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Generation of a joint pattern for optical speckle JTC by using a liquid crystal cell and a birefringent plate

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A method to form a joint pattern before and after the displacement of a light scattering object is presented by using a spatial shifter consisting of a twisted nematic liquid crystal cell and a birefringent plate. The polarization of the speckle pattern is switched by the 90° twisted nematic liquid crystal and, then, the spatial shift is introduced to the pattern by passing through the birefringent calcite plate depending on its p- or s-polarized state. The generation of the joint pattern is verified by the experiment. It is possible to perform a real-time all optical joint transform correlation (JTC) based on the proposed method.

1. Introduction

The method of the joint transform correlation is frequently used as a powerful tool for such as an object identification or a displacement measurement. Though many papers have been published for the optical joint transform correlator, the optical implementation to calculate the correlation function and/or the evaluation of only the output performance of the joint transform correlation are the main concerns in those papers [1,2]. Most of the papers have not mentioned how to generate a joint transform pattern for real-time optical processing. In the usual case, a joint transform pattern was synthesized by computer software and the generated pattern was displayed on a TV monitor or taken as a master photographic film for the correlation input. It is difficult to implement real-time optical processing by those methods. In practice, how to generate or acquire a joint transform pattern is the key point to realize the fast "real-time" joint transform correlation.

Recently, a real-time optical joint transform correlator for speckle displacement or velocity measurement is proposed by using an Optic RAM detector and a liquid crystal television [3–7]. In the previous papers, the doubly exposed joint pattern was obtained electronically by the Optic RAM device. After the detection of the joint transform pattern, the cross-correlation function was optically calculated by using an LCTV spatial light modulator. A joint pattern can be formed rather faster than the conventional method by use of the Optic RAM detector. But, because of the sequential read-out of the memory contents, it is not still sufficient to realize a "real-time" optical correlator in many applications which require a fast processing of the signal.

As an alternative or more efficient method to produce a joint pattern, we propose a new method to form a joint pattern for speckle applications in this paper. The joint pattern before and after the displacement of a light scattering object is formed through a spatial shifter consisting of a twisted nematic liquid crystal cell and a birefringent plate with a polarization plate. The generation of the joint pattern is verified by the experiment. In this paper, to confirm the usefulness of the method, the speckle patterns are taken by a CCD camera and, then, the joint pattern is synthesized by a computer. Finally, the joint transform correlation function is calculated by a computer. It is possible to implement a real-time correlator based on the proposed method together with such as the previously proposed LCTV-based optical correlation technique [6].

2. Principles of the method

The main elements of the module to produce a spatially shifted joint pattern are a 90° twisted nematic liquid crystal (TN-LC) cell and a birefringent calcite ($CaCO_3$) plate. By using this module, a spatial offset between the successive two speckle patterns can be easily and quickly given. For example, we consider the situation where an s-polarized pattern as shown in fig. 1 passes through a TN-LC cell. The director of the LC molecules at the front surface in fig. 1 is chosen to be aligned to the same direction as the s-polarization of the incident light. The polarization of the pattern remains unchanged when the voltage is applied to the TN-LC cell, because the twist of the molecules is dissolved and the director of the LC molecules is aligned to the direction of the light propagation.

On the other hand, it is rotated 90° when no voltage is applied, since the polarization rotates along the rotation of the molecule directors. Then the polarization of the pattern is switched from s- to p-state. To give a spatial shift to the second pattern, a birefringent plate is inserted behind the TN-LC cell. If the optic axis of the birefringent crystal is lying at the same plane as the p-polarization as shown in fig. 1a, the transmitted beam through the plate becomes an o-ray and no spatial shift of the pattern occurs. At the same optic axis, however, the s-state of the polarization becomes an e-ray after passing through the birefringent plate as shown in fig. 1b and, thus, a certain amount of the spatial shift is given to the pattern. The amount of the transverse shift depends on the length of the crystal along the transmission. In the experiment, a spatial shifter consisting of a TN-LC cell and a birefringent plate is inserted in front of a CCD camera to detect speckle patterns and the patterns before and after the displacement of a light scattering object are taken by the CCD camera. The whole operation of the experimental system is described in the following section.

