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Measurement Affecting Errors in Digital Image Correlation

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Abstract. Optical full-field measurement methods such as Digital Image Correlation (DIC) are increasingly used in the area of experimental mechanics. The reliability for each measurement technique depends on the knowledge of its uncertainty and the sources of errors of the results. The aim of this work is to systemize the sources of errors related to digital image correlation (DIC) technique applied to strain measurements. The paper is concluded by some suggestions proposed in order to minimize the errors.

1. Introduction

Nowadays Digital Image Correlation (DIC) is widely spread optical technique for strain measurement. The technique was proposed by Peters et al. in the 1980s [1, 2]. It allows to carry our investigation of deformation and fracture processes of heterogeneous materials (metals, alloys, ceramics, polymers etc.) as well as makes it possible estimating mechanical state of loaded machine parts and structure components. Application of this method benefits on high resolution and sensitivity, and provides reducing manufacturing and operational costs of the instrumentation. The strain measurement in the DIC technique consists of two principal stages: determination of optical flow and subsequent computation of deformation components.

As a measurement method, the accuracy of DIC at strain calculation is of crucial importance. There are many error sources involved in the DIC measurement procedure, either originating from the experimental set-up or from the employed correlation algorithm, which bring in difficulties for the uncertainty quantification [3].

2. Errors affecting DIC measurements

It is of importance to distinguish between systematic error (displacement of the average, resulting in lack of accuracy) and random error (large standard deviation, resulting in lack of correctness/robustness) [4]. In fact, accuracy and robustness of the DIC measurements cannot be taken for granted if the measuring system and the numerical processing have not been optimized and validated [4]. The displacement and strain affecting errors are originally induced by the overall quality of the raw experimentally gained images. A DIC-computed displacement field is less sensitive to variation of calculation parameters (specified by the user), while their effect is larger computation the strain [5, 6]. Palanca M. showed [6] the importance of a careful optimization of the DIC software and hardware settings to minimize random and systematic errors. The settings that allowed minimizing the random errors were also associated with averaging over a larger area, and were therefore associated with poorer spatial resolution. Accuracy and robustness of the DIC-system in computing the displacements are in the order of 0.01 pixel [5, 7, 8]; however with some optimizations errors can be further reduced [9]. The discrepancies between DIC evaluated displacements and specified ones have been statistically analyzed [8] in terms of random errors and systematic ones; in doing so they were correlated with the fractional part of the displacement component expressed in pixels. Main results are as follows: calculated displacement amplitude is almost insensitive to subset size, standard deviation of random error increases with enlarging noise level and decreases with enhancing subset size. However, the DIC formulations can be split up into two main families regarding displacement sensitivity to noise. For the first one, the amplitude of the latter increases with noising while it remains nearly constant against the subset size. In addition, for the first family, a strong dependence of random error with τ is observed for noisy images. DIC-computed strain values are generally quite accurate (systematic errors is of the order of few microstrains). Conversely, large noise usually largely affects DIC-computed strains: an accuracy of some hundreds of unit can be achieved only under optimal conditions [4].

The DIC analysis relies on the presence of a suitable pattern on the specimen surface [4]. In order to evaluate the errors related to its morphology, digital images of the speckle patterns were varied [10], numerically deformed [11], correlated in a zero-strain condition [12]. Inappropriately chosen speckle pattern is likely to make the correlation impossible at some patches (square–shape image regions), reducing the number of measurements points [10]. It is shown that the size of the speckles combined with the size of the used pixel subset clearly influences the accuracy of the measured displacements [11]. An optimal ratio exists between the patch size and the mean speckle size to reduce errors affecting DIC-computed displacements [11, 13]. They also showed that a limited scatter of speckle sizes yields more accurate displacement measurements, and that larger size dots ensures larger random errors in the constructed displacement field. The differences between black-on-white and white-on-black speckle patterns are negligible in terms of measurement quality [9]. A clear relationship exists between the measurement error and the uniqueness of the pattern, which depends on the speckle size and shape, and on the patch size [14]. Errors reduced with increasing number of speckles in the pattern, with enlarging speckle size providing a greater variation of shape, resulting in a lower error than patterns with smaller speckles. The airbrush airgun method provides a better detectability of the dots dimension as compared to the use of powder speckle [15]. Even if at a limited extent an airbrush airgun can be adjusted to produce the desired speckle dots [14], the performance of DIC stands quite robust and stable [16].

