Influence of displacement gradients on laser speckle photography

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Abstract. The influence of first and second order displacement gradients on laser speckle photography is investigated in a simulative study that is supported with experimental data. The systematic error is found to scale linearly with the second order gradient, while the random error scales with the first order gradient. The gradient-based error dominates the uncertainty budget of an in-process measurement during single tooth milling close to the machined surface.

1 Introduction

Laser speckle photography (LSP) is a fast and non-invasive measurement technique for displacement and strain fields. The optical measurement principle enables in-process applications with high requirements on both spatial and temporal resolution such as surface inspection during manufacturing. Laser speckles are used as surface markers in order to calculate local in-plane displacements with a two-dimensional digital image correlation (DIC) [1]. The spatial discretization along with under-matched shape functions for the subsets in the DIC algorithm lead to systematic measurement errors in the case of displacement fields with higher order displacement gradients [2]. High displacement gradients occur when either the load or the material properties are highly inhomogeneous, i.e. close to the tool during manufacturing or around cracks and notches [3].

For DIC with white-light speckles, theoretical and experimental studies were conducted on systematic errors caused by displacement gradients [2]. However, laser speckles are an interference pattern and do not deform like white-light speckles that are a part of the deforming surface. While a rigid body movement of the sample leads to a global displacement of the entire speckle pattern, displacement gradients alter the pattern of the speckles, which leads to a decorrelation of the two speckle images (before and after deformation) and, thus, affects the DIC evaluation [1]. It remains to be investigated to what degree the systematic errors are caused by displacement gradients in LSP. Of particular interest is the comparison of systematic to random errors, the latter of which are mainly dominated by speckle noise.

2 Methods

In order to statistically study the effect of different displacement gradients on speckle patterns and quantify the resulting systematic errors, a speckle simulation was employed. The simulation setup is schematically shown in Fig. 1. First, an isotropic, Gaussian surface topography with a desired roughness S_q and lateral correlation length L is simulated with the moving average method [4]. A displacement gradient is then applied to the surface topography. In order to more accurately represent subpixel displacements and avoid aliasing, the surface is upsampled by a factor of 30 via bicubic interpolation before the deformation. The speckle image is then simulated according to [1]. The aperture D of the optical 4f-system can be varied in order to adjust the speckle size. An augmented-Lagrangian digital image correlation [5] is used to calculate the resulting displacement fields, which can then be compared to the predefined displacement. The simulated displacements vary only along the abscissa. Thus, the deviation of the mean along the abscissa from the respective predefined displacement value yields the systematic error, while the standard deviation of the mean along the ordinate yields the random error.

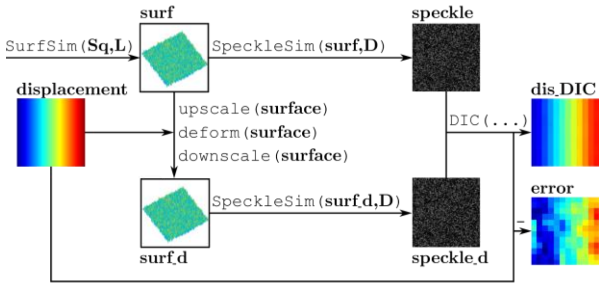

Fig. 1. Speckle simulation setup.

3 Results

We investigate systematic errors that are caused by first and second order displacement gradients by simulating a displacement field, which is composed of two parabolic segments (one with a positive and one with a negative

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Laplacian), i.e. the displacements d_x scale quadratically along the x-axis. The specified displacement profile and the displacements calculated with DIC from the simulated speckle patterns are shown in Fig. 2a. Deviations of the DIC results from the true values occur where the displacement field has higher order gradients. In addition, the moving average of the predefined displacement is calculated in Fig. 2a with a subset size equal to that of the DIC. The deviations of the DIC result from the moving average indicate that the systematic errors are not only caused by the spatial averaging over an evaluation window. Fig. 2b shows the random error and the displacement gradient over x. Evidently, the displacement gradient not only causes systematic errors, but also increases the random error due to decorrelation. In Fig. 2c the displacement interval in x-direction is varied. Thereby the first and second order displacement gradients, i.e. the Laplacian, are adjusted. Identical to the findings from Xu [2] on white-light speckles, the systematic error of LSP depends linearly on the Laplacian of the displacement field. Decreasing the DIC evaluation window size W_{ev} reduces the systematic error, but in turn increases the random error.

