Holographic metrology: some examples of imaging in medicine and non-destructive inspection

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Abstract: A pulsed ruby laser was used in an unstable environment to overcome the high stability requirements when a hologram is recorded. The images were recorded for the purpose of measurement applied to non-destructive inspection (NDI) and medical applications. High-resolution photographic film or plates coupled with wet processing was employed as the recording material, but other recording materials are considered. The paper also explores the potential of electronic and digitized processes currently being developed.

Keywords: holography, hologrammetry, interferometry, NDI, optical metrology

1 INTRODUCTION

This paper describes previously unpublished work showing holographic images recorded with a pulsed laser, the use of which overcomes the stability problems associated with continuous wave (CW) lasers. The images were recorded for the purpose of measurement, using conventional holographic methods with photographic film or plates, i.e. coupled with wet processing. It also briefly explores the potential of electronic and digitized processes currently being developed, which the author believes will result in a renaissance of this technology.

The holographic process records the wavefront of light emanating from an object illuminated by a coherent source of light such as a laser. When the processed hologram is placed in a similar coherent light source the wave front is reconstructed, revealing an image of the original object with all dimensions present, and parallax limited only by the size of the window set by the dimensions of the recording material.[1] In the illustrations that will be discussed, the objects are undergoing stress in a cyclic or pulsating manner, such as to cause out-of-plane motion of the surface in order to reveal subsurface anomalies. Firing the laser Q-switched[2] twice during the cycle causes the laser to emit two separate pulses of light synchronized to the object cycle, thus making two holographic records superimposed on a single recording material. Ideally, the first record is obtained when the object is passing through what would be its normal or unstressed position, and the second at some subsequent point of out-of-plane displacement; thus the two superimposed images are identical except where some motion occurred during the interval between the laser pulses. These two images remain superimposed at the reconstruction stage Any out-of-plane motion within the object is seen as a phase shift that generates secondary interference fringes on the reconstructed image, thus forming a contour map of the surface displacement motion; each fringe separation being equal to 0.5 wavelength (λ) of the laser light, in the examples in this paper $\lambda/2=0$ 3.5 µm ($\lambda=694$ nm for ruby). The actual laser pulse separation time, usually a few tens of microseconds, is selected to permit the object sufficient out-of-plane movement to optimize the fringe density in the final record.

Two entirely different applications are reported here, but both employ the common holographic interferometric technique. One example uses the technology to aid neurosurgery, while the other is

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the non-destructive inspection (NDI) of aircraft fuselages for subsurface structural defects.

For the work discussed in this paper, a specially designed and constructed holographic camera including a beam compensation path of one metre was used. It incorporated a pulsed ruby laser into its housing, thus making the entire system portable and able to be used remotely from the laboratory.[3] The laser had a Q-switched output pulse duration of ~25 ns (λ=694.3 nm), and a maximum output power of ~0.75 J, the actual laser output level being adjustable for any specific application. The two Q-switched pulses were extracted from a single excitation of the ruby crystal. The interpulse delay could be varied between 10 and 1000 μs. Both the vibration cycle of the object and the laser pulses were separately recorded on an oscilloscope. On the occasions this system was used in conditions of normal room lighting or daylight, a fast-acting electrically operated shutter, synchronized to the triggering of the laser was placed in front of the recording hologram together with a narrow bandwidth colour filter selected to transmit freely at the ruby laser wavelength, thus minimizing the fogging effect of ambient light on the holographic material. An existing stock of Agfa 8E75 holographic material was used to record the holograms. However, this material is no longer manufactured. Admittedly, materials sensitive to red light are available, but either the emulsion speed is very low as compared with 8E75 or 10E75, particularly when used with the extremely short pulse width (~25 ns) generated by the pulsed ruby laser, or the spectral sensitivity does not extend to the far red of the ruby wavelength. In consequence, for such interferometric applications it is now more general to use a NDYAG laser with a frequency doubled output generating a green light at λ=532 nm; at this wavelength a recording material called Millimask is currently available; this is the same emulsion as Agfa 8E56 holographic film that is no longer available. However, technology has moved on and non-silver-based photo recording systems such as electrostatic or photo refractive materials have been developed[4] suitable for use with the far-red emission of the ruby and having somewhat similar sensitivity to 8E75.

