Coherent Measurement Techniques

Pulsed digital holographic interferometry for endoscopic investigations (HoEnd)
Supported by: Landesstiftung Baden-Württemberg

Multi-Functional Encoding System for the Assessment of Movable Cultural Heritage (Multi-Encode)
Supported by: European Union (006427 SSPI)
Project: “Multi Encode”

Time resolved digital holographic interferometry for the investigations of dynamic events
Wavefront reconstruction using sequential intensity measurements of a volume speckle field
Supported by: DFG (OS 111/19-1)

Compensation of the misalignment between master and sample in comparative digital holography
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Digital holographic microscopy in the deep UV (DUV)
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Modified convolution reconstruction algorithm for high numerical aperture holograms
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Phase retrieval using a movable phase mask
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Pulsed digital holographic interferometry for endoscopic investigations (HoEnd)

G. Pedrini, W. Osten

Holographic interferometry combined with endoscopy enhances the versatility of standard 2D-endoscopic imaging as it opens up the possibility of measuring additional parameters on hidden surfaces. Combinations of digital holography, with an endoscope to transfer the image, and a pulsed laser as a light source, allows measurements in an industrial environment (e.g. vibration measurements, non-destructive testing of technical objects) and in vivo investigation of biological tissues. It might be useful for the detection of pathology in medicine.

Fig. 1 shows schematic illustrations of rigid and flexible endoscopes combined with a system based on pulsed holographic interferometry. The optical set-up consists of the pulsed laser, the interferometer unit with the CCD-camera and the endoscope unit. Fig. 1.a) shows the arrangement for a rigid endoscope but this endoscope can be replaced with a flexible fibre endoscope, as shown in Fig. 1.b). Rigid and flexible endoscopes have a lot in common. The objective lens forms an image of the subject which in turn is transferred by the relay optics and magnified by a lens system onto the sensor. The difference is in the relay itself.

For both arrangements, the recording procedure and the way to process the digital holograms is exactly the same. The pulsed laser emits short (20 ns) Q-switched pulses, which are divided at the beamsplitter into the reference and the object beams. The reference beam is conveyed to the interferometer unit with a single-mode optical fibre. The object beam is coupled into a fibre bundle and conveyed to the object. The light is diffusely reflected back from the surface towards the endoscope, which brings the object image to the interferometer unit. An image-plane hologram is formed on the CCD-detector as a result of the interference between the slightly off-axis reference beam and the object beam. The aperture serves to limit the spatial frequencies of the interference pattern, in such a way that the detector resolves it. Two or more digital holograms, corresponding to different laser pulses, are captured on separate video frames by the CCD-camera.

For one of our investigations the test object was a metallic cylinder with a diameter of 65 mm and a height of 110 mm. The end of a rigid endoscope, which was combined with a system based on digital holography, was inserted into the cylinder through an aperture in order to measure the vibration inside the object. Fig. 2.a) shows an example of a measurement with the object excited at the frequency of 5010 Hz using a shaker. The flat inner surface was examined. There is a discontinuity in the fringes due to a delamination defect of the object surface. A pseudo 3D representation of the deformation can be seen in Fig. 2.b.

Recently, with the newer smaller CCD detector arrays, it has become possible to build the complete interferometric system (CCD included) within small dimensions (diameter 6 mm). Fig. 3.a) and b) show a sketch and a picture of the prototype.

The illumination of the object is from a multimode fiber that has a 600 μm diameter. The reference beam is conveyed with a single mode fiber and is directed towards the sensor by a small prism. This prototype has been used to perform measurements inside a cylinder and some results (phase measurements) are presented in Fig. 4.
Fig. 4: Measurements inside a cylinder using the prototype shown in Figure 3. Image of the object (a) and phase maps obtained by harmonical excitation of the object with frequencies 950 Hz (b), 4024 Hz (c), and shock (d). Image size: 5x4 mm².

The quality of the phase maps is not as good as that obtained by using a rigid endoscope combined with an external holographic system. This is due to the fact that in the miniaturized prototype a color camera has been used and this is not well suited for the recording of digital holograms. Unfortunately it was not possible to find a B/W miniaturized camera with small dimensions. Furthermore, the acquisition speed of the camera was limited to 50 images/s.

