The visualisation of acoustic waves by schlieren and photoelastic techniques

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THE VISUALISATION OF ACOUSTIC WAVES
BY SCHLIEREN AND PHOTOELASTIC TECHNIQUES

by

K.G. HALL
(ASSOCIATE OF THE INSTITUTE OF PHYSICS)

A Thesis submitted for the Degree of
Doctor of Philosophy

Department of Electronics Design
and Communication
The Open University
October 1975
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ABSTRACT

Visualisation of acoustic waves in transparent media is described using schlieren and photoelastic principles. Continuous and pulsed waves are examined. Enhanced sensitivity results for both visualisation systems when a thyatron-triggered spark light source is introduced.

The schlieren apparatus demonstrates the Fresnel and Fraunhofer fields of acoustic waves in water. Reflection, refraction, diffraction and transmission through thin plates is demonstrated. The schlieren system is applied to the design of a water column-coupled ultrasonic probe array, for rail testing.

Photoelastic experiments include methods of construction of the "plane" and "circular" polariscopes. Three methods by which acoustic waves may be identified are described. The suitability of glass for test pieces is emphasised and compared with modern photoelastic materials.

Ultrasonic probes are shown invariably to transmit more than one wave type. Explanation of the sources of these waves is given. Studies of the interactions of compressional and shear waves with horizontal cracks and inclined cracks situated at a model rail bolt hole, are illustrated. Experiments to measure the depth of surface-breaking cracks in rail heads, using Rayleigh waves, show the existence of three received "A scope" signals on the ultrasonic display. These are explained when the interactions of waves with cracks are visualised. An improved testing method is suggested.

The circular polariscope is employed to identify the types of stress associated with compressional and shear waves in glass test pieces. The magnitude of static stresses in a cantilever beam is first
obtained by Tardy compensation. Further development produces equations enabling stress magnitudes to be calculated using measured optical retardations. A linear relationship is experimentally derived between the probe excitation voltage and the induced stress magnitude for both compressional and shear waves.

Stress measurements are verified by comparison with amplitude measurements of received signals expressed logarithmically.
MEMORANDUM

This thesis is submitted in support of an application for the Degree of Doctor of Philosophy in Technology from the Open University, Milton Keynes.

This thesis, or any part of its contents has not been submitted for other Degrees or Diplomas from this University or any other Institution.

Any assistance given in the programme of work is fully acknowledged in the text.

I hereby declare that the statements in this Memorandum are true in every respect.

K.G. Hall
October 1975
Throughout this programme of work I have been grateful for the assistance and interest shown by a number of my colleagues at the Railway Technical Centre. I would first like to acknowledge the suggestion by one of my former colleagues, Mr. C.R. Theumer, to pursue this work for Ph.D. purposes.

The construction of mechanical and electronic equipment has been an important part of this research programme. For this constructional work I would like to thank Mr. J. Broadhurst for his enthusiastic approach to these activities. For the electronic design of the variable time delay and its associated electronic circuits, I wish to thank Mr. D. Cook of the N.D.T. Group of the Physics Section.

A method of measuring the spectral distribution of the spark light source presented a problem during the later stages of the programme. Mr. B. Littlewood of the British Rail Scientific Services Division at Derby kindly agreed to produce the required data.

During the schlieren work and later during early photoelastic experiments, some difficulty was experienced in photographing the acoustic waves. My thanks are extended to Mr. L. Gell of the Research Department Instrumentation Section for his advice during this period.

The production of research reports for Open University credit purposes and the production of this thesis, have demanded a high degree of expertise and patience of the typing bureau and tracing department staff. I would like to thank the typists, in particular Mrs M. Cooper for her effort in producing this thesis. Due to the large number of illustrations required, this has required a considerable effort on behalf of Mrs M. Chidlow of the tracing office.
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I would like to express my appreciation to British Rail for the facilities extended to me at the Technical Centre at Derby and for permission to submit this work for a Ph.D. degree.
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1. INTRODUCTION

The non-destructive examination of components on British Railways began in 1946 when ultrasonic testing of railway carriage axles was introduced on the L.M.S. Railway. Since that time non-destructive testing on the railways has expanded considerably. Ultrasonic examination in particular of a wide range of components is currently undertaken. Rails and axles continue as components of primary importance in these examinations.

The information received during ultrasonic testing may be displayed in various forms. The interpretation of this information may in some cases be quite simple, in others a complex pattern of received information will be presented. In these difficult cases techniques which aid signal interpretation will be welcomed by the engineer or physicist. Thus visualisation of sound waves within test pieces aids interpretation. Similarly a quantitative visual assessment of the stresses accompanying sound waves will assist in the design of probes. Two techniques of visualisation have been used here for these purposes; these employ schlieren and photoelastic principles.

The display of acoustic waves by optical methods depends upon refractive index changes that are produced by stress causing strain. Both compressional and shear waves are accompanied by stress waves which modify the optical properties of the transparent medium. Gross changes of optical density causing refractive effects are used when the schlieren technique of display is adopted. More subtle changes of a birefringent nature can alternatively be used. When they are, the technique of photoelastic stress analysis can be applied.
In making a choice of the more suitable technique, a number of factors are relevant. In this work the practical applications of each development are constantly reviewed. Consequently acoustic wave visualisation in both liquids and solids must be achieved. Schlieren visualisation may be applied to both media, but photoelastic examination can be applied only to solids since pure liquids show no birefringence.

It would seem then that only schlieren visualisation is necessary but there are three reasons why photoelasticity has also been applied here. First a quantitative assessment of wave stresses is of interest. This can more readily be achieved by photoelasticity. Second, models for schlieren work must be more carefully selected and prepared, the latter process is a costly one. Third, the apparatus for sensitive schlieren systems is quite elaborate and expensive, whereas some photoelastic apparatus is available.

The light sources necessary for this work are each of a rather special type. Three sources will be used here, one of continuous output and two stroboscopic. A mercury arc lamp will be used to a limited extent in continuous wave work. A commercial stroboscope with a xenon tube and a thyratron-triggered spark light source will be employed for pulsed work. Improvements in the sensitivity and resolution for pulsed work, which is of more interest here, will be compared for the two stroboscopic sources.

A theoretical study of acoustic waves and their generation will be given. Chapter I will later assist in the explanation of observed effects during experimentation.

Schlieren equipment will be used to visualise continuous and pulsed ultrasonic waves. The phenomena of reflection, refraction,
diffraction and transmission of waves will be recorded. The principal application of the schlieren system will be made to the design of a water-coupled ultrasonic probe array. During this application work the interaction of compressional waves within "water boxes" will be given detailed consideration. The feasibility of using membranes of selected materials to support the water column will be investigated by examining pulses propagating through such membranes.

The application of photoelastic visualisation will be made first by use of the "crossed" plane polariscope, to a range of phenomena. These will include the generation of ultrasonic waves, identification of wave types and the interaction of waves with cracks and component geometries. The study of the mechanisms involved in the measurement of the depth of surface-breaking cracks, by Rayleigh waves, will receive detailed examination.

Residual stresses in rails will be examined by the "sing around" residual stress measuring method. Selection of suitable ultrasonic probes for this purpose will be made by observation of the pulses transmitted into glass test pieces.

The methods by which rail bolt holes and cracks associated with them, may be detected by means of normal incidence compressional waves and obliquely incident shear waves will be described.

Quantitative measurements of the stresses associated with compressional and shear waves will be made by means of the "standard" circular polariscope. The technique used is described as "Tardy Compensation". The relationship between the voltage applied to the ultrasonic probe and the stress induced in "glass" will be determined for the first two half cycles of the waves. Identification of the stress types associated with the first two half cycles of the
waves will be investigated. The way in which the stress magnitude has been found to decrease experimentally with the distance travelled by the wave will be demonstrated. Comparison between these experimental results and theoretically predicted stresses will be made.

The advantages of visualising ultrasonic waves have been appreciated by lecturers at the British Railways N.D.T. school. Interest in these techniques has also been shown by the Derby & District College of Technology and the Harwell N.D.T. Centre.

1.1 Schlieren Principles

Schlieren principles involve changes in refractive index in the field under investigation. Such changes in refractive index may be produced by an acoustic wave propagating in a transparent medium. Visualisation of these effects may be achieved by optical methods employing lenses and mirrors. Several approaches are possible; mirror systems due to Toepler$^{14}$ and parallel beam lens systems,$^{15}$ are amongst those most commonly used. Typical systems are illustrated in figure 1.1.

In each system the deflection of a ray of light from its undisturbed path will occur when there is a gradient of the refractive index normal to the ray.

In the Toepler system of figure 1.1(a) the source is focussed by means of a lens (not shown) through a rectangular slit positioned at the focus of mirror M.1. The mirror is angled to produce a parallel beam through the schlieren field. The beam then passes to the second mirror and is focussed on to the knife edge. A focussing lens is arranged to cast an image of any optical inhomogeneities that may exist in the schlieren
FIG. II

a) SOURCE THRO' SLIT.

DEFLECTED RAYS

NON-DEFLECTED RAYS

FOCUSING LENS

KNIFE EDGE

SCREEN, FILM.

b) L.S. C. A. L_1 ULTRASOUND BEAM L_2 S. L_2 I

FIG. II OPTICAL SYSTEMS FOR SCHLIEREN VISUALISATION.
field onto a screen. The knife edge is adjusted to produce a uniform reduction in the light intensity on the screen in the absence of optical disturbance in the schlieren field. This disturbance may be due to the propagation of an acoustic wave which will produce refractive index changes of an alternating form. With such a disturbance present part of the image on the screen will either increase or decrease in intensity depending on whether the light is deflected predominantly towards or away from the knife edge. The position of the knife edge must be perpendicular to the direction of density gradients since displacement of the light, in fact the image of the source, parallel to the knife edge produces no effect at the screen as no change in masking occurs. It may be convenient to have a knife edge which is rotatable, to aid its adjustment to a position perpendicular to the density gradients. Alternatively a schlieren stop may be preferred.

In figure 1.1(b) when the light source is monochromatic, a number of parallel diffraction images of the slit A will appear at the schlieren stop S. (An illustration of a typical diffraction pattern is shown in figure 1.2(a)). The positions of these images are given by the equation

\[ \Lambda \sin (n\beta) = n \lambda \]  

(1.1)

where \((n\beta)\) is the diffraction angle between the zero and order diffraction images, \(\Lambda\) is the wavelength of the ultrasonic waves in the visualisation medium, and \(\lambda\) is the wavelength of the monochromatic light. When the light beam and sound wavefronts are parallel, \(\beta = \beta_i = 0\) and the right and left order spectra of the same order are of equal intensity.

The propagation of ultrasound in the medium causes refractive index gradients in the schlieren field and deflects the light around the schlieren stop. This light is imaged by lens L2.
FIG. 1-2.

a.) NORMAL, RAMAN-NATH DIFFRACTION

b.) DIFFRACTION PATTERN OBTAINED AT A SCHLIEREN STOP, MAGNIFIED APPROXIMATELY 50x

FIG. 1-2. DIFFRACTION EFFECTS ASSOCIATED WITH SCHLIEREN VISUALISATION.
and the ultrasonic waves may be viewed on a screen. Alternatively waves may be viewed when the eye of the observer is placed immediately after the stop S. Recording of the waves may be made by placing a camera lens immediately after the stop. Ultrasound is usually visualised as a bright image on a dark field. When the ultrasound is in the form of a continuous wave or a lengthy wavetrain the action is that of a phase diffraction grating. A series of diffraction orders as seen in figure 2(b) are produced around the stop by the mechanism shown in figure 2(a). The direction of the incident light beam is usually arranged to be normal to that of the sound waves, i.e. $\phi = 0$. For pulsed ultrasonic waves the light scattering is aperiodic.