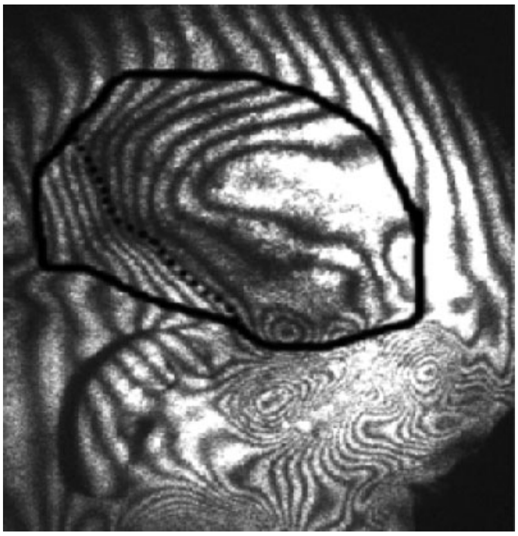
2 HOLOGRAPHIC METROLOGY IN NEUROSURGERY

Holographic interferometry applied to medicine has most often been applied to rigid structures such as prosthetic appliances and bone, including cadaveric human skulls[5,6] with CW lasers which, as discussed above, when used to record holograms have associated stability requirements that would certainly preclude the recording of living tissue. The availability of a pulse laser, which has output duration of a few nanoseconds, thus overcoming the inherent environmental or object stability problem, gave the opportunity to work with living tissue. The recording technique adopted was largely that described for the NDI engineering situation. However, there were other problems in applying this technique to living subjects, i.e. ensuring patient safety with regard to the laser hazard issues and producing the necessary out-of-plane motion in the living tissue. The paper makes an objective assessment of the accuracy of this method in describing the geometry when the technology is applied to the measurement of cranial defects.

The current report departs from earlier holographic work[7] with cadavers by using the cerebral pulsations in conscious persons as the displacement method. Five patients with cranial vault defects underwent holographic interferometric imaging. Four patients had the status of post-missile (bullet) wounds to the head, with the initial event on average four months earlier, and one patient developed a post-operative infection following tumour removal. The interest here is the area of cranial bone loss that might be measured in preparation for a surgical implant. The scalp overlying the regions of bony loss moves in response to the cerebral pulsations between the two firings of the laser. The area of the scalp above the intact cranium experiences relatively no displacement due to the damping effect of the underlying bone. One important advantage of this application of holographic imaging is that the need for X ray examination is avoided.

All patients were anticipating cranioplastic procedures to re-establish normal cranium contour and shielding. The widest dimension of the area of bone loss ranged from 2.2 cm to 7.5 cm, as calculated from the holographic records. All patients were presumed to have normal intracranial pressure at the time of imaging.

The patients were positioned approximately 50 cm from the holographic camera to provide an optimal view of the area with bony loss. Standard ECG electrodes were placed on the patient's head, producing a signal from the complex of the cardiac cycle. This was amplified and used to trigger the circuit for



1 Tumour had caused cranial damage. Displacement was low within the region of interest, but abrupt change in fringes pattern where defect is located was sufficient to plot cranial bone loss with high accuracy

the firing of the laser. An adjustable delay generator was used to optimize synchronization to the cardiac cycle of the individual patient. A further delay generator was added to control the delay between the first and second laser pulses and general set to ~350 μs.

