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Test method

A camera-based strain measurement technique for elastomer tensile testing: Simulation and practical application to understand the strain dependent accuracy characteristics

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ABSTRACT

The present work investigates the precision characteristics of two optical strain measurement techniques applied to elastomers subjected to large deformations. The measurement approach is based on generating intensity profiles by using several horizontal image lines in the region of an optical marker to be detected. For detectability and accuracy reasons, these lines are combined using a rank (maximum) value filter and a moving average filter, while the calculation of the marker centers is carried out either geo- or gravimetrically. Based on simulated profiles, the first part of this work investigates the influence of method related parameters on the measurement precision obtained, expressed in terms of the root mean square error (*rms*). Further, it establishes model relations between most important image/profile parameters and *rms*. In the second part, experimental image data obtained during tensile testing of an elastomer sample is analyzed by i) applying the strain measurement technique, ii) determining experimental *rms*-values and iii) discussing them in comparison to values predicted by the *rms*-model of part one. It was found that, for the gravimetrical center calculation, *rms* strongly depends on the number of profile pixels which is caused by image noise. In the present approach, image noise was reduced by multiple image line fusion, which can be assumed to be in terms of computation effort more effective than averaging multiple images. The developed *rms*-models were found to represent the strain dependent decrease of accuracy efficiently up to high strains (e.g. 900%) under practical conditions. To obtain optimal measurement precision with the presented methods in practice, appropriate low marker detection threshold intensities of about $0.3g_s$ (g_s −signal intensity) and application of a single application cycle of the moving average filter were proved to yield optimal results. At high strains, the application of the rank filter in combination with a geometric center calculation results in best measurement precision, while the differences to the gravimetric method are less but its trend is comparable to the simulation.

1. Introduction

Optical strain measuring techniques based on image evaluation are widely used in materials characterization [1–4]. Their application offer a number of advantages in comparison to other techniques such as non-contact measurements, characterization of small samples, thin sheets, large strains or complex components (strain field). However, understanding the advantages and limitations in accuracy and robustness are important to obtain optimal measurement results in mechanical characterization of polymers.

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Most significant in tensile testing of elastomers while measuring the strain optically is the constitution of the optical markers. Because stuck markers rotate on the samples, especially in the strain hardening region, and, therefore, give incorrect strain data, markers painted on the specimens are considered. They are found to be the better choice at high deformations because they deform simultaneously with the sample. By increasing elongation, however, the contrast between markers and their background becomes weak which is usually accompanied by a decrease in lateral accuracy, not quantified so far. Therefore, interactions between image quality, methods and method related parameters are essential to understand the strain dependence of accuracy for highly strained elastomers.

In the past, several works were published dealing with the improvement and understanding of different optical strain measuring techniques [5–9]. The variety of methods can be divided into three groups: i) methods based on tracking geometric objects, e.g. dots or elliptical shapes, ii) grid line methods and iii) methods based on digital image correlation. A tracking method was presented by G'Sell and Hivers, who calculated the centers of gravity of dots [10,11]. They used their strain measurement procedure to derive the material response within a very small representative volume element (RVE), and to keep the strain rate constant in this RVE. However, no information was given on the accuracy achieved. Bretagne developed a mark tracking technique for strain field and volume variation measurements and evaluated it, without pre-processing, by applying a low pass filter and with several bilinear interpolations of the image, depending on the mark diameter [12]. The obtained uncertainties were reported to be in the range of 0.2-0.25 px for mark diameters of 1 pixel and, typically, 0.025-0.05 pixel for diameters ranging from 4-16 pixel. A semi-automated image analysis technique was developed by Haynes and co-workers to measure the surface strain from a printed grid [13]. For this method, the measurement error was estimated to be ±1px at each edge. Because of profile spreading, if deformation is increasing, the strain error becomes smaller and it was reported that the marker contrast is reducing in the same direction. Starkova use a custom made camera based technique to obtain the volume strain of elastomers where larger strain value deviations are found at higher elongations [14].

A qualitative evaluation of the performance of video extensometry based on mark tracking in comparison to e.g. the Moiré technique, holographic interferometry and image correlation is given by Sinn and co-workers [15]. They addressed three main advantages of mark tracking: i) it is fast (Only a small area around one point needs to be analyzed.), ii) the measurement arrangement is easy to use, not only under laboratory conditions, and iii) it is applicable to a wide range of specimens by changing the optical magnification. As a limitation, Sinn mentions the sample preparation, in particular the placement of the required amount of markers on the sample in such a way that its influence on the mechanical properties can be neglected. The mark tracking method developed by Rotinat was proved to yield high precision values, but its applicability was reported to be limited to strains of approximately 56% [16]. He observed that accuracy depends on the pixel diameter of the markers.

In digital image correlation (DIC), a reference image is divided into small portions/facets which may partially overlap. From each facet, a grey value array is analyzed and correlated with all grey value arrays of the following images. The maximum of the calculated correlation result in each frame indicates the highest linearity between the current image facet and the reference facet and, therefore, coincides with the new position of the reference facet in the current image. The displacement is given by the “movement” of that facet with respect to the original one. Suitable interpolation of the correlation results allows subpixel accuracy [17,18]. Hoult evaluated the influence of out-of-plane movement using the digital image correlation technique. He compared the deviation (accuracy) of the optical strains with that obtained by a strain gauge in the Mohr's circle, and showed that out-of-plane errors can be effectively reduced from about 100με down to 5με [19]. The maximum precision of DIC was given by Chevalier to be approximately 1/100 px [20].

When testing new algorithms, generation of synthetic images, which e.g. contain objects subjected to known deformations, is reported to be a useful procedure [21]. Koljonen, for example, presented a method to create synthetic images by artificially deforming real images with control of *SNR*, while Robinson predicted the performance limits of image registration techniques based on the mean square error and the Cramer-Rao inequality [21,22].

Apart from the errors originating from the specific evaluation approach, the signal-to-noise (*SNR*) ratio plays an important role. To decrease image noise, specific filters are available in literature [19,23–25]. Image noise belongs to that type of error that is caused by the sensor. The most significant are dark current noise and non-uniform sensor response. Davidson mentions that flat-field errors originate from variations of the charge collection efficiency and, for high energy radiation, from variations of the detector thickness [26]. To minimize such errors, the sensor response is measured under flat field conditions to calculate a gain map which is used for compensation later. Dark current errors originate from the noise which individual sensor elements generate without being exposed to irradiation [27]. Further, the lens system used influences image quality and measurement precision. In particular, lens distortion causes non-uniform geometric distortion in the images. In literature, several methods are presented for compensation [28–30]. The impact of such systematic strain errors is reported to depend on the strain level [31]. Considering them is of significant importance at micro strain level. Additionally, the optical transfer function of this lens system can be expected to smooth the intensity profile to some extent.

In the present work, synthetic marker intensity profiles with defined *SNR* and width are generated. After shifting these markers, their centers are calculated by two algorithms to establish relations between most important parameters, and to quantify the accuracy expressed in terms of the root mean square error. Maximum and average filters are implemented by using different image lines, which is faster than commonly used multiple image fusion. Further,