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References:


Multi-Functional Encoding System for the Assessment of Movable Cultural Heritage (Multi-Encode)

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The protection of cultural heritage using speckle interferometry and holography sensors is the subject of the Multi-Encode Project. This topic is of great interest to museums and galleries. The principle is that interferometric signatures of artwork are collected, that can later be used to identify forged artwork or identify that recent damage has occurred.

ITo have developed a portable compact shearography prototype, see Fig 1, specifically for cultural heritage applications. The sensor is based on the out-of-plane displacement gradient sensitive shearography configuration and has a high degree of automation of peripheral devices and sensor components. For example the object loading is controlled and the experimental conditions are recorded automatically. In operation, for the user to assess the object defect locations, wrapped and unwrapped phase maps are displayed in real-time at 1 Hz, and a comprehensive data set is archived, including experimental conditions.

One aspect of the collection of interferometric signatures of artwork is the development of standardised loading conditions. Artwork objects have a complex structure. They are often constructed on an unstable base, e.g. a wooden panel or a stretched canvas, upon which a number of layers of dissimilar materials, e.g. gesso, oil paint, gold leaf, are added. The types of defect are many and varied and include cracks and delaminations of different sizes and additionally for panel paintings nail holes and surface scoring. In the standardisation of the measurement procedure, a range of defect types and sizes in a number of artwork samples, prepared by project partners at the National Gallery of Athens and Tate, London, were studied and the optimal loading conditions for defect location and identification for the different artwork types were established as the standard. The measurement sensitivity of the sensor was also determined.

Fig 2 shows an example from the measurement programme. This 19th century British landscape painting has undergone restoration and this included the affixing of a second canvas behind the original. Defects present in the central region can clearly be seen from the phase map.

Fig 1: The photograph of the shearography prototype shows the main components: tripod mounted sensor head, electronics controller, PC and the laser. The object under investigation is a canvas painting sample from the Tate Gallery, London.

Fig 2: Location of defects in a 19th century British landscape painting.

Current research is the study of artwork through artificial aging processes and the development of image processing techniques to compare interferometric signatures with those already stored in a database.

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References:

Time resolved digital holographic interferometry for the investigations of dynamic events

G. Pedrini, W. Osten

In order to measure dynamic events, high speed digital holographic interferometry was developed. In this technique the phase of a wavefront recorded at different times is calculated from the recorded intensity by use of a 2D digital Fourier-transform method. As we obtain the phase from a digital hologram, only one image hologram is needed for the phase to be determined at a given time. No temporal phase-shift methods are used. By unwrapping the phase in the temporal domain it is possible to get the displacement including the direction of motion of an object as a function of time.

Fig. 1 shows a sketch of the measuring system used for our investigations. Light from a laser is divided into a beam for illumination of the object and a reference beam. The object beam illuminates the object along a direction \( \mathbf{e}_o \). Some of the light is scattered by the object in the observation direction \( \mathbf{e}_o \) towards the detector, where a positive lens forms an image of the object on a CCD sensor. An image-plane hologram is formed on the CCD as a result of the interference between the reference beam and the object beam. The aperture serves to limit the spatial frequencies of the interference pattern. The reference beam diverges toward the detector system from a point located close to the aperture. The reference wave is carried by an optical fiber, which makes the arrangement more compact, as no additional beamsplitter is needed to recombine the object and reference waves.

![Fig. 1: Optical arrangement for high speed digital holographic interferometry](image)

The intensity is recorded on a two dimensional electronic device composed of an array of sensors and the information about the amplitude and phase of the object wave is obtained by spatial filtering using the Fourier transform method. By using a high power cw-laser and a high speed recording device, we are able to record a sequence of holograms and to determine from the intensity the phase difference between two successive wave fronts recording. In order to avoid a spatial phase unwrapping we require a phase difference that is smaller than \( \pi \) between two holograms. A phase map corresponding to the deformation of the sample between the beginning of the measurement \( t=0 \) and any other point in time can be calculated by summing the phase differences. This phase map can be used to determine the displacement observed along the direction of \( \mathbf{s} = \mathbf{e}_o - \mathbf{e}_i \), where \( \mathbf{e}_o \) and \( \mathbf{e}_i \) are the unit vectors of illumination and observation respectively. Fig. 2 shows a result obtained by using a metallic brass plate (63 mm x 70 mm x 0.5 mm) located 1400 mm from the imaging lens. The plate was clamped at one edge and excited by a small shaker at a frequency of 943 Hz. A sequence of interferograms has been acquired with an integration time for each interferogram of 30 \( \mu s \) and the vibration as a function of the time is calculated from the phases.