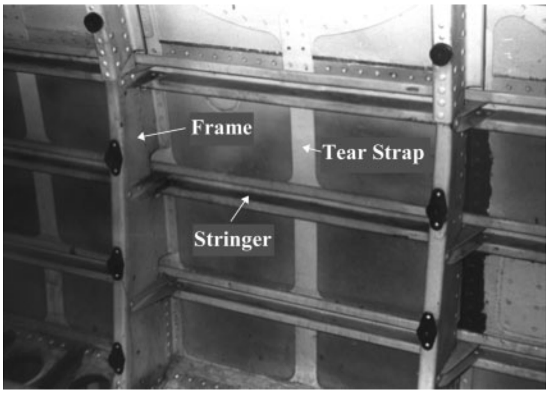
Subsequent to processing, the reconstructed holographic images were captured using a high resolution Megaplus camera (Kodak Rochester, MA) and a frame grabber (Univision Technologies Inc. (UPX-2600AT), Burlington WA.). Subsequent image processing was performed on the Tag Image File (TIF) format graphic files using the Bioscan Optimas (Bothwell Inc., WA) software package, which includes built-in measurement routines. In the example illustrated in Fig. 1, there are spurious fringes (probably due to whole head motion by the patient), but the region of bony loss remains clearly delineated. Three different operators calibrated linear measurements. Then the outline of the interferogram was manually traced on the computer screen. Bioscan then calculated all relevant measurement values, including circumference, major and minor axis, area, etc. The data obtained from evaluating the holographic interferogram was compared with the actual defect during surgery and found to coincide very closely. The full analysis and medical discussion of these results is to be found elsewhere.[8,9] Note that in Fig. 1 there are other fringe patterns around the facial area caused by pulsating blood vessels in fleshier regions.

2 Circular fringe pattern clearly illustrates region of calvarial loss caused by bullet wound

Figure 2, which was a bullet wound, shows an area of rather less bone loss than in the patient in Fig. 1. The fringe pattern is denser and more obvious in the region of interest. It was easily plotted with a high degree of accuracy on the Bioscan package.

3 HOLOGRAPHIC NDI: AIRCRAFT

Most passenger and freight aircraft fuselages are pressurized on the occasion of each flight. Passengers actually fly in what is essentially a tube pressurized for their comfort at an equivalent altitude of about eight thousand feet. The pressure difference between the interior of the aircraft and outside atmosphere when flying at normal operating height is great; consequently so is the stress exerted on the structure of the aircraft. Each takeoff and landing represents a pressure cycle causing an associated expansion and contraction of the panels equal to several thickness of the aircraft skin. This in turn generates mechanical strain not only on the skin but also on the entire structure, including the underlying framework to which the skin is fastened. Such strain can cause cracking of frames/stringers or the detachment of the skin from fasteners. In addition, there is the problem of corrosion that may occur along rivet fastener lines, possibly causing detachment of the tear straps or defects in bonded joints as well as metal thinning. To effect normal inspection, which usually occurs about every four years, it is necessary to strip the entire



3 Interior of aircraft fuselage showing semi-monocoque design. Stringers, tear straps and e-frame structure to which skin is fastened are illustrated

fittings from the aircraft interior to carry out visual inspection and also apply various NDI systems requiring local physical contact with the region being inspected. Many of these existing systems are based on eddy current or acoustic probing. It is a manual task and very much dependent upon the judgement and skill of the inspector.

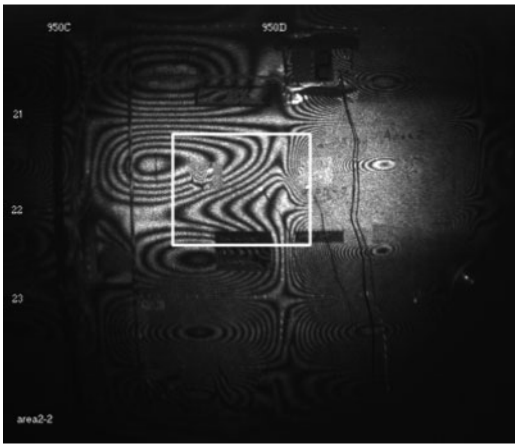
At the invitation of Boeing Aircraft Corporation and as part of their ongoing test programme, we participated in a particular experiment at the time the fuselage of a 737 aircraft was being tested to destruction. The objective was to discover whether holographic interferometry could detect a fractured frame within the main body of the aircraft by looking only at the external surface of the aircraft skin. Modern fuselage design is semi-monocoque, with a structure of frames circumferential to the body and stringers running the length. It is to this subsurface structure that the skin is fastened. Figure 3 illustrates the typical internal frame and stringers construction of an aircraft fuselage.

