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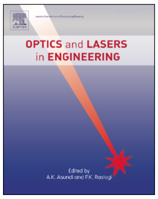

Image pre-filtering for measurement error reduction in digital image correlation

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ABSTRACT

In digital image correlation, the sub-pixel intensity interpolation causes a systematic error in the measured displacements. The error increases toward high-frequency component of the speckle pattern. In practice, a captured image is usually corrupted by additive white noise. The noise introduces additional energy in the high frequencies and therefore raises the systematic error. Meanwhile, the noise also elevates the random error which increases with the noise power. In order to reduce the systematic error and the random error of the measurements, we apply a pre-filtering to the images prior to the correlation so that the high-frequency contents are suppressed. Two spatial-domain filters (binomial and Gaussian) and two frequency-domain filters (Butterworth and Wiener) are tested on speckle images undergoing both simulated and real-world translations. By evaluating the errors of the various combinations of speckle patterns, interpolators, noise levels, and filter configurations, we come to the following conclusions. All the four filters are able to reduce the systematic error. Meanwhile, the random error can also be reduced if the signal power is mainly distributed around DC. For high-frequency speckle patterns, the low-pass filters (binomial, Gaussian and Butterworth) slightly increase the random error and Butterworth filter produces the lowest random error among them. By using Wiener filter with over-estimated noise power, the random error can be reduced but the resultant systematic error is higher than that of low-pass filters. In general, Butterworth filter is recommended for error reduction due to its flexibility of passband selection and maximal preservation of the allowed frequencies. Binomial filter enables efficient implementation and thus becomes a good option if computational cost is a critical issue. While used together with pre-filtering, B-spline interpolator produces lower systematic error than bicubic interpolator and similar level of the random error. Cubic B-spline interpolator can achieve comparable efficiency as bicubic interpolator, while quintic B-spline interpolator requires about 1.5 times the running time.

1. Introduction

Digital image correlation (DIC) is a non-contact optical metrology for full-field deformation measurement [1]. Given a pair of images captured before and after the deformation, DIC extracts the image displacements by optimizing the correlation between the intensities of the corresponding locations. Recent studies show that the measurement error of DIC is highly related to the imaging system and the image matching algorithm [2–12]. The imperfection of the imaging process, including lens distortion and varying image and object distance, causes the non-linearity between the image displacement and the actual object displacement. This can be corrected by using high-quality camera lenses (e.g. telecentric lenses) [5,10] and distortion compensation methods [9,11]. On the other hand, the measured image displacement itself usually deviates from its true value due to the image matching error, which is largely attributed to the decorrelation of the corresponding intensities. Several factors leading to the decorrelation include sub-pixel intensity interpolation, image noise, and the mismatch of the shape function. While the shape function mismatch can be mitigated by using sophisticated model [3,13], subset control [14,15] or adaptive weighting [16,17], intensity interpolation and image noise are inevitable. The target position of a reference pixel generally falls on a non-integer location in the deformed image. Its corresponding intensity must be interpolated from the sampled intensities at integer locations whose values are usually corrupted by image noise.

Schreier et al. discovered that the commonly used interpolations, e.g. bicubic and B-spline interpolation, introduce a systematic error in the measured image displacements [2]. The error depends on the

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interpolator, the sub-pixel position, and the frequency contents of the image. For a given interpolator, the amplitude of the error increases toward higher frequency component. Unfortunately, the speckle pattern used in DIC calculation usually has a wide spectrum due to its random nature. The image noise, generally modelled as additive white Gaussian noise (AWGN) [18], would further increase the energy in the high frequencies of the image, making the systematic error even higher. Furthermore, the noise is also the major source of the random error in the measurements [4,6,14]. Given that the additive noise has zero mean and finite variance, the standard deviation of the measured displacements is proportional to the standard deviation of the noise amplitude [6]. Therefore, mitigating the negative effect of the intensity interpolation and the image noise is critical to the measurement error reduction of DIC.

An intuitive solution is to apply a low-pass filtering to the recorded images prior to the correlation. By suppressing the high-frequency image contents, the systematic error caused by the intensity interpolation can be reduced. The low-pass filtering also decreases the noise power, which might enables random error reduction in the meantime. Schreier et al. test a 3 × 3 binomial filter on simulated noise-free speckle images and achieve a decrease in the systematic error [2]. Pan evaluates the measurement error after a Gaussian filter is applied to a selected speckle image with simulated superposed AWGN [19]. The results show that Gaussian filtering with proper kernel size only reduces the systematic error and the random error slightly increases after pre-filtering.