![Fig. 2: Plate vibrating at 943 Hz, (60 x 60 x 0.5 mm³). a-h) deformation of the plate as a function of the time.](image)

References


Wavefront reconstruction using sequential intensity measurements of a volume speckle field

G. Pedrini, P. Almoro, A. Anand, W. Osten

Phase retrieval methods have been utilized with the purpose of reconstructing amplitude and phase from intensity patterns only (in this case no reference is added to the wave front). We have shown that by recording a sequence of intensity patterns of the object at different planes and by application of iterative algorithms, it is possible to increase the quality of the reconstructed wavefronts. Fig. 1a) shows the experimental set-up for the recording of a volume speckle field.

![Fig. 1: Schematics of the phase retrieval methods: a) intensity measurements, and b) wave field reconstruction.](image)

When a coherent light source, such as a laser, illuminates the rough surface of an object it generates a volume speckle field. The intensities of the speckle patterns (I1, I2, ..., Ik) at equal-interval planes are sequentially measured using a CCD camera and stored in the computer. Fig. 1b) shows the diagram for the reconstruction of the test object wave field, represented by intensity I0 and phase φ0  located at the origin. The measured intensities are utilized to reconstruct the object wave field. The reconstruction process starts with the wave amplitude being obtained from the square root of the first intensity distribution measured at position d0. This amplitude is multiplied by the phase (initially a constant) and the resulting complex-valued function representing the wave field at that particular plane is propagated to the next plane. The propagation of the wave is done according to the Rayleigh-Sommerfeld equation. The process of multiplying the square root of the measured intensity distribution with the calculated phase at each plane followed by wave propagation is repeated until the quality of reconstructed image at the object plane changes by amounts that are smaller than a threshold. Increasing the number of intensity measurements will result in better approximation of the true phase. The calculated wavefront in the measurement planes should also exhibit numerical focusing when propagated back to the image space. The technique is a very promising wavefront reconstruction method because it offers a very simple setup and a straightforward procedure. Fig. 2 shows the experimental results for a diffusely transmitting object. The test object used is a transmitting mask with a ground glass diffuser attached to it in order to randomize the phase. After calculation of the wavefront (amplitude and phase) in the measurement planes, numerical focusing is obtained when propagated back to the image space.

![Fig. 2: Reconstructions of a diffusely transmitting object at 2 mm-interval reconstruction planes using multiple intensity measurements. The width of the whole object is 2 mm.](image)

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References

Compensation of the misalignment between master and sample in comparative digital holography

X. Schwab, G. Pedrini, W. Osten

Comparative digital holography (CDH) is a technique suitable for shape and deformation comparisons between master and sample objects with rough surfaces. The innovative aspect of CDH is the illumination of the sample by the conjugated wavefront of the master, as a type of coherent mask, using a liquid crystal display (LCD) (Fig. 1). The resulting interferogram indicates directly the shape or the deformation differences between the master and sample. As it is not necessary that both objects to be compared are located at the same place for this technique, remote shape or deformation comparison is possible. A current research topic is the precise alignment of the sample and the reconstructed master wavefront.

Here we present the experimental result of a shape difference measurement. As master object, we used a cone with a given surface microstructure and for the sample object, the same cone with a modified surface microstructure, but containing one defect at the point. In Fig. 2a, we see the illumination of the misaligned sample object with the reconstructed master wavefront. Due to the misalignment, additive fringes appear in the resulting interferogram (Fig. 2b). These fringes disturb slightly the evaluation of relatively large defects, however small defects are more sensitive to the fringe pattern due to misalignment, with the effect that small defects cannot be precisely located in position or size. In the presence of a misalignment, we lose the main advantage of the null test, the direct difference between master and sample. Therefore we have to compensate for this misalignment.

