Image Noise Reduction by Acousto-Optic Bragg Diffraction

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Abstract　We present a simple single-lens image processing system consisting of a Bragg cell to achieve image noise reduction. Experimental results are provided.

Key words　noise reduction,　Bragg cell,　angular spectrum,　spatial angular filtering.

1 Introduction

Noise is an unfavorable factor for optical measurement and information processing. Some recent reports about noise reduction have appeared[1, 2]. In this paper, we use a simple but effective image processing system consisting of a Bragg cell (i. e., an acousto-optic cell) to reduce the noise on an interferogram. In section 2, we describe the image processing system. In section 3, we first summarize the theory of acousto-optic Bragg diffraction in terms of angular spectrum transfer functions. We then illustrate how the noise on the interferogram can be reduced in the image processing system. Finally, in section 4, experimental results and summary are given.

2 Image Processing System

The configuration of the image processing system consisting of a Bragg cell is shown in Fig. 1. The laser beam is expanded and collimated to form a plane wave. The plane wave is then reflected by a mirror M and illuminated the transparency (or interferogram) being processed. After diffracted by the Bragg cell, the two images corresponding to the zeroth order and the first order are formed on the observation plane. The images can be observed by using a CCD camera and a display device.

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Fig. 2 is the partial light path of the image processing system. The planes P and P′ represent the original transparency and its image refracted by the two parallel surface planes of the Bragg cell, respectively. The distance between P and the Bragg cell is d_0, and the distance between P′ and the Bragg cell is d. The distance between the Bragg cell and the lens is b. S and S' represent the distance from P′ to the lens (the object distance) and the distance from the lens to the observation plane (the image distance), respectively. L is the width of the Bragg cell along the z direction. According to Bragg diffraction[3], Snell′s refraction law and image formation formula[4], the separation CC′, i.e., the centers of the two images formed by the lens, is derived as, after some algebra[5],

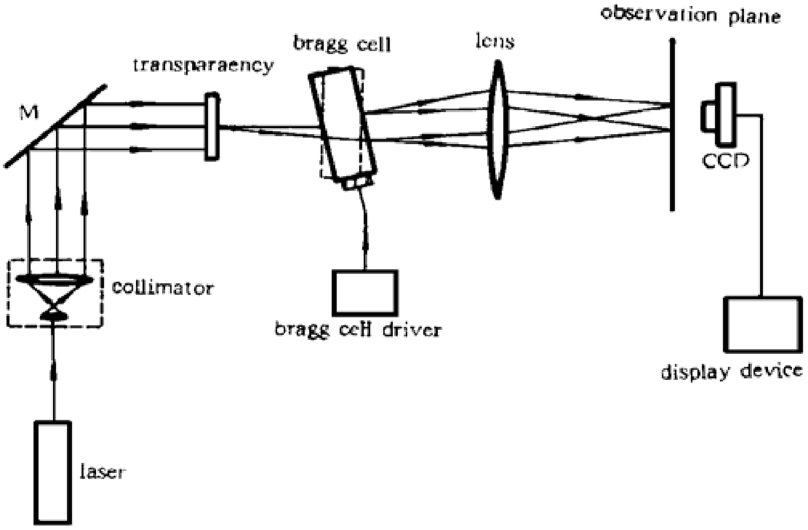

Fig. 1 Image processing system

$$CC' = \frac{n\lambda f}{v}\,\frac{d_0 - (1 - 1/n)L}{d_0 + L/n + b}S', \quad (1)$$

where f and v are the frequency and velocity of the sound wave passing through the Bragg cell along x direction; n represents the refraction index of the Bragg cell. The two images on observation plane corresponding to the zeroth order and the first order can be separated if the following condition is satisfied[5],

