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Fourier-based image shift for periodic effect compensation in displacement monitoring using vision systems

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Abstract – **In a wide range of monitoring applications, vision systems are nowadays applied. The main advantages of vision-based monitoring include the possibility to: i) measure a wide region of the target, obtaining a dense measurement, ii) obtain a 3D estimation of shape, displacements and strain field, iii) measure with a completely contactless technique, therefore avoiding loading effect and wear of measuring components and target. Digital Image Correlation (DIC) is an image processing technique that allows measuring the displacement and strain fields of target, as well as the 3D shape of the measurand in the case of stereo DIC. Displacement measurement obtained by DIC are affected by a systematic effect in displacement data. In this paper, we propose and qualify an image pre-processing technique, to be applied to the images before running the DIC analysis, capable to strongly reduce the systematic effect affecting the displacement results.**

I. INTRODUCTION

Digital Image Correlation (DIC) is an image processing technique that allows measuring the displacement and strain fields of target, as well as the 3D shape of the measurand in the case of stereo DIC. This technique was proposed in [1] and, thanks to the strong developments obtained in the last decades [2], is nowadays used in a wide range of engineering applications [3].

As it is well known in literature [4], in order to run a DIC analysis it is necessary to use a shape function for local fitting of the images brightness distribution. However, shape function approximation generates a systematic effect in displacement measurements. Of course this effect also affects the strain data, estimated relying on displacements. The intensity of the mentioned systematic effect mainly depends on the type of adopted shape function, on the type of pattern and on the level of blurring due to the optics [5][6][7]. It is difficult to estimate the intensity of the systematic effect that affects the measurements, and it is therefore impossible to compensate for it directly.

In this work a new sub-pixel shifting technique is proposed, capable to reduce the systematic (bias) effect by means of pre-processing the images, before applying the DIC computation. The proposed methodology consists of numerically shift the images using a numeric procedure based on Fourier Transform prior to run the DIC computation. Since the systematic effect generates overestimation and underestimation of the displacements with a periodicity of one pixel, imposing a controlled sub-pixel shift to the images and running the correlation two times, it is possible to obtain a double set of results, affected by unknown but nearly opposite systematic effect. Averaging the two set of data, the subpixel effect is strongly reduced. The proposed methodology does not need to quantify the amplitude of the systematic effect: this is a key point because, since the effect depends on many parameters, its estimation is affected by a very large uncertainty and therefore compensation techniques are hardly applicable. In this work the compensation of the systematic effect is based on the characteristic of periodicity of the effect itself and relies on image pre-processing. The proposed methodology is validated by means of numerical result.

II. THE PROPOSED COMPENSATION TECHNIQUE

In this work the basic idea is to take the advantage of a characteristic of the sub-pixel effect: which is the periodicity [8] with a trend that is similar to a harmonic pattern (see Figure 1, from [9]). Although the amplitude of the systematic effect is not known, the trend of it is quasi-harmonic, therefore we can assess that the numerical value of the overestimation in a given position is nearly equal in amplitude but opposite in sing to the numerical value of the underestimation in a 0.5px shifted position. Relying on this evidence, in this work we propose an image pre-processing technique to reduce the amplitude of the systematic effect. The proposed approach requires to run the DIC computation two times, shifting the reference image in order to obtain in the two computations an equal and opposite systematic effect. The approach is represented in Fig. 2, where the red circle represents as an example the systematic effect in estimated displacement. The black stars represent the systematic effect obtained if

the second image on the DIC is shifted 0.25px in one direction and 0.25 px in the opposite direction. Fig. 2 shows that the two new positions are affected by a bias with the same amplitude but opposite sign. At this point, averaging the displacements estimated with ±0.25px shift, the actual displacement is estimated, while the systematic effect is compensated for, regardless to the amplitude of it. To improve the processing efficiency, only the reference image is shifted twice, back 0.25px and forward 0.25px respectively, while all the other images remain unmodified.
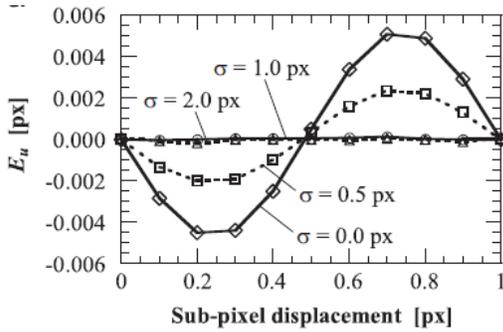

