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Non-uniform illumination correction based on the retinex theory in digital image correlation measurement method

GUOQING GU[1*], BIN SHE[1], GUIZHONG XU[1], XING XU[2]

[1]School of Civil Engineering, Yancheng Institute of Technology, Yancheng 224051, China

[2]Shenzhen Orbbec Co., Ltd., Shenzhen 518000, China

[*]Corresponding author: gqgu@ycit.edu.cn

Digital image correlation is a well-known optical measurement method for full-field deformation and strain measurements. The quality of speckle images used in digital image correlation calculation can directly affect the measurement accuracy of digital image correlation. In most practical measurement circumstances, a uniform illumination environment is usually required to illuminate the detected object in order to capture speckle images upon different deformed states with uniform background intensity. However, the tested object becomes so large that the adopted light source cannot cover all the interested area with uniform illumination, and the speckle images acquired by CCD camera may have non-uniform background intensity distributions. In this paper, the influence of non-uniform illumination is first analyzed in detail by means of a comparison of experimental results of digital image correlation using speckle patterns with both uniform and non-uniform intensity distributions. Then, a new correctional method based on the combination of the basic retinex theory and the illumination formulae of a point light source is proposed. Finally, a real experiment with non-uniform illumination is implemented to verify the effectiveness of this method.

Keywords: digital image correlation (DIC), non-uniform illumination correction, retinex theory, deformation measurement.

1. Introduction

Digital image correlation (DIC) is a non-contact and powerful optical measurement tool which directly provides full-field displacements and strains with high accuracy. A relatively comprehensive review of two-dimensional DIC is presented by BING PAN *et al*. [1]. In recent years, more and more applications of the DIC method are reported in many industry fields [2–5]. Doubtlessly, DIC method is gradually becoming an important optical measurement technique due to its advantages of full-field measurement, high precision, simple structure, and so on.

In practice, the accuracy of deformation measurement using DIC method can be affected by many factors, such as interpolation algorithm, speckle size and density, subset size. During the past few years, the effects of these factors on deformation measurement have been investigated by many researchers. For example, LONG LUU *et al.* [6] studied the performance of interpolation algorithms on subpixel accuracy and employed B-spline interpolation to enhance the accuracy of DIC. TAO HUA *et al.* [7] studied the mean bias error caused by the speckle size and density and provided a novel parameter called mean subset fluctuation to assess the quality of different speckle patterns which affect the accuracy of DIC. BING PAN *et al.* [8] investigated the problem of the subset size selection which is found to be critical to the accuracy of measured displacement.

Furthermore, the intensity of images is also a factor which has an important influence on DIC measurement accuracy. Generally speaking, the intensity of the images used for DIC calculation should keep unchangeably and have a uniform distribution. However, when using the DIC method for practical applications, the intensity of a point in reference and deformed images may change. For overcoming this disadvantage, different models for intensity change between the two images were discussed in detail by XIAO-YONG LIU *et al.* [9]. The experimental results reveal that the algorithm generated using the non-linear intensity change model is the most accurate, robust and efficient. Similarly, the intensity of images may have a non-uniform distribution in some cases. For example, the detected object is so large that the light source cannot cover all interested areas with uniform illumination, which directly leads to the non-uniform intensity distribution of the speckle patterns. The most common used solution is the use of two or more light sources. It is no doubt that this solution is costly. As a result, we consider DIC measurement system using only one light source and focus on the correction of the errors caused by non-uniform illumination.

Recently, we have successfully put forward an uneven intensity change correction method based on morphological top-hat transform to eliminate the effect of the uneven intensity change of speckle images [10]. As well known, the gray values distribution of speckle images used for correlation calculation directly influences the measurement accuracy of DIC. Although it is effective to realize the background intensity uniformization of speckle images by means of morphological top-hat transform, the crucial disadvantage is that the entire gray values of speckle images may inevitably decrease due to the substraction of the extracted background image from the initial speckle image. In this work, we will propose an alternative novel non-uniform illumination correction method based on the combination of the basic retinex theory and the illumination formulae of a point light source. Firstly, several comparisons of results acquired by DIC using the images with uniform intensity and non-uniform intensity, respectively, are implemented for quantitatively evaluating the influence of non-uniform illumination on the measurement accuracy of DIC. Then, the non-uniform illumination correction is discussed, and the procedure of correction is thus accomplished by a corrector formula obtained by the use of combining the basic retinex theory and the illumination formula of the point light source. Finally, a practical DIC measurement experiment with non-uniform illumination is investigated to verify the effectiveness of the proposed correction method.