It has been described by Willard (16) that the diffraction effects occurring as a result of ultrasonic waves may be divided into two types. Both normal, or Raman-Nath diffraction and abnormal, Bragg diffraction, may occur. The criterion that normal diffraction occurs depends upon not exceeding a specific value of the function $w^2p$, where $w$ is the width of the sound beam, $f$ is the frequency of the sound, $0.4 < p < 1.0$ for mercury (green) light and visualisation occurring in water. Normal diffraction is produced for $w^2p$ values $< 34 \times 10^{-2}$ m.$\text{MHz}^2$ and $w^2 < 90 \times 10^{-2}$ m.$\text{MHz}^2$.

It is not proposed here to consider more deeply the diffraction effects associated with acoustic waves. Certain effects occurring in the visualisation of continuous waves may be associated with an abnormal diffraction situation. This is considered during the discussion of practical experiments in 2.2.
1.2 Schlieren Apparatus

1.2.1 Optical

The apparatus used for schlieren visualisation was selected to a certain degree from available equipment. Consequently a parallel beam lens system was produced. It is acknowledged that for a given size of field of view a mirror system will be less expensive and produce a high sensitivity. It may require more space in which to operate. The components of the schlieren system which have been used to visualise both continuous and pulsed acoustic waves are described in 1.2.1.1 to 1.2.1.6.

1.2.1.1 Light Sources

The choice of a light source for visualisation of continuous waves depends to a large extent on the method of viewing the schlieren field. Viewing methods may include viewing by eye, projection of the image on to a screen, or display on a closed circuit television screen. When a reflex camera is placed after the knife edge a further method of viewing the acoustic waves is achieved.

A special design of lamp has been made and is shown in figure 1.3. This design enables light from the condenser lens to be brought to a focus at the slit, which is then used as a source for the schlieren system. Adjustment of the slit position in the direction of the optical axis and in a rotational manner is possible.

For the study of the transmission of ultrasonic pulses, the choice of light source is limited by the tight
FIG. 1.3.

A CONTINUOUS LIGHT SOURCE OF SPECIAL DESIGN.
specification. Corresponding to each ultrasonic pulse emitted the light must flash briefly in the manner of a stroboscope and it must be a concentrated "bright" source. For the earlier work a commercial stroboscope was selected. For later work a specially constructed spark light source was used. A comparison of these two sources is made in chapter 4.

1.2.1.2 Knife Edge or Filter

The knife edge may be manufactured using a standard razor blade and is suitable for sensitive schlieren systems. An alternative is to use a filter having a graded wedge section between black and white of different widths to give different degrees of sensitivity. It is reported that graded filters give better definition pictures than a sharp knife edge (17). Colour filters are also available for colour schlieren work.

1.2.1.3 Tank

The tank for the study of ultrasonic waves in water was constructed with an iron frame, suitably painted, of overall dimensions 470 mm x 360 mm x 250 mm. The windows through which the light passes were plate glass television anti-implosion screens. These were not schlieren quality material but were found to be free from ream and gas bubbles, imperfections which would impair the schlieren picture.
1.2.1.4 Optical Bench

A rigid optical bench is essential for schlieren work since precise settings of the slits and knife edges or schlieren stops must be made. For this work a heavy bench, previously used for photoelasticity, has been adapted to take the optical components, which were thus firmly located.

1.2.1.5 Lenses

Lens systems have been developed as the work progressed. The earlier work used single element acrylic lenses 7.5 cm diameter. At the next stage a single element glass lens 30 cm diameter was tried for $L_1$ and for $L_2$ a 7.5 cm diameter Kodak Aero Ektor lens, F 2.5, 17.5 cm focal length was used. The final arrangement enlarged the field of view to 10 cm by means of two F 5.6, 50 cm focal length anastigmats. In this arrangement, for continuous wave excitation, the Aero Ektor lens was positioned after the knife edge, to focus the ultrasound onto a screen. In pulsed work this same lens was used to focus the stroboscopic source at the slit.

1.2.1.6 A complete schlieren optical system

A schlieren system, which comprises many of the elements previous described, has been constructed to produce the optimum in design features using available components. This system is shown in figure 1.4 (a) and (b). Here the light source is a xenon discharge lamp of the "strobotac", a commercial stroboscope manufactured by General Radio. The source is brought to a focus at a slit, the position of which is adjustable by means of a vernier control. The light beam then diverges until
FIG. 1.4. THE SCHLIEREN SYSTEM APPLIED TO WATER BOX DESIGN.
reaching \( L_1 \) which is positioned to produce a parallel beam of light through the working section. The lens \( L_2 \) converges the light to the position of the knife edge, \( S \). The ultrasound may be viewed by the eye of the observer placed immediately after the knife edge, or by other methods previously indicated. The television camera and display on a monitor is the most convenient method of viewing the disturbances, since this allows for adjustments to the probe whilst observing the effects.

### 1.2.2 Electrical Systems for Schlieren Visualisation

Electrical systems have been produced for the excitation of ultrasonic probes in the continuous and pulsed modes of operation. Two basic systems are described in 1.2.2.1 and 1.2.2.2.

#### 1.2.2.1 Continuous or Interrupted Continuous Wave System

An electrical system capable of generating displays of the visualised waves and the electrical signals producing them is shown in figure 1.5(a). Provision for the measurements of the voltage applied to the probe and the frequency generated are made. Adjustment of the mark to space ratio of the Bervomex enables satisfactory viewing time to be selected with minimum heating of the probe. The minimum electrical impedance of the probe may be determined by plotting out the variation of probe impedance with frequency. This procedure may be carried out by the sweep frequency oscillator display of figure 1.5(b). Measurement of the series resonance frequency, \( f_s \), may be made precisely by insertion of an external frequency marker and the impedance at series
FIG. 15.

SERVOMEX
WAVEFORM
GENERATOR
TYPE 141

RADIOSPARES
RELAY
12v

LORENZ C.W.
GENERATOR
TYPE SGLE02/2

FREQUENCY COUNTER
VENNER
TYPE TSA 6636

ULTRASONIC
PROBE

R.M.S. VOLTMETER
HEWLETT
PACKARD
TYPE 3400 A

a.) CONTINUOUS OR INTERRUPTED CONTINUOUS WAVE EXCITATION

Sweep Oscillator
3211 A.
Hewlett Packard

R.F. R.F.
Out In
Vert. Horiz. Marker

Hewlett Packard Storage
Oscilloscope

C.W. generator Airmec, CT 218

b.) DISPLAY OF RESONANT FREQUENCIES OF AN
ULTRASONIC PROBE.

FIG. 15. ELECTRICAL SYSTEMS FOR CONTINUOUS
MODE OPERATION OF ULTRASONIC PROBES.
resonance obtained from the calibrated graticule. The current flowing through the piezoelectric plate may be determined from the probe impedance and applied voltages. Values of current should not exceed 0.5 ampere for continuous work, or damage to the probe may result. The parallel-resonance frequency, $f_p$, is also indicated by this display.

1.2.2.2 Pulsed Wave System

Two pulsed mode visualisation systems are shown in figure 1.6. They differ principally in the ultrasonic flaw detector used. Later work changes to the Kelvin Mk 9 set in which higher transmitter voltages excite the selected probes. External triggering voltages must be available to trigger the light flash.

By means of these systems simultaneous displays of the electrical signals and visualised waves producing them can be shown. In figure 1.6(a) the probe is operated in the transmit and receive mode via a matching transformer adjusted to produce maximum brightness in the visualised pulse with a minimum number of cycles in the pulse wavetrain.

A display of the "A Scan" signals received by the ultrasonic set can be displayed on the oscilloscope and photographed. A variable time delay triggers the stroboscope lamp at a selected interval after the generation of the transmitter pulse. By variation of this time delay the acoustic wave may be stroboscopically "frozen" at the required position during propagation within the testpiece.
Fig. 1-6. Electrical systems for pulsed mode visualisation.

a.) Krautkramer U.S.E.I. Ultrasonic Set.

b.) Krautkramer U.S.I.P. 10 Ultrasonic Set
The second system, figure 1.6(b) shows an alternative method of triggering the stroboscope lamp, using as a transmitter the Krautkramer U.S.I.P. 10 ultrasonic set. System (a) was considered superior due to the higher transmitter voltages achieved.

1.3 Photoelastic Principles

Photoelasticity makes use of the changes in optical path length produced as a result of mechanical deformation. It is found that when a solid block of transparent isotropic material is stressed it behaves optically as a uniaxial crystalline material, the optic axis being directed along a stress line. As a result an optical technique can be used with transparent testpieces to indicate the magnitude and direction of the stress existing. Similarly the oscillatory stresses associated with the passage of compressional, shear or surface waves can be seen and measured. The optical and electronic systems are fully described but first the principles of the optical phenomena are given detailed consideration.

Conventional photoelasticity most frequently examines the effects produced when comparatively large static stresses are applied to birefringent models. In this work the smaller dynamic stresses associated with acoustic wave propagation have been used to visualise particular types of waves generated by ultrasonic probes.

1.3.1 Optical Retardation produced by the Application of a Stress

When an isotropic model is subjected to a compressive stress it will behave anisotropically. The optical interference produced is shown diagrammatically in figure 1.7(a)-(d), in which the system is viewed against the direction of the light.
a) ACTION OF PLANE POLARISER ON UNPOLARISED LIGHT.

b) EFFECT OF STRESSED MODEL ON PLANE POLARISED LIGHT

c) FORM OF LIGHT EMERGING FROM MODEL

d) TREATMENT BY ANALYSER OF ELLIPTICALLY POLARISED LIGHT BEAM.

FIG. 1.7. INTERFERENCE PRODUCED BY A MODEL PLACED IN A "CROSSED" PLANE POLARISCOPE.
beam. Plane polarised light is produced as in (a) and is incident on the model. In (b) this plane polarised wave is divided by the model into two mutually perpendicular planes coinciding with the planes of principal stresses p and q. The light components travel in these planes with different velocities. The p component travels with the faster velocity since this plane corresponds to a direction parallel to the optic axis of a negative crystal plate. Consequently the phase and in the case shown, the amplitude of the waves will differ. The form of the light vibration leaving the model is shown in (c). The component of this elliptically polarised light transmitted by the analyser may be seen from (d).

The phase difference, or relative path retardation, of the waves leaving the model is directly proportional to the difference in principal stresses. In addition it is proportional to the model thickness. This enables an expression for the relative retardation to be written in terms of the principal stresses, p and q, the model thickness 't' and a constant known as the stress-optical coefficient 'C'. The relationship is as shown by the following equation

\[ R = C(p - q)t \]  \hspace{1cm} (1.2)

When the phase difference is one wavelength, or an integral number of wavelengths, then extinction of the light emerging from the analyser results. For one half wavelength or an odd number of half wavelengths of phase difference, the light emerging from the analyser is of maximum brightness. These conditions may be summarised
as follows:

<table>
<thead>
<tr>
<th>Light Intensity</th>
<th>Retardation</th>
</tr>
</thead>
<tbody>
<tr>
<td>I max.</td>
<td>$\frac{\lambda}{2}$, $\frac{3\lambda}{2}$, $\frac{5\lambda}{2}$, $\frac{7\lambda}{2}$ etc.</td>
</tr>
<tr>
<td>I min.</td>
<td>0, $\lambda$, $2\lambda$, $3\lambda$ etc.</td>
</tr>
</tbody>
</table>

It follows that when a crystal plate, or model, is placed between crossed polarising filters which are then rotated in synchronism, then excluding isoclinics, there will be two planes of the analyser for which the light is extinguished. Conversely there will be two positions at 45° to the extinction planes at which the light intensity will be a maximum.