Images acquired by the digital camera are subjected to random errors affect, being induced by thermal noise (or dark noise), excess noise due to the CCD-sensor and electromagnetic noise of the relative measurement channel [17]. Moreover, a source of systematic error in 2D-DIC derives from out-of-plane displacements of the specimen during loading. That is why 2D-DIC is often chosen in investigations at the microscopic level [18, 19]. In practical applications, various unavoidable disadvantageous factors, such as small out-of plane displacement of the test object surface occurred during loading, small out-of-plane motion of the sensor target due to the self-heating or temperature variation of a camera, and geometric distortion of the imaging lens, may seriously impair or slightly change the originally assumed linear correspondence. In certain cases, these disadvantages may lead to significant errors in displacements and strains measured by 2D-DIC [19]. Suboptimal choice of the calculation parameters (specified by the user) can result in higher noise, or, conversely, could hide existing strain gradients [20]. The optimal parameters can be identified through virtually imposed displacement [10]. Numerically "deformed" images were prepared to evaluate the accuracy and robustness at constructing the displacement field, and identify the optimal parameters [16, 21, 22, 23].

3. Conclusions and recommendations to minimize measurement errors

It is required to validate DIC measurements by their comparison against independent measurements; in [7, 24, 25] the DIC-computed strains were compared against single strain gauges. A more extensive validation may include the use of specimens with known material properties, subjected to well-defined loading conditions [7, 24, 25]. Moreover, preliminary tests to identify the spatial displacements could help in avoiding out-of-plane artifacts in 2D-DIC measurements.

The quality of the applied random speckle pattern is of crucial importance. It exerts some influence on the correlation results [10]. A low quality speckle pattern results in no correlation at some mesh nodes of the virtual grid. It also exerts certain influence on the accuracy at calculating correlation function. Using an optimized speckle pattern that can be printed directly on the surface of the sample is an efficient solution. Thus, the obtained speckle pattern will be independent of the operator and; hence the results would be more reproducible. To optimize the speckle pattern a factorial design to adjust the airbrush settings is proposed to form a pattern having the required average speckle element size with minimal scatter [7, 26, 27]. Paper [26] shows that it is possible to obtain a pattern with a highly controllable average and a limited scatter of speckle sizes, so as to match the ideal distribution of speckle sizes for DIC. Although the settings identified here apply only to the specific equipment being used; however this method can be adapted to any airbrush to produce a desired speckle pattern.

The lens distortion is responsible for a systematic error, which can be partially compensated through dedicated algorithms [28], or an appropriate calibration [29, 30]. A method of lens distortion correction was proposed [28] in order to improve the measurement accuracy of digital image correlation for 2D displacement measurement. The amounts of lens distortion are evaluated from displacement distributions obtained in a rigid body in-plane translation or rotation test. After detecting the lens distortion, its coefficient is determined using the method of the least squares. Then, the corrected displacement distributions are obtained. Such artefacts can be completely eliminated with telecentric lenses [19], or by exploiting the central portion of the lens angle [7]. An in-house smart solution consists in performing 3D deformation measurements with a single camera using a biprism to avoid distortion of the images [31, 32].

As shown by the test, the errors related to the variation of the lighting source may be of importance [10]. The illumination must be stable and uniform to reduce the noise and register better quality raw experimental images. Noise and its influence can be somehow reduced, but not completely eliminated, even with high-performance hardware (i.e. lenses, cameras, frame grabber, etc.) [4].

The main destination of the subset is to characterize the similarity between two patches while it depends on the speckle pattern [10]. When a subset size is too small it is likely to find wrong correlation due to the increase in the number of local minima of the correlation coefficient distribution. The increase of the subset size enhances the correlation. The increase of the subset size over a given dimension does not present a tangible enhancement of measurements quality. One should keep in mind that the increase of the subset size is synonymous to the increase of computation time. So the subset size should cover a given range and one may try several sizes for the subset to find its appropriate value that presents a good compromise between accuracy and computational time. It should be noticed that the subset size is closely linked to the dimension of the speckle pattern [10].

Filtering can also help reducing the noise in the DIC-computed strains. However, filtering should be used with extreme caution to avoid loss of information in high-gradient regions [33, 34]. A careful optimization of the entire measurement chain can reduce the errors and provide more accurate and precise outputs [7]. DIC is aimed to measuring displacements with very high accuracy and robustness. However, to obtain accurate and precise strain measurement data, it is required to take care of surface preparation, as well as finding appropriate hardware and software settings [4].

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