2. Digital image correlation

Digital image correlation (DIC), which was initially proposed by PETERS and RANSON in 1982 [11], has been developed for thirty years and now is widely used in many fields. A brief description of this method is given in this section. The basic principle of 2D DIC is to match the same subset of two images recorded before and after object deformation. Herein, the subset is usually a square sub-image of $(2n + 1) \times (2n + 1)$ pixels centered at a point from the reference image, and used to track its corresponding location in the deformed image to compute the displacements of the point. The matching process is implemented by searching the peak position of the distribution of a correlation coefficient which is predefined and reveals the similarity between two subsets. Once the correlation coefficient extremum is found, the relative displacement of two subsets can be determined. The zero-mean normalized cross-correlation (ZNCC) criterion, which is insensitive to the scale and offset changes in illumination lighting fluctuations, is utilized in this work

$$C_{\mathrm{ZNCC}} = \frac{\sum_{i=1}^{n}\left[f(x_i, y_i) - f_{\mathrm{m}}\right]\left[g(x_i', y_i') - g_{\mathrm{m}}\right]}{\sqrt{\sum_{i=1}^{n}\left[f(x_i, y_i) - f_{\mathrm{m}}\right]^2}\sqrt{\sum_{i=1}^{n}\left[g(x_i', y_i') - g_{\mathrm{m}}\right]^2}} \tag{1}$$

where $f(x_i, y_i)$ and $g(x_i', y_i')$ are the intensity values at (x_i, y_i) in the reference subset and (x_i', y_i') in the deformed subset, respectively; f_{m} and g_{m} are the mean intensity values of the reference and deformed subsets; n denotes the number of pixels contained in the reference subset.

3. Influence of non-uniform illumination

In general, a successful DIC measurement depends on several critical factors, one of which is the quality of the reference and deformed images obtained by a CCD camera. If the illumination is uneven or is the use of ambient light, the obtained images will be with non-uniform intensity distribution which immediately decreases the contrast of the images and the accuracy of the DIC measurement. Several experiments were conducted to quantitatively evaluate the influence of non-uniform intensity images on the measurement accuracy of DIC in this section.

An 8-bit speckle pattern of 1024×1024 pixels with uniform intensity distribution which was taken from our previous experiment was used as the first reference image. Then we added three different non-uniform background images to this image to get the other three reference images which have non-uniform intensity distributions. In the following numerical studies, the pure in-plane translation tests were performed. As for the first reference image, its deformed images can be generated by applying the appropriate shift in Fourier domain according to the phase shifting theorem [12]. The displacements applied in the x direction range from 1 to 10 pixels, corresponding to a shift of 1 pixel between two successive images. The deformed images of the other three

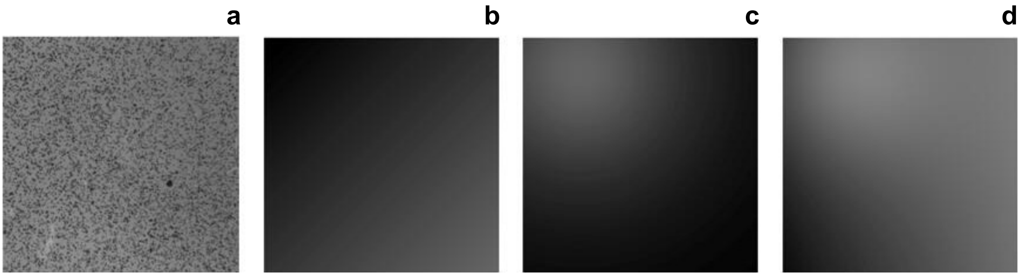

Fig. 1. Reference image (**a**) and three different backgrounds (**b**–**d**).

reference images must be generated by adding the background to the relevant deformed images of the first reference image. Then, the displacements were computed using the Newton–Raphson algorithm with the ZNCC criterion. The calculated area used is 791 × 811 pixels and the subsets are 25 × 25 and 41 × 41 pixels, respectively.