1.3.2 A Stressed Photoelastic Model viewed in Monochromatic Light

When a photoelastic model is placed in a "crossed" plane polariscope illuminated with a monochromatic light source, then, since it is isotropic, the model will appear dark when no stress exists within it. As an increasing tensile or compressive stress is applied, regions within the model will appear bright or dark corresponding to the phase difference $\pi R$ existing at points within it. The loci of points where the retardation is equal to an integral number of wavelengths of the light used will be defined by black lines, which may be called monochromatic bands or "fringes". The first black line which appears results from zero retardation and is known as the "zero order" fringe. When the retardation is equal to one wavelength the corresponding black line produced is called the "first order" fringe.

Further increases in the principal stress difference producing retardation of two wavelengths, gives the second order fringe, and so on. It is anticipated that the small
stresses associated with acoustic waves used here will produce only a fraction of a fringe order. Hence only black and white zones associated with an acoustic stress wave should result for monochromatic light sources.

There will be a further condition which will produce black lines within the model in a plane polariscope. This occurs when the principal stress lies along or is perpendicular to the plane of polarisation of the linear polarisers. The resulting black lines, known as isoclinics, are more fully described in 1.3.3.

1.3.3 A Stressed Photoelastic Model viewed in White Light
When a stressed model is viewed in a crossed plane polariscope illuminated by a white light source the model will appear to be covered with a series of coloured bands, called isochromatics. Any light whose wavelength is equal to, or a submultiple of the relative retardation R, will be extinguished by interference. Light waves whose wavelengths approaches the critical value of R will be partly extinguished. The analyser will now transmit the complementary colour of the light extinguished at particular points in the stressed model. When wavelengths corresponding to red light are extinguished the light transmitted by the analyser will be blue. Should the relative retardation be increased progressively from zero, all the colours of the spectrum will be extinguished in turn, from violet, 350 nm, to red 700 nm. The complimentary colour to the extinguished one appears in the model. These effects are illustrated in figure 1.8. When the retardation is increased to $2\lambda$ a second interference of the colours of the spectrum arises. The colours of the second order are
<table>
<thead>
<tr>
<th>Fringe Order</th>
<th>Approximate Relative Retardation nm</th>
<th>Colour Observed</th>
<th>Colours Extinguished</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Black</td>
<td>All</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>Grey</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>200</td>
<td>White</td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>400</td>
<td>Lemon-Yellow</td>
<td>Violet</td>
</tr>
<tr>
<td>R</td>
<td>450</td>
<td>Orange</td>
<td>Blue</td>
</tr>
<tr>
<td>S</td>
<td>500</td>
<td>Deep Red</td>
<td>Green</td>
</tr>
<tr>
<td>T</td>
<td>590</td>
<td>Purple</td>
<td>Yellow</td>
</tr>
<tr>
<td></td>
<td>650</td>
<td>Deep Blue</td>
<td>Orange</td>
</tr>
<tr>
<td></td>
<td>700</td>
<td>Green</td>
<td>Red</td>
</tr>
<tr>
<td>S</td>
<td>800</td>
<td>Pale Yellow</td>
<td>Deep Red (1st),</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Deep Violet (2nd)</td>
</tr>
<tr>
<td>E</td>
<td>900</td>
<td>Orange</td>
<td>Blue</td>
</tr>
<tr>
<td>C</td>
<td>1000</td>
<td>Orange</td>
<td>Blue</td>
</tr>
<tr>
<td>O</td>
<td>1180</td>
<td>Purple</td>
<td>Yellow (2nd),</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Violet (3rd)</td>
</tr>
<tr>
<td>N</td>
<td>1300</td>
<td>Emerald Green</td>
<td>Orange-red (2nd),</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Indigo Blue (3rd)</td>
</tr>
</tbody>
</table>

Figure 1.8 Colour sequence, for the 1st two fringe orders, produced by the progressive increase in stress in a model, viewed in a *crossed* plane polariscope illuminated with white light.
not identical with those of the first since the extinction of more than one colour may occur at a time. This is due to this overlapping of extinguished colours, second order colours being paler than the first. Eventually at higher orders, about number 8, the model appears white.

1.3.4 Isoclinics

Isoclinc lines can be observed in a model viewed in a "crossed" plane polariscope. They may later be seen superimposed on the photographs of ultrasonic stress waves propagating in birefringent materials. In appearance isoclinics are black contours within the model produced by the following means.

At any point within the model the direction of one of the principal stresses may coincide with the polarisation plane of the incident light. Such a point will appear dark when viewed through the "crossed" analyser. The locus of points at which the principal stress direction coincides with the direction of polarisation of the incident light wave, appears as a dark line. Such lines are called isoclinic lines. Consequently the stress pattern from a plane polariscope may contain an isoclinic line, superimposed over the general stress pattern obtained from the difference in principal stresses.

When the "crossed" plane polariscope is rotated the isoclinic lines will move across the model. These contours may be plotted for particular settings of the polariscope, hence obtaining the directions of the principal stresses at every point within it.
To illustrate the principles involved an experiment was carried out using a glass block to which a compressive point load was applied. The isoclinic lines viewed in the plane polariscope are shown in figure 1.9(a)-(d) for particular polariscope settings.

When the analyser is set with its plane of polarisation in the vertical axis, in (a), this corresponds to the "Zero" isoclinic, being the plane of the analyser which coincides with the direction of the applied compressive stress. When the polariscope is rotated in increments of 20° the corresponding isoclinic is indicated in figures (b)-(d).

For the purposes of the visualisation work isoclinics may impair the visualisation of the stress wave. They will only occur however in models illuminated with plane polarised light, since using this light the directions of principal stresses are selected as the reference due to Frocht describes, (18).

This treatment concludes that isoclinics are the loci of points of principal stresses of constant parameter \( \theta \), or the loci of points of parallel principal stresses.

When visualisation models contain a considerable residual stress, due to machining for example, examination in the plane polariscope will display isoclinics. These isoclinics may impair wave visualisation or could improve the contrast, when a bright wave is superimposed on a black isoclinic line. Frocht explains how conversion to a circular polariscope removes the isoclinics. This solution is a simple one in conventional photoelasticity using a monochromatic light
FIG. 1.9. MOVEMENT OF AN ISOCLINIC IN A GLASS BLOCK UNDER POINT COMPRESSIONAL LOAD, DUE TO ROTATION OF THE FILTERS OF A "CROSSED" PLANE POLARISCOPE.
source, but there are certain disadvantages described in 5.6. An ideal solution may be the effective annealing of the glass model. On some machined models this has been extremely difficult to perform as described in 4.3.

1.3.5 Isochromatics

Isochromatics, or fringes produced in a model are lines joining points of equal principal stress difference $(p-q)$. When monochromatic light is used the fringes produced, which increase in number with the applied stress, are all black. When white light is used only the zero order fringe is black; other fringes are coloured.

In the work on acoustic stress waves, the level of stress is such that only fringes between zero and the first order are observed. The fringe pattern does, even for a non-monochromatic light source, show a black and white pattern. Black lines correspond to the zero phase difference, produced when the mechanical deflection of the piezoelectric plate is zero. Other parts of the visualised pulse will have a colour corresponding to the retardation. For stress levels used here, the retardation should produce white intermediate bands between zero orders.

1.3.6 Identification of Isoclinics and Isochromatics

Identification of the black or coloured bands in the model viewed in a plane polariscope may be made by two means. Firstly if the "crossed" filters are rotated in synchronism the isoclinics will move across the model. This is due to the planes of the filters being changed with respect to the
model so that they are searching out the location of stresses having their particular orientation. Isochromatics will remain in a fixed position but will show variation in intensity with rotation by a mechanism to be described later in 3.2.

1.3.6.1 Static Stresses producing Isochromatics

To illustrate the formation of isochromatics a series of experiments were conducted in which an araldite cantilever beam was subjected to incremental static loads. Figure 1.10(a) shows the beam clamped rigidly at end A. When a load is applied at B, figure 1.10(b), the upper surface will be subjected to a tensile stress and the lower surface to a compressive stress. Along the centre line, or neutral axis, zero stress will result. Providing that the point B of the beam is depressed only by a small amount, the beam should show equal tensile and compressive isochromatics or fringe orders proportional to the applied load.

The beam was examined in a "crossed" plane polariscope, with the analyser set at 45° to the beam, and illuminated with the tungsten electrode spark light source. These source electrodes characteristically emit light over a range of wavelengths and will consequently approximate to a white light source. The beam was examined in an unstressed and a stressed condition. The observations are illustrated in figure 1.10(c) and 1.11(a)-(c).
FIG. I.10. RELATIVE RETARDATION, INDICATED BY ISOCHROMATICS, PRODUCED BY THE APPLICATION OF STRESS TO AN ARALDITE CANTILEVER BEAM.

a.) THE CANTILEVER BEAM

b.) APPLICATION OF A SMALL LOAD TO A CANTILEVER.

c.) NO LOAD, ZERO ISOCHROMATIC

d.) LOAD 0.2 kg at B.
When zero load is applied the beam appears black corresponding to a phase difference of zero. As the load is increased a point is reached corresponding to the phase difference due to dynamic ultrasonic waves, when the fringe order is between zero and one fringe. Further increases in load show retardations approaching the second fringe order, figure 1.10(d). When loads of the order 0.1 kg to 0.3 kg are applied, fringe orders over the range 0 to 2\(\frac{1}{2}\) approximately, indicated by figure 1.11 are produced. The medium used here for convenience is araldite, similar effects would be anticipated in glass models subjected to incremental stresses.

1.3.6.2 Dynamic Stresses producing Isochromatics

When an ultrasonic probe is coupled to a model and electrically excited, a stress wave will be caused to propagate within the model. The principal wave which propagates will be characteristic of the probe, but secondary waves may also be generated. This work will be concerned with three basic wave types:

(a) Compressional

(b) Shear

(c) Rayleigh

Associated with these waves will be compressive and tensile stresses for compressional wave, shear stresses for the shear wave and a combination of these three types for the Rayleigh wave.
FIG. 1.11.

a) LOAD 0.1 kg. at "B" cf. FIG. 1.10

b) LOAD 0.2 kg. at "B"

c) LOAD 0.3 kg. at "B"

FIG. 1.11. RETARDATION PRODUCED BY INCREMENTAL LOADING OF A CANTILEVER BEAM.
(a) **Compressional Wave Stresses**

Idealised electrical waveforms producing compressional waves and their action on a particle within the model is compared in figure 1.12(a)-(h). An idealised excitation waveform is indicated in (a) and the associated compressional wave in (b). An element of area $A$ within the model is acted upon by particular parts of the wave as it progresses. In (c) the area $A$ is acted upon by a compression and is subjected to a compressive stress $p$. The light intensity transmitted by the analyser set at $45^\circ$ to the direction of stress, is a maximum for this condition. When $A$ is acted upon by a zero stress point of the acoustic wave, as shown in (e) minimum light intensity is transmitted shown by (f). A rarefaction, $R$, next reaches $A$ to subject this area to a tensile stress $p$. The resulting light intensity is again a maximum as seen in (h). The action of both compressions and rarefactions is to produce lines of maximum light intensity. By this means two bright lines will be produced per cycle of the acoustic wave. Bright lines will be divided by narrower black lines, parallel to them, corresponding to regions of zero stress associated with zero retardation.

