PHASE IMAGING WITH AN X-RAY SHEARING INTERFEROMETER

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ABSTRACT

In this paper, we investigate a shearing type of X-ray interferometer, where two slightly sheared X-ray beams are produced and both of them are transmitted through the object. The two beams are superposed and interfered after they are transmitted through the interferometer. The interfered beams show intensity variation with high contrast due to the phase difference between them. Conventional X-ray sources can be used in this interferometer because the phase difference is small. Phase image is obtained by mechanical scanning or with an X-ray camera. Some simple objects of acrylic resin are measured with good contrast, showing the validity of the interferometer. Possibility of more efficient imaging schemes is discussed on the basis of the experimental results.

1. INTRODUCTION

In the conventional X-ray imaging such as computer tomography or radiography, we measure intensity of the X-rays which pass through the object to be measured. The intensity distribution reflects the distribution of absorption coefficient inside the object. However, absorption becomes low for materials of low atomic number and for hard X-rays. In such cases high contrast images are difficult to obtain (Hendee and Ritenour, 1992).

An alternative way is to measure distribution of refractive index for X-rays. Spatial variation of refractive index causes spatial variation in the phase of the transmitted X-rays. By observing the phase variation, we can get images containing information of the inside of the object. This is called phase imaging.

Two methods are being investigated for observing the phase of X-rays. The first method corresponds to Shlieren method or shadowgraphy adopted for visualizing flow of transparent fluid with the visible rays (Merzkirch, 1974a). They measure the deviation of propagation direction of rays from the incident direction, which corresponds to the spatial differentiation of phase distribution. These methods give us high contrast X-ray images in a relatively easy way (Davis et al., 1995), but the resultant intensity is difficult to evaluate quantitatively. The other method is interferometry (Bonse & Hart, 1965) which is also used in flow visualization in the visible spectrum (Merzkirch, 1974b). Quantitative phase can be obtained. In the usual Mach-Zehnder type of X-ray interferometer, however, one of the interfering beam travels through the object and the other beam is a reference beam, which travels outside the object (Momose et al. 1995 and Bonse, U et al. 1997). Therefore, phase difference between the two interfering beams becomes large for large objects; coherent X-rays such as synchrotron radiation have to be used.

In this paper, we investigate an X-ray shearing interferometer (Nakano et.al, 1996), which is also used in the visible spectrum (Murty,.1978). In this interferometer two slightly sheared X-ray beams are produced and both of them are transmitted through the object. The two beams are superposed and interfered after they are transmitted through the interferometer. In this type of interferometer, phase difference is not so large that a conventional X-ray source can be used. We construct a shearing interferometer and phase images are obtained both by mechanically scanning the object and with an X-ray camera. In this paper image acquisition using this interferometer is discussed qualitatively. Quantitative phase measurement is discussed elsewhere (K.Iwata, in prep.).

2. X-RAY SHEARING INTERFEROMTER

Figure 1 shows the schematic diagram of the shearing interferometer. It consists of two pairs of two blades and a base. The whole interferometer is cut from a silicon single crystal. Two distances between the paired blades are the same. The incident beam is diffracted by Bragg diffraction at the first pair of blades and two parallel beams a and b are formed. Both beams are transmitted through the object to be tested and diffracted by the second pair of plate. Two (B1 and B2) of the four diffracted beams are superposed after diffraction and interfere.

Because both superposed beams are diffracted twice by the blades and transmitted twice through the blades, they have the same intensity. Interference fringes formed by the two beams with the same intensity have unity contrast. Thus we can obtain good contrast fringes.

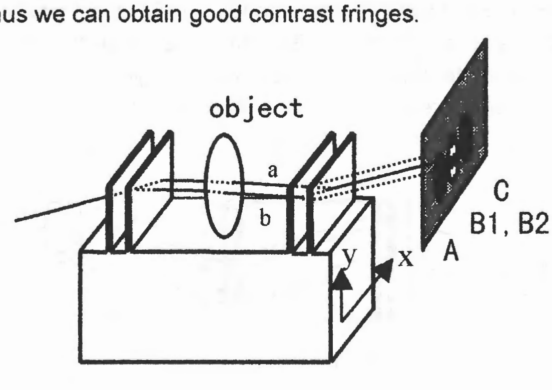
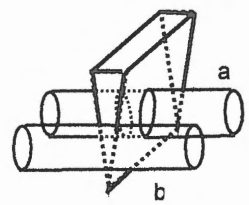
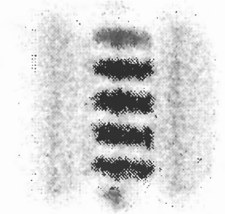


Figure 1 Schematic diagram of the X-ray shearing interferometer



(a)



(b)

Figure.2 X-ray beams at the output plane.
(a) Acrylic wedge and X-ray beams.
(b) Output beams with interference fringes .

