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Digital Image Correlation Technique in Dynamic Applications on Deformable Targets

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Abstract

Digital Image Correlation (DIC) is a widely used optical measurement method to find the field of displacement and strain on the surface of an object. Even though a lot of studies have been done on this method and its uncertainty, there is still the possibility to do some improvements, especially in the case of dynamic conditions. In dynamic conditions since the target is moving, images acquired during the test have motion effect (blurring). This blurring can increase the uncertainty of the motion measurement. The present study aims to investigate the uncertainty of DIC method in dynamic conditions on deformable targets by conducting experiments and exploring the effect of the settings of the camera and of the motion parameters on the measuring uncertainty. Moreover, deconvolution method, which was previously proposed for rigid targets, is used here to improve the results in the case of dealing with deformable targets in dynamic conditions. Deconvolution method is a processing technique based on deconvolution that estimates the displacement of the target and the amount of motion effect that exists in an acquired image. The focus of this study is only on 2D DIC, but similar problems also exist in 3D DIC. Hence, an understanding of two-dimensional problems can be helpful for future studies in 3D conditions too.

Keywords: Digital image correlation, Vibration based measurement, Motion blur, Uncertainty, Deconvolution

Introduction

Over the recent years, using vision-based measurements has been a popular method in experimental mechanics. Digital image correlation is one of the main techniques used in vision-based measurements. For many years, application of DIC method and studies on its performances were focused on static conditions [1-6]. However, in recent years, the application of DIC method has been extended to dynamic applications too. It is known that in static conditions the measuring uncertainty of a vision-based measurement system is dependent on image resolution, contrast, processing algorithm, noise, etc. but in dynamic conditions there are also other factors like exposure time of the camera or relative motion between the camera and the object [7,8]. The problem of using DIC method in dynamic conditions is that dealing with targets in motion causes blurring in the acquired images. This blurring mainly depends on the exposure time of the camera and velocity of the target. Since motion blur is an important source of measurement uncertainty in DIC measurement, setup of the camera and specifying its different parameter can be important for a DIC analysis in dynamic conditions.

In order to reduce the motion blur, it is possible to reduce the exposure time, however, this leads to darker images and therefore, the lighting device has to be boosted. In practical applications, the lighting condition often has limitations on maximum intensity, because of different reasons. For example in outdoor applications or in the case of very large targets the lighting conditions cannot be tuned arbitrarily [9]. Moreover increasing the power of the illumination devices might lead to problems with an excessive heat generation.

This study includes experiments on a deformable object (cantilever beam) to find out the important parameters of the camera that can affect the uncertainty of DIC method. Moreover, the uncertainties of two different image processing methods were investigated and the deconvolution method was used to improve the accuracy in the case of having motion effect in the acquired images. The deconvolution method was suggested in [10] for the application on rigidly moving targets. In this method, the motion effect that affects an acquired image is estimated by a deconvolution operation. Then this motion is used to simulate an equivalent motion effect on the reference image. In this way, the reference image has the same blurring that the acquired image has and this was shown to be an effective method to increase the DIC accuracy in dynamic conditions [10,11]. This work aims to estimate the uncertainty in DIC

measurement for flexible targets, explore the effect of acquisition parameters on it and finally reduce the uncertainty due to motion blur for flexible targets, by means of deconvolution method.