Fig. 1. Systematic effect in DIC-based displacement estimation [9]. Note in particular the curve with $\sigma=0$, which correspond to images without any preprocessing.
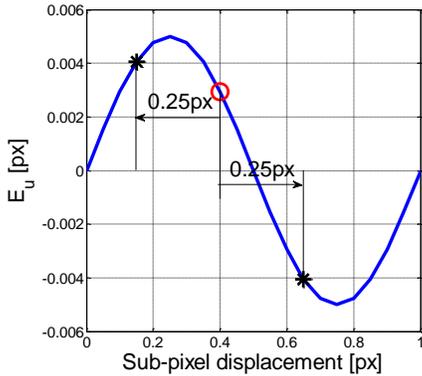

Fig. 2. The compensation technique

The compensation approach proposed in this work can be in principle applied to both 2D and 3D DIC, however in this work the 2D case is studied in order to provide a first qualification of the proposed method.

In a generic 2D DIC processing, a reference image im1 is correlated with an image of the deformed target im2, to get the displacement field.

It is known in literature that an image can be numerically shifted of a sub-pixel amount by means of different techniques: the most accurate approach is to use a Fourier-based shift approach [10], which allows shifting images of

an arbitrary sub-pixel amount, without modifying the spectral content of the image.

Relying on the periodicity property stated above and on the Fourier-based image shifting technique, the proposed technique consists in:

1. consider a couple of images: im1 assumed as a reference image and im2 assumed as the images to be correlated with im1;
2. numerically shift the image im2 of an amount of 0.25px, obtaining im2A;
3. apply the DIC to the im1 and im2A and obtain the first estimation of the displacement field EsA;
4. numerically shift the image im2 in the opposite direction with respect to the step 2 (shift=-0.25px), obtaining im2B;
5. apply the DIC to the im1 and im2B and obtain the second estimation of the displacement field EsB;
6. average the displacement fields EsA and EsB, to obtain a displacement field with compensated systematic effect.

In this work the case of mono-dimensional displacement is considered for a first validation of the proposed technique, however the proposed approach can be applied also in the case of 2D displacement and strain.

III. VALIDATION OF THE PROPOSED TECHNIQUE

A. Fourier-based shifting technique

In order to validate the proposed compensation technique, it is fundamental to use sets of images where a reference speckle image is shifted of known sub-pixel amounts. To obtain these sets of images we used the approach proposed in [10]. The main steps are:

1. apply the 2D Fourier Transform to the reference image im_ref;
2. modify the phase values in the spectrum of the reference image, adding a linear trend to the phase data. The slope of the additional phase trend depends on the desired amount of shift;
3. apply the inverse Fourier transform to the modified spectrum, in order to obtain a shifted version of the image.

Thanks to the procedure described above, it is possible to apply any amount of displacement, including the sub-pixel values, without the need of brightness intensity fitting, and therefore eliminating the problem of image degradation due to sub-pixel shift ([10] and [11]).

B. Issues related to image representation

It should be noted that the Fourier-based shift technique

guarantees that the spectral content of the image is preserved, however it does not guarantee that the range of brightness level generated in the shifted image remains within the brightness levels of the original image.

The range of the brightness of the original image is between 0 and 255, which is determined by the format of the 8-bit grayscale image. In Figure 3 an example of speckle pattern is displayed: usually the pattern for DIC are characterized by a high contrast because this helps the reduce the uncertainty associated to the result of the DIC. This means that the brightest pixel in the image often assume values very close to 255, while the darkest ones can assume values very close to 0.

