Real-Time Holography

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ABSTRACT

As part of our coherent optics course for senior level undergraduates, our students complete a laboratory in which they are trained in laser safety and set up a complete holographic system. The students perform all phases of the setup from aligning pinholes for spatial filters to ensuring the correct illumination levels for plate exposure. The students are then required to investigate some aspect of holography. The topic may be of their own choosing or can be selected from a list a topics provided by the instructor. In this paper we will describe the contribution of various student groups to the analysis of vibrating objects with or without static deformation using real-time holography. Three years ago we started this project by asking two very simple questions; first, "why are there twice as many fringes in time-average holography?"; and second, "can the fringe contrast for real-time holography be enhanced?" In the course of this research, we "discovered" quite a few things which were already well known, and a few things that are not. But in the course of this work, all of the authors, faculty and students, enhanced our understanding of holography and its applications.

Keywords: Real-Time, Time-Average, Holography, Phase Stepping, Vibration, Education

2. INTRODUCTION

GMI Engineering and Management Institute (GMI-EMI) is a fully accredited, private college offering Bachelors Degree Programs in Electrical Engineering, Industrial Engineering, Mechanical Engineering, Manufacturing Systems Engineering, Management, Applied Physics, Computer Engineering, Environmental Chemistry and Applied Mathematics. Approximately 2500 undergraduates are enrolled in a five year program of alternating 12 week periods of classroom studies and paid work experiences at one of over 500 corporate affiliates. Minors are offered in several areas including Applied Optics.

Coherent Optics and the accompanying laboratory introduce students to laser applications including laser scanners, alignment techniques, optical triangulation, interferometry, heterodyning, holography, holographic interferometry, Fourier optics, optical data processing, speckle photography and speckle interferometry. In the laboratory, the students receive instruction in laser safety, radiation measurements, holography and Fourier optics. The students have access to two optical tables, a 50 mW Helium Neon laser, an Argon laser, Newport thermoplastic holographic camera, computer vision system, and a wide variety of optical components. A sketch of the holographic system is shown in figure 1. Thermoplastic plates are used as the recording media. Thermoplastic plates have a number of advantages over photographic plates for real-time holographic interferometry. The plates can be developed in situ quickly, and bias fringes due to expansion or shrinking of the emulsion are not present. The students are responsible for all aspects of their project including experimental design and setup, data acquisition, data analysis, and reporting. Each student team is required to submit a formal report and to deliver a 15 minute presentation to which all interested faculty and students are invited to attend.

3. HOLOGRAPHIC INTERFEROMETRY

A standard technique used when analyzing vibrating objects is to first use real-time holographic interferometry to determine a resonant frequency of an object. This technique produces low contrast fringes which are difficult to observe. The contrast of these fringes will usually change with time due to instability in the holographic

0-8194-1884-6/95/$6.00

system and/or static object deformation. To obtain high contrast fringes once a resonance has been located, a time-average hologram is produced. If this two step process is repeated for each resonant frequency of an object, it can be very time consuming.

On a thermoplastic plate the interference pattern is recorded as thickness variations. That is, a phase hologram is produced. The complex amplitude vectors of the object and reference beams are $\mathbf{U}_o$ and $\mathbf{U}_R$, respectively. All beams are polarized in the vertical direction. When played back with the reference beam, the complex amplitude U_3 of the light producing the holographic image being observed is

$$\mathbf{U}_3 = -j C \mathbf{U}_o \tag{1}$$

The multiplicative constant C is proportional to the irradiance of the reference beam and -j represents a $-\pi/2$ phase shift of $\mathbf{U}_3$ relative to $\mathbf{U}_o$[1].

3.1 Time-Average Holography

Using equation (1) and assuming C=1, the irradiance I of the play back light for a phase hologram used for double exposure holographic interferometry can be shown to be

$$\mathbf{I} = 4\mathbf{I}_o \cos^2(\Delta\theta/2) \tag{2}$$

where $\Delta\theta$ is the phase shift between exposures and $\mathbf{I}_o$ is the irradiance of the object beam. Figure 2 is a sketch of the holographic system geometry and its coordinate system. A phase shift due to object deformation can be found by using

$$\Delta\theta = \Delta\mathbf{k}\cdot\Delta\mathbf{d} \tag{3}$$

where $\Delta\mathbf{d}$ is the displacement vector of point P on the object and $\Delta\mathbf{k}$ is the sensitivity vector[2]. The sensitivity vector $\Delta\mathbf{k}$ is equal to the propagation constant vector difference ($\mathbf{k}_1$ - $\mathbf{k}_2$). The propagation constant vectors $\mathbf{k}_1$ and $\mathbf{k}_2$ represent the light illuminating point P on the object and light scattered to point Q on the hologram. The playback light due to a hologram used for time-average holographic interferometry can be shown to be

$$\mathbf{I} = \mathbf{I}_o J_o^2(\alpha) \tag{4}$$

where $J_o(\alpha)$ is a Bessel function of the first kind of the first order. The function $J_o^2(\alpha)$ varies between zero and some maximum ensuring excellent fringe contrast. For a point on the object vibrating with simple harmonic motion in a direction parallel to the z axis

$$\alpha = (\Delta\mathbf{k}\cdot\hat{\mathbf{k}})A \tag{5}$$

where A is the vibrational amplitude.

3.2 Real-Time Holography

The equations necessary to evaluate vibrating objects with real-time holographic interferometry can also be derived starting from equation (1). Setting C=1, the complex amplitude vector representing the holographic image is

$$\mathbf{U}_3 = -j\,\hat{\mathbf{i}}\ \mathrm{R}\ \mathbf{U}_o\ e^{j\Delta\beta}, \tag{6}$$

and the complex amplitude vector representing the object beam is

$$\mathbf{U}'_o = \hat{\mathbf{i}}\ \mathrm{R}\ \mathbf{U}_o\ e^{j(\Delta\phi\ +\ \psi)}. \tag{7}$$

The phase shifts $\Delta\phi$, $\Delta\psi$, and $\Delta\beta$ are due to object vibration, static deformation of the object, and phase variations introduced in the reference beam, respectively. The ratio of the object beam to playback beam complex amplitudes is R. The resultant complex amplitude vector due to the interfering object and playback is

$$U = \hat{i} \ U_o \ [\ -je^{j\Delta\beta} + R \ e^{j(\Delta\phi + \Delta\psi)}]. \tag{8}$$

The irradiance I of the light can be shown to be

$$\begin{aligned} I = I_o \ [\ 1 + R^2 - 2R \sin(\Delta\phi + \Delta\psi - \Delta\beta) = \\ I_o \ [\ 1 + R^2 - 2R \sin(\Delta\psi - \Delta\beta) \cos(\Delta\phi) - 2R \cos(\Delta\psi - \Delta\beta) \sin(\Delta\phi)]. \end{aligned} \tag{9}$$

For integration times which are long compared to the vibrational period of the object under test,

$$<\cos(\Delta\phi)> = J_o(\alpha), \text{ and } <\sin(\Delta\phi)> = 0. \tag{10}$$

Yielding,

$$I = I_o \ [\ 1 + R^2 - 2R \sin(\Delta\psi - \Delta\beta) \ J_o(\alpha)]. \tag{11}$$

Fringes described by this equation have maximum contrast if $\sin(\Delta\psi - \Delta\beta) = \pm 1$ and R=1. Two problems exist. One is that $\Delta\psi$, the phase shift due to static deformation, is not constant for the entire image. That is static deformation fringes are present which interfere with the fringes due to vibration. The contrast can also drift due to thermal variations which alter the reference phase $\Delta\beta$. A second problem is that even if $\sin(\Delta\psi - \Delta\beta) = \pm 1$, the fringe contrast is still low when compared to time-average holograms due to the DC bias term $(1 + R^2)$.

4. STUDENT RESEARCH

4.1 Introduction

In this section the student's contribution to our understanding of real-time holography will be discussed. In the 1991 Fall semester, Ed Barshaw and Ben Lewis were able to design an experiment in which they used real-time holography to measure the vibrational amplitude of a circular diaphragm vibrating in its fundamental mode. Their work verified existing theoretical development, and established the basic groundwork for future investigations.