3. Experiments and results

The schematic diagram of speckle detection and the calculation of the correlation function is shown in fig. 2. A collimated light beam from a HeNe laser illuminates a moving ground glass plate. The speckle patterns are detected by a CCD camera through a two-lens imaging system with a pinhole at the filter plane. The two-lens imaging system was employed because of the small decorrelation of the speckles for the translation of the pattern at the detection plane. The pinhole controls the speckle size on the detector. The focal length of the lenses L1 and L2 are 100 and 130 mm, respectively, and the size of the pinhole used in the experiment is 0.75 mm, so that the average size of the speckles at the detector plane is calculated to be 0.134 mm. Then the speckle size corresponds to about 6 pixels of the CCD element.

The 90° TN-LC cell has an aperture of 2.0×2.0 cm^2 and is driven by a sinusoidal wave from a function generator. The switching speed of the TN-LC is rather slow and is about 100 ms at the applied volt-

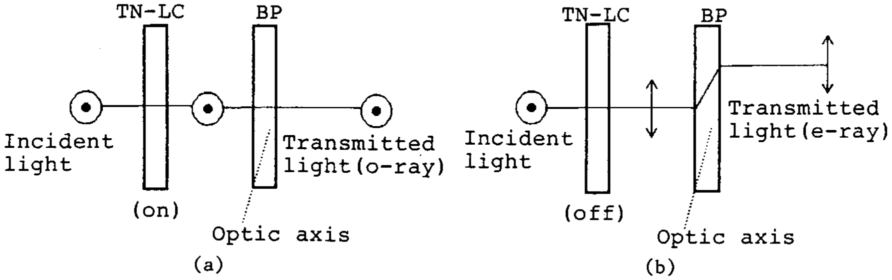

Fig. 1. Principle operation of the spatial shift. TN-LC: TN-LC cell and BP: birefringent plate.

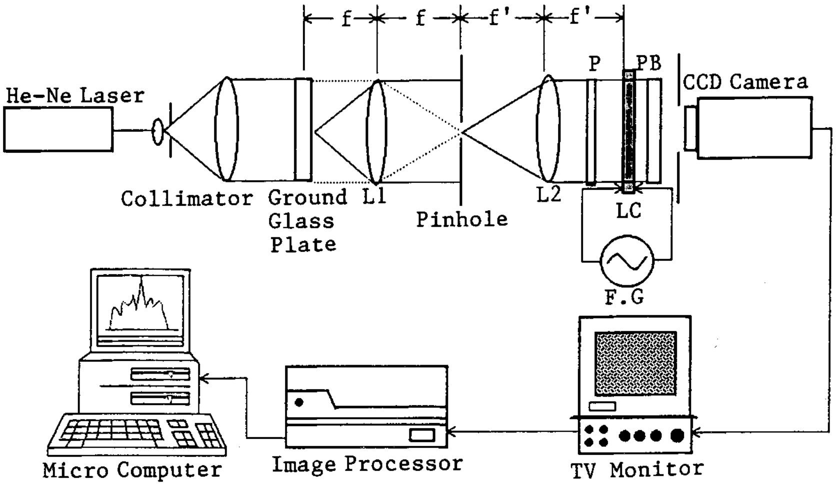

Fig. 2. Schematic diagram of speckle detection and processing. L1 and L2: lenses, P: polarization filter, TN-LC: TN-LC cell, PB: birefringent plate, and FG: function generator.

age of 5.0 V. The birefringent calcite plate has also a clear aperture of 2.0×2.0 cm^2 and a thickness of 9.19 mm which corresponds to a shift of the e-ray of 1 mm at the wave length of $\lambda=0.63$ µm. The module is placed in front of the CCD camera with a polarization filter which enables the polarization of the pattern to be s-polarized state as shown in fig. 1.