(b) **Shear Waves Stresses**

A shear wave, of constant amplitude, is seen to produce variations in the transmitted light
FIG. 1.12. THE EFFECT OF A DYNAMIC COMPRESSSIONAL WAVE ON THE LIGHT INTENSITY TRANSMITTED BY THE ANALYSER OF THE "CROSSED" PLANE POLARISCOPE.
intensity through the analyser, in figure 1.13(a)-(f). In (a) the action of a "positive going" shear stress is seen to produce a resultant stress in the area 'A' considered, at 45° to the applied stress. The resultant light amplitude is shown to be a maximum in (b). When the wave progresses until a zero shear stress is applied to 'A', then (d) shows there to be a minimum light intensity transmitted by the analyser. Further progression of the wave causes a maximum "negative going" shear stress to be applied to 'A' and a corresponding maximum light intensity results, shown by (e) and (f).

(c) Rayleigh Wave Stresses

The particle vibration direction in Rayleigh waves will be shown in 1.6 to be more complex than basic compressional or shear waves. Its motion is of an elliptical nature. Consequently the stresses involved in Rayleigh waves will include compressive and tensile components and additionally shear stress components. When viewing surface waves in a "crossed" plane polariscope it is unlikely that any plane of the analyser will give complete extinction of the wave. The position for maximum intensity too is difficult to define, since it depends upon the ratio of the major to minor axes of the elliptical motion.

1.4 Photoelastic Apparatus

The photoelastic polarisscopes used here are of "plane" and "circular" types. The methods by which these may be constructed
FIG. 1.13. THE EFFECT OF A DYNAMIC SHEAR STRESS WAVE ON THE LIGHT WAVE AMPLITUDES TRANSMITTED BY THE ANALYSER IN A "CROSSED" PLANE POLARISCOPE.
1.4.1 Construction of a "Crossed" Plane Polariscope

In order that a simple plane polariscope may be set up, identification must be made of the planes of polarisation of the linear polarising filters. Firstly a reference source of plane polarised light must be available. As described in Jenkins and White (19) this may be produced by the reflection of unpolarised light incident at the polarising angle on a glass plate. The plane polarised light produced is polarised perpendicular to the plane of incidence; hence a source of known polarisation is obtained. When a polarising filter is placed in the path of this reflected light and rotated, a point is reached when the light viewed beyond the filter becomes extinct. When this occurs the plane of polarisation of the filter is perpendicular to that of the source and hence becomes known. The identification of the plane of polarisation of the second filter is then easily obtained by viewing a source of unpolarised light through both filters. When the second filter is rotated with respect to the first, extinction occurs when the planes of polarisation are perpendicular. This in fact is precisely the arrangement in the plane polariscope. When this arrangement is used the polariscope is described as being "crossed", the planes of polarisation of the filters being mutually perpendicular.

Plane polariscopes in which the filters are "crossed" are used in this work. When no stress exists in the model the background will appear dark. The introduction of an acoustic stress wave will be indicated as a bright image against the dark background.
FIG. 1.14. DIFFUSE LIGHT PLANE POLARISCOPES HAVING CONTINUOUS AND PULSED LIGHT SOURCES.

a) A DIFFUSE LIGHT POLARISCOPE FOR CONTINUOUS WAVE VISUALISATION.

b) A POLARISCOPE FOR PULSED WAVE VISUALISATION.
1.4.1.1 **Plane Polarisopes for Continuous and Pulsed Mode Visualisation**

Three types of plane polariscope have been tried in practice, the fundamental difference concerned the light source. These included a mercury vapour continuous wave source, a commercial stroboscope and a stroboscopic source of special design. Three arrangements used with them are shown in figure 1.14(a) and (b) and 1.15(a).

The relative positions of the planes of polarisation of the linear polarisers is indicated in figure 1.15(b).

The polarisopes shown here which use a diffuser allow easy viewing by eye. The type employing a converging lens makes the position of the eye more critical. Photography with this polariscope as with the others, is not a problem, the camera being located at the position of the "eye" in figure 1.15(a).

1.4.2 **Electrical Systems for Photoelastic Visualisation**

Three electrical systems have been used for photoelastic visualisation. For continuous waves and pulsed excitation using the commercial stroboscope the systems are as outlined for schlieren work.

The most frequently used system in photoelastic visualisation is that shown in figure 1.16. The variable time delay used here is of special design, similar time delays may be obtained commercially, alternatively variable time delays are fitted on certain oscilloscopes. The Trigger Unit and Thyratron Bias and Excitation unit have been constructed using information supplied by the thyratron valve manufacturers.
a.) A PLANE POLARISCOPE WITH A SINGLE CONVERGING LENS.

b.) TRANSMISSION PLANES, OR PLANES OF POLARISATION OF LINEAR POLARISERS, RELATIVE TO EACH OTHER.

FIG. 1.15. A PLANE POLARISCOPE WITH STROBOSCOPIC SPARK LIGHT SOURCE AND THE RELATIVE TRANSMISSION PLANES OF THE LINEAR POLARISERS.
FIG. 1.16. ELECTRICAL SYSTEM FOR PHOTOELASTIC VISUALISATION USING A THYRATRON-TRIGGERED SPARK LIGHT SOURCE.
The matching auto transformer may be necessary for the electrical matching of the probe impedance to that of the ultrasonic flow detector used. In experiments with a Kelvin Mk 9 set, no matching was necessary due to its low output impedance.

1.5 **Light Sources**

In order to view the stresses associated with dynamic stress waves a flashing light source is required. To achieve waveform resolution and enhanced sensitivity the source must satisfy a tight specification, particularly at higher ultrasonic frequencies of the order of 5 MHz.

The waveform resolution capability of a system depends upon the duration of the flash and the time jitter relative to the firing of the ultrasonic transmitter pulse. A flash duration of about a quarter of the period of the oscillations within the ultrasonic pulse, with considerably smaller time jitter is suggested by Wyatt (22). In addition the light flash must be repetitive at a rate of about 50 per second, or greater to comply with the pulse repetition frequency of the ultrasonic flow detector.

This is a particularly tight specification, there are few devices by which it can be satisfied. Most short duration light sources, described by Holder and North are "single shot" devices and this property alone makes them unsuitable. Additionally the duration of the light flash should be of the order of 50 n.s. at half peak intensity. Most commercial light sources fail to meet this specification. For the "strobotac" a flash duration at half peak intensity of 250 n.s. and a time jitter of 150 n.s. is quoted. This makes 1 MHz the upper limiting frequency on Wyatt's
criterion. The need is now established for a superior light source than has previously been available. The design criteria of short duration light sources will now be described, some of the features will find application in a new stroboscopic source.

1.5.1 Short Duration Light Sources

The simple types of short duration light source discharge a capacitor through a flash tube or spark gap. The light source is connected in parallel with the capacitor which is charged from a high voltage source. When the voltage has risen to a sufficiently high level, the spark gap breaks down and an arc discharge takes place. The resistance of the arc discharge path falls to a low value and a large oscillatory current flows in the circuit decreasing in amplitude as the energy stored in the capacitor is dissipated. The gas in the spark gap is heated to a high temperature by the passage of a large current and acts as a source of high colour temperature. For a given flash tube or spark gap, the intensity of the emitted light increases with the peak current and also with the rate of rise of current, which is inversely proportional to the period of oscillation.

The peak amplitude of the current is given by:

\[ I_{pk} = V_0 \left[ \frac{C}{L} \right]^{\frac{1}{2}} \]  

and the period of oscillation by

\[ P = 2\pi \left[ \frac{L.C.}{L} \right]^{\frac{1}{2}} \]  

where \( L \) is the inductance of the complete discharge circuit. For a typical flash tube capacitance of 0.1 \( \mu \)F and circuit inductance of 40\( \mu \)H, a period of 12 \( \mu \)s approximately results.
The objectives of maximum intensity and minimum duration of the light source are enhanced by using a high voltage $V_0$, a high ratio $C/L$ and a small $LC$. The effect of increasing the capacitance, used at its maximum voltage, is to increase the light output as shown in figure 1.17. The period of oscillation is thus increased due to the increase in capacity and the inductance associated with a larger capacitance. For practical purposes the shortest duration of light output is obtained when the capacity and consequently the total light output is small. By increasing $V_0$ the light output increases significantly being proportional to $\frac{1}{2} CV^2$ and in practice high voltages are used. The duration of the light pulse will be extended in some spark tubes due to an "afterglow" effect. The light emission lags behind the current through the source. When the current decreases, the light emission decays at a comparatively slower rate and does not fall to zero when the current ceases to flow. The presence of the afterglow may be several microseconds and depends upon:

1) the nature and pressure of the gas in the flash tube.

and

2) the material of the electrodes.

The afterglow effect lengthens the light pulse with respect to the current duration, becoming increasingly significant with decreasing light pulse times.

The light intensity will be increased by using gases such as mercury vapour, krypton, xenon and argon but for a particular spark system the afterglow using these gases is longer than with air. When a short duration of light is required a special design of spark gap may be used as designed by Thackeray. (23) The light durations of $10^{-7}$ second, at half peak
FIG. 1.17. THE VARIATION WITH CAPACITOR SIZE OF THE LIGHT OUTPUT OF A SPARK GAP.
amplitude of the light intensity are typical with such devices. The commercially available version of Thackeray's Argon Jet Light source is also limited in its repetition rate to one per second.

1.5.1.1 Spark Light Sources

When a short duration of light is required a special design of spark gap must be used. There are however simpler arrangements of electrodes which may be used to produce spark discharges, the simplest of which consists of two electrodes separated by an air gap. This type has the disadvantage that successive discharges may take different paths between the electrodes so that the effective position of the light source is not constant. This feature will be more important in schlieren than in photoelastic systems due to the cut-off setting of the schlieren stop or knife edge.

Several spark gap designs to constrain the discharge position have been made. These have been described as: the "End Fire gap", "Libbessart", "Tube Gap" and "Sandwich Gap". All of these have been designed for the "single shot" mode but they could be applied to repetitive firing light sources. A further alternative is the three electrode device, which will be triggered by the thyratron valve. These spark gaps are illustrated in figure 1.18.

It is recommended in the literature that the small circular light sources of the types described above are suitable for direct-shadow apparatus or schlieren apparatus using a graded filter. For a conventional knife edge schlieren system two other types are preferred.
FIG. 1-18.

a) END-FIRE GAP

b) LIBESSART GAP

c) TUBE GAP

d) SANDWICH GAP

e) THREE ELECTRODE SPARK GAP.

FIG. 1-18. SPARK ELECTRODE ARRANGEMENTS.
The first of these is shown in figure 1.18(c). Here the discharge takes place in a glass capillary tube set perpendicular to the optical axis. The source in this case has a long thin rectangular shape. Problems may arise with this type due to shattering of the glass or lack of transparency of it after long usage.