As a consequence, applying the Fourier-based image shift technique, some pixel that have low-brightness level in the original image, might assume values lower than 0 after the Fourier-base shift. For the same reason, some pixel with original brightness values close to 255 can assume brightness larger than 255 after shift. Images for DIC are often represented as 8-bit grayscale images, therefore, after the Fourier-based image shift, it is necessary to covert the data from double precision to unsigned 8-bit representation in order to save the shifted image. In this conversion the values below 0 and above 255 are set to 0 and 255 respectively.

Another issue related to the 8-bit representation of the images is the quantization noise. For image shift equal to any integer pixel value, the original brightness levels remain unchanged in the shifted image and therefore can still be represented by unsigned 8-bit numbers. However, sub-pixel image shift generates brightness levels in the shifted image that are in general non-integer and not necessarily ranging between 0 and 255. Two issues should be therefore considered: the quantization noise introduced by the eight-bit image representation and the clipping of possible brightness values exceeding 255 or lower than zero.
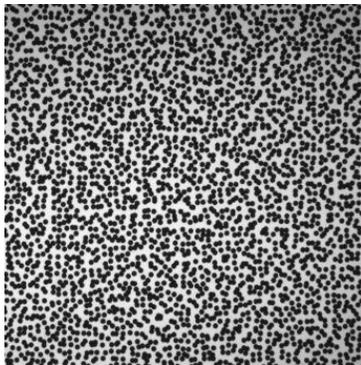

Fig. 3. DIC speckle pattern

The quantization error is equivalent to an additional noise level commonly affecting the digital images.

The clipping of brightness levels exceeding the 0 to 255 range, has to be managed. The clipping of brightness level leads to the change of the shape of the distribution of the brightness. Since DIC technique is based on correlating algorithm, the change of the shape of the distribution of the brightness reduce the measuring accuracy.
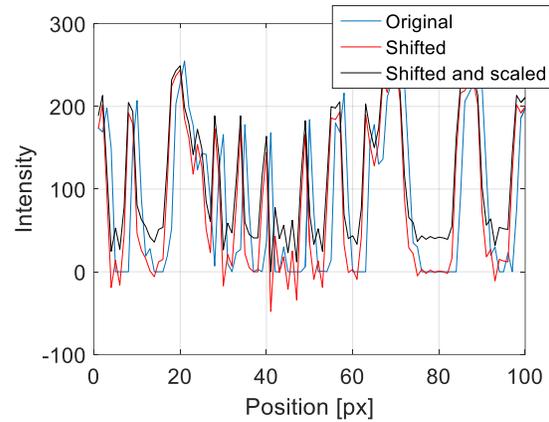

Fig. 4. Brightness profile of a portion of original image, after 1.35px shift and scaled profile

Figure 4 shows an example of brightness profile of a reference image and the corresponding brightness profile after 1.35px image shift, obtained with Fourier-based shift technique. Values below zero can be clearly seen. If these brightness profiles are saved in 8-bit format, the negative values would be clipped and set to zero. This data clipping generate a distortion in the DIC results. To avoid this problem, it is proposed here to scale the brightness values between 0 and 255 before converting to 8-bit. The scaling procedure affects both the mean brightness value and the contrast of the image. However modern DIC approaches apply a zero-normalized sum of square differences algorithm (ZNSSD) and are therefore not affected neither by brightness offset, nor by changes in the contrast [3]. It is therefore possible apply the brightness scaling without compromising the results of DIC.

C. Results of the validation

In [9] it was proposed to remove the sub-pixel effect by means of a Gaussian low-pass filter applied to the images. In the present work the same images used in [9] are analyzed, but instead of applying a Gaussian filter to reduce the sub-pixel systematic effect, here we use the Fourier-based image shit technique. In this way the Fourier-based shift technique proposed in this work will be validated.

The pattern is composed of circular speckles with a diameter of 4.5pixel and on-center spacing of 6 pixel along the horizontal and vertical directions. The speckle are

randomly distributed to avoid a periodic pattern that would generate ambiguous match in the DIC. The full image is composed by 2000x2000pixel. A portion of the pattern is shown in Figure 5.
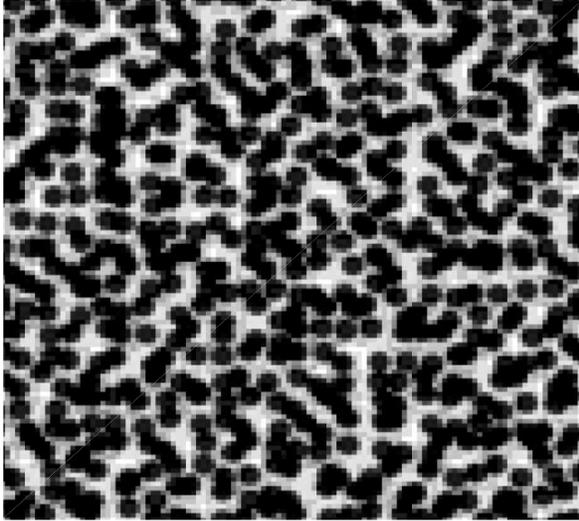

Fig. 5. Portion of the DIC speckle pattern used for the validation of the proposed technique

Figure 6 shows the subpixel effect due to the analysis of the original images and the reduction of it, thanks to the proposed Fourier-based shift technique.
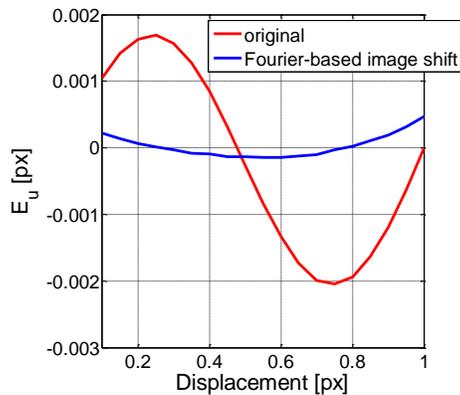

Fig. 6. Systematic effect with common DIC and applying the proposed image shift of the reference
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As well-known in literature, the noise associated to the brightness values of the image has a strong effect on the uncertainty of the DIC results [12]. In order to explore this issue, the speckle images used to obtain the results shown in Fig. 6 were corrupted by an additive Gaussian noise and then the proposed bias-compensation technique was applied again.

Three levels of Gaussian noise where considered: with zero mean and the following values of σ (standard deviation): σ=1, σ=2 and σ=5. Noise with standard deviation equal to 1 and 2 represent a realistic condition where the images are acquired with a good hardware and in the case of nearly ideal illumination conditions. The case of standard deviation equal to 5, on the contrary, can represent a condition of quite poor illumination conditions, that requires a longer exposure time, leading to a larger acquisition noise.

The proposed bias-compensation technique was applied to the images affect to the mentioned noise and the results are shown in Fig. 7.

As can be seen, the Gaussian noise does not affect significantly the value of Eu (bias of the displacement): this result is coherent with the literature, where the effect of noise on the images is mainly related to the uncertainty (i.e. the standard deviation) of the estimated displacement, while it does not affect significantly the bias [12].

What is more interesting here is however the effect of the proposed compensation technique on the systematic effect: also in the case of images affected by noise, the compensation technique allows to strongly reduce the systematic effect.
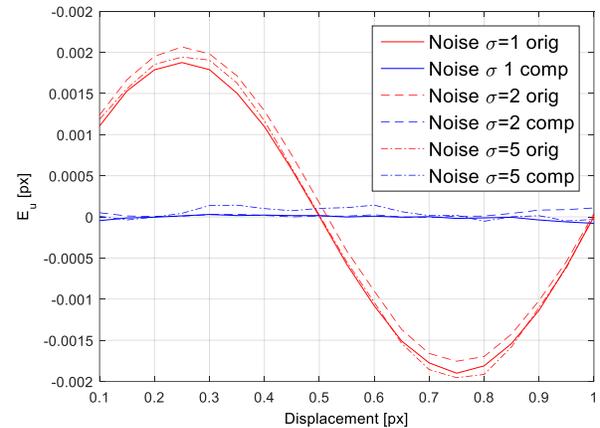

Fig. 7. Portion of the DIC speckle pattern used for the validation of the proposed technique

In order to check the applicability of the proposed technique to other speckle types, it is considered here an example of speckle pattern downloaded by open-access "Digital Image Correlation Challenge" dataset [13]. This speckle pattern is representative of typical spray-painted ones and is fundamentally different from the "designer patterns" in Figure 5.

A portion of the pattern from DIC challenge using in this work is shown in Figure 8.

Figure 9 shows the systematic effect on the displacement estimated with DIC. The red line show the result in the

case of normal DIC processing, while the blue line represents the results in the case of bias-compensation, as proposed in this work.
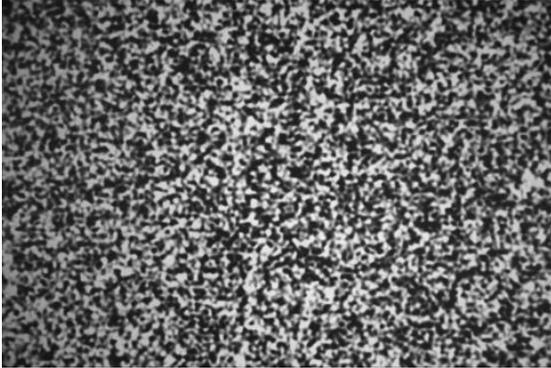

Fig. 8. Portion of the DIC speckle pattern used for the second validation of the proposed technique (speckle image from DIC Challenge [13])
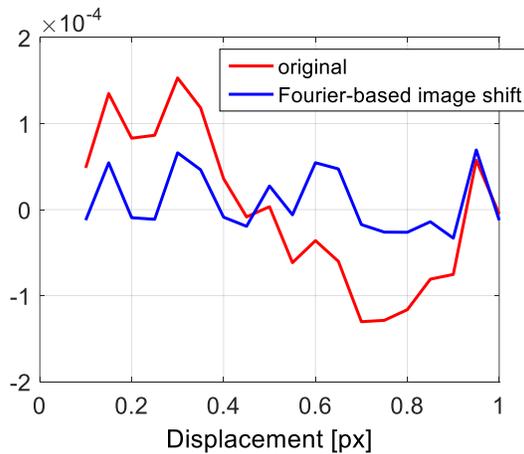

Fig. 9. Systematic effect with common DIC and applying the proposed image shift of the reference image (speckle image from DIC Challenge [13])

As can be seen in Figure 9, although the level of noise in the result is higher than in the previous validation with the pattern of Figure 5, the reduction of the systematic effect obtained thanks to the Fourier-based shift technique is visible.

IV. CONCLUSION

In the Digital Image Correlation (DIC) technique shape function are applied in order to allow sub-pixel area matching and also to model the modification of the aspect ration and shape of the subsets between the reference image and the other ones. The use of shape function however imposes the interpolation of the gray intensity. This leads to a systematic effect in the displacement estimation. The amplitude of the effect is difficult to estimate accurately since it depends on different parameters. It is however demonstrated in literature that the mentioned systematic effect can introduce bias on the displacement estimation even larger than 1% and bias of the strain measurement more than 40% [5]. Of course this might compromise the reliability and accuracy of the measurement in unacceptable way.

Based on the periodic and nearly harmonic character of the trend of systematic effect, the compensation method proposed in this work is to impose two known shift of the reference image, for each of them run the DIC analysis and finally average the obtained displacement field. The systematic effect can be in this way strongly reduced, as demonstrated in the paper.

To apply the proposed compensation technique it is necessary to shift the reference image: the shift is performed using an approach based on the Fourier transform shift, because this approach is demonstrated in literature to be the most accurate. However the image shift involves the risk of image distortion due to the 8-bit representation of the intensity levels. Due to this reason, a scaling of the brightness levels is proposed in this work, to avid this problem.

The validation of the proposed technique is based numerical tests based on different patterns: in all the cases the proposed technique allowed to reject the bias effect efficiently. To consider the effect of the noise in image acquisition, test with Gaussian noise added to the images were also performed.

The proposed methodology is easy to apply, since it only need to apply a subpixel shift of ±0.25px to the reference image. The computation effort required for image shift is negligible, however the proposed procedure requires to run the DIC analysis two times and the averaging the results, therefore the computation time required for DIC is doubled with respect to the common DIC processing.

V. CITATIONS AND REFERENCES

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