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New method for measuring high field electrostrictive response of barium titanate/polyurethane elastomer

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Abstract: A new method for measuring the characteristic of electrostriction by a digital speckle correlation method (DSCM) is presented. The in-plane displacement is obtained by using the DSCM, and the out-plane displacement is obtained by the geometrical relation of the triangle theory. In this application, high field electrostrictive strains of barium titanate/polyurethane elastomer composite materials are measured. The electrostrictive strain is evaluated when the application of an electric field is repeated, and then the electrostrictive coefficient of the sample is obtained. To improve the measuring accuracy, the bilinear interpolation of gray value is used to obtain the sub-pixel gray value. The results are compared with those obtained from the surface fitting algorithm. The experimental results demonstrate that the electrostrictive response of polyurethane increases with the introduction of barium titanate into polyurethane. And by using the DSCM, the measurement of the characteristic of electrostriction can be done quickly and accurately. The DSCM provides an effective tool for the evaluation of electrostrictive response.

Key words: digital speckle correlation method; electrostrictive response; barium titanate/polyurethane elastomer composite material; electrostrictive strain

Polymers, as electromechanical materials, have some advantages such as flexibility, low density, and ease in molding as compared with conventional electromechanical ceramics. In particular, polyurethanes have drawn much attention since a high electric-field-induced contraction was reported[1,2]. The substantial magnitude of the observed strains combined with the polyurethanes' high compliance has led some researchers to investigate the possibility of using electrostrictive polymer films as advantageous alternatives to piezoelectric materials in sonar and loudspeaker design.

However, the poor fundamental understanding of electrostriction in polyurethanes and the lack of reliable and complete electrostrictive coefficient data have hindered the development of polyurethane-based electromechanical applications. Although some advanced techniques such as the laser interferometer method, the double-beam interferometer method and the electrical method have been reported to measure the electrostrictive response of polyurethane[3,4], the measurement results of the extremely soft nature materials are extremely sensitive to the experimental conditions, especially the mechanical boundary conditions. Optical methods are adapted to the measurement of electrostrictive response, but the conventional laser interferometer method cannot obtain a high accuracy. For this reason, DSCM[5,6] is used to measure the electrostrictive response of polyurethane due to the advantages of automatic, non-contact, full field and real time.

1 Theoretical Analysis

1.1 Electrostrictive response

Electrostriction is the fundamental mechanism of electromechanical coupling in all insulator materials. The application of an electric field to any material can displace charge and lead to field-induced elastic strains. If the signs of the strains are unchanged on reversal of the electric field, this property is termed electrostriction and it occurs in all materials whether crystalline or not. Electrostrictive strain is proportional to the square of the applied electric field, and as a function of the applied electric field it can be expressed as

$$\varepsilon = QP^2 \tag{1}$$

where ε is the electrostrictive strain (ε = change in

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thickness/original thickness), $Q(\mathrm{m}^2/\mathrm{V}^2)$ is the electrostrictive coefficient, and $P(\mathrm{V/m})$ is the applied electric field. In this paper, the DSCM is used to measure the electrostrictive strain of material.

1.2 Digital speckle correlation method

The DSCM is one of the most commonly used methods for high-resolution measurement. It is a computer-vision-based, nondestructive, whole-field technique for static and dynamic deformation measurement. The basic principle of the DSCM is to match two speckle patterns before and after deformation. Based on the predefined correlation function, the matching procedure is completed through searching for the peak position of the distribution of correlation coefficients, which indicates the similarity of the two speckle patterns. Finally, the displacement is extracted by the peak position. A better and more commonly used correlation function is defined as

$$c = \frac{\sum\sum[f(x,y)-\bar{f}][g(x+u,y+v)-\bar{g}]}{[\sum(f(x,y)-\bar{f})^2\sum(g(x+u,y+v)-\bar{g})^2]^{\frac{1}{2}}} \tag{2}$$

where the scale of the given subset is $m \times n$; $f(x, y)$ and $g(x+u, y+v)$ are the gray values of subset centered at the source and the target point, respectively; u and v are the displacements between the two images; $\bar{f}$ and $\bar{g}$ are the ensemble averages; c is the correlation coefficient.

In the DSCM, one of the important assumptions is the uniform displacement or small displacement of the subset between two correlation images. In this assumption, a square subset of speckle pattern will retain its shape. But in the large strain field measurement, this assumption cannot be obeyed and the shape of the subset will be changed. Therefore, an effect on the reducing accuracy of the correlation operation exists. To enhance the sensitivity and the accuracy of the measurement further, sub-pixel algorithms are required. A simple and effective method is the two-step searching method. It includes a coarse search and a fine search. The coarse search, which provides estimates of the displacement field by integer increments of the distance between pixels, is used as the initial condition for the fine search scheme. During the fine search the gradient terms are optimized in conjunction with the displacement field. Displacement continuity across correlation windows is also utilized to improve the computational efficiency of the correlation process.

To obtain the sub-pixel gray value[7,8], the surface fitting algorithm and the bilinear interpolation of the gray value are often used. In this paper, the bilinear interpolation of gray value is used to obtain the sub-pixel gray value. The formula of the bilinear interpolation of gray value is

$$f(x,y) = (1-\alpha)(1-\beta)f(x_1,y_1) + \beta(1-\alpha)f(x_1,y_2) + \alpha(1-\beta)f(x_2,y_1) + \alpha\beta f(x_2,y_2) \tag{3}$$

where f represents the gray value of point; α and β are the proportionals and they are governed by

$$\alpha = \frac{x-x_1}{x_2-x_1}, \quad \beta = \frac{y-y_1}{y_2-y_1} \tag{4}$$

The sketch of the bilinear interposition is shown in Fig. 1. Once we get the gray value of sub-pixel, the second correlation calculation can be performed and an accurate sub-pixel value with a high correlation coefficient will be obtained.

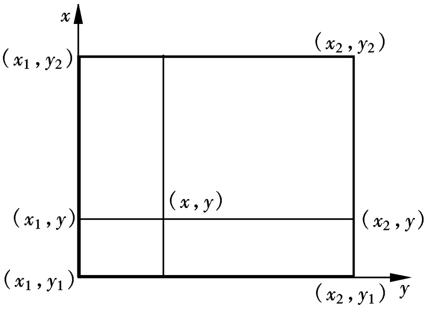

Fig. 1 Sketch of the bilinear interposition

The surface fitting algorithm[9] is a popular method to obtain the sub-pixel gray value. The computation time of this algorithm is less than that of the bilinear interpolation of gray value. The algorithm utilizes the statistical properties of the correlation coefficients around the accurate matching point and obtains the fitting surface of the correlation coefficients around this point. The accurate matching points, on which the first derivative of the correlation coefficient is equal to zero, can be obtained easily.

2 Experimental Illustration

The schematic of the optical system is shown in Fig. 2. In normal view, the in-plane displacement u due to thickness change Δh is given by

$$u = \frac{\Delta h}{k} \tag{5}$$

where k, which can be obtained by calibration, is an

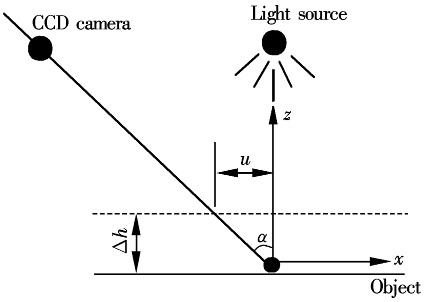

Fig. 2 Schematic of the optical system

optical coefficient related to the configuration of the system. The value of k is evaluated to be 13. 545, then Eq. (5) can be expressed as $\Delta h = 13.545u$; the unit of Δh is μm and the unit of u is pixel.

The experimental setup is shown in Fig. 3. The environmental temperature during the experiment is 22 ℃. In this experiment, a prestressing force is used to eliminate the falsity strains arising from the defects of the sample surface. These samples are molded with the introduction of barium titanate into polyurethane in order to improve the electrostrictive response of the polyurethane, and the content of barium titanate of materials is shown in Tab. 1.

