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Application of Digital Image Technology in Testing Mechanical Properties of Materials

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The purpose of this study is to improve digital image technology and meet its requirements for engineering measurement. To this end, this paper studies the application of digital image technology in material mechanical property testing. Based on pixel point grey value and point-by-point search strategy, particle swarm optimization (PSO) algorithm was also integrated to optimize the correlation functions. Then, an application simulation experiment was conducted. The experimental results show that the calculated displacement obtained by the optimization algorithm is closer to the normal distribution, and the dispersion degree of the calculation results is significantly reduced. Therefore, the digital image correlation method (DICM)-based integer pixel search algorithm has certain adaptability to environmental changes, and it is more suitable for practical measurement.

1. Introduction

With the rapid development of science and technology, new materials have been constantly emerging nowadays, and also been well applied in special fields. Strain and displacement are ones of the basic tasks in the measurement of mechanical properties. Generally, resistance strain gauges, mechanical gauges, etc. are used for measurement, but with certain defects. The digital image correlation method (DICM) has significant advantages such as low requirements on the environment etc. It has been widely used in experimental mechanics. However, DICM also has disadvantages, e.g., low computational efficiency. For this, this paper proposes a new algorithm based on digital image technology and applies it to the material mechanical property testing; then, according to pixel point grey value and point-by-point search strategy, PSO algorithm was also integrated to optimize the correlation function; finally, based on this, the application simulation experiment was conducted.

2. Literature review

Many scholars at home and abroad have done a lot of research on how to speed up the related operations and how to improve the accuracy of the operation. In 1983, Sutton, Wolters, and Peters proposed a coarse-fine search method. Through the two-step operation of coarse correlation and fine correlation, the original digital image correlation method is simplified, and the calculation speed is improved. In 1985, Chu, Ranson, and Sutton et al. gave basic theories of object deformation and digital correlation. Based on this, the relationship between surface displacement and strain of the measured object is established, and the basic theory of digital image correlation method is further improved. In 1986, Sutton et al. introduced optimization theory into digital image correlation calculation, and proposed an optimized search algorithm to further improve the speed of related calculations (Awada and Nathanson, 2015). After a series of hard work by Sutton and Peters research team, a new optimization search algorithm based on Newton-Raphson iterative method was proposed in 1989. The algorithm reconstructs sub-pixel grayscale images using bicubic spline interpolation. The Newton-Raphson iterative method for solving nonlinear equations in numerical analysis is used to solve the extreme point positions of correlation coefficients, which improves the correlation calculation speed. The research results show that the time-consuming calculation of the algorithm under the same solution accuracy is 1/8~1/4 of the coarse-final method. The Newton-Raphson algorithm is a major

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improvement in digital image correlation methods, which makes the theory of digital image correlation methods more complete (Cantrell et al., 2017). However, the Newton-Raphson algorithm needs to calculate the second-order partial derivative of the correlation function (ie, the Hessian matrix), which increases the complexity of the algorithm calculation. To this end, Vendroux and Knauss improved the Newton-Raphson algorithm. By approximating the Hessian matrix, the first-order partial derivatives of the correlation coefficients need only be calculated. Without affecting the accuracy, the calculation is simplified and the programming complexity is reduced (Hong et al., 2015).