Figure 1.18(c) shows a sandwich gap which eliminates the difficulties of the tube gap. The spark occurs between flat electrodes which are held in a sandwich between glass plates. When the gap is rotated about the optical axis the range and sensitivity, in a schlieren system, may be adjusted by changing the length of the spark. Aberrations may result in schlieren systems due to this procedure, according to Holder and North.

The "Three Electrode" spark gap is shown in figure 1.18(e). This is the type which will be used later in both visualisation systems. The two main electrodes are of tungsten steel. The spark gap can be changed by means of the screw adjustment on the pointed electrode. Spark gaps are typically 2 mm to 4 mm; the gap size being selected for consistent firing and optimum brightness. Auxiliary electrodes of steel or brass have been used, supported in either perspex or tufnol formers. This electrode's position is adjusted with respect to the upper electrode (cathode), to produce consistent firing but avoiding a breakdown between itself and the lower pointed electrode. In this three electrode device the auxiliary electrode is not triggered, but electrically "floating".
A triggered, three electrode spark source has been produced by Baborovsky and Marsh in which a large thyratron is used to provide a switching pulse to the "active" auxiliary electrode. This type of system has not yet been considered.

1.5.2 Spark Gap Triggering Methods

In the simpler systems described earlier the gap is connected across a capacitor which is charged through a resistance. The spark occurs when the voltage rises to a sufficient value to break down the gap. The time at which breakdown occurs is not accurately controlled. When precise triggering times are required the trigger may consist of a second spark gap, or Thyratron in series with the light source, or a trigger electrode in the source itself, as in the three electrode system. The thyratron spark source uses a transistor trigger unit, described by the valve manufacturers, to make the thyratron conduct and discharge a capacitor across the spark gap.

1.5.3 Operation of the Thyratron Spark Light Source

The circuit for the thyratron spark light source is shown in figure 1.19. The capacitor C is charged to the full H.T. voltage through resistors Rc and Rp. The fast rising trigger pulse applied to the thyratron grid G2 through the resistor Rt, switches the thyratron to its conducting condition after a short time lag, called the anode delay time, and begins the discharge of the capacitor C. The current rising rapidly in the discharge circuit produces a fast rising negative going voltage step across Rp. A discharge will occur across the gap at some point on the voltage pulse, depending upon the
FIG. 1.19. CIRCUIT DIAGRAM OF THYRATRON-TRIGGERED SPARK LIGHT SOURCE.
spark gap parameters, when C discharges through the gap and thyratron producing a bright light flash of short duration.

When $R_p$ is of a suitable value, e.g. $2.2 \text{k} \Omega$, the full E.H.T. voltage is produced across the gap before breakdown. This value of resistor should be selected however for optimum brightness and, according to the valve manufacturer, should not be made too large.

The capacitor and its connections influence the performance of the light source as discussed earlier. Capacitance $"C"$ must have low internal inductance and robust internal connections to withstand a heavy discharge current. The capacitor used is an "$Erie" 500 pF, 20 kV d.c. working, ceramic type of low inductance. It is suggested in the N.P.L. booklet that the capacitor may be worked above its normal maximum voltage rating. The advantages gained are a decrease in inductance and size for a given stored energy. Hence the flash brightness is increased, but a decrease in the component life results. This suggestion has not so far been implemented.

A second suggestion from the same reference is that the inductance may be minimised for tubular capacitors if the connections between the capacitor and spark gap are made coaxial. In this way the period of current oscillation is minimised. Thus the emitted light, which increases with peak current and also with rate of rise of current, is inversely proportional to the period of oscillation.

From equation (1.4) it can be seen that large inductances will limit the rate of rise of current and hence light intensity for a given spark gap. This coaxial suggestion
has been incorporated in the mechanical design of the spark source.

The thyratron used is an English Electric CX.1191 hydrogen filled tetrode thyratron. Although a glass envelope type its specification is sufficiently rugged and size suitable for laboratory applications on visualisation. It may be used for switching peak powers up to 3.2 MW at high repetition rates. Its life expectation is about 3 000 hours.

1.5.3.1 Thyratron Bias and Excitation Circuits

The thyratron bias and excitation circuits are shown in figure 1.20, these being recommended by the valve manufacturer. These circuits provide a negative bias for the control grid 2, and a d.c. excitation current for grid 1. The step-up pulse transformer is used to increase the trigger voltage level to that required for thyratron firing.

1.5.3.2 Circuit of Trigger Unit for Thyratron

The requirements of the thyratron trigger pulse are that it should be derived from a source of low impedance and should have a high rate of rise of voltage. The voltage pulse amplitude should be sufficient to cause rapid ionisation of the gas in the grid-cathode space, thus producing minimum jitter and anode delay time drift. If a trigger pulse is used which is greatly in excess of the minimum specified, it is not only unnecessary but may prevent recovery after the main current pulse has been switched.
The circuit of the trigger unit for the thyatron is shown in figure 1.21. This circuit is now used in some modern flaw detectors to excite ultrasonic transducers. The capacitor \( C_1 \) is charged via the 100 k.\( \Omega \) and 100 ohm resistors from the 300 V supply. The transistor 2N3501 has a rated collector - emitter voltage of 150 volts, in this case its \( V_{ce} \) is approximately 300 volts, thus it operates in the avalanche mode. When a positive-going input pulse is applied from the variable delay a current flows through \( C_2 \) and the 1 k.\( \Omega \) resistor. The differentiated "sharpened" voltage at the transistor base causes it to conduct for the pulse duration. The capacitor \( C_1 \) now discharges in the manner shown. The diode 1N914, is normally used for protection of the transistor; in this application however only positive-going pulses are fed to the input.

Pulse repetition rates of 50 per sec. and 200 per sec. have been used with the complete systems. The maximum repetition rate of the trigger unit is governed by the time constant of the \( C_1, R_1, R_2 \) circuit which will not be a limiting factor for the repetition rates which are needed here.

1.5.3.3 Mechanical Construction of the Spark Light Source

When using thyatrons of this type which operate at E.H.T. voltages of 16 kV, there will be some X-radiation emitted from them. The valve manufacturers give warning of this fact which may constitute a health hazard. Some absorption of X-rays by the instrument's metal case will take place, but some penetration may also occur. The
FIG. 1.21. CIRCUIT OF TRIGGER UNIT FOR THYRATRON
construction of this spark light source and a
description of the precautions taken now follows.

The mechanical arrangement of the device is shown in
figures 1.22 and 1.23. It differs from the ceramic
one used by Wyatt in as much as the thyratron has a
larger physical-size and has a glass envelope. The
electrical characteristics are however similar and may
be compared by reference to the English Electric Data
book for ceramic thyratron CX1157 and glass envelope
thyratron CX1191. The glass thyratron costing £70 is
approximately half the price of the equivalent ceramic
version.

The figures show the thyratron valve, 500 pF capacitor
and spark gap to be arranged coaxially within the
aluminium main case. A perforated top, not shown, is
made of steel and with this fitted the rigidity of this box
design is improved. The perforations allow cooling of the
thyratron to take place by convection.

The two main electrodes are made of 3 mm diameter tungsten
steel rod, the lower earthed electrode is shaped to a
point. The two electrodes working alone produce rather
inconsistent firing and the auxiliary passive trigger
electrode was added. This in the first instance consisted
of a pointed 3 mm diameter tungsten rod supported in
perspex, positioned as shown earlier in the basic three
electrode drawing. The alternative second auxiliary
electrode is that shown in figure 1.22. It consists of
a brass rod supported in tufnol. The end of the rod has
a chisel-shaped point which was positioned about 1 mm
FIG. 1.22. THE MECHANICAL ARRANGEMENT OF THE THYRATRON TRIGGERED SPARK LIGHT SOURCE.
FIG. 1.23. THE SPARK GAP OF THE THYRATRON TRIGGERED LIGHT SOURCE SHOWING POINTED ANODE, CYLINDRICAL CATHODE AND CHISEL-SHAPED NON-TRIGGERED AUXILIARY ELECTRODE.
beneath the "live" electrode and offset to one side. The adjustments with this type of auxiliary electrode were easier to produce consistent firing, than the earlier type. The auxiliary electrode enables larger gaps and hence greater brightness of light output to be achieved with a consistent spark.

It is reported that the auxiliary electrode may be represented by a resistance path or resistance/capacitance path to earth. There is a low energy spark discharge existing when the voltage across the gap is low which improves the consistency of the spark. This low energy spark has been seen to occur between one corner of the chisel-shaped electrode and the cathode.

1.5.3.4 The possible Health Hazard due to X-rays from Thyratron CX1191

There are various illnesses which may arise due to over exposure to X-rays (23). In order to avoid the possibility of any health risk for persons using the thyratron spark light source, the Radiological Protection Service was asked to measure the radiation levels in the region of the source. The measurements made were carried out using portable instruments, which were screened from radio interference, film badges and electro-luminescent devices which were exposed for 10 hours in close proximity to the spark source case. Figure 1.24 shows the report received from the R.P.S. Personnel involved in radiation work usually carry personal radiation monitors in order to check their received dose over a period of
VISIT REPORT

Subject: Thyratron controlled Arc Device
Address visited: The Railway Technical Centre
              N.D.T. London Road
              Derby
Report for: Mr. K.G. Hall
Date of visit: 3 May 1973
Date of report: 14 June 1973

Description

An English Electric thyratron, type CX 1191, is used to control a pulsed arc, the light from which is directed through a photo-elastic analyser system. The thyratron is operated at 16 kV, and either 50 or 200 Hz.

General conclusion

Under the present working conditions the radiation doses received by operators of the photo-elastic apparatus are likely to be considerably less than three-tenths of the maximum permissible doses specified in the 'Code of Practice for the Protection of Persons exposed to Ionising Radiations in Research and Teaching', (H.M.S.O., 1971).

Recommendation

Further advice should be sought from this Centre if the working time on this apparatus increases to 15 hours (or more) per week.

Measurements

Measurements indicate that the dose rate close to the top and bottom of the case containing the thyratron may be up to 1.5 mrem/h.

Discussion

At present operation of the thyratron controlled arc device is limited to approximately five hours per week. The majority of work on the photo-elastic apparatus is carried out at the analyser end of the bench, that is to say approximately four feet away from the thyratron arc device. Consequently designation of operators need not be considered until there is at least threefold increase in operating time.

G.G. Harris

Figure 1.24 Report on the X-radiation emitted from the CX 1191 thyratron
GGH/ILS/14.6.73
time. It is recommended in the R.P.S. report, that should the time which a person uses the spark increase to 15 hours per week or more, then further advice must be sought. Possibly a film badge will have to be worn to enable periodic checks of dosage to be made.

1.6 Acoustic Waves

1.6.1 Wave motion is only possible in matter which has the property of recovery from changes in shape or size. This type of behaviour, sometimes described as "elastic", applies to wave motions of the type to be considered here. When compressional or tensile forces are involved the bulk modulus of elasticity is relevant; when shear forces are encountered the rigidity or shear modulus is appropriate. Since solids will support both compressional and shear forces the propagation of both wave types may occur. Most fluids will resist only changes of size but not of shape, consequently only compressional waves may propagate within them. The surface of a fluid may be taken as a special case supporting motions of a generally transverse but complex nature. Acoustic waves relevant in ultrasonic testing include compressional shear, Rayleigh, Lamb and Love waves. Those which have found applications here include the first three mentioned.