In this paper, we wish to study the effect of the pre-filtering from a more comprehensive perspective. Because the measurement error of DIC depends on many factors including the interpolator used, the spectrum of the speckle image, and the level of the additive noise, an analytical study is not trivial. Therefore, an experimental study is carried out instead. A total of four widely used de-noising filters, namely binomial, Gaussian, Butterworth and Wiener filter, are tested in combination with three popular interpolation methods, namely bicubic, cubic B-spline and quintic B-spline interpolation. Each of the twelve combinations is evaluated on real-world speckle images with different power spectra, noise levels, and prescribed translations. By assessing the systematic error and the random error of the measured displacements, we are particularly interested in the following issues:

- Does pre-filtering enable error reduction on different types of speckle image?
- Which interpolator should be used in combination with pre-filtering?
- Can the systematic error and the random error be simultaneously reduced by using proper filters?
- How to select the filter and determine its parameters to obtain desirable results?

The rest of the paper is organized as follows. Section 2 outlines the DIC algorithm and introduces the four image filters under test. Section 3 details the datasets used in the numerical study and the experimental results are presented and discussed regarding the above issues in Section 4. In Section 5, a real-world translation experiment is adopted for further validation. Finally, Section 6 gives the conclusion.

2. Pre-filtering prior to image correlation

2.1. Digital image correlation

Digital image correlation tracks a reference point in a target image by finding the best image warping that optimizes the correlation between the intensities around the two correspondences. The objective in the optimization, the correlation coefficient, is required to be robust to illumination variation and able to be minimized efficiently. One of the choices is zero-mean normalized sum of squared difference (ZNSSD):

$$C_{ZNSSD}(\mathbf{p}) = \sum_{\Omega} \left[\frac{F(x,y)-F_m}{\sqrt{\sum_{\Omega}[F(x,y)-F_m]^2}} - \frac{G(x',y')-G_m}{\sqrt{\sum_{\Omega}[G(x',y')-G_m]^2}} \right]^2 \tag{1}$$

where Ω is the selected reference subset. $F(x,y)$ and $G(x',y')$ are the intensities at corresponding locations in the reference and the target images and F_m and G_m are the mean intensities in the two subsets, respectively. The correspondence is determined by first-order shape function:

$$\begin{cases} x' = x+u+u_x\Delta x+u_y\Delta y \\ y' = y+v+v_x\Delta x+v_y\Delta y \end{cases} \tag{2}$$

where $(\Delta x, \Delta y)$ is the deviation from the reference point, and the deformation parameter $\mathbf{p}=(u,v,u_x,u_y,v_x,v_y)$ is composed of the displacements and their first-order gradients at the reference point.

When the intensity is evaluated at a sub-pixel location, interpolation is required as a digital image only has sample values at integer coordinates. Bicubic, cubic B-spline, and quintic B-spline are the most widely used interpolators because they achieve high reconstruction accuracy [2,20]. Bicubic interpolation can be very efficient by using convolution [21] or pre-computed coefficient table [22]. B-spline interpolators can also achieve comparable efficiency after a sequence of filtering is applied in advance [20,23]. To minimize the non-linear correlation coefficient, an iterative algorithm (e.g. Newton–Raphson or Levenberg–Marquardt) is usually used, which starts from an initial parameter and iteratively refines the parameter [24]. The initialization must be sufficiently good in order to enable correct and rapid convergency [25].

2.2. Spatial-domain filters

As previously mentioned, both bicubic and B-spline interpolators produce a systematic error of the measured displacements and the error increases toward high-frequency component of the image. Intuitively, suppressing the high-frequency content prior to the correlation can be helpful to reduce the systematic error. Schreier et al. [2] demonstrate that a 3 × 3 binomial filter is effective, and later Pan [19] achieves similar results by using Gaussian low-pass filter.

Image filtering using binomial filter or Gaussian filter requires convoluting the input image with a two-dimensional (2D) kernel. Fortunately, both filters are separable in the sense that the 2D kernel can be expressed as an outer product of two identical one-dimensional (1D) kernels. Therefore, the image filtering can be implemented more efficiently by two successive 1D convolutions in the horizontal and vertical directions, respectively. The 1D kernel of a binomial filter can be computed by repeated convolution with the kernel [1/2 1/2]. Specifically, the 1D kernels of size 3 and 5 are

$$\mathbf{h}_{b,3} = \frac{1}{4}[1\ \ 2\ \ 1] \tag{3}$$

$$\mathbf{h}_{b,5} = \frac{1}{16}[1\ \ 4\ \ 6\ \ 4\ \ 1] \tag{4}$$

The 1D kernel of a Gaussian filter is obtained by

$$\mathbf{h}_g(x) = Ce^{-x^2/2\sigma^2} \tag{5}$$

where $x=-m,\ldots,m$ and $(2m+1)$ is the kernel size. The factor C is chosen such that the kernel sum up to unity.