1. State of the Art

1.1 DIC in Static Applications

Two-dimensional (2D) Digital Image Correlation (DIC) technique was first developed in the 1980s by Sutton et al. [12]. In the past few years, the DIC technique had been significantly improved through the improvements of computation, advancements in computers and imaging devices, achievement of high accuracy contour/deformation measurement and expansion of its range of application. The available literature in applications of DIC in static conditions is wide and a lot of studies have been done to investigate the uncertainties of this method [1-4]. In 2002, the symmetric errors that arise from the use of under matched shape function, i.e., shape functions of lower order than the actual displacement field were analyzed by H. W. Schreier et al. [5]. In 2009, M. Bornert et al. [6] suggested a general procedure to assess DIC displacement measurements errors. It uses synthetic speckle pattern images undergoing spatially fluctuating sinusoidal displacement fields. They evaluated the RMS error of displacement obtained with various DIC formulations for different subset sizes, speckle sizes and other parameters. In 2015, a numerical and experimental study was done on the effect of Gaussian pre-filtering on the uncertainty of 2D DIC measurements for the specific case of numerically-designed speckle pattern having particles with well-defined and consistent shape, size and spacing by Paolo Mazzoleni et al. [13]. In 2013, three-dimensional digital image correlation was used for health monitoring of bridge structures. By means of this technique, C. Nonis et al. [14] were able to locate the non-visible cracks and estimate their widths using DIC method. In another study, in 2014, P. Poozesh et al. [15] used 3D DIC to monitor a large area on a unity-scale composite wind turbine blade during static and fatigue testing. They have shown that DIC technique can provide more structural information than discrete point strain measurements.

However, using DIC method is not limited to static conditions. It can also be applied to the specimens in motion. But using it in dynamic conditions arise the motion effect in the acquired images. Therefore, the application of DIC in dynamic applications should be investigated as well.

1.2 Implementing DIC in Dynamic Applications

Although, DIC uncertainty studies were mostly concentrated on static cases, its application expanded to the dynamic conditions too. Some dynamic applications of DIC that have been studied recently are focused on mode shape recognition [16-19] and vibration analysis [20, 21]. In 2003, an advance 3D image correlation photogrammetry was applied on two dynamic applications by T. Schemidt et al. [22]. The first application was using short duration white light pulses to study an automobile tire on a road with up to 240 km/h speed and the second study was using a pulsed laser to study a flywheel.

In 2007, M.S. Kirugulige et al. [23] used a DIC methodology to investigate the dynamic crack growth of a polymeric beam, subjected to impact loading. In 2009, DIC method was used for shape recognition of a circular plate by W. Wang et al. [24]. In the same year, T. Siebert et al. [25] showed applications of DIC to measure the different mode shapes in case of harmonic vibrations, a shock phenomenon and noise excitation. In another research, in 2009, DIC approach was performed on vibration analysis of a membrane for an impact test and an excitation of a circuit board using white noise [21]. At the same time, M. N. Helfrick et al. [26] investigated the possibility to use three-dimensional DIC for detecting damages through curvature methods.

Later, in 2011, vibration mode shapes of a composite panel were measured by a DIC system and the results were used to modify and update a FE model to predict the structural responses by W. Wang et al. [17]. In another work, M. N. Helfrick et al. [20] measured the vibration of a metal base dryer cabinet by DIC approach along with traditional acidometers and a scanning laser vibrometer and then compared the results with a finite element model.

1.3 Uncertainty in General Dynamic Applications

Dealing with a target in motion can cause motion effect on the acquired images. This motion effect is an important source of measurement uncertainty in DIC technique. Unlike DIC in static conditions, there are not many studies on DIC uncertainties in dynamic conditions.

In 2007, a new approach was followed by E. A. Patterson et al. [27] to establish a reference material as an international standard to access the uncertainty of a full-field optical system suitable for measuring static, in plane strain distributions. Reference materials provide a simple definition of the measuring quantity that can be traced to an international standard and can be used to assess the uncertainty associated with a measuring system. Efforts are now underway to extend this idea to a system measuring 3D deformations or in dynamic motion. The primary design for a reference material have been completed and is being evaluated now [28, 29].

In 2013, E. Zappa et al. [11] investigated the uncertainty of DIC method for a translating target in dynamic conditions. They suggested a numerical technique, to estimate the motion effect of an acquired image and proposed two different methods to simulate the motion effect on a reference image. Using this predicted motion effect and simulating it on the reference image, the performances of DIC method in dynamic applications can improve [10].

1.4 Parameters of the Camera for DIC Method in Dynamic Conditions

Using a camera as a displacement transducer has been an interesting subject in the recent years. Advances in computers and digital imaging technology boosted this type of applications. The main advantage in this kind of measurement is that with only one camera, each pixel of the image can be considered as a transducer itself. Moreover, the measurement set up is easy since only one camera, some targets and a computer are needed, and the measurement in this method is contactless [30]. The vision-based measurement was first proposed in almost static applications, where the targets move slowly with respect to the exposure time of the camera, so the motion effect can be neglected. But later on, with the improvement of technology, the application of cameras as transducers were applied to dynamic applications too [3, 20, 31, 32, 35]. The literature in uncertainty analysis of vision-based measuring devices in static applications is so strong, but there is still needs for further analysis in the case of dynamic motions. A recent study on performance evaluation of cameras in dynamic measurements has been done by G. Busca et al. [7] in 2014. In this research, it is proven that the most important parameter of a camera for dynamic tests is exposure time. Moreover, some indexes are suggested to qualify the measurement uncertainty in case there is no prior information available about the acquisition conditions and reveal information about the reliability of the tests.

To the best of our knowledge, no research have focused on different methods of image processing in dynamic applications, specially applying deconvolution method to generate new reference images with blurring, and influence of different parameters of the camera on the uncertainty of these methods.

2. Experiments

In this work, in order to investigate the effect of settings of the camera like exposure time, gain, diaphragm and also contribution of the relative motion between camera and the specimen on DIC uncertainty several experimental tests were carried out on a vibrating cantilever beam.

2.1 Experimental Setup

First, a speckled pattern shown in Figure 1 was painted on one side of the beam by stencil technique. The beam is made of aluminum, with a rectangular cross section (10×30 mm). The speckle pattern was painted on the 10 mm face of the beam by a frame with circle shape holes with 1.2 mm diameter. This diameter was chosen 1.2 mm because, in the specific setup conditions, it corresponds to speckles with diameter of 4 pixels in the images, which is the optimal size according to the literature [33, 34].

Then the beam is mounted on the shaker as represented in Figure 1. The shaker excites the beam in transversal direction. A laser sensor is placed under the beam to record the vertical displacement of one point of the beam during the test. The camera is located exactly in front of the central point of the beam at a distance that allows to fit the field of view with the length of the beam. There are also two lighting devices in front of the beam to have a uniform lightening across the speckled surface. The specification of the devices used in this research can be seen in Table 1.

There were two sets of experiments done in this study. In the first experiment, the beam has free vibration. One side of the beam is fixed and an initial displacement is applied to the tip of the cantilever beam. In this experiment, the variables are the amount of applied initial displacement and exposure time of the camera. The first natural frequency of the beam is 7.6 Hz and the sampling rate of the camera is 50 fps.

Figure 1: (Left) Position of the beam, shaker and laser sensor in the experiments, (Right) Schematic configuration of the first experiment, front view (Up), top view (Down)

Table 1: Experimental setup of the experiments

	Device	Brand and Type	Specifications
1	Camera	Allied Vision Technologies – GX3300	Resolution : 3296 * 2472 Sensor type : CCD Progressive Max frame rate at full resolution : 17 fps
2	Vibration Exciter	TIRA Unternehmensgruppe – TV 50101-80	Frequency range : 2Hz – 20 kHz Rated peak force for sine : 650 N
3	Beam		Material : Aluminum
5	Laser Sensor	Micro Optronic – ILD 1400-20(00)	Range : 20 mm
6	Lighting device	Smart vision lights –SC75 series	

The second experiment is done using the shaker to excite the beam with a harmonic imposed motion. The shaker excites the beam in the first or second mode shape (9.25 Hz and 56 Hz respectively) with a constant amplitude in each frequency. Besides, the configuration of the camera was changed for each test in order to explore the uncertainty of the measurement in each condition. The exposure time was between 0.125 to 3 ms, the gain was set between 1 dB and 9 dB, and the diaphragm aperture of the camera was set to f-number between 1:2.8 and 1:6.66. The sampling rate of the camera was 50 fps for the first mode shape and 30 fps for the second mode shape. This is because the second natural frequency of the beam was 56 Hz, but maximum sampling rate of the camera is 52 fps. Therefore, the frame rate of the camera was set equal to 30 fps to conduct the experiment in controlled aliasing.

For both experiments before starting the motion one image was taken in static conditions so it can be used as a reference image in the analysis. Afterward, the beam was vibrated and the camera took images with the desired setting. Meanwhile, the laser sensor captured the motion of one point on the surface of the beam. Furthermore, to calibrate the camera a reference target with dot grid pattern was used.

3. Methods

The images acquired during the experiments were processed with two different methods: the commercial DIC software Vic-2D (developed by Correlated Solution Incorporation) and deconvolution method proposed in [10]. Afterward to reduce the uncertainty caused by the blurring in the images, deconvolution method was used to generate new reference images for DIC analysis as described in section 3.3.

3.1 Digital Image Correlation

The first method used in this study was DIC. In this method, Vic-2D calculates the displacement using the acquired images during the motion and one reference image, which was acquired in the static condition. Subset and step sizes are two important values, which should be chosen in DIC. Subset size is the portion of the image that is used to track the motion of each point and the step size is the spacing of the points that are analyzed in correlation [33].

Two outputs of Vic-2D used in this study are matrices V and sigma. Matrix V shows the vertical displacement of the points on the surface of the beam and matrix sigma contains the standard uncertainty associated to the estimated displacement of each region of the beam. The values of sigma matrix are used to remove the displacement of the points which are poorly estimated by the software. By post-processing the output of DIC analysis, it is possible to plot the profile of the beam for different images and track the motion of any point on the beam in time history.

3.2 Deconvolution Method

One method to estimate the displacement and motion effect in acquired images is to perform a deconvolution analysis [10]. It can be seen in Figure 2 that convolving an image with a square pulse gives the same image with displacement and motion effect equal to shift and width of the square pulse respectively. Deconvolution analysis is done by determining the square pulse, which could be convolved with the reference image acquired in static conditions to recreate the acquired image with motion blur. Once the square pulse is determined, the corresponding width would be an estimation of motion effect (w) and the shift would represent the net displacement (a).

It is obvious that the motion of the beam at different points of its length is different. Therefore, to calculate the vertical motion of the beam at each point, the length of the beam was divided to portions with 16 pixels width. The motion of each portion was considered equal to the displacement of its center.

Figure 2: Convolution of an image with a square pulse to obtain an image with displacement equal to ' a ' and motion effect equal to ' w '

3.3 Improved DIC with Deconvolution

Using deconvolution method is useful to estimate the displacement of rigid targets without any deformation on their surface. However in our experiment, the beam is deformable and in order to calculate the field of displacement and strain on its surface we need to use DIC. A new method named improved DIC with deconvolution, which was proposed in [10] for rigidly moving targets, is applied and qualified here for deformable targets. After finding out the value of motion effect (w) by deconvolution method, this blurring can be added to the reference image. The newly generated image would be the reference image with the same amount of motion effect that exists in the acquired image. Now if this generated image is considered as the new reference image, it is expected to be able to decrease the contribution of motion effect (i.e. blurring) in the final uncertainty of displacement estimation.

4. Results and Discussion

In order to compare the accuracy of the results in different conditions, two parameters are used: NRMSE (Normalized Root Mean Square Error) and peak spectrum error. These parameters show the accuracy of the motion estimation done with the vision-based system in front of the laser sensor, which was used as a reference.

If $A(i)$ is the reference motion measured by the laser sensor in time history and $B(i)$ is the motion in a point in front of laser sensor estimated by DIC method, NRMSE is calculated as bellow:

$$RMSE = \sqrt{\frac{\sum_{i=1}^N [A(i) - B(i)]^2}{N}} \quad (1)$$

$$NRMSE = \frac{RMSE}{\max(A(i)) - \min(A(i))} \quad (2)$$

Furthermore, the peak spectrum error is the error between the maximums of the spectrum diagrams of the motion, estimated by DIC method and the laser sensor. Peak spectrum error can be computed from the spectrum diagram as following:

$$Peak\ Spectrum\ Error = \frac{|A_r - A_m|}{A_r} * 100 \quad (3)$$

Where A_r is the peak of the spectrum diagram of the motion, measured by the laser sensor, and A_m is the peak of the spectrum diagram of the motion estimated by DIC method. Of course, care was taken to select an integer number of vibration cycles in the time data, in order to avoid leakage in the spectrum.

4.1 Analysis of DIC Performances

As explained in section 3.1, one reference image and all the acquired images during the experiment are analyzed with DIC. The first experiment was analyzed with different subsets (15*15, 21*21 and 27*27 pixels) and it was proven that the results are not affected by this parameter. The results shown in the following are the ones obtained with a subset of 15*15 px for the first experiment. As for the second experiment the pixel to millimeter scaling was slightly different with respect to the first test, therefore the subset size was set to 17*17 px to obtain the same subset size in millimeters that was used in the first experiment. Moreover, the step size was 3 pixels for the first experiment and 4 pixels for the second experiment. Then vertical displacement of each point (v) and the estimated uncertainty of the displacement (σ) are computed by DIC method. Since in some points of the beam the error of the displacement is very high due to decorrelation, “sigma” is used to remove the data with low accuracy. Decreasing the value of the sigma limit, increases the accuracy of the analysis, but at the same time it increases the number of eliminated points. Motion matrix (v) has a specific number of rows in each column, depending on the height of the area of interest of the images, the subset size, and the step. The average of the values in each column is assumed as the vertical displacement of the beam in that point. The problem arises when the error is high for all the values of a column of the motion matrix. Thus, if the sigma limit is set to a high value, the error of the motion is high on that point of the beam, and if the sigma limit is lower than all sigmas on that column, the motion on that point of the beam is missing. Consequently, there should be a compromise between these two effects to choose the sigma limit. In this project, all the analysis are done with a sigma limit value between 0.01 and 0.09 pixels that produce no more than 5% of missing points on the beam. After applying this sigma limit and filtering the data, an interpolation algorithm was used to recover those missing points and complete the profile of the beam.

The next step is to take an average of the displacement of each column of the displacement matrix (V), so the displacement of the beam in each column (i.e. in each section of the beam) can be estimated. Beam profiles for first and second mode shape of the beam are plotted in Figure 3.

Figure 3: Profile of the beam by DIC in first mode shape for 15 acquired images by sampling rate of 50fps from 0.033s to 0.5s (up), Profile of the beam by DIC in second mode shape for 15 acquired images by sampling rate of 30fps from 0.02s to 0.3s (down)

To calculate the values of NRMSE and peak spectrum error in different conditions, the motion of the beam in front of the laser sensor was computed. In the first experiment, the frequency of the beam and sampling rate of the camera in first mode shape are 7.6 Hz and 53 Hz respectively. However, in second experiment, as explained in section 2.1, the sampling rate of camera is 50 fps for the first mode shape and 30 fps for the second mode shape to do the measurement in controlled aliasing. Figure 4 represents the motion of the beam in the second mode shape measured by laser sensor and DIC method in controlled aliasing condition. In order to compare the results, the data saved by the laser sensor is then resampled synchronously with the data from the camera. Afterward, the spectrums of the motion estimated by the camera and laser sensor are computed and peak spectrum error is calculated as explained before.

Figure 4: Motion of a point on the beam in front of the laser sensor in the second experiment (second mode shape) measured by the laser sensor and by DIC method in controlled aliasing condition

The procedure explained above was applied on different tests of the first experiment; in these tests the variables were the initial displacement applied to the tip of the beam and exposure time of the camera. Figures 5 and 6 show that the peak spectrum error and the NRMSE have the same trend. The same trend is also visible in the product of the exposure time and initial beam displacement. The product of the exposure time and initial displacement is an index of the maximum motion blur that affects the images [36], which is shown to be proportional to the peak spectrum error and NRMSE. Furthermore, high motion effect will reduce the accuracy of DIC. The worst condition is the test in which exposure time, gain and initial displacement imposed to the tip of the beam are 4000 μ s, 0 dB and 13.2 mm respectively. In this case, initial displacement multiplied by exposure time and consequently the blurring in the acquired images was so high that DIC was not able to track the motion in front of the laser sensor properly due to decorrelation.

Figure 5: Peak spectrum error of normal DIC and Exposure time of camera multiplied by initial displacement at a point on the beam in front of the laser for the tests of the first experiment (Ex = Exposure time [μs], G = Sensor gain [dB], In. di. = Initial displacement applied to beam [mm], Decor. = Decorrelation)

Figure 6: NRMSE of normal DIC and Exposure time of camera multiplied by initial displacement at a point on the beam in front of the laser for tests of the first experiment (Ex = Exposure time [μs], G = Sensor gain [dB], In. di. = Initial displacement applied to beam [mm], Decor. = Decorrelation)

Figures 7 and 8 represent the effect of exposure time on NRMSE and the peak spectrum error, having constant diaphragm and gain value. The percentage of the saturated pixels on the surface of the beam is also written in the figures for the tests with partially saturated images. It is evident that increasing the exposure time until a value, which is 1000 μs in our experimental conditions, does not affect the accuracy considerably, but after this value, increasing the exposure time reduces the accuracy of DIC due to increase of the motion blur. Saturation in the images can also affect the accuracy of the results. Therefore, it is fundamental to avoid saturation in the images.

Figure 7: NRMSE for tests with constant Diaphragm and Gain value, changing the exposure time – numbers written in percentage are amount of saturation of the images in each condition (D = Diaphragm, G = Gain)

Figure 8: Peak spectrum error for tests with constant Diaphragm and Gain value, changing the exposure time – numbers written in percentage are amount of saturation of the images in each condition (D = Diaphragm, G = Gain [dB])

In the next step, the effect of gain in the accuracy of DIC was investigated. Figure 9 shows that increasing the gain for the bright images causes saturation in parts of the images that can lead to a higher amount of error. To have a better understanding of the dark images (lower exposure times) which have a lower error, both diagrams are plotted in logarithmic scale. Evidently, in case of having dark images, increasing the gain can slightly reduce the peak spectrum error, but NRMSE is fluctuating. This is likely because NRMSE is sensitive to the noise and although increasing the gain increases the brightness in the images and the results are expected to improve, at the same time it increases the noise of the images too. Therefore, NRMSE does not have a trend as the peak spectrum error does.

Figure 9: Peak spectrum error and NRMSE over gain for tests with different diaphragms and exposure times – numbers written in percentage are amount of saturation of the images in each condition (E = Exposure time [μs], D = Diaphragm)

The diaphragm aperture has a well-known effect on depth of view in the image acquisition: the closer is the diaphragm (i.e. larger f-numbers) the larger is the depth of view. As for the effect of diaphragm on DIC uncertainty in dynamic conditions, Figure 10 shows that the diaphragm aperture of the camera is only a variable to keep the brightness of the image in a proper range and avoid saturation and other than that, it has no significant effect on the uncertainty of DIC method.

Figure 10: Peak spectrum error and NRMSE over diaphragm for tests with gain equal to 9 and different exposure times – numbers written in percentage are amount of saturation of the images in each condition (E = Exposure time [μ s], G = Gain [dB])

4.2 Applying Deconvolution

In this section, the images acquired by the camera are analyzed by deconvolution method. As it was discussed earlier in section 3.5, parameter ‘a’ represents the net displacement of the target with respect to the reference image. Thus, to calculate the vertical motion of the beam at each point, the length of the beam was divided to portions with 16 pixels width. The motion of each portion was considered equal to the displacement of its center. Finally, the profile of the beam over its length was estimated for each image. Figures 11 show that in case of having a high error due to

Figure 11: NRMSE of normal DIC and deconvolution method, and multiplication of exposure time and initial displacement for 6 tests in different settings (Ex = Exposure time [μ s], G = Sensor gain [dB], In. di. = Initial displacement applied to beam [mm])

motion effect in the images, deconvolution method can improve the results. However, this method does not allow estimating the strain of the target and therefore, is only interesting for rigid targets. Hence in the next section (4.3) deconvolution method is used to improve the results in case of having a deformable object, by means of using it to generate modified reference images for DIC.

4.3 Improved DIC with Deconvolution

Deconvolution analysis to make new reference images was done as explained in section 3.3. First, the value of the motion blur (w) for each image was calculated by means of deconvolution. We considered here the portion of the image in front of the laser sensor, in order to allow a comparison. After finding ' w ' for all the images of a test, the proper amount of motion effect was simulated on a portion of the reference image in front of the laser sensor, for each image of the test. One sample of the generated reference image can be seen in Figure 12. This generated image (Figure 12 [c]) has the same blurring that its corresponding acquired image (Figure 12 [b]) has. Finally, the acquired images and the new reference images were analyzed with DIC, comparing each image with its corresponding generated reference image.

Figure 12: [a]: Original reference image, [b]: An acquired image during the test, [c]: Generated reference image with $w = 5.49$

Figure 13 shows the motion of the point in front of the laser sensor for an experiment with $3000 \mu s$ exposure time, estimated with two different methods: normal DIC and DIC with reference images with numerically-generated motion blur. The motion measured by the laser sensor is also plotted as a reference. It can be seen that with normal DIC estimation of displacement in many images the results are affected by a high error while using the generated reference images, the matching with the laser is much better. Therefore, NRMSE decreases from 0.74 to 0.06 using deconvolution method for this experiment.

Figure 13: Displacement estimation for 98 images of a test in the second experiment with normal DIC, DIC with generated reference images and the laser sensor

The procedure was done in nine different conditions, in which error is high due to motion effect or saturation in the images, and peak spectrum error and NRMSE were calculated for them. The results are plotted in Figures 14 and 15. Tests in which there is a red square around their conditions are the ones with partially saturated images. It is evident that using deconvolution to generate new reference images is very useful in case of having partial saturation or high amount of motion effect in the acquired images.

Figure 14: Peak spectrum error for different settings of the camera, for normal DIC and DIC with deconvolution method (Ex = Exposure time [μs], G = Sensor gain [dB], D = Diaphragm, s = Percentage of saturation)

Figure 15: NRMSE for different settings of the camera, for normal DIC and DIC with deconvolution method (Ex = Exposure time [μs], G = Sensor gain [dB], D = Diaphragm, s = Percentage of saturation)

5. Conclusion

Digital image correlation (DIC) technique has a lower accuracy in dynamic conditions if compared with the static cases, because in dynamic conditions, the target is moving with respect to the camera, therefore the acquired images are affected by motion blurring. In this study, two sets of experiments were done on a deformable target in dynamic conditions. In the first experiments, a cantilever beam was subjected to an initial displacement and its free vibration was acquired by a camera. The exposure time and gain of the camera were changed in different tests and the effects of acquisition parameters on DIC results were analyzed. During the second experiments, a shaker was used to vibrate the beam and again the effects of motion blur on accuracy of the results were analyzed. Besides, other than exposure time and gain index, the diaphragm of the camera was changed in different tests. Uncertainties of the measurement obtained with normal DIC technique were calculated for each test in terms of peak spectrum error and NRMSE.

The results show that increasing the exposure time (and therefore the motion blur) the uncertainty of the results grows. However the effect of low levels of motion blur on uncertainty is quasi negligible, while increasing it more than a threshold, the uncertainty decreases strongly. Furthermore, in case of dark images, increasing the gain slightly decreases the peak spectrum error due to having a better brightness, but NRMSE fluctuates as it is also sensitive to the noise. Moreover, diaphragm aperture of the camera is only important to regulate the brightness of the images and avoid saturation.

In the last part of the paper, the accuracy of the measurement obtained with DIC was improved by using deconvolution method to generate a new reference image. The results show a considerable improvement of accuracy in case of high motion blur in the acquired images.

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