Applied to NDI in industry, holography interferometry can be used both to map nodal patterns of vibrating objects and, as shown in this paper, to detect subsurface defects such as structural damage in pressurized fuselages of aircraft where vibration (excitation) was artificially introduced in the region of the fuselage being inspected by a 1500 W variable frequency vibrator transducer unit attached to the skin of the aircraft and operated at one of the resonant frequencies of the aluminium skin. The rather complex method of selecting the optimum frequency has been described elsewhere,[3,10] but is accomplished by analysing the output from a array of accelerometers attached to the aircraft skin in the region to be inspected. Synchronization is achieved by using the output from the accelerometer situated on an antinode

It is essential to ensure that the actual modal shapes and their phase are optimized before recording the hologram. For example, to detect a frame fracture, the likelihood is that the crack will have propagated inwards from a point where the skin is attached to the frame, progressing towards the centre of the aircraft. By selecting a frequency that ensures antinodes of the same phase relationship are located either side of the frame to be inspected the crack (if present) is pulled open as the antinode moves out of plane in the direction of the holographic camera, which is located on the exterior of the aircraft, similarly a loose fastener or debonded joint is detected in the same way. The presence of the frame ensures that this modal pattern and phase can be achieved. Such an example is illustrated in Fig. 5 The problem is that adjacent antinodes (unless separated by a structure such as a frame or stringer) in such a structure normally are of opposite phase therefore, to inspect a particular region of the aircraft, two holograms have to be recorded where the antinode phase is reversed. This is simply accomplished by an additional delay, equal to half the excitation frequency, in the firing the laser. The condition required is achieved by the use of an array of accelerometers and a small computer program to analyse the received accelerometer data. Synchronization is accomplished by triggering of one of the accelerometers via a suitable delay unit.

A second method of inspecting the actual phase of the antinodes was devised and accomplished by causing one of the reference beam mirrors to rotate by a fraction of a degree ($>1^\circ$) between the two pulses generated by the laser; thus causing the reference beam to scan the hologram. At the reconstruction stage, if the eyes are moved along the hologram in the direction of the scanning reference beam used in the recording, the interference fringes contouring the antinode are seen to expand if the antinode is moving away from the aircraft, or contracting if the antinode motion is opposite.

The complete holographic procedure adopted was that described in previous papers.[3,4] The region of interest was excited to the pre-selected resonant frequency and a double pulse holographic interferogram was recorded as described above. The results are illustrated in Figs. 4 and 5. Figure 4 is a record



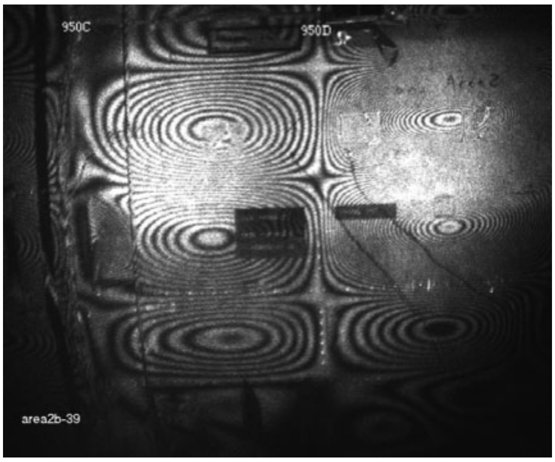
4 Fringe pattern shows deviation from normal and highlights region of damage to frame

with the damage present before repair was effected. The region where deviation of the fringe pattern from what would be the normal symmetrical pattern is highlighted but is also obvious because it crosses the region where the frame should securely restrain the skin; the damaged frame is being mobilized by the vibrating skin. Normally, the regions of the frame and stringer would be clear of fringes because the skin is held rigid. This is shown in Fig. 5, which was taken after the repair of the fractured frame; the frame and stringer lines are now seen to be fringe free.