The compensation can be done by using the phase shifting properties of the LCD. By adding a phase factor to the original hologram, the sample object will be corrected illuminated (Fig. 3a) so that the defects are directly visible and quantifiable without the application of complex image post-processing (Fig. 3b). The phase factor is dependent on the misalignment compensation and this compensation can be done for all six degrees of freedom of the object.

Fig 1: Coherent illumination of the sample with the optical reconstructed wavefront of the master in CDH.

Fig 2: Shape comparison in CDH in the presence of a misalignment. a) Illumination of the misaligned sample object (shown by the circle) with the reconstructed master wavefront, by writing the original master phase hologram in the LCD. b) The corresponding shape difference between the master and sample objects.

Fig 3: Shape comparison in CDH. a) Correct illumination of the misaligned sample object (shown by the circle) with the reconstructed master wavefront, by writing the corrected master phase hologram to the LCD. b) The corresponding shape difference between the master and sample objects.

References:


Digital holographic microscopy in the deep UV (DUV)

F. Zhang, G. Pedrini, W. Osten

Digital holography is a well established technique which is frequently used for the investigation of microscopic objects. The method allows for the reconstruction of both the amplitude and the phase of a wavefront from the acquisition of a single hologram recorded by a CCD. Previously digital holographic microscopy was explored for applications in visible and infrared light.

The spatial resolution of the method is given by the numerical aperture and the wavelength. In order to increase the resolution we developed a microscope system based on digital holography working at the wavelength of 193 nm. Fig. 1 shows the optical arrangement. Basically, it is Mach-Zehnder interferometer configuration. Directly after the laser output aperture, a spatial filter is inserted to improve the poor beam quality and to reduce the beam intensity. Then the randomly polarized laser beam is converted to linear by polarizer Pol1, and is split by a polarized beamsplitter PBS1 into two beams. One is used as the reference and the other is for illumination. The illumination beam is further split by the beamsplitter BS and may in turn be used to illuminate the object from two opposite sides, thus allowing the investigation of reflecting and transmitting samples. PBS3 directs the reference beam into a delay line, where the optical path length of the reference arm can be matched to the path length of the object arm. Matching the optical path lengths is necessary because the coherence length of the laser is only of the order of 100 µm. PBS2, placed just in front of the CCD, directs the object beam and the reference beam to the CCD. Their common polarization components, selected by the second polarizer (POL2), interfere on the CCD.

A CCD camera with excellent UV sensitivity (PCO Sensicam em680 with quantum efficiency of 20% at 193 nm) is used to record the interference pattern. The recorded intensity is processed to get the amplitude and the phase of the wavefront at the object plane. It is well known that one may get an aberration free reconstruction only when the reference in reconstruction is exactly the same as the one used in the physical recording. Technically it was not possible to produce an ideal reference wave at 193 nm (e. g. spherical), for this reason we had to deal with a not well-defined wave. Therefore an algorithm was developed to determine the curvature of the reference. By knowing this we were able to get an aberration free reconstruction. Other reconstruction algorithms which are free from aberration and are suitable for high numerical aperture holograms are proposed and described in the references [1-4].

Fig. 1: Experimental setup for hologram recording.

Fig. 2 shows an example of a reconstructed amplitude and phase wavefront. The sample was an electronic circuit (Pentium I processor).

The setup was designed to be able to investigate both reflection and transmission samples [5]. Figure 3 shows the result of the investigation of a lenslet array.

Future work will focus on the combination of information obtained in reflection and transmission of a semi-transparent samples.

Fig. 2: Reconstructed wavefront from a digital hologram of a microcircuit illuminated in reflection. Amplitude (a) and phase (b) are represented. The field of view is 300 x 300 µm².
**Fig. 3:** Investigation of a lenslet array. Object intensity (a); phase map (b) and pseudo 3D representation (c) of the transmitted wave front; phase map (d) and pseudo 3D representation (e) of the reflected wave front; reflected and transmitted wavefront along two lines (f).

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**References:**


**Modified convolution reconstruction algorithm**

**for high numerical aperture holograms**

F. Zhang, G. Pedrini, and W. Osten

In the reconstruction of digital holograms recorded at a very short object to sensor distance, one has to evaluate the Rayleigh-Sommerfeld integral without any approximation. The three commonly used fast algorithms, i.e., Fresnel algorithm, angular spectrum algorithm (AS), and convolution algorithm (CV), have their respective drawbacks and can not be applied directly. The Fresnel algorithm is limited to Fresnel holograms due to its involved approximation. Although the AS and CV algorithms do not make any approximations of the diffraction integral in its analytical form, their conventional implementation gives a samplings only on a computation grid with the same spacing as the sensor pitch. For holograms recorded of high numeral aperture (NA), such a computation grid is too coarse to present the object precisely, i.e., the sampling interval is too larger than the physical resolution.

To overcome this drawback, the CV algorithm is modified by redefining the reconstruction co-ordinate system. Two shift parameters, accounting for the relative displacement of object coordinate and the hologram coordinate, are introduced in the discretized diffraction kernel. Combination of the results for different shift values gives object sampling on any computation grid. Compared with other methods that are mostly based on interpolation, this method is free from artifacts. We also proved that the modified CV algorithm is capable of achieving aberration free reconstruction for various recording numerical apertures if the object extension is finite. Notice that no requirement on the bandwidth of object is imposed and the object can be arbitrarily rough.

Results obtained from experimental data are shown in Fig. 2. The object consists of a set of black spots. The blur caused by spherical aberration in Fresnel algorithm can be easily seen in (a), as indicated by a white box; but it is less noticeable in the reconstruction by the modified CV method (b). The recording numerical aperture for the holograms used is only about 0.2. Further work is to record a hologram with a higher NA and to show the improvement quantitatively.

![Fig. 2: Comparison of the reconstruction with (a) the Fresnel algorithm (b) the modified convolution algorithm.](image)

**Fig. 1:** Reconstruction of a simulated four-point object by (a) Fresnel algorithm and (b) the modified CV algorithm.

**References:**

Phase retrieval using a movable phase mask

F. Zhang, G. Pedrini, and W. Osten

The existing phase retrieval algorithms have been demonstrated successfully in many applications, but mainly for phase only or amplitude only objects. Although the phase retrieval of complex-valued fields is of general interest in many fields, it still remains a difficult problem. In this work, we proposed a new idea to solve the problem by using a mask.

Fig. 1 illustrates the experimental arrangement. An extended object, which can be of transmissive or reflective type, is illuminated by coherent light. A pixelated phase mask, mounted on a linear stage, is positioned in the path between the object and the sensor (CCD: charge coupled device). The phase of the plate distributes uniformly between 0 to 2π and is known. The transmissive area of the mask is limited by an aperture to ensure the resultant diffraction pattern is resolvable by the CCD. Four or more diffraction patterns are collected as the mask shifts by a multiple of its pixel size. The complex amplitude immediately before the mask is retrieved using an iterative algorithm. At each iteration, the modulus of the calculated complex amplitude on the CCD plane is replaced by the square root of recorded intensity, while the modulation introduced by the mask is updated to that of the next mask position. The iteration loop starts from a random guess of the complex amplitude before the mask and ends when the difference in amplitude between two successive retrieved estimates is less than a given value. Further propagation of the retrieved wavefront from the mask to the object gives the original object field. Simulations show that this approach works even for the most difficult object field – random amplitude plus random phase. The convergence is also fast, good reconstruction can be obtained within 30, 50, 110, or 1840 iterations when 6, 5, 4, or 3 recordings are to be used.

Fig. 2 and 3 show the experimental results. The light source was a He-Ne laser with a wavelength of 632.8 nm. The camera, a Tel-C83910, had 1300 x 1030 pixels with a pixel size of 6.7 µm. The bit-depth was 8. In fig. 2(a–b), the object was a resolution target illuminated by a spherical wave. In fig. 3, the mask was simply illuminated with a spherical wave that was modified by a singlet lens. As is shown, the reconstruction quality is comparable to holography. With this technique no aberration compensation is required.

This technique has a very simple set-up and is robust to external disturbance and sensor noise. It is also suitable for various wavelengths. Therefore, we believe that the technique would find many practical applications in phase contrast imaging, wavefront sensing and metrology.

Fig. 1: Experimental arrangement.

Fig. 2: Experimental results: Retrieved (a) amplitude and (b) phase of a resolution target illuminated with a spherical wave (after 80 iterations and using 5 recordings).

Fig. 3: Retrieved phase on the mask after 140 iterations using 4 recordings.

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References: