Determination of elastic and optical properties of thin plates and investigation of the mechanisms involved in the laser generation of ultrasound

by David Howard Hurley

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering
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Abstract:
The focus of this paper is two-fold. First, the shear wave velocity, Poisson's ratio, and optical absorption coefficient of a thin glass plate will be estimated using a Nd: YAG pulsed laser. Second, the combined influence that an ablative and thermoelastic source has on the elastic wave form generated by a pulsed laser will be investigated.

Thermoelastic waves are introduced into a sample when a portion of the laser's energy is optically absorbed along the depth of the specimen causing a steep thermal gradient. Neglecting the effects of heat conduction, the thermoelastic displacements are determined by solving the uncoupled displacement equations of thermoelasticity.

As the laser's energy is increased, a thin layer of atoms at the sample's surface is vaporized. The momentum transferred to the sample from the vaporized atoms constitutes the second generation mechanism and is termed ablation. The ablative mechanism, which is modeled as a normal force, in conjunction with the differential equations of isothermal elasticity is used to determine the displacement due to ablation.

The stress free boundary conditions of both the thermoelastic and ablative problems lead to the Rayleigh-Lamb frequency equation, the solution of which represents the various modes of propagation present in an infinite plate. For a given frequency bandwidth there is a plate thickness below which only the first symmetric (s0) and first asymmetric (a0) modes of propagation will be observed. Thus, by considering only thin plates, all but the first two modes of propagation are eliminated, resulting in a waveform with characteristics that are easy to distinguish.

To simplify the problem of determining the elastic constants and the optical absorption coefficient in a thin glass film, it is desired to generate only thermoelastic waves. This restriction is achieved by simply decreasing the power of the Nd: YAG laser. By adjusting the size of the laser beam radius, the Rayleigh velocity and the group velocity of the s0 mode at zero wavenumber can be measured experimentally. Measurement of these two velocities leads to an estimation of the elastic constants. The estimated elastic constants are refined by comparing experimental and theoretical velocity data for the a0 mode. Next, the amplitude of the theoretical and experimental velocity data for the a0 mode are compared, which allows the optical absorption coefficient to be determined.

Ablation occurs when the sample's surface reaches its melting point; therefore, ablation must be accompanied by thermoelastic waves. For the a0 mode, this experimental reality is modeled theoretically by simply combining the thermoelastic and ablative solutions. For specimens with large optical absorption coefficients, the thermoelastic and ablative solutions add constructively. This theoretical result, while verified in copper and brass samples, is not witnessed in stainless steel samples. Stainless steel shows what is thought to be a small time delay between the thermoelastic and ablative waves. The theoretical solution closely resembles the experimental data if a 160 ns time delay

is included between the thermoelastic and ablative solution. This phenomenon might be attributed to thermal shielding due to the formation of plasma during ablation.

DETERMINATION OF ELASTIC AND OPTICAL PROPERTIES OF THIN PLATES AND INVESTIGATION OF THE MECHANISMS INVOLVED IN THE LASER GENERATION OF ULTRASOUND

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APPROVAL

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This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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TABLE OF CONTENTS

Page

TABLE OF CONTENTS -Continued

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES-Continued

LIST OF FIGURES-Continued

ABSTRACT

The focus of this paper is two-fold. First, the shear wave velocity, Poisson's ratio, and optical absorption coefficient of a thin glass plate will be estimated using a Nd:YAG pulsed laser. Second, the combined influence that an ablative and thermoelastic source has on the elastic wave form generated by a pulsed laser will be investigated.

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To simplify the problem of determining the elastic constants and the optical absorption coefficient in a thin glass film, it is desired to generate only thermoelastic waves. This restriction is achieved by simply decreasing the power of the Nd:YAG laser. By adjusting the size of the laser beam radius, the Rayleigh velocity and the group velocity of the s_o mode at zero wavenumber can be measured experimentally. Measurement of these two velocities leads to an estimation of the elastic constants. The estimated elastic constants are refined by comparing experimental and theoretical velocity data for the a_o mode. Next, the amplitude of the theoretical and experimental velocity data for the a_o mode are compared, which allows the optical absorption coefficient to be determined.

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CHAPTER 1

INTRODUCTION

The use of ultrasonic techniques as an interrogative probe for characterizing material properties has been a successful reality for the past 35 years. Ultrasonic testing was first used for locating material flaws in plates, forgings, and welds. Since the early days, ultrasonic testing has lent itself to an ever widening array of applications. These applications include characterization of porosity distribution in ceramics, evaluation of microstructural properties, such as grain size in metals, and ultrasonic testing to determine the stress distribution in load bearing structures.

The appeal of ultrasonic testing over other characterization techniques, such as tension tests and hardness tests, is that ultrasound can be used non-destructively. Another advantage of this non-destructive technique is its ability to detect microstructural flaws. Therefore, with growing emphasis on conservation of exotic materials and safety of sophisticated structures, ultrasonic testing has become an ideal tool to characterize material properties.

While there are a large number of ultrasonic techniques, the governing concept of all the techniques is the same. This concept consists of generating ultrasonic waves in a material, and then analyzing this disturbance after it has passed through the material. Tiny cracks and voids, as well as the elastic properties of the material itself, can alter the form and characteristics of the traveling wave as it passes through the material. With the use of a suitable theory, the researcher can analyze this altered ultrasonic disturbance to determine various material properties. The material property of interest dictates to a large extent the theory and experimental procedure used.

Generation Mechanism of Laser Generated Ultrasound

Ultrasonic waves may be produced when a material is subjected to a laser pulse of sufficient intensity. There are two basic mechanisms responsible for producing ultrasound in this manner. The first mechanism that will be discussed can be described in a thermoelastic regime. As the laser irradiates the material, a portion of the laser's energy is optically absorbed along the depth of the specimen causing a steep thermal gradient, both spatially and temporally. This temperature gradient results in rapid thermal strains which in turn cause ultrasound to propagate through the material.

Valuable insight may be gained by giving a microscopic view of the above thermoelastic process. The laser pulse is composed of photons (quanta of light) which all have the same energy. These photons are absorbed by the material causing atoms that make up the material to rise to a higher energy state. A portion of the excited atoms release their energy in the form of kinetic energy to surrounding atoms. It is this rise in kinetic energy to the surrounding atoms that was classically described above by a rapid increase in temperature.

While a portion of the laser's energy was optically absorbed into the specimen, the remaining energy is either reflected from the surface or responsible for vaporizing a thin layer of atoms at the sample's surface. Vaporization of a thin layer of atoms at the specimen's surface constitutes the second generation mechanism. Atoms at the surface that are given a sufficient amount of energy to escape the attractive forces of the material are said to be vaporized. As the vaporized atoms leave the surface they transfer a portion of their momentum to the surface resulting in the generation and propagation of ultrasonic waves through the specimen. This generation mechanism is known as ablation.

The experimental procedure used to generate ultrasonic waves takes advantage of coherent, monochromatic, and directionality properties of a Nd:YAG pulsed laser. These distinguishing features enable a narrow beam of high intensity light to be directed over large distances without dispersing. Upon striking the sample's surface, this high intensity beam generates ultrasound in accordance with the generation mechanisms listed above.

Objective

The overall objective of this thesis is two-fold. The first objective will be to estimate the elastic constants and the optical absorption coefficient of a thin glass film using laser generated ultrasound. Secondly, the combined influence that an ablative and a thermoelastic source have on the elastic wave form generated by a pulsed laser will be examined.

The first step in meeting the above objectives is to design an experiment that is capable of both producing and detecting ultrasound in thin glass and metallic samples. While the apparatus and experimental setup for similar experiments were provided by Idaho National Engineering Laboratory (INEL), the details pertinent to this experiment still needed to be furnished. A thorough discussion of the experimental procedure will be presented in chapter two of this document.

The next step involves the development of a reliable theory that predicts the amplitude and time characteristics of the laser generated elastic waves. This theory has to accurately model the generation source while accounting for the geometry of the specimen. Theoretical details will be discussed in chapter three.

Literature Review

The generation of high frequency ultrasonic pulses by absorption of electromagnetic radiation was first demonstrated by White[1] in 1963. Later White[2] used a *Q*-switched ruby laser to produce Rayleigh surface waves in piezoelectric and nonpiezoelectric solids. Mechanical comb transducers were employed to detect surface waves on nonpiezoelectric specimens, while interdigital electrode transducers were used for piezoelectric substances. In this paper he proposed that the efficiency of generating surface waves could be increased by periodically distributing heat sources along the surface of the sample.

In 1980 Aindow *et al.*[3] reported the effects of ablation on elastic waves generated by an Nd:YAG laser. Their study showed that in the ablation regime the plasma formed causes a reduction in lateral thermal gradients which in turn serves to decrease both lateral and normal gradients in the acoustic source. The momentum transfer due to ablation partially camouflages the thermal shielding caused by the plasma, resulting in an enhancement of the longitudinal pulse.

Measurement of thin metallic film thickness using laser generated ultrasound was first described by Dewhurst et al.[4] in 1987. The method involved using a high power pulsed laser to generate both symmetric and asymmetric Lamb waves. A Michelson interferometer in conjunction with a He-Ne laser was used to detect these waves. By obtaining time-of-flight measurements and determining the velocity of the ultrasonic disturbance, the thickness of the material was ascertained.

Later Hutchins and Lundgren[5] demonstrated that the film thickness and the elastic constants could be estimated by using a wide bandwidth and well-defined source and receiver locations. For a given frequency bandwidth, there is a plate thickness below which only two Lamb modes will be detected (first asymmetric and symmetric mode). The first symmetric mode for very thin materials is virtually dispersionless and has velocity (C_e). By measuring the velocity (C_e) and fitting an approximate dispersion relation for the first asymmetric mode to the dispersion curve obtained experimentally, an estimation of the film thickness and elastic constants is obtained.

Recently Roy[6] has studied the influence that optical absorption and diffusivity have on the elastic wave form generated by a pulsed laser. His one dimensional solution consists of solving the heat conduction equation and then solving the uncoupled thermoelastic wave equation to obtain an expression for displacement. The solution predicts that for moderate values of absorptivity (10^4 - 10^5 cm^{-1}) the magnitude and the time characteristic of the waveform remain relatively unchanged for wide variations in diffusivity.

CHAPTER 2

EXPERIMENT

The experimental setup that is used to generate and detect ultrasound in thin glass and metallic samples is shown in Fig. 1. The primary components of this setup are an Nd:YAG pulsed laser, an Argon constant wave (cw) laser, a confocal Fabry Perot interferometer, and signal conditioning equipment. The Nd:YAG laser is responsible for generating ultrasound, while the detection of ultrasound is achieved by modulation of the Argon laser beam as it is reflected from the surface of the vibrating sample. The interferometer is employed to demodulate the Argon beam. The demodulated signal leaving the interferometer is then conditioned as it passes through an array of signal conditioning equipment. These components serve to divide the experimental procedure into four main categories.

The first category involves the generation of ultrasound in thin elastic samples (Lamb waves). The generation of Lamb waves is accomplished by irradiating the sample with high intensity light from an Nd:YAG pulsed laser. For this experiment the Nd:YAG laser has a pulse rate of 10 Hz, a pulse duration of 10 ns, and a typical power of 10 mj/pulse.

The source/receiver separation, shown in Fig. 2, is regulated by moving the generation beam (laser pulses) while keeping the receiver location fixed. An optical stage and lens apparatus, Fig. 2, is utilized to move the generation beam perpendicular

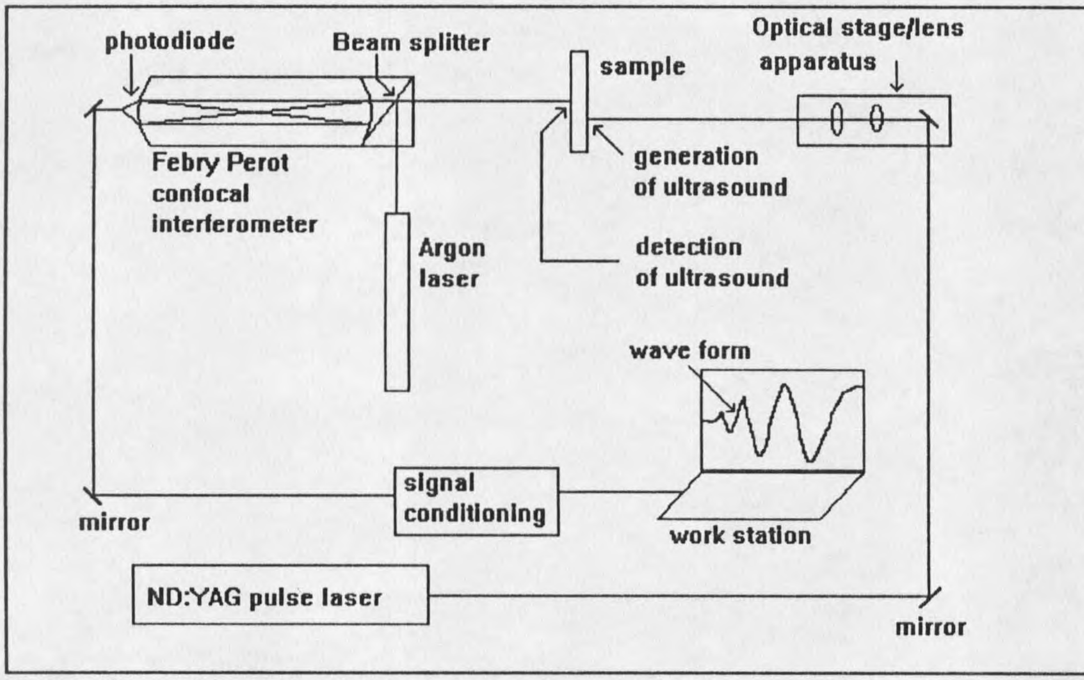

Fig. 1. Experimental setup

to the surface of the sample. By moving the generation beam in this manner the radial profile of laser pulses as projected on the sample is preserved. The location of the generation beam relative to the receiver location is then determined. This is done by replacing the specimen with a photographic film, and then exposing the film with both the Argon and Nd:YAG lasers, as demonstrated in Fig. 2. The film is examined under a microscope to accurately determine the source/receiver separation.

The next category concerns the detection of Lamb waves using an Argon laser. The first step in this procedure is to direct the Argon beam through a polarizing beam-splitter, shown in Fig. 1. One beam is use as a reference beam, while the other beam is steered towards the vibrating sample. Upon reflection from the vibrating surface, the laser light experiences a shift in frequency due to the Doppler effect. This modulated

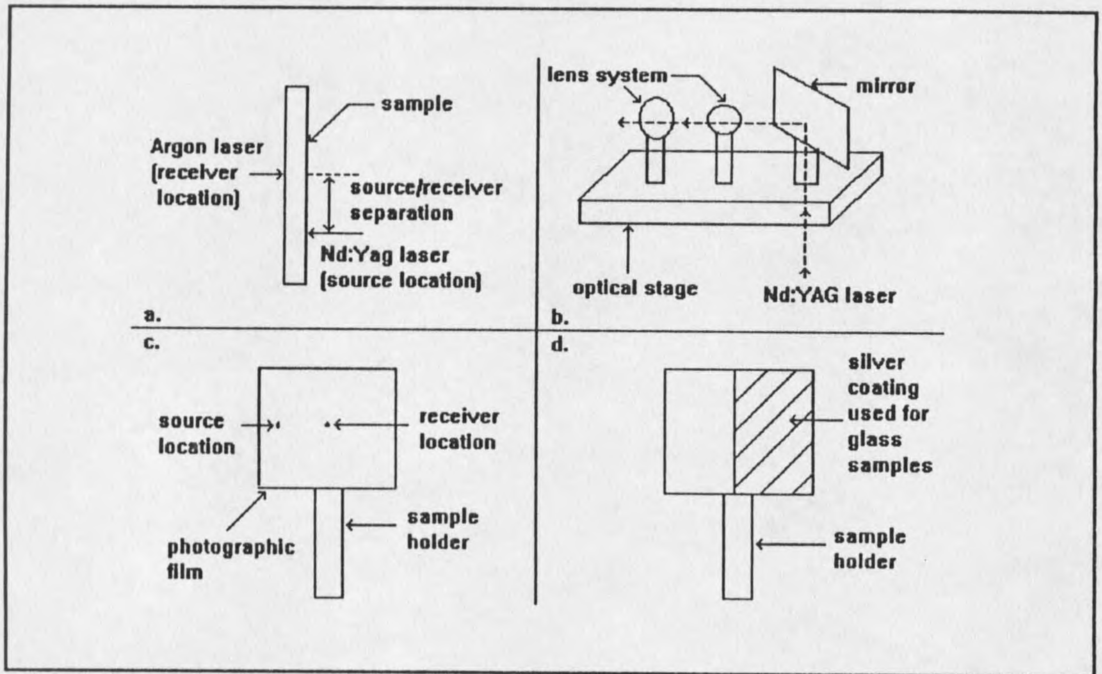

Fig. 2. Details of experimental setup. a. Source receiver separation b. Optical stage/lens apparatus. c. Photographic film. d. Silver coating used for glass samples.

beam contains the amplitude and time characteristics of the vibrating surface, information that will be deciphered by demodulating the Argon beam.

It should be noted that this detection scheme is noncontacting, thus lending itself to environments that would be hostile to contacting transducers. However, this noncontacting method requires that semi-transparent films, such as glass, undergo special preparation in order for this method to work. This difficulty is due to the dual reflection that would be encountered when the Argon beam is reflected from a semi-transparent film. A portion of the beam would reflect off the front surface while the remaining portion would reflect off the back surface of the sample, resulting in the combination of time and amplitude characteristics of both the front and back vibrating surfaces. This