1.6.2 Acoustic Wave Velocities

The velocities of compressional and shear waves are related to their corresponding elastic moduli and the density of the medium through which they propagate. These relationships are shown in figure 1.25. In addition equations which enable the "thin rod" compressional wave and the Rayleigh wave velocities to be calculated are included.
<table>
<thead>
<tr>
<th>Wave Type</th>
<th>Velocity Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thin Rod Compressional</td>
<td>$C_0 = \left[ \frac{E}{\rho} \right]^{1/2}$</td>
</tr>
<tr>
<td>Bulk Compressional</td>
<td>$C_c = \left[ \frac{E}{\rho (1 + \sigma)(1 - 2\sigma)} \right]^{1/2}$</td>
</tr>
<tr>
<td></td>
<td>or $C_c = \left[ \frac{K + \frac{4}{3}G}{\rho} \right]^{1/2}$</td>
</tr>
<tr>
<td>Bulk Shear</td>
<td>$C_s = \left[ \frac{G}{2\rho (1 + \sigma)} \right]^{1/2}$</td>
</tr>
<tr>
<td></td>
<td>or $C_s = \left[ \frac{G}{\rho} \right]^{1/2}$</td>
</tr>
<tr>
<td>Rayleigh (Surface)</td>
<td>$C_R = C_s \left[ \frac{0.87 + 1.12\sigma}{1 + \sigma} \right]^{1/2}$</td>
</tr>
<tr>
<td></td>
<td>or $C_R = 0.9\left[ \frac{G}{\rho} \right]^{1/2}$</td>
</tr>
</tbody>
</table>

**Symbols:**
- $C_0$ = "Thin Rod" Compressional Wave Velocity
- $C_c$ = Bulk
- $C_s$ = Shear
- $C_R$ = Rayleigh
- $E$ = Young's Modulus of Elasticity
- $G$ = Shear
- $K$ = Bulk Modulus
- $\sigma$ = Poisson's Ratio
- $\rho$ = Density

**Fig. 1.25**
Relationship between the velocities of acoustic waves and the elastic constants of isotropic solids.
The velocity of each of these waves is equal to the product of wavelength and frequency.

1.6.3 Acoustic Wave Generation

1.6.3.1 Compressional and Shear Waves at Normal Incidence

The generation of acoustic waves here will rely upon the use of piezoelectric devices in ultrasonic probes. Electrical excitation of the piezoelectric plate causes it to vibrate in its characteristic mode, radiating sound waves from its front and rear faces. The rearward propagating sound is usually absorbed. Shown in figure 1.26 is a typical probe designed for normal incidence generation. Part of the rearward propagating wave is reflected by the crystal backing medium, a factor of considerable importance in stress measurements associated particularly with the first two half cycles of the acoustic wave, described in 5.9.2. The proportion of energy reflected depends upon the reflection coefficient $m$, which is the ratio of the acoustic impedance of the backing medium to that of the crystal. For a value of $m$ less than unity the reflected wave is in phase with the radiation from the front face. For this condition both the amplitude and duration of the transmitted pulse are increased. When $m$ is greater than unity, amplitude and duration are decreased and this is the usual case. Ideally in pulse echo testing the probe should send out a single pulse of ultrasound without ringing and then be quiescent until an echo is received, which again should not produce ringing. The condition of $m > 1$ does reduce ringing time and hence improves
FIG. 1.26. THE ULTRASONIC PROBE AND ITS VOLTAGE EXCITATION WAVEFORM.

a) AN ULTRASONIC PROBE, $O^\circ$ TYPE.

b) PROBE EXCITATION VOLTAGE WAVE FORM.
resolution. The part of the rearward travelling radiation which is transmitted into the backing medium should be dissipated by scattering within it. A practical absorbing medium for this purpose is a mixture of two parts tungsten powder to one part araldite.

Both compressional and shear waves may be generated in this way by insertion of the appropriate piezoelectric plate in the probe. To generate shear waves by normal incidence a coupling medium capable of supporting shear waves must be located between the piezoelectric plate and testpiece.

In non-destructive testing surface waves may be generated by constraining either compressional or shear waves to run along the surface of a testpiece. There are several methods by which this can be achieved. In general an obliquely incident wave, either compressional or shear, may propagate through a liquid or solid medium to strike obliquely a boundary with a solid. The angle which the incident wave makes with a normal to the boundary is chosen to produce a refracted wave angle of $90^\circ$. The mode of the refracted wave in propagating along the surface so changes, from either compressional or shear, to a surface wave. However the fraction of the incident wave energy refracted into the testpiece will not all be converted into surface wave energy, as practical experiments will show, by any of the techniques to be described in 1.6.3.4 to 1.6.3.6.
1.6.3.2 Shear waves generated by obliquely incident compressional waves at a water/steel boundary.

When a sound wave is obliquely incident at a boundary, reflected and transmitted waves are produced. Figure 1.27(a)-(f) shows an obliquely incident compressional wave at the boundary between two media. For low angles of incidence both reflected and refracted compressional waves are shown. In addition, there is for low angles of incidence a shear wave of low energy. The angle of the reflected wave is, from the reflection laws, of the same value as that of the incident wave, and occurs in the same plane. The angle of propagation of the refracted wave may be calculated from Snell's Law concerning refraction,

\[
\frac{\sin \alpha_1}{\sin \alpha_2} = \frac{C_{c,\text{medium 1}}}{C_{c,\text{medium 2}}} \quad (1.5)
\]

where \( \alpha_1 \) is the angle of incidence of compressional waves of velocity \( C_{c,\text{medium 1}} \) in medium 1 and \( \alpha_2 \) is the angle of refraction of compressional waves of velocity \( C_{c,\text{medium 2}} \) in medium 2.

When the angle of incidence is as shown, (a), 10° at a water/steel boundary, the refracted angle is 43°. Since the ratio of velocities of compressional waves in steel, to that in water is approximately 4:1 the refracted angle is for certain incident angles \( \leq 9° \), four times the incident angle. The extent of this linearity effect is shown in figure 1.21(b). For angles of incidence of 14° and above, the refracted compressional wave propagates along the
FIG. 1.27.

a.) Water/Steel boundary wave at low incidence angle, $i = 10^\circ$

b.) Variation of refracted angle with angle of incidence for compressional waves.

c.) Compressional wave incident at the critical angle, $\alpha_1 c = 14.3^\circ$

d.) Compressional wave incident at an angle slightly greater than the critical angle.

e.) Compressional wave incident at the critical angle, $\alpha_2 c = 27.5^\circ$

f.) Incidence angles in water in the range $\alpha_1 c$ to $\alpha_2 c$

FIG. 1.27. COMPRESSONAL WAVES INCIDENT OBLIQUELY AT A WATER/STEEL BOUNDARY.
surface of the steel. This effect is shown in figure 1.22(c). This angle is known as a critical angle to be called \( \alpha_1^c \). Its value may be calculated from equation

\[
\alpha_1^c = \sin^{-1} \frac{C_1}{C_2}
\]

where \( C_2 > C_1 \).

It is precisely at this angle that the compressional wave disappears from the steel, since it is totally internally reflected within the water. Beyond \( \alpha_1^c \) the compressional incident wave is converted to a shear wave, for which the propagation direction may be calculated.

Beyond the critical angle \( \alpha_1^c \), the energy of the incident wave is divided between reflected and refracted (transmitted) waves. The reflected wave propagates at an angle equal to that of incidence in water and the refracted part is theoretically a single shear wave.

In order to establish the way in which incident wave energy is divided by the reflection and mode conversion processes at the boundary, equations due to Schoch may be used (24).

The acoustic pressure of this shear wave increases with angle. Its propagation direction may also be calculated using the refraction law when the compressional wave velocity in water and the shear wave velocity in steel are substituted.
When the angle of incidence is further increased, a second critical angle will be reached at which the shear wave in steel is totally internally reflected as shown in figure 1.27(c). This second critical angle will be called $\alpha_2$. The useful range of shear waves in steel will therefore lie between $\alpha_1$ and $\alpha_2$ since above $\alpha_2$ no waves of any type will propagate into the steel rail. The relationship between incident compressional wave angles and refracted shear wave angles is shown in figure 1.27(d). These relationships have been illustrated for plane waves, when spherical wavefronts are incident obliquely at a boundary these effects will be subject to some modifications.

1.6.3.3 Shear Waves generated by obliquely incident Compressional waves at a perspex/steel boundary.

A number of ultrasonic rail testing probes currently in use, rely for their operation upon the refraction effects which take place at a perspex/steel boundary. When compressional waves propagating in perspex are incident at the perspex/steel boundary the reflection and refraction behaviour of the waves may be explained by means of the appropriate laws.

Figure 1.28(a) shows possible wave propagation directions which may result when variation of the angle of oblique incidence of a compressional wave at the boundary takes place. In figure 1.28(b) the appropriate velocities are given from which the possible propagation directions may be calculated.
(a) THE POSSIBLE REFRACTION/REFLECTION PRODUCED WHEN A COMPRESSIONAL WAVE IS INCIDENT OBLIQUELY AT PERSPEX/STEEL BOUNDARY.

<table>
<thead>
<tr>
<th>MEDIUM</th>
<th>VELOCITY m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>COMP</td>
</tr>
<tr>
<td>PERSPEX</td>
<td>2730</td>
</tr>
<tr>
<td>STEEL</td>
<td>5900</td>
</tr>
</tbody>
</table>

(b) VELOCITIES OF COMPRESSIONAL AND SHEAR WAVES IN STEEL AND PERSPEX.

FIG. 1.28. THE POSSIBLE WAVE PROPAGATION DIRECTIONS WHICH MAY BE CALCULATED FROM WAVE VELOCITIES, FOR AN OBLIQUELY INCIDENT COMPRESSIONAL WAVE AT A PERSPEX/STEEL BOUNDARY.
The boundary effects will be considered first with respect to low angles of incidence of compressional waves in perspex. In figure 1.29(a) the low angle compressional wave produces both reflected and refracted waves. The reflected wave angle again follows the reflection laws and the refracted wave obeys Snell's Law. The relationship for low angles of incidence is shown in figure 1.29(b). Here the relationship is linear below an incidence angle of $20^\circ$ after which the graph follows a curve until $\alpha_1$, a critical angle is reached. At this value of incidence, compressional waves are totally internally reflected, the refracted wave then propagates at $90^\circ$ to a normal to the boundary, i.e. along the surface of the steel.

For angles of incidence below $\alpha_1$, the refracted compressional wave in steel will be accompanied by a weak shear wave. Above $\alpha_1$, the shear wave is "strong" and theoretically is the only wave generated. The angles of these waves may be calculated by use of the refraction law. The relationship between the energy levels of these waves will later be described.

When the incidence angle exceeds $\alpha_1$, the refracted wave angle is as shown in figure 1.29(c). The linearity, figure 1.29(d) holds until a $50^\circ$ incidence angle, above which the relationship follows a curve until a second critical angle is reached at $57.6^\circ$. This is the angle at which shear waves in steel are totally internally reflected. At angles of incidence below $30^\circ$ some shear wave energy will be reflected, the level of which may be
(a) COMPRESSIONAL WAVES IN STEEL.

(b) $\alpha_1/\alpha_2$ RELATIONSHIP FOR COMPRESSIONAL WAVES.

(c) SHEAR WAVES IN STEEL BY REFRACTION.

