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Phase measurement errors due to holographic interferograms compression

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ABSTRACT

Digital holographic interferometry allows accurate measurements on a microscopic level. As the number and size of the recorded digital holograms increase so does their data volume. As a result the volume of holographic data can substantially constrain applications where storage or transmittance of such data is required. Compression of holographic data in order to reduce their storage requirements has been studied. The speckled nature of the interferograms makes their compression nontrivial; however image compression algorithms such as JPEG, JPEG2000 and Set Partitioning In Hierarchical Trees (SPIHT) have been shown to perform adequately. So far the compression effects of the holographic interferograms using such coding methods have mainly been studied in terms of errors at the reconstruction intensity. On the other hand, metrology applications usually rely on the holograms' reconstructed phase. In this paper we investigate hologram compression and how it affects the reconstructed phase. Holographic interferometry experiments are carried out to investigate measurement error due to interferograms compression using image compression methods. The results indicate that compression can be achieved while the measurement error due to compression is retained low.

Keywords: digital holography, digital holographic interferometry, holographic data compression, interference patterns coding.

1. INTRODUCTION

In digital holography (DH), holograms are recorded in digital form using CCD sensors and then numerically reconstructed by computers[1]. DH allows amplitude and phase quantitative analysis of the object wavefields following numerical reconstruction. A wide range of DH applications in metrology[2], micro-interferometry[3], 3-D imaging[4], and particles analysis[5] have been presented. As the size of the recorded holograms increase, so does the amount of data to be stored making DH data compression necessary. DH interferograms are continuous tone grey scale images and hence image compression algorithms can be used to compress them. Compression of phase-shifting interferometry (PSI) DH data using image compression algorithms has been suggested [6, 7]. The same algorithms can be used for the compression of ordinary digital holograms.

The compression effects of the image compression methods have been studied mainly on the intensity of the reconstructed holograms [6-9]. In this paper we focus on the compression effects on the reconstructed phase where most of the DH applications rely on. To this end three real DH interferometry cases are studied, namely two for smooth and highly reflective objects, and one for a diffuse object. The captured holograms are compressed to several compression rates using baseline JPEG[10], JPEG2000[11], and Set Partitioning In Hierarchical Trees (SPIHT)[12] compression. The reconstructed phase is then obtained from the decoded holograms and quantitative analysis is carried out to assess the compression performance.

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Figure 1: Digital holographic interferometry setups, (a) for smooth and highly reflective objects and (b) for diffuse objects.

The paper is organized as follows. In Section 2 holographic interferometry and the setups that were used to record the experimental data are given together with a brief description of the methods that are used for the compression of the recorded data. In Section 3 the experiments and the obtained numerical results are presented, and Section 4 concludes the paper.

2. DATA ACQUISITION AND COMPRESSION

2.1 Digital holographic interferometry

Digital holographic interferometry is a non-destructive and non-contact inspection method exploiting differences at light path lengths with a very high precision. Figure 1(a) shows the basic interferometry setup for smooth and highly reflective objects. A portion of the laser beam passes through the beam splitter and is reflected on the mirror at the right hand side. It then passes through the beam splitter and reaches the recording camera providing the reference beam. Another portion of the laser beam through the beam splitter illuminates the investigated object and the object wave reaches the recording camera through the beam splitter. The recorded object has in general a different profile from the reference mirror, hence the light path length of the reference beam and the object beam differ. The light path length differences appear as phase differences between the reference and the object beams. This phase difference can be numerically evaluated from the reconstructed hologram. In order to avoid the twin image effect on the reconstructed phase an off-axis recording is usually done by tilting the reference mirror. In Fig. 2 an example of phase imaging using this setup is shown. The examined object is a portion of a reflective USAF target. Figure 2(a) shows the measured phase and Fig. 2(b) the corresponding phase profile of the object.

Figure 2: Phase imaging example. (a) is the measured phase and (b) the corresponding phase profile.

Figure 3: Digital holographic interferometry. (a) is the reconstructed phase difference between the reference and the deformed state and (b) the resulting surface profile.