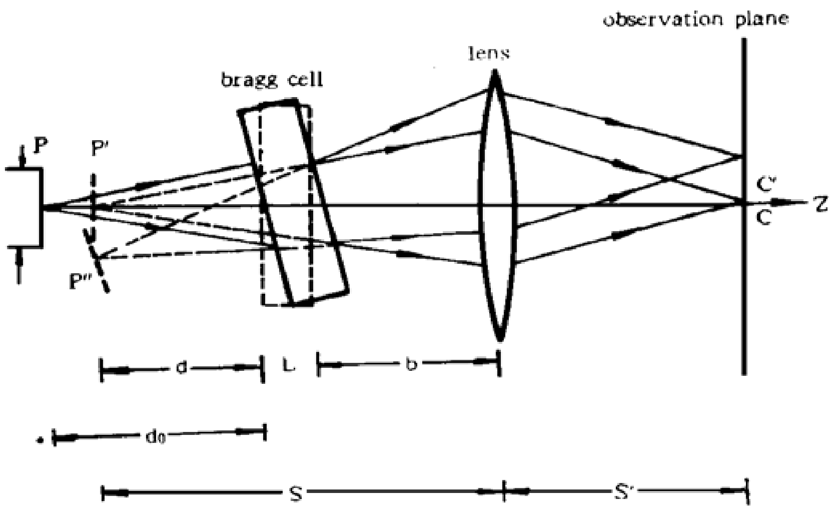

Fig. 2 Partial light path of the image processing system

$$CC' > lS'/(d_0 + L/n + b), \quad (2)$$

where l is the width of the original transparency along the x direction. According to equations (1) and (2), and the image formation formula[4], one can determine the light path parameters, such as d_0, b, and S' conveniently. Next we will analyze the effects of the Bragg cell on the images by using the concept of angular spectrum transfer function. Only one dimensional effect (along the x direction) is considered here since we assume that the Bragg cell which the light field passes through, consists of the medium with constant permeability but with permittivity slowly varying as a function of x and z.

3 Angular spectrum transfer function and noise reduction

We first remark the definition of the angular spectrum distribution of a function according to Fourier transform theory[6]. Assuming $F(\phi)$ to be the angular spectrum distribution of a function $f(x)$, under paraxial approximation, the relation between $F(\phi)$ and $f(x)$ is as follows:

$$F(\phi) = \mathscr{F}\{f(x)\} = \int_{-\infty}^{\infty} f(x)\ \exp\left(-j\frac{2\pi}{\lambda}\phi x\right)\mathrm{d}x, \tag{3}$$

and

$$f(x) = \mathscr{F}^{-1}\{F(\phi)\} = \int_{-\infty}^{\infty} F(\phi)\ \exp\left(j\frac{2\pi}{\lambda}\phi x\right)\mathrm{d}\left(\frac{\phi}{\lambda}\right), \tag{4}$$

where symbols $\mathscr{F}$ and $\mathscr{F}^{-1}$ represent the operation of Fourier transform and inverse Fourier transform, respectively, and ϕ is the angular variable in the angular spectrum domain. Basically, an arbitrary function $f(x)$ in the spatial domain can be considered as being composed of many plane waves traveling at different angular directions. A larger angular direction corresponds to a higher spatial frequency of the function $f(x)$.

In Fig. 2, if the amplitude transmittance of the transparency is expressed by $f(x)$, according to diffraction theory[6] and the definition of angular spectrum stated above, the angular spectrum distribution just in the left surface plane of the Bragg cell can be described as, when the transparency is illuminated by a monochromatic plane wave of light with unit amplitude,

$$U(\phi) = \mathscr{F}\{f(x) * h(x; d_0)\}, \tag{5}$$

where $h(x; d_0)$ is the free-space spatial impulse response function concerning the diffraction distance d_0 from P to the Bragg cell; the symbol $*$ denotes convolution. By introducing the angular spectrum transfer function of the Bragg cell, $H_m(\phi)$, the angular spectrum distribution of the output light field from the Bragg cell may be written as,

$$U_m'(\phi) = U(\phi)H_m(\phi)\mathscr{F}\{h(x; L/n)\}, \tag{6}$$

where m may take 0 and 1, representing the angular spectra of the zeroth order and the first order diffracted light derived from the Bragg cell, n represents the refraction index of the Bragg cell. Note that eq. (6) has been derived under the approximation of small Bragg angles.

By using the Korpel-Poon multi-scattering theory[7], $H_0(\phi)$ and $H_1(\phi)$ are[8, 9]

$$H_0(\phi) = \exp\left[-j\frac{Q\phi}{4\phi_B}\right]\left\{\cos\left[\left(\frac{Q\phi}{4\phi_B}\right)^2 + \left(\frac{\alpha}{2}\right)^2\right]^{1/2} + j\frac{Q\phi}{4\phi_B}\frac{\sin\left[(Q\phi/4\phi_B)^2 + (\alpha/2)^2\right]^{1/2}}{\left[(Q\phi/4\phi_B)^2 + (\alpha/2)^2\right]^{1/2}}\right\}, \tag{7}$$

and

$$H_1(\phi) = \exp\left[j\left(\frac{Q\phi}{2\phi_B}\right)\right] - j\frac{\alpha}{2}\left\{\frac{\sin\left[(Q\phi/4\phi_B)^2 + (\alpha/2)^2\right]^{1/2}}{\left[(Q\phi/4\phi_B)^2 + (\alpha/2)^2\right]^{1/2}}\right\}, \tag{8}$$

where $\phi_B = \lambda_0/2\Lambda_0$ is the Bragg angle with λ_0 and Λ_0 denoting the wavelengths of light and sound inside the Bragg cell, $Q = 2\pi L\lambda_0/\Lambda_0^2$ is the Klein-Cook parameter[10], $\alpha = CkSL/2$ represents the peak phase delay of the light through the Bragg cell with C denoting an acousto-optic strain constant, $k = 2\pi/\lambda_0$ is the propagation constant of the light in the Bragg cell, and S is the amplitude of the sound wave.

By employing $U_m'(\phi)$, the field distribution of the images on the observation plane is

$$u_m(x) = \{\{\mathscr{F}^{-1}\{U_m'(\phi)\} * h(x; b)\}\ \exp[jk_0x^2/2f]\} * h(x; S'), \tag{9}$$

where b and S' are the distance from the Bragg cell to the lens and from the lens to the observation plane, k_0 is the propagation constant of the light in free space, and f' is the focal length of the lens. Replacing $U'_m(\phi)$ by equation (5) and (6), (9) becomes

$$u_m(x) = \{\{\mathscr{F}^{-1}\{\mathscr{F}\{f(x)\}H_m(\phi)\} * h(x;\ L/n + d_0 + b)\}\ \exp[jk_0x^2/2f']\} * h(x;\ S') \quad (10)$$

where $h(x;\ L/n + d_0 + b) = h(x;\ L/n) * h(x,\ d_0 + b)$.

Supposing that there is no sound wave in Bragg cell, the field distribution of the image on the observation plane is reduced to a standard imaging equation:

$$u'(x) = \{\{f(x) * h(x;\ L/n + d_0 + b)\}\ \exp[jk_0x^2/2f']\} * h(x;\ S'). \quad (11)$$

Equation (11) shows us the physical process of image formation by diffraction theory, and gives the field distribution of the image corresponding to a transparency not being processed, if S and S' satisfy the image formation formula. Comparing equation (10) with equation (11), it is easy to find that the main difference between them are the term $\mathscr{F}^{-1}\{\mathbf{F}\{f(x)\}H_m(\phi)\}$ in equation (10) and the term $f(x)$ in equation (11). The latter is the field distribution of the transparency, and the former is the field distribution of the transparency whose angular spectrum has been processed by the Bragg cell. Hence, the angular spectrum distribution of the output image depends on $H_m(\phi)$. In other words, the role of the angular spectrum transfer functions, $H_0(\phi)$ and $H_1(\phi)$, are similar to an angular spectrum filter, through which the angular spectrum distribution of the transparency is filtered. Fig. 3 shows the curves of the magnitude of the angular spectrum transfer function versus angular variable ϕ when $Q = 28$, $\alpha = 0.65\pi$. Obviously, the angular spectrum transfer function of the zeroth order exhibits highpass filtering while the first order lowpass filtering. We can use the lowpass characteristic of the first order to reduce the noise on the transparency.