Figure 1**a** shows the uniformly illuminated reference image and Figs. 1**b**–1**d** represent three different background images obtained by numerical simulations, respectively. The first background image as shown in Fig. 1**b** is produced by making a uniform decrease of the gray value from the upper left corner to the lower right corner, and the second background image as shown in Fig. 1**c** is generated by making the maximum gray value decrease with the increases of the distance far from the point, while the last background image as shown in Fig. 1**d** is obtained by the summation of Figs. 1**b** and 1**c**. Figure 2 shows another three reference images with non-uniform intensity distribution obtained by adding the three background images into the first reference image, respectively.

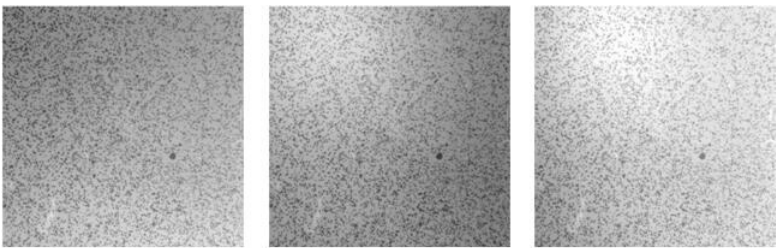

Fig. 2. Images with three different non-uniform intensity distributions.

Figure 3 shows the mean bias errors, and Fig. 4 shows the standard deviation errors of the detected displacements for the four reference images using the subset of 25 × 25 (**a**) and 41 × 41 (**b**) pixels subset. It is observed from Figs. 3 and 4 that:

– The mean bias error and the standard deviation error of DIC using the reference image with uniform intensity distribution are stable with the increase of preassigned displacement. However, these two errors of DIC using the other reference images with

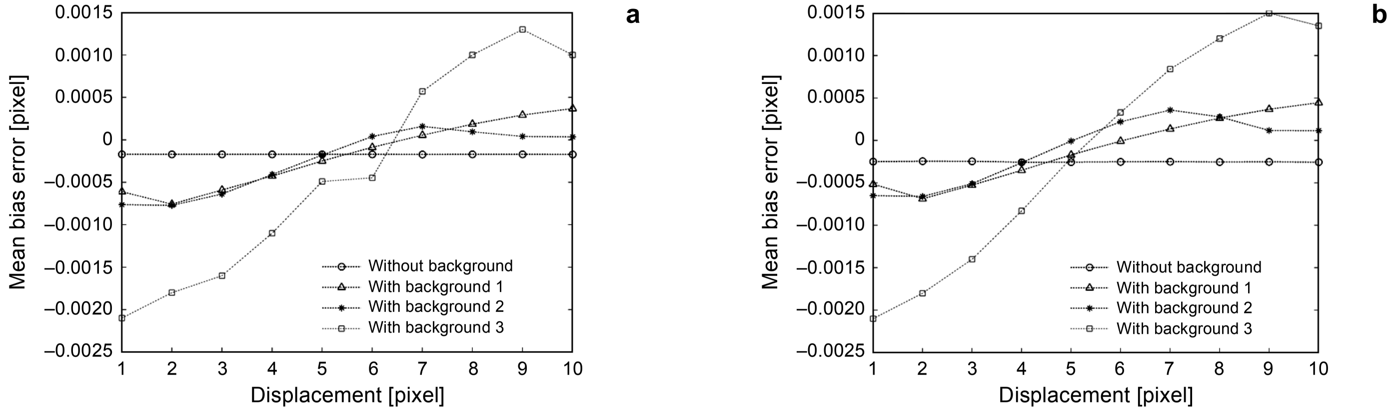

Fig. 3. Mean bias error as a function of preset displacement for four image sets with various illumination: subset of 25 × 25 pixels (**a**), and subset of 41 × 41 pixels (**b**).