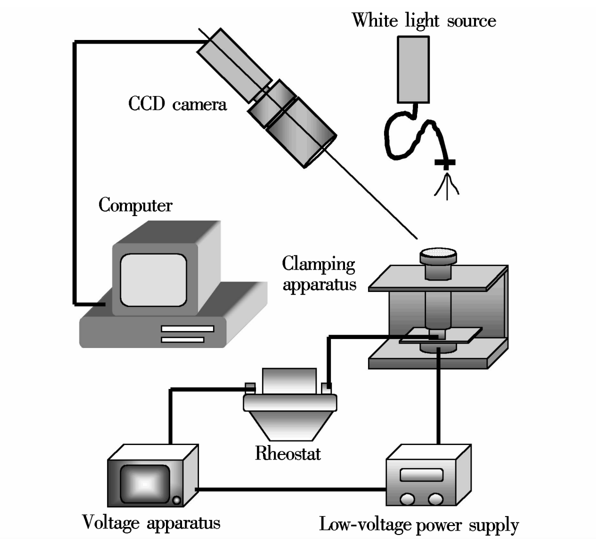

Fig. 3 Experimental setup

Tab. 1 Influence of barium titanate content on electrostrictive coefficients

Polyurethane code	Content of barium titanate/%	Electrostrictive coefficient $R/(m^2 \cdot V^{-2})$
PUE-A	0	-3.4×10^{-15}
PUE-0	0	-2.9×10^{-15}
PUE-1	0. 5	-6.563×10^{-15}
PUE-2	1. 1	-5.474×10^{-15}

3 Results and Discussion

The images are captured at the interval of 10 s, and the electrostrictive strains of barium titanate/polyurethane elastomer composite materials have been evaluated. The typical measuring results of the electrostrictive strain are shown in Fig. 4. The vertical axis means the electrostrictive strain. The results evaluated by the bilinear interpolation of gray value are designated as strain 1. From Fig. 4, it is observed that the electrostrictive strain of the sample exhibits the corresponding shrink and recovery to the application of the electric field. And the response of shrink is slower than that of its recovery. It is due to the increase of sample dielectric constant with the introduction of barium titanate, and the increase of sample dielectric constant leads to the increase of the sample permittivity. However, the electric charge cannot release instantaneously and completely. From Figs. 4(a) and (b) it is also observed that the electrostrictive strain of the barium titanate/polyurethane elastomer composite materials decrease with the increase of barium titanate content.

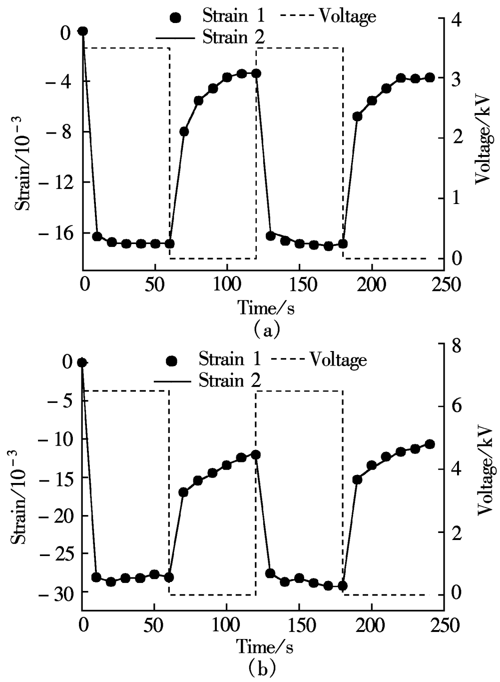

Fig. 4 Electrostrictive strain. (a) Sample PUE-1 during an electric field (3. 5 kV) is repeated; (b) Sample PUE-2 during an electric field (6. 5 kV) is repeated