In 1993, Chen et al. proposed a Fourier-based frequency domain correlation method. The method transforms the speckle image from the spatial domain to the frequency domain by fast Fourier transform, and then performs correlation calculation. Since the image information will have a certain loss during the conversion process, the calculation accuracy of the method is not high, and it is not widely used in practical applications. In 1994, Yan Jiabai and Jin Guanchang proposed a cross search algorithm through the research of related search methods, which greatly shortened the calculation time. However, the calculation accuracy of this algorithm is not high. It is usually used for integer pixel search (Kalali et al., 2015). In 1998, Davis et al. presented a sub-pixel matching algorithm based on spatiotemporal gradient based on optical flow calculation, which improved the matching speed. Later, many scholars at home and abroad made further research and improvement on the algorithm. In 2002, Hou Zhende et al. introduced fractal theory into related calculations and proposed a new image fractal correlation algorithm. The algorithm eliminates the traditional correlation coefficient defined by image grey scale, and establishes a correlation function based on fractal dimension, which can quickly obtain the displacement domain of the surface of the measured object. In 2003, Jian Longhui and Ma Shaopeng proposed a digital image correlation search algorithm based on orthogonal wavelet transform, and accelerated the search speed by multi-level decomposition of wavelet. In the same year, Yoneyama et al. proposed a color speckle correlation method for displacement measurement, which improved the accuracy of displacement measurement. In 2008, Wang Min et al. proposed a digital image correlation method based on weighted window. First, the method defines a weighting factor associated with the position of the pixel in the calculation window. Then, the weighting factor is introduced into the correlation function to obtain a new correlation coefficient calculation formula. Finally, the correlation coefficient formula is applied to perform related search calculations, and good results are obtained (Popovich et al., 2017). In 2010, Possant et al. proposed a digital image correlation method based on subset segmentation. When the algorithm detects a discontinuous domain, the image subset is automatically split into two parts, thereby realizing the measurement of the surface of the object with "displacement jump". Compared with the traditional methods, the method shows that the method has a good effect on the displacement measurement of discontinuous regions such as cracks, slits and faults (Rashed et al., 2016).

At present, digital image correlation methods have become an important non-contact measurement method in the field of experimental mechanics. In recent years, with the continuous improvement of digital image correlation theory and the rapid development of computer technology and optical information processing technology, this method has been widely used. In 1983, Peters et al. of the University of South Carolina in the United States successfully completed the measurement of the two-dimensional steady-state laminar flow field using the digital image correlation method for the first time. In 1987, Wu and Peters completed the measurement of mechanical properties of the retina, and realized the measurement of flexible materials and soft tissues by digital image correlation methods. In 1989, Russel and Sutton applied digital correlation methods to achieve quantitative non-destructive evaluation of impact and installation damage in glass fiber reinforced systems. In 1990, Kahn-Jetter and Chu used two fixed cameras to simultaneously capture the speckle field of an object, and used the parallax associated with the two-dimensional digital image of the two cameras to solve the three-dimensional coordinates of the object. This opens the theoretical and applied research on 3D digital image correlation methods. In 1995, Sutton et al. applied the digital image correlation method to measure the displacement and strain field of the crack tip, and realized the application of the method in the field of failure mechanics. Later, Zink et al. applied this method to complete the measurement of wood strain and Poisson's ratio. With the wide application of various advanced electron microscopes, Knauss et al. combined digital image correlation with an electron microscope to achieve mesoscopic mechanical measurements. In 1996, Sutton et al. completed an experimental study on the measurement of surface displacement and deformation of high temperature objects by digital image correlation methods. Good results were obtained with temperatures up to 650 °C. Since then, Anwander et al. have further studied the application of digital image correlation methods to high temperature measurements. A digital image correlation high temperature measurement system using laser speckle was developed. The measurement temperature can reach 1200 °C.

With the development of materials science, digital image correlation methods have also been used to study the mechanical behavior of various new materials (Tymrak et al., 2014). Gonzales and Knauss applied this method to study the mechanical properties of composites. Chevalier et al. used this method to analyze the mechanical behavior of polymer materials under uniaxial and biaxial tensile conditions, and established a model to simulate its mechanical behavior. Betzwar-Kotas et al. performed tensile tests on different ceramic (alumina, silicon carbide and carbide) fibers and carbon fibers to obtain their stress-strain curves. Nunes applied this method to measure the shear modulus of a polydimethylsiloxane adhesive. In 2009, Pankow and others used a single high-speed camera and three-dimensional digital image correlation technology to achieve measurement of large off-plane displacement. In the same year, Gren and Hutt published papers respectively on the feasibility and analysis of the feasibility of digital image correlation methods for sealing characteristics research and buttonhole crack detection. The application field of the digital image correlation method is further expanded. The domestic application of digital image correlation methods began in the late 1980s, and has achieved considerable results. Gao Jianxin of Tsinghua University systematically analyzed the digital image correlation method and carried out the initial application research. The method was applied to the preliminary study of the flow field, large deformation of the forging and crack. Recently, Pan Bing developed a high temperature deformation measurement system using digital image correlation technology and transient aerodynamic thermal test simulation system, and the measurement temperature reached 1200 °C.