4.2 Fringe Doubling

In the 1992 Fall semester, Pat Auth, Quinten Geyer, and Cindy Newmeyer investigated the fringe doubling seen in time-average holography. With some guidance, they hypothesized that the fringe doubling occurs since in time-average holography the object spends most of its time maximally displaced from equilibrium. Therefore, the peak to peak displacement is being measured. On the other hand, in real-time holography, the first exposure of the hologram is taken with the object at rest. When the object is vibrating it again spends most of its time displaced maximally toward or away from the hologram. However, since real-time holography records the magnitude of the displacement and **not the direction**, the displacement is recorded with respect to the equilibrium position - exactly half of the peak to peak displacement. This is illustrated in figure 3.

To test this hypothesis, the students first obtained a real-time hologram of a circular diaphragm vibrating in its fundamental mode. They used the computer vision system to store and display this image, switched off the vibration, and then they used a micrometer to displace the center of the diaphragm until the number of fringes observed was exactly the same as the number seen when the diaphragm was vibrating. In effect, they forced a static displacement equal to the maximum displacement of the vibrating diaphragm. They then erased the hologram, exposed it again, backed the micrometer off, and reestablished fundamental mode resonance. The number of interference fringes observed in the resulting real-time hologram was exactly twice the number originally observed since the total peak to peak displacement was now being recorded.

4.3 Physical Contrast Enhancement

Equation (11) shows that the interference fringe contrast in a real-time hologram will vary from zero to some maximum value as the difference between the reference and object beam path lengths change. Therefore, the contrast in real-time holograms can drift due to thermal instabilities in the optical set-up. In his undergraduate thesis, Mark Lott interfaced a home-built, piezoelectric mirror placed in the reference beam path, to a high voltage amplifier and digital to analog converter. Using a computer vision system, he then designed a control algorithm which changed the mirror position to keep a user specified, stationary area on the object light or dark, thereby forcing maximum interference fringe contrast. He was able to demonstrate that the system efficiently removed much the instability initially present.

In the 1994 Summer semester, Jason Butler and Rob DeWys investigated a variety of ways in which the interference fringe contrast in real-time holography could be further enhanced. They investigated the use of polarizers, object to reference beam intensity ratios during exposure and playback, the effect of varying coherence length, and the effect of removing stray reflections from background objects. They found that polarizers and a dark background behind the object improved the interference fringe contrast slightly. They found that as long as the difference between the object and reference beam path lengths was within the coherence length of the laser used, path length variations had little effect other than those discussed in the previous section. They also found that the optimum object to reference beam intensity ratio was 11:1 on exposure and 1:1 on playback.

4.4 Software Contrast Enhancement

In the Fall of 1994 semester John Sundeen and Matt Wavra investigated two phase stepping techniques[3,4]. The first is applicable if static deformation is not present. In this technique a real-time image is stored electronically, the piezoelectric mirror in the reference beam is used to introduce a 180° phase shift, and then a second image is stored. The two images are then subtracted to yield an enhanced image.
Starting from equation (11), if the piezoelectric mirror in the reference beam path is adjusted so that a stationary region on the object is bright then $\sin(\Delta\psi - \Delta\beta) = -1$ and if the stationary region is dark then $\sin(\Delta\psi - \Delta\beta) = +1$. Taking the difference of the two stored images yields

$$|I_1 - I_2| = 4RI_o|J_o(\alpha)|, \tag{12}$$

thereby removing the DC bias term in equation (11) and greatly improving fringe contrast. Figure 4a shows a real-time hologram for the circular diaphragm vibrating in its fundamental mode, and figure 4b shows the enhancement obtained by this image subtraction technique. Vibrational fringes are enhanced; however, a static deformation fringe does obscure these fringes on the right hand side of the image.

The second technique enhances the interference fringe contrast and allows the effects of static and vibrational deformation on an object to be separately resolved and analyzed[5]. In this technique, four separate images are stored at phase shifts of 0 , 90 , 180 , and 270 . The phase shifts can be accurately generated by carefully calibrating the piezoelectric mirror, and by monitoring the average intensity of a static point on the object. The data in these images were processed to generate Fourier coefficients a_o, a_1, and b_1 which were then used to produce two separate images. Specifically, for phase holograms

$$a_o = \frac{1}{N}\sum_{i=1}^{N} I_i = |I_o|(\,1 + R^2),\quad a_1 = \frac{1}{N}\sum_{i=1}^{N} I_i\cos(\Delta\beta_i) = -2R|I_o|\,\sin(\Delta\psi)\,J_o(\alpha),$$

$$\text{and } b_1 = \frac{1}{N}\sum_{i=1}^{N} I_i\sin(\Delta\beta_i) = -2R|I_o|\,\cos(\Delta\psi)\,J_o(\alpha) \tag{13}$$

where $\Delta\beta_i = \frac{2\pi i}{N}$. As indicated above, we used N=4. The enhanced fringe pattern can be obtained using the following:

$$I'(x,y) = \frac{\sqrt{a_1{}^2 + b_1{}^2}}{a_o} = |J_o(\alpha)| \frac{2R}{1 + R^2} \; . \tag{14}$$

