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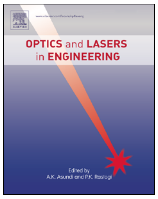

Gaussian pre-filtering for uncertainty minimization in digital image correlation using numerically-designed speckle patterns

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ABSTRACT

This paper discusses the effect of pre-processing image blurring on the uncertainty of two-dimensional digital image correlation (DIC) measurements for the specific case of numerically-designed speckle patterns having particles with well-defined and consistent shape, size and spacing. Such patterns are more suitable for large measurement surfaces on large-scale specimens than traditional spray-painted random patterns without well-defined particles. The methodology consists of numerical simulations where Gaussian digital filters with varying standard deviation are applied to a reference speckle pattern. To simplify the pattern application process for large areas and increase contrast to reduce measurement uncertainty, the speckle shape, mean size and on-center spacing were selected to be representative of numerically-designed patterns that can be applied on large surfaces through different techniques (e.g., spray-painting through stencils). Such "designer patterns" are characterized by well-defined regions of non-zero frequency content and non-zero peaks, and are fundamentally different from typical spray-painted patterns whose frequency content exhibits near-zero peaks. The effect of blurring filters is examined for constant, linear, quadratic and cubic displacement fields. Maximum strains between ± 250 and $\pm 20{,}000\ \mu\varepsilon$ are simulated, thus covering a relevant range for structural materials subjected to service and ultimate stresses. The robustness of the simulation procedure is verified experimentally using a physical speckle pattern subjected to constant displacements. The stability of the relation between standard deviation of the Gaussian filter and measurement uncertainty is assessed for linear displacement fields at varying image noise levels, subset size, and frequency content of the speckle pattern. It is shown that bias error as well as measurement uncertainty are minimized through Gaussian pre-filtering. This finding does not apply to typical spray-painted patterns without well-defined particles, for which image blurring is only beneficial in reducing bias errors.

1. Introduction

The design and implementation of effective speckle patterns on two-dimensional measurement surfaces are key to enhance the accuracy of digital image correlation (DIC), along with suitable displacement and strain field estimation algorithms [1,2]. The accuracy of DIC measurements was studied as a function of mean speckle size and subset size, for which desirable ranges were reported [3–5]. Several techniques have been used to create speckle patterns, depending on the specimen dimensions and materials. Spray paint or toner powders are typically used for larger specimens, whereas lithography is preferred for smaller patterns [6]. The resulting speckle patterns are characterized by non-repetitiveness and high contrast between light and dark areas. As shown by Wang et al. [7] for translation in two planar directions, x and y, the form of the covariance matrix for the displacement vector, $\mathbf{d}$, is written in Eq. (1):

$$\mathrm{Var}(\mathbf{d}) \cong \sigma_I^2 \begin{bmatrix} \sum\limits_{\text{subset}} \left(\frac{\partial I}{\partial x}\right)^2 & \sum\limits_{\text{subset}} \left(\frac{\partial I}{\partial x}\cdot\frac{\partial I}{\partial y}\right) \\ \sum\limits_{\text{subset}} \left(\frac{\partial I}{\partial y}\cdot\frac{\partial I}{\partial x}\right) & \sum\limits_{\text{subset}} \left(\frac{\partial I}{\partial y}\right)^2 \end{bmatrix}^{-1} \qquad (1)$$

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where: **d** is the displacement vector, (u,v), in the x and y direction, respectively; σ_I is the standard deviation in the intensity pattern noise (gray levels); and $I = I(x,y)$ is the reconstructed deformed intensity pattern (gray levels). If the gradients in both directions are independent, then the off-diagonal term tends to zero, and the matrix is approximately diagonal. In this case, the standard deviation in each displacement component, σ_u and σ_v, can be written per Eq. (2):

$$\mathrm{Var}(u) \cong \frac{\sigma_I^2}{\sum\limits_{\text{subset}} \left(\frac{\partial I}{\partial x}\right)^2} \Rightarrow \sigma_u \cong \frac{\sigma_I}{\sqrt{\sum\limits_{\text{subset}} \left(\frac{\partial I}{\partial x}\right)^2}}$$

$$\mathrm{Var}(v) \cong \frac{\sigma_I^2}{\sum\limits_{\text{subset}} \left(\frac{\partial I}{\partial y}\right)^2} \Rightarrow \sigma_v \cong \frac{\sigma_I}{\sqrt{\sum\limits_{\text{subset}} \left(\frac{\partial I}{\partial y}\right)^2}} \quad (2)$$

where “high contrast” corresponds to the summation of high gradients in intensity within a subset, increasing the denominator and reducing variability in the measured displacement. With maximum range between brightest and darkest regions, smooth transitions in intensity across the camera's dynamic range can be accurately reconstructed by interpolation algorithms, offering the potential for high accuracy when performing subset matching with DIC algorithms. Thus, the gray level distribution within the speckle pattern can be used as a measure of the effectiveness of a speckle pattern [8]. Schreier et al. [9] proposed the implementation of low-pass image filters in the pre-processing stage to produce blurring, either by defocusing the camera's optics prior to image acquisition or by applying digital filters on the acquired image data. The latter option is more attractive as it allows for better control of the parameters selected to produce blurring. In fact, digital filters are commonly used in image processing. For example, Berg et al. [10] and Cantatore et al. [11] implemented digital filters to produce image blurring, thereby improving the accuracy of algorithms for edge detection.

The effect of digital image pre-filtering on the uncertainty in two-dimensional DIC measurements is discussed in this paper for the specific case of high-contrast speckle patterns whose particle shape, mean size and on-center spacing are designed for use in efficient patterning of large areas (“designer patterns”). This case represents instances where numerically-designed speckle patterns are applied to the measurement surface through different techniques, such as using laser-printed adhesive coatings on fiber-reinforced polymer composite coupons [12], or spray-painting through a flexible polymer stencil placed against the surface of concrete and masonry specimens [13] as demonstrated in Fig. 1. These solutions are especially appealing and practical for large regions of interest (i.e., having sides of the order of meters) on full-scale specimens such as structural concrete and masonry walls (Fig. 12) or portions of bridge girders, when spray-painting or using toner powders is less practical and may pose aliasing problems whereas using relatively large speckles (e.g., through time-consuming manual painting) may result in an insufficient spatial resolution [13]. The resulting “designer patterns” are characterized by speckles with well-defined edges and consistent shape and spacing, making their frequency content fundamentally different from that of typical spray-painted patterns. In the latter case, pre-processing image blurring can be effective in reducing the bias error [9,14]. However, the concurrent reduction in noise level and intensity pattern gradients (i.e., numerator and denominator for σ_u and σ_v in Eq. (2), respectively) may result in a negligible change or even an increase in measurement uncertainty.

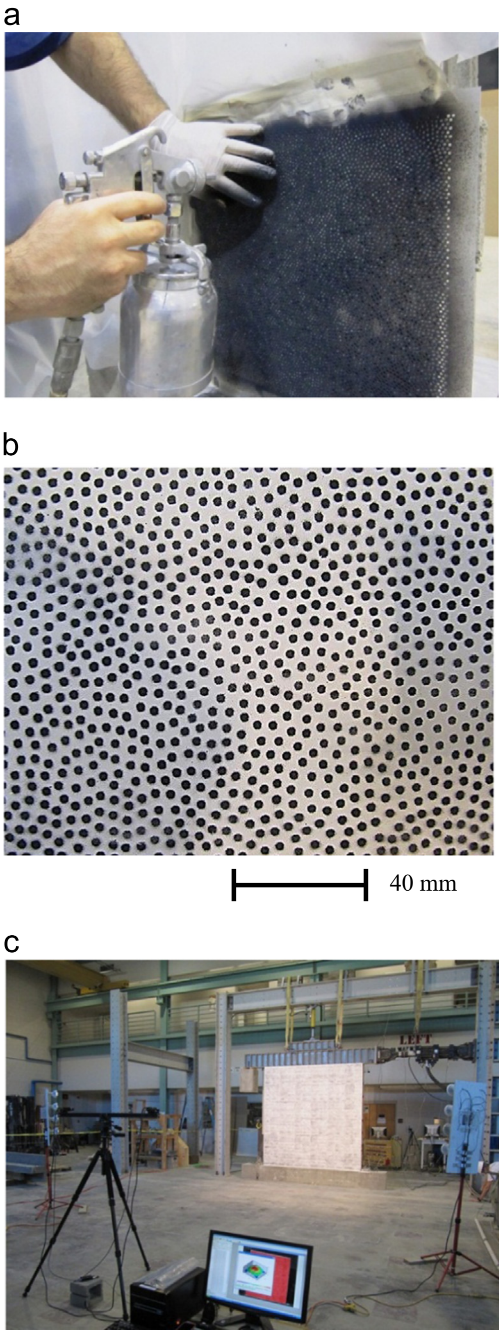

Fig. 1. Numerically designed speckle pattern on 2.43 × 2.49 m concrete and masonry wall surface: (a) spray painting through stencil; (b) close-up of 150 × 120 mm speckle pattern area; and (c) stereo vision system setup with specimen ready for in-plane load test [13].

The methodology followed in this study employs numerical simulations where images are pre-processed using Gaussian low-pass (blurring) filters [15]. First, the effect of blurring is examined on a numerically built speckle pattern as a function of the standard deviation of the Gaussian kernel (i.e., filter cut-off frequency). The resulting patterns are used to quantify the DIC measurement uncertainty for the case of constant, linear, quadratic and cubic displacement fields and the associated strain fields. The robustness of the simulation procedure is verified through experiments where a planar specimen with a “designer pattern” is subjected to a constant displacement. For comparison purposes, the effect of image blurring is also assessed on a speckle pattern that is representative of typical spray-painted ones [16,17] subjected to constant displacements. Finally, the stability of the relation between Gaussian standard deviation and measurement uncertainty is tested via numerical simulations using different levels of