To sum up, in the more than 30 years since the digital image correlation method was proposed, many research and engineering technicians at home and abroad have been working on the application of this method. It has been successfully applied in many aspects of mechanical research. Although the digital image correlation method has many of the above advantages, it also has some disadvantages. First, the method of calculating integral pixel displacement based on the correlation of points is computationally expensive and inefficient. Second, the sub-pixel iteration algorithm based on optical flow equation is sensitive to environmental changes and affects the accuracy of measurement. Third, the use of the same size image subset in the iterative calculation lacks adaptability and affects measurement accuracy and speed. Therefore, there is still much work to be done in the digital image correlation method. Aiming at the above shortcomings of digital image correlation method, a new algorithm is proposed based on digital image technology and applied to the material mechanical property test. According to the pixel point grey value and the point-by-point search strategy, combined with the particle swarm algorithm, the correlation function is optimized. On this basis, an application simulation experiment was conducted.

3. Principles and methods

A new DICM method based on genetic algorithm (GA) can improve the digital image correlated matching process and the search efficiency. Because the method can perform fast global search in a large range and has strong robustness to the distribution of correlation coefficients, it is mostly used for integer pixel displacement search in digital image correlation technology to achieve global, fast, and accurate positioning of integer pixel more for correlation coefficients under multi-peak conditions. The GA-based integer pixel displacement search process includes: encoding and decoding of variables, generation of initial population, determining fitness function, individual selection operation, crossover operation, and mutation operation. Figure1 shows the flow chart of a digital image related integer pixel displacement search method based on GA, indicating that the calculation process of this method is more complicated, and the programming implementation is relatively difficult.

The PSO algorithm is an optimization algorithm based on the swarm intelligence principle proposed by American social psychologist J. Kennedy and electrical engineer R. Eberhart in 1995. In this algorithm, each individual is considered to be a particle with no weight and volume in the search space, and these particles are the potential solutions to the optimization problem. All particles have an adaptive value determined by the optimized function. The correlation coefficient distribution surface is obtained by performing correlation calculation point by point in the search subset. The position with the largest correlation coefficient is the target subset position we are searching for. The coordinate difference between the reference subset and the centre point of the target subset is the displacement vector d=(u, v). Therefore, the displacement solving problem can be regarded as a function optimization problem.

Uniaxial stretching is the most straightforward way to obtain the basic mechanical properties of materials. For some flexible materials (such as fabrics, plastics, etc.), large deformation materials (such as rubber), and small specimens etc., measurement cannot be completed using a conventional contact extensometer. Therefore, the development of non-contact measurement technology has become particularly important. This test system uses a dual CCD camera instead of the two-cutting edge for the strain gauge extensometer, in order to reduce the field of view, improve the measurement accuracy of small deformation, and ignore the influence of lens distortion. Digital image correlation is then adopted to make measurements by tracking the displacement of the region at both ends of the specimen gauge length. The composition of the test system is shown in Figure 2 (1: White light source; 2: CCD camera 1; 3: Camera bracket; 4: CCD camera 2; 5: Electronic universal testing machine; 6: Extensometer; 7: Round test piece), mainly including two CCD cameras, a light source, a computer (with an image acquisition card), an electronic universal testing machine, a camera bracket, and a CCD camera synchronization control circuit. The two CCD cameras in the test system are manufactured by Allied AVT, Germany, and they're responsible for continuously shooting the speckle images at both ends of the gauge length during the stretching process, and then digitizing them through the image acquisition card and storing them in the computer. The tested piece was a dumbbell type standard round bar, with the material of Q235 and the size of Φ10×210mm. After the surface of the specimen was polished, a uniform distribution of speckle was produced by manually spraying black and white paint, and the specimen produced is shown in Figure 3.

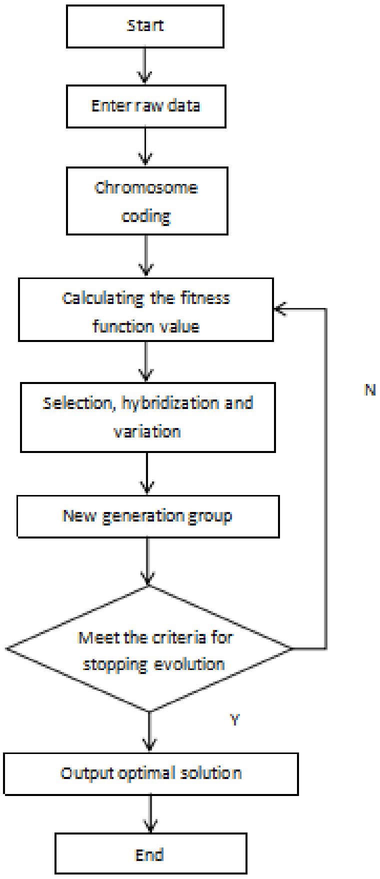

Figure 1: Flow chart of digital image correlation integer pixel displacement search method based on GA

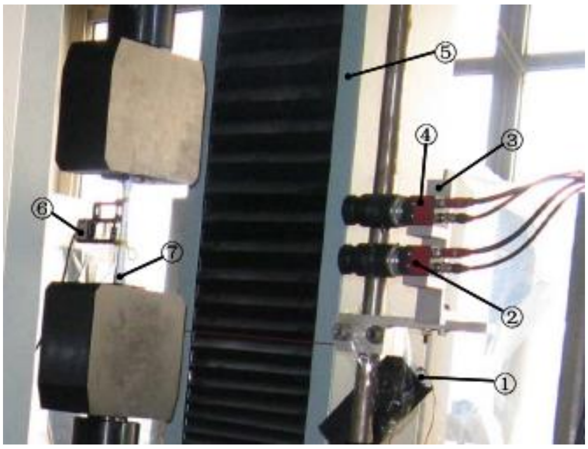

Figure 2: test system hardware components

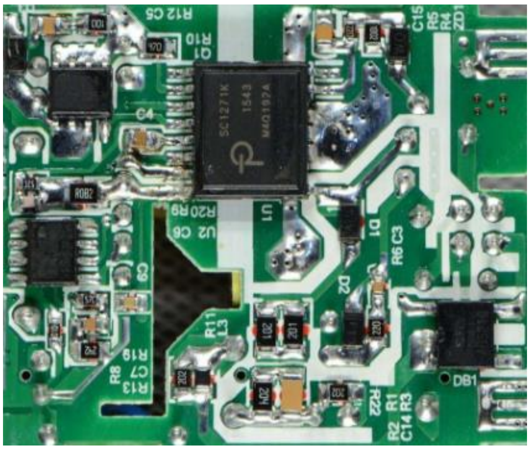

Figure 3: synchronous control circuit

In addition, in order to verify the measurement accuracy of the test system, the CBY series strain gauge extensometer was used for simultaneous measurement. To start and end the extensometer measurement system simultaneously with the video measurement system, another output signal was added to the synchronous trigger circuit of the upper CCD camera, and the signal was simultaneously outputted with the camera trigger signal, triggering the left-key click signal output of the upper computer mouse in the electronic universal testing machine.

4. Results and analysis

The steps for calibrating the pixel equivalent include: (1) Mount the round specimen with speckles on the chuck of the electronic universal testing machine, and adjust the focal length and aperture of the two camera lenses as well as the illumination source of the system, so that the best quality speckle pattern of the piece can be obtained for the imaging system; then, by taking this as the initial state, shoot two speckle patterns; (2) Loosen the upper collet of the test machine (non-moving collet) and use the control system of the test machine to make it moving 5 times in steps of 0.01mm; two CCD cameras in the imaging system record 5 speckle patterns respectively, and the actual displacement is read by the dial gauge; (3) Apply DICM to measure the displacement for 5 times.

Table 1: Pixel Equivalent Calibration Results

Actual displacement	Pixel shift		Pixel equivalent	
	Upper camera	Lower camera	Upper camera	Lower camera
0.0094	0.4496	0.4095	0.0211	0.0213
0.0195	0.9235	0.9027	0.0210	0.0215
0.0294	1.3851	1.3698	0.0212	0.0214
0.0395	1.8655	1.8691	0.0212	0.0211
0.0501	2.3264	2.2386	0.0215	0.0214
Average pixel equivalent	0.0212		0.0213	

After the pixel equivalent calibration was completed, the lower collet of the testing machine was moved to the initial position, the specimen was re-tensioned, and the tensile test was prepared after the extensometer was mounted on the specimen. Figure4 shows the force and deformation curves of the two specimens measured by the extensometer and DICM at the elastic deformation stage. It can be seen from the two graphs that at the elastic stage, the force-deformation relationship curve obtained by the measurement system based on the DICM in this paper exhibits a very good linear relationship, which is basically consistent with the curve obtained by the extensometer. This fully demonstrates that the test system can be applied to the mechanical properties testing of materials.

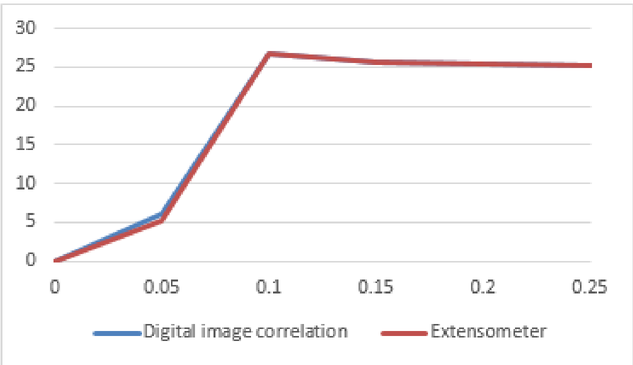

Figure 4: Relationship between force and deformation of specimen in elastic stage

Table 2 lists the elastic modulus of the specimens measured by this measuring system and the extensometer. It can be seen from the data in Table 2 that the elastic modulus measured by the measurement system is in good agreement with the value measured by the extensometer, and the maximum relative deviation of the measured value is within 6%, while the relative deviation of the measurement results for the second specimen is only 0.86%. This further demonstrates that the measurement system of material mechanical property based on the DICM can achieve non-contact measurement of the material mechanical quantity, and obtain satisfactory measurement results. In addition, the standard values of the elastic modulus for the specimens are also given in the table. It can be found that the elastic modulus measured by the DICM is closer to the standard value than that by the extensometer, which fully demonstrates the feasibility and superiority of the measurement system based on DICM in the field of material mechanical property testing

Table 2: Measurement results of elastic modulus of specimens

Specimen	Measuring system	Extensometer	Relative error	Standard value
1	2.0610	1.951	5.69%	2.00～2.10
2	2.0273	2.010	0.86%	

Through the above actual measurement experiments on the elastic modulus of the material, it can be seen that the material mechanical property testing system based on the DICM has various errors in the actual application process. Since the loading mode of the testing machine is a homogeneous deformation mode in the above tensile test, the deformation increment is 0.002 mm/s, so the deformation increment of each sample should be constant in the DICM or the extensometer (i.e., within the time interval of 0.1s, the deformation increment should be 0.0002mm). The measurement accuracy of the extensometer is 0.0001mm, so, the measured deformation increment within 0.1s is 0.0001mm or 0.0002mm. However, the DICM is affected by various noises, and the measured deformation increment fluctuates greatly.

5. Conclusions

In this paper, the important non-contact measurement method in experimental mechanics, i.e., the DICM, was studied. The main conclusions are as follows: Based on the digital image correlation theory proposed in this paper, an experimental test was conducted for the material mechanical property testing system based on dual camera tracking. Through the tensile test on the standard specimen, the force-deformation curves were obtained, which is in line with the curve obtained by the extensometer. The measured elastic modulus is within the standard value range, proving that the test system has good practicability and can test the mechanical properties of various materials. Although certain achievements have been made in the research of DICM, these results have accelerated the practical application and development of related products.

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