The X-ray source in the present experiment has Mo target and wavelength 71pm of Kα line is mainly used. Bragg diffraction in the interferometer is caused by 111 crystal planes which is perpendicular to the blade surface. As the lattice spacing is 313pm, Bragg angle is 6.5 degrees. The amount of shear is 0.7mm as the distances between the paired blades are 2.5mm. The beam width is determined by the width of X-ray source (0.4mm).

To certify the interference effect a wedge made of an acrylic resin is inserted in one of the parallel beams as shown in Fig.2(a). A photograph of the output beams for this object is given in Fig.2(b). Three beams are seen separately in Fig.2(b) because the beam width is smaller than the shear. The middle beam is the superposition of two beams B1 and B2. Interference fringes are seen according to the phase change due to the wedge. From the fringe spacing and the wedge angle, we can calculate refractive index of the acrylic resin as $1\text{-}0.7\text{x}10^{-6}$. The two outer beams A,C in the figure does not show interference effect.

3. PHASE IMAGE OBTAINED BY MECHANICAL SCANNING

To demonstrate the phase image using the shearing interferometer, we insert an object shown in Fig. 3 in the interferometer. The object consists of two acrylic plates of thickness 1.8mm with a triangular sheet of sellotape of thickness 0.05mm between them. The object is covered with aluminum foil on the one side. The two X-ray beams transmit through the object.

To obtain a phase image we put a small pinhole with diameter 0.1mm in the interfered beam and detect the intensity with a scintillation counter. The object is mechanically scanned in x and y direction with x-y stage controlled by a computer. The obtained intensity variation

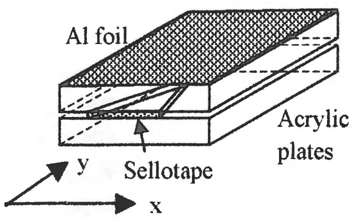


Figure.3 Object to be tested.

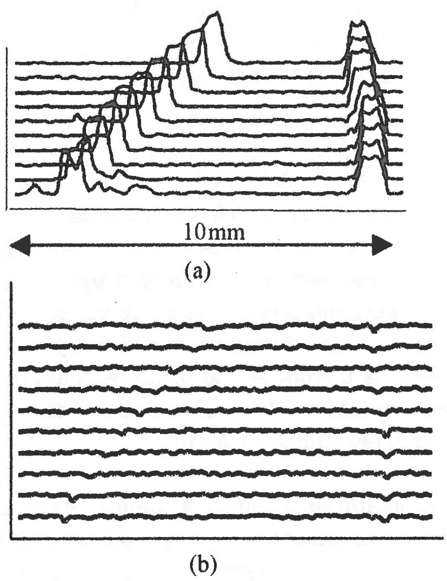


Fig.4 Two-dimensional intensity distribution of X-rays transmitted through the object in Fig.3.
(a) Intensity measured with the interferometer.
(b) Intensity measured with one beam blocked.

is shown in Fig.4(a). The intensity variation clearly shows the variation of phase due to the sellotape. High intensity portions correspond to the place where only one of the beams passes through the sellotape. Thus the width of the portion corresponds to the amount of shear. To obtain better spatial resolution smaller shear is required.

For comparison intensity image obtained without interference is shown in Fig.4(b). It is obtained by blocking one of the interfering beams from entering to the object. Absorption of the sellotape is not appreciable, as seen from the image. Small linear dip in the intensity is perhaps due to refraction of X-rays. Because the propagation direction of X-rays are changed at the edge of the cellotape, slight deviation from Bragg condition occurs at the second paired blades causing little intensity dip. The width of the line is smaller than the phase image, showing the better spatial resolution. However, the contrast is poor and its depth is near the noise intensity.

The overall path length for the X-rays through this object is calculated by the thickness of the acrylic plates and its refractive index. Path difference between the beam and the reference beam outside the object is calculated as 2.5nm, which corresponds to more than 30 fringes. Thus we cannot obtain interference fringes with a Mach-Zehnder type inteferometer using conventional X-ray source.

4. PHASE IMAGE OBTAINED BY AN X-RAY CAMERA

Mechanical scanning requires much time. To obtain a phase image faster, we introduce a cooled X-ray CCD camera (Hamamatsu C4880). Size of the CCD is 12x12.2mm^2 with pixel size 12x12μm^2. X-ray intensity is taken into an image processor and displayed on the CRT display.

To obtain a larger image, we have to broaden the X-ray beam. For the purpose we use a line focus of the X-ray source. The focus is rectangular with size 0.4mm x 8mm as shown in Fig.5. In the experiment of the previous section we take out the X-ray beam in the direction parallel to the line; the beam width was 0.4mm. In this section we take out the X-ray beam in the direction perpendicular to the source line.

The beams are diffracted by the blades of the interferometer by Bragg diffraction. Beams satisfying the condition of Bragg diffraction are limited to a small range of angle in the order smaller than tens of seconds of arc. Hence only the parallel beams satisfying the condition come out of the interferometer to the observation point. Thus the effective width of the beam is determined by the source width of 8mm. This situation is shown in Fig.5.

In this configuration the non-interfered beams A and C overlap with the interfered beams B1 and B2. This overlap deteriorates the fringe contrast. The four beams have the same intensity because they are diffracted twice and transmitted twice at the blades. Thus the maximum intensity is six times the intensity of a single beam and minimum intensity is two times. Thus fringe contrast in the overlapping region is calculated as 1/2. This is a

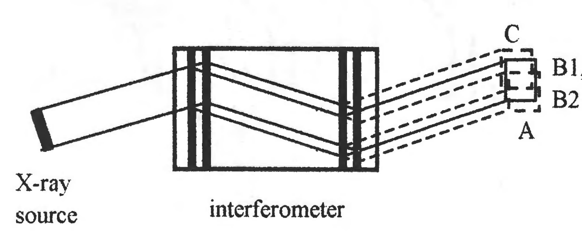


Fig.5 X-ray source and beam width.

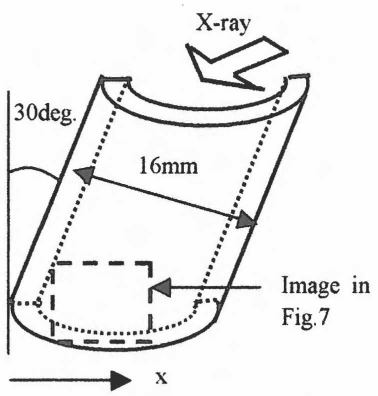


Figure 6 Object to be tested (inclined pipe of acrylic resin).

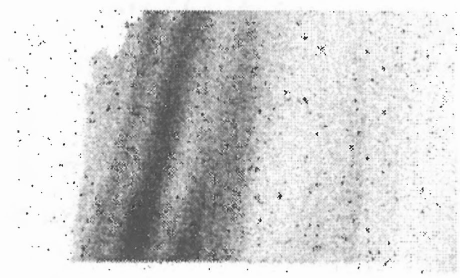


Figure. 7 Interference fringes due to an inclined pipe of acrylic resin.

permissible value.

With this system we take an image of the inclined pipe of acrylic resin shown in Fig.6. The result is shown in Fig.7, which corresponds to the portion surrounded by the broken rectangle in Fig.6. In the figure, inclined fringes are seen corresponding to the inclination of the object. Reasonable fringe contrast is obtained. The white portion in the left side of Fig.7 is a part where X-ray is blocked by an obstacle.

5. DISCUSSION AND CONCLUSION

In this paper we obtain phase images using X-ray shearing interferometer. But to make this new technique practical we have to solve many problems.

One of the problems is the time required for making the image. The X-ray source in our experiment is the one for analyzing crystals using X-ray diffraction. We used it with the tube current of several tens of mA. It takes several hours for obtaining the image of Fig.4 by mechanical scanning. On the other hand the exposure time for taking the image of Fig.7 is about two hours. To shorten the time strong X-ray source have to be developed or efficient use of X-ray energy is necessary.

Another problem is spatial resolution. As it is mainly determined by the amount of shear, smaller shear is required. It is obtained by reducing the Bragg angle and the distance between the paired blades. The former is attained by using X-ray of shorter wavelength. Blade spacing in the order of 0.5mm can be obtained by the present state of the art, but smaller spacing requires the improvement of machining technology.

The interferometer have to be constructed by a single silicon crystal because the crystal lattice planes of the four blades should be parallel within the deviaton angle much smaller than one second of arc. However, the size of the crystal is limited to radius of about 15cm, large interferometer is difficult to construct. Thus for obtaining images of larger objects some other breakthrough is necessary.

In conclusion this paper shows a possibility of obtaining good contrast images for objects whose X-ray images are difficult to produce using conventional X-ray diagnostic apparatus and reveals some problems for making it practical.

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