When applying the voltage to the TN-LC cell, the first speckle pattern is taken by the CCD camera. Then, after a certain time offset, the voltage is turned off and the second speckle pattern is detected. The second pattern is spatially shifted from the first pattern due to the applied voltage to the TN-LC cell even if there is no displacement of the object. During the successive exposures, the pattern moves for a certain direction in speckle measurement. Therefore, the displacement of the speckle is added to the spatial offset. The speckle pattern is digitized by 512×512 pixels with an 8-bit gray scale through an image processor. In the actual calculation of the correlation function, this image was reduced to the size of 128×128 pixels and the calculation was performed with 128×128 pixels by a micro-computer. The detected speckle patterns before and after the displacement of the object are sent to the image processor. The speckle patterns are clipped to have a binary level at the mean intensity because we can obtain a sharp correlation function which enables the accurate detection of the correlation peak. These two speckle patterns are sent to the memory of the micro-computer and a joint pattern is produced. The joint pattern is something like a specklegram but it should be distinguished from an ordinary specklegram because a certain spatial offset is given between the successive speckle patterns. Then, the correlation function is calculated by employing a two-dimensional fast Fourier transform (FFT) method by the computer.

Figure 3 shows the speckle patterns with and without the applied voltage to the TN-LC cell taken by 512×512 pixels with an 8-bit gray scale when the ground glass plate is stationary. As is seen from this figure, the speckles in fig. 3a shift horizontally to the right direction along the positive Y direction in fig. 3b. Therefore, the distance of the corresponding speckle pairs between figs. 3a and b becomes the spatial offset in the speckle displacement or velocity measurement. To show the shift more clearly, the same frame of each speckle pattern in figs. 3a and b is scanned and each intensity distribution is displayed in fig. 4.

Figure 5 shows the calculated joint transform correlation function of the clipped specklegram by the computer when the object is stationary. The quarter of the area (i.e. 64×64 pixels) for the calculated correlation function is plotted in this figure. The origin of the X–Y coordinate corresponds to the correlation peak of the stationary speckle pattern without the spatial shifter. The correlation peak shifts 14

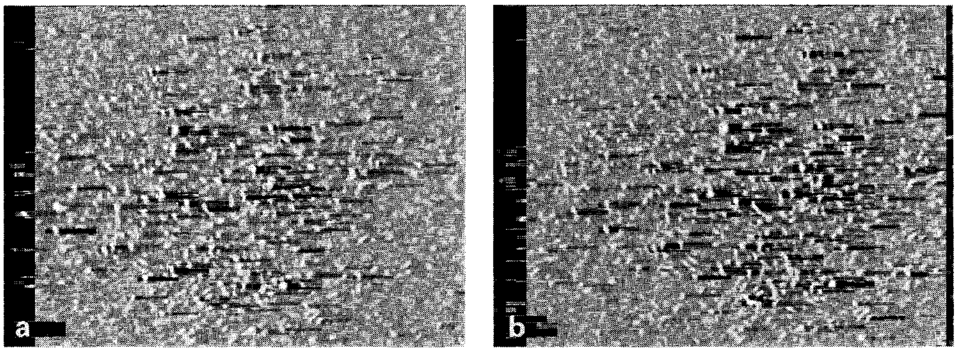

Fig. 3. Speckle patterns (a) with and (b) without an applied voltage to the TN-LC cell. The object is stationary.

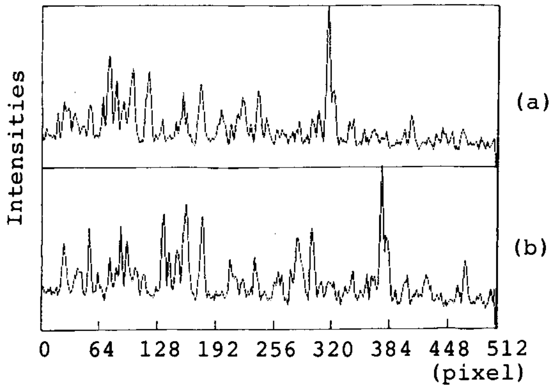

Fig. 4. One-dimensional scan of the intensity of each speckle pattern shown in figs. 3a and b.

pixels from the center of the coordinate to the *X* direction. Then, the position of the shifted correlation peak in fig. 5 becomes a new origin for the speckle displacement measurement in the proposed method of the joint transform correlation.