This technique eliminates fringes due to static deformation. The contrast term $2R/(1 + R^2)$ has a maximum value when $R = 1$. The phase shift $\Delta\psi$ due to static deformation can be obtained using

$$\Delta\psi = \tan^{-1} \frac{a_1}{b_1} \; . \tag{15}$$

One of these images contains fringes which are related entirely to the vibrational displacement of the object, and the other image contains fringes which are related to the static displacement of the object. Figure 5a shows a real time hologram of the vibrating diaphragm which had been purposefully tilted in at the top to introduce a large static deformation. Notice that the combination of static and vibrational interference fringes is very difficult to resolve. Figure 5b shows the processed image corresponding to vibrational displacement, and figure 5c shows the processed image corresponding to the static deformation. Note that the effect of static deformation is separated out and high contrast fringes result which can be easily analyzed to extract topological information.

5. CONCLUSION

GMI-EMI students taking the Applied Optics minor have been involved in an on-going investigation of real-time holography. Each student group has contributed to the advancement of this research, and each group has been exposed to the challenges of experimental design and the intricacies of an advanced optical system. By involving undergraduates in this research, their educational experience has been enhanced, the research progressed (if slowly) in an institute primarily known for undergraduate education, the faculty and students progressed along a path of learning, and excellent results were obtained.

6. ACKNOWLEDGMENTS

The authors would like to thank Newport Corporation for their generous equipment donation. A special thanks to GMI students Pat Auth, Ed Barshaw, Jason Butler, Rob DeWys, Quinten Geyer, Ben Lewis, Cindy Newmeyer, John Sundeen and Matt Wavra whose laboratory research projects are the focus of this paper.