The approach for pure phase reconstruction that is described above is applicable only for highly reflective and relatively smooth objects. In the case of non-highly reflective objects this method performs poorly as the object wave is not strong enough to create adequate interference with the reference wave. Hence the recordings have to be done with a setup like the one shown in Fig. 1(b) where fiber coupling is used in order to provide separately the reference beam and the object illumination. In this way the laser power ratio between the object and the reference beam can be controlled effectively. In the case of diffuse objects, interferometry is usually used to measure displacement differences between two or more states of the object. One is the reference state and the others are the deformed states. The deformation results from an applied force, usually caused by loading. Two holograms are recorded, one for the reference state and one for the deformed state. These two holograms are reconstructed individually and the interference phase can then be calculated as [13]

$$\Delta\varphi = \begin{cases} \varphi_1 - \varphi_2 & , \text{ if } \varphi_1 \geq \varphi_2 \\ \varphi_1 - \varphi_2 + 2\pi & , \text{ if } \varphi_1 < \varphi_2 \end{cases} \quad (1)$$

where φ_1 and φ_2 are the phase of the reconstructed holograms for the reference and the deformed state respectively. In this case the effect of the twin images are suppressed by the subtraction and hence in-line recording is usually utilized.

By using Eq. (1) the modulo - 2π or wrapped phase is calculated. To convert the wrapped phase into continuous one an unwrapping algorithm has to be used. Depending on the quality of the phase map several unwrapping algorithms can be used. The simpler one is the Sequential Line Scanning Method (SLSM) [13, 14] but it performs poorly on noisy phase maps. In such cases more sophisticated noise immune unwrapping methods need to be used [15]. An example of this procedure is shown in Fig. 3. The examined object is a membrane initially perpendicular to the optical axis. At the deformed state the membrane has been tilted by an external force. Figure 3(a) shows the resulting wrapped phase after subtracting the reconstructed phases using Eq. (1) and Fig. 3(b) shows the object deformation profile corresponding to the unwrapped phase.

2.2 Compression of digital holograms

The interference patterns that are used in DH are actual grey scale images captured by CCD sensors. This makes possible the use of sophisticated and hence highly effective compression methods. In this paper we make use of standard image compression techniques for the compression of interferograms. The main disadvantage of the popular image coding techniques is that they were designed to offer optimal compression performance on natural, real world images and not on interferograms. As a result it is not clear that the high frequency fringe structure present within interferograms [16] can be appropriately processed with such algorithms. In this paper we demonstrate that the fringe information of the interference patterns can be effectively retained by this form of compression.

However, the fact that interference patterns contain high frequency components due to the size of the micro-fringes structures they depict limits the compression rates that can be achieved in this way. In this paper we investigate the use of the widely used baseline JPEG[10] and JPEG2000[11] image compression techniques, as well as the use of the SPIHT coding algorithm [12].

JPEG and JPEG2000 are well known image coding standards which are based on the Discrete Cosine Transform (DCT) and on the wavelet decomposition respectively. The SPIHT has been shown to be a very efficient coding technique for image and video compression. SPIHT is a wavelet based coding technique which takes advantage of the spatial self-similarity between subbands. SPIHT divides the wavelets coefficients in spatial orientation trees, which effectively define the spatial relationship on a hierarchical pyramid fashion, orders them based on a particular developed importance criteria and processes them serially based on their importance. The resulting coded bitstream is produced one bit at a time and hence the coding procedure can be stopped at any point where any predefined data volume or quality metric requirements are fulfilled. In this way fully embedded bitstreams are produced meaning that depending on the proportion of the bitstream that is to be processed, the obtained quality increases progressively. This enables us to control the amount of the resulting data size to a bit by bit level and hence gives the advantage of full control of the compression rate achieved. Another advantage of the SPIHT algorithm is that it can be used for lossless coding (in conjunction with special selected wavelet bases) by calculating and storing all the bits of the bitstream, as well as its both encoding and decoding speed and relative simplicity. More detailed description of the algorithm and its characteristics can be found in literature.

In this paper baseline JPEG, JPEG2000, and SPIHT are used without any special arrangement on aspects such as quantization tables or wavelet filters. A more thorough tuning of such aspects is expected to increase the performance and efficiency of the methods but it falls outside the scope of this paper.

3. EXPERIMENTS AND NUMERICAL RESULTS

In order to quantify the introduced error the Normalized Root Mean Square (NRMS) error metric was utilized. The intensity NRMS error can be defined as:

$$NRMS_{\text{int}} = \left[\frac{\sum_{N_x} \sum_{N_y} (|U|^2 - |\hat{U}|^2)^2}{\sum_{N_x} \sum_{N_y} (|U|^2)^2} \right]^{1/2}, \quad (2)$$

where U and $\hat{U}$ are the propagated wavefronts resulting from the original and the compressed data respectively, and N_x and N_y are the size of the hologram on the x and y directions respectively in pixels. Similarly the phase NRMS error metric is defined as

$$NRMS_{\text{phase}} = \left[\frac{\sum_{N_x} \sum_{N_y} (\varphi - \hat{\varphi})^2}{\sum_{N_x} \sum_{N_y} (\varphi)^2} \right]^{1/2}, \quad (3)$$

where φ and $\hat{\varphi}$ are the unwrapped reconstructed phase from the uncompressed and compressed data respectively. Also the compression rate is measured as

$$r = \frac{s}{S}, \quad (4)$$

where S and s are the size of the original and the compressed interferograms respectively in bytes.

3.1 Curved mirror study

By using the experimental setup shown in Fig 1(a) the curvature of a curved mirror is expected to be revealed as the length of the light path differs for each point of it. The object was positioned at a distance of $d = 300mm$ and a high pass filter was used to reduce the zero order term before the reconstruction. Figures 4(a)-(c) show the wrapped phase of real image, the unwrapped phase, and the corresponding phase profile that result from the original uncompressed data using this approach. Figures 4(d)-(f), 4(g)-(h), and 4(j)-(l) correspond to the same reconstructions but from compressed data using JPEG, JPEG2000, and SPIHT respectively. It can be noticed that errors appear more noticeable at the edges of the reconstructed phase. Hence, it does not significantly affect the central part of the obtained profile of the curved mirror. The numerical results are shown in Figs. 5(a) and (b) for the intensity and the phase respectively.

Figure 4: Reconstructed phase images. (a), (d), (g), and (j) corresponds to wrapped phase, (b), (e), (h), and (k) to unwrapped phase, and (c), (f), (i), and (l) to the resulting phase profile respectively. Also (a) – (c) correspond to the original data, (d) – (f) to compressed using JPEG, (g) – (h) using JPEG2000, and (j) – (l) using SPIHT respectively. Compression rates are ~17:1, 20:1, and 20:1 respectively.

Figure 5: (a) Intensity, and (b) Phase NRMS error numerical results for the curved mirror.

It can be noticed in Figs. 5(a) and (b) that the intensity and the phase NRMS errors are low (below 0.22 and 0.052 respectively) which indicates that in this case the compression does not severely affect the reconstructed phase or intensity. It can also be noticed that in some cases the phase and the intensity NRMS errors are not increasing monotonically as the compression rate increases. One possible reason for this is that, as the errors due to compression are low, speckle noise may be affecting more the reconstruction in some cases causing these fluctuations on the NRMS error versus compression rate curves.

3.2 USAF target study

In this experiment the studied object was a portion of the reflective USAF target. The target consists of a flat glass substrate on which the test pattern is imprinted. The imprinted pattern alters the length of the light path and hence the holographic interference patterns. Phase changes can directly be observed at the phase of the reconstructed hologram as shown in Fig. 6(a). For this experiment the setup shown in Fig. 1(a) was used and the object was positioned at a distance $d = 320mm$ from the recording camera. Figures 7(a) and (b) show the resulting numerical results.

Figure 6: Reconstructed phase profiles of the USAF target from (a) original, (b) JPEG, (c) JPEG2000, and (d) SPIHT coded data. Compression rates are ~19:1, 29:1, and 20:1 respectively.

Figure 7: (a) Intensity, and (b) Phase NRMS error numerical results for the USAF target.

It can be noticed from Fig. 6 that the obtained phase images remain practically unaffected by compression at rates approximately 20:1. In addition, it can be seen in Figs. 7(a) and (b) that the introduced error due to compression remains low. More specifically, the intensity NRMS error is approximately 0.16, 0.14, and 0.12 for compression rates of 39, 43, and 40 for JPEG, JPEG2000 and SPIHT respectively while the phase NRMS error is approximately 0.24, 0.2, and 0.25.

3.3 Membrane study

For this experiment the investigated object was a membrane which could be rotated along the axis of one of its sides by a force applied on it. The force was caused by an electromechanical mechanism so that the displacement of the membrane could be controlled. A setup similar to the one shown in Fig. 1(b) was used as the membrane was neither highly reflective nor diffuse. For the reference state no force was applied to the membrane so it was on its natural position approximately perpendicular to the optical axis. A recording for an additional deformed state caused by an applied force was also done. The membrane was positioned at an approximate distance $d = 272\text{mm}$ and in order to reduce the zero order term high pass filtering was applied on the interferograms before the reconstruction.

Figure 8(a) shows the obtained wrapped phase map from the original data. A phase profile resulting from the averaging of this phase map is shown in Fig. 9(a). Figures 8(b)-(d) show the same wrapped phase map resulting from the JPEG, JPEG2000, and SPIHT coded data respectively. Similarly Figs. 9(b)-(d) show the phase profiles resulting from averaging these phase maps for JPEG, JPEG2000, and SPIHT coded data respectively.

It can be seen in Fig. 8 that compression introduces speckle-like noise on the reconstructed phase causing irregularities on the phase profiles shown in Fig. 9. Although small, these fluctuations severely affect the performance of the unwrapping algorithm as it is shown in Fig. 10 which shows the resulting unwrapped phase maps using the SLSM phase unwrapping algorithm. The SLSM algorithm is known to be very sensitive to the speckled kind of noise that compression introduces to the wrapped phase maps. It can be seen in Fig. 10 that the compression noise causes severe discontinuities at the unwrapped phase maps. In Fig. 11 the numerical results of the NRMS phase error calculated using Eq. (3) from the unwrapped phase map are shown. It can be noticed that the introduced phase error due to compression results in relatively low numerical values even for compression rates as high as 40:1. Although the introduced numerical errors comprise low values, the compression artifacts severely affect the unwrapping procedure.

Figure 8: Wrapped phase maps. (a) from the original interferogram, and (b) to (d) from JPEG, JPEG2000, and SPIHT compressed interferograms respectively. Compression rates are $\sim 25:1$, $25:1$ and $20:1$ respectively.

Figure 9: Averaged phase profiles. (a) from the original interferogram, and (b) to (d) from JPEG, JPEG2000, and SPIHT compressed interferograms respectively. Compression rates are $\sim 25:1$, $25:1$ and $20:1$ respectively.

Figure 10: Unwrapped phase images. (a) from the original interferogram, and (b) to (d) from JPEG, JPEG2000, and SPIHT compressed interferograms respectively. Compression rates are $\sim 25:1$, $25:1$ and $20:1$ respectively.

3.4 Remarks on Interference Patterns Compression

In this paper we have investigated the use of well established image coding algorithms, namely JPEG, JPEG2000 and SPIHT, for the compression of interferometric digital holograms. In general, the coding performance of these methods is comparable. JPEG shows slightly lower performance than JPEG2000 and SPIHT in most cases. Although the three methods yield similar performance they are not identical. JPEG has reduced coding flexibility as it cannot fully control aspects such as the compression rate or the amount of the introduced error. In addition its compression performance is slightly lower compared to the other techniques at low bit rates however its computational cost is significantly lower. JPEG2000 has a significantly higher computational cost compared to JPEG however it achieves marginally better compression performance. It offers increased flexibility and full control of the coding aspects. Finally, SPIHT offers similar performance, and flexibility with JPEG2000. SPIHT performs compression progressively hence its computational cost is proportional to the required compression rate nevertheless the fact that it is neither standardized nor widely accepted makes it less attractive.

Figure11: Phase NRMS error numerical results for deformed membrane.

4. CONCLUSIONS

In this paper new compression methodologies of holographic interferograms were presented. The performance of these algorithms was assessed on three different examples of real digital holographic interferograms. The results reveal that image compression methods can be used for effective digital hologram compression. More specifically, we showed how common image compression techniques such as JPEG, JPEG2000, and SPIHT can be used to compress holographic interferograms. Some indicative numerical results were presented to quantify compression performance. Although these algorithms have been optimized for image compression applications the results that have been shown in this paper indicate that the phase information of the interferograms that are compressed using image compression algorithms can be retained at low levels for compression rates of ~40:1 or higher.

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