High-speed optical diagnostics of laser-interactions

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HIGH-SPEED OPTICAL DIAGNOSTICS OF LASER-INTERACTIONS

by

Mohamad Kadim bin Suaidi, B.Sc. (Hons.), M.Sc.

A Doctoral Thesis

Submitted in partial fulfilment of the requirements for the award of Doctor of Philosophy of the Loughborough University of Technology

October 1991

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To

KARTINI

and

Our Parents

Ayahnda Suaidi Hj Arshid dan Bonda Halimah Hj Sulaiman
Ayahnda Ahmad Mokhtar dan Bonda Salbiah Sulaiman
ACKNOWLEDGEMENTS

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ABSTRACT

The interaction of an 8 ns, 10 mJ and 1.06 \( \mu m \) infrared pulse of radiation from a Q-switched Nd-YAG laser with water near a solid boundary is studied using high speed photographic techniques. The laser-liquid interaction has been used to generate high frequency sound waves by the mechanism of dielectric breakdown of the liquid around the beam waist of the focused laser beam. This leads to the production of a short duration plasma which rapidly heats and vaporises the surrounding liquid giving rise to a vapour cavity and the formation of a cavitation bubble resulting in the emission of a spherical acoustic wave. The acoustic transient associated with the breakdown, in turn interacted with a liquid-polymer interface leading to the generation of acoustic waves at this boundary and the propagation of stress-waves in the solid.

Diagnostics of the laser-interaction events are recorded using a Mach-Zehnder interferometer illuminated by a sub-nanosecond nitrogen laser-pumped dye laser and computer-controlled video-imaging and capture systems. Measurements of the transient pressure distributions from the digitally recorded interferograms are carried out using a process known as Abel inversion. Dynamic photoelastic studies of the stress-waves propagation in the solid are performed using a circular polariscope arrangement thus producing the photoelastic fringe patterns. Identification of the wave structures are greatly enhanced by also recording the events in schlieren and focused shadowgraphy as well as by the combination of the above techniques.

The initial part of the project also involved the design and development of a nitrogen laser and tunable dye laser system. The short-duration and high peak power output pulse of the nitrogen laser is then used to pump the dye laser giving sufficiently high power output with good spectral linewidth to provide an ideal light source for high-speed photography of the laser interaction events.
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CHAPTER ONE

INTRODUCTION

When Albert Einstein discovered the physical principle responsible for the amplification of radiation in materials in 1916, it took another 45 years or so before T. H. Maiman constructed the first laser and thus establishing the laser as a scientific and technological discovery of great magnitude. It has found applications in most areas of science and technology with laser techniques being employed in such diverse fields as spectroscopy, metrology, diagnostics and inspection, communications, fusion research, defence and medicine. It is able to generate a well-collimated, intense beam of coherent light at a precisely defined wavelength and a variety of lasers with different output parameters: continuous or pulsed mode, with pulse lengths from milliseconds down to femtoseconds, at wavelengths from infrared down to ultraviolet and power from milliwatt to several megawatt can be readily designed and constructed. It is therefore conceivable that lasers with suitable power densities can be utilised in the study of optical breakdown in gases, solids and liquids.

The laser-interaction mechanisms in different media and their applications have became areas for intense research activity. The nature of these interactions have been found to depend on the wavelength and intensity of the incident laser beam as well as on the optical and thermal properties of the medium in relation to the beam parameters. At lower incident powers and if the target medium is initially transparent to the laser radiation, for instance, transient heating of a restricted volume can cause a strain in the body and subsequently generates acoustic wave. At higher powers and when the medium is opaque, the radiation is absorbed within a thin surface layer. Explosive vaporisation in the case of liquids or material ablation on solids together with plasma formation in the medium can occur with the effect of generating high intensity shock waves.
The specific phenomenon of laser interaction with respect to the generation of acoustic waves in the host media has also found a variety of scientific and practical applications. Optical excitation of sound has only been investigated extensively since the advent of the first lasers although physicists have been intrigued by the idea of contactless generation of acoustic energy as early as the nineteenth century (Tyndall 1881). Energy can be transmitted through solids, liquids and gases as acoustic waves and propagates with a velocity which is characteristic of the medium. Elastic solids will transmit tensile and compressive stresses and the motion of particles will be in the direction of the wave propagation. This longitudinal wave takes the form of alternate compressions and rarefractions and are also known as a compression wave. This behaviour is analogous to the propagation of sound in fluids, which can only support this mode of propagation. In an elastic solid the situation is more complicated because it also transmits shear stress where the motion of particles is transverse to the direction of propagation. There is no analogue to this behaviour in a liquid or gas.

Laser generated acoustic waves range in frequency from 1 - 10 MHz depending on the pulse duration of the laser radiation and majority of published works make use of the Q-switched laser pulses of duration from 10 - 30 ns (Krehl et al. 1975, Docchio, et al. 1991). When a laser generated acoustic wave impinges on a boundary between two media, it undergoes changes at the interface. Some of the energy will be transmitted into the second medium and refraction will occur. The proportions of the energy transmitted and reflected depend on the properties of the media. Mode conversion of waves can also occur if one of the materials is solid and this can either be advantageous since it will give information on the specimen or can be complex leading to difficulties in interpreting the data. Surfaces and interfaces can also supports various types of surface and interface waves. The most important being the Rayleigh wave which causes the particles to move in elliptical paths. There also exist Lamb waves in plates which readily couple the energy of the main bulk waves to the motions on the interface.

The laser-interaction studies described in the thesis are mainly concerned with the interaction of a 1.06 μm infrared pulse from a Q-switched Nd-YAG laser with water near the boundary with a solid polymer. The 10 mJ and 8
ns pulse laser beam is focused into water resulting in a beam cone angle of 20° and a beam waist of ~ 40 μm. This corresponds to an average optical density of ~ 50 GWcm⁻² in water leading to dielectric breakdown and plasma formation which rapidly heats and vaporises the surrounding liquid giving rise to a vapour cavity or cavitation bubble. This optical cavitation in turn generates acoustic waves which propagate in the liquid and hence in the neighbouring solid. Two types of polymer are used in the study namely polymethyl-methacrylate (PMMA), trade name perspex, and a photoelastic material, polycarbonate (PC), trade name PSM-1. The laser breakdown in the water is arranged to occur as near as possible to the solid surface subject to the proviso that the surface is not directly damaged by the laser beam.

Diagnostics of the laser-interaction events are recorded using an experimental arrangement which is centred around a Mach-Zehnder interferometer. Recording of the stress-waves propagation is difficult because of the high velocity of the transient acoustic waves and a source of extremely short-duration pulses is necessary to record them with sufficient temporal resolution. This is achieved by illuminating the interferometer with a 0.5 ns, 514 nm pulse from a nitrogen laser-pumped dye laser system. The extremely fast event also requires the use of a video-imaging and capture system for accurate and consistent timing to synchronize the sound generating laser and the illuminating laser systems. The main components of the imaging system which is software driven from an IBM compatible computer, consists of a CCD video camera, a digital frame store and a trigger control unit. The system is operated in single pulse mode to produce single frames in a repeatable set of experiments resulting in movie like sequence of pictures of the wave propagation.

Transient pressure profiles associated with the passage of the acoustic waves can be obtained by analysing the digitally recorded interferograms. Fringe shift on the interferogram is a measure of the change in refractive index which can be translated into changes in density and pressure through the Gladstone-Dale relationship and the use of an Abel inversion technique gives the true radial pressure or longitudinal stress profiles in the liquid and solids. The above experimental arrangement when used with PMMA is not sensitive to shear stresses in the solid (Ward and Emmony 1990). A dynamic
photoelastic measurement technique is used in conjunction with the interferometer to visualise all the stresses with the PC replacing the PMMA. The formation of photoelastic fringe pattern when using the polycarbonate, can be described as a case of optical interference due to the material being doubly refractive or birefringent when stressed. The essential optical effects for an understanding of the photoelastic phenomena associated with dynamic loading can be observed by using a circular polariscope arrangement. Identification of the wave structures through the measurements of positions, displacements and velocities and the understanding of how acoustic waves interacted with defects are greatly enhanced by also recording the events in schlieren and focused shadowgraphy as well as by the combination of the above techniques.

Prior to starting the optical diagnostics studies, the author's project also involved the designing and construction of a suitable nitrogen laser-pumped dye laser system. Several systems were reviewed with the objective of building a system on a modest cost but with sufficiently high power output to provide an ideal light source for high speed photography of the laser interaction events. A compact nitrogen laser based on the transversely excited atmospheric laser with pressurised spark-gap was constructed and tested. The design of the laser, which was made from a double sided printed circuit board, allows for multipulse operation for multiframing photography. The high efficiency of the nitrogen laser pumping allows for the use of a simple dye laser design based on the Hansch (1972) oscillator.

The scope of study which covers laser-interaction, high speed video photography, ultrasonics and the equipment used in this project provides the author with a valuable training in the current research techniques. Vogel et al. (1986) have investigated the application of Q-switched Nd-YAG lasers in ocular surgery by means of high-speed photography and hydrophone measurements. The incisive effect relies on the optical breakdown at the laser focus. Cavitation bubbles and acoustic transients are thereby generated. Emmony (1989) reviewed the surgical application of the 1.06 μm radiation of Nd-YAG lasers. Infrared laser-induced breakdown, plasma growth and shock wave generation led to no apparent burning of biological tissue, only the physical disruption of the nearby tissue. The non-invasive character of the
laser as a photodisruptor means that surgical procedures can be performed in less time with the minimum of psychological and physical stresses. The use of water, distilled or deionised, as a medium to study the laser-liquid interactions has been extensively investigated as a plausible model for ocular media (Docchio et al. 1986, Loertsher 1983).

Laser generated ultrasonics has been used in materials characterization whereby the measurement of mechanical and materials parameters such as internal stress, grain size and elastic constants are undertaken using ultrasonics that can probe the interior of solids non-destructively. Tam (1984) reported the use of laser generated ultrasound coupled with a high frequency zinc-oxide piezoelectric receiver to measure the thickness of stainless steel films while Dewhurst and Al'Rubai (1989) have used a picosecond laser and polyvinylidene fluoride transducer to study the ultrasonic echoes in duralumin plates of thickness between 250 μm and 3 mm. Calder and Wilcox (1980) combined the laser source with an interferometer receiver to make non-contact materials characterization systems. Bresse et al. (1989) have applied laser generated ultrasound to flaw detection of bonds in layered composites. They investigated the transient Lamb waves and the resonance caused by reflections from the boundaries between the layers of composites.

Direct measurement of the pressure profile in the acoustic wave is difficult and non-contacting optical methods are required especially in the study of laser-liquid-membrane interactions simulating ophthalmological surgical procedure. Most previous studies, for example Vogel et al. (1986), used a conventional high-speed drum camera with a framing rate of 20,000 frames a second and although recent streaked and framing image converter cameras have been employed with framing rates up to 1 million per second (Fujimoto and Shima 1990), it has not been possible to obtain detailed information about the shape of collapsing cavitation bubbles at their point of collapse. Vogel and Lauterborn (1988) used high speed photography to observe the motion of the generated bubble and the associated acoustic wave and a 1.2 MHz bandwidth hydrophone for pressure measurement which was located at a large distance from the acoustic wave emission centre. Direct measurements of the high time resolution, digitally recorded series of interferograms at various time delays obtained through the excellent pulse to
pulse reproducibility of the laser generated acoustic waves provide detailed information of the transient pressure distributions.
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CHAPTER TWO

NITROGEN LASER PUMPED DYE LASER SYSTEM

2.1 INTRODUCTION

Considerable research and development activities have been conducted on nitrogen lasers since Mathias and Parker (1963) first reported lasing in the nitrogen first positive system and later that year Heard (1963) observed lasing in the second positive system of nitrogen. Theoretical and experimental studies have been performed and different aspects of the lasers have been investigated. These include the optimization of power output and efficiency, dependence of pulse width and power output on design parameters, power input and gas flow conditions, lasing frequencies and their spectral examination under different experimental conditions and mechanisms for population inversion. The number of designs and experimental arrangements that have been reported can be broadly classified into two types with each type being pulsed discharge operated by a high voltage source:

i) Longitudinal (Axial) Excitation (LE).

ii) Transverse Excitation (TE).

The high peak power and short pulse duration of nitrogen lasers have been found to be an ideal pump source for dye lasers by Zvenevich et al. (1983) and Schaefer (1977). Veith and Schmidt (1978) used it in dye laser oscillator-amplifiers and Bor et al. (1982) employed it in pumping distributed feedback dye lasers (DFDL) which have found enormous use in the study of laser induced fluorescence, time resolved fluorescence and life time studies of excited states of a number of molecules in vapour and liquid phases. Nitrogen lasers have found applications in the field of plasma diagnostics (Nawrot and Pokora 1982), remote sensing (Kagawa et al. 1979), high speed
photography (Bergmann 1977), sub-nanosecond interferometry and holography (Udrea 1982), medical treatment of dermatomycosis (Maeda et al. 1981) and also in the study of excited states of molecules by the use of a dual channel nitrogen laser (Stephenson and McDowell 1972).

In 1965, Sorokin and Lankard, first discovered that solutions of organic dyes could be made to emit laser radiation and at about the same time, Schafer, Schmidt and Volvze (1966) observed laser action in other dye solutions. Since then dye lasers have been pumped by flashlamps, nitrogen lasers and many other type of lasers. Nitrogen laser-pumped dye lasers are by far the most attractive lasers for a modest research programme. The reasons being the availability of several designs for low cost, reliable, high peak power nitrogen lasers and the high efficiency of the nitrogen laser pumping allows the use of simple dye laser designs. The high peak powers produced by these lasers and their tunability permit many interesting experiments to be performed relatively easily.

2.2 NITROGEN LASER

2.2.1 Introduction

Nitrogen laser technology is still growing rapidly even nearly three decades after the advent of the first laser. This is one of the simplest lasers to construct and efforts are being made continuously to improve its efficiency, power and stability. Molecular nitrogen has been observed to lase on the following identified transitions: the second positive system, \((C^3\Pi_u \rightarrow B^3\Pi_g)\) in the ultraviolet, the first positive system \((B^3\Pi_g \rightarrow A^3\Sigma_g^+)\) in the infrared, the \((a^1\Pi_g \rightarrow a^1\Sigma_u^-)\) system (McFarlane 1965) between 3.29 \(\mu m\) and 3.47 \(\mu m\) and at approximately 8.15 \(\mu m\) to 8.21 \(\mu m\), and the \((\omega^1\Delta_u \rightarrow a^1\Pi_g)\) system at approximately 3.7 \(\mu m\) (McFarlane 1966), the \((a^1\Pi_g \rightarrow \chi^1\Sigma_g^+)\) system (Tagliaferri et al. 1973) and the \((\omega^3\Delta_u \rightarrow B^3\Pi_g)\) system (Suchard et al. 1975). Oscillation has also been observed at about 80 lines on unidentified transitions at wave lengths between 5.4 \(\mu m\) and 8.07 \(\mu m\) (Beck et al. 1975).
Though lasing has been reported in the above systems for a number of bands, the (0,0) band of \((C \rightarrow B)\) transition has been very much in focus and therefore, we would normally refer to nitrogen laser lasing at 337.1 nm. The two factors responsible for such enhanced activity are:

(i) nitrogen lasers with moderate power (100 - 500 kW peak power), lasing at 337.1 nm (0,0 band) without cavity, can be built easily and design considerations are not particularly critical. Indeed these lasers frequently do not need an optical cavity in which case the output is probably more accurately referred to as amplified spontaneous emission, ASE, nevertheless they have come to be called lasers.

(ii) the frequency and power output are excellently suited for pumping many dyes to superradiance in simple experimental arrangements leading to very efficient dye lasers.

Historically, longitudinally or axially excited lasers were the first to be built in which the laser emission is in the direction of the electrical field. These were followed by transversely excited lasers in which the laser emission is perpendicular to the direction of the electrical field. The second type has the advantage of yielding a higher output power for similar operating voltage. Svedberg et al. (1968) first reported the successful operation of a nitrogen laser at atmospheric pressure. Subsequently a number of Transversely Excited Atmospheric (TEA) nitrogen lasers have been developed which give high power, high energy and short pulse duration.

Generally, flowing nitrogen gas is used, although there are occasional reports of nitrogen lasers for non-flowing nitrogen gas (von Bergmann 1977). In none of the laser systems mentioned above is it known with certainty about the exact mechanisms that produce the population inversion. It is clear, however, that electrons are primarily responsible for the excitation, and calculations based on models that assume the excitation of both upper and lower laser levels is by direct electron impact from the ground state gives good agreement with experimental observations performed by several workers.
2.2.2 General Theory

In gases, as in other materials, amplification of radiation takes place in the condition of population inversion. It is a nonequilibrium condition, characterised by a distribution of atomic systems such that for some pairs of stationary energy levels more atoms are found in the higher than in the lower energy state. To describe this, it will be necessary to deal with spectroscopic properties of molecules and with an excitation process peculiar to gases: excitation by means of collisions. The inclusion of molecular gases among laser materials requires the consideration of some of the laws of molecular spectroscopy. In molecules, we encounter a series of discrete energy level which consist of the superposition of electronic, vibrational and rotational levels.

When examining the energy level structure of the nitrogen molecule, we must do so on three different scales, Fig. 2.1 (Herzberg 1950). Fig. 2.1a shows the first four electronic levels displayed with a few of the vibrational levels added whilst the rotational level cannot be shown on this scale. Fig 2.1b shows the ground electronic state with its first four vibrational states on a tenfold enlarged scale. Another tenfold enlargement in Fig 2.1c shows the rotational levels of a single vibrational state. In analogy to atomic spectroscopy in which the letters S, P, D are used to designate different electronic configuration types, corresponding Greek capital letters Σ, Π, Δ are used in molecular spectroscopy. They indicate the value of a quantum number that specifies the component of orbital angular momentum along the molecular axis. The letter Σ indicates that this component is 0, Π is h and Δ is 2h. The multiplicity of the level is indicated by a subscript to the left. When there are two electrons participating in the formation of the molecule, the symbol \( ^1\Sigma \) - pronounced singlet sigma - indicates that the spins of these electrons are opposite, while the symbol \( ^3\Sigma \) - triplet sigma - indicates a sigma configuration with the two spins aligned parallel. The symbol + is added as a superscript if the molecular wave function remains unchanged on reflection in a plane through the molecular axis. The symbol - is used when such reflection changes the sign of the wave function. There is an additional pair of symbols, g and u, used to indicate the parity of the electronic states. It refers to the symmetry of the electronic state for reversal of all coordinates,
FIG. 2.1: ELECTRONIC, VIBRATIONAL AND ROTATIONAL LEVELS OF NITROGEN MOLECULE.
that is, inversion about the centre of the molecule. The vibrational terms of a molecule are characterised by the vibrational quantum numbers. In the case of the nitrogen molecule there is only one vibrational degree of freedom, therefore, one quantum number $v$ is sufficient.

Fig. 2.2 illustrates the potential energy curves and laser transitions of the nitrogen molecule relevant to the first positive and second positive systems. In both the systems, which will be considered here, the lower laser lifetimes are much longer than the upper state lifetimes and both are inherently transient laser systems and thus have been operated only under various pulsed excitation conditions. The ultraviolet ($C \rightarrow B$) and infrared ($B \rightarrow A$) laser actions are coupled with each other in the sense that they share the common level $B^3 \Pi_g$, that is, the $B^3 \Pi_g$ lower level for the ultraviolet laser transitions is the upper level for the infrared transitions. The ultraviolet system will operate superradiantly without cavity mirrors, but for obtaining oscillation on the lower gain infrared transitions, feedback by means of cavity mirrors is necessary. It appears that the difference in gain between the two systems gives rise to a time lag of about 40 ns between the ultraviolet and infrared transitions as shown in Fig. 2.3 (Willet 1974).

The excitation of nitrogen molecules is from the ground state, $X^1 \Sigma^+_g$ to $C^3 \Pi_u$ and to $B^3 \Pi_g$, the upper state of the ultraviolet and infrared lasers respectively. With reference to the second positive system, oscillation has been observed from two vibrationally excited levels of the $C^3 \Pi_u$ upper state ($v' = 0, 1$) giving rise to laser lines as indicated in Fig 2.2, at 337.1 nm ($v' = 0$ to $v'' = 0$), 357.7 nm ($v' = 0$ to $v'' = 1$) and 315.9 nm ($v' = 1$ to $v'' = 0$). The laser bandwidth of these transitions is typically of the order of 0.1 nm and involves many rotational transitions.

It is now a fairly well known fact that excitation of the upper laser level is brought about by direct electron impact and theories have been developed to explain lasing in nitrogen (ultraviolet and infrared) on this basis. The onset of spontaneous emission from the $C^3 \Pi_u$ state immediately on the commencement of the excitation current pulse, and superradiant emission during the rise time of the excitation pulse, provides strong evidence for excitation of the $C$ state by direct impact involving high energy electrons.
FIG. 2.2: PARTIAL POTENTIAL ENERGY LEVEL DIAGRAM OF NITROGEN RELEVANT TO THE (C - B) AND (B - A) LASER SYSTEMS, SHOWING OBSERVED LINES AND EXCITATION PATHS.
FIG. 2.3: TIME RELATIONSHIP BETWEEN EMISSION OF ULTRAVIOLET LASER PULSE AND THE INFRARED LASER PULSE OF A TRANSVERSELY EXCITED NITROGEN LASER (WILLET, 1974).

SI PHOTODIODE OUTPUT
The time history of nitrogen gas excitation and observation of spontaneous emission and stimulated ultraviolet (and infrared) emissions together with the formation of nitrogen atoms and $N_2^+$ molecules is shown in Fig 2.4 (Massone et al. 1972). It is clear from the figure that recombination of dissociated nitrogen atoms that can only occur towards 100 $\mu$s after the initiation of the discharge cannot account for excitation of the C - state. Likewise, recombination of $N_2^+$ molecules with electrons cascading into the C - state which can only be of significance at 10 ms after the initiation of the current pulse cannot be the excitation process of the $C^3\Pi_u$ state.

Massone et al. (1972) found that cooling axially excited nitrogen lasers to liquid-air temperatures gave a substantial increase in laser output over that obtained at room temperature. The effect is not considered to be due to the increased molecular ground state concentration $N_0$, at the lower temperature at a fixed pressure that follows from the relation $N_0 = p/kT$, as the output maximizes at both temperatures at the same value of $N_0$. Fig. 2.5. If collisions of the second kind, involving the metastable $a^1\Pi_g$ state, were responsible for enhanced excitation of the C - and B - states, it would be expected that the laser intensity would decrease as the collision frequency decreased with a decrease in gas temperature (as in He-Ne laser) (Singh and Thakur 1980). However, on cooling to liquid-air temperatures the intensity did not decrease instead the intensity increased. Therefore, the direct electron impact excitation appears to be the dominant mode of excitation.

Zapesonyi and Skubenich (1966) and Nichols (1961) calculated the total cross-section for excitation from the $X^1\Pi_g$ ground state ($v'' = 0$) to the $C^3\Pi_u$ and $B^3\Pi_g$ states. Fig. 2.6 (Zapesonyi and Skubenich 1966), shows that the total maximum cross-section of the $B$ - state is about $13 \times 10^{-17}$ cm$^2$, and is approximately five times larger than that of the C - state. Based on these values and the similarity of the shape of the excitation functions, and the occurrence of their maximum cross-sections within a few eV of each other, it appears that it would be impossible to produce population inversion between the C - and B - states by electron impact excitation from the ground state under any discharge conditions. However, a large number of vibrational levels contribute to the total cross-section of the B - state, while only a few levels ($v' = 0, 1, 2$) contribute significantly to the cross-section of the C - state.
FIG. 2.5: NITROGEN LASER INFRARED AND ULTRAVIOLET EMISSIONS INTENSITIES AS A FUNCTION OF (a) PRESSURE AND (b) MOLECULAR CONCENTRATIONS AT DIFFERENT TEMPERATURES (MASSONE 1972).
FIG. 2.6: EXCITATION FUNCTIONS OF VARIOUS ELECTRONIC STATES OF NITROGEN (ZAPESONYI 1966).
Thus, when the individual cross-sections for each vibrational level of the B-state are calculated it was shown that the cross-section for transition from the ground state \((v'' = 0)\) to the vibrational level \((v' = 0)\) of the B-state, \(Q^B_{00}\), is smaller than \(Q^C_{00}\) of the C-state by a factor of 3.5 as shown in Table 2.1. The cross-section data presented in Table 2.1 indicates that the only cross-sections of the C-states larger than those for excitation of vibrational levels of the B-state are:

\[
Q^C_{00} > Q^B_{01} > Q^B_{00}
\]

and

\[
Q^C_{01} > Q^B_{00}
\]

Based on the relationships of these cross-sections, population inversion between vibrational levels of the C- and B-states of nitrogen that could be produced by electron impact excitation from the ground state during the risetime of the discharge current pulse should only be possible between

\[
C^3\Pi_u (v' = 0) \text{ and } B^3\Pi_g (v'' = 0 \text{ and } 1)
\]

\[
C^3\Pi_u (v' = 1) \text{ and } B^3\Pi_g (v'' = 0)
\]

with the \(v' = 0\) to \(v'' = 0\) at 337.1 nm being predominant.

The relative probability of emission in the \((C \rightarrow B)\) band system is directly proportional to the product of the excitation cross-section \(Q\) and the Frank-Condon factors for emission, \(q\). Values of \(q\) for the \((C \rightarrow B)\) transition are given in Table 2.2 (Nichols 1961). Due to the fact that the equilibrium internuclear separations in the electronic states are in the order:

\[
\text{\(r_e(A^3\Sigma_u^+) > r_e(B^3\Pi_g) > r_e(C^3\Pi_u) > r_e(X^1\Sigma_g^+)\)}
\]

according to the Frank-Condon principle, the transition \(X \rightarrow C\) has the highest Frank-Condon factor and would be more probable.

Additional evidence to support the theory of electron impact excitation is that the transitions stated for the second positive system are spin forbidden. However, this is not a severe constraint in the case of electron exchange collisions in which the incident electron may be considered to have replaced one of the valence electrons (of the molecule) during the collisions with its
<table>
<thead>
<tr>
<th>VIBRATIONAL QUANTUM NUMBER $v$</th>
<th>C STATE</th>
<th>B STATE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 1 2 3 4</td>
<td>0 1 2 3 4 5 6 7 8 9 10</td>
</tr>
<tr>
<td>CROSS-SECTION $Q_{ov} \times 10^{-18}$ cm$^{-2}$</td>
<td>6.2 4.6 1.9 1.7 0.2</td>
<td>1.8 4.5 6.5 7.1 7.1 4.8 3.6 2.0 1.2 0.9 0.6</td>
</tr>
<tr>
<td>(a)</td>
<td>3.5 2.0 0.3 0.1</td>
<td></td>
</tr>
<tr>
<td>(b)</td>
<td>3.8 1.6 0.7 0.3</td>
<td></td>
</tr>
</tbody>
</table>

### Table 2.2: Frank-Condon Factors for Low Vibrational Quantum Numbers of the Second Positive System of Nitrogen (Willet, 1974)

<table>
<thead>
<tr>
<th>UPPER STATE \ v</th>
<th>LOWER STATE \ v</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0.449</td>
</tr>
<tr>
<td>1</td>
<td>0.390</td>
</tr>
<tr>
<td>2</td>
<td>0.135</td>
</tr>
<tr>
<td>3</td>
<td>0.024</td>
</tr>
<tr>
<td>4</td>
<td>0.002</td>
</tr>
</tbody>
</table>
spin aligned parallel to other valence electron. Electron exchange collisions dominate transitions involving a change in multiplicity with the total electron spin differing by unity from that of the ground state. Such collisions have large cross-sections close to the threshold, Fig. 2.6, which is characteristic of a transition involving a spin change and their excitation functions exhibit sharper maxima than optically allowed transitions. This kind of process appears to be operating in the direct excitation by high energy electron impact (Rhodes 1974).

To understand the characteristics of nitrogen lasers, Gerry (1965) was the first to propose the simple theory of direct electron impact excitation and established the rate equations involving the population densities of the upper and lower levels which were solved under the approximation that the laser power density was saturated. This accounts for most of and is in good agreement with the observed features in experiments by Leonard (1965). This theory was later extended by Ali et al. (1967) to include the effect of collisional mixing of the laser levels by electron impact and collisional ionization from the upper laser level, whose contributions are significant at electron densities greater than 6 x 10^{14} \text{ cm}^{-3} and an electron temperature of 4 \text{ eV}. In these formulations, an ultraviolet nitrogen laser is considered as a three level laser: X^1\Sigma_g^+ (ground state level 1), B^3\Pi_g (lower laser level 2) and C^3\Pi_u (upper laser level 3). If we populate the the C^3\Pi_u level of nitrogen in a time which is short enough with respect to its natural radiative lifetime, \tau_{32} (40 \text{ ns}), it is possible to establish a population inversion between the C^3\Pi_u and B^3\Pi_g level to obtain stimulated emission. The B^3\Pi_g level has a radiative lifetime, \tau_{21} = 10 \mu\text{s} (Lichten 1957). The population inversion is therefore self terminating because \tau_{32} < \tau_{21} leading to automatic pulsing with a pulse width ranging from sub-nanosecond to about 20 ns for ultraviolet radiation.

If we now call \mathcal{N}_1, \mathcal{N}_2 and \mathcal{N}_3 the population densities of the ground state, the lower (i) and the upper (j) laser levels respectively and \chi_{ij} denotes the rate of collisional excitation by electron impact from level i to j where i < j. The same way we call \gamma_{ji} the rate of collisional de-excitation from j to i, \tau_{ji} the radiative lifetime from j to i and \gamma_{ji} the rate of the radiative decay. Finally \mathcal{R}_{ji} denotes the rate of induced emission. Then the rate equations governing the population densities of these levels with time are written as :
where \( g_2 \) and \( g_3 \) are the statistical weights of the upper and lower laser levels respectively. The induced emission and absorption rates are neglected along with the rate of the collisional de-excitation from the the laser levels to the ground state. If we use the fact that \( T_{31} \approx T_{32} \), the \( C^3\Pi_u \) state being metastable, that \( X_{13} > X_{12} \), being taken as proportional to the Frank-Condon factor, and \( \tau_{31} \gg \tau_{32} \), then the sum of equations 2.1 and 2.2 can be written as

\[
\frac{dN_3}{dt} = X_{13}N_1 + (\tau_{31}^{-1} + Y_{31})N_3 - (\tau_{31}^{-1} + Y_{31} + X_{23})N_2 + R_{32}^{-1}N_3 - N_2(g_3/g_2) \tag{2.4}
\]

which on integration yields

\[
N_3 + N_2 = X_{13}N_1t \tag{2.5}
\]

Here it is assumed that \( N_1 \) and pumping rates are constants. Using equations 2.4 and 2.5 in equation 2.1, we have:

\[
\frac{dN_3}{dt} = X_{13}N_1 + (X_{13}N_1t - N_3)X_{23} - \beta N_3 \tag{2.6}
\]

where \( \beta = (\tau_{32}^{-1} + Y_{32}) \). The solution to equation 2.6 is straightforward, resulting in:

\[
N_3 = (N_1X_{13}/\alpha^3)(Y_{32} + \tau_{32}^{-1})(N_1X_{13}/\alpha^3)Y_{32} + \tau_{32}^{-1})e^{-\alpha t} + (N_1X_{13}X_{32}/\alpha) \tag{2.7}
\]

where \( \alpha = \beta + X_{32} \). For small times interval one can write equation 2.7, by expanding \( e^{-\alpha t} \) up to terms in \( t^2 \), as:
Equations 2.5 and 2.8 yield:

\[ N_3 = N_1X_{13}t - \frac{1}{2}N_1X_{13}(Y_{32} + r^{-1}_{32})t^2 \]  \[ 2.8 \]

Thus:

\[ N_2 = \frac{1}{2}N_1X_{13}(Y_{32} + r^{-1}_{32})t^2 \]  \[ 2.9 \]

It is now possible to obtain the condition of population inversion, that is \( N_3 > N_2 \), thus:

\[ t < \frac{1}{(Y_{32} + r^{-1}_{32})} \]  \[ 2.10 \]

which implies that population inversion takes place in a small time compared to \((Y_{32} + r^{-1}_{32})^{-1}\).

For \( r^{-1}_{32} > Y_{32} \), neglecting the collisional mixing effect, the population inversion can result during a time shorter than the radiative lifetime of the \( \text{C}^3\Pi_u \) state (40 ns), this is no longer true when the electron density \( N_e \) exceeds \( 6 \times 10^{14} \) cm\(^{-3}\) because the collisional mixing of the laser levels by electron impact becomes dominant. Then, \( Y_{32} > t^{-1}_{32} \) and the inversion duration is shortened. Therefore, it is necessary to have a fast excitation of nitrogen compared with 40 ns, the lifetime of the \( \text{C}^3\Pi_u \) state.

### 2.2.3 Excitation Techniques

The short lifetimes of the respective upper levels of the ultraviolet and infrared transitions means that inversion can only be obtained by utilising short-risetime, high-voltage pulsed excitation in which the current-pulse risetime is comparable or less than that of the effective lifetimes of the upper laser levels. However, there are also reports of nitrogen lasers being developed using relativistic electron beams which involve a large volume of gas in the excitation processes as compared to the electrical discharges.
FIG. 2.7: EQUIVALENT CIRCUIT FOR (A) BLUMLEIN AND (B) CAPACITOR TRANSFER CIRCUITS.
Another technique is the proton-beam excitation which was first demonstrated by Goiden et al. (1978) showing laser action in Ar-N₂ mixtures using a current and space charge-neutralized proton beam as a pump source.

2.2.3.1 Electrical Discharge Configurations

An important factor affecting the energy output of a nitrogen laser is the time scale for excitation of nitrogen molecules. This refers to the time required to transfer the electrical energy stored in the capacitor into excitation energy of the gas bearing in mind that population inversion can only be achieved during the period of less than 40 ns. The electrical design of the exciting circuit is of primary importance because the restriction imposed on the discharge requires that the rise time of the high voltage pulse produced by the circuit must be shorter than 40 ns.

In the majority of transversely excited nitrogen lasers, a Blumlein circuit is employed as an efficient discharge circuit for producing a fast rising discharge. Another type of circuit that is often used is a variation of the Blumlein circuit called capacitor transfer circuit. Both circuits consist of the energy storage capacitor, pulse forming line capacitor, triggering switch or spark gap and the laser discharge channel as shown in Fig. 2.7. The main difference is in the location of the switch and the laser channel.

For the Blumlein circuit, the two energy storage capacitors are the same and the high voltage supply charges capacitor C₂ directly and C₁ through resistor R to full voltage. Then as soon as the switch breaks down, the stored electrical energy in the capacitor is transferred to the laser tube during the discharge of the capacitor, initiating the gas discharge in the laser channel. In the capacitor transfer circuit, the switch is in the charging circuit, and the energy storage capacitance C₁ is greater than the pulse forming capacitance C₂ because all the charges stored on C₁ is transferred to the pulse forming line and then to the laser tube through the switch, to compensate for the losses in the switch. Although the initial current rise is faster thus making the discharge faster in this configuration, this does not always lead to a substantial increase in output power.
The required current rise is of the order of $10^{12}$ A/s and places severe restrictions on inductance and resistance (impedance) of the entire discharge circuit. Since the rate of rise of voltage on the pulse forming line is a function of the switch inductance and the effective capacitance of the energy storage and pulse forming line, the inductances of all the circuit elements must be minimised (Ruhl et al. 1974). Ali (1969) has determined the laser power density and its time history and the effect of various discharge circuitry parameters on the electron temperature and electron density in the nitrogen ultraviolet laser. The laser power density is essentially proportional to the electron density and the rate of the excitation of the upper laser level and this rate is a function of electron temperature. The time history of the electron temperature early in a pulsed discharge in nitrogen for different discharge-circuit inductances is shown in Fig. 2.8 and the effect of the current pulse risetime on the production of electrons for different values of circuit inductance is shown in Fig. 2.9. The combined effect the circuit inductance has on the electron density and the electron temperature affect the power density as shown in Fig. 2.10.

A variety of switches have been used to trigger the electric circuit for excitation of the discharge. Nagata and Kimura (1973) used a simple air spark gap (spark plug), Levatter et al. (1974) used a pressurised spark gap, Schildback and Basting (1974) used a laser triggered spark gap and Woodward et al. (1973) used thyratron switching which gives a uniform discharge with better pulse to pulse reproducibility but at a price.

2.2.3.2 Transversely Excited Nitrogen Lasers

Transverse electric field excitation has been widely employed in the investigations of the ultraviolet nitrogen laser system and high electric field values are required for producing laser oscillation in the second positive system at both low and high pressures operations. Leonard (1965) was the first to introduce transverse excitation for nitrogen lasers when he observed an increase in the intensity of 337.1 nm transition by applying the electric field at right angles to the propagation of the radiation in the laser cavity. Takushi et al. (1984) constructed a 1 MW transversely excited Blumlein type
nitrogen laser using 44 (1000 pF) ceramic capacitors with an active length of 93 cm and cavity volume of 600 cm$^3$, Fig. 2.11. Nagata and Kimura (1973) investigated the variation of laser output by changing the configuration of commercially available ceramic capacitors arranged suitably along the length of the laser channel. Shipman and Kolb (1966) used the Blumlein transmission line of a parallel plate capacitor, Fig. 2.12 and this design was modified later to obtain unequal beam intensity at both ends in the ratio of 1 : 10. Schenk and Metcalf (1973) used a single low inductance storage capacitor (12 pF, 20 kV) which is charged directly from the dc power supply. The energy is transferred by means of a thyratron switch to a set of 20 door knob type ceramic capacitors (500 pF, 20 kV) connected in series and distributed uniformly along the length of the laser channel. The inlet and outlet for the gas are situated at the two ends of the laser cavity and the optimum pressure is about 20 torr. They obtained a peak output of 160 kW with a pulse duration of 10 ns. Feldman et al. (1978) improved on the design by using transverse gas flow for obtaining a more uniform pressure. They obtained a peak laser power of 0.7 MW and 9 ns pulse duration at 24 kV applied voltage.

Increasing the number of active molecules in the discharge cavity by increasing either the length of the cavity or the the gas pressure inside it will enhance the output power of the nitrogen laser. However, Knayzev et al. (1972) found an optimum channel length of about 1 m at which saturation is reached and as a result high pressure (atmospheric pressure) nitrogen laser appears more promising. As one increases the pressure the voltage required for charging also increases in order to drive the discharge at a constant value of $E/p$ and non-uniformities in the discharge leading to the formation of an arc tend to degrade laser performance. Since the gain depends on the length rather than the separation of the two electrodes, the former difficulty can be overcome by reducing the electrode separation to about 1 mm, so that laser action can be obtained at 10 - 15 kV. The second difficulty is more severe and several techniques have been employed that led to better stability and uniform discharges. This includes uniform field electrode profile by Chang (1973), photopreionization with low treshold seed gas (von Bergmann and Hasson 1976), preionization by incorporating a razor blade for corona-to-glow discharge and suitable choice of gas flow inlets through the
FIG. 2.11: CERAMIC CAPACITORS BLUMLEIN TYPE NITROGEN LASER. ACTIVE LENGTH IS 93 cm, CROSS-SECTION. OF (3 x 2) cm, ELECTRODE SEPARATION OF 2.5 cm AND 44 (x 1000 pF) CAPACITORS (TAKUSHI 1984).
electrodes along the channel (Bauer and Kowalzyx 1977). Knyazev et al. (1972) first reported the successful operation of a transversely excited atmospheric pressure (TEA) nitrogen laser and thus started the widely favoured design for high-pressure nitrogen lasers because of their simplicity, high power density, short pulse duration and the fact that they do not require a vacuum system. A number of TEA ultraviolet nitrogen laser designs have been reported and they are basically intended for realising high power, high energy and short duration pulses. Salzmann and Strohwald (1974) observed travelling wave excitation in segmented flat plate Blumlein circuit at atmospheric pressure with a 50 cm long discharge channel. The output power in the forward direction was 200 times more than in the reverse direction. Laser pulse duration was 400 ps with peak power of about 1 MW. von Bergmann and co-workers also constructed a variety of high pressures nitrogen lasers. In one of their designs, a travelling wave excitation type pulsing system was employed which consisted of auxiliary switches and the segmented device was constructed from a double sided copper-clad circuit board and could be charged up to 25 kV. Strip razor blades were used as corona electrodes to produce a preionizing discharge for a uniform laser discharge in the cavity. The laser output obtained with a 70 cm long cavity was more than 2 MW. Bergmann et al. (1978) constructed a simple TEA nitrogen laser by improving the design of the coronal electrodes of von Bergmann et al. The main electrodes are placed symmetrically along the edge of the copper film that make up the capacitors and this edge also plays the role of coronal electrodes. The coronal discharges occur at the edge of the copper film producing photoionization in the discharge medium which ultimately produces uniform glow discharge, Fig. 2.13. A peak power output of 355 kW per pulse of \( \approx 1 \) ns duration has been reported.

Baltog et al. (1986) constructed a four channel TEA nitrogen laser for interferometric measurements on a plasma focus. Four pulses having a delay of about 20 ns with respect to each other and a jitter less than 2.5 ns are generated. At a charging voltage of 16 kV the characteristics of each emitted pulse are 780 \( \mu \)J with 1 % output reproducibility and \( \approx 2.5 \) ns pulse duration. The system consists of four identical nitrogen lasers with transverse excitation obtained by conventional Blumlein technique. Each laser is fired by a spark-gap switch triggered from a common thyatron switch through four
FIG. 2.13: SCHEMATIC REPRESENTATION OF BERGMANN (1975) BLUMLEIN ASSEMBLY WITH PREIONIZERS.
FIG. 2.15: ENERGY PER PULSE VS DISCHARGE CHANNEL'S LENGTH FOR TRANSVERSELY EXCITED NITROGEN LASER (SLAZMANN AND STROHWALD 1974).
high voltage coaxial cables as delay lines. The delay lines of different length are also the pulse forming lines for ignition of each laser, Fig. 2.14.

The behaviour of the output power with respect to changes in voltage, capacitance and flow rate is the same for high pressure operation and low pressure nitrogen lasers. The output saturates much faster with the length of the channel, Fig. 2.15, and passes through a maximum as the electrode separation is continuously increased, Fig. 2.16 and Fig. 2.17, the value depending on the charging voltage and capacitance. The output power increases with an increase in pressure up to a maximum and then decreases with any further increase in pressure, Fig. 2.18.

2.2.3.3 Longitudinal Excitation

The superradiant nitrogen laser action was first observed by Heard (1963) using longitudinal excitation. There are several versions of axial excitation which is based on a capacitor charged to a high voltage of between 20 - 40 kV and then discharged via a spark-gap switch through the flowing nitrogen gas in a glass or quartz tube which makes up the laser channel. The length varies from 7.5 to 120 cm with a bore diameter of 1 to 8 mm, Fig. 2.19 (Kaslin and Petrash 1976). Copper ring electrodes or tungsten electrodes are fitted near the two ends of the tube with quartz windows sealed at the ends for the laser beam to emerge. Water flowed through the inner tube to cool the discharge and maintain a high rate of heat transfer from the tube walls. Wladmiroff and Anderson (1977) have reported a nitrogen laser in which the dumping capacitor, spark-gap and pulse generator were rigidly attached to the discharge tube to obtain a compact form but the system was difficult to construct and operate. The whole setup was enclosed within a thick steel tube for radiofrequency free operation. A peak output power of 200 kW with 4 ns pulse duration and pulse to pulse reproducibility of better than 3 % has been reported. The first observation of a longitudinally excited atmospheric (LEA) nitrogen laser was recorded by Svedberg et al. in 1968. Kōbayashi et al. (1979) developed a multi electrode LEA nitrogen laser that was operating slightly above atmospheric pressure and in the travelling wave mode. Different lengths of coaxial cables were used to excite the gas in a 25 cm
FIG. 2.16: TEA LASER ENERGY PER PULSE AS A FUNCTION OF ELECTRODES SEPARATION AT DIFFERENT CHARGING VOLTAGES (SINGH and THAKUR, 1980).
FIG. 2.17: TRANSVERSELY EXCITED ATMOSPHERIC LASER ENERGY AS A FUNCTION OF ELECTRODES SEPARATION AT DIFFERENT STORAGE CAPACITANCES (SINGH and THAKUR, 1980).
FIG. 2.18: PEAK POWER AS A FUNCTION OF PRESSURE AT DIFFERENT CHARGING VOLTAGE (HASSON and von BERGMANN, 1979).
FIG. 2.19: LONGITUDINALLY EXCITED NITROGEN LASER (KASLIN AND PETRASH, 1976).
long discharge channel and yielded a peak power of about 300 kW. A reflecting mirror is generally used to increase the power and reduce the divergence. Pumping in the gas column of an axial or longitudinal field laser is not uniform because the electrical discharge starts with a breakdown front which propagates as an ionizing wave potential gradient from the high voltage electrode along the gas column to the earthed electrode. In all the designs, the electrical energy is stored in a high voltage, low inductance capacitor of a few nanofarads. A triggering switch is used to transfer this energy into the discharge tube to excite the laser medium within a few nanoseconds. For high output power, one needs long discharge tubes which in turn require enormously high voltage for excitation. This makes the design difficult and uneconomical to fabricate which explain the lack of interest in this type of nitrogen lasers.

2.2.3.4 Electron Beam Excitation

In the electrical discharge systems, the power output is limited by the small gas volume and this can be overcome by exciting larger volume using high energy electron beam generators. When the high energy electron beam is propagating in the same direction as the laser beam, the excitation is called longitudinal electron-beam excitation and it is transversely excited if the beam propagates perpendicular to the laser beam. Fig. 2.20 (Sauebery and Longhoff 1980) shows one of a typical longitudinal electron-beam excited laser. When the primary electron pulse propagates down the laser tube, a longitudinal field is produced along the tube and the secondary electrons (cascade electrons) are produced by the ionization of gas molecules by primary electrons. The primary electrons then drifted in the field and avalanched to produce a plasma of electrons that played a dominant role in the pumping process. Dreyfus and Hodgson (1972) were first to report a nitrogen laser excited by a 4 GW longitudinal electron-beam. The laser cavity was in the form of a stainless steel tube of length 175 cm and diameter 1.9 cm and the electron beam was prevented from diverging by an axial magnetic filed of 2 - 10 kGauss. The tube was filled with 20 torr of nitrogen gas and a peak power of 60 kW at 337.1 nm with a pulse duration of 2 ns was reported without the use of a mirror.
FIG. 2.20: RELATIVISTIC ELECTRON BEAM LONGITUDINALLY EXCITED LASER (SAURBERY AND LONGHOFF 1980).
2.2.3.5 Proton Beam Excitation

A high energy proton beam (energy 0.5 J and 450 keV) produced from a reflex tetrode of Fig. 2.21 (Wiley and Hammer 1983) was incident transversely on the mylar window gas cell containing an Ar-N$_2$ mixture (95% : 5%) at a total pressure ranging from 1 to 1.5 atm. The cavity was formed with two highly reflecting dielectric spherical mirrors. The stimulated emission was observed at 357.7 nm and 380.5 nm corresponding to the (0,1) and (0,2) transitions of nitrogen (C - B). The beam divergence was $< 13$ mrad and the spot size of 1.3 cm at a distance of 1 m from the mirror. Higher reflectivity of the output coupling mirror yielded laser pulses of $\approx 5$ mJ for 0.5 J proton energy with an efficiency of $> 1\%$. The dependence of laser output on gas pressure and pumping pulse were similar to that of electron-beam excitation. Proton-beam excitation has the advantage over electron-beam because of the large ionization and excitation cross-sections that leads to heavy pumping of the gas responsible for laser action and it tends to be more compact and efficient than the electron-beam excited laser.

2.2.4 Optical Characteristics

The beam quality of nitrogen lasers are rather poor because it is normally operated in superradiance but some workers like Armandillo (1982) obtained a remarkably good beam with 3.6 mrad divergence in the vertical and 4.6 mrad in the horizontal plane. The coherence (spatial and temporal) properties are also not well defined. Jitsuno and Nakaya (1972) studied the spatial coherence of the laser beam with a rectangular cross-section by measuring the fringe visibility in a Young's type interference experiment. They found that the coherence along the shorter side was more than the longer side of the rectangular cross-section. They also found that coherence was better for high pressure lasers than those operated at low pressures. Schmidt et al. (1975) reported that fringe visibility of TEA nitrogen lasers is characterized by a doublet beating up to an optical path difference of 15 cm. Kim (1978) measured the fringe visibility curve of a low pressure nitrogen laser with a Michelson Interferometer and the fringe visibility was observed for a path difference of up to 8.2 cm.
FIG. 2.21: TRANSVERSELY EXCITED PROTON BEAM EXCITED NITROGEN LASER (WILEY AND HAMMER, 1983).
The pulse width strongly depends on the pressure of the filling gas as well as on the channel length and repetition rate. In order to obtain short pulses, laser channels of smaller lengths are employed, and by increasing the pressure from 1 atm to 6 atms, pulse width has been reduce gradually from 3 ns to 50 ps, Fig. 2.22. This reduction in pulse width, FWHM at high pressures is connected to the termination of the laser due to collisional mixing of the upper laser level.

2.3 DYE LASER

2.3.1 Introduction

In 1965, Sorokin and Lankard (1966) at IBM Research Centre were the first to obtain stimulated emission from an organic compound, namely chloro-aluminium-phthalo-cyanine. However, a year earlier in 1964, Stockman (1964) performed the first experimental study that might have led to the development of an organic laser after he found an indication of a small net gain in his system when pumping a solution of perylene in benzene between two resonator mirrors using a high-power flashlamp. Since then much progress had been made in the field of dye lasers research and the development of various types of tunable dye lasers has made considerable impact on several areas of science and technology. It is not surprising that most applications of dye lasers that have been reported depend on their unique capability to tune the laser wavelength continuously over a wide range, and to channel the laser energy into a narrow spectral line. Pulsed dye laser radiation can now be generated at any wavelength from the near ultraviolet to the near infrared using both flashlamp and laser pumping. A bandwidth of less than 1 pm and laser oscillation in a single cavity mode can be enforced in flashlamp-pumped dye lasers with multiple Fabry-Perot etalons (Bradley et al. 1971) or with Lyot filters and diffraction gratings (Walther and Hall 1970).
Considerably narrower lines can be achieved with continuous dye lasers. Single-mode operation and bandwidths of the order of 10 - 50 MHz have been achieved with intracavity prisms and Fabry-Perot etalons (Hercher and Pike 1971). Extremely narrowband dye lasers with multiple wavelength selectors which can be tuned continuously and smoothly over wide spectral regions have been difficult to develop but several workers have successfully demonstrated schemes for stabilizing the dye laser frequency to atomic or molecular resonance lines (Wather and Hartig 1973; Klein 1972).

It is also well known that lasers in general are superior to conventional light source in their spatial coherence and in the case of dye lasers, spatial coherence can be comparable to that of gas lasers. The oscillation of laser pump pulsed or continuous dye lasers can be restricted to the fundamental transverse TEM$_{00}$ mode. Difficulties are sometimes encountered with flashlamp pump dye lasers because irregular filaments in the flashtubes can result in poorly defined pump geometry.

Other important parameters for dye laser applications are the available light energy and power. The energies of pulsed dye lasers ranges from a few microjoules to more than 10 joules per pulse and the peak power ranges from milliwatts to more than 100 MW. Q-switched solid state laser pumped dye lasers can be used as an efficient wavelength converters in order to produce high-power tuneable radiation. Juhasz et al. (1988) obtained conversion efficiencies of up to 50 % with certain dyes under pulsed excitation. Continuous dye lasers, pumped by argon-ion lasers can provide powers from a few mW to several watts with an efficiency exceeding 10 %. The efficiency is generally lower if narrow linewidths are required.

Dye lasers are also versatile with respect to pulse duration where different applications require different pulse lengths. Flashlamp pump devices can provide pulses ranging from a fraction of a microsecond to several milliseconds. Laser pumped dye lasers operate in the region of less than 1 ns to several hundred nanoseconds. Mode-locking can reduce the pulse widths down to a few picoseconds (Hanna et al. 1986).
For some experiments, such as those relating to multiphoton absorption and non-linear optics, two or more intense, pulsed, independently tunable laser wavelengths are required simultaneously. As the duration of the laser pulse is typically of the order of 5 ns, synchronisation of two separate lasers is difficult due to the jitter in each of them. Two-wavelength dye lasers pumped by a single pulse which ensures that the outputs are co-temporal, avoid this difficulty. Several different types of two-wavelength dye lasers have been developed by several workers (McIntyre et al. 1985; Nenchev et al. 1985).

Dye lasers which do not have to meet extreme requirements can be technologically simple and the active medium is generally inexpensive and easily available. The problems of heat dissipation or material damage are easily avoided by circulating the liquid laser medium or operating in pulsed mode with very short pump pulse duration. Although better pump sources, such as suitable light emitting semiconductor diodes, would be desirable if dye lasers are to compete successfully with solid state lasers, gas lasers or semiconductor lasers in many applications which do not require wavelength tunability, the nitrogen laser pumped dye laser looks extremely attractive due to its low cost, short pulse duration, high peak power and reliability.

2.3.2 Excitation Conditions

In principle, by utilizing either the fluorescence or the phosphorescence emission, there are two possible ways of using an organic solution as the active medium in a laser. However, there are several difficulties associated with using the phosphorescence of a dye which makes it largely ignored. In contrast, if the fluorescence band of a dye solution is utilized, the allowed transition from the lowest vibronic level of the first excited singlet state to some higher vibronic level of the ground state will give a high amplification even at low dye concentrations. Therefore, generally we only deal with dye lasers of fluorescence emission.

Solutions of organic dye molecules exhibit relatively broad, continuous absorption and fluorescence bands. The visible and near ultraviolet absorption and fluorescence spectra of rhodamine 6G, a common laser dye in
methanol as solvent, are shown in Fig. 2.23. Stimulated emission or laser action can occur over the fluorescent band. The important features of dye laser operation can be explained qualitatively by a highly simplified energy level diagram of Fig. 2.24. The molecule has two groups of closely spaced electronic energy levels; the singlet states $S_0$, $S_1$ and $S_2$, and the triplet states $T_1$ and $T_2$. The electronic energy levels are not sharply defined, but are rather a band of levels formed by smear of vibrational and rotational levels. This is due to the complex intermolecular interactions and also by the effects of the molecule-solvent interactions.

If a molecule is excited by the absorption of light of optical frequency, $v_p$ from the ground state $S_0$ to the highest band of the first excited singlet state $S_1$, radiationless interactions bring the molecule to the bottom of $S_1$ within a few nanoseconds (Schafer 1973). Stimulated emission then occurs from the lowest level of $S_1$ to the higher levels of $S_0$. Non-radiative interaction will quickly bring the molecule to the bottom of $S_0$. The triplet states can play an important role in some dye lasers. Non-radiative transitions from the singlet levels to the triplet levels will produce a significant loss mechanism for the laser emission in many cases because the triplet states often have absorption bands in the wavelength region in which fluorescence occurs. Triplet-triplet absorption can also inhibit laser action if the absorption overlaps the fluorescence band. Due to the short pulse duration of the nitrogen laser used in pumping the dye, this does not play an important part although it affects the dynamics of flash-lamp pumped dye lasers and cw dye lasers. Therefore, for the nitrogen laser-pumped dye laser, we can neglect the triplet effects and restrict the discussions to the singlet states.

It is worth considering the excitation and lasing processes in more detail in order to arrive at the quantitative predictions for the relative population of the upper and lower states required to produce optical amplification in the dye medium. With reference to Fig. 2.24, absorption of pump radiation at frequency $v_p$ and cross-section $\sigma_p$ lifts the molecule from the ground state with population $N_0$ into the first excited singlet state $S_1$ with population $N_1$. If $N_0$ and $N_1$ are the thermalized population due to the optical excitation and distributed according to the Boltzmann distribution of molecules, it can be shown that under rapid thermalization the distribution functions are given by:

$$\text{52}$$
FIG. 2.23: ABSORPTION AND FLUORESCENCE SPECTRA OF RHODAMINE 6G IN METHANOL.
FIG. 2.24: SIMPLIFIED ENERGY LEVELS DIAGRAM OF A TYPICAL ORGANIC DYE MOLECULE WITH BROADEN ENERGY LEVELS.
\[ N_0(E_0) = F_0 g_0(E_0) \exp (-E_0/kT) \]  

for molecules distributed in \( S_0 \) with energy \( E_0 \) and

\[ N_1(E_1) = F_1 g_1(E_1) \exp (-E_1/kT) \]  

for molecules in \( S_1 \), where \( g_0(E_0) \) and \( g_1(E_1) \) are the degeneracy factors for the two levels, \( F_0 \) and \( F_1 \) are the normalizing factors and \( N_0 \) and \( N_1 \) are total number of dye molecules per unit volume.

The absorption coefficient for radiation of frequency \( \nu \) is defined by the relation:

\[ k_\nu = -(1/I_\nu)(dI_\nu/dx) \]  

where \( I_\nu \) is the intensity of radiation at frequency \( \nu \). For a simple system of two discrete energy levels, \( k_\nu \) can be written in terms of the Einstein coefficients for stimulated emission and absorption:

\[ k_\nu = \frac{h\nu n}{c} (B_{01}N_0 - B_{10}N_1) \]  

where \( n \) is the refractive index of the absorbing medium and \( c \) is the speed of light. For such a system laser action can only take place if \( N_1 > N_0 \), and this population inversion is accomplished by the broad width of the two energy levels which provide a means of achieving gain with optical excitation. It is appropriate to introduce the gain coefficient, \( \alpha(\nu) \) as the negative of the absorption coefficient:

\[ \alpha(\nu) = -k(\nu) \]
For the broad energy levels of the dye molecules, the Einstein coefficients are frequency dependent and thus:

\[ \sigma_0(v) = \frac{h\nu n}{c} \left[ B_{10}(v) N_1 - B_{01}(v) N_0 \right] \]  \hspace{1cm} [2.16]

It is customary to write this expression in terms of the frequency dependent cross-sections for stimulated emission \( \sigma_e(v) \) and absorption \( \sigma_a(v) \):

\[ \sigma_e(v) = \frac{h\nu n}{c} B_{10}(v) \]  \hspace{1cm} [2.17]

\[ \sigma_a(v) = \frac{h\nu n}{c} B_{01}(v) \]

and also the cross-sections are defined in terms of electron distribution functions (Stefanov and Rubinow, 1968):

\[ \sigma_e(v) = \int \sigma_e(E_1,v) N_1(E_1) dE_1 \]  \hspace{1cm} [2.18]

\[ \sigma_a(v) = \int \sigma_a(E_0,v) N_0(E_0) dE_0 \]  \hspace{1cm} [2.19]

Hence the gain coefficient can be written as:

\[ \alpha(v) = N_1 \sigma_e(v) - N_0 \sigma_a(v) \]  \hspace{1cm} [2.20]

The necessary condition for amplification at frequency \( v \) is that \( \alpha(v) \) is greater than 0 or

\[ \frac{N_1}{N_0} > \frac{\sigma_a(v)}{\sigma_e(v)} \]  \hspace{1cm} [2.21]

To determine the ratio of the absorption and emission cross-sections, assume that \( F_1 = F_0 \) and equating for up and down transitions:
\[ \sigma_c(E,v)g_c(E) = \sigma_o(E,v)g_o(E) \]  \hspace{1cm} [2.22]

where \( E_1 = E_0 + h(v - v_0) \) as shown in Fig. 2.24.  \hspace{1cm} [2.23]

From equations 2.11, 2.12, 2.17, 2.20, 2.22 and 2.23, we obtain:

\[ \frac{\sigma_c(v)}{\sigma_o(v)} = \exp \left[ -\frac{h(v_0 - v)}{kT} \right] \]  \hspace{1cm} [2.24]

The condition stated in equations 2.21 and 2.24 implies that the population ratio necessary for net amplification is given by:

\[ \frac{N_2}{N_1} > \exp \left[ -\frac{h(v_0 - v)}{kT} \right] \]  \hspace{1cm} [2.25]

From above it is clear that if \( v > v_0 \) the condition for gain is achieved only if there is a net population inversion between levels 0 and 1. For the case where \( v < v_0 \), amplification can occur even though there is no net population inversion. This is a very important distinction between a system of two discrete energy levels and a system of two broad bands.

2.3.3 Practical Pumping Arrangements

A wide variety of optical pumping and resonator schemes are possible for organic dye lasers. The ability to adjust the concentration of the dye molecules allows flexibility in adjusting the lasing solution to fit the spectral and spatial requirements of the pumping source. The nitrogen laser as a pumping source gives the advantage of precise control over the optical pumping geometry than is possible from a flashlamp.

In its simplest form a dye laser consists of a square spectrometer cuvette filled with the dye solution which is then excited by the pumping laser beam. As shown in Fig. 2.25a, the resonator is formed by the two glass-air interfaces of the polished sides of the cuvette and the exciting laser and dye laser beams are at right angles to each other. Reflective coatings on the
FIG. 2.25: LASER CAVITY CONFIGURATIONS FOR NITROGEN LASER PUMPED DYE LASERS.
windows consisting of a suitable metallic or multiple dielectric layers enhance the Q of the resonator. It is also possible to use antireflective coatings or Brewster windows at the cuvette and separate resonator mirrors. In the transverse pumping arrangement of Fig. 2.25a, the population inversion in the dye solution is non-uniform along the exciting laser beam, since the beam is attenuated in the solution. As a result, threshold might only be reached in a thin layer directly behind the entrance window of the exciting beam and thus gives rise to large diffraction losses and beam divergence angle.

A similar transverse arrangement is often used for nitrogen laser-pumped dye lasers but now the exciting beam is focused by a cylindrical lens into a line that coincides with the axis of a quartz capillary of inside diameter $d \approx 1$ mm, as in Fig. 2.25b. The presence of a thin coating of aluminium on the back surface of the tube, cause reflection of the transmitted pump beam. The focal line, $H$, is given by the product of the cylindrical lens focal length, $f$ and the nitrogen laser beam divergence, $\alpha$ and $H$ is best chosen so that it is about a quarter of the inside diameter of the tube. The end faces of the tube can either be normal to the axis and act directly as resonator mirrors, or set at the Brewster angle for use with external mirrors.

One particular design that has found widespread usage in recent years is the "Hansch" oscillator, Fig. 2.26 (Hansch 1972). The nitrogen laser radiation is focused into a line of about 0.15 mm width at the inner wall of a 10 mm long and 12 mm diameter dye cell by a 135 mm focal length spherical lens. To provide a near-circular active cross-section, the dye concentration is adjusted so that the penetration of the pump light is also of the order of 0.15 mm. Antireflection coated quartz windows are sealed to the ends of the cell under a wedge angle of about 10 degrees to avoid internal cavity effects. A plane output coupling mirror is mounted at one end of the cavity at a distance of 50 mm. The other end of the cavity contains an inverted telescope, consisting of two lenses $L_1$ and $L_2$ of focal lengths $f_1 = 8.5$ mm and $f_2 = 185$ mm and are used slightly off-axis to avoid back reflection and etalon effects. The laser is tuned by using a diffraction grating in a Littrow mount as the wavelength selective feedback element.
FIG. 2.26: BASIC COMPONENTS OF 'HANSCH' OSCILLATOR.
Melikechi and Allen (1986) reported a modified Hansch-type dye stage to operate two widely separated wavelengths. In the two-wavelength modification, the two portions of the collimated beam leaving the telescope are sent to different parts of the diffraction grating as shown in Fig. 2.27. The pumping nitrogen laser beam is focused transversely by means of a 40 mm focal length cylindrical lens into two different dye solutions. Light of one wavelength travels only through its own amplifying medium whilst the light of the other wavelength passes through both dyes and so suffers some attenuation. However, the spatial separation of the entrance windows of the two dye cells allows the second beam to travel through a layer of dye which is not excited by the pump laser beam, provided the dye concentrations are appropriately chosen. Two tunable, simultaneous, pulsed laser outputs separated by more than 50 nm in the green and yellow were obtained with Coumarin 540 (1 x 10^{-2} M in ethanol) and Rhodamine 590 (4.5 X 10^{-3} M in ethanol).
FIG. 2.27: TWO-WAVELENGTH DYE LASER (MELIKECHI and ALLEN, 1986).
2.4 DESIGN AND CONSTRUCTION DETAILS OF THE LASER SYSTEMS

2.4.1 Introduction

The main object of the development of the nitrogen laser pumped dye laser system is to use it in recording the laser generated events which evolved on a sub-microsecond timescale. In conjunction with a video photographic technique, the very short duration and high intensity of the laser pulses are ideal light sources for 'freezing' the events with high temporal resolution. The high peak power of the nitrogen laser provides a suitable pumping method for the dye laser and also the fact that the CCD image-recording device used in the video-imaging system is only sensitive down to wavelengths of around 400 nm, it is necessary to convert the ultraviolet radiation of the nitrogen laser into visible light. The dye laser is diffraction grating tuned to minimise the bandwidth of the laser beam resulting in a good spectral linewidth which is sufficient to illuminate the interferometer.

2.4.2 Nitrogen Laser

The transversely excited atmospheric (TEA) nitrogen lasers proved to be more popular than low pressure nitrogen lasers, because of their compact design, high power density, short pulse duration and the fact that they do not require a vacuum system. Bearing in mind the application of the laser system in high speed photography, several designs were initially considered. It was envisaged that the laser would be a multichannel system giving out two or more laser pulses which would provide sequence photography with excellent time resolution. This can be used to take, say, a series of interferograms on one frame of for double pulsing different dye lasers for high resolution interferometry. Several systems have been designed which made use of the multi-pulse capability and have been applied to the electron density measurement in a plasma focus device (Baltog et al. 1986), observation of the early development of laser generated waves by the absorption of a 20 J CO₂ laser pulse on a plexiglass target using a five channel laser (Hugenschmidt and Volradth 1978) and simultaneous pumping of two dye
FIG. 2.28: SCHEMATIC DRAWING OF THE NITROGEN LASER ASSEMBLY.
lasers by a double-channel nitrogen laser (Laval and Laval 1980). At the start of the project, several possible applications of the laser were considered although high-speed photography of laser interactions and pumping a dye laser were always given priority. We were not sure at this stage, of the final form of the laser and the eventual applications with respect to the photographic techniques being employed. Using a double pulsing source for illuminating the interferometer presents its own problem with the video photographic technique. The method will need two frame grabber/video camera systems in synchronisation. The associated electronics and synchronisation difficulties, although not impossible to overcome, are highly complex bearing in mind that they also need to be synchronised to the acoustic wave generating laser as described in section 3.3. However, the multipulsed capability with two wavelength output, could easily be adapted for use with SLR cameras, positioned at the two outputs of the interferometer. This can then be use in two wavelength interferometry but with the disadvantage of not having the video capability of viewing the interferogram immediately and digitally analysing them with a computer. It was decided, therefore, to design a laser with multi-pulse capability in mind.

The schematic diagram of the laser components is shown in Fig. 2.28 in which the principal dimensions are indicated. The laser is designed with the laser head positioned at one edge allowing another cavity, with the proper synchronisation, of the same design to be placed on top of it to allow multi-pulse application. This is a departure from the nitrogen laser designed by Baltog *et al.* (1986) whose design this laser is based on but with the important modification above and different from the usual printed circuit based laser designs where the channel is positioned such that the energy storage and pulse forming capacitors made up the sides of the cavity. The dielectric is exposed at least 25 mm all round acting as an insulator to prevent arcing across the edges of the capacitors plates, Fig. 2.29. The laser is excited by a conventional Blumlein circuit with low characteristic impedance, short circuited by a pressurised spark gap. The capacitors are etched from a double sided copper-clad printed circuit board with dielectric insulation of 1 mm and the dielectric constant of 5.97 made from fibreglass-epoxy material. The capacitance was measured using an AC bridge as 4.5 nF for the energy storage and 4.9 nF for the pulse forming capacitor.
TWO PIECES OF DOUBLE SIDED PRINTED CIRCUIT BOARD FOR THE CAPACITORS $C_1$ AND $C_2$. SPARK-GAP FILM 25mm. EXPOSED DIELECTRIC.

FIG. 2.29: TOP VIEW OF THE TEA NITROGEN LASER SHOWING THE ETCHED PRINTED CIRCUIT BOARDS USED AS THE CAPACITORS.
The brass discharge electrodes, Fig. 2.30, are 250 mm long with the electrodes having a round profile on the spark-gap side and a knife edge shape on the energy storage capacitor side. Baltog et al. (1986) has shown that the above profiles reduce the formation of electrical arcs where energy is dissipated and lost in these arcs thus no longer contributes to gas excitation. A 1.6 mm slot is milled in one of the electrode in order to incorporate the edges of the capacitors with their common ground plate insulated from the electrode by a layer of silicone rubber. This also serves to hold the capacitors in place and provides for good electrical contact. The electrodes are 'pegged' by mean of bolts and washers to the perspex covers with the provision for one of the electrodes to be adjustable in order to change the inter-electrodes separation. The adjustment of the electrode spacing has to be performed before commencement of laser operation. Lue (1985) reports that there is a noticeable improvement in laser output when electrodes spacing is slightly closer at the mirror end so that electrical excitation commences at this end and occurs in better synchronisation with the short laser pulse travelling towards the output end. This travelling wave discharge excitation does result in short laser pulses (Salzman and Strohwald, 1974). Bergmann (1977) suggests a spacing of 1 mm for every 5 kV of the static breakdown voltage of the initiating spark gap. The laser requires no optical windows since it is operated at atmospheric pressure and nitrogen gas flows freely out of the ends of the laser tube from an inlet through the perspex cover at the middle of the channel length. This effectively and continuously purges the laser system of air and possible contaminants. The flow rate is adjusted for some minimal value consistent with maximum observed output and this is about 1 litre/min. The mirror used is a front-aluminised flat of moderate quality and is adjusted for best apparent output collimation.

The design and development of an appropriate spark gap is important for the optimum performance of the laser system. The high potential difference across the storage capacitor must be transferred to the laser gap promptly and efficiently. The triggered spark gap switch, Fig. 2.31, is of low inductance (< 0.4nH) and is based on the design by Veith and Schmidt (1978) with the exception that the author's spark gap operates at high pressure filled with nitrogen gas. This serves to reduce the jitter and gives high reproducibility in the pulse to pulse operation. It also allows for precise
FIG. 2.30: BRASS ELECTRODES FOR THE LASER CAVITY.
FIG. 2.31: DETAIL OF THE SPARK-GAP DESIGN.
control of the breakdown voltage as well as having a noiseless operation. The electrodes are made of brass for ease of machining in the form of discs with rounded edges of 60 mm radius of curvature. The spark-gap has an earthed aluminium case of cylindrical symmetry with an outer diameter of 60 mm in contact with the bottom part of the capacitor. The central high-voltage electrode is of 15 mm diameter insulated from the case by nylon and is in direct contact with the upper part of the capacitor, hence the high-voltage supply. The electrode is adjustable in order to change the inter-electrodes distance even while in operation. The distance between the electrodes can be adjusted continuously according to laser operating voltage which is about 1 mm per 2 kV. The earthed electrode is 20 mm diameter with a hole (3 mm bore diameter) to accommodate the trigger pin from a car spark plug (1 mm diameter). According to Schmidt (1977), using a negative 12 kV trigger pulse provides for a strong electron field emission at the point of the inner trigger electrode and favours a fast breakdown between the earthed and the trigger electrodes. The gap is triggered by a trigger pulse from a laser trigger unit designed to work in repetitive mode or single pulse mode. The unit provides a 400 V pulse from a high voltage thyristor stepped up by a car ignition coil giving out a negative pulse of 12 kV.

The high DC voltage is provided by a Brandenburg Generator with a maximum supply voltage of 30 kV and current cutout limit of 0.5 mA. The supply is connected to the upper part of the pulse forming capacitor through a 10 MΩ current limiting resistor to prevent the current surges from damaging the supply and from tripping the current overload protection circuit. The two capacitors are electrically connected through a 5 kΩ resistor. Before the onset of spark-gap breakdown, the voltage on the upper plate of the pulse forming capacitor and the electric field across the spark gap is at the highest. The energy storage capacitor by the virtue of being connected via the resistor is also charged. The application of a trigger pulse to the gap initiates a breakdown and thus suddenly reducing the potential of the upper plate of the capacitor towards earth. The spark in the spark-gap may be viewed as a short-circuit, inducing a rapid transfer of charge and the voltage front travels away from the region of breakdown. There is a momentary drop of the full applied potential between the two electrodes inside the laser cavity immediately after the voltage front arrives at the gap. The resistor which
FIG. 2.32: SCHEMATIC OF THE BLUMLEIN DISCHARGE CIRCUIT, ELECTRICAL CONNECTIONS AND GAS HANDLING SYSTEM.
acted as a short circuit for the two electrodes before now appears as a relatively high resistance. This causes the breakdown of the gas and the potential difference collapses through the plasma very rapidly instead of through the resistor producing a glow type discharge to be established inside the cavity. The voltage pulse developed across the electrodes is extremely fast, limited by the inductance of the resistor connecting the gap and the associated inductances and impedances of the spark gap and pulse forming lines. The arrangement gives rise to strong electromagnetic interference in the proximity of the laser and creates problems when using electronic equipment located nearby. It is necessary to shield the laser inside an earthed metal box thus reducing rf interference outside the box. All earthed connections are connected to a common ground with their ends kept floating in order to avoid earth looping. Fig. 2.32, gives a schematic of the electrical connections and shielding as well as the gas handling system.

It is worth mentioning here about the simplicity and compactness of the design. The normal design of having the cavity in the middle of two flat capacitors arranged side by side results in enlarged dimensions of the laser system. The possibility of multi pulse operation is enhanced by positioning the laser cavity at the edge and stacking several cavities together, either side by side and or on top of each other, each being triggered from a master spark-gap. The channels can either be simultaneously triggered or delayed from each other by a laser trigger controlled unit to produce multi frame images for movie like sequence of events. The multi channel laser can also be used to pump a single dye laser to produce several pulses.

2.4.3 Dye Laser

In recent years several workers have adopted one particular type of pulsed dye laser cavity design first demonstrated by Hansch (1972) and it is based on this design that we set out to develop our dye laser. The schematic of the laser is shown in Fig. 2.33, with the stated principal dimensions. Precise and accurate determination of the output wavelength is not necessary in the interferometric measurements described in section 4.3 since we are only interested in the quantity \( \Delta f_\lambda \) (Optical Path Length). It was therefore decided
FIG. 2.33: SCHEMATIC DIAGRAM OF THE DYE LASER CAVITY.
to leave out the beam expanding telescope because the gain in the reduction of bandwidth does not severely affect the analysis of the recorded interferograms. The nitrogen laser beam is focused with a cylindrical lens into a dye cell containing the dye solution. The partially reflecting mirror provides feedback of some of the spontaneous emission from the excited dye molecules. Lawler et al. (1976) have shown that the optimum distance between the centre of the dye cell and the mirror is about 50 mm. The weak amplified spontaneous emission is incident directly on the Littrow mounted diffraction grating. Hence a narrow range of wavelengths is sent back to the dye cell, where further stimulated emission occurs at these wavelengths.

The 8 mm focal length cylindrical lens is made of high uv transmission BK-7 glass and is mounted on a longitudinal traverse for ease of focusing the nitrogen beam. The dye cell of 10 mm x 10 mm and 50 mm height is a fused quartz fluorimetry cell where the junctions between the entrance and exit windows are optically flat to avoid distortion of the dye laser beam. The cell is placed in an aluminium holder mounted on a modified x-y rotating mirror mount. A wedge has been placed at the foot of the holder tilting the cell by about 14° with respect to the exit windows of the cell. This serves to reduce the undesired stimulated emission from the excited dye molecules cause by the reflection of laser light from the solvent-glass and glass-air interfaces due to the exit windows being perpendicular to the dye laser beam (Hansch, 1972). The diffraction grating used is a 1200 lines/mm, 25 mm x 25 mm x 10 mm reflection grating blazed at 500 nm with a blaze angle of 17° 26'. The grating is mounted on a modified x-y rotation mirror mount for fine tuning the angular position of the grating and therefore the output wavelength of the laser. The output wavelength of the dye laser can be tuned by turning the Littrow mounted grating about an axis parallel to the grooves. Several dye solutions can be pumped by the nitrogen and Coumarin 500 in ethanol because of its better absorption in the uv. It is also desirable to use an illuminating wavelength that falls within the peak spectral response of the CCD video camera used for imaging the events. All components are rigidly mounted on their respective holders and mounts securely fastened to a 30 cm x 30 cm x 10 mm thick steel plate. The plate is then fastened to the optical table by suitable optical posts to avoid vibrations and movements.
The rectangular beam shape and relatively poor optical quality of the nitrogen laser requires that a transverse pumping arrangement be used (Hilborn, 1976). The dye laser is tuned by providing feedback at the desired wavelength to the pumped dye molecules. The very short pulse duration of the laser (~ 2 ns) means that the light diffracted from the grating must be returned to the dye cell while the dye molecules are still being pumped and this limits the optical path and hence the overall cavity length. To improve the resolving power, the angular dispersion of the grating must be made as large as possible. For grating in Littrow mount, Fig. 2.33a, angular dispersion, $D_\theta$, is given by (Hilborn, 1978):

$$D_\theta = \frac{d\theta}{d\lambda}$$  \[2.26a\]

$$= 2 \tan \theta / \lambda$$  \[2.26b\]

where $\lambda$ is the wavelength of the light output.

Dunn 1989 considers the combination of the dye cell and the plane mirror which terminates one end of the cavity, then in terms of geometrical ray tracing, he regards the dye cell as being illuminated by its image in the plane mirror. If $w$ is the beam radius at the dye cell, which is determined by the absorption length of the pump beam in the dye (= 0.1 mm), the approximate angular spread $\theta$ of the light propagating towards the grating is given by:

$$\theta_1 \approx w / 2L$$  \[2.26c\]

where $L$ is the distance between the mirror and the dye cell. He also gives the angular spread due to diffraction which ultimately determines the divergence of the beam within the cavity as:

$$\theta_2 \approx \lambda / \pi w$$  \[2.27\]
FIG. 2.33a: GRATING IN LITTROW CONFIGURATION.
For the above case and using Dunn's calculation, the geometrical spreading is about 1 mrad and diffraction spreading is 2 mrad. The equation relating wavelength to angle of incidence on the grating in the Littrow configuration is:

\[ n\lambda = 2d \sin \theta \]  
[2.28]

Therefore the spectral linewidth as determined by angular spread of the incident and diffracted light is:

\[ \delta \lambda = (\lambda/\tan \theta) \delta \theta \]  
[2.29]

If the light is allowed to strike the grating directly then a spectral linewidth of 3.27 nm is expected which is well below the minimum spectral resolution required of the laser for the purpose of our work. Laser parameters that also influence the wavelength selectivity include the Q and Fresnel number of the cavity, and the non-constant gain characteristics of the organic dye, so the grating selectivity can be used only as a guide in determining actual spectral linewidth.

2.4.4 Measurements of Laser Characteristics

2.4.4.1 The Detection System

The laser action may easily be detected visually if a UV fluorescent material e.g. a piece of white paper is held across the path of the nitrogen laser beam. The dye laser containing coumarin gives out visible laser radiation. Commercially available photodetectors for monitoring the laser signal and estimating the pulse width and the integrated energy include photomultiplier tubes, vacuum photocells and photodiodes. Photomultipliers with peak sensitivity of a few thousand amperes per Watt of incident power at around 337 nm and risetime of about two nanoseconds are available from various manufacturers. The cost and complexity of using the tubes render their use undesirable particularly when the cheaper photodiodes can give adequate
sensitivity and risetime.

For our measurements an Instrument Technology Limited vacuum photodiode with spectral sensitivity of 40 mA/W at 337 nm and 55 mA/W at 500 nm was the only useful detector available. The photocurrent pulses were detected across a 50 \( \Omega \) resistor by a 100 MHz bandwidth Textronix 466 analogue scope. The photodiode risetime of 1 ns was extended by the load resistor, the stray capacitance of the connecting wires and ultimately the scope amplifier. It was necessary to attenuate the laser beam intensity before shining it to the photocell. The beam was 'bounced' off a series of glass sides with the reflected beam being 4 % of the incident each time it hits the glass slide.

2.4.4.2 Nitrogen Laser

The laser beam was rectangular in shape and upon close inspection of the bluish glow discharge, it was seen to contain innumerable fine streamers. Using the arrangement as stated in chapter 2.4.4.1, the peak power at the optimum operating condition of 18 kV and 16 psi spark-gap pressure was found to be 98 kW. The recorded full width half maximum (FWHM) pulse duration at optimum condition was 4 ns, Fig. 2.34. Since the bandwidth of the Tektronic 466 oscilloscope used to measure the signal was only 100 MHz, the recorded FWHM duration of the pulse was extended by the internal electronics and the length of cable used to connect the photodiode to the oscilloscope. The pulse duration was also affected by the amount of laser beam incident on the photodiode. The vacuum photodiode used in the measurements has its photoemissive surface (the photocathode) placed inside a vacuum tube with another electrode, the anode, placed nearby and biased positively with respect to it. When the photocathode is illuminated the emitted electrons will be collected by the anode and current flowed in the external circuit. If the bias voltage is large enough (few hundred volts) all the emitted electrons will be collected and the current will be almost independent of the bias voltage and also will be proportional to the light intensity. The pulse width increases at high incident intensity. It was necessary to measure the highly attenuated beam until it just triggered the oscilloscope.
FIG. 2.34: TEMPORAL PROFILE OF THE NITROGEN LASER PULSE AT OPTIMUM OPERATING CONDITION OF 18 kV AND 10 psi SPARK-GAP PRESSURE. (Time Base : 10 ns/div).
There are many parameters that can affect the laser output power as discussed in chapter 2.2.3. The rear mirror which doubles the effective length of the laser channel was observed to increase the output power by a factor of two as might be expected. The variation of peak power output with voltage at different spark-gap pressures is given in Fig. 2.35. It appears from that, at 10 psi and spark gap distance of 8 mm, the output power increases linearly and it is not possible to explain at this stage whether it will continue to rise with increase voltage until non-uniform discharge and arcing starts to take place. It was also observed that the delay between input trigger pulse and the evolution of the nitrogen laser pulse was 24 μs with the jitter being reduced to about 100 ns at the optimum operating voltage of 18 kV and 16 psi spark-gap pressure.

It was observed that the laser output power also strongly depended on an arc-free uniform glow discharge. By permitting the end of the spark-gap side upper capacitor plate to extend slightly into the laser cavity, Fig. 2.28, preionization can be achieved (Bergmann 1976). This helps to reduce arcing and it is believed that the photopreionization results from uv light produced by the discharge in the large electric field region that exist at the edge of the extended capacitor plate during the electrical transient initiated by the spark gap.

2.4.4.3 Dye Laser

In measuring the peak power of the dye laser output, it was necessary to defocus the nitrogen pump beam to just below superradiance to avoid spontaneous radiation. At this stage the grating was isolated from the cavity and the dye ceased to 'lase'. By introducing the grating into the cavity and after careful tuning the dye started lasing, showing stimulated emission. This can be confirmed by again isolating the grating and the lasing should stop. With Coumarin 500 a peak wavelength in the green corresponding to the centre of the emission profile was observed and by tuning the grating either side of the brightest spot, a range of colours from blue (~490 nm) to yellow (560 nm) was obtained.
FIG. 2.35: VARIATION OF PEAK POWER AT DIFFERENT OPERATING VOLTAGES AND AT DIFFERENT SPARK-GAP PRESSURES AND ELECTRODES SEPARATIONS.
By using the same arrangement to calculate the peak power as before and with the vacuum photodiode spectral sensitivity of 55 mA/W at 500 nm, the peak power of the dye laser beam when pumped at the nitrogen laser optimum operating condition was found to be 6.36 kW representing an efficiency of about 6.49 %. 
2.5 REFERENCES


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3.1 INTRODUCTION

Since the invention of laser at the beginning of the 1960’s, its applications to various fields of science have been advancing rapidly. The laser’s ability to generate a well-collimated, intense beam of coherent light at a precisely defined wavelength make it a very versatile device. Lasers can be readily constructed to operate in continuous or pulsed mode with pulse duration from milliseconds down to picoseconds and at wavelengths from infrared to ultraviolet. The interactions of laser radiation with matter and their applications thereafter have been extensively studied. A whole range of research into high power laser applications in laser processing, laser annealing, laser fusion, laser monitoring of the atmosphere, lasers in medicine and to low power applications in optical fibre communications and spectroscopy were carried out. Not all the applications take advantage of all the features of the laser: laser welding, for instance mainly requires a high intensity, well-collimated beam that can be accurately focused, while others, say interferometry, utilise the accurate wavelength and high coherence.

Whilst there is no doubt that the greatest initial impact of lasers was on optical techniques, there are recent significant contributions of lasers in the field of acoustics. It was soon discovered that when an intense laser beam was focused into a liquid, an interesting phenomenon, bubble formation or cavitation and acoustic waves excitation, occurred. Many investigations of the effect of laser radiation interaction with liquids have been conducted, both experimentally and theoretically since the generation of sound by the absorption of laser radiation was first reported by Askar’yan et al. (1963). The contactless generation of acoustic waves in the media by optical
radiation had aroused the interest of physicists and yet only after the advent of lasers has the investigation of the optical excitation of sound been conducted on a large scale. The combination of laser techniques with ultrasonics has led to some exciting new discoveries and applications. The application of optical methods to ultrasonics predates the laser in such techniques as Schlieren photography for visualising the ultrasonic fields. However the advent of the laser has made such a large contribution to the subject that measurements using conventional light sources are now slowly falling into insignificance. The laser generation and diagnostics of ultrasound can thus be used in experimental studies of acoustic wave propagation. The study of acoustic wave propagation is difficult under transient conditions (i.e. short pulses). This difficulty is further evidenced when the waves undergo significant amounts of reflection, refraction, diffraction and mode-conversion. Transients associated with the laser-liquid interactions are rapid, generally propagating at the speed of sound in the liquid and the dimensions of the interaction region are usually small (~ 1 mm) with the acoustic wavefronts having thicknesses of about 10 μm.

As proposed by Hu (1969) and described by Emmony (1985) and Sigrist (1986), the generation of acoustic waves can be attributed to several important interaction mechanisms. Their effects are dependent on the optical and thermal properties of the liquid and the parameters of the incident laser beam. In transparent media, where sound generation due to ordinary absorption does not occur, dielectric breakdown is the dominant mechanism at laser intensities above \( \approx 10^{10} \text{ W cm}^{-2} \), which is easily obtainable from a focused pulsed laser. Felix and Ellis (1971) reported that micron size particles and dissolved air in the liquid have the effect of lowering the threshold and the formation of an opaque short duration plasma rapidly absorbs further radiation. According to Barnes (1969) a laser intensity of approximately \( 5 \times 10^{11} \text{ W cm}^{-2} \) is necessary to induce breakdown in well filtered water by the impact of a Q-switched ruby laser pulse. Laser induced dielectric breakdown in the bulk of the liquid associates with the formation of a plasma-filled cavity universally known as 'optical cavitation'. This leads to the production of a shock wave which propagates initially at supersonic speed in the medium. Lyamshev and Naugol'nykh (1981) reported that the efficiency of converting optical energy into acoustic energy by this process
can reach 30% making it the most efficient interaction mechanism.

In the case of an absorbing liquid, thermoelastic process, which is based on the transient heating of a finite volume by the absorbed laser energy, is the important sound generating mechanism. As a result of thermal expansion, the laser induced impulse causes a temperature gradient resulting in a stress in the liquid. This generates an acoustic wave which propagates away from the heated region. Efficient thermoelastic sound generation requires short duration laser pulses in the nanosecond region. The process occurs at low energy densities below the boiling point of the liquid (Emmony 1985) and has found interesting applications in photoacoustics, ultrasonics and non-destructive testing. Bunkin and Komissarov (1973) reported a conversion efficiency of < 10⁻⁴.

Absorption of the laser radiation at higher laser energy densities which exceeds the vaporization threshold of the liquid can lead to the generation of a vapour cavity and the formation of microbubbles. At higher energy densities, this is followed by vapour breakdown and for long duration laser pulses this can result in explosive vaporization with violent expulsion of liquid droplets, the emission of sound and light and the generation of high pressure shock waves in the liquid. The conversion efficiency for this process can reach 1.3% for a CO₂ infrared radiation interaction with water as calculated by Feiock and Goodwin (1972).

The fourth interaction mechanism which is always present in polarizable liquids due to the electric polarizability of molecules causing them to move into or out of the regions of high electric field gradients, such as those which exist in intense laser beams, depending on negative or positive polarizability. As a result of the movements of the molecules, a density gradient is established thus generating an acoustic wave similar to the thermoelastic process (Brueck et al. 1980). This interaction mechanism is known as electrostriction and is important as a sound generating mechanism in weakly absorbing liquids. Stimulated Brillouin scattering has been observed by Carome et al. (1966) for laser intensities below the breakdown threshold of the liquid and this is attributed to electrostrictive coupling (Chiao et al. 1964). As a stress wave generating mechanism, electrostriction is important
only for transparent media and for laser intensities that imply an electric field strength of the order of $10^7$ V cm$^{-1}$ (Sigrist and Kneubuhl 1978). For the case of water with a high absorption coefficient in the infrared, the effect is negligible but can be significant in cryogenic liquids such as N$_2$ and O$_2$. Sigrist (1986) also include a fifth mechanism, the radiation pressure. For the case of total reflection of the laser radiation at the surface of the medium, the amplitude of the radiation pressure is given by:

$$P_{\text{rad}} = \frac{I}{c}$$ \hspace{1cm} [3.1]

where $I$ is the laser intensity and $c$ is the velocity of light in vacuum. Taking as an example, an intensity of $10^6$ W cm$^{-2}$, one obtains a radiation pressure of 0.3 mbar compared to a few bars in the case of thermoelastic sound generation under identical conditions.

Askaryan et al. (1963) initiated the first laser-liquid interaction study when he directed a focused and an unfocused high power ruby laser beam into clear and coloured water, thus simulating different power densities and different levels of absorption by the liquid. For the clear water, bubbles were observed to appear in the path of a sufficiently high laser beam. He attributed this to rapid heating of various inhomogeneities in the liquid which acted as centres for vaporization and boiling. For the coloured water under focused radiation, the liquid was ejected from its container by much greater absorption of energy in the thin surface layer. Barnes and Reickhoff (1968) focused the Q-switched radiation from a 30 MW ruby laser into distilled water producing shock waves with peak pressure of up to 250 kbar. They used a photodiode arrangement to record the temporal profile of the generated plasma and found that the profile was similar to the profile of the 30 ns laser pulse but retarded by 15 ns. Fujimoto et al. (1985) studied the early development of the laser generated plasma at delays of less than 10 ns. They used a frequency doubled 10 mJ, 10 ns duration pulse from Nd-YAG laser. The emitted acoustic waves were found to propagate at the sound speed of the liquid for delays greater 60 ns. This corresponds to a shock radius of 100 $\mu$m.
Sigrist (1986) used a grating tuned hybrid CO$_2$ laser giving 10.6 $\mu$m radiation, to carry out thermoelastic studies of the laser interaction in pure H$_2$O and D$_2$O. The focused laser beam was directed vertically into the free and rigid boundary of the liquid. The detection of the acoustic signal was carried out in real time with a fast piezoelectric transducer. Acoustic waveforms were calculated analytically on the basis of a model laser pulse shape which they formulated and they found good agreement between the theoretical and experimental results with respect to waveforms and amplitudes.

Berthelot (1989) investigated the acoustic field excited in a liquid by a train of pulses. He reported an expression for the optimum repetition rate determined by the optical frequency of the laser and the laser beam diameter. As a result of the study, a continuous thermoacoustic highly collimated sound beam could be generated by high repetition rate pulsed lasers in such a way that the signals are easily detectable several kilometres away from the source. This thermoacoustic generation of sound beams in the ocean has potential military applications.

The application of Mach-Zehnder interferometric techniques to the diagnostics of laser-liquid interaction work was reported by Emmony et al. (1980). The authors studied the effect of the 10.6 $\mu$m radiation from a CO$_2$ laser on water by recording the generated acoustic wave on a single interferogram captured on a conventional camera. The event was illuminated by an ultraviolet pulse from a nitrogen laser.

In the experimental works described in this chapter and the following chapters 4 and 5, the interaction of a Q-switched Nd-YAG laser radiating at 1.06 $\mu$m with water and the subsequent generation and propagation of acoustic waves are studied using high speed photographic techniques. The production of infrared laser induced high frequency acoustic waves in water near a neighbouring solid is thus a convenient method of generating stress-waves in the solid. Most of the benefits of laser generated acoustic waves are similar to optical diagnostics of the ultrasonic fields. It offers a technique which is non-contact, remote and having high spatial and temporal resolution. The problems of stress-wave propagation are of particular interest.
in non-destructive testing (Burger et al., 1982), geophysics (Rowlands et al., 1974) and excavation and mining (Reindhart et al. 1971). There are several other possible applications of laser generation of acoustic waves and the diagnostics of their propagation. The study of acoustic wave propagation through anisotropic materials that are very difficult to model theoretically, can be carried out in laboratory condition with ease. A pulsed laser can be used to generate broadband elastic waves in composite materials, either in combination with a laser interferometer receiver or an alternative broadband receiver (Buttle and Scruby, 1988). Another application might be in scaled-down measurements of geological structures, for example sub-sea exploration for oil and gas deposits depend on acoustic measurements using a broadband source (small explosion) and hydrophone detectors. Model experiments in the laboratory can be carried out using a pulsed laser source and a broadband optical receiver with a suitable scale factor.

3.2 LASER INDUCED OPTICAL BREAKDOWN

The transient physical phenomena which accompany the optical breakdown process, namely plasma formation, acoustic wave generation and propagation, as well as cavitation bubble formation have attracted considerable interest, non more so than in the field of ophthalmic surgery. The investigation of the properties of Nd-YAG infrared laser induced optical breakdown in liquids has become increasingly popular. Among liquids, water, either in distilled, deionised or ultrapure form, has been extensively investigated as a plausible model for ocular media due to interest in the field of laser eye surgery. Laser induced optical cavitation formed as a result of dielectric breakdown of the liquid in the close vicinity of solid surface is also a useful technique for studying the phenomenon of cavitation erosion under laboratory conditions (Tomita and Shima, 1986). The joint action of a high-speed liquid jet and compressional acoustic waves formed as a result of cavitation-bubble oscillation can cause pitting on the solid surface due to the erosive action of the collapsing cavity (Knapp 1955).
The laser liquid interaction models have been considered by several authors and the thermoelastic process has been theoretically and experimentally studied. This process offers the advantage of being fairly well understood and easily controllable and thus has found a wide application. The first theoretical treatment by Gournay (1966) was concerned with a 1-D model with uniform heating of the surface and absorption following normal Beer's Law, \( I = I_0 e^{-\alpha x} \) where \( \alpha \) is the absorption coefficient. In the case of water, \( \alpha \) is \( \sim 10^{-6} \) cm\(^{-1}\) in the visible and rises to \( 10^3 \) cm\(^{-1}\) at 10.6 \( \mu \)m, the CO\(_2\) laser wavelength (Emmony 1985). Assuming for low thermal conductivity in the liquid, the process is adiabatic and strain only occurs normal to the surface where the particle displacement, \( u \), is given by:

\[
\frac{\partial^2 u}{\partial x^2} - \frac{1}{c^2} \frac{\partial^2 u}{\partial t^2} = \beta \frac{\partial \theta}{\partial x}
\]

where \( \beta \) is the coefficient of thermal expansion, \( \theta \) is the temperature rise and \( c \) the sound velocity. The reported discrepancy (Hutcheson et al. 1971) between the 1-D model and observed experimental acoustic pulse is attributed to non-linear effects in the generation of acoustic pulses. Hu (1969) presented a 3-D model with an analytical treatment of the thermoelastic spherical waves. The model predicts a symmetric pressure pulse with respect to the time axis with the peak amplitudes proportional to the laser power and inversely proportional to the radius of the pressure pulse. Hu also specifies in the model that the time separation, \( T \), between the compressive and rarefraction pulses is dependent on the duration of the incident laser pulse. The symmetry and the \( 1/r \) law have been verified by Sigrist and Kneubuhl (1978). They also discovered the inadequacy of the model where the theoretical time dependence though symmetry deviates considerably from experiment, Fig. 3.1, and \( T \) is dependent on the properties of the liquid and not the duration of the laser pulse. The authors proposed a 3-D heat pole as the thermal source which arise from the absorption of the laser pulse in the liquid surface. The temperature distribution, \( \theta(r,t) \) is represented by the three dimensional heat pole:

\[
\theta(r,t) = \frac{|E/\rho s(4\pi kT)^{3/2}|}{\exp(-r^2/4kT)}
\]
FIG. 3.1: THEORETICAL THERMOELASTIC ACOUSTIC WAVE ACCORDING TO HU (1969) (---) SUPERIMPOSED ON THE EXPERIMENTAL RECORD OF SIGRIST AND KNEUBUHL (1978) (----).
where \( E \) = absorbed laser energy
\( \rho \) = density of the liquid
\( s \) = specific heat of the liquid

No information on the time dependence of the laser pulse is contained in the model and hence it only refers to a short duration laser pulse. Their solution of the wave equations leads to the pressure \( p(r,t) \):

\[
p(r,t) = \frac{\rho EC^3}{2\pi^2/2r_0^3} \left( t - \frac{r}{c} \right) \exp \left\{ -\left[ \frac{c}{r_0} \left( t - \frac{r}{c} \right)^2 \right]\right\}
\]

where \( r_0 \) is the radius at which the laser energy density is \((1/e^2)\) of its maximum value.

When the pulsed radiation from a Q-switched Nd-YAG laser is focused into the interior of a transparent liquid, molecular absorption, which leads to heating, may initiate the onset of laser induced breakdown around the focal point if the peak optical power density of the beam exceeds the vaporization threshold. The processes of laser generation of acoustic wave are strongly non-linear if explosive boiling, dielectric breakdown and plasma formation take place in the medium. The production of the short duration plasma which rapidly absorbs further radiation, heats and vaporizes the adjacent liquid, forming a localised body of high temperature vapour and a cavitation bubble. The enclosed pressure of the cavity is much higher than the ambient pressure of the surrounding liquid. The high pressure expands the cavity causing its walls to move outward at velocities greater than the speed of sound of the liquid thereby generating a high-frequency spherical acoustic wave which propagates away from the laser focus. The bubble undergoes several expansions and contractions (collapse) and these oscillations have been extensively studied by several workers; Lauterborn 1980 and Vokurka 1987. Ward and Emmony (1990) investigated the focused infrared Q-switched laser generated cavitation bubbles in water. Depending upon the initial position of the bubbles with respect to the free and rigid boundaries which enclose the liquid, these bubbles undergo two or more radial oscillations on a timescale of about half a millisecond of which the first cycle occupies 200\( \mu \)s. For heavily-damped oscillations and bubbles generated in a large expanse of
liquid, the rebound radius $R_{m2}$ is a small proportion of the initial maximum radius $R_{m1}$. Bubbles formed near boundaries suffer lightly damped oscillations and $R_{m2}$ is a much larger fraction of $R_{m1}$. They give a plot of the notional radii of typical symmetrically and asymmetrically oscillating bubbles as a function of time, Fig. 3.2.

The presence of a certain threshold before laser induced breakdown can occur in the liquid, makes it an important feature of the laser-liquid interaction. The threshold value depends on the properties of the liquid. The presence of solid microparticles in the medium, determines the value since such particles absorb the radiation and are heated to temperatures of the order of $10^4$ K (Lyamshev 1981), which corresponds to the first order ionization of the atoms and formation of a dense plasma. Light is absorbed strongly in the plasma, which causes further heating. Crum (1980) observed that the acoustic cavitation threshold of water is substantially below the theoretical threshold for inception based upon homogeneous nucleation of a cavity within the liquid.

Although much experimental work has been done on the optical breakdown and prebreakdown phenomena in liquids, a theory of these phenomena as a whole and of the excitation shock waves is still continuously being developed. The excitation, propagation and evolution of the acoustic waves are described by the simplest model of the phenomena based on experimental observations and on ideas developed in the theory of underwater explosions and pulsed electric discharges (Cole, 1948)

The experimental work described here is centred on a Mach-Zehnder interferometer, described fully in section 4.4, around which a dynamic photoelastic method has been developed, detailed in chapter 5, and beam deflection techniques of shadowgraphy and schlieren are also carried out. Highly localised optical breakdown in water is generated by a Q-switched Nd-YAG laser and visually recorded using a video photographic technique with an illuminating nitrogen-dye laser light source. A computer which controls the operation of the frame grabber also serves to store the digitally recorded images for eventual processing and analysing. The details of the experimental methods and apparatus are described in the following sections.
FIG. 3.2: PLOTS OF THE RADIUS OF A LIGHTLY DAMPED (THICK LINE) AND A HEAVILY DAMPED (THIN LINE) OSCILLATING CAVITATION BUBBLES PRODUCED BY A FOCUSED Nd-YAG LASER IN WATER (WARD, 1991).
3.3 GENERATION OF ACOUSTIC WAVES

3.3.1 Nd-YAG Laser System

Extensive use of the Nd-YAG laser as a source of generating highly localised and reproducible plasma associated events in the liquid started just after its development in mid 1960's. The focused laser radiation has found popular use in performing non-invasive intraocular surgery by photodisruption because at low intensity the 1.06 μm radiation will only be weakly absorbed by all parts of the eye and the fluence can easily be kept below the threshold on the retina. The output from the Nd-YAG laser is used to stabilise retinal detachment and to disrupt in cutting and drilling in the treatment of a range of eye disorders. Lauterborn (1972) first showed that a Q-switched laser is an effective tool for investigating cavitation bubble dynamics and opened a new avenue of optical cavitation. Using a laser has the notable advantage that the bubble generation is precisely controlled both temporally and spatially without causing any disturbance in the liquid.

The active medium for this laser is yttrium aluminium garnet (Y₃Al₅O₁₂) with the rare earth metal ion neodymium Nd³⁺, present as impurity, providing the energy levels for both transitions and pumping. The YAG host does not participate directly in the lasing action but provides the so called crystal field which modifies the transition probabilities between various energy levels of the Nd³⁺ ions so that some forbidden transitions are now allowed. It is essentially a four level system and population inversion is achieved by pumping the Nd³⁺ ions using an intense flash of light from a xenon flash tube fired from a discharging capacitor bank. Q-switching the laser provides for short, intense bursts of radiation. In non Q-switched mode, the output consists of many random 'spikes' of about 1 μs duration with a separation of about 1μs and peak power in the order of kilowatts. When the laser is Q-switched, however, the result is a single spike, typically in the megawatt range and ~ 10 - 100 ns duration. It is a near infrared pulse with wavelength of 1064 nm. Although Q-switching results in a vast increase in peak power, the total energy emitted is less than in non Q-switched operation due to losses in the Q-switching system and spontaneous fluorescence.
The generation of acoustic waves in our studies was carried out using a JK-Lasers System-7839 Mini-Q Nd-YAG laser giving an 8 ns, 10 mJ Q-switched output pulse. The linearly polarised beam had a temporal jitter of about 100 ns and the beam diameter at the output was 1.2 mm. The laser was operated in TEM\(_{00}\) uniphase mode with spectral linewidth of about 100 pm and 10 mm coherence length. The symmetrical and Gaussian properties of the uniphase beam was checked by recording the considerably attenuated beam on a CCD video system and profiling the digitally recorded image. The laser system comprised a power supply unit, a control unit and a Pockels-cell Q-switch driver, in addition to the laser head which has an internal cooling system. The external cooling system is required if the laser is operated at high repetition rates but for the normal operating frequency of \(~1\) Hz in our work, the internal cooling was sufficient. Maximum population inversion in the Nd\(^{3+}\) ions was achieved by switching the Pockels cell at a constant delay of 145 \(\mu\)s after the initial trigger pulse with a bias voltage of 4 kV. By varying the supply voltage on a 40 \(\mu\)F charging capacitor up to a maximum of 1 kV, the output energy of the laser beam, which depends on the energy supplied to the xenon flash tube, can be varied. The laser head was positioned vertically such that the incident infrared beam was normal to the plane of the interferometer. This required the head to be securely mounted on a vertically positioned optical rail clamped to a rigid rig on the optical bench. The synchronous firing of the laser with the recording apparatus described later, was achieved by applying a 100 ms, 12 V pulse to the 'external trigger' input on the control unit. This signal was passed to the Pockel cell driver where the 145 \(\mu\)s Q-switched delay was automatically introduced. The laser is also capable of operating on internal mode in which case the trigger is provided by the control unit. A typical trace of the Nd-YAG laser pulse temporal profile is shown in Fig. 3.3. This was obtained by directing a highly attenuated beam on to a 1 ns risetime ITL vacuum photodiode connected to a Textronix 466 oscilloscope. The FWHM of the pulse was measured to be 8 ns with pulse to pulse variation of less than 1 ns. The short pulse duration and high peak power of the Q-switched infrared laser pulse enabled the Nd-YAG laser to be an excellent generator of ultrasound.
FIG. 3.3: TEMPORAL PROFILE OF THE Nd-YAG LASER PULSE AT THE OPTIMUM OPERATING VOLTAGE OF 800 V. (Time Base : 10 ns/div).
3.3.2 Focusing Arrangement

An actual laser beam may give different results from an ideal one due to diffraction effects and lens aberrations. In a real lens, a geometrical blur circle is formed at the front of the paraxial focus and thus the laser beam has a finite spot size at the focal point. Additionally, the beam intensity is not uniform in space and these conditions thus require a suitable control of the laser beam energy to generate the smallest focal spot size in order to exceed the energy threshold for optical breakdown in water. It is imperative to talk about Gaussian beam focusing in finding the suitable arrangement for our experimental setup.

Fig. 3.4 shows a Gaussian amplitude distribution in the transverse direction of the lowest order mode laser beam. The electric field amplitude, \( E \) varies in the transverse dimension, \( r \) as:

\[
E = E_0 \exp\left(-\frac{r^2}{w^2}\right) \tag{3.5}
\]

where \( E_0 \) is the central amplitude (at \( r=0 \)) and \( w \) is a measure of the width of the distribution, commonly known as spot radius (spot size) when \( r = w \) and \( E = E_0/e \). The beam has an irradiance profile:

\[
I(r) = I(0) \exp\left(-2r^2/w^2\right) \tag{3.6}
\]

where the peak irradiance is related to the optical power \( P \) in the beam by:

\[
I(0) = \frac{2P}{\pi w^2} \tag{3.7}
\]

The spot size \( w \) can be defined as the effective radius of the beam (the radius at which \( I \) drops to \( I(0)/e^2 \)). All Gaussian beams have a position along their axis at which the wavefront become plane and the spot size goes through a minimum, Fig. 3.5, which gives the beam waist. The variation of the radius, \( w \), along the propagation axis can be written as:
FIG. 3.4: THE VARIATION OF FIELD AMPLITUDE, IN THE TRANSVERSE DIRECTION FOR A GAUSSIAN BEAM.

\[ E = E_0 e^{-r^2/w^2} \]
FIG. 3.5: GEOMETRY OF A GAUSSIAN BEAM AT THE FOCAL REGION SHOWING THE WAIST POSITION.
where \( z_R = \frac{n' \lambda}{2} \) and is known as the Rayleigh range.

In the paraxial approximation, the half-cone angle of the divergence \( z/z_R \) is given by:

\[
\theta_D = \frac{w(z)}{z} = \frac{\lambda}{\pi w_0} = \frac{w_0}{z_R}
\]

The two regimes \( z \ll z_R \) and \( z \gg z_R \) are generally known as the near-field and the far-field region respectively.

The effect of focusing the beam as given by Walker (1989) gives the focal spot as:

\[
w_0' = \frac{\lambda f}{\pi w_L}
\]

where \( w_L \) is the radius at the lens and assuming the lens f-number is small compared to \( 1/\theta_D \). The new waist will be near the focal point of the lens and the radius given by equation 3.10:

\[
w_0' = 0.64 FL
\]

where \( F \) is the f-number of the lens \((F = f/2w_L)\). It is interesting to note that 86 \% of the power passing through the lens falls within the radius \( w_0 \) and gives a measure of the degree by which an optical beam is being focused.

The total power within radius \( a \), from the axis of a Gaussian beam can be obtained by integrating equation 3.6:

\[
P_a/P = 1 - \exp(-2r^2/w^2)
\]

This indicates that at spot radius of \( r = w \), the power enclosed is 0.865 of the total power enclosed in the beam. In designing an optical system through which a Gaussian beam is to be relayed, it is usually sufficient to make all
apertures and lenses $> 3w$ in diameter, provided the beam remains accurately centred. However, diffraction based calculations are rarely sufficient when considering the focusing of Gaussian laser beams. Geometric aberrations, particularly spherical aberration, are particularly significant contributors to actual spot size. Only when large f-numbers are being used (e.g. $F > 10$, for visible wavelengths) will the focus produced by a single (optimum) shape thin lens be the size predicted by Gaussian beam formulae.

The focusing arrangement for the generation of acoustic waves is shown in Fig. 3.6. The laser beam was expanded using a 25 mm focal length, 10 mm diameter plano-concave lens before being focused by a 28 mm focal length, f/2 wide angle camera lens. The first lens served to expand the laser beam diameter to fill the aperture of the camera lens to give minimum spot size at the focus. This gives a theoretical beam waist of about 2.7 $\mu m$ and a beam cone angle of $28^\circ$ in air. Due to the refractive effect at the air-water interface, the full cone angle of the beam was reduced to only $20^\circ$ in water. A more realistic beam spot size of 20 $\mu m$ in air was adopted after measuring the highly attenuated focused Nd-YAG beam at a point. This represents an optical power density at the focus of about 50 $GWcm^{-2}$.

The laser interactions took place in different cuvettes. The most successful in terms of ability to obtain good interference fringes were made from parallel machined aluminium plate with a 'U' shaped section cut from them. Two microscope slides (1 mm thick) were then carefully stuck with thin epoxy to the flat faces. Two cuvettes were made from adjacent areas on the aluminium plate. The polymers used in the study were machined with great care in order to reduce the permanent mechanical and thermal stress in the test blocks which had dimensions, (25 x 25 x 9) mm. The block was then placed in the water filled cuvette. The cuvettes were positioned normal to their respective interferometer arms at the focal plane of the final focusing lens.
FIG. 3.6: EXPERIMENTAL SET UP FOR THE LASER GENERATED ACOUSTIC WAVE IN WATER.
3.4 OPTICAL DETECTION OF THE ACOUSTIC TRANSIENTS

3.4.1 Introduction

The experimental arrangement for the recording of the laser-interaction studies is centred around a Mach-Zehnder interferometer, described fully in section 4.4. The interferometer, lit by a pulsed nitrogen laser pumped-dye laser light source, is used in conjunction with a video-imaging and capture system and in addition a He-Ne laser is used in the alignment procedure, Fig. 3.7.

3.4.2 Nitrogen Laser-Pumped Dye Laser System

The extremely fast evolution time (sub microsecond) of the laser-interaction events and the high resolution needed to gather the necessary information regarding the wave propagation, requires an illuminating source of extremely short duration and excellent temporal jitter. The adoption of a video photographic technique eliminates the need for the multipulse system, proposed in section 2.4, at least in the scope of this project. The moderately high temporal jitter of the home built nitrogen laser-pumped dye laser, although sufficient in conventional photography, poses significant technical problems when used in conjunction with the computer controlled video imaging system. However, a commercial nitrogen-dye laser system with very low jitter became available to the author at the start of the experimental works on laser-interaction studies.

The system was based on a PRA Nitromite model LN103 TEA nitrogen laser pumping a PRA LN102 Dye Laser which, when operated with the dye Coumarin 500, was tuned to emit visible radiation at wavelengths centred upon 514 nm with a coherence length of about 20 μm and a beam divergence of 4.4 mrad. The nitrogen laser itself produced a 0.3 ns duration, 80 μJ pulse operating in the ultraviolet region of the spectrum at 337 nm. The laser was operated at atmospheric pressure with the pressurised spark gap kept at 20 psi and an optimum operating voltage of 13.5 kV. When
FIG. 3.7: GENERAL EXPERIMENTAL ARRANGEMENT FOR THE LASER-INTERACTION STUDIES.
externally triggered by a 100 ns duration, 5 V TTL pulse, the delay between the input trigger pulse and the evolution of the laser beam was 37 μs with a reported temporal jitter of 2 ns. It was necessary to convert the ultraviolet light of the nitrogen laser into visible light because the video camera utilised a solid state CCD device that was only sensitive down to 400 nm. A further problem with using 337 nm is that this wavelength is strongly absorbed in compound lenses (in the cement) and good quality singlets are difficult to obtain and uncemented doublet is expensive. The pumped dye laser, when tuned to the peak spectral emission of Coumarin 500 at 514 nm, produced a slightly extended pulse of 0.5 ns duration and spectral line width of about 10 nm. The output pulse energy of 15 μJ represented an efficiency of 19 % and a transient power output of 30 KW. This was sufficiently great to illuminate the interferometer for clear illumination of a field of view of 10 mm diameter. The total jitter of the illuminating laser system and the ultrasound generating Nd-YAG laser were small compared to the duration of the measured events.

Before entering the interferometer, the light from the dye laser was directed through a beam collimating system. The amplitude of the wave of the probe laser beam is not uniform across the wave front but drops off from the centre as a Gaussian function. In practice the wave amplitude has further irregularities, diffraction patterns caused by surface defects or dust on the various components. These can be removed by passing the light through a spatial filter. The dye laser beam was first passed through a x40 microscope objective which then focused it to a point image, of Gaussian form rather than an Airy disk (Steel, 1983). A 50 μm pinhole placed at this image allows the direct beam to pass but stops any light diffracted by defects. The pinhole was mounted on a traverse which allowed lateral motions for better location of the focus. The clean emerging beam was then collimated to a parallel beam of 25 mm diameter by a 50 mm focal length, f/1.7 camera lens. The recombined light at the output of the interferometer was focused to the sensing device on the video camera by a 135 mm focal length, f/2.8 telephoto camera lens.
3.4.3 Video Imaging and Capture System

The extremely fast event associated with the laser interaction necessitates the use of a very accurate and consistent timing sequence to synchronise the Nd-YAG laser and the nitrogen-dye laser system. Normal photographic techniques using rotating mirror, rotating-drum and image converter cameras have insufficient temporal resolution to 'freeze' the high-speed acoustic transients. A simple SLR camera and conventional film has been used for earlier experiments when testing the home built nitrogen laser pumped dye laser systems. The pumped dye laser was synchronised by means of an electronic trigger unit initiated by a pulse generated by the flash-synch facility of the SLR camera to photograph breakdown across a spark gap. Although the results were very encouraging, however, the use of conventional photography would mean delays associated with developing and printing of the photographs. Analysis and evaluation of the recorded images are slow and this limit the rate at which data can be generated from the experiments. The video technique provides for immediate and real time viewing of the interactions and interesting events are less likely to be missed.

The main components of the imaging system consisted of a NEC TI-22C interline transfer CCD video camera, an Eltime Image III monochrome digital frame store, a laser trigger unit and an Amstrad 1640 personal computer, Fig. 3.8. The use of the video monitor is to display the images, either real time or captured, while the video printer will print the desired pictures. The function of the Philips PM3311 digital storage oscilloscope was to measure the respective synch signals of the acoustic wave generating and illuminating laser systems. This served to accurately display the delay between the two lasers by using the synch pulse of the first laser to trigger the oscilloscope.

The solid state CCD video camera used as the sensing device was operated at the 50 Hz mains frequency giving an interfield time between successive images of 20 ms. For image capture using the frame store, the 500 $\mu$s field-synch pulse of the camera was used as a reference against which all timing delays were made. The sensitivity of the CCD unit ranged from 400 to 1100 nm and the output wavelengths of both lasers fell within this range.
FIG. 3.8: VIDEO-IMAGING AND -CAPTURE SYSTEM.
It was therefore necessary to use a narrow bandwidth interference filter with peak transmittance at 510 nm in order to remove the scattered Nd-YAG radiation. This also served to remove a large proportion of the background white light and significantly reduced the effect of flash produced by the breakdown.

The use of the video camera, however, prohibited the recording of multiple pictures of the progress of a single laser-interaction event. With the acoustic wave velocity in the region of 2 mm/μs, it would be impossible to follow the propagation of a single wave from its generation using the same CCD image sensor with its 50 Hz framing rate. Due to the excellent reproducibility of the two lasers, and the events themselves, this can be overcome by operating the system in single pulse mode to produce a single frame representing a unique stage in the propagation of the wave. It was therefore necessary to capture and retain a single 20 ms field of information from the video camera for each stage of the event. The digital frame store served this purpose and it was operated as four separate 64 kbyte field stores, each with a resolution of 256 x 256 pixels with 64 grey levels of light intensity in each pixel. The store was linked to the computer via an interface card where the captured images were stored for eventual processing and analysing. The recorded pictures, which each occupied 64 kbyte of computer data storage facility were stored permanently in an external tape backup system, which can take up to 600 pictures, after initial saving on the computer's own 20 Mbyte hard disk.

The incoming 1 V video signal was synchronised to the frame store by the application of a 150 μs TTL pulse from a laser trigger unit. This pulse instructed the image capture circuitry to accept the next complete field of data reaching it. The laser trigger unit provided an accurate synchronisation of the two lasers with respect to the field snatch frame store. Taking its cue from the 50 Hz field synch pulse of the video camera, the trigger unit initialised the frame store, then provided the pulse for the Nd-YAG to start the event and finally, after suitable delay introduced by the operator, provided the trigger pulse to fire the nitrogen-dye laser to illuminate the event. The unit can be operated in an automatic mode where a continuous train of low frequency (1 Hz) TTL pulses were generated or in manual mode, where an event can be generated and recorded by a simple push button.
The scheme by which the frame store was controlled from the computer was centred around computer software developed for the video photographic studies of laser induced cavitation bubbles in water (Ward 1990). The main part of the computer program, written in Turbo Pascal compiler, was to extract information from the digitally recorded images and carrying out calculations and measurements on the retrieved data. The automatic evaluation of the results obtained from the interferometric setup, which involved the use of Abel inversion techniques described in section 4.4, were carried out by the computer after feeding in the relevant information required by the program. In all the techniques used here (schlieren, shadowgraphy and dynamic photoelasticity), it was usual to enhance the recorded images by simply subtracting a constant background image, Fig. 3.9a from a particular image of the event, Fig. 3.9b. This results in the enhanced dynamic photoelastic fringe pattern of Fig. 3.9c. The measurements of acoustic wave positions were carried out from the keyboard using cursors on the screen after first calibrating the program with prerecorded horizontal and vertical scaling procedures in the form of an image of a mm ruler placed at the breakdown site. Hard copies of the digitally recorded pictures can be produced by a Mitsubishi Video-Copy Processor P60B thermal device with a grey scale resolution of 16, which was adequate for normal inspection and is used for all the laser interaction events imaged in this thesis.

3.4.4 Focused Shadowgraphy and Schlieren Techniques

Recording of the events in shadowgraph and schlieren modes, although not utilised as quantitative diagnostic tools, allowed accurate measurements of the acoustic wave position and dimensions. In its simplest form, the shadowgraph technique does not need any optical component, and the effect can be observed in many situations outside the laboratory. The utilisation of the shadow effect for scientific testing was first carried out by Dvorak (1880) and since then the arrangement has been extensively used in the study of shock waves. An essential feature of the method is the use of a point light source. The light diverging from this point source is transmitted through the test field, and the shadow picture produced by the inhomogeneous density field can be recorded in a vertical plane placed at a distance $l$ behind the
FIG. 3.9: (A) BACKGROUND (B) ORIGINAL ISOCHROMATIC FRINGE PATTERN AND (C) ENHANCED IMAGE OF (B), WHERE THE HORIZONTAL BAND IS THE BOUNDARY BETWEEN THE SOLID (BOTTOM) AND LIQUID (TOP). LASER BREAKDOWN CENTRED ON THE CAVITATION BUBBLE (DARK CIRCULAR AREA).
Instead of the simple arrangement stated above, a shadowgraph system can be represented by a parallel light beam through a test facility, as shown schematically in Fig. 3.10. Light from the point source is collimated by L₁ and deflected from its optic axis before being focused down by L₂ and the camera lens onto the imaging device, F. The test specimen is positioned normal to the parallel light beam with its central plane coincident with the object plane of L₂. When passing through the test specimen under investigation, the individual light rays are refracted and bent out of their original path. The shadowgraph technique is sensitive to the changes in second derivative of the density field. Therefore it is not suitable for quantitative measurement of the density (thus the refractive index) and hence the pressure of the acoustic wave.

Shadowgraphy has been applied to problems of compressible flows, convective heat transfer and stratified flow. The shadowgraph arrangement was used by Carome et al. (1966) in their study of laser generated spherical acoustic transients and Emmony et al. (1983) used it in a high speed photography of CO₂ laser generated shock waves at water surfaces.

To undertake shadow photography of the acoustic wave generation and propagation, only minor adjustment to the working of the Mach-Zehnder interferometer was required. Light travelling in the reference arm of the interferometer was blocked to give a single probe beam travelling through the test specimen to the image sensing device, Fig. 3.12. It was found necessary to enhance the shadowgraphs to get a better contrast of the final images as explained in section 3.3.

Another type of beam deflection technique, known as schlieren, involves the measurement of the first derivative of the density, ρ, which allows for the qualitative visualization of the optical inhomogeneities. The principle of the method was developed by both Foucault in 1859 and Toepler in 1864. Foucault used this device, of which the principal component is a knife edge, to check the quality of optical elements, whereas, it was Toepler who described the method for visualization of compressible flows. Many modified
FIG. 3.10: FOCUSED SHADOWGRAPH SYSTEM WITH PARALLEL LIGHT THROUGH TEST FIELD.
FIG. 3.11: OPTICAL ARRANGEMENT OF THE TOEPLER SCHLIEREN SYSTEM.
systems have been derived from the original optical arrangement depending on the intended applications, but the basic system is schematically shown in Fig. 3.11. A parallel light beam passes through the test specimen with the image of the light source being formed in the plane of the knife edge, which is in turn in the focal plane of the second lens. The camera lens serves to form an image of the test section on to the recording device. The method is much more sensitive to small changes in refractive index, hence density and pressure, than the shadowgraphic technique.

In the experimental arrangement used in the project, the schlieren method can be incorporated by making a similar procedure as for shadowgraphy. The reference beam was blocked out by placing a paper screen in the arm. Accurate positioning of the razor blade at the back focal plane of the focusing camera lens was carried out using an x-y translator, illuminated by the He-Ne beam. The schlieren technique was only used in cases where shadowgraphy was not responsive enough to the changes in density associated with the transient laser generated events. This normally meant the recorded images were not displaying significant changes in intensity across the image plane.
FIG. 3.12: EXPERIMENTAL ARRANGEMENT FOR FOCUSED SHADOWGRAPHY AND SCHLIEREN PHOTOGRAPHY (KNIFE EDGE) WITH THE REFERENCE BEAM OF THE INTERFEROMETER BLOCKED.
3.5 REFERENCES


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CHAPTER FOUR

INTERFEROMETRIC STUDIES OF LASER LIQUID INTERACTIONS

4.1 INTRODUCTION

The methods used in the project are essentially those which provide the desired information from a light beam, which propagates through the infrared laser induced events. The term 'optical diagnostics' refers to the dependence of the recorded information on the variation of an optical property of the medium, the refractive index. Generally, variations of the refractive index remain invisible to the naked eye and in the case of the laser generated acoustic transients, the events occur with a very short duration. This requires certain optical methods for making such changes visible. The variation of the refractive index is caused by the changes in the density of the medium associated with the passage of the acoustic waves. However, it is more usual to describe the event in terms of changes in pressure or stress relative to an ambient value rather than changes in density.

When a light beam passes through a test region, it will be disturbed due to the inhomogeneous distribution of the refractive index in the region and two simultaneous changes to the probe light beam may occur. Firstly, the light beam might be deflected from its original direction, and secondly, the phase of the disturbed light wave is shifted with respect to that of the undisturbed case. Visualisation of the acoustic wave generation and propagation by shadowgraphy or schlieren techniques as well as interferometry, used these two effects. It is therefore evident that an important requirement for quantitative measurements on the transient acoustic waves is a knowledge of the relation between refractive index and the density, hence the pressure in the material.
Optical diagnostics are extensively used to make measurements of plasmas because optical probes do not perturb the measured medium. Among them the measurement of the refractive index and its variation gives direct access to the electron density and its gradient and the dynamics of the plasma. Schlieren and shadowgraphy show qualitatively the density gradients and can even give quantitative information if certain conditions are fulfilled, in particular symmetry. Laser interferometry (Jahoda et al. 1964) gave a very precise density measurement of a theta-pinch plasma in an ionised deuterium. Time resolution was achieved by using an ultra short light pulse from a ruby laser.

Two wavelength interferometry of a Q-spoiled ruby laser induced spark in air was reported by Alcock and Ramsden (1966) when they used both the fundamental wavelength, 694 nm, and its second harmonic, at 347 nm, to illuminate a Mach-Zehnder interferometer. A second Q-spoiled ruby laser initiated the laser induced breakdown in air and the simultaneous measurement of the transient events at both wavelengths produced two interferograms with a time resolution of the order of 30 nsec. They found it necessary in the interferometric study of plasmas to make simultaneous two wavelength measurements because of the relatively large dispersion of the electrons compared with the almost constant refractivity of the neutrals and the negligible contribution of the ions. It is then possible to determine independent values of the density of electrons and of the nonelectronic components of the plasma.

Schmidt et al. (1975) demonstrated for the first time the feasibility of sub-nanosecond interferometry of the plasma focus using a nitrogen ultraviolet laser. Mach-Zehnder interferograms of the dense phase of a 30 kJ plasma focus were obtained with an exposure time of less than 500 psec on a polaroid film. The extremely short exposure time and the short illuminating wavelength lead to an improvement in the temporal and spatial resolution in the optical diagnostics of the dense plasma. Emmony (1980) used a 1 nsec duration nitrogen laser as the light source for Mach-Zehnder interferometry of the first few microseconds following the impact of a carbon dioxide laser pulse on water and partially transmitting cyclohexane. Abelisation of the resulting interferograms gave quantitative measurements of the laser
generated shock wave.

The use of a laser-pumped dye laser was reported by Kimura et al. (1986) when they utilised a pair of KrF excimer lasers to preionise a gas-spark column and pump a dye laser operating at 393 nm. The light beam from the dye laser was then used to illuminate a Mach-Zehnder interferometer. A Mach-Zehnder interferometer with a pulsed nitrogen laser-pumped dye laser light source was used to observe the collapse of laser produced cavitation bubbles in water by Ward and Emmony (1990). Interferograms of the cavitation events showed changes in pressure of the liquid as fringe displacements. The use of a high-speed video imaging system represents a significant development in the study of cavitation bubble dynamics and the associated transient acoustic wave generation.

4.2 LIGHT DEFLECTION AND RETARDATION IN A VARYING DENSITY FIELD

4.2.1 Introduction

When a laser induced breakdown is formed, either in a solid, liquid or gaseous medium, the adjacent molecules are rapidly heated giving rise to a spherical compression wave in the medium. The wave propagates outward from its emission centre causing a rise in density within the acoustic wave which is higher than the surrounding undisturbed region of the medium. Consider a light beam which is transmitted through this region of varying density. Assuming that the molecules of the medium have no net electric dipole moment, the probe light beam with the electric field vector $E$ distorts the charge configuration of the molecules. A dipole moment $p$ is thereby induced per molecule which is proportional to $E$:

$$p = \alpha E$$

where $\alpha$ is the electronic polarizability.
The distortion of the electronic charge configuration is therefore frequency dependent since $E$ describes an oscillating field. The field $E$ can be represented as:

$$E = E_0 \exp(i2\pi v t)$$ \[4.2\]

where $E_0$ is the amplitude and $v$ is the frequency of the probe light beam.

Lorentz classical radiation interaction theory relates the dipole moment to the electric field by utilizing the model of an induced harmonic electron oscillator. Assuming that several distorted electrons per molecule with different resonant frequencies, $v_i$, and oscillator strengths, $\tilde{q}_i$, contribute to the induced dipole moment, therefore

$$p = \frac{e^2 E}{4\pi^2 m_e} \sum_i \frac{\tilde{q}_i}{v_i^2 - v^2}$$ \[4.3\]

where $e$ is the charge and $m_e$ the mass of the electron. The resonant frequencies $v_i$ are assumed to be far from the frequency $v$ of the probe light beam.

So far it has been assumed that only the external field vector $E$ plays a role in the induced dipole moment per molecule without taking into consideration that molecules in the vicinity of the affected region also become electric dipoles. This generates a secondary electric field, which is superimposed on the external electric field $E$. Taking this into account, we have:

$$p = a E_{\text{eff}}$$ \[4.4\]

where $E_{\text{eff}}$ is the effective field vector. The influence of the secondary field may be neglected, however, if the average distances between molecules are large, for example in gases. For a dielectric medium with randomly distributed molecules,
\[ E_{\text{eff}} = E + \frac{4}{3} \pi p \]  \[ [4.5] \]

where \( p \) is the net dipole moment per unit volume of the dielectric medium denoted by the polarization vector. If there are \( N \) molecules in the medium, the polarization vector \( \mathbf{P} \) given by Lorentz is:

\[
\mathbf{P} = \alpha N (E + \frac{4}{3} \pi p) \]

\[ [4.6] \]

\[
= (\varepsilon - 1)E/4\pi
\]

\[ [4.7] \]

where \( \varepsilon \) is the dielectric constant and the refractive index \( n \) of the medium is related to \( \varepsilon \) by:

\[
n = \sqrt{\varepsilon}
\]

\[ [4.8] \]

The number density \( N \) can be replaced by the density \( \rho \) of the medium through

\[
N = \mathcal{L} \rho / M
\]

\[ [4.9] \]

where \( \mathcal{L} \) is the Loschmidt's number and \( M \) the molar weight.

From equations 4.6, and expressing the product \( (Na) \) as a function of \( \varepsilon \), the refractive index \( n \) can be related to the density \( \rho \) in terms of molecular constants and properties of the medium and the probe frequency \( \nu \):

\[
\frac{n^2 - 1}{n^2 + 2} = \frac{\rho \mathcal{L} \varepsilon^2}{3 \pi m \rho M} \sum_i \frac{q_i}{\nu_i^2 \cdot \nu^2}
\]

\[ [4.10] \]

This is the well known equation of Clausius-Mossotti and can be simplified as:

\[
\frac{n^2 - 1}{n^2 + 2} = K \rho
\]

\[ [4.11] \]
where the constant \( K \) is dependent only upon the molecular properties of the material and the frequency of the incident radiation. Since the refractive index of most gases is very close to one, the Clausius-Mosotti relation can be simplified for the case of a gas by setting \((n^2 - 1) \approx 2(n - 1)\) and \((n^2 + 2) \approx 3\).

This will give the so called Gladstone Dale relation:

\[
n - 1 = K \rho \tag{4.12}
\]

where \( K = 3K/2 \), is the Gladstone-Dale constant and has a dimension of \( 1/\rho \).

The difference \((n - 1)\), called the refractivity, is several orders of magnitude larger for condensed materials than for gases. Therefore, even small density differences in liquids and solids can produce considerably large changes in refractive index. Fiedler et al. (1985) reported that water being at rest in a normal tank may develop a small difference in temperature between the bottom and the upper surface and that the low thermal stratification is sufficient for visualising flows in such tank with a schlieren system. This also means that both interferometric and beam deflection measurement techniques are much more sensitive to changes in density in the two condensed states of matter.

4.2.2 Deflection and Retardation of the Probe Beam

The problem of how a probe light beam can be disturbed in an inhomogeneous medium can easily be explained once the relationship between the refractive index and density has been established. Weyl (1954) treated the problem in terms of geometrical optics thus excluding diffraction or dispersion from the analysis. The propagation of a single light ray, initially parallel to the \( z \) axis, in the refractive field (also called a phase object) is described by Fermat's principle, which states that a light ray, in going from points \( A \) to \( B \), traverses the route having the minimum optical path length, \( (OPL) = \int_s n(s) \, ds \). There is no variation of optical path length along a light ray in the phase object, hence:
\[ \delta \int n(x, y, z) \, ds = 0 \]  \hspace{1cm} [4.13]

where \( s \) denotes the arc length along the ray, and \( ds \) is defined by

\[ ds^2 = dx^2 + dy^2 + dz^2 \]  \hspace{1cm} [4.14]

Weyl (1954) showed that equation 4.13 is equivalent to the following set of differential equations:

\[
\frac{d^2x}{dz^2} = \left\{ 1 + \left( \frac{dx}{dz} \right)^2 + \left( \frac{dy}{dz} \right)^2 \right\} \left\{ \frac{1}{n} \frac{\partial n}{\partial x} - \frac{dx}{dz} \frac{1}{n} \frac{\partial n}{\partial z} \right\}
\]  \hspace{1cm} [4.15]

\[
\frac{d^2y}{dz^2} = \left\{ 1 + \left( \frac{dx}{dz} \right)^2 + \left( \frac{dy}{dz} \right)^2 \right\} \left\{ \frac{1}{n} \frac{\partial n}{\partial y} - \frac{dy}{dz} \frac{1}{n} \frac{\partial n}{\partial z} \right\}
\]

The solution (equations 4.15) to the system which describes the path of the light beam through the refractive index field, \( x = x(z) \) and \( y = y(z) \) can be determined by certain initial conditions, which specify the particular light ray in the transmitted, parallel beam. This initial condition is given by specifying the coordinates of the entrance and exit planes of the test volume as well as the respective inclinations of the ray at the exit point. Merzkich (1981) simplified the system by making several assumptions: the slopes of the ray, \( dx/dz \) and \( dy/dz \), are very small everywhere as compared to unity; and since in most cases \( \partial n/\partial x, \partial n/\partial y, \partial n/\partial z \) are of the same order of magnitude, the simplified system of equations becomes:

\[
\frac{d^2x}{dz^2} = \frac{1}{n} \frac{\partial n}{\partial x}
\]  \hspace{1cm} [4.16]

\[
\frac{d^2y}{dz^2} = \frac{1}{n} \frac{\partial n}{\partial y}
\]
Due to the simplification introduced above, the probe light beam enters and leaves the test volume at the same $x$ and $y$ coordinates but at an angle that is determined by the line integral of the derivative of the refractive index distribution in the test field. From Fig. 4.1, one may determine the following three quantities, for each ray, in order to predict the observable pattern in the recording plane, at a distance $l$ from the exit plane of the test field:

i) the displacement $\Delta \xi$ of a deflected or disturbed ray;

ii) the deflection angles $\epsilon_x$ and $\epsilon_y$ of the ray; and

iii) the retardation of the disturbed ray with respect to an undisturbed ray.

The latter quantity can be expressed by the time difference $\Delta t$ between the arrival of the two rays in the recording plane. The simplified set of equations 4.16 determines the above quantities in terms of the respective $x$ and $y$ components:

\[ (\Delta \xi)_x = l \int_{\xi_1}^{\xi_2} \frac{1}{n} \frac{\partial n}{\partial x} \, dz \]  
\[ [4.17a] \]

\[ (\Delta \xi)_y = l \int_{\xi_1}^{\xi_2} \frac{1}{n} \frac{\partial n}{\partial y} \, dz \]  
\[ [4.17b] \]

\[ \tan \epsilon_x = \int_{\xi_1}^{\xi_2} \frac{1}{n} \frac{\partial n}{\partial x} \, dz \]  
\[ [4.17c] \]

\[ \tan \epsilon_y = \int_{\xi_1}^{\xi_2} \frac{1}{n} \frac{\partial n}{\partial y} \, dz \]  

\[ \Delta t = \frac{1}{c} \int_{\xi_1}^{\xi_2} \left( n(x, y, z) - n_\infty \right) \, dz \]  
\[ [4.17c] \]
where \( c \) is the velocity of light in vacuum,

\[ n_\infty \]

the refractive index of the undisturbed test field in which the reference ray propagates,

\( \xi_1 \) and \( \xi_2 \) the coordinates of the surfaces where a ray enters and leaves the test field

The quantity \( \Delta t \) can be converted into the optical phase difference \( \Delta \phi \) between the disturbed and the undisturbed ray in the recording plane:

\[
\frac{\Delta \phi}{2\pi} = \frac{1}{\lambda} \int_{\xi_1}^{\xi_2} (n(x, y, z) - n_\infty) \, dz
\]

[4.18]

where \( \lambda \) is the wavelength of the probe beam.

The displacement \( \Delta \vec{d} \), as represented by equation 4.17a, can be visualized by the shadowgraphic technique and the schlieren system measures the deflection angle \( \epsilon \) described by equation 4.17b. Optical interferometers will record the optical phase changes experienced by a light ray in the density field according to equation 4.18. Merzkich (1981) showed that these different classes of visualization method also exhibit another systematic behaviour: the shadowgraph is sensitive to changes in the second derivative of the gas density \( \rho \), the schlieren system records the changes in the first derivative of \( \rho \), and quantitative measurement of the absolute density changes is possible with interferometers.

The simplifying assumptions of Merzkich (1981) for both equations 4.17 and 4.18 are not exactly true if the rays of light do not follow a straight line path through the test field to the recording plane. These deviations are particularly prominent in liquids with high refractivity \((n - 1)\) value. However, Winkler (1948) and Vest (1975) reported good results for all reasonable changes in refractive index.
4.3 PRESSURE PROFILING

4.3.1 Introduction

The laser generated acoustic wave, which causes the density within it to increase with respect to the surrounding region, increases the optical path length of the affected density field and as a result the phase of the illuminating test beam is retarded with respect to an undisturbed reference beam. The development of instruments, known as interferometers, designed to visualize this alterations or difference in optical phase has been one of the great achievement in the field of optics. In the late 19th century, Ernst Mach started the application of optical interferometers to experimental flow studies when he used a Jamin interferometer to visualize the compressible flow around a projectile flying at supersonic speed. The Mach-Zehnder interferometer, to be described in section 4.4, is basically a two beam interferometer in which one visualizes the interference of a wave, which has passed through the test region, with a second wave, which propagates to the recording plane along a different optical path. The refractive index changes in the test arm of the device manifest themselves as fringe distortions from their original straight and uniformly spaced undisturbed condition.

Fig. 4.2 represents a schematic of a general linear setup of a two-beam interferometer with a parallel light beam passing through the test region. The incident light propagates in the z-direction with the lateral displacements of the test and reference beams, $d$ and the test field is bounded by surfaces $\xi_1(x, y)$ and $\xi_2(x, y)$. Each ray of the incident light beam, therefore has a conjugate ray, with coordinates $y + (d/2)$ and $y - (d/2)$, respectively. The interferometer unit causes the two conjugate rays either to coincide after having passed through this unit, or they are made to intersect in the recording plane. If the conditions of optical coherence are met, the conjugate rays interfere thus producing an interference pattern in the recording plane.

The difference in optical path length, $\Delta t$ between the two conjugate rays of Fig. 4.2 is:
FIG. 4.2: PRINCIPAL ARRANGEMENT OF TWO BEAM INTERFEROMETER WITH PARALLEL LIGHT THROUGH THE TEST FIELD.
The equation was derived under the assumption that the light rays suffered negligible deflection due to strongly refracting medium, section 4.2.2. The presence of two unknowns, namely the values of \( n \) at two different positions, poses a problem. The solution can be achieved by having the separation between the two conjugate rays, \( d \), greater than the diameter of the field of view. This results in one ray of each pair of conjugate ray propagating outside the test field and therefore remains undisturbed. Since one ray passes along a constant refractive index \( n_{\infty} \), the difference in optical path length between the conjugate rays is:

\[
\Delta l(x, y) = \int_{\xi_1}^{\xi_2} [n(x, y, z) - n_{\infty}] \, dz
\]

[4.20]

therefore the optical phase difference \( \Delta \Phi \) between the test and reference rays

\[
\Delta \Phi(x, y) = 2\pi \frac{\Delta l(x, y)}{\lambda}
\]

[4.21]

which is similar to equation 4.18 obtained earlier.

In the simplest case where the refractive index \( n \) or the density \( \rho \) do not vary in the \( z \)-direction, and the test medium has a uniform width \( \int_{\xi_1}^{\xi_2} = \xi \), the equation of the fringes is given by:

\[
\frac{1}{\lambda} \int_{\xi_1}^{\xi_2} [n(x, y) - n_{\infty}] \, dz = 0, \pm 1, \pm 2 \ldots \ldots
\]

[4.22]
and the fringes are curves of constant refractive index or constant density.

Equation 4.22 applies to an alignment of the interferometer for which a uniform test field appears uniformly illuminated, that is, no fringe is seen in the field of view. This is the case of 'infinite fringe width' alignment. A system of equidistant, parallel interference fringes can be obtained for the case of 'finite fringe width' alignment. A density variation in the test medium will distort this regular fringe pattern, and the deviation or shift of a fringe from its undisturbed position is a measure of the density disturbance. A fringe shift by one fringe width is equivalent to a difference in optical path length of one wavelength. It follows that a fringe shift $\Delta F$ in a point $(x, y)$ measured in terms of the undisturbed fringe separation or width $F$ is

$$
\frac{\Delta F(x, y)}{F} = \frac{1}{\lambda} \int_{\zeta_1}^{\zeta_2} \left( n(x, y) - n_\infty \right) dz
$$  \[4.23a\]

$$
= \Delta F/2\pi
$$

$$
= \frac{\Delta n(x, y)}{\lambda} \zeta
$$

$$
= \Delta f(x, y) \quad \text{[4.23b]}
$$

where the change in refractive index $\Delta n$ is the difference between $n(x, y)$ and $n_\infty$, and as a result the refractive index change in the test arm is proportional to the fractional shift $\Delta f(x, y)$ in the interferogram at the output. The undisturbed fringe separation $F$ is initially a constant width when the optical components are flat but the introduction of imperfect specimen holders in both arms of the interferometers may cause it to vary across the field of view.
4.3.2 Inversion Techniques

Inversion of Abel's integral, such as equation 4.23, is an essential step in the analysis of measured data in numerous fields of research. In plasma diagnostics by Barr (1962), for example, Abel's equation relates the measured line-of-sight radiance of a cylindrically symmetric source to its emission coefficient distribution. If the source is optically thin so that no absorption occurs within the source, the measured radiance data can be Abel inverted to obtain the physically important emission coefficient distribution. Deutsch (1984) presented an extension of the theory of Abel type equations to the case of non-zero constant absorption in the source. Vest (1975) discussed the inversion of measurements of optical path length through strongly refracting, radially symmetric phase objects, such as plasmas. Wing and Neidigh (1971) presented a rapid graphical technique for performing the Abel inversion of data representing a circularly symmetric system projected into one dimension.

The two dimensional information that is obtained from an interferogram can be used for determining the density in the test region. When the spherical acoustic wave is visualized by the Mach-Zehnder interferometer, the intensity at each point, \((x, y)\) on the resulting two-dimensional image is generated from the integral sum of the optical path length differences along the z-axis at that coordinate. In the simplest case, the source is optically thin and the refractive index profile has spherical symmetry about the emission centre, \(\Delta n(r)\). A simple geometric argument can show, with the help of Fig. 4.3, that the total change in optical path length is related to the changes in refractive index by:

\[
\Delta l(y) = \int \frac{\Delta n(\sqrt{x^2 + y^2})}{+\sqrt{a^2 - y^2} - \sqrt{a^2 - y^2}}
\]  

\[\text{[4.24]}\]

It is assumed that the axisymmetric test field is bounded by the radius \(a\) and that \(n\) and \(\rho\) are constant for \(r \geq a\) (i.e. outside the test field). The function \(\Delta n(r)\) therefore vanishes beyond the finite radius \(a\) and a change of variable from \(z\) to \(r\) and the line element \(dz = rdr/\sqrt{r^2 - y^2}\), gives the basic integral.
FIG. 4.3: CROSS-SECTION OF AN EXTENDED RADIATION SOURCE CIRCULARLY SYMMETRIC WITH RESPECT TO THE X-AXIS WHICH IS NORMAL TO THE PAGE (MINERBO and LEVY, 1969).
equation with respect to $r$:

$$\Delta l(y) = 2 \int_{y}^{a} \frac{\Delta n(r)}{\sqrt{(r^2 - y^2)}} rdr$$  \hspace{1cm} [4.25]$$

This is a form of Abel's integral equation. The exact inverse of this equation for the refractive index changes, following the widely used methods of Nestor-Olsen (1960) and Bockasten (1961) can be written as:

$$\Delta n(r) = \frac{1}{\pi} \int_{y}^{a} \frac{\Delta l'(y) dy}{\sqrt{(r^2 - y^2)}}$$  \hspace{1cm} [4.26]$$

where $\Delta l'(y)$ is the first derivative of $\Delta l(y)$ taken with respect to $y$. In practice the inversion procedure necessary to obtain $\Delta n(r)$ presents many problems, particularly in the presence of experimental fluctuations.

Another approach of resolving the axisymmetric refractive index distribution makes use of discrete numerical summations in place of the integral. A direct approximation for evaluating the integral in equation 4.25 has been described by Schardin (1942), while numerical integration of equation 4.26 by interpolation formulas of low order was the basis of the methods of Nestor and Olsen (1960), Frie (1963) and Bockasten (1961). Since then, numerical inversion techniques have been simplified and refined for improved accuracy and reduced execution times. The basis of the inversion procedure developed in this work is similar to the method of orthogonal polynomials of Minerbo and Levy (1969) and the rapid graphical technique of Wing and Neidigh (1971) as adopted by Ward and Emmony (1990).

A circular cross-section of the test field of radius $a$ is subdivided into $n$ annular zones of equal width and labelled $j = 1$ at the centre to $j = n$ at the edge of the sphere, Fig. 4.4. It is assumed that the refractive index change $\Delta n_j$ is constant within each annular zone, and that it changes discontinuously from one zone to the next. This means that the density, and hence pressure, is also considered as constant if evaluating with the reference beam.
FIG. 4.4: CIRCULAR CROSS-SECTION OF THE TEST FIELD SHOWING 5 POINT GRAPHICAL REPRESENTATION OF THE ELEMENTAL THICKNESS $t_\parallel$ USED DURING THE ABEL INVERSION.
interferometer of Mach-Zehnder as used in this work. The spherical test field is also divided into \( n \) equally spaced chordal regions and labelled \( i = 1 \) to \( n \) as before. It is assumed that the fractional fringe shift, \( \Delta f_j \), is constant within these horizontal chordal regions, and has the effect of digitizing the analogue fringe shift profile into \( n \) discrete values along the \( y \) axis. The horizontal chords and concentric zones intersect each other thus resulting in a set of irregularly shaped areas, designated \( t_{ij} \) in the \( z \) direction. Within each chordal region, summation of the total optical path length difference was then carried out over these small areas.

If a ray passes through the outermost chordal region \((j = n, i = n)\), the optical signal it delivers is sufficient for determining the value of the refractive index change, \( \Delta n \), as a result of the fractional fringe shift, \( \Delta f_n \), and because \( \Delta n \) is constant within the outer zone,

\[
\Delta n = \frac{\lambda \Delta \phi_{AV}}{t_{nn}} \tag{4.27}
\]

where \( t_{nn} \) is the total thickness or length of the outer chordal region. It is therefore necessary to have a scaling relationship between the physical dimensions \( t_{ij} \) of the regions within the spherical refractive index profile and the smaller elements \( t_{ij} \) in our geometrical construction. Taking into account the multiplying factor which arises as a result of the two separate quadrants in Fig. 4.4, the scaling equation is given as:

\[
t_{ij} = \frac{2a}{n} \tag{4.28}
\]

Ward and Emmony (1990) obtained the modified relationship between \( \Delta n \) and \( \Delta f_n \) using a normalised wavelength, \( \delta \), of the original probe beam wavelength, \( \lambda \), which has been scaled up to the dimensions of the semicircular figure to give:

\[
\Delta n = \delta \Delta f_n / t_{nn} \tag{4.29}
\]
where \( \delta = n\lambda/2a \)

Consider now the second chordal region, \( i = n-1 \), the optical path length difference in this region will be the contributions of the previously determined value of the outermost zone, \( j = 1 \), and the neighbouring zone, \( j = 2 \). As a result the refractive index change, \( \Delta n_{n-1} \) is given as:

\[
\Delta n_{n-1} = \frac{(\delta \Delta f_{n-1} - t_{n-1} \cdot n \cdot \Delta n_{n})}{t_{n-1}, n-1}
\]

This procedure continues until one arrives at the ray through the emission centre that is the central chordal region. However, the calculations can be terminated at any chosen radius, \( r \), thus giving the flexibility of obtaining the pressure profile of the acoustic waves in the desired region within the waves. This is particularly useful, as can be found out later, when it is rather difficult to trace the fringes of the interferogram in the region where the respective waves interact with each other resulting in complicated patterns.

The elemental thickness, \( t_{ij} \), can be calculated as a fractional chord length using the general Pythagorean relationship from the geometrical construction of Fig. 4.4:

\[
t_{ij} = \sqrt{(j^2 - (i - 1)^2)} - \sqrt{(j - 1)^2 - (i - 1)^2}
\]

Having obtained this, equations 4.29 and 4.30 can be generalised to give the linearised change in refractive index, \( \Delta n_i \) at the \( i \)th chordal region:

\[
\Delta n_i = \frac{1}{t_{ij}} \left( \Delta f_i - \sum_{j=i+1}^{m} t_{ij} \cdot \Delta n_j \right)
\]

where \( \Delta f_i \) is the corresponding fractional fringe shift.
Generally, the accuracy of the method increases with the higher values of $i$ because it involves the use of lesser numbers of previously determined values of $\Delta n_j$. Inversion technique tend to compound measurement errors in the fringe displacements, $\Delta f_i$ at smaller radial distances from the emission centre.

### 4.3.3 Relationship Between Pressure and Refractive Index

Equation 4.12 is modified to give the relationship between the changes in refractive index, $\Delta n$ and changes in density, $\Delta \rho$ and can be conveniently expressed as:

$$\Delta n = K \Delta \rho$$  \[4.33\]

Changes in pressure or stress, $\Delta p$, relative to an ambient value are more appropriate when considering the propagation of acoustic waves in the different media. Partington (1953), in his work on different gases, showed that the relation above is accurate to about 100 bars. Since the pressure generated during the course of this project are rather low, $< 100$ bar, it is safe to assume a constant of proportionality between the two variables in each medium. We can then write the modified Gladstone-Dale relation between changes in pressure and refractive index as:

$$\Delta n = C \Delta p$$  \[4.34\]

where the usual units of the constant $C$ are bar$^{-1}$.

In recent years transparent plastic materials, such as those used in the author's work, have come into wide use in the fabrication of optical components (Hinchman 1975). In order to make optimal use of these materials, component designers require basic optical and material parameters such as refractive index, thermo-optic coefficient, linear thermal expansion coefficient, elastic moduli and photoelastic constants. Waxler et al. (1979) reported measurements of the above properties on the two commercial
plastic materials as used by the author, i.e. perspex, a polymethy methacrylate, and Lexan (other trade name is PSM-1), a polycarbonate. They interferometrically measured the properties and determined the evolution of the derivative of refractive index with respect to temperature, $dn/dT$, with the temperature between $-160 ^\circ C$ and $+60 ^\circ C$. Although it has been observed to vary discontinuously with $T$, nevertheless at room temperature $dn/dT$ increases linearly and relatively slowly. Some of the optical properties were experimentally confirmed by Cariou et al. (1986) when they tested both PMMA and PC for variations of $(n^2 + 2)/(n^2 - 1)$ and $dn/dT$ with temperature. The results by Cariou also showed the change in refractive index with density to obey the Clausius-Mosotti relation to a high degree of accuracy within a given phase.

Waxler et al. (1979) also gave the experimental value of $\rho dn/d\rho$ for both solids and the constant $c$ in equation 4.34 can be calculated from these values as shown by the following relations. The bulk modulus $B$ can be defined as:

\[ B = -V \frac{d\rho}{dV} \]

\[ = \frac{E}{3(1 - 2\sigma)} \]

where $E$ is the Young's modulus and $\sigma$ the Poisson ratio,

and $d\rho/dV = -\rho/V$ \[4.35a\]

where $V$ is the volume of the solid material. In the limit as $dn$ and $d\rho$ tend to zero, $c$ is given by:

\[ \frac{dn}{d\rho} = \frac{dn}{d\rho} \frac{dV}{d\rho} \]

\[4.36\]
Substituting equations 4.35 and 4.35a into 4.36 we have,

\[ \frac{dn}{dp} = \frac{1}{B} \rho \left( \frac{dn}{d\rho} \right) \]  \text{[4.37]}

For the case of water, several workers had empirically determined the change of refractive index with pressure and temperature. Waxier and Weir (1963) showed, by a specially designed interferometer for refractive index measurements at elevated pressures, the variation to be nearly proportional for pressures less than 1kbar. Vedam and Limsuwan (1975) also showed that the change in refractive index with pressure remains almost constant with temperature.

Table 4.1 gives the optical characterization and the physical properties of the specimen used in the experimental work (Waxier, 1979).

4.4 MACH-ZEHNDER INTERFEROMETER

4.4.1 Introduction

Ernst Mach recognised that for better applicability of the method of interferometry in experimental flow studies and gas dynamic phenomena, it was desirable to have an instrument with the test and reference beams more widely separated. This led to the practical realisation of the idea which was independently developed by Zehnder (1891) and Ernst Mach's son, Ludwich Mach (1892). Winckler (1948) and Bershader (1954) among others, have since then, continuously improved the instrument and the methods of evaluating the interferograms. A number of modifications and applications of the Mach-Zehnder interferometer have been reported. Howes (1984) describes an arrangement whereby a schlieren system of large aperture is followed by a relatively small Mach-Zehnder interferometer setup thus overcoming the limitations in the size of the field of view. Large object fields
<table>
<thead>
<tr>
<th></th>
<th>PMMA</th>
<th>PC</th>
<th>WATER</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n \ (486.1 \ nm)$</td>
<td>1.5014</td>
<td>1.5995</td>
<td>1.333</td>
</tr>
<tr>
<td>$q_{11}$</td>
<td>$26.7 \times 10^{-12} \ Pa^{-1}$</td>
<td>$-4.6 \times 10^{-12} \ Pa^{-1}$</td>
<td></td>
</tr>
<tr>
<td>$q_{12}$</td>
<td>$25.5 \times 10^{-12} \ Pa^{-1}$</td>
<td>$34.6 \times 10^{-12} \ Pa^{-1}$</td>
<td></td>
</tr>
<tr>
<td>$s_{11}$</td>
<td>$303 \times 10^{-12} \ Pa^{-1}$</td>
<td>$403 \times 10^{-12} \ Pa^{-1}$</td>
<td></td>
</tr>
<tr>
<td>$s_{12}$</td>
<td>$-108 \times 10^{-12} \ Pa^{-1}$</td>
<td>$-165 \times 10^{-12} \ Pa^{-1}$</td>
<td></td>
</tr>
<tr>
<td>$\frac{dn}{dp}$</td>
<td>$1.12 \times 10^{-5} \ bar^{-1}$</td>
<td>$1.65 \times 10^{-5} \ bar^{-1}$</td>
<td>$1.39 \times 10^{-5} \ bar^{-1}$</td>
</tr>
<tr>
<td>$(n - 1)$</td>
<td>$4.95 \times 10^{-1}$</td>
<td>$5.89 \times 10^{-1}$</td>
<td>$3.36 \times 10^{-1}$</td>
</tr>
</tbody>
</table>

**TABLE 4.1 : OPTICAL CHARACTERISTICS OF PMMA, PC AND WATER (WAXLER et al., 1979).**
are allowed in the schlieren system, and the interferometric arrangement can be kept small. Yokozeki and Mihara (1979) superimposed moire patterns on Mach-Zehnder interferograms taken in finite fringe width mode. Xia (1985) allowed the test beam to pass twice through the test field, as in Michelson interferometer, thereby doubling the sensitivity. The number of applications of Mach-Zehnder interferometer are immense, especially in the field of compressible aerodynamics, both in wind tunnels and in shock tubes (Anderson et al., 1977), plasma diagnostics, convective heat transfer problems, both in gases (Pera and Geghardt, 1975) and in liquids (Bathelt and Viskantha, 1980).

The Mach-Zehnder interferometer combines a wide separation of test beam and reference beam with a relatively large field of view. In a basic arrangement of Fig. 4.5, light from a point source is made parallel by the lens $L_1$. The essential components of the interferometer are the plane, fully reflecting mirrors $M_1$ and $M_2$, and the plane, semi-reflecting mirrors (beam-splitters), $B_1$ and $B_2$. These four main optical elements are arranged to form a rectangle or parallelogram with the individual component being allowed to rotate around a horizontal and vertical axis for the basic adjustment and alignment of the interferometer. The collimated light from the source incident on $B_1$, which has its semi-silvered surface facing the source, is divided into reference and test beams before being redirected by $M_1$ and $M_2$ towards $B_2$, which has its semi-silvered positioned on the opposite side to that of $B_1$. The second beam splitter serves to recombine the initially separated test and reference beams so that they coincide and interfere with one another. This ensures that the optical path lengths in both arms of the interferometer are equal by limiting each beam to a single pass through a beam splitter. The glass-cuvette holding the test specimen, is brought into the path of the test beam, while an identical cuvette is inserted in the reference beam in order to compensate for the large optical path length travelled by the test beam in the glass and in the liquid/solid media. The imaging device is focused, with $L_2$, onto a plane in the test arm.

If all mirrors are inclined at exactly 45° to the incident collimated light beam, and assuming all optical components are of perfect quality, the light reaching the recording plane is in phase, and no fringes appear in this basic position.
FIG. 4.5: BASIC ARRANGEMENT OF THE MACH-ZEHNDER INTERFEROMETER,
This is the 'infinite fringe width' alignment. A series of straight and parallel fringes can be observed at the image plane, by tilting the final beam-splitter, $B_z$, by a small angle, $\theta$. This finite fringe width alignment allows the rays, $r_1$ and $r_z'$, to intersect at $P$ and exhibit a phase difference owing to their different path length, Fig. 4.6:

\[
\Delta l = OP - QP
\]
\[
= b \frac{1 - \cos (2\theta)}{\sin (2\theta)}
\]
\[
= b \tan \theta
\]
\[
\approx b\theta
\] [4.38]

Tilting the final beam-splitter, $B_z$ is equivalent to inserting a wedge of angle $\theta$ in to the path of one light beam. In the linear representation of the interferometer, the planes $R_1$ and $R_2$ correspond to plane $R$ in the real system and they coincide at $\theta = 0$. The interfering waves have zero phase difference at the points $O$ and on the bisector of the angle $2\theta$. If $\Delta l = N\lambda$, with $\lambda$ being the wavelength, there will be $N$ fringes between $O'$ and $P$, in the recording plane $PO'P'$ with fringe direction normal to the plane of the figure. The separation of the resulting fringes is given by:

\[
F = b/2N
\]
\[
= \lambda/2\theta
\] [4.39]

where $N\lambda = \theta b$

Therefore, $F$ is proportional to the wavelength of the illuminating source and inversely proportional to the angle of tilt. The fringe direction can be altered by rotating the tilted beam-splitter, $B_z$. The interference in the point $P$ is established by two rays, which originated from two different points of the plane $R$. Although this requires all points of $R$ to be coherent, it is adequate that the interference be produced by the two components ("conjugate rays")
FIG. 4.6: FINITE FRINGE WIDTH ALIGNMENT WITH THE FORMATION OF INTERFERENCE FRINGES ON THE SCREEN PO’P’.
of one single ray separated at the beam-splitter, $B_2$. Depending on the relative orientation of the optical elements, one may distinguish between two possible cases, real and virtual fringes. In the first case, the locus of intersection of the conjugate rays is the location of the interference, and the fringes are thus real and are formed in the recording plane. If the elements are tilted in a way causing the conjugate rays to intersect within the interferometer (i.e. before they reach $B_2$), the fringes are virtual.

### 4.4.2 Alignment and Fringe Localization

High-precision mechanical performance and high-quality optical components are essential requirements in order to obtain sufficiently straight interference fringes for measurements of the changes in refractive index. The best quality control of the instrument is to check the parallelism of the interference fringes in the finite fringe width mode. A deviation of not more than one tenth of a fringe width is desirable. Mechanical and optical tolerances of surface flatness, surface parallelism, translational and rotational displacements and control of tilt must be in the order of $\lambda/10$. These make the instrument expensive, and the cost increases rapidly with increasing diameter of the mirrors, that is larger field of view. The four plane optical components used in the interferometer, each with diameter of 100 mm, were manufactured to a flatness of within $\lambda/10, = 50 \text{ nm}$, over their complete surfaces and individually mounted in a rotation stage that allows for tilt about vertical and horizontal axes. The rotation stage of the final beam-splitter, $B_2$, was additionally secured on a horizontal translation stage which permits motion in a direction parallel to the optical axis of the final focusing lens.

The finite fringe width setup used in the quantitative measurements of the interferograms is shown in Fig. 4.7. Real fringes were localised in the region in which the emerging rays originating from the same incident ray meet. This region could be moved about by modifying the orientation of the elements which acted on the relative inclination of the associated plane waves of the two beams, the mirror $M_1$ and final beam-splitter, $B_2$. If $B_2$ was turned around an axis perpendicular to the plane of Fig. 4.7, the region of localisation was
FIG. 4.7: LOCALIZATION OF FRINGES IN THE FINITE FRINGE WIDTH ARRANGEMENT.
near $M_1$ and by slight rotation of both $M_1$ and $B_2$, the fringes could be localised at the plane $XX'$, midway along the line $M_1B_2$. The test sample was positioned with its central plane coincident with $XX'$ and the identical reference sample was placed at the reference arm of the interferometer, midway between $M_2$ and $B_2$. The lens $L_2$ was positioned such that the object plane of the imaging device, $C$ coincides with $XX'$.

The basic alignment of the Mach-Zehnder interferometer was a tedious process because of the need to equalise the path lengths of the arms to within $10 \, \mu m$, the coherence length of the illuminating dye laser beam. The process sometime required several days of work in order to achieve the desired results. Successive alignment and adjustment procedures using three continuous wave visible light sources of successively shorter coherence lengths were necessary to get localised fringes of maximum visibility.

After initially securing the Nd-YAG laser and its focusing arrangement on a rig directly above the optical table, as described in section 3.3, the nitrogen laser pumped-dye laser system was positioned such that the beam remained at a constant height when directed by a plane mirror along the length of the table to a point on the laboratory wall. A 5 mW and 300 mm coherence length continuous wave He-Ne laser beam was then introduced by a removable mirror in the path of the dye-laser beam. Keeping the He-Ne beam at the same constant height and the same wall’s position as the dye-laser beam served to make the two beams superimposed and the coaxial alignment beam was then ready to be used in the preliminary alignment procedure. The first beam-splitter, $B_1$, was then positioned at $45^\circ$ to the incident He-Ne beam and both transmitted and reflected beams were kept at a constant height above the table and their positions on the laboratory walls marked. The first mirror, $M_1$, was then placed at a distance of about 60 cm from $B_1$ with the final position being determined by measuring the reflected beams from both elements. With the reflected beam from $M_1$ being kept at the same constant height as before, its spot on the wall was also marked and the separation of the reflected beams’ spots on the wall must be the same as the distance $B_1M_1$. The procedure was carried out using a metre rule clamped to an optical post mounted onto an x-y traverse placed on the table. Successive measurements of the reflected beams at successively greater
distances from both elements ensure a very high degree of parallelism of the two beams. With the introduction of the second mirror, $M_2$, the above procedure was repeated using another laboratory wall. Finally, the beam-splitter, $B_2$, was then introduced at the intersection of the two split beams. The semi-silvered surface of $B_2$ was chosen to be the crossing point on the element and by careful adjustments of $B_2$, the two redirected beams were superimposed at both outputs of the interferometer. At this stage, very good He-Ne fringes were obtained due to the long coherence length of the laser light but the dye laser fringes were still not visible.

To further minimise the optical path length differences in both arms of the interferometer, it was therefore necessary to introduce the first extended light source as the next step in the alignment procedure. A sodium discharge lamp, making use of the two 'D' lines, covered with a tracing paper acting as diffuser, was placed at the second input of the interferometer after removing the He-Ne laser beam. The 600 $\mu$m coherence length of the source produced narrow vertical fringes of maximum visibility (contrast) after careful adjustments of $M_2$ and $B_2$. The second extended source of diffused white light from an incandescent lamp, with coherence length of 1 $\mu$m, was then allowed to illuminate the interferometer. At this point, $B_2$ was then moved with great care along the traverse until white light fringes appeared superimposed on the sodium fringes. The sodium light was then removed with the resulting white light fringes normally localised at infinity behind the source.

The respective video-imaging system and the spatial filter and beam collimating arrangements were then aligned with the interferometer. The Nd-YAG laser was then operated at a modest repetition rate and allowed to cause air breakdown in the middle of the test beam. Due to the need for superimposing the breakdown site and the position of the fringes, a 1mm thick steel plate with a 1cm x 1cm slot, was positioned at the point where the breakdown occurred. The slot, which acted as a suitable point of reference for the final localization of the fringes, was then imaged by the imaging lens on to the video camera. Fine adjustments to the rotations of $M_2$ and $B_2$ were carried out until the white light fringes were localised, as seen by the naked eye looking into the interferometer, at the object plane of the imaging device and hence coinciding with the breakdown site. At this stage,
the fringes should appear on the monitor with the video camera switched to the real-time mode. Further delicate adjustments to $M_1$ and $B_2$ resulted in the required orientation and separation of these localised fringes, as seen on the monitor. It was possible to obtain fringes of very good contrast by gradually enlarging the aperture, thus reducing the depth of focus of the imaging lens. In this way the localised fringes were imaged at their correct position along the test arm.

The next step was to place the test and reference samples in their respective positions in the test and reference arms of the interferometer. With these in place, white light fringes were then relocalised at the central plane of the test sample by fine and delicate adjustments of the optical elements as before. At this point, the interferometer had been aligned and the illuminating dye laser fringes localised with maximum visibility at the required position in the test beam.

In the interferometric studies of the laser generated acoustic waves, the direction of the fringe shifts associated with the changes in refractive index and hence the pressure was fixed by the relative orientation of the mirrors and beam-splitters. In this arrangement the direction was deduced from experiments in which the optical path length of one arm of the interferometer was varied with respect to the other. The movement of $B_2$ on its traverse, towards, or away from $M_2$ resulted in a decrease and increase in optical length in the test and reference arms respectively. This was accompanied by a fringe movement to the right, or left as viewed by the video camera. This means that, an increase in refractive index and pressure in the test arm will result in the fringes being displaced to the right and conversely, a shift to the left indicated a decrease in pressure.

4.4.3 Computerised Interferogram Analysis

One of the advantages of using the video-imaging system, apart from the obvious provision of immediate and real time viewing of the laser interactions, is that the recorded images are in a format suitable for digital
image processing. Other manipulations such as subtraction of alignment errors and averaging are important for absolute accuracy (Koliopoulis, 1988). With the measured data available in the computer, interactive graphics offers the operator a complete quantitative display of the images. The advantage of computerised automated data evaluation was obviously to speed up the analysis of the interferograms and several computer programs and appropriate algorithms have been reported and described (Reibold and Molkenstruck, 1981; Eichhorn and Osten, 1988). As mentioned in section 3.3, the main computer software was a series of menu driven modules used to view, copy, store and extract the information contained within the digitally recorded images and carry out calculations on the retrieved data.

The analysis procedure started with the recorded background interferogram, without any disturbance in the test field, as shown in Fig. 4.8a. Using a cursor system controlled from the keyboard, the dimensions of the stored images were first calibrated using a previously recorded images of vertical and horizontal scales placed at the object plane of the imaging system. The initial fringe spacing, $F$, of the undisturbed fringes was then measured and noted, in this case it is 880 $\mu m$. In the interferogram of Fig. 4.8b, which shows the shifted fringes caused by the disturbance due to the acoustic wave propagation, the compressional wave was assumed to be spherically symmetrical with its emission centre at the point on the solid surface where the laser generated acoustic wave in water first interact with the boundary, marked *. This position was defined and stored in the computer memory. The gradient and position of the undisturbed central fringe closest to the emission centre was determined and highlighted in the figure. Fig. 4.8c shows the schematic of the procedure by which the fringe shifts, $\Delta F_n$, at radial coordinates $r_n$ were measured. The minimum and maximum radii, within which the inversion was to be carried out, were first specified. The fringe shifts were all measured from the displaced fringe perpendicular to the undisturbed fringe. The distribution of the fringe shifts was recorded and Fig. 4.8d shows the highlighted displaced fringe with data points set at every vertical pixel. After feeding in the relevant values of density, $dn/dp$, and velocity of sound in the medium, the inversion and calculations of pressure change were then automatically carried out within the computer to give final values of $\Delta p(r)$. 

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FIG. 4.8: COMPUTERIZED INTERFEROGRAM ANALYSIS OF THE ACOUSTIC WAVE AT TIME $t = 1.5 \mu s$. (a) ORIGINAL BACKGROUND INTERFEROGRAM, (b) LASER GENERATED ACOUSTIC WAVE WITH THE UNDISTURBED FRINGE HIGHLIGHTED, (c) SCHEMATIC DIAGRAM OF THE ORIGINAL AND SHIFTED FRINGES, (d) SHIFTED FRINGE HIGHLIGHTED IN THE INTERFEROGRAM.
It has been mentioned in section 4.3.2, that the accuracy of the inversion method tends to increase at larger radial distances from the point of emission. The random errors on the measured data are typically less than 5\% but since the frame store was operated as four separate 64 kb field stores, each with a resolution of 256 x 256 pixels, the pixel size limits this error and thus did not severely affect the results. With the horizontal dimension of the recorded images of approximately 8mm, thus each pixel corresponds to 31 μm. The maximum value of the fringe shift, depended on the time delays of the recorded image, for the interferogram of Fig. 4.8d it is about 2 fringes corresponding to horizontal pixel-widths of about 50. The uncertainty that arises from their measurement in this case was about 4\%. However, at larger delays, smaller fringe displacements mean the uncertainty increases. When using PMMA, it was possible to calculate the maximum corresponding variation in the pressure profile across the wavefront. Since there were no significant variations in fringe shifts at all positions on the wavefront, Δp for each dark fringe shift was obtained. The variation in Δp(r) was found to be about 10\%. The same procedure cannot be applied to PC as explained in section 6.1.
4.5 REFERENCES


Zehnder, L., 1891, Zeits. f. Instrumtenk. 11, 275.
CHAPTER FIVE

DYNAMIC PHOTOELASTIC STUDIES OF LASER
GENERATED STRESS-WAVES IN SOLIDS

5.1 INTRODUCTION

In 1816, Sir David Brewster discovered the phenomenon of temporary double refraction induced in amorphous transparent materials by mechanical stress. Many transparent non crystalline materials that are optically isotropic when free of stress become optically anisotropic and display characteristics similar to crystals when they are stressed. These characteristics persist while loads on the materials are maintained but disappear when the loads are removed. This has turned the photoelastic effect into a powerful stress analysis tool and in combination with other optical methods, such as interferometry and holography, along with photographic techniques produced highly effective procedures for the solution of problems which might not be treated by any other means. The next important event was the formulation of the Maxwell-Neumann stress-optic law. According to this law, changes in refractive indices are related linearly to the stresses or strains developing in a linearly elastic material and, based on such a relationship, models of structural components can be constructed and analysed so as to determine the state of stress in the model.

The name photoelasticity reflects the nature of this experimental method: photo implies the use of light rays and optical techniques, while elasticity depicts the study of stresses and deformations in elastic bodies. The formation of photoelastic fringe patterns can be described as a case of optical interference due to the material being doubly refractive or birefringent. This is a property whereby polarized light, upon entering a stressed transparent model, is resolved into components along the axes of principal stresses. The
components of the light are retarded by differing amounts due to the different refractive indices and upon recombining outside the specimen, will form interference patterns, or fringes. Analysis and interpretation of these fringes, with the prior knowledge of the material's physical and optical properties, can give information on the magnitudes of the principal stresses that are present in the model. By using simple predetermined equations, the stresses in the actual component can be calculated irrespective of the component's actual material, be it plastic, wood, steel, glass or other metals.

A vast number of experimental techniques were developed out of this fundamental idea, often combined with numerical or analytical procedures. The development and introduction of new photoelastic materials provided almost unlimited possibilities of modelling most mechanical systems. While the virtues of the experimental solution of static, elastic, two-dimensional problems are now largely overshadowed by analytical methods and finite element analysis, problems involving three-dimensional geometry, dynamic loading and inelastic material behaviour are usually more suitably solved by experimental analysis.

Dynamic photoelasticity applies the basic photoelastic approach to all areas of elastodynamics which can be broadly defined to cover any body where stresses and deformations change as a function of time. As an optical method, it gives full-field visualisation of transient phenomena and it is applicable under a variety of conditions, two- and three-dimensional, elastic and inelastic, isotropic and anisotropic. The variations of the stresses are due to the load or displacements which change with time, or they are due to relatively sudden changes in the geometry of the body. The field of elastodynamics is quite large and can be divided into the following sub-topics:

(i) stress-wave propagation
(ii) vibration and impact
(iii) fracture dynamics

The problem of stress-wave propagation is of particular interest in non-destructive testing, geophysics, excavation and mining. In stress-wave
propagation, the loading is applied for a time which is less than the observation interval. Stresses are imparted to a localised region surrounding the load point while the remainder of the body remains stress free. Stresses and, hence, fringes are transmitted through the body by stress-waves which propagate at extremely high velocity. As can be shown later, dynamic photoelasticity can be effectively applied to investigate the problems of stress-wave propagation.

Impact and vibration both involve time-varying forces over periods which are relatively long compared to the observation period. The development of stresses depends upon the velocity of impact and are transmitted through the body by stress-waves. However, the stress-waves are often of such low magnitude that multiple reflections are required to develop the fringe patterns (Daniel et al. 1976). Fringe velocities are usually much lower than stress-wave velocities. Dynamic photoelasticity can be applied to study the time varying states of stress in impact problems. In fracture propagation, the applied displacements are usually fixed with time and the boundaries of the model suddenly change by the propagation of the crack. The fringes move with the crack tip at velocities usually less than 35% of the shear wave velocity (Dally 1979). The stress-waves are usually small in magnitude and dynamic photoelasticity is the most suitable means for determining the stress-intensity factor at the crack tip.

The first known attempt to apply dynamic photoelasticity was by Tuzi (1928) using a movie camera at 32 frames per second. Tuzi and Nisida (1936) used a rotating drum at a rate of 1200 frames per second, thus improving the results substantially. With the development of improved recording techniques and the use of new materials, the method received great impetus in the 1950s and 1960s. The introduction of low-modulus photoelastic materials with wave propagation velocities of the order of 50 ms⁻¹ allowed the use of conventional high-speed photography as performed by Perkins (1953) and Dally et al. (1959). High modulus photoelastic materials with wave propagation velocities of the order of 2500 ms⁻¹ were able to be investigated with the rapid improvement in high-speed photographic techniques. Rowlands et al. (1969) used a sequential pulsed ruby laser synchronised with a high-speed framing camera whilst Dally and Sandford (1982) developed a
hybrid Cranz-Schardin laser system which employed a ruby laser with fibre optic output.

Naude and Ellis (1961) showed the possibility of obtaining fringe pictures of a photoelastic material near collapsing vapour bubbles by using a high-speed framing camera (1 million frames per second). Fujikawa and Akamatsu (1980) and Shima et al. (1984) also used a photoelastic technique and a high speed recording system for visualization of pressures developed during cavitation bubble collapse. They do not quantify the stress level in the material associated with the collapse nor do they give an estimation of change in optical parameters resulting from these stresses. The problem of isochromatic fringes identification and numbering is difficult especially in dynamic photoelastic studies of wave-propagation problems. There is no well known way of of numbering unambiguously the isochromatic obtained with monochromatic light and recorded in a single photograph. Durelli et al. (1969) did attempt to number the fringes but no systematic methodology was presented nor a justification of the procedure that had been used. Durelli and Shukla (1983) reported simple guidelines in a fringe numbering procedure but the system breaks down in cases where the different waves interact with each other or wave-defect/crack interaction takes place thus producing a very complex fringe patterns as often encountered in the work presented in this thesis. As a result only qualitative treatment of the problem was possible.

Dynamic photoelasticity is a prime candidate for gaining the necessary understanding of the ways in which elastic waves scatter, transmit, reflect and mode-convert at boundaries and defects. Non-destructive testing for defects in structures is assuming greater importance as the level of sophistication in our technology increases. When used in conjunction with modern methods of signal analysis for frequency and phase information, the full-field nature of photoelasticity creates a powerful tool for progress in acoustic evaluation of cracks and defects.

A variety of model materials have been used for dynamic photoelastic studies. Transparent urethane rubber has been used for wave propagation studies using moderate speed cameras. Plasticised polyvinyl chloride (PVC)
has been used for photoviscoelastic studies. Harder materials used are
epoxies and polyesters with the latter commonly used in dynamic fracture
studies. Dynamic photoelastic methods have been extended to opaque
materials using birefringent coatings on three-dimensional models and
anisotropic materials. Most recent work has concentrated on fracture
dynamics although earlier applications dealt with wave propagation and
dynamic stress concentration problems.

5.2 CIRCULAR POLARISCOPE

The essential optical effect necessary for an understanding of the
photoelastic phenomena can be observed by using a circular polariscope. It is
an instrument that utilises the properties of polarized light in its operation.
For experimental stress-analysis work, two types are frequently employed,
the plane polariscope and circular polariscope. The names follow from the
type of polarized light used in their operation. The plane polariscope produce
plane polarized probe beam which passes through the stressed material and
emerging as elliptically polarised due to the anisotropy of the material. This
light is then converted back to plane polarized by a second polarizer, or
analysrer, before going to the imaging device. Production of circularly
polarized light requires the use of a linear polarizer together with an optical
element known as quarter-wave plate. Because of the non-directional
character of circularly polarized light, the isoclinic fringes will not be
superimposed upon the fringe pattern unlike in plane polariscope. All the
observer will see under these conditions are the isochromatic fringes which
give information on the stress magnitudes.

Fig. 5.1 shows a schematic arrangement of the elements in a circular
polariscope for dark-field use. Dally and Riley (1978), in their analysis of
the working of a circular polariscope, considered the plane-polarized beam
emerging from the polarizer as :

\[ A_1 = a \cos \omega t \]  \hspace{1cm} [5.1]
FIG. 5.1: A STRESSED PHOTOELASTIC MODEL IN A CIRCULAR POLARISCOPE ARRANGEMENT WITH CROSSED POLARIZERS AND CROSSED QUARTER-WAVE PLATES.
If the first quarter-wave plate is arranged with its principal axes at 45° with the horizontal and vertical axes, the light beam upon entering this plate is resolved into the components $A_2$ and $A_3$ along the principal F- and S- axes (fast and slow axes):

\[
A_2 = a \cos \omega t \sin 45^\circ = \frac{\sqrt{2}}{2} a \cos \omega t = b \cos \omega t \quad [5.2]
\]

\[
A_3 = a \cos \omega t \cos 45^\circ = \frac{\sqrt{2}}{2} a \cos \omega t = b \cos \omega t \quad [5.3]
\]

where $b = a \frac{\sqrt{2}}{2}$

The beams then emerge with a $\pi/2$ relative phase difference:

\[
A_4 = b \cos \omega t \quad [5.4]
\]

\[
A_5 = b \cos (\omega t - \frac{\pi}{2}) = b \sin \omega t \quad [5.5]
\]

which indicates that the light is circularly polarized due to the fact that equations 5.4 and 5.5 are the parametric equations of a circle. If a doubly refracting plate or a stressed photoelastic material is placed in the path of the light with one of its principal axes making an angle $\beta$ with the polarizer, as shown in Fig. 5.2, then the components $A_4$ and $A_5$ are resolved into components $A_6$ and $A_7$ respectively, which have directions of vibration parallel to the principal-stress directions in the model. Therefore,

\[
A_6 = A_4 \cos \left(\frac{\pi}{4} - \beta\right) + A_5 \sin \left(\frac{\pi}{4} - \beta\right)
\]

\[= b \cos \left(\omega t + \beta - \frac{\pi}{4}\right) \quad [5.6]\]
FIG. 5.2: RESOLUTION OF THE COMPONENTS OF LIGHT ENTERING A STRESSED TRANSPARENT MODEL.
\[ A_7 = A_4 \cos \left( \frac{\pi}{4} - \beta \right) + A_4 \sin \left( \frac{\pi}{4} - \beta \right) \]

\[ = b \sin \left( \omega t + \beta - \frac{\pi}{4} \right) \]  \[ \text{[5.7]} \]

and the emerging components after the introduction of an additional relative retardation due to the passage through the material are given by:

\[ A_8 = b \cos \left( \omega t + \beta - \frac{\pi}{4} \right) \]  \[ \text{[5.8]} \]

\[ A_9 = b \sin \left( \omega t + \beta - \frac{\pi}{4} - \alpha \right) \]  \[ \text{[5.9]} \]

The second quarter wave plate in this case is oriented with its F- and S- axes perpendicular to the corresponding axes of the first one. Upon entering the plate, as shown in Fig. 5.3, the components of the light vector are:

\[ A_{10} = A_8 \sin \left( \frac{\pi}{4} - \beta \right) + A_9 \cos \left( \frac{\pi}{4} - \beta \right) \]

\[ = b \left[ \cos \left( \omega t + \beta - \frac{\pi}{4} \right) \sin \left( \frac{\pi}{4} - \beta \right) + \sin \left( \omega t + \beta - \frac{\pi}{4} - \alpha \right) \cos \left( \frac{\pi}{4} - \beta \right) \right] \]  \[ \text{[5.10]} \]

\[ A_{11} = A_8 \cos \left( \frac{\pi}{4} - \beta \right) - A_9 \sin \left( \frac{\pi}{4} - \beta \right) \]

\[ = b \left[ \cos \left( \omega t + \beta - \frac{\pi}{4} \right) \cos \left( \frac{\pi}{4} - \beta \right) - \sin \left( \omega t + \beta - \frac{\pi}{4} - \alpha \right) \sin \left( \frac{\pi}{4} - \beta \right) \right] \]  \[ \text{[5.11]} \]

With the introduction of an additional relative phase difference of \( \pi/2 \) from the second plate, the beams emerge as:

\[ A_{12} = b \left[ \cos \left( \omega t + \beta - \frac{\pi}{4} \right) \sin \left( \frac{\pi}{4} - \beta \right) + \sin \left( \omega t + \beta - \frac{\pi}{4} - \alpha \right) \cos \left( \frac{\pi}{4} - \beta \right) \right] \]  \[ \text{[5.12]} \]
FIG. 5.3: RESOLUTION OF COMPONENTS OF LIGHT ENTERING THE SECOND QUARTER WAVE PLATE.
If the analyser is oriented perpendicular to that of the polarizer, as in Fig. 5.4, the emerging light vector will be presented by:

\[ A_{14} = b \frac{\sqrt{2}}{2} (A_{12} - A_{13}) \]

\[ = -\left[ \sin(\omega t + \beta - \frac{\pi}{4}) \cos(\frac{\pi}{4} - \beta) + \cos(\omega t + \beta - \frac{\pi}{4} - \alpha) \sin(\frac{\pi}{4} - \beta) \right] \]

\[ - \sin(\omega t + \beta - \frac{\pi}{4} - \alpha) \cos(\frac{\pi}{4} - \beta) \]

\[ = a \sin -\frac{\alpha}{2} \sin \left( \omega t + 2\beta - \frac{\alpha}{2} \right) \]  \[ \text{[5.14]} \]

The intensity, \( I \), is given by twice the square of the amplitude (Dally and Riley, 1978), thus,

\[ I = 2 a^2 \sin^2 \frac{\alpha}{2} \]

\[ = 2 a^2 \sin^2 \frac{\pi d}{\lambda} \left( n_2 - n_1 \right) \] \[ \text{[5.15]} \]

where \( \alpha = \text{relative phase difference} = \frac{2\pi d}{\lambda} \)

\[ \delta = \text{linear phase difference} = d \left( n_2 - n_1 \right) \]

\( d = \text{thickness of the stressed photoelastic material} \)

\( n_2, n_1 = \text{refractive indices for the two principal directions of the doubly refracting plate} \).
FIG. 5.4: COMPONENTS OF THE LIGHT VECTORS WHICH ARE TRANSMITTED THROUGH THE ANALYSER
The intensity is maximum when

\[ \alpha = (2n + 1)\pi \]  

[5.16]

and the condition for extinction is

\[ \alpha = 2n\pi \]  

[5.17]

where \( n \) is an integer.

Therefore substituting \( \alpha \) into equation 5.24:

\[ \alpha = \frac{2\pi \delta C}{\lambda} (\sigma_1 - \sigma_2) \]  

[5.18]

which will give \( \alpha \) in terms of the principal stresses as we can see later in section 5.3

The arrangement of the optical components in the dark field setup as described above, can easily be adapted for light field use. This is done by simply rotating the analyser through 90° so that both polarizer and analyser are parallel. The same effect can also be obtained by rotating the second quarter wave plate through 90° but letting the position of the analyser as in dark field arrangement. Throughout the experimental work described in this thesis, a circular polariscope in the light field arrangement was used. The consequence of using the light field mode is that the first fringe order \( N \) is now 0.5, not zero as in light field, and the subsequent orders given by \( N = 0.5 + n \), where \( n \) is an integer.
Almost all transparent materials possess the property of temporary double refraction while under load. This phenomenon may be due to stress or strain, or both, depending on the material. For linear elastic materials, the optical effect can be referred to either as stress or strain because the two are linearly related. Neumann (1841), proposed the strain-optical description: the difference in velocities of two oppositely polarized (at right angles) light waves passing through a tested beam in flexure, in a direction normal to the plane of bending was directly proportional to the difference of the two principal strains in the plane of the wavefront. Maxwell, in 1853, expressed the principal wave velocities in terms of stresses and much of the theory which relates changes in the refractive indices of a material exhibiting temporary double refraction to the state of stress in the material is due to him.

The refracting properties of a birefringent isotropic material under load can be represented by an index ellipsoid (Frocht, 1948), Fig. 5.5. The principal axes 0A, 0B, 0C of the index ellipsoid represent the principal refractive indices, \( n_1 \), \( n_2 \) and \( n_3 \), of the material at the point. Any radius, say 0M, of the ellipsoid represents a direction of light propagating through the point. A plane through the origin, 0, which is perpendicular to the radius, intersects the ellipsoid as an ellipse, ST. The semiaxes of this ellipse represent the refractive indices associated with the light waves having planes of vibration, SOM, TOM, which contains the radius vector and an axis of the ellipse. For an isotropic body, the three principal axes of the ellipsoid are equal which means the three principal refractive indices are equal to each other and the ellipsoid becomes a sphere. These terms are analogous to the corresponding terms in the specification of the strain, or stress whose geometric representation of the state of stress at a point, known as stress ellipsoid, is shown in Fig. 5.6 (Dally and Riley, 1978). In general, three mutually perpendicular planes, A0B, B0C and C0A, exist at each point of the loaded body. These planes are defined as the principal planes and the normal stresses acting on them defined as the principal stresses \( \sigma_1, \sigma_2 \) and \( \sigma_3 \). The similarities which exist between the stress-ellipsoid representation of the state of stress at a point in a loaded body and the index-ellipsoid.
FIG. 5.5: THE INDEX ELLIPSOID

FIG. 5.6: THE STRESS ELLIPSOID
representation of the optical properties of a material exhibiting temporary
double refraction suggest the presence of a relationship between the two
quantities which may form the basis of the experimental determination of
stresses, or strains. The relationship is known as the stress-optic law of
photoelasticity.

Maxwell found that the principal optical axes coincide with the directions of
the principal stresses and that the ellipticity of the index ellipsoid is
proportional to the applied load. The principal stresses are therefore linearly
related to indices of refraction and follow the relationship:

\[ n_1 - n_o = C_1 \sigma_1 + C_2 (\sigma_2 + \sigma_3) \]  \hfill [5.19] 
\[ n_2 - n_o = C_1 \sigma_2 + C_2 (\sigma_3 + \sigma_1) \]  \hfill [5.20] 
\[ n_3 - n_o = C_1 \sigma_3 + C_2 (\sigma_1 + \sigma_2) \]  \hfill [5.21]

where \( \sigma_1, \sigma_2 \) and \( \sigma_3 \) = principal stresses at the point

\( n_o \) = refractive index in the unstressed state

\( n_1, n_2 \) and \( n_3 \) = principal refractive indices in the stressed state

\( C_1 \) and \( C_2 \) = absolute stress-optical coefficients.

Equations 5.19, 5.20 and 5.21 are the fundamental relations between stress
and optical effect and indicate that the complete state of stress at a point can
be determined by measuring the three principal indices of refraction and
establishing the directions of the three optical axes and are known as the
stress-optic law. These measurements are usually very difficult to perform in
the three-dimensional case and practical application has been limited to a
two-dimensional situation by letting \( \sigma_3 = 0 \):
This is the two-dimensional stress-optic law in terms of absolute retardation which give the change in the index of refraction of each refracted beam with respect to the original index of refraction in the unstressed state. Post (1954) used the relations in a series of interferometers for determination of absolute retardation while Favre (1929) determined the individual principal stresses by means of a Mach-Zehnder interferometer. Measurements can be very precise but they are difficult and time consuming. As a result relative retardation which is a measure of the relative change in indices of refraction of the refracted beams is employed. By eliminating \( n_0 \) from equations 5.19, 5.20 and 5.21:

\[
\begin{align*}
\Delta n_1 &= (C_2 - C_1)(\sigma_2 - \sigma_1) = C(\sigma_2 - \sigma_1) \\
\Delta n_2 &= (C_2 - C_1)(\sigma_3 - \sigma_2) = C(\sigma_3 - \sigma_2) \\
\Delta n_3 &= (C_2 - C_1)(\sigma_1 - \sigma_3) = C(\sigma_1 - \sigma_3)
\end{align*}
\]

where \( C = C_2 - C_1 \) = stress-optical coefficient, a constant for the material, measured in \( \text{m}^2/\text{N} \).

Equation 5.15a can be used to relate the relative phase difference, \( \alpha \) (or relative retardation) to changes in the refractive indices in the material resulting from the stresses. Consider, say a slice of material, thickness \( d \) oriented perpendicular to one of the principal-stress directions at the point of interest in the model. If a beam of plane-polarized light is passed through the slice at normal incidence, the relative retardation, \( \alpha \), accumulated along each of the principal stress directions can be obtained from equations 5.24, 5.25 and 5.26:
where \( \alpha_{12} \) is the magnitude of the relative retardation developed between components of a light beam propagating in the \( \sigma_3 \) direction. The two components of the beams would have electric vectors oriented in the \( \sigma_1 \) and \( \sigma_2 \) directions. The component associated with the principal stress \( \sigma_1 \) would propagate at a higher velocity than the one associated with the stress \( \sigma_2 \) (taking \( \sigma_1 > \sigma_2 > \sigma_3 \)). Similar meanings can be attached to the retardations \( \alpha_{23} \) and \( \alpha_{31} \).

Equations 5.27, 5.28 and 5.29 express the stress-optic law as it is commonly applied in photoelasticity. The relative retardation \( \alpha \) is linearly proportional to the difference between the two principal stresses having directions perpendicular to the path of propagation of the light beam. The third principal stress, having direction parallel to the path of propagation of the light beam, has no effect on the relative retardation. Also, the relative retardation \( \alpha \) is linearly proportional to the model thickness, \( d \) and inversely proportional to wavelength, \( \lambda \) of the light source.

For two-dimensional or plane stress problems, where one of the principal stresses is zero (say \( \sigma_3 = 0 \)), the stress optic law in terms of the non-zero principal stresses and for light at normal incidence to the plane of the model can be written without the subscripts as in equations 5.18.

\[
\alpha = \frac{2\pi d \sigma}{\lambda} (\sigma_1 - \sigma_2) \tag{5.18}
\]

Equation 5.18 is frequently expressed in the following form for practical work:
\[
\sigma_1 - \sigma_2 = \frac{Nf}{d} \tag{5.30}
\]

where

\[
N = \frac{\alpha}{2\pi} = \frac{dC}{\lambda} (\sigma_1 - \sigma_2) \tag{5.31}
\]

is the relative retardation in terms of a complete cycle of retardation and

\[
f = \frac{\lambda}{C} \tag{5.32}
\]

is the property of the model material known as the material fringe value. For PSM-1, the model material used in the experimental works, the material fringe value is given as 7 kN.Fr/m.

From equations 5.18 and 5.31, the intensity of light beam emerging from the circular polariscope is a function only of the principal stress difference. This also indicates that isoclinics have been eliminated from the fringe patterns observed with the circular polariscope and the pattern that resulted is the isochromatic fringe pattern.

With monochromatic light, the individual fringe in an isochromatic fringe pattern remains sharp and clear to very high orders of extinction. Since the wavelength of light is fixed, equation 5.31 can be written in terms of the material fringe value and the fringe order \( N \) as:

\[
N = \frac{d}{f} (\sigma_1 - \sigma_2) \tag{5.33}
\]

Here the number of fringes appearing in an isochromatic fringe pattern is controlled by the magnitude of the principal stress difference \( \sigma_1 - \sigma_2 \), by the thickness of the model and by the sensitivity of the photoelastic material, as denoted by the material fringe value, \( f \).
FIG. 5.7: EXPERIMENTAL SET-UP FOR DYNAMIC PHOTOELASTIC STUDIES WITH THE CIRCULAR POLARISCOPE ARRANGEMENT.

Q1 Quarter Wave Plates
P1 Polarizer
P2 Analyser

NITROGEN LASER-PUMPED DYE LASER

HE-NE LASER

TEST SAMPLE

REFERENCE SAMPLE

FRAMESTORE

VIDEO MONITOR

VIDEO CAMERA

COMPUTER

TRIGGER CONTROL

UNIT

ND:YAG LASER

M1

B1

B2

N2
Fig. 5.7 shows how the Mach-Zehnder interferometer was upgraded to incorporate the dynamic photoelastic studies. The main additional components were the pair of polarizers, \( P_1 \) and \( P_2 \), and a pair of quarter wave plates, \( Q_1 \) and \( Q_2 \). The recording of the isochromatic fringe pattern was carried out by blocking the reference beam of the interferometer. Fig. 5.8 shows a series of the digitally recorded images of the laser generated acoustic wave propagating in PC taken at the same delay of 2.0 \( \mu s \) after the breakdown in the liquid. Fig. 5.8a shows the various dynamic photoelastic fringe patterns corresponding to (i) without the use of any polariscope (shadowgraph), (ii) the use in conjunction with a plane polariscope and (iii) circular polariscope setup. Fig. 5.8b shows the corresponding interferograms. As would be expected in Fig. 5.8a, since the probe beam is unpolarized, the resulting image of the acoustic wave would be 'fuzzy'. All the components of the unpolarized beam contributed to the resulting fringe formation that is the different components undergo their different respective retardations resulting in the interference patterns being superimposed on each other. The enhanced shadowgraph, a(i), is able to show the longitudinal wavefront in the solid although the visualisation of the shear disturbance is still not possible. However, the complimentary interferogram, a(ii), clearly shows the disturbance due to the shear components. The corresponding interferogram of the acoustic transient in perspex, Fig. 6.2c, does not show this phenomena. The use of plane polariscope in Fig. 5.8b, removes the fussiness and shows both the isoclinic and isochromatic fringe patterns. This can be very confusing when information on stress magnitudes is required. Fig. 5.8c shows the recorded images obtained with the circular polariscope arrangement and clearly seen from this images, the bulk waves and mode converted waves in the solid, as explained in section 6.3
FIG. 5.8: (a) DYNAMIC PHOTOELASTIC FRINGE PATTERNS OF THE GENERATED ACOUSTIC WAVES AT TIME OF 1.0 μs CORRESPONDING TO (i) WITHOUT POLARISCOPE (SHADOWGRAPHY) (ii) WITH PLANE POLARISCOPE (iii) WITH CIRCULAR POLARISCOPE. (b) THE INTERFEROGRAMS OF (a).
5.4 RECORDING TECHNIQUES

5.4.1 Introduction

Various photomechanic techniques have been applied to transient stress problems. An early approach was to use soft model materials of low modulus of elasticity such that the low propagation velocities enabled dynamic fringes to be photographed with conventional high-speed photography. Subsequently, stiffer model materials were used in order to simulate more accurately the mechanical behaviour of the actual component's materials. As a result of high modulus of elasticity and hence high wave velocities demand more sophisticated recording techniques. Several types of recording systems are possible. They include single flash photography, streak cameras, framing cameras, multiple spark-gap (Cranz-Schardin) systems, laser systems and digital imaging cameras. Recording of the transient isochromatic fringe patterns is the most important aspect of dynamic photoelasticity and it is difficult because the fringes propagate at velocities between 50 and 3000 ms\(^{-1}\) and for this project the compression wave velocities of PC is about 2000 ms\(^{-1}\) and PMMA is 2700 ms\(^{-1}\).

5.4.2 Single Flash Photography

Single flash photography is used in conjunction with repeatable and controlled loading such as air shock loading, explosives and water jets (Daniel et al. 1964). A typical flash unit may consist of an air flashtube, a reflector, the rectifier transformer and a power supply, used in conjunction with an inexpensive camera as the recording device. A 2kV pulse triggers the flashtube and generates a brilliant flash of up to 5 \(\mu s\) duration. The flash unit can be used with a delay generator for synchronisation with the various stages of a reproducible event. Modulated ruby laser can also generate single flashes of high intensity light of short duration (40 ns). It allows the use of large size film and gives good definition of details, especially around stress concentrations.
5.4.3 Framing Cameras

Depending on the type of photoelastic material and the type of loading being used, there is a wide range of high-speed framing cameras available for use in dynamic photoelastic studies with conventional high-intensity light sources. One example is a camera that makes use of a continuously moving roll of film with a rotating optical system which holds the image formed by the main lens stationary with respect to the moving film. It can record events at rates varying from a few hundred to over 2000 frames per second with exposure times typically equal to one third of the inter-frame time interval. A common light source is a number of flashbulbs with light duration of up to 100 ms and this system has been used in photoelastic studies of materials with propagation velocities of the order 50 ms\(^{-1}\). Higher modulus materials require higher framing rates and recording is usually accomplished by combining a rotating mirror with a stationary strip of film on a drum. High-speed framing cameras require high-intensity illumination because of the short exposure times and the losses due to the polariscope elements. Two types of continuous light source have been used, argon flashbulbs or electronic flash. The electronic light source employs one or more xenon flash lamps which are energised and switched by a specially designed power supply and circuit. They have a rise time of approximately 45 \(\mu s\) and a controlled effective duration varying from 20 to 100 \(\mu s\). The first application of a high-speed framing camera was reported by Feder (1956) and since then other workers like Flynn et al. (1962) introduced many improvements in the applications of this type of camera to a variety of problems in dynamic photoelasticity. Cameras with framing rates of up to 10,000,000 frames per second and 50 - 100 frame capability had been reported (Clark and Durelli 1983).

5.4.4 Streak Photography

A streak photograph, in contrast to a full two dimensional image photograph, is obtained from a very narrow rectangular zone of the model. The model is normally masked so that light is received by the camera and focused as a strip image on a continuously moving film. The strip is orientated to be at
right angles to the direction of motion of the film. The resulting photograph gives a continuous time record of the birefringent along the line being photographed. The effective time of exposure is calculated as:

\[ t = \frac{d}{v} \]

where \( d \) = width of slit image on the film and \( v \) = linear velocity of the film. For purposes of comparison with framing photography the equivalent framing rate is given by:

\[ R = \frac{1}{t} = \frac{v}{d} \]

The application of streak photography to dynamic photoelasticity was described by Frocht et al. (1957). They achieved exposure times of 2/3 \( \mu s \) and obtained fringe patterns in discs and beams under impact.

### 5.4.5 Multiple Spark Systems

The multiple spark gap camera, originally developed by Cranz and Schardin in 1929, has been applied by many investigators. It consists of an array of spark gaps which are fired in sequence to provide controlled illumination as shown in Fig. 5.9. For a typical 4 x 4 array of spark gaps, Riley and Dally (1969), obtained 16 distinct images, corresponding to 16 different time instances in the event on one sheet of film. The light from each gap passes through a polarizer, the transparent specimen, an analyzer, and then it projects and focuses the image of the specimen on a separate camera lens. The time sequence of the sparking is governed by the inductances in the control circuit. The light pulse duration of a spark gap is approximately 0.5 \( \mu s \) which is adequate for recording fast-moving densely spaced fringes of 0.6 fringes mm\(^{-1}\) at 2500 ms\(^{-1}\). Conway (1975) proposed a simplified version whereby the spark gaps are replaced by xenon flash tubes. Dally and Sandford (1982) developed the system further by replacing the spark gap light sources by ruby lasers with fibre optic light guides. Six independent Q-switched ruby lasers provide six very intense and ultra short (30 ns) pulses of light. A computer controlled synchronisation procedure for Q-switching the
FIG. 5.9: ARRANGEMENTS OF ELEMENTS IN OPTICAL SUBSYSTEM OF CRANZ-SCHARDIN CAMERA.
lasers provides for improved control and versatility.

5.4.6 Laser Recording Systems

The laser provides an ideal light source for dynamic photoelasticity. The highly collimated beam of monochromatic light of high intensity and extremely short pulse duration can be used to produce single frames in a repeatable experiment. Rowlands et al. (1969) successfully coupled a sequential pulsed ruby laser with a high-speed framing camera. They used a modified streak camera whereby the light entering the camera is collected by an objective lens, reflected by a rotating mirror and then projected onto a stationary film. The system was applied to transmitted and scattered light photoelasticity and synchronisation of events is achieved by means of a trigger pulse from the camera which discharges the laser and triggers the explosive loading in the model. Hendly et al. (1975) have also developed a hybrid Cranz-Schardin laser system by using an acousto-optic deflector to divert the beam from a sequentially pulsed laser and a multiple-lens system to produce up to five images. Unfortunately high-order oscillations in the acousto-optic deflector reduces the quality of the fringe patterns.

5.4.7 Photodetectors and Digital Imaging Systems

Photodetectors, in the form of photocells, photomultipliers or photodiodes, have been used for measuring dynamic birefringent by a number of workers (Chase and Goldsmith, 1974; Peeters and Parmeter, 1974) and are mainly utilised in material characterisation studies where the aim of the experiment is to measure birefringence at a point. Cunningham et al. (1970) used the photosensitive devices for the study of impact and wave propagation problems. One of the recent developments in this area is that of the digital imaging camera and a new field known as "half-fringe photoelasticity" has emerged (Voloshin and Burger 1983). The technique is based on a digital grey level analyser and picture processing system. The intensity field of a half-fringe light-field photoelastic pattern is divided into 256 grey levels for an equivalent fringe multiplication of 512 times. This method is a full-field
one and would allow the use of low birefringent sensitivity materials such as glass and transparent composites.
5.5 REFERENCES


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CHAPTER SIX

DIAGNOSTICS OF THE STRESS-WAVE PROPAGATION

6.1 INTRODUCTION

The optical diagnostic techniques, as described in this thesis, are especially suited for the observation and measurement of parameters in wave propagation problems. They afford numerous advantages such as rapid and simultaneous recording of the stress-field, non-disturbance of the process under observation and quantitative information about the events. The methods also yield high spatial and temporal resolution in combination with the high-speed photographic techniques whereas video photography allows for detection of temporal variations.

A variety of models have been used for dynamic photoelastic studies. A photoelastic material must fulfil a number of requirements. Firstly, it should be transparent and isotropic when unstressed and should not scatter light; this eliminates semicrystalline plastics. Secondly, flat sheet or three-dimensional models should be easy to prepare, that is, the models are cast from a thermosetting material with low shrinkage on curing. Extruded thermoplastic sheet, (polycarbonate is a good example) can be used, but it needs careful drying and removal of any molecular orientation by annealing. The sheets of materials should be easily machined to shape without leaving permanent or residual stress. Thirdly, the material should be elastic, with a linear stress-strain relationship and little creep if a constant load is applied. In the interferometric studies of the wave propagation, the material should ideally be optically similar to glass with good surface finish and transparency. Fig. 6.1 shows the stress-strain optical behaviour of polycarbonate (Brinson, 1972). Feldman (1975) reported a method of measuring photoelastic and elastic constants of transparent materials and
Waxler et al. (1979) measured the photoelastic and elastic constants of PMMA and PC by the same method. They subjected the specimen to a uniaxial stress, which produced a change in optical path length within the specimen and the shift of interference fringes per unit of applied stress \(\Delta N/\Delta P\) when measured in a Twyman-Green interferometer is given as:

\[
(\Delta N/\Delta P) = \left(2s/\lambda\right)\left[(n^2/2)q - (n - 1)s,_{12}\right]
\]  

where 
- \(t\) = specimen thickness  
- \(\lambda\) = wavelength of probe beam  
- \(q = q_{11}\) for radiation polarized along the stress axis  
- \(q = q_{12}\) for radiation polarized perpendicular to the stress axis

The significant Waxler results, the values of the relevant constants as given in Table 4.1, can be shown in the Mach-Zehnder interferograms of Fig. 6.2. The interferograms showed the different shifts in interference fringes at different points on the wavefront which depended on the direction of polarization relative to the principal stresses. Fig. 6.2a shows the result when using a linearly polarised probe beam, perpendicular to the interface between the two media whilst fig. 6.2b was obtained with the probe beam parallel to the interface. The liquid-solid interface is represented by the dark horizontal band with the liquid above the band. This resulted in the interpretation of the interferogram being rather difficult when using the optically anisotropic material. It is therefore important to have the arrangement of the circular polariscope components constant throughout the experimental work. As described in section 5.2, the circular polariscope was setup in a light field arrangement. Abel inversion of the recorded image was carried out with the dark fringe nearest the centre of emission of the acoustic wave for all interferograms. These problem do not arise in optically isotropic PMMA, where \(q_{11} = q_{12}\) as shown in Fig. 6.2c., where an unpolarized probe beam can be used. Equation 6.1 also shows that for a unit of applied uniaxial stress, the PC will show a greater fringe shift than PMMA and thus PC is more sensitive than PMMA assuming the same pressure exists at the same wavefront radius in both materials. Figs. 6.2a and 6.2b, for PC and 6.2c, for PMMA, also show that whereas a shear disturbance can be visualised in PC, this is obviously absent in PMMA although the laser interaction is the same.
FIG. 6.2: INTERFEROGRAMS OF THE LASER GENERATED ACOUSTIC WAVE AT TIME $t = 1.5 \mu s$ CORRESPONDING TO (a) LINEARLY POLARIZED PROBE BEAM, PERPENDICULAR TO THE LIQUID-PSM-1 BOUNDARY and (b) PARALLEL TO THE BOUNDARY, (c) UNPOLARIZED PROBE BEAM FOR THE LIQUID-PERSPEX INTERFACE.
in both cases. It was necessary to have the laser breakdown as near as possible to the liquid-solid interface, Fig. 6.2c, in order to get an appreciable shift in interference fringes in the perspex. This is another disadvantage of the perspex compared to the PSM-1 because of the difficulty in visualising the transients in the solid. Unless the initiating source was directly on the surface, which means damaging the material, the acoustic waves would be rather weak in the solid. When the laser was focused above the perspex, the disturbance associated with the acoustic transients were difficult to visualise even though the instrument was setup in focused shadowgraph technique. The difficulties associated with the perspex means that only PSM-1 was used in the experiments described in the following sections and hence the incorporation of the dynamic photoelastic technique.

6.2 ELASTIC WAVE PROPAGATION IN SOLIDS

The effect of a sharply applied, localized disturbance in a medium soon transmits or spreads to other parts of the medium. The manifestation of this phenomenon such as the transmission of sound in air, the spreading of ripples on the surface of water, the transmission of seismic tremors in the earth or the transmission of radio waves are familiar to us. These provide an illustration of the propagation of waves through gaseous, liquid and solid media and free space. The outward propagation of waves from a disturbance would inevitably encounter and interact with boundaries. As mentioned in chapter 1, in the case of a solid, two distinct types of oscillation will be possible in a wave. In one case, the solid will transmit tensile and compressive stresses and the motion of particles will be in the direction of the wave motion. This wave is a longitudinal (or sometimes $P$) wave. In addition the solid may transmit shear stress where the motion of the particles is transverse to the direction of propagation. Whereas in the first case the behaviour is analogous to that of fluids, which can only support this mode of propagation, there is no analogue to the second case in liquids or gases. The transverse nature of the second mode of propagation closely resemble electromagnetic waves. The interaction of elastic waves with
boundaries in solids differs considerably from that in fluids. In a solid a single wave, be it compression (p) or shear (s), will generally produce both compression and shear waves on striking a boundary (a phenomenon known as mode conversion), whereas acoustic and electromagnetic waves in fluids will only generate waves of their own type.

Although the propagation of waves in solids may be roughly divided into three categories, it is the scope of this project that only propagation that assumes elastic behaviour is considered. The experimental measurements and observations of the propagation of elastic waves, where the stresses in the material obey Hooke's Law, provide much information on the properties of the solids and has found varied practical applications. The other two main categories, viscoelastic waves, where viscous as well as elastic stresses occur, and plastic waves in which the yield stress of the solid is exceeded.

The theoretical background to some of the treatises on the subject of wave propagation has been progressively developed in order to enable ultrasonic and acoustic data to be interpreted. Kolsky (1953), Ewing et al. (1957), Achenbach (1973) and Graaf (1975), among others, have given a full account of such theory. However, the theory of acoustic wave propagation in solids is more difficult under transient conditions particularly when the waves undergo significant amounts of reflection, refraction and diffraction. In addition to the two bulk waves, dynamic loading in an elastic solid generates a third type of wave along the surface, which travels at a slightly slower velocity than the shear wave. Aki and Richards (1980) give full numerical solutions for wave propagation in an infinite body whilst Pekeris and Lifson (1957) considered propagation in a half space and Pao et al. (1979) treated the infinite plate situation. Apart from the works of Chapman (1981) and Ogilvy and Temple (1983) when they published solutions for the diffraction of ultrasonic pulses, only approximate solutions are available for more complex bodies. The concept of laser generation and detection/reception of acoustic waves can be used either to confirm wave propagation theory or to extend it to problems that are not amenable to easy theoretical solution, and hence their use in experimental studies of elastic wave propagation.
Graaf (1975) considers the governing displacement equations in the absence of body forces, given by:

\[(\lambda + \mu)\nabla \nabla \mathbf{u} + \mu \nabla^2 \mathbf{u} = \rho \ddot{\mathbf{u}}\]  \[6.2\]

By performing a vector operation of divergence:

\[(\lambda + \mu)\nabla \cdot (\nabla \mathbf{u}) + \mu \nabla \cdot (\nabla^2 \mathbf{u}) = \rho \nabla \ddot{\mathbf{u}}\]  \[6.3\]

which reduces to:

\[\nabla^2 \Delta = \frac{1}{c_L^2} \frac{\partial^2 \Delta}{\partial t^2}\]  \[6.4\]

where the propagation velocity \(c_L\) is given by:

\[c_L = \sqrt{\left[ \frac{\lambda + 2\mu}{\rho} \right]}\]  \[6.5\]

where \(\lambda\) and \(\mu\) are the Lame constants
\(u\) represents the particle displacements in the \(x, y, z\) directions.
\(\Delta = \nabla \mathbf{u}\) defined the dilatation of the material (Graaf, 1973)
\(\rho\) is the density

\(c_L\) is the compressional or longitudinal wave velocity which involves no rotation and can also be expressed in terms of the elastic moduli:

\[c_L = \sqrt{\left[ \frac{K + 4/3 \mu}{\rho} \right]}\]
\[ E(1-\sigma) \sqrt{\frac{E(1-\sigma)}{\rho(1+\sigma)(1-2\sigma)}} \]  

where \( E \) is the Young's Modulus 
\( G \) is the rigidity or shear modulus which is equivalent to \( \mu \) 
\( K \) is the Bulk modulus 
\( \sigma \) is the Poisson's ratio

It is clear that the various moduli are related:

\[ \lambda = \frac{E\sigma}{(1+\sigma)(1-2\sigma)} \]  
[6.7]

and

\[ G = \frac{E}{2(1+\sigma)} \]  
[6.8]

It is of interest to note that the ratio of the Lamé constants is:

\[ \frac{\lambda}{G} = \frac{2\sigma}{1-2\sigma} \]  
[6.9]

and therefore depends only on the Poisson's ratio, \( \sigma \)

By performing the operation of curl on equation 6.3 and since the gradient of a scalar is zero, this gives:

\[ \mu \nabla^2 \omega = \rho \frac{\partial^2 \omega}{\partial t^2} \]  
[6.10]

where \( \omega = (\nabla \times u)/2 \), the rotation vector.

This result is in the form of vector wave equation and may be expressed as:
where the propagation velocity $c_s$ is given by:

$$c_s = \sqrt{(G/\rho)}$$  \hspace{1cm} [6.12]

$$= \sqrt{\left(\frac{E}{2\mu(1+\nu)}\right)}$$  \hspace{1cm} [6.13]

$c_s$ is the transverse or shear wave velocity of the acoustic wave in the medium and involves no volume change. It is interesting to note that in an ideal fluid, for which $G = 0$, a transverse wave cannot propagate.

The ratio of the two wave velocities may be expressed as:

$$k = \frac{c_L}{c_s} = \sqrt{\left(\frac{2 - 2\sigma}{1 - 2\sigma}\right)}$$  \hspace{1cm} [6.14]

Since the Poisson ratio is $0 \leq \sigma \leq 0.5$, we see that $c_L > c_s$.

A variety of terminology exists for the two type of waves. Compressional waves are also called longitudinal, irrotational or primary ($P$) waves whereas the transverse waves are also called distortional, equivoluminal, secondary or shear ($S$) waves. Table 6.1 gives nominal values of the velocities of the different materials used in the experimental works and are calculated from data on elastic constants and density (Kaye and Laby, 1972).

Rayleigh (1885) theoretically showed the possibility of a two-dimensional wave propagating with an elliptical motion on the surface of a solid. The longitudinal (compressional) component of the wave, parallel to the surface, is in the direction of propagation and a transverse (shear) component is
normal to the surface. The discovery of this type of wave was closely related to seismology, where it was observed that earthquake tremors consisted of two early, rather minor disturbances corresponding to \( P \) and \( S \) waves, followed closely by a significant damage-causing tremor. Rayleigh also showed that their effect decreases rapidly with depth and their velocity of propagation is less than the bulk waves.

An approximate expression that has been developed for the Rayleigh velocity, \( c_R \) (Viktorov, 1967) is:

\[
\frac{a^6}{8(1-a^2)} + a^2 = \frac{1}{1-\sigma}
\]

where

\[ c_R = a c_s \]

Since the range of possible values of \( \sigma \) is 0 to 0.5, the corresponding range of \( a \) is 0.87 to 0.96. Knopoff (1952) has computed the ratios \( c_R/c_L \), \( c_R/c_s \) for all possible values of \( \sigma \). These are shown in Fig. 6.3. Using the value of \( c_R/c_p \) for PSM-1, a surface acoustic wave would be shown on the interferograms of Fig. 6.4 with velocity of about 0.41 of the compressional wave in the solid.

6.3 STRESS-WAVE PROPAGATION AT A LIQUID-SOLID INTERFACE

As described in section 3.3, the Nd-YAG laser pulse is focused into the distilled water at about 0.4 mm from the solid surface, Fig. 3.3. This resulted in the dielectric breakdown and the production of a plasma within the water near the focal region. The outwards motion of the resulting cavitation bubble generates a longitudinal wave in water and the interaction of this wave with the solid boundary creates both longitudinal \((P)\) and shear\((S)\) waves in the
FIG. 6.4: (A) ISOCROMATIC FRINGE PATTERNS and (B) INTERFEROGRAMS OF THE LASER INDUCED ACOUSTIC WAVES NEAR LIQUID-PSM-1 BOUNDARY AT TIMES OF (i) 0, (ii) 0.5, and (iii) 1.0 μs.
FIG. 6.4: (A) ISOCROMATIC FRINGE PATTERNS and (B) INTERFEROGRAMS OF THE LASER INDUCED ACOUSTIC WAVES NEAR LIQUID-PSM-1 BOUNDARY AT TIMES OF (i) 1.5, (ii) 2.0, and (iii) 2.5 μs.
FIG. 6.4: (A) ISOCHROMATIC FRINGE PATTERNS and (B) INTERFEROGRAMS OF THE LASER INDUCED ACOUSTIC WAVES NEAR LIQUID - PSM-1 BOUNDARY AT TIMES OF 3.0 μs.
bulk of the solid and a guided surface wave at the liquid-solid interface (Suaidi et al., 1991).

Fig. 6.4 shows a sequence of images of the acoustic waves generated by the action of the focused laser beam on a water-PC (PSM-1) boundary. Fig. 6.4a represents the isochromatic fringe patterns while Fig. 6.4b shows the complementary interferograms. The transparent solid was prepared from a 9 mm cast sheet of PSM-1 which was cut into blocks with sides length of 25 mm. The blocks were carefully cut and hand polished in water as coolant so as not to produce residual or permanent stresses. The polished original cast surfaces were used as the probe beam's entry and exit faces. The specimen block was then placed in the water filled glass cuvette and positioned in the test arm of the interferometer with a matching water-PC sample positioned in the reference arm of the instrument. The images of both test and reference samples were closely superimposed across the field of view as seen on the video monitor. The dark circular area just above the boundary is a developing cavitation bubble which grows in size with subsequent images.

For this study of the laser interaction at a liquid-solid boundary, the infrared laser beam is focused into distilled water about 0.4 mm from the solid surface, which is the centre of the cavitation bubble, well away from the upper liquid surface and cuvette walls which act as free and rigid boundaries. Breakdown was initiated just above the PC surface so as not to damage the solid and therefore allow good reproducibility from one event to another. As may clearly be seen from the second picture in each series, the resultant supersonic motion of the bubble wall generated an acoustic wave in the water, \( c_{w1} \) which separates from the bubble and propagates radially away from its centre of emission. When this wave encounters the solid boundary, energy is reflected from and transmitted across the boundary. Due to the compressional nature of the wave in water, the particle displacement is in the direction of motion of the wave and thus the acoustic wave hits the boundary normal to the surface. On impact therefore a reflected compression wave in water occurs, \( c_{w2} \) and only a compression wave, \( c_p \) is initially generated in the solid and this propagates radially away from the surface forming a hemispherical wave.
At the point where this compression wave, that is $c_p'$, encounters with the boundary it generates a conical shear head wave in the solid, $c_{ss}$ and launches a conical compressional head wave in the liquid, $c_{pw}$. These waves appear as straight lines beginning from the point where $c_p'$ interacted with the boundary tangential to $c_{w1}$ for $c_{pw}$, and tangential to $c_{s}$ for $c_{ss}$. This so-called head wave was generated by that part of $c_p'$ which caused a horizontal motion of particles of the solid at the interface (Ewing et al., 1957). The conical wave front in the liquid is linked to the reflected compression wave, $c_{w2}$ because $c_p'$ is only formed when the initially downward propagating water wave became incident upon the interface since the source of the water wave lay slightly above the boundary. The conical wavefront makes a Mach angle $\theta_3$ with the boundary given by: \[ \sin \theta_3 = c_w/c_p. \] As the compressional wave in water moves away from its point of impact on the surface, it starts to generate a hemispherical shear wave, $c_s$ in the solid. This is very weak directly below the impact point but the shear component grows as the angle of incidence of $c_{w1}$ increases at larger radii. The $c_{w1}$ wave also produces a surface acoustic wave $c_R$ and mode converts into shear head wave $c_{sw}$ in the solid. The surface wave is clearly shown in the interferograms just inside the the hemispherical water wave on either side of the liquid-solid boundary. The disturbance in the solid caused by the propagation of the surface wave can clearly be seen in the isochromatic fringe patterns where it extends about 800 $\mu$m into the solid as seen from the image corresponding to delay of 3 $\mu$s. The isochromatic fringe patterns within the shear wavefront are rather complicated. This is due to the interactions between hemispherical shear wave, the conical head waves and the surface wave. The deviation of the leading fringe, associated with the compressional wave in the solid, from its circular path near the boundary is due to the superposition of the two bulk waves in this region. Fig. 6.5 shows a schematic of the different wave structures that can be identified and their respective velocities calculated by measuring the distance travelled by the wavefront at the different time delays, Fig. 6.10. The spacing of the wavefronts in Fig. 6.5 is in accord with their differing velocities. Graaf (1975) reported that the surface wave undergoes an amplitude attenuation with distance of $r^{-0.5}$ while the bulk waves in the solid suffers a more severe attenuation of $r^{-1}$. 

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FIG. 6.5: SCHEMATIC DIAGRAM OF THE ACOUSTIC WAVES GENERATED FOR THE WATER - PSM-1 BOUNDARY AT TIME OF 2.0 μS.

\[ \sin \theta_1 = \frac{c_s}{c_p} \quad \sin \theta_2 = \frac{c_s}{c_w} \quad \sin \theta_3 = \frac{c_w}{c_p} \]
Fig. 6.6 shows four radial pressure profiles of the compressional wave, \( c_p \) in the bulk of the solid as calculated from the interferograms of Fig. 6.4. The shift in the most central dark fringe was used in each case, so giving a measure of stress directly beneath the centre of emission on the boundary. No rarefactual components are present from the profiles and the stress remains above its ambient value at all times. The longitudinal transient is made up of the compressional pulse with a rise time \( r \) of approximately 50 ns. The pulse has a total duration of about 250 ns corresponding to a frequency of about 4 MHz and wavelength of 500 \( \mu \)m. The peak stresses, \( P_p \), arising from the compressional wave in the solid are plotted in Fig. 6.7 as a function of \( 1/r \) where \( r \) is the radial position at which \( P_p \) occurs. From these data, it is clearly shown that the amplitude of the wave is roughly attenuated in inverse proportion to the distance travelled.

Fig. 6.8 shows the radial pressure profile of the main hemispherical longitudinal wave in water above the cavitation bubble. It can be seen that the water wave is also compressional in nature with rise time similar to the compressional wave in the solid. The wave also follows the \( 1/r \) attenuation of the peak compressional pressure as seen from Fig. 6.9. As determined directly from the interferograms and isochromatic fringe patterns of Fig. 6.4, the velocities of the respective waves are found to be in very good agreement with their theoretical values as given in Table 6.1. The measured values of the velocities can be found from the gradients of the respective curves of Fig. 6.10 where:

\[
\begin{align*}
    c_p &= 1960 \pm 90 \text{ ms}^{-1} \\
    c_s &= 877 \pm 40 \text{ ms}^{-1} \\
    c_R &= 845 \pm 42 \text{ ms}^{-1} \\
    c_w &= 1560 \pm 80 \text{ ms}^{-1}
\end{align*}
\]

These values were also compared to the values obtained by measuring the respective angles, as shown in Fig. 6.5, on the recorded images and were found to be in good agreement.
Radial Pressure Profile For PSM-1

FIG. 6.6: RADIAL PRESSURE PROFILES OF THE COMPRESSONAL WAVE IN PSM-1 NEAR A WATER - PSM-1 BOUNDARY.
FIG. 6.7: PLOT OF THE PEAK PRESSURE AS A FUNCTION OF $1/r$ FOR THE COMPRESSIONAL WAVE IN PSM-1.
Radial Pressure Profile For Water

FIG. 6.8: RADIAL PRESSURE PROFILES OF THE LONGITUDINAL WAVE IN WATER NEAR A WATER - PSM-1 BOUNDARY.
FIG. 6.9: PLOT OF THE PEAK PRESSURE AS A FUNCTION OF $1/r$ FOR THE LONGITUDINAL WAVE IN WATER.
PSM-1

$C_L$ 2016 ms
$C_s$ 887 ms
$C_R$ 824 ms

WATER

1500 ms


FIG. 6.10: DISPLACEMENTS OF THE ACOUSTIC WAVES AS A FUNCTION OF TIME FOR THE WATER - PSM-1 BOUNDARY.
Ward (1991) adopted a modified relation of Cole (1948) between the energy and the pressure of the spherical acoustic transient where \( E \propto \int P^2 \, dr \). If the sound speed \( c \) in the media is assumed to remain constant across the acoustic wave then,

$$\Delta E = \frac{4\pi r_p^2}{pc} \int_{r_a}^{r_b} P^2(r) \, dr \tag{6.16}$$

where \( P \) is the maximum pressure at the radial distance \( r_p \), \( r_a \) and \( r_b \) define the inner and outer points at which appreciable changes in pressure \( P(r) \) such that \( r_a < r_p < r_b \).

Using the above equation, the acoustic energy of the compressional wave in the liquid at time of 2 \( \mu s \) is about 150 \( \pm \) 17 \( \mu J \) and the corresponding value in the solid is about 32 \( \mu J \). For the case of solid, this represents a value of about 1/150 of the total energy incident upon the liquid, which was measured as 4.6 mJ. Then the fraction of this energy converted directly to changes in pressure within the solid is 0.7 \( \pm \) 0.1 %. The remainder of the energy was either not absorbed by the water initially, converted to potential energy of the expanding vapour cavity, reflection at the liquid-solid boundary due to poor acoustic 'coupling', absorbed by the solid or the action of all of the above mechanisms. Ward (1991) in his study of the laser breakdown in air at an air-solid boundary found only about 0.03 % of the incident laser energy was converted into the acoustic energy in the solid. This can mean that the transfer of acoustic energy is less efficient in a air-solid boundary as compared to interaction at a liquid-solid interface.

The ability to visualise the refractive index disturbances associated with the different acoustic waves in PSM-1 with the circular polariscope arrangement, Fig. 6.4, increases the information that can be retrieved from the interferometric studies of dynamic photoelasticity. Shear waves can be visualised in PSM-1 as opposed to their absent in the optically isotropic perspex, because of the birefringence properties of PSM-1 when stressed. Shear waves, though not involving volume change associated with its propagation, can be detected by the photoelastic technique because of the
large difference between the constants $q_{11}$ and $q_{12}$ which is associated with stress induced birefringence. Waxler et al. (1979) gave the relation between fringe shift per unit of applied stress using polarimetric technique as:

$$\Delta N/\Delta P = \left( m \pi n^2 (q_{11} - q_{12}) \right)^{1/2}$$  \[6.17\]

where $m$ is the number of passes the probe beam makes through the specimen. Due to the similar value of the constants (Table 4.1), the shear disturbance would not show in perspex. Compressional wave disturbance which involves volume change can easily be seen in perspex by the shadowgraph, schlieren and interferometric techniques where the acoustic wave generates sufficiently high $(dn^2/dx^2)$, $(dn/dx)$ and $(dn/dx)$ respectively with $n$ being the refractive index along the axis of the probe beam through the disturbance.

It can be summarised that the action of a focused Nd-YAG laser beam in water at the liquid-solid boundary can generate a spherical wave in water, a hemispherical compressional and shear waves in the solid and an elliptical Rayleigh type surface acoustic wave on the interface, in addition to the various conical head waves generated in both media by mode conversion.

### 6.4 ACOUSTIC WAVE DIFFRACTION AROUND A 90° STEP

The next stage of the experimental work was to study the propagation and diffraction of the acoustic waves when they interact with simple defect in the solid. This extension of the technique to the study of the diffraction of the various ultrasonic modes around geometrical fault was possible after having acquired the necessary understanding of the acoustic waves generation and propagation at the plane liquid-solid boundary. Three types of model were prepared and investigated. The first of these was an internal 90° corner made by machining a square hole, under water, out of half of the top surface of the block, Fig. 6.11. It was necessary to have air in the hole, hence the corner, so as to minimise the complexity of the generated image due to the interaction
FIG. 6.11: PSM-1 BLOCK WITH THE 90° INTERNAL STEP.
and generation of various head waves and surface wave if the boundary were to be liquid. The hole was then covered with a thin microscope glass cover slip glued to the surface. The laser breakdown was initiated at about 0.8 mm from the edge of the hole, the minimum distance possible without any part of the incident beam being blocked by the glass slip. The block was immersed in the water-filled cuvette as before with a similarly machined reference block in the reference arm of the interferometer. Various step heights of the corner were made with great care in order to achieve minimal residual stress at the worked edges and surfaces. It was found that best results were obtained with a 1 mm deep corner corresponding to an angle, $\phi = 55^\circ$. It would be expected that the region within this angle is the shadow region for the acoustic waves diffracted by the obstacle.

Fig. 6.12, shows a sequence of images recorded by (A) circular polariscope and (B) a combination of circular polariscope and interferometer arrangement. The figure shows the interaction of the acoustic waves with the internal step and the subsequent diffraction of the waves as a result of the obstacle. The first picture in both sets of images shows the original background image before the generation of the spherical acoustic wave in the liquid. The residual stress, as a result of machining the block while making the step, is clearly seen in the pictures. This made the recorded images even more complex but the subsequent images showed clearly the diffraction of the main compressional wave in the solid. Enhancing the images of (A) greatly increased the ability to identify the different wave structures as shown by a selection of images in Fig. 6.12 (C).

Before coming into contact with the step, the hemispherical compressional wave in the solid propagates outward from its emission centre, as in section 6.3, with mode conversion occurring near the interface and launching the compressional head wave in the liquid. The developing compressional wave when first interacting with the step, was transmitted and reflected at the interface. This generated surface wave at the interface and mode conversion also occurred. The interaction of the various waves near this interface make the recorded images highly complex in this region thus the difficulty in identifying the various waves structures. The spherical acoustic wave in water also suffers diffraction when interacting with the side of the microscope slip.
FIG. 6.12: (A) ISOCHROMATIC FRINGE PATTERNS and (B) INTERFEROGRAMS OF THE LASER INDUCED ACOUSTIC WAVES INTERACTING WITH A 90° INTERNAL STEP AT TIMES OF (i) 0, (ii) 0.5 and (iii) 1.0 μs.
FIG. 6.12: (A) ISOCROMATIC FRINGE PATTERNS and (B) INTERFEROGRAMS OF THE LASER INDUCED ACOUSTIC WAVES INTERACTING WITH A 90° INTERNAL STEP AT TIMES OF (i) 1.5, (ii) 2.0 and (iii) 2.5 μs.
FIG. 6.12: (A) ISOCROMATIC FRINGE PATTERNS and (B) INTERFEROGRAMS OF THE LASER INDUCED ACOUSTIC WAVES INTERACTING WITH A 90° INTERNAL STEP AT TIMES OF (i) 3.0 and (ii) 3.5 μs.
FIG. 6.12: (C) ENHANCED ISOCHROMATIC FRINGE PATTERNS OF THE LASER INDUCED ACOUSTIC WAVES INTERACTING WITH A 90° INTERNAL STEP AT TIMES OF (i) 0.5, (ii) 1.0, (iii) 2.0, (iv) 2.5, (v) 3.0 and (vi) 3.5 μs.
FIG. 6.13: FRACTIONAL FRINGE SHIFT $\Delta F/F$ AS A FUNCTION OF ANGLE DUE TO COMPRESSIONAL WAVE PROPAGATION AND DIFFRACTION AROUND THE STEP.
FIG. 6.14: FRACTIONAL FRINGE SHIFT DIFFERENCE AS A RESULT OF THE PROPAGATION AND DIFFRACTION OF THE COMPRESSIONAL WAVE FOR MODELS WITH AND WITHOUT THE STEP.
This can be clearly seen at times of 1.0 and 1.5 μs when the wave was reflected back towards the emission centre. The wave also generated bulk waves in the glass and the surface skimming part of the compressional wave in the glass launched a head wave in the liquid. Since the sound speed in glass is about 2.5 times that of PSM-1 and 3.5 times that in water, the resulting head wave that linked itself to the reflected compressional wave in water, produced a smaller Mach angle, \( \theta_3 \), than the PSM-1 - water interface. Beneath the emission centre in the solid, the generated hemispherical shear wave interacted with the reflected part of the compressional wave.

After passing the barrier, the part of the compressional wave that strike the edge of the step, get diffracted into the shadow region behind the barrier. Fig. 6.13 shows the fractional fringe shift \( \Delta F/f \) associated with the compressional wave in the solid from the interferogram at time of 2.0 μs measured as a function of angle. The resulting fractional fringe shift was compared with the fractional fringe shift obtained for the case without the step. Fig. 6.14 shows a plot of the difference between the fractional fringe shift between both cases. It can be seen that while the compressional wave generally follows the pattern of the case without the step at an angle of less than 130°, the fractional fringe shifts are reduced considerably in the shadow region thus agreeing with simple diffraction theory.

6.5 ACOUSTIC WAVE DIFFRACTION AROUND A HORIZONTAL SLOT

The next set of investigation concerned the diffraction of the laser induced acoustic waves with a 0.8 mm air filled horizontal slot which was cut with a fine saw under water, Fig. 6.15. The slot was covered rather crudely with plasticine in order to keep pocket of air inside. A second reference sample was also made for the interferometric study of the diffraction of the waves around the slot. The Nd-YAG laser beam was focused at a point near the interface directly above the edge of the obstacle. Fig. 6.16 shows the two sets of recorded images of the acoustic waves propagation corresponding to (A) the isochromatic fringe patterns and (B) the complementary
FIG. 6.15: PSM-1 BLOCK WITH THE AIR FILLED SLOT CUT PARALLEL TO THE AXIS OF THE PROBE BEAM.
FIG. 6.16: (A) ISOCROMATIC FRINGE PATTERNS and (B) INTERFEROGRAMS OF THE LASER INDUCED ACOUSTIC WAVES INTERACTING WITH A HORIZONTAL SLOT AT TIMES OF (i) 0, (ii) 0.5 and (iii) 1.0 µs.
FIG. 6.16: (A) ISOCROMATIC FRINGE PATTERNS and (B) INTERFEROGRAMS OF THE LASER INDUCED ACOUSTIC WAVES INTERACTING WITH A HORIZONTAL SLOT AT TIMES OF (i) 1.5, (ii) 2.0 and (iii) 2.5 μs.
FIG. 6.16: (A) ISOCHROMATIC FRINGE PATTERNS and (B) INTERFEROGRAMS OF THE LASER INDUCED ACOUSTIC WAVES INTERACTING WITH A HORIZONTAL SLOT AT TIMES OF (i) 3.0 µs and (ii) 3.5 µs.
FIG. 6.16: (C) ENHANCED ISOCHROMATIC FRINGE PATTERN OF THE LASER INDUCED ACOUSTIC WAVES INTERACTING WITH A HORIZONTAL SLOT AT TIMES OF (i) 0.8, (ii) 1.5, (iii) 2.0, (iv) 2.5, (v) 3.2 and (vi) 3.8 \( \mu \)s.
FIG. 6.17: FRACTIONAL FRINGE SHIFT $\Delta F/F$ AS A FUNCTION OF ANGLE DUE TO COMPRESSIONAL WAVE PROPAGATION AND DIFFRACTION AROUND THE SLOT.
FIG. 6.18: FRACTIONAL FRINGE SHIFT DIFFERENCE AS A RESULT OF THE PROPAGATION AND DIFFRACTION OF THE COMPRESSIONAL WAVE FOR MODELS WITH AND WITHOUT THE SLOT.
interferograms. Fig. 6.16(C) shows the enhanced isochromatic fringe patterns of selected images. It was not possible to get a straight edged slot due to the limitation imposed by the piercing saw and as a result a round edged slot was produced. As can be seen from the interferograms, the slots of the reference and test samples were not perfectly superimposed resulting in imperfect path length compensation.

As before, the laser induced acoustic wave in water interacts with the interface resulting in the generation of the bulk waves in the solid and mode conversions at the interface. The main compressional wave in the solid first hit the obstacle at a time of 1.0 $\mu$s and as can be seen in the subsequent images, this resulted in the diffraction of the wave round the slot and highly complex region of waves interactions above the slot. The left hand portion of the compressional wave that did not hit the obstacle continue to propagate with the right part being diffracted into the geometrical shadow region. Fig. 6.17 shows the fractional fringe shift as a function of angles for the main compressional wave in the solid. It can be seen that, compared to the fractional shifts for the model without the slot, there is a sharp difference in fractional shift for angles less than 100° at time of 2.0 $\mu$s, Fig. 6.18. The strength of the main compressional wave was greatly reduced at smaller angles. The subsequent images also showed that the diffracted wave has a radius given by the difference between the distance from the lower corner of the slot to the interface and the radius of the main undiffracted compressional wave. Because of the spherical nature of the incident compressional wave when hitting the obstacle, the resulting diffracted wavefront would be approximately ellipsoidal with its major axis lying normal to the image plane. Also visible in the image at time of 2.5 $\mu$s is the compressional wave that was reflected from the top of the slot back towards its emission centre and transmitted into the water. This wave is roughly centred at the top edge of the slot at the point where the main compressional wave first hit the obstacle.
6.6 INTERACTION OF THE ACOUSTIC WAVE WITH A CYLINDRICAL HOLE

The final set of experiments was to study the interactions of the acoustic waves with a cylindrical hole parallel to the axis of the interferometer's probe beam. The 1 mm diameter hole was drilled, as usual with plenty of coolant, parallel to the axis of the probe beam, Fig. 6.19. A second similar model was made as the compensator in the interferometer setup. The laser beam was focused in the water near the interface directly above the centre of the hole. Fig. 6.20 shows a short sequence of images of the laser induced acoustic waves. From the pictures it can clearly be seen that there exists a complex structure masking the hole. This is due to the action of the drill which caused flaking of the materials in the region at the entrance of the hole due to the brittle nature of the solid. Also from the first picture of the background image, the drilling, even though performed with great care, produced a highly complex fringes associated with the permanent stressed induce birefringent. It was therefore difficult to make any sort of measurements especially from the interferograms.

However, the enhanced images of the isochromatic fringe patterns are able to show the propagation of the acoustic waves. The compressional wave in the solid interacted with the hole and part of it was reflected towards the interface while a proportion was diffracted around the hole. It can be seen from the pictures corresponding to time of 2.2 $\mu$s that the compressional wave immediately beneath the hole, suffered a reduction in strength due to the diffraction effect. The diffracted wave although linked to the main compressional wave has a greater radius of curvature compared to the incident wave. The propagation of acoustic wave in a region of permanent stress induced birefringent can help in the study of residual stress measurement of structural materials. Residual stresses are generally not desirable because they may take materials up to quite large fractions of the yield stress even in the absence of external stresses. Thus when the structure is loaded, it may fail at a lower load than expected, and defects present may grow at a higher rate than predicted. It has been reported that ultrasonic velocities show a small dependence on stress (Sayers et al., 1986). However,
FIG. 6.19: PSM-1 BLOCK WITH THE 1 mm DIAMETER AIR FILLED CYLINDRICAL HOLE PARALLEL TO THE AXIS OF THE PROBE BEAM.
FIG. 6.20: (A) ENHANCED ISOCHROMATIC FRINGE PATTERNS and (B) INTERFEROGRAMS OF THE LASER INDUCED ACOUSTIC WAVES INTERACTING WITH A 1 mm DIAMETER CYLINDRICAL HOLE PARALLEL TO THE AXIS OF THE PROBE BEAM AT TIMES OF (i) 0, (ii) 0.5 and (iii) 1.0 μs.
FIG. 6.20: (A) ENHANCED ISOCHROMATIC FRINGE PATTERNS and (B) INTERFEROGRAMS OF THE LASER INDUCED ACOUSTIC WAVES INTERACTING WITH A 1 mm DIAMETER CYLINDRICAL HOLE PARALLEL TO THE AXIS OF THE PROBE BEAM AT TIMES OF (i) 1.5, (ii) 1.9 and (iii) 2.2 µs.
the effect of stress is only second order, being to departures from linearity of
the elastic constants, so that it only produces very small changes in
ultrasonic velocity. This measurements would be limited by the present
experimental arrangement because Sayers also mentioned the accuracy of 1
part in 10,000 in the measurements of the ultrasonic velocity.


CHAPTER SEVEN

CONCLUSIONS AND RECOMMENDATIONS

The work described in this thesis can be broadly divided into several areas of interest but with a common and shared objective in high-speed optical diagnostic techniques. The techniques of high-speed video photography, interferometry, dynamic photoelasticity and shadowgraphy have been developed and applied to laser-liquid-solid interaction studies. The diagnostics system which is centred around a Mach-Zehnder interferometer has been found to be a suitable tool in visualizing the very high speed process involved in the propagation of laser generated acoustic waves in liquid and solid media. The varied and wide field of study involving several different techniques is a valuable training in fundamental principles that are usually found in a university research group.

The first area of study concerned the design and construction of a nitrogen laser-pumped dye laser system as a suitable light source in high-speed photography. A compact home built system was successfully constructed and tested with a conventional photographic technique, that is by using an SLR camera. Although the jitter of the system was less suited for work in conjunction with high-speed video techniques as compared with the expensive commercial dye laser system, nevertheless the constructed system offers an excellent light source in high-speed photography using a conventional camera. The positioning of the nitrogen laser cavity at one edge allows for another cavity of similar design to be placed alongside or on top of the first laser and with proper synchronisation, this arrangement can be used to pump two dye lasers for multi-pulse application. The efficiency of approximately 0.05% for the electrical energy conversion in the storage capacitor to the laser pulse light is in good agreement with more bulky and complicated designs as reported by several authors (Silva Reis et al., 1985; Chang et al., 1984). The development of the dye laser as part of the system
offered flexibility in tuning the output laser beam which can easily find
applications in several other optical diagnostics studies, for instance
two-wavelength interferometry. To narrow the linewidth of the dye laser
output still further, additional wavelength selective elements must be
employed either within the cavity as part of the wavelength
selective/feedback or as filters outside the cavity. A beam expanding
telescope serves to expand the dye laser beam to illuminate the full
diffraction grating and also to reduce the divergence of the dye laser beam.
Etalons of various types (Lawler et al, 1976) have been used to reduce the
bandwidth to less than $10^{-4}$ nm. It has been shown in chapter 2 how a
relatively simple nitrogen laser pumped dye laser system capable of a
repetition rate greater than 2 pulses per second can be built in a laboratory
at a very modest cost. It is also worth mentioning that the advantage of a
home made laser system is that repairs can be easily carried out without
resorting to manufacturer's assistance.

The development of a high-speed video photographic technique for use in
conjunction with the Mach-Zehnder interferometer and dynamic
photoelasticity setup offers an accurate measurements of transient pressure
variations in the medium as well as the visualization of the acoustic wave
propagation with high temporal and spatial resolution. Focusing of the
infrared Nd-YAG laser beam in water generates high-intensity acoustic
waves due to the electric breakdown in the liquid and subsequent expansion.
The method provides a convenient technique of generating acoustic waves in
a neighbouring solid without permanently damaging the solid in the process.
The excellent shot-to-shot reproducibility of the acoustic wave generating
laser coupled with good synchronisation procedures developed for the work,
provided a simple and cheaper alternative to the very expensive system of
streaked or multiframing image converter cameras. The video imaging and
capture system when illuminated using the 0.5 ns pulse from a nitrogen-dye
laser provided a set of images at different stages of development of the
acoustic transients thus producing movie-like sequences of events. The used
of photoelastic material, PSM-1, a polycarbonate (PC) enables the
visualisation of a shear disturbance which is not seen when perspex, a
polymethymethacrylate (PMMA) is used as the test specimen. The velocities
of the bulk waves in the solid, the compressional wave in water as well as
the different head waves caused by the interaction at the interface between the liquid and solid, were measured and found to be in good agreement with theoretical values. In cases where the propagation of the acoustic wave interacts with defects and boundaries, the resulting images provide visual information of the process as well as quantitative information of the interactions. Quantitative measurements of the changes in refractive index are carried out by an inversion technique called Abel inversion. The inversion of the fringe shifts of the interferogram leads to the radial pressure profile associated with the passage of the acoustic wave. The isochromatic fringe patterns, however only represent the difference between the principal stresses and do not give directly the absolute values of the stress. A further problem is due to the patterns being associated with a three dimensional stress field associated with the laser induced acoustic wave propagation.

The limitations in the accurate measurement of the fringe shifts of the Mach-Zehnder interferograms greatly affect the determination of the radial pressure profile. One of the alternative methods to overcome the problem as proposed by Peck et al (1953) and Holloway and Emmony (1990) is termed phase quadrature. This involves upgrading the Mach-Zehnder interferometer to work with two orthogonally polarized components of light, the phase relationship between them depending on the relative optical path difference of the arms of the interferometer. This makes use of both outputs of the interferometer, thus producing two sets of orthogonally polarized fringes. A $\lambda/4$ birefringent retardation plate is positioned into one of the outputs so as to produce a relative retardation of $\pi/2$. The resulting interference fringes at both outputs are said to be in phase quadrature and a complete phase map of an event could be generated without having to manually follow the path of the shifted fringe. By this method, enough information is available at a single instant to calculate the phase of interference over the image plane with high accuracy (Holloway and Emmony, 1990). Displacements due to the varying density field can be deduced with similar sensitivity to holographic methods by comparing the change in interference phase before and after the event.

Another method of overcoming uncertainties in phase difference, which is associated with the optical path difference, is by the use of two different probe beam wavelengths (Creath et al., 1985). These may be produced by the
simultaneous pumping of two different dye lasers or frequency doubling a suitable laser system to give out two wavelengths, \( \lambda_1 \) and \( \lambda_2 \). Wyant (1971) has showed that this generates two different sets of phase information which by subtraction produce a set of phase information corresponding to an equivalent wavelength \( \lambda_q \), where \( \lambda_q = \lambda_1 \lambda_2 / (\lambda_1 - \lambda_2) \)

Both light field and dark field isochromatic fringe patterns can be obtained by utilising both outputs of the interferometer to record either of these arrangements. The advantage of simultaneous recording of the patterns is that twice as much data is obtained for the determination of \( \sigma_1 - \sigma_2 \). This greatly assists in the determination of fringe orders to the nearest 0.5 order. Clark (1956) showed that the material fringe value of the photoelastic material varies with load rate (impact duration). It is therefore essential that dynamic material fringe value be used when quantitative measurement of the difference in stresses are to be carried out. As a result, dynamic calibration of the material ought to be undertaken for the above purpose (Nienaltowska, 1989). This is rather difficult in the author’s experimental setup because the calibration has to be carried out with the same impact condition as in the experiment. However, in the observation of wave propagation, this does not appear to be a significant problem (Frocht, 1960).

The above modifications, if implemented, would certainly enhance the quantitative measurement of the recorded images. However, the use of both interferometer outputs means that two video cameras coupled to two frame store would have to be used Fig. 7.1. The associated electronics with regard to synchronisation of the increase number of components, however difficult and expensive would be compensated by the resulting increase in accuracy.

Finally, the laser generation and detection of acoustic waves developed in this thesis would no doubt find application in such field as non destructive testing, NDT. The high speed photographic techniques are well suited to observing the interaction of ultrasonic fields with surface and bulk defects for both experimental and industrial NDT.
FIG. 7.1: MACH-ZEHNDER INTERFEROMETER UPGRADED TO PHASE QUADRATURE SETUP.
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