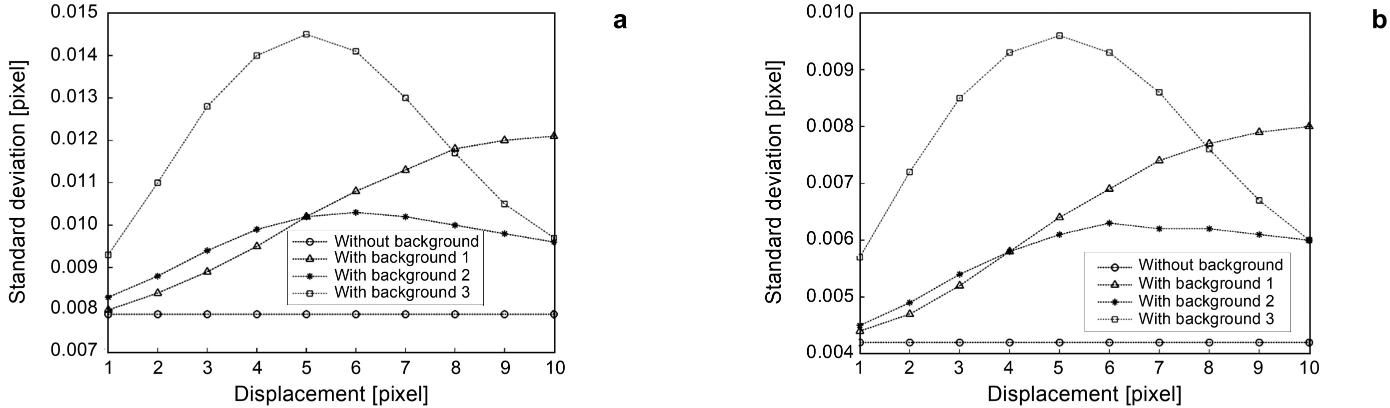

Fig. 4. Standard deviation as a function of preset displacement for four image sets with various illumination: subset of 25 × 25 pixels (**a**), and subset of 41 × 41 pixels (**b**).

non-uniform intensity distribution are larger than those using uniform intensity images with the increase of preassigned displacement;

– The mean bias error does not depend on the calculated subset used, but the standard deviation error using 25 × 25 pixels is larger than that using 41 × 41 pixels subset;

– It is worthy to note that these two errors calculated by the DIC method using the images with different non-uniform backgrounds are determined by the intensity distribution of the background. According to the above discussions, an important conclusion can be obtained that non-uniform illumination, *i.e.* uneven intensity distributions, in DIC experiment can bring about a higher error than the uniform illumination. As a result, a non-uniform illumination correction process is required to execute prior to DIC calculation using non-uniform intensity images.

4. Correction of non-uniform intensity

4.1. Correction method

In most of the DIC experiments, the illumination is even because the interested area of the detected object is so small that the light source can cover all the area with even illumination or use two or more light sources. However, the use of only one light source cannot meet the requirement of even illumination if the interested area is very large. For overcoming this limitation of uneven illumination, the correction process needs to be implemented.

According to the basic retinex theory [13], the intensity of the image can be written as

$$f(x, y) = i(x, y)\, r(x, y) \tag{2}$$

where $f(x, y)$ is the intensity, *i.e.*, the gray value of the image; $i(x, y)$ is the illumination component which is determined by the used light source; $r(x, y)$ is the reflection component determined by the original appearance of the detected object. The reason of

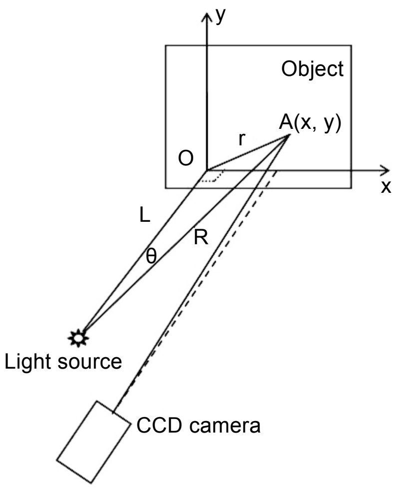

Fig. 5. Schematic illustration of a DIC measurement system.

non-uniform intensity distribution of an image is that its illumination component $i(x, y)$ changes with different points of the object.

