STUDY AND APPLICATION OF HOLOGRAPHY SYSTEM FOR MECHANICAL STRESS AND SURFACE DEFORMATION

KUA HOCK CHUAN

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Dedication to my beloved father, mother and family

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ABSTRACT

Holography is a technique to record information and reconstructs it in three-dimensions. Although the technique was developed almost 40 years ago, it still possesses great potential and present rapid research in its application will continue. The aim of this project is to study various techniques of holography and the applications of holographic interferometry in mechanical stress and surface deformation measurement. Initially, a dark room and a vibration-free optical table are set-up. Low power He-Ne laser with output power of 1 mW and 10 mW are employed as light source. Various alignment techniques of holography setup are implemented and compared including Gabor holography, reflection holography, transmission holography, rainbow holography, data storage holography and double exposure holographic interferometry. In particular, the double exposure technique is applied to measure the Young's modulus of aluminum can and surface deformation of an object. Although the optical alignment is different for each technique, in general, they need to go through similar procedure: recording, developing, reconstruction and permanent record of hologram image. All the holograms are successfully developed and viewed in three dimensions. Double exposure hologram produces interference patterns which indicate the occurrence of deformation due to the stress given. The Young's modulus of the Aluminum can was measured to be $(0.80 \pm 0.18) \times 10^8$ Nm^{-2} which is in the same order of magnitude with the mechanical measurement of $(1.76 \pm 0.01) \times 10^8$ Nm^{-2} by the Universal Testing Machine by taking into account the calibration and measurement error. On the other hand, a surface deformation measurement system is developed and capable of detecting displacement up to 2.69 μm.

ABSTRAK

Holografi adalah satu teknik untuk merekod maklumat dan membinanya semula dalam tiga dimensi. Walaupun teknik ini telah pun berkembang sejak 40 tahun yang lalu, potensinya masih tidak terhad dan kajian terkini dalam aplikasinya terus berkembang. Matlamat projek ini adalah untuk mengkaji pelbagai teknik holografi dan aplikasi holografi interferometri dalam pengukuran tekanan mekanik and kecacatan permukaan. Pertamanya, satu bilik gelap dan satu meja bebas getaran disediakan. Laser He-Ne berkuasa rendah yang mempunyai keluaran kuasa 1 mW dan 10 mW digunakan sebagai sumber cahaya. Pelbagai teknik holografi disusun termasuk holografi Gabor, holografi pantulan, holografi pancaran, holografi pelangi, holografi simpanan data, dan holografi interferometri menggunakan teknik dedahan berganda. Teknik dedahan berganda diaplikasikan dalam pengiraan Modulus Young bagi tin Aluminium dan mengukur kecacatan pada satu permukaan objek. Walaupun susunan optik bagi setiap teknik adalah berlainan, semua jenis hologram yang dibina masih perlu melalui proses yang sama iaitu proses merekod, proses mencuci, proses membina semula dan proses untuk merakam imej kekal holografi. Kesemua hologram berjaya dibina dan dilihat dalam bentuk tiga dimensi. Hologram dedahan berganda menghasilkan corak interferen yang mana menunjukkan kecacatan yang disebabkan oleh tekanan yang diberi. Nilai Modulus Young bagi tin Aluminium yang diperolehi daripada eksperimen adalah $(0.80 \pm 0.18) \times 10^8$ Nm^{-2} di mana ia mempunyai nilai kuasa yang sama dengan nilai pengiraan mekanik iaitu $(1.76 \pm 0.01) \times 10^8$ Nm^{-2} yang diambil daripada mesin ujian umum setelah mengambil kira faktor ralat kalibrasi dan ralat pengkuran. Manakala sistem pengukuran kecacatan pada permukaan berjaya mengesan sesaran dalam julat 2.69 μm.

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LIST OF SYMBOLS

R	-	Coherence reference beam
O	-	Coherence object beam
I_o	-	Object wave irradiance
a_o	-	Amplitude of object wave
a_R	-	Amplitude of reference wave
a_c	-	Amplitude of reconstruction wave
$U_o\,(x,y)$	-	Complex amplitude of object wave
U_o^*	-	Conjugate of the complex amplitude
$U_R\,(x,y)$	-	Complex amplitude of reference wave
$U_c\,(x,y)$	-	Complex amplitude of reconstruction wave
$U_I\,(x,y)$	-	Complex amplitude of reconstruction wave after illuminated through the hologram.
$\phi_o\,(x, y)$	-	Phase of light wave
$I\,(x, y)$	-	Irradiance at the film plane
$t\,(x, y)$	-	Amplitude transmittance
t_b	-	Attenuated transmittance
β	-	Film constant
t	-	Transmittance of the hologram
f_y	-	Spatial frequency of the reference wave
θ_R	-	Angle between the reference wave and horizontal axis
λ	-	Wavelength
$O_o\,(x,y)$	-	Object wave
$R_o\,(x,y)$	-	Reference wave
φ_o	-	Spatial phase variation of the object beams
φ_R	-	Spatial phase variation of the reference beams
$H\,(x,y,x)$	-	Total field at the hologram
δ	-	Constant phase difference

$\lvert H \rvert^2$	-	Resultant irradiance of the standing wave pattern
χ	-	Constant of resultant recorded signal, D proportional to resultant irradiance of standing wave pattern, $\lvert H \rvert^2$
ε	-	Dielectric constant of the medium
dr	-	Amplitude reflection coefficient
$d\varepsilon$	-	Different between dielectric constants
D	-	Resultant recorded signal
$d\psi$	-	Amplitude of the wave at the surface of the layer
$A\ (x, y, z)$	-	Complex amplitude
$a\ (x, y, z)$	-	Real amplitude of light wave
$\varphi\ (x, y, z)$	-	Phase of light wave
A_i	-	Image wavefront
ΔO	-	Optical path length
Δy	-	Displacement
n	-	Integer number of fringes
α	-	Incident angle
β	-	View angle
t_1	-	Exposure time for A_1 wave
t_2	-	Exposure time for A_2 wave
d	-	Fringes spacing
θ	-	Angle between the reference and object beam

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CHAPTER I

INTRODUCTION

1.1 History

In life we see everything in three dimensions, and we accept it as it is. However, when we look at a hologram, in which shows three-dimensional image of an object, we are impressed, even though the object does not existed but the image of the object is appearing. Possibly the most exciting application of the laser is in other type of photography called holography. It came from the Greek word 'holos' meaning 'the whole or entirely' and 'gram' meaning 'the information', so hologram is the whole of information (Develis and Reynolds, 1967).

Holography is based on the wave nature of light. Thomas Young had demonstrated a simple experiment for the first time in 1801. He let a ray of sunlight into a dark room, placed a dark screen in front of it, pierced with two small pinholes, and beyond this, at some distances, a white screen. He then saw two darkish lines at both sides of a bright line, which gave him some idea to repeat the experiment. He used a spirit flame as light source, with a little salt in it, to produce the bright yellow sodium light. Finally, he saw a number of dark lines, regularly spaced; the first clear proof that light added to light can produce darkness. This phenomenon is called interference. Thomas Young had expected it because he believed in the wave theory of light. His great contribution was the intuition that monochromatic light represents regular, sinusoidal oscillations, in a medium. If this is so, it must be possible to produce more light by adding wavecrest to wavecrest, and darkness by adding wavecrest to wavethrough (Gabor, 1971).

Light which is capable to produce interference is called coherent. Coherence is conveniently measured by the path difference between two rays of the same source, by which they can differ while still giving observable interference contrast. This is called the coherence length, an important quantity in the theory and practical of holography.

The basic theory of the holography was discovered by Gabor (1948). His original effort was to improve the resolving power of the best light microscopes. After pondering this problem for a long time, he finally realized that the important of coherent electron beams, with electron waves which have a definite phase. For his discovery, Gabor was awarded the Nobel Prizes in physics in 1971 (Francon, 1974).

The idea of holography lay undeveloped until the invention of laser in the early 1960s. Leith and Upatniek, (1962, 1964) of the United States and Denisyuk (1962) of the Soviet Union then added their own concept and produced holograms that formed the foundation of those found today. These advances initiated an explosive growth of activity in optical holography, which among other achievements led to the discovery of holographic interferometry by Stetson and Powell in 1965.

The applications of holographic interferometry are numerous and varied, spanning across areas in science, engineering, technology, medicine and agriculture. Holographic interferometry has helped to improve product design and develop safer, quieter, and more efficient systems. Indeed, the applications are so vast that they are limited only by the imagination of researchers and scientists (Sirohi *et al.*, 2001).

Holography was invented almost 40 years ago but because of its unique interdisciplinary nature, involving science and technology, art and craft, the potential of the subject is still underestimated and present rapid growth in its application will continue.

Although there are many commercial holography systems that are available in the market, as a researcher, it will not be an interesting to buy a complete system without any valuable experience of making the system on our own. Furthermore, it is very expensive. Definitely, the experience to develop the system will help lay down a foundation and permit a good prospect for further research in industrial applications e.g NDT (Non-Destructive Testing), advertisements, storage of information, accurate measuring techniques, and art.

1.2 Photography and Holography

Holography records phase as well as amplitude. It produces three dimensional view of picture unlike conventional photography which only produces two dimensional picture. Holography is a relatively new approach that is similar to photography in some respects but is nonetheless fundamentally different. Because of this fundamental difference, holography and photography will not be competing in the same areas. There are several applications for which holography are more suitable than photography, while most of the more important uses for photography remain unchallenged. Furthermore, there are several tasks that can be performed with holography but not at all with conventional photography (Smith, 1975).

In order to point out the fundamental differences between holography and photography, it is important to understand the working principle of them. Photography basically provides a method of recording two dimensional irradiance distribution of an image. Generally, each "scene" consists of a large number of reflecting or radiating points of light. The waves from each of these elementary points all contribute to a complete wave, which is called the "object" wave. This complex wave is transformed by the optical lens in such a way that it collapses into an image of the radiating object. This image then recorded on the photographic emulsion (Smith, 1975).

Holography, on the other hand, is quite different. It does not records the image of the object optically, but formed the object wave itself. This wave is recorded in such a way that a subsequent illumination of this record serves to reconstruct the original wave, even in the absence of the original object. A visual observation of this reconstructed wavefront then yields a view of the object or scene that practically indiscernible from the original. It is thus the recording of the object wave itself, rather than an image of the object, which constitutes the basic difference between conventional photography and holography (Smith, 1975).

1.3 Holographic Interferometry

Holographic interferometry is an extension of interferometric measurement techniques in which at least one of the waves that interfere is reconstructed by a hologram. The unique capabilities of holography interferometry are due to the fact that holography permits storing a wavefront for reconstruction at a later time. Wavefronts, which were originally separated in time or space or even wavefronts of different wavelengths, can be compared by holographic interferometry. As a result, changes in the shape of the objects with rough surfaces can be studied with interferometric precision (Hariharan, 1996).

It is well known that holographic interferometry technique yield extremely accurate measurement of minute surface deformities (Hildebrand and Haines, 1966). Its advantages are (Spetzler *et al.*, 1974):

a) Strains can be measured simultaneously in any direction.
b) Strain variation over the entire sample can be observed.
c) No physical contact with the sample.
d) No special sample preparation is required.
e) The experiment set-up is simple; it involves laser, mirrors and lenses.

One of the most important applications of holographic interferometry is in non-destructive testing. It presents a holographic image of the object along with a region of flaw. The flawed region appears in the form of anomalies in the fringes pattern. However, the success of holographic non-destructive testing depends on the judicious choices of the method of excitation: mechanical, pneumatic, thermal, acoustical or vibratory and impact loading have been used for excitation of the object (Grant and Brown, 1969; Water, 1971; Vest and Sweeney, 1977; Vikram *et al.*, 1980; Rastogi *et al.*, 1988; Wood and Trolinger, 1990; Zhu, 1996).

There are also great applications of holographic interferometry in solid mechanics in measurement of static displacements, dynamic displacements and stress analysis. The measurement of static or quasi-static displacements brought about by the applications of mechanical, pneumatic and thermal loading. The test objects are in the form of bars, cantilevers, cylinders, plates, diaphragms, pipes, cylindrical shell (Gottenberg, 1968; Wilson, 1970; Matsumoto *et al.*, 1974; Mader, 1985; and Balalov *et al*, 1990).

Vibration is a major cause of noise, wear and failure in machinery and systems. It is also a source of music, creating pleasant sensations. Holographic interferometry enables whole-field inspection of vibration modes and measurement of their amplitudes and phases. The holographic record is made over a time period that spans several vibration cycles, and hence an average exposure is recorded. This method is known frequently as time-averaged holographic interferometry, which has been applied to the study of acoustic transducers, cylinder structures, antennas, bridge, storage tanks, engine and car body (Monahan and Bromley, 1968; Barbato and Barbisio, 1974; Geldmacher *et al.*, 1983; Carlsson *et al.*, 1988; and Kreuttner *et al.*, 1993).

It can be used wherever the presence of a structural weakness results in a localized deformation of the surface when the specimen is stressed, either by the application of a load or by a change in pressure or temperature. Crack detection and the location of areas of the poor bonding in composite structures are fields where holographic interferometry has been found useful. It also can be used to determine the material properties such as Poisson's ratio, Young's modulus, shear modulus, thermal expansion (Yamaguchi and Saito, 1969; Ashton *et al.*, 1971; Robertson and King, 1974; Holloway, 1982; Antonov, 1983; Cuche, 1988).

The recent research on stress analysis has reported by Sanchez and Hornberger, (2002) who studies residual stresses in plastic part. It was shown that holographic interferometry has the potential to be a practical tool for the inspection of manufactured plastic parts of the presence of residual stress.

Before that, Monteiro *et al.*, (2001) reported their finding of measuring the displacement field in the plane of a part through crack existing in a plate. It is a very applicable tool in fabrication processes that responsible for the generation of cracks.

An allied area of application has been in medical and dental research, where it has been used to study the deformations of anatomical structures under stress, as well as for nondestructive tests on prostheses (Greguss, 1976; Wedendal and Bjeikhagen, 1974; and Podbielska, 1989).

Recently, the application of holographic interferometry technique was found in measurement of oxide thin film growth. Thokale *et al.*, (2002) reported their finding to study different parameters of cobalt oxide thin films. Holographic interferometry technique permits the quantitative and qualitative study of minute changes in the object contours by comparing each point on its surface with itself before and after a change has taken place.

Habib, (2001) in his investigation has reported that the application of holographic interferometry for the first time to monitor the thickness of oxide film growth on aluminum samples during the initial stages of oxidation processes in aqueous solution without any physical contact. The thickness of the oxide film on the aluminum samples was measured by the real time holographic interferometry.

In double-exposure holographic interferometry, interference takes place between the wavefronts reconstructed by two holograms of the object recorded on the same photographic plate. Typically, the first exposure is made with the object in its initial, unstressed condition, and the second is made with a stress applied to the object. When the processed hologram is illuminated with the original reference beam, it reconstructs two images, one corresponding to the object in its unstressed state, and the other corresponding to the stressed object. The resulting interference pattern reveals the changes in shape of the object between the two exposures (Hariharan, 1996).

1.4 Research Objective

i) Study and develop various techniques of holography system as an initial stage before going further through the application of holographic interferometry. Those types of holography including:

a. Gabor holography
b. Reflection holography
c. Transmission holography
d. Rainbow holography
e. Data storage holography
f. Interferometry holography-double exposure technique

ii) Study the applications of holographic interferometry in:

a. Elasticity measurement
b. Surface deformation measurement

1.5 Research Scope

Lasers and several optical components are employed. Various of holography systems are developed and aligned. The holograms are recorded using holographic plates and films. The reconstructions of the images are made using laser light and white light. The holographic interferometry is utilized to determine the Young's modulus of metal specimen. The holographic interferometry setup is also developed a surface deformation measurement system in order to detect point stress.

reduction data. An array of data hologram was produced. The data can be selected and read during reconstruction process. Without using any magnifying glass, the image observed has similar size with the original data.

For double exposure holographic interferometry technique, the same construction and reconstruction setups as the off-axis transmission hologram were used. Two exposures were given to the same object and on the same hologram plate. The first exposure was taken with unstressed object and the second exposure was taken when the object was given stressed. As a result, interference pattern appeared on the hologram image which shows the deformation of the test object.

In this project, double exposure technique was applied to measure the elasticity of the Aluminum can and detecting the static surface deformation due to a point stress. The results showed the relation of the spacing between the fringes line and the given load. As the load increased, the spacing between the fringes line was found to be decreasing. The Young's modulus of the Aluminum can measured from the system has a good agreement with the mechanical measurement system using Universal Testing Machine; while, the point stress capable to detect displacement in the range of 2.69 μm.

As a conclusion, holography is an obvious technique to record and display information. The most interesting phenomenon is that the information can be observed in three dimensional, and the measurement can be made in micro size.

7.2 Problems and Suggestions

The main problem which affected the results is actually noise from the environment. This is because noise waves produced will disturb the systems during recording process. As a result, the hologram image produced will become blurred. So, in order to prevent such problem, all the recording process was carried out at night or during weekend.

The other problem was the failure to get the real time hologram, which can save a lot of hologram plate because the real time hologram technique only uses one master piece hologram. As an alternative technique, double exposure hologram was employed in this project.

The permanent recorded of the hologram depends on the capability of the camera and the art of taking a photograph. Furthermore, the permanent recorded of the hologram image was done in the darkroom. Probably by using more sophisticated digital camera; the focal depth problem could be overcame.

For future research, the real time holography system can be studied and investigated to replace double exposure technique which will give more advantages to the researcher. The reconstruction setup can be carried out using CCD (Charge-Coupled Device) camera which can provide better quality of image.

As mentioned in the first chapter, this project is an initial stage of gaining holography knowledge. Hopefully, the experiences and the contributions in making these experiments will be a good reference for future researcher to involve in this field and generate new ideas.

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