The influences of barium titanate content on electrostrictive coefficients are listed in Tab. 1. The electrostrictive coefficient of PUE-A was obtained by Asi et al. [10]. The sample was the pure polyurethane elastomer without the introduction of barium titanate and it was also preloaded. To comparison, the electrostrictive response of the polyurethane elastomer without the introduction of barium titanate is also measured, and the code of this sample is PUE-0. It can be seen that the electrostrictive coefficients are all in the same order. The electrostrictive coefficients of PUE-0 and PUE-A are designated different, and the discrepancy is 0.5×10^{-15}. This is due to two different weights preloaded on the sample. From Tab. 1, it is observed that the electrostrictive coefficient increased with the introduction of barium titanate into polyurethane, and the electrostrictive coefficient of the composite materials decreased with the increase of barium titanate content.

To verify the accuracy of electrostrictive strain measurement, the surface fitting algorithm is also applied to the same samples. Fig. 4 also shows the comparison of electrostrictive strains measured by two algorithms. Results evaluated by the surface fitting algorithm are designated as strain 2. It can be observed that the results from these two algorithms agree well. The maximum discrepancy between strain 1 and strain 2 is approximately 0.223×10^{-3}. And this conclusion proves the accuracy of the DSCM.

In order to obtain the information of electrostrictive strain in detail and the recovery time of the sample, the frequency of imaging rate is increased. The images are captured at the interval of 1 s. The electrostrictive strain of PUE-1 measured when the application of an electric field (3.5 kV) is repeated is shown in Fig. 5. From Fig. 5 it can be seen that more information of electrostrictive strain has been obtained and the recovery time of PUE-1 at 3.5 kV is about 150 s.

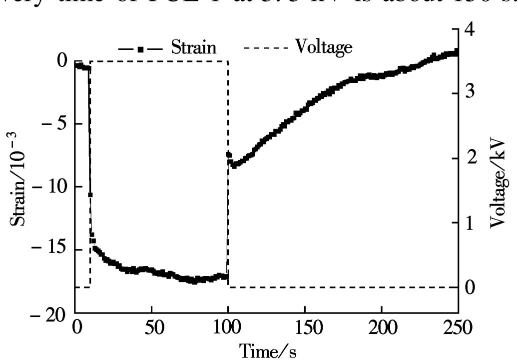

Fig. 5 Electrostrictive strain of PUE-1 during an electric field (3.5 kV) is repeated

4 Conclusion

The electrostrictive strain of the barium titanate/polyurethane elastomer composite materials exhibits the corresponding shrink and recovery to the application of the electric field. The response of shrink is faster than that of its recovery. And the electrostrictive response increases with the introduction of barium titanate into polyurethane. This paper gives a new idea for research into the electrostrictive response.

This paper gives a non-contact optical method for measuring the strain field of electrostriction. Two algorithms are used to obtain the sub - pixel displacement. One is the bilinear interpolation of gray value and the other is the surface fitting algorithm, and the results of the two algorithms agree well. Due to the advantages of automatic, non-contact, full field, real time and the simple optical arrangement, the DSCM has become an effective optical method. The experimental results prove that the DSCM provides an effective tool for the evaluation of electrostrictive response.

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一种测量钛酸钡/聚氨酯材料电致伸缩性能的新方法

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摘要: 提出利用数字散斑相关方法测量材料的电致伸缩性能的新方法. 通过数字散斑相关方法得到面内位移,从而由几何三角关系得到离面位移,实现电致伸缩应变的测量. 采用该方法对高电场作用下钛酸钡/聚氨酯复合高分子材料的电致伸缩性能进行了测量. 在高电场作用下,对重复加电放电过程进行分析,得到电致伸缩应变,从而获取材料的电致伸缩系数. 实验中采用双线性插值方法获取亚象素灰度值,以提高测量精度,并将结果与曲面拟合算法的计算结果进行了比较. 结果表明:钛酸钡的加入提高了聚氨酯材料的电致伸缩性能;数字散斑相关方法可以有效地实现材料的电致伸缩系数的测量. 该方法为电致伸缩性能的研究提供了一种有效的工具.

关键词: 数字散斑相关方法;电致伸缩效应;钛酸钡/聚氨酯材料;电致伸缩应变
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