The schematic illustration of the DIC method is shown in Fig. 5. Assuming that the detected area in the object is so large that the light source cannot cover the whole interested area with uniform illumination, the light source used here is an approximate point light source. According to the illumination formula of the point light source, the illumination of any point $A(x, y)$ in the object surface can be expressed as

$$i(x, y) = \frac{I\cos(\theta)}{R^2} \tag{3}$$

where I is the luminous intensity of the light source which is a constant; R is the distance between the light source and point $A(x, y)$; θ is the angle between $\overline{\mathrm{OS}}$ and $\overline{\mathrm{AS}}$. Equation (3) can be rewritten as

$$i(x, y) = \frac{IL}{R^3} = \frac{IL}{(L^2 + x^2 + y^2)^{3/2}} \tag{4}$$

where L is the orthogonal distance between the light source and the object plane. According to Eq. (4), the value of illumination component $i(x, y)$ decreases with the increase of the point (x, y).

By taking the gray value of the point $O(0, 0)$ as the reference point, the gray value of a particular point $A(x, y)$ can be achieved by replacing its illumination component $i(x, y)$ with the illumination component of the point $O(0, 0)$ (*i.e.* $i(0, 0)$), which can be expressed as follows

$$f'_A(x, y) = i(0, 0)\, r(x, y) \tag{5}$$

where $f'_A(x, y)$ represents the modified gray value of any other point. The real gray value of the point $A(x, y)$ can be written as follows

$$f_A(x, y) = i(x, y)\, r(x, y) \tag{6}$$

Substituting Eq. (6) into Eq. (5), the modified intensity of the point $A(x, y)$ can be further obtained by

$$f'_A(x, y) = \frac{i(0, 0)}{i(x, y)} f_A(x, y) = \frac{(L^2 + x^2 + y^2)^{3/2}}{L^3} f_A(x, y) \tag{7}$$

On the basis of the above analysis, the correction process can be accomplished with two steps. First, we need to find the reference point and take it as the origin of the coordinate. In general, the area around the reference point has the highest gray in the image of the detected object. Therefore, we find the area with the highest gray in the image and put the center of this area as the reference point. Second, we calculate the gray

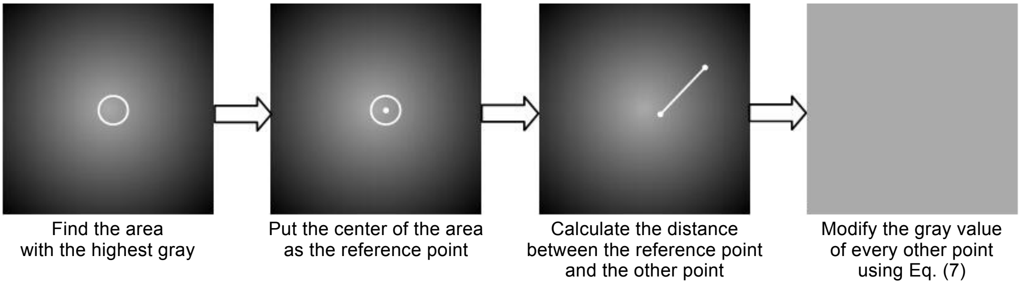

Fig. 6. Detailed correction procedure.

value of the other points using Eq. (7). Accordingly, taking the image simulated based on the Gaussian distribution as an example, the explicit correction procedure is graphically shown in Fig. 6.

4.2. Verification using a practical experiment

In order to verify the usefulness of the correction method mentioned above, a practical rotation experiment was carried out. The experiment specimen was a circular thin plate which was clamped along its edges. In order to generate the high quality artificial speckle field, the specimen surface was burnished by using the coarse sand paper and then sprayed with the glass beads paint. With the help of the rotation device fixed on the rear of the plate, a rigid body in-plane rotation deformation can be thus realized. A CCD camera (Point Grey Flea2) with a resolution of 2560 × 1920 pixels was used as an image acquisition device to capture speckle images. Besides, a cold light source was employed to illuminate the tested specimen. All experimental equipments were fixed on a vibration isolation precise optical table to avoid environmental disturbance.

The images captured before and after in-plane rotation are, respectively, shown in Figs. 7**a** and 7**b**. It is obviously seen from Fig. 7 that the phenomenon of non-uniform illumination exists. In order to eliminate this phenomenon, the correction procedure indicated in Fig. 6 is then carried out. As a result, the corresponding images after cor-

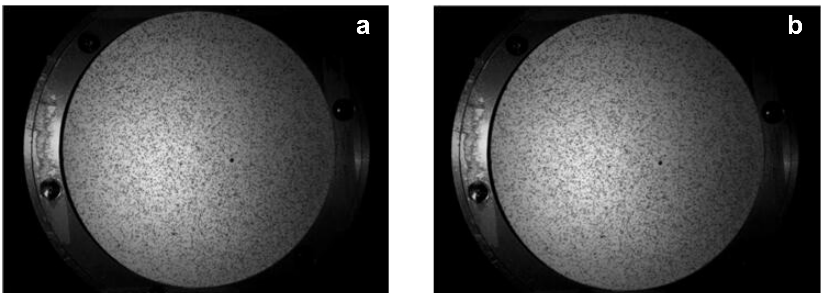

Fig. 7. Original images acquired before and after the object deformation: reference (**a**) and deformed image (**b**).

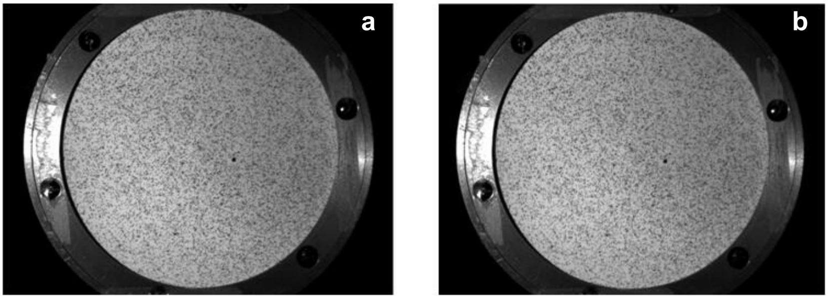

Fig. 8. Images after non-uniform illumination correction: reference (**a**) and deformed image (**b**).

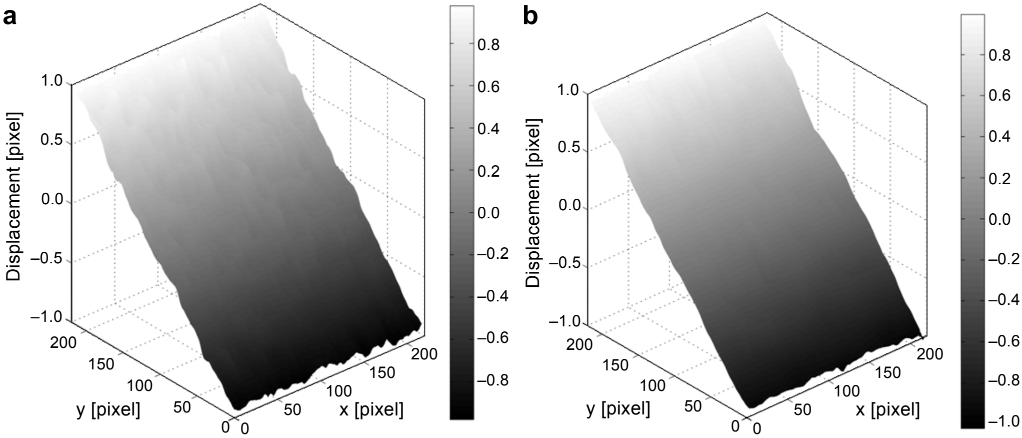

Fig. 9. The u-field displacement distributions of in-plane rotation: before (**a**) and after (**b**) correction.

rection are, respectively, shown in Figs. 8**a** and 8**b**. From Fig. 8, we can easily find that the intensity of the images after correction is more uniform than the original images.

The displacements of the two sets of images before and after correction are, respectively, calculated by DIC method which uses the Newton–Raphson algorithm with the ZNCC criterion, the subset size of 31 × 31 pixels and the grid step of 5 pixels. The measured u-field displacement distributions before and after correction are shown in Figs. 9**a** and 9**b**, respectively. It is obviously found that the u-field displacement distributions are much smoother after correction procedure.

5. Conclusions

In this paper, a non-uniform illumination correction method based on the retinex theory is proposed for eliminating the uneven intensity distributions of a speckle image. The experiments using speckle images with uniform intensity distribution and non-uniform intensity distribution are implemented using DIC calculation. The results show that the mean bias error and the standard deviation error of the measured displacement using speckle images with non-uniform intensity distribution are larger than those using speckle images with uniform intensity distribution. The effectiveness of the correction method based on the retinex theory is finally validated by a practical experiment.

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