The joint transform correlation functions are shown in fig. 6 when the object is displaced along the *Y* direction (the *X* component is set to be zero). The values of the displacement are 0.2, 0.5, and 1.0 mm from figs. 6a to c, respectively. The correlation peaks also move to the *Y* direction. As is well known, the speckles move over the several mean speckle sizes remaining the peak value unchanged due to the employment of the two-lens imaging system, namely, the decorrelation of speckle pattern is small over a wide range of the speckle translation. Furthermore, due to the clipping effect of the speckle intensities, the correlation function is sharpened compared with the ordinary full-bit correlation function. This effect makes it easy to detect the peak position with high accuracy [2,5,6].

From the obtained correlation functions such as shown in fig. 6, the distances of their peak positions from the correlation peak in fig. 5, i.e. the origin, are plotted against the actual displacements of the object. The result is shown in fig. 7. As is seen from this figure, there is a good linear relation between the peak positions and the object displacements. One of the

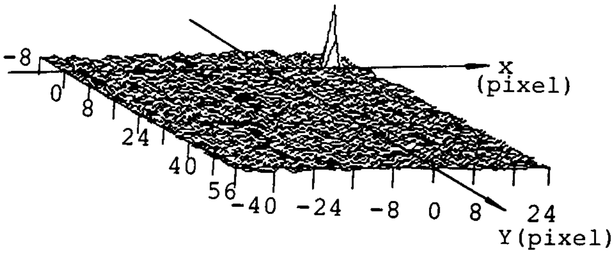

Fig. 5. Joint transform correlation with no displacement of the object.

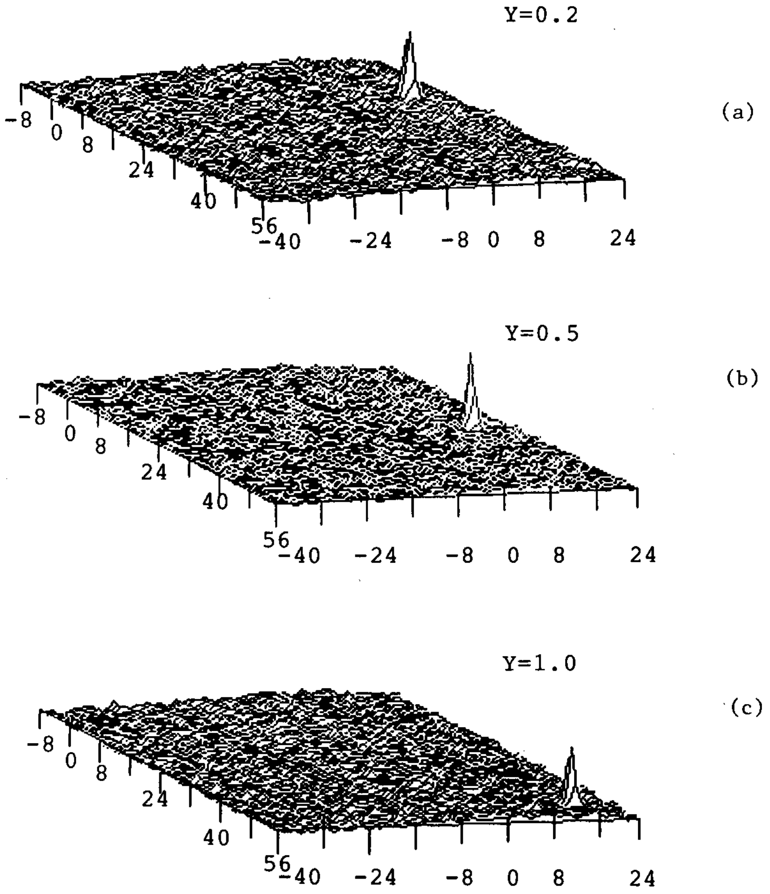

Fig. 6. Joint transform correlations for the displacement of the object.

main features of this method is that the direction of the displacement can be detected from the direction of the correlation peak. In this case, the correlation peak, i.e. the speckles, moves to the positive direction in the *Y* coordinate (while the *X* component of the displacement is zero), so that it is concluded the object actually moves to the negative *Y* direction in the object plane due to the employed imaging geometry. Thus, the two-dimensional measurement for the displacement or velocity of the light scattering object is conducted by using the proposed method.

In the experiment, we have used a ground glass plate which is a rather well-defined diffuser and has little depolarization effect. When we use an actual diffuser such as a rough metal surface or an opal glass plate, the depolarization effect by such a light scattering object plays an important role for the formation of the speckle pattern. But, in this case, we can select a certain polarized state of the speckle pattern through a polarizer. Actually, the polarization filter is inserted in front of the spatial shifter in the experiment as shown in fig. 2. We have also tried to measure the displacement for a light scattering object having a depolarization effect and verified that this method can be applied to such an object. As for the deformation of speckles, the effect of the speckle decorrelation may not assumed negligible for a large surface deformation, although speckles deform little

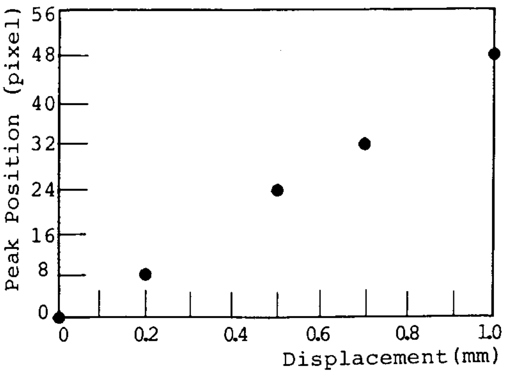

Fig. 7. Relation between the displacement and the peak position of the correlation function.

for a pure translation state of a light scattering object. But, the deformation under usual interests in speckle applications is small, so that one can expect a similar speckle pattern after the deformation of the object as before and the proposed method can be still applied.

4. Conclusion

We have described a method for the generation of a joint pattern to calculate a joint transform correlation function for speckle applications. To give a spatial shift to the pattern, the combination of a 90° TN-LC cell and a birefringent calcite plate has been used based on the polarization switching by the TN-LC cell and the optical path separation between the o- and e-rays through the birefringent plate. The successive two speckle patterns before and after the displacement are detected. A spatial shift is given to the latter pattern, so that the joint pattern which is something like a specklegram but is different from an ordinary one is formed from the two patterns. Then, the joint transform correlation function is calculated. A good linear relation between the peak position of the correlation function and the object displacement has been obtained, which enables the application of this method to displacement and velocity measurements in speckle techniques. A real-time optical correlator can be implemented by the previously proposed LCTV-based optical correlator [5] together with the spatial shifter discussed here.

The switching speed of the TN-LC cell used in the experiment is rather slow and is about 100 ms. Therefore, this TN-LC cell is suited for the displacement measurement or the velocity measurement of a slowly moving object. For a velocity measurement in most cases, a faster polarization switching device may be necessary to realize a real-time joint transform correlation based on the proposed method. Currently, a ferroelectric liquid crystal (FLC) device which has a switching speed of the order of micro-second to several tens of micro-second is available as the polarization switch. This value of the switching speed is satisfactory for most mechanical applications in speckle metrology. In this case, a spatial light modulator (SLM) having a faster switching speed compatible with the speed of the FLC polarization switching device is also required to implement a real-time optical correlator. Fortunately, an FLC-SLM which has the same switching speed as the FLC polarization switching device is now available. An FLC-SLM also has the attractive feature of double exposure capability of images, so that a joint pattern can be easily formed in real-time. We are now preparing an experiment using such devices and the results will be given elsewhere.

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