Techniques such as this do have real economic and safety potential in various branches of industry. They offer a very efficient method of subsurface inspection of components and other materials based on the fact that surface vibration patterns have a direct relationship to subsurface structures.[10]

4 DISCUSSION: FUTURE OF HOLOGRAPHIC METROLOGY

With the cessation of the production of Agfa holographic recording materials, particularly the far-red sensitive emulsions suitable for ruby lasers, difficulties were foreseen for the future of pulsed holography, particularly using the ruby laser. As discussed earlier, other recording materials, plates and films are now available in both the red and green regions of the spectrum. However, both conventional photography and holographic recording are inexorably moving towards digital processes, and much can be achieved using this technique that could satisfy the present requirement of holographic interferometry. But also much remains to be accomplished before digital results compare in recording quality to those which can be achieve by conventional means, particularly for high-resolution, display or art holography.



5 After repair. Antinodes are restricted to unsupported region of skin panels. Structure lines of frames and stringers are relatively fringe free

Digital holograms can be reconstructed numerically or by optical techniques.[11] To improve the quality of optical reconstruction existing tools such as digital mirror devices (DMD) have to be improved in order to control the amplitude as well as the phase of the reconstruction wave front. A larger number of sensor elements in the electronic camera leads to larger holograms and therefore to very high data storage requirements. These very high requirements can be reduced by compression of information, but in order to ensure loss-free compression and reconstruction, algorithms have to be developed and used that are adapted to digital holography.

Interferometry is perhaps the classic application of holographic metrology and has regained considerable interest over the last few years with the appearance of fast, high-resolution, *in situ* recordable and erasable media such as photorefractive materials. However, with regard to the advancement of digitizing technologies, the area of application becomes much broader as digitizing technology improves, but the resolution limitations of the present recording systems restrict it to simple optical geometry holography.[12] In addition to the type of applications discussed above, applying techniques such as holographic metrology and speckle interferometry to the restoration and preservation of ancient artefacts, as well as providing enhanced knowledge of object dimensions, structure and condition, can also help to improve methods of restoration and preservation.

Artworks and historical monuments are subject to risk of damage and deterioration due to environmental influence, disasters and human activity. Holographic metrology and other laser-based techniques such as shearography and speckle have been used in the past and, with the evolution of new technologies, has the opportunity for further contribution. Besides the well-known applications of these optical techniques, further applications could include the storage of full information and continuous monitoring of priceless cultural heritage objects (which is an important and pressing social task), computerized, portable, multi-functional phase-stepping interferometer that could be applied to continuous monitoring, measurements and remote non-destructive testing of historical monuments for conservation, restoration and preservation. Interferometry can also be applied for lifetime prediction, early diagnosis and prediction of sudden (catastrophic) failures. Recorded as digital images, this information can be readily computerized for storage or rapid transmission of information and analysis in near real time.

The probability is that funding will not be made available directly for the improvement of digital recording systems for holographic purposes, particularly for the preservation of art, but rapid progress is being made in digitizing equipment for commercial and military applications, and that is finding its way into holography by what is often termed 'spin off'. Some forward-looking research establishments have recently been developing remotely operated underwater holography using both conventional recording materials with pulsed lasers and advanced techniques employing diode lasers with digitized recording of the hologram. This offers the potential of remote operation and recovery of the digitized images.[13]

In conclusion, holographic recording techniques and other laser-based systems, together with advances in data compression, give a future expectation of compact, convenient and rapid application of recording systems that can produce data together with virtually instantaneous on-line images that can be remotely interrogated and analysed or rapidly transmitted for remote analysis.

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