7. REFERENCES

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8. FIGURES

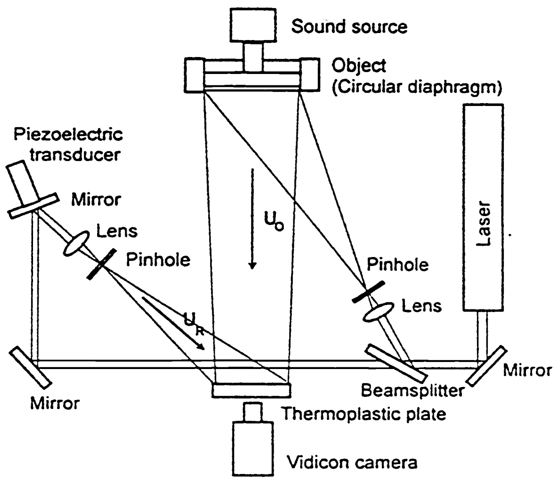


Figure 1. Holography System

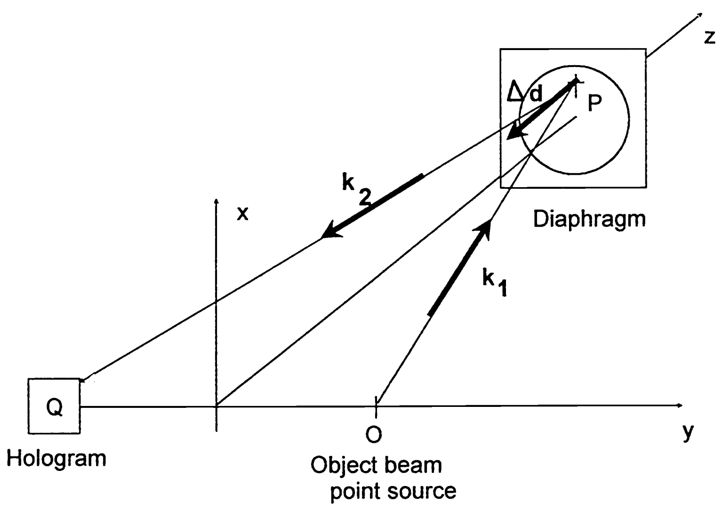


Figure 2. Geometry and Coordiante System

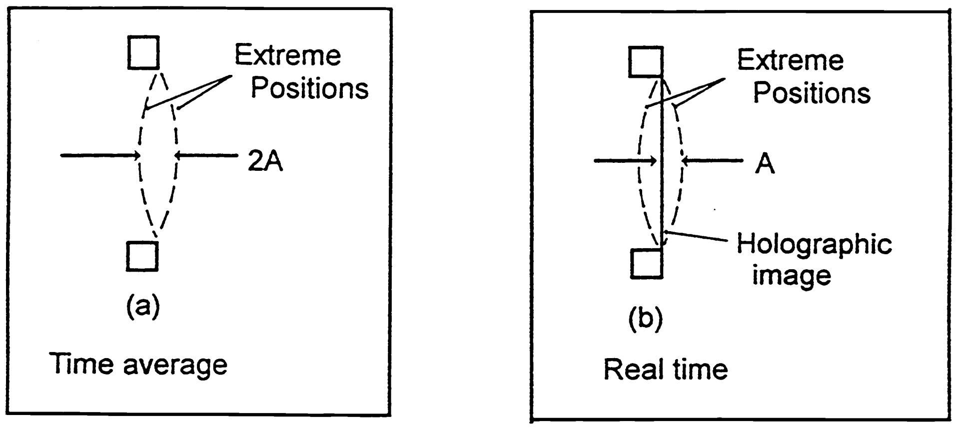
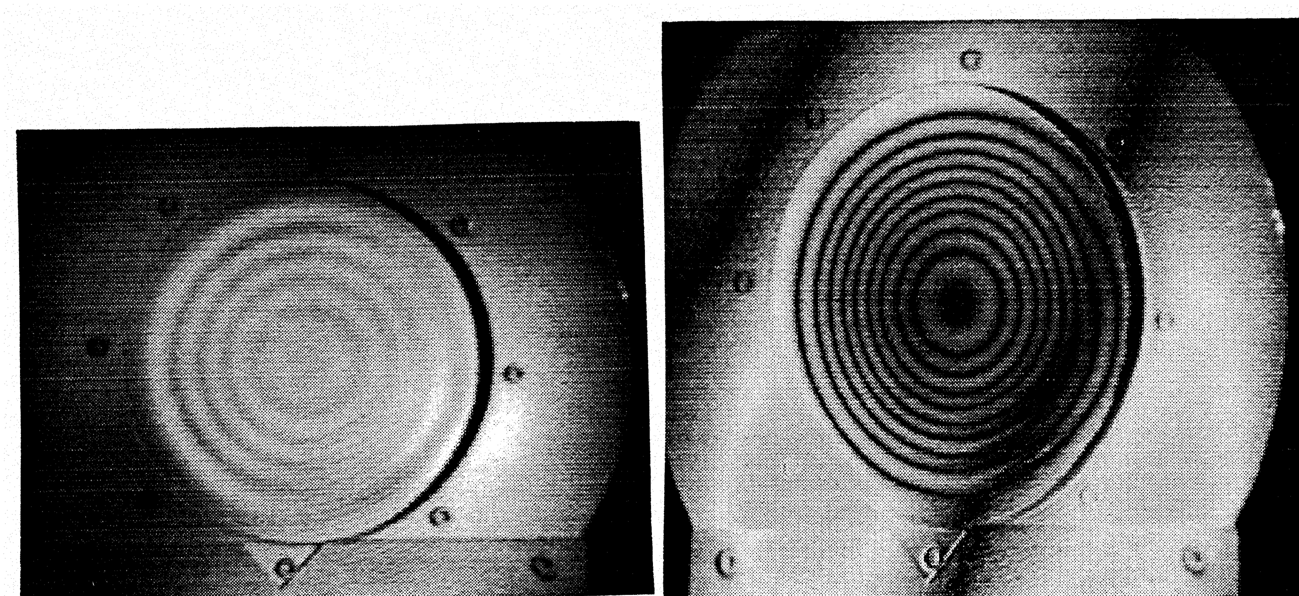