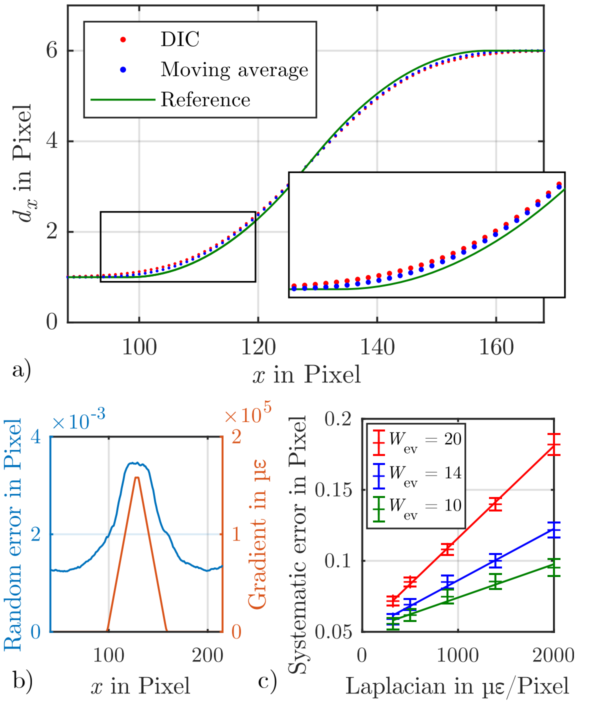

Fig. 2. a) Predefined, averaged and measured displacements. b) Random error and displacement gradient over x. c) Maximum systematic error over Laplacian of displacement for three evaluation window sizes W_{ev}.

In order to demonstrate the relevance of the systematic errors studied here, an in-process measurement during a single tooth milling process from [6] is considered. Fig. 3a shows the displacement field captured with LSP. The highly localized load causes displacement gradients at the machined surface. In Fig. 3b the measured displacements are plotted in y-direction, along with the modelled displacements in the simulation. From the simulation, we estimate a maximum systematic error of around 60 nm with $W_{ev} = 10$ Pixel. The maximum cumulative uncertainty of the measurement reported in [6] is 22 nm. Thus, systematic errors due to displacement gradients are a significant and previously not considered contribution to the measurement uncertainty budget, which deserve further attention.

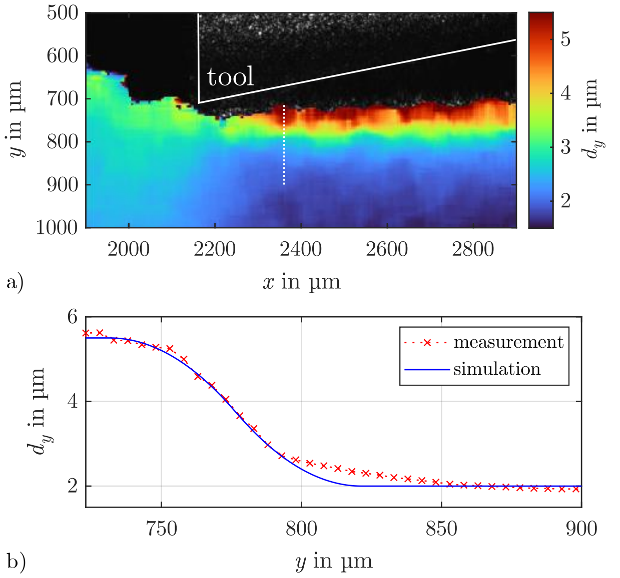

Fig. 3. a) Displacement field measured during single tooth milling. b) Measured displacements at $x = 2360$ µm (indicated as dotted white line in a) compared to simulated displacements.

4 Conclusion

Through a simulative study that is supported with experimental data it was shown that significant systematic errors in LSP measurements are caused by displacement gradients. The systematic errors scale linearly with the Laplacian of the displacement field and decrease with smaller DIC evaluation windows. Displacement gradients also cause the random errors to increase due to the decorrelation of the evaluated image pairs. For an in-process measurement of single tooth milling it is estimated that systematic errors due to displacement gradients are a dominant factor close to the machined surface, i.e. where a measurement is of particular interest due to the maximal load that the workpiece experiences. Further experiments with reference measurements are needed to validate the simulative findings.

The authors gratefully acknowledge the financial support by the DFG for subproject C06 'Surface optical measurement of mechanical working material loads' within the Transregional Cooperative Research Center SFB/TRR136.

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