides. There are still errors affected long wavelengths on the “off” state. And the rate of the “on” state is not the complementary of the “off” state. Then, experiments are set up to calculate the coefficient of the errors. After the compensation of the “on” state, and both states, the spectrum is more identical with the reference then the one without compensated. But since there may be some errors cause by
the noise of the background, the effect of the compensation is not very well. It needs to improve the experiment to increase the measure accuracy in further research.

Fig 8 (a) the background spectrum tested by moving a board in front of the plane of DMD (b) matrix H (c) original tested spectrum (d) the spectrum which have compensated both “on” and “off” state

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