(d) REFRACTED SHEAR WAVES WITHIN THE PRACTICAL TESTING RANGE (PERSPEX/STEEL.)

FIG. 1.29. VARIATION OF THE ANGLE OF INCIDENCE OF COMPRESSIONAL WAVES AT A PERSPEX/STEEL BOUNDARY.
calculated using the equations due to Schoch\textsuperscript{(24)} For practical shear wave testing applications the angles of incidence between $\alpha_1$ and $\alpha_2$ will be of particular interest.

The relationship between the incident and reflected waves in the wedge is shown in figure 1.30(a) and 1.31(b). The distribution of incident energy to the reflected and refracted waves may be seen in figures 1.30(c) and 1.30(d). Here the sound pressure levels are shown for the case of perspex coupled to steel with a liquid coupling film.

1.6.3.4 **Rayleigh Waves generated by obliquely incident Compressional Waves at a Water/Steel Boundary**

Practical transducers which employ the principle of a liquid launching medium must of necessity use a compressional wave generator. The mechanism involved is shown in figure 1.31(a). Typical liquids chosen for launching the obliquely incident wave are oil and water. The angular relationship between incident and refracted waves is shown in figure 1.31(b).
(a.) The reflection processes for a Perspex steel boundary.

(b.) Angular relationship between incident compressional and refracted shear waves.

(c.) Variation in sound pressure levels for a compressional wave incident between $\alpha_1$ and $\alpha_2$.

(d.) Variation of sound pressure level with angle for the reflected shear wave.

**Fig. 1-30.** Sound pressure levels for reflected and refracted waves at a Perspex/steel boundary.
a) Generation of a surface wave by mode conversion.

b) The angular relationship for a water/steel boundary.

FIG. 1.31. THE PRODUCTION OF SURFACE WAVES IN STEEL BY MODE CONVERSION FROM COMPRESSIONAL WAVES IN A LIQUID.
In order to determine the precise angle of the incident wave, the relationship between $\alpha_1$, the critical incident wave angle, and the refracted compressional wave propagating along the surface, the law of refraction is used. When the media are water and steel, with compressional wave velocities of 1,480 m/s and 5,900 m/s respectively, then the critical angle may be calculated from equation

$$\sin \alpha_1 \text{(water)} = \sin \alpha_2 \text{(steel)} \quad (1.7)$$

For this particular case the critical angle is approximately $142^0$ at which the refracted compressional waves propagate along the surface of the steel testpiece. In practice this is the angle selected by commercial probe manufacturers for the generation of Rayleigh waves in these circumstances. There will in addition be a refracted shear wave in the testpiece which can cause problems during testing. Critical angle $\alpha_2$ is obtained by inserting the compressional wave velocity of water and the shear wave velocity of steel in equation (1.8)

$$\sin \alpha_1 \text{(water)} = \sin \alpha_2 \text{(steel)} \quad (1.8)$$

Hence $\alpha_2 = 27^0$, and the refracted shear wave travels along the surface of the steel testpiece.

In order to achieve the theoretically correct angle for Rayleigh wave generation, the velocities $C_c \text{(water)}$ and $C_R \text{(steel)}$ must be inserted in equation (1.7) giving

$$\sin \alpha_1 \text{(water)} = \sin \alpha_2 \text{(steel)} \quad (1.9)$$

$$\frac{2,790}{1,480}$$
Hence $\alpha_1 = 33^\circ$. Using this method theoretically there are no other waves generated in the testpiece. Consequently more efficient testing should result. Ultrasonic probes are at present under construction based on this principle.

1.6.3.5 Rayleigh Waves generated by obliquely incident compressional waves at a Perspex/Steel Boundary

A more practical means of generating Rayleigh waves is by perspex wedge mode conversion. This launching medium is found to be suitable for producing Rayleigh waves in steel. This condition must apply for a suitable wedge material for the incident wave. Compressional waves travel in perspex at 2 670 m/s whilst Rayleigh waves in steel propagate at 2 790 m/s. Using these velocities the refraction law gives a critical angle calculable as follows:

$$\sin \alpha_{1c \text{ (perspex)}} = \frac{C_{\text{compressional (perspex)}}}{C_{\text{Rayleigh (steel)}}}$$

The critical angle for this particular case is $72^\circ$ approximately.

For testpieces of Rayleigh wave velocity less than 2 670 m/s this method could not be used. However the shear wave velocity in perspex of 1 430 m/s is considerably lower than the Rayleigh wave velocity in steel and other metals. In order to generate a Rayleigh wave on a steel surface an incident shear wave must propagate at an angle calculated by equation (1.11)

$$\sin \alpha_{1 \text{(perspex)}} = \frac{C_{\text{shear (perspex)}}}{C_{\text{Rayleigh (steel)}}}$$

For a shear wave velocity in perspex of 1 430 m/s and a Rayleigh wave velocity in steel of 2 790 m/s, the
critical angle is approximately $31^\circ$.

1.6.3.6 **Rayleigh Waves generated by obliquely incident shear waves at a Copper/Steel Boundary**

A medium which offers certain advantages as a surface wave generating wedge when coupled to steel, is copper. Its shear wave velocity, 2 260 m/s, is less than the Rayleigh wave velocity in steel, the important criterion. Copper is also less attenuating than perspex for shear waves and in addition gives better acoustic matching between itself and a steel testpiece. Using equation (1.12) the critical angle for a copper/steel boundary is found to be approximately $54^\circ$.

$$\sin \alpha_1 (\text{Copper}) = \frac{C_{\text{shear (Copper)}}}{C_{\text{Rayleigh (Steel)}}} \quad (1.12)$$

The mode conversion process is described by figure 1.32(a). A probe based on this principle is indicated in figure 1.32(b), the application of probes of this type will be made in 4.13, when crack depth measurement by Rayleigh waves will be described.

1.6.4 **Reflection of Obliquely Incident Waves at a free boundary**

The conversion of wave modes by oblique reflection at boundaries is of considerable practical importance in ultrasonic testing. Complications of the basic "A scan" display may result due to delayed reflections produced by mode conversions within the testpiece. This condition is particularly relevant in railway axle testing.
a) SHEAR TO RAYLEIGH WAVE CONVERSION, $\lambda_s = \lambda_R \sin \theta$

b) A COPPER WEDGE RAYLEIGH WAVE PROBE.

FIG. 1.32. RAYLEIGH WAVE GENERATION IN STEEL BY A COPPER WEDGE PROBE.
1.6.4.1 Incident Compressional Waves

When a compressional wave transducer is positioned on a steel testpiece, as shown in figure 1.33, the oblique incidence of the peripheral part of the wavefront strikes the upper horizontal surface. Waves produced by this reflection may be of both compressional and shear types depending upon the incidence angle.

For a steel testpiece, shear waves reflect from the sidewall at an angle of $33^\circ$ to the normal almost independently of the incidence angle, providing it exceeds $70^\circ$. The relationship between incident compressional waves and reflected shear may be obtained from equation (1.13)

\[
\frac{\sin \beta_s}{\sin \alpha_c} = \frac{Cs}{Cc}
\]

from which the graphical relationship of figure 1.33(b) has been produced. The reflected compressional wave obeys the law of reflection.

The graphical relationship between acoustic pressure and incident angle for compressional waves is illustrated in figure 1.34(a) whereas figure 1.34(b) shows the case for reflected shear waves. It may be seen here that compressional waves are reflected weakly between $60^\circ$ and $70^\circ$ and over this range a strong shear wave is produced propagating at an angle below $30^\circ$.

1.6.4.2 Incident Shear Waves

When shear waves are incident obliquely, as indicated in figure 1.35(a) then both shear and compressional
FIG. 1.33.

(a) Grazing incidence of a compressional wave at a steel/air boundary.

(b) Graphical relationship

FIG. 1.33. Angular relationship between incident compressional waves and reflected shear waves at a steel/air boundary.
FIG. 1.34. ACOUSTIC PRESSURE DIAGRAMS FOR OBLIQUELY INCIDENT COMPRESSional WAVES.

(a) REFLECTION AT A STEEL/AIR BOUNDARY FOR COMPRESSional COMPRESSional WAVES

(b) REFLECTED SHEAR WAVE
FIG. 1.35.

a.) A VERTICALLY POLARISED SHEAR WAVE, INCIDENT AT A SOLID/GAS BOUNDARY.

b.) GRAPHICAL RELATIONSHIP.

FIG. 1.35. ANGULAR RELATIONSHIPS BETWEEN INCIDENT SHEAR WAVES, VERTICALLY POLARISED, AND REFLECTED COMPRESSIONAL WAVES AT A STEEL/AIR BOUNDARY.
waves may be reflected. The angle of the reflected compressional wave is greater than the incident shear wave angle.

The relationship between these angles and the wave velocities is given by equation

$$\frac{\sin \alpha_2}{\sin \beta_2} = \frac{C_c}{C_s}$$

where \(C_c\) is the compressional wave velocity

\(C_s\) is the shear wave velocity

\(\alpha_2\) is the reflected compressional wave angle

\(\beta_2\) is the reflected shear wave angle

This relationship is shown graphically in figure 1.35(b) Above 33° the compressional wave is extinguished since it is reflected at 90° and the shear wave is totally reflected. This situation will always occur, due to the refraction, when the velocity of the reflected, or transmitted wave, is greater than that of the incident wave.

These conditions may occur in both axle testing and rail testing by ultrasonics and consequently are of particular importance in the applications of this work.

1.6.5 Reflection and Transmission Coefficients for Ultrasonic Waves

The reflection and transmission of ultrasonic waves will be of particular interest in the application of schlieren visualisation. Here the reflection of waves at a water/steel boundary will be considered. The reflection coefficient \(R\) and the transmission coefficient \(T\), for acoustic pressure in terms of incident angle, may be calculated from the following
equations, found in the reference due to Krautkramer

\[
R = \frac{1}{N} \left[ \left( \frac{C_S}{C_C} \right)^2 \sin 2 \alpha_c \sin 2 \alpha_s + \cos^2 2 \alpha_s - \frac{Z_1 \cos \alpha_c}{Z_2 \cos \alpha_c} \right] \quad (1.15)
\]

where

\[
N = \left( \frac{C_S}{C_C} \right)^2 \sin 2 \alpha_c \sin 2 \alpha_s + \cos^2 2 \alpha_s + \frac{Z_1 \cos \alpha_c}{Z_2 \cos \alpha_c} \quad (1.16)
\]

and

- \( C_s \) is the velocity of shear waves in solid
- \( C_c \) is the velocity of compressional waves in solid
- \( \alpha_c \) is the angle of refraction of compressional waves in solid
- \( \alpha_s \) is the angle of refraction of shear waves in solid
- \( \alpha_0 \) is the angle of incidence of compressional waves in liquid
- \( Z_1 \) and \( Z_2 \) are the acoustic impedances in solid and liquid respectively.

\[
T_{cc} = \frac{2}{N} \cos 2 \alpha_s \quad (1.17)
\]

\[
T_{sc} = -\frac{2}{N} \left( \frac{C_S}{C_C} \right)^2 \sin 2 \alpha_c \quad (1.18)
\]

where \( T_{cc} \) is the transmission of a compressional wave referred to an incident compressional wave and \( T_{sc} \) is the transmission of a shear wave referred to an incident compressional wave.