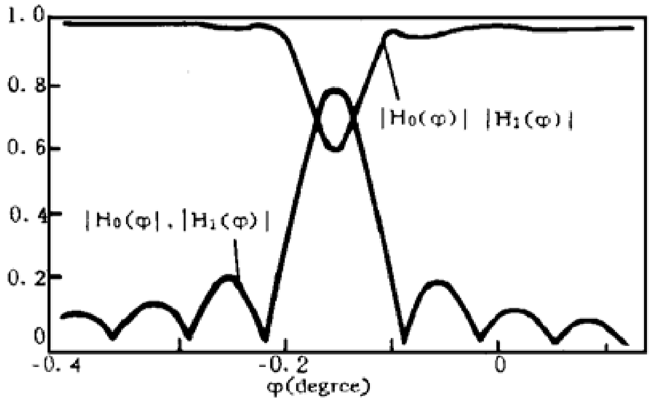

Fig. 3 Angular spectrum transfer functions of the Bragg cell, $H_0(\phi)$ and $H_1(\phi)$, when $Q = 28$, $\alpha = 0.65\pi$

4 Experimental results and summary

We employ the image processing system shown in Fig. 1 and perform noise reduction on an interferogram. In the experiment, $Q = 28$, $\alpha = 0.65\pi$; the transparency processed is part of an interferogram, whose area is about $4\times 4\ mm^2$. The focal length of the lens is 195 mm. The thickness of the Bragg cell, L, is 60 mm. The refraction index of the Bragg cell, n, is 1.616, and the Bragg angle ϕ_B is 0.154°. We let $d_0 = 220$ mm, $b = 25$ mm, and $S' = 690$ mm after considering the following factors: obtaining clear images on the observation plane and separating two images diffracted by the Bragg cell (see section 2). The experimental results are given in Fig. 4. Fig. 4(a) is the image of the original transparency (interferogram), in which there are some noise (kind of like diffraction fringes running along the x-direction). Fig. 4(b) is the image of the first order on the observation plane, which displays noise reduction apparently.

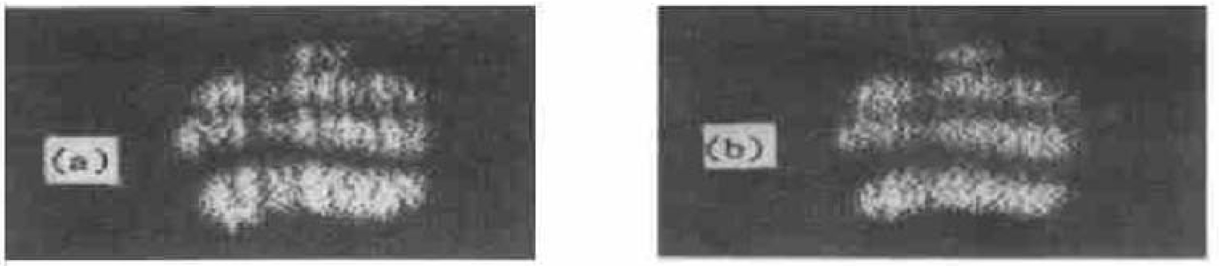

Fig. 4 Experimental results: (a). image of the interferogram which will be processed; (b). image of the first order diffracted light on the observation plane

Through this experiment, we accomplish noise reduction on an interferogram by using a single-lens image processing system consisting of a Bragg cell. The method used in the experiment is simple and effective. In addition, image processing is performed parallel optically.

In the experiment, we only examine the reduction of noise, the diffraction fringes overlapping with interference fringes, on an interferogram. For other noise, such as laser speckle, there still is the possibility to reduce it by choosing a feasible spatial spectrum transfer function of the first order, $H_1(\Phi)$, since $H_1(\Phi)$ can be altered by changing the Klein-Cook parameter, Q, and the peak phase delay, α, as it is evident from eqs. (7) and (8).

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利用声光布拉格衍射实现图像噪声减弱

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摘 要 利用含有布拉格(Bragg)声光元件的单透镜象处理系统实现了图像噪声的减弱, 并给出了实验结果。

关键词 噪声减弱, 布拉格声光元件, 角谱, 空间角谱滤波。