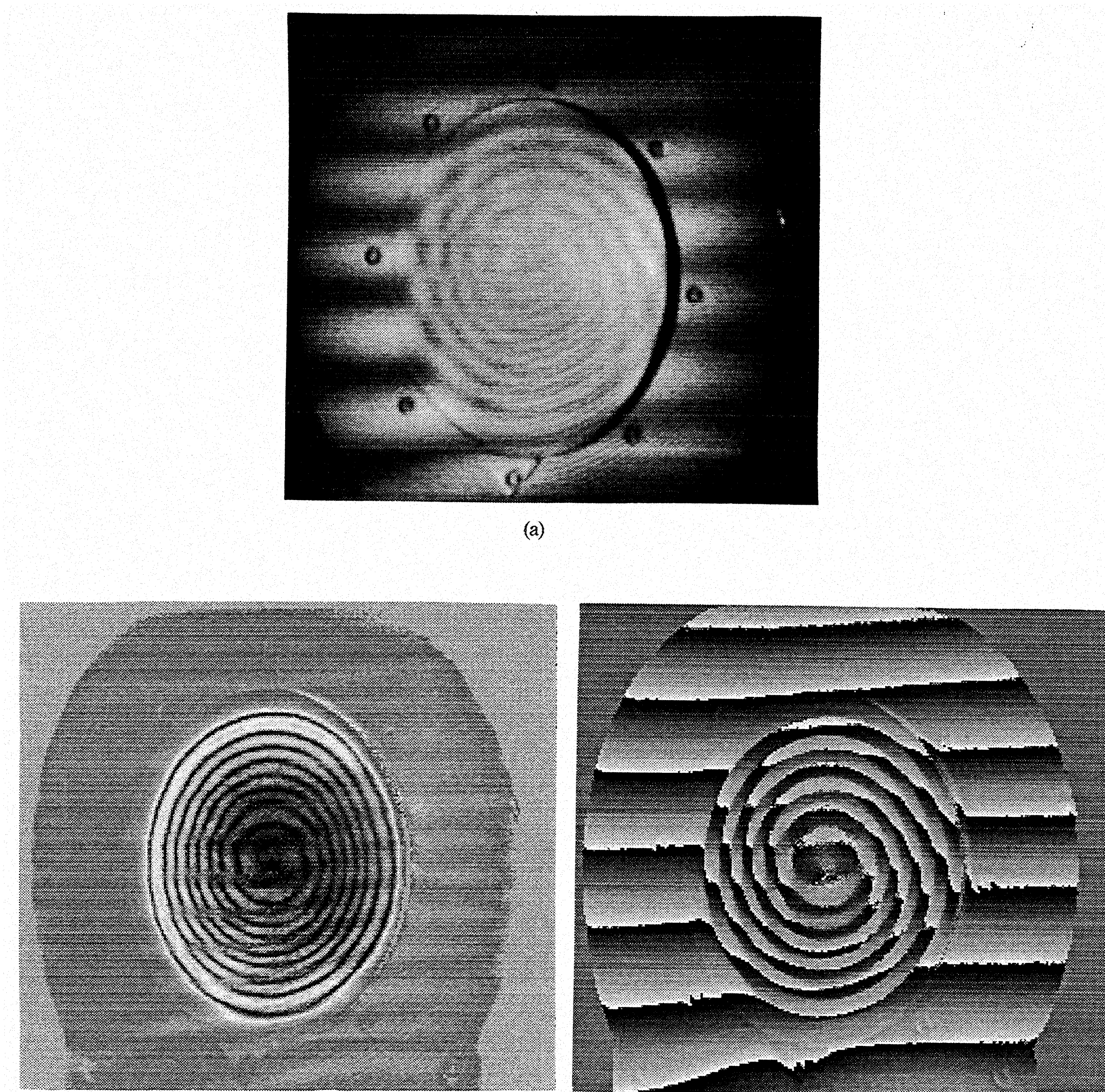


Figure 3. Recorded Diaphragm Displacement a) Time Average Holography b) Real Time Holography



(a) (b)

Figure 4. Image Subtraction Technique a) Original Hologram b) Enhanced Hologram



(a)

(b)

(c)

Figure 5. Phase Stepping Technique a) Real-time Hologram b) Vibrational Fringes c) Static Deformation Fringes.