When typical angles of incidence which will be used here are substituted for a water/steel rail boundary, namely \( 0^\circ \), \( 17.5^\circ \) and \( 25^\circ \) respectively, relevant in later work, values for reflections coefficient \( R \) of \( 94\% \), \( 71\% \) and \( 69\% \) are obtained.

Consequently only small percentages of the incident energy will propagate into the steel rail and in addition the energy must return, this time through a steel/water boundary. Equations
for the reflection and transmission coefficients may be calculated for incident waves in steel. Some energy is again reflected and some transmitted.

For the reflected compressional wave,

$$ R_{c/c} = \frac{1}{N} \left[ \left( \frac{C_s}{C_c} \right)^2 \sin 2\alpha_c \sin 2\alpha_s - \cos 2\alpha_s + \frac{Z_1 \cos \alpha_c}{Z_2 \cos \alpha} \right] $$ (1.19)

and for the reflected shear wave

$$ R_{s/c} = \frac{2}{N} \left( \frac{C_s}{C_c} \right)^2 \sin 2\alpha_c \cos 2\alpha_s $$ (1.20)

For the transmitted compressional wave in the liquid (water)

$$ T_{c/c} = \frac{2}{N} \frac{Z_1 \cos \alpha_c \cos 2\alpha_c}{Z_2 \cos \alpha} $$ (1.21)

When the incident wave in the case of a solid/liquid boundary is shear in nature, this will occur within the rail, then a further series of equations is required. These will be as follows:

$$ R_{s/s} = \frac{1}{N} \left[ \left( \frac{C_s}{C_c} \right)^2 \sin 2\alpha_c \sin 2\alpha_s - \cos 2\alpha_s - \frac{Z_1 \cos \alpha_c}{Z_2 \cos \alpha} \right] $$ (1.22)

$$ R_{c/s} = -\frac{1}{N} \sin 4\alpha_s $$ (1.23)

$$ T_{c/s} = \frac{2}{N} \frac{Z_1 \cos \alpha_c \sin 2\alpha_s}{Z_2 \cos \alpha} $$ (1.24)

It should be observed that the intensity of the transmitted or reflected waves is equal to the square of the S.P.L. For normal incidence the intensity of the reflected wave in water is 88% of that incident. A summary of relevant reflection coefficients and intensities is given in figure 1.36.
<table>
<thead>
<tr>
<th>Angle of Incidence in Water (Degrees)</th>
<th>Reflection Type</th>
<th>Coefficient</th>
<th>Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Rc/c</td>
<td>94</td>
<td>88</td>
</tr>
<tr>
<td>17.5</td>
<td>Rc/c</td>
<td>71</td>
<td>50</td>
</tr>
<tr>
<td>25</td>
<td>Rc/c</td>
<td>69</td>
<td>48</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Angle of Incidence in Steel (Degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
</tr>
<tr>
<td>40</td>
</tr>
<tr>
<td>70</td>
</tr>
</tbody>
</table>

FIGURE 1.36 Reflection coefficients for some relevant angles of compressional and shear waves in the water column coupled probe array.
2. SCHLIEREN APPLICATIONS

2.1 Introduction

The schlieren apparatus has found applications as a teaching aid and in the design of a water-column coupled ultrasonic probe array for rail testing. The general principles of ultrasonic wave propagation have been demonstrated and this information in the form of slides will be supplied to the British Rail N.D.T. School. A study of the interactions occurring within a water column-coupled probe array has indicated a suitable method of design. The transmission of acoustic waves through membranes supporting the water column has received detailed consideration. The suitability of the array for the detection of various types of rail flaws has been comprehensively examined.

2.2 Continuous and Pulsed Waves in water, visualised for teaching purposes.

The optical and electrical apparatus described in 1.2 was used for this work. The optical apparatus was standardised as that shown in figure 1.4. The electrical apparatus depended upon the mode of operation. For the generation of continuous waves the probe was excited by the system of figure 1.5(a) at the series resonant frequency determined as indicated by figure 1.5(b). The waves transmitted were examined in both the "near" and "far" field. The reflection of continuous waves in these regions was also recorded when an aluminium plate was inserted in the path of the beam.

For the pulsed mode the electrical system of figure 1.6(a) was used. The waves generated by a probe of nominal frequency 3 MHz and crystal plate dimensions 10 mm x 20 mm were viewed both in the 10 mm and
20 mm planes. The pulse divergence, reflection and transmission were investigated.

For continuous waves the recorded phenomena are shown in figures 2.1 and 2.2. The pulsed mode is displayed in figures 2.3 and 2.4.

The divergence effect is for the continuous mode demonstrated by the illustrations. The position after which divergence occurs, 80 mm from the source, agrees with that calculable from the near field equation, \( N = \frac{D^2}{4\lambda} \). The reflection of these waves from a thin aluminium plate shows reflection in agreement with the fundamental law. Diffraction too occurs around the edge of the plate. An area in the centre of these waves appears dark. In principle the region disturbed by the ultrasonic wave should appear bright. The effect shown here has been displayed by Mayer,\(^{(26)}\) although no comment concerning optical density variation within the beam was made. Perhaps abnormal diffraction effects described by Willard, attributed to high electrical excitation levels of the probe, may account for this effect.\(^{(27)}\)

The pulsed mode photographs show first the effect of the source diameter on the shape of the transmitted waves. When a probe dimension of 10 mm was perpendicular to the light beam a curved wavefront was produced. A 20 mm dimension, similarly placed, produced plane waves.

Progression of the wave shows the divergence and outlines more clearly the presence of side lobes. The division of the wave into transmitted and reflected parts on meeting an aluminium plate is clearly shown.
FIG. 2-1. CONTINUOUS WAVES, GENERATED BY A 5 MHz 10 mm. DIAMETER SOURCE, VIEWED IN WATER BY SCHLIEREN VISUALISATION.
FIG. 2.3.

a.) PROBE VIEWED IN 10 mm. PLANE SHOWING CURVED WAVEFRONTS.

b.) PROBE VIEWED IN 20 mm PLANE SHOWING PLANE WAVEFRONTS. MAGN. x1.

FIG. 2.3. ULTRASONIC PULSES, FREQUENCY 3.3 MHz TRANSMITTED INTO WATER BY A 10 mm. x 20 mm PROBE, VIEWED BY A SCHLIEREN METHOD.
FIG. 2.4.

a.) DIVERGENCE OF WAVES VIEWED IN 10 mm. PLANE.

b.) REFLECTION AND TRANSMISSION OF WAVES BY AN ALUMINIUM PLATE.

FIG. 2.4. DIVERGENCE, REFLECTION AND TRANSMISSION OF 3.3 MHz PULSES IN WATER, VIEWED BY THE SCHLIEREN METHOD.
2.3 Design of a Water-column coupled Ultrasonic Probe Array for Rail Testing at Speed.

2.3.1 Introduction

The rails used on British Railways are basically of two main types, namely "flat bottomed" and "bullhead". The former is gradually replacing the bullhead rail. Consequently the design of any new ultrasonic system must be directed towards examination of the "flat bottomed" type shown in figure 2.5. The rail cross section is by some standards of unusual geometry but is reasonably consistent along its length. The track is constructed basically in lengths of 18 m, which are joined together either by a bolted fishplate or welded by one of three standard types of weld.

Any comprehensive ultrasonic testing method used must be able to detect flaws in many different planes and heights within the rail section. Flaws may conveniently be classified first according to the rail part in which they occur and second according to the prime cause of crack formation.

2.3.2 Rail Flaws

Rail head flaws include "tache ovales", "horizontals" and vertical/longitudinal splits. The "tache ovale" is a most serious type. Examples are shown in figure 2.6(a) and (b). The name originates from the Société Nationale des Chemins de Fer (French Railways) and means "kidney-shaped defect". The flaw itself originates from the inclusion of hydrogen gas in the rail head. A survey has shown that the defect may be oriented on planes between 5° and 35° with respect to a normal to the rail head, sloping downwards in the direction of traffic as indicated.
FIG. 2-5. FLAT BOTTOMED RAIL TO BS II, BASIC DETAILS OF RAIL SECTION.
FIGURE 2.6

a) A SMALL "TACHE OVALE"

b) A LARGE "TACHE OVALE"

c) TYPICAL ORIENTATION OF "TACHE OVALES" WITH RESPECT TO TRAFFIC FLOW.

FIG. 2.6. CHARACTERISTICS OF "TACHE OVALE" DEFECTS.
The defect planes are always related to the direction of rail traffic flow as indicated in figure 2.6(c). The size of "tache ova"les" may increase in certain cases to the limit when a breakage of the rail head occurs, making imperative their early detection.

Typical horizontal flaws occurring in the head are shown in figure 2.7(a) and (b). In (a) a large horizontal crack is shown whereas in (b) a small one, photographically enlarged, is indicated. In each photograph a "magnetic ink" test has been applied to outline the crack.

Cracks occurring in the vertical plane can result in a splitting of the head into two parts. Again serious consequences may result.

Flaws associated with the rail head alone can be seen to occur in various orientations, so requiring a comprehensive ultrasonic testing system.

When the rail web is considered a more complicated arrangement of flaws are presented. Again cracks of horizontal and vertical orientations do occur but in addition cracks associated with rail bolt holes are present. These result from the stresses induced by the passage of heavy traffic. They are of a most serious nature since at the present time they form some fifty percent of all rail failures. It should be mentioned here that the term "failure" on British Railways is used to indicate that the rail is defective in some way which justifies its removal. It is not necessarily broken. Figure 2.8(a) shows a vertically oriented web defect, called "piping" and in 2.8(b) a rail breakage due to bolt hole "star cracking" is shown. This particular
FIG. 2.7. HORIZONTAL CRACKS IN RAIL HEADS, MADE CLEARLY VISIBLE BY A "MAGNETIC INK" METHOD.
a.) PIPING IN THE RAIL WEB.

b.) "STAR CRACKS" AT THE RAIL BOLT HOLE.

FIG. 2.8. CRACKS ASSOCIATED WITH THE RAIL WEB.
example emphasizes the severity of this type of failure.

Rail foot cracks are less frequent causes of rail breakages, but when they do occur the consequences will be a danger to rail traffic flow. A comprehensive description of the classification of rail failures is to be found in a handbook produced by the B.R.B. Civil Engineers department.\(^{(29)}\)

It has been shown that there may exist a wide range of defects, randomly oriented, within the rail. All of these must be detected by any proposed new system. For these reasons it was decided to use an array of probes, comprising five transducers, which would comprehensively survey the whole of the rail height. It is acknowledged that testing methods using probe arrays already exist, and some of these are described in 2.3.3, but the new array differs basically in the manner in which coupling of the ultrasonic waves into the rail is achieved.

2.3.3 Rail Testing by existing Ultrasonic Methods

Ultrasonic waves used for the detection of flaws in rails are chosen for two principal reasons. The first is their suitability for detecting particular types of flaws and the second is the practicability of generating waves within the rail at the sites required. Purposefully designed testing methods currently in use include "hand testing", testing at a slow walking speed and testing from a moving vehicle. In each method the coupling of the ultrasonic waves to the rail is aided by a water film. Couplants such as oil and grease are not allowed due to the problem of locomotive wheel slip. It is believed that an array of probes which are coupled by a water column having a substantial water film thickness, may produce the most reliable coupling conditions. Further, the interactions within the rail
may be arranged to occur within the "Far Field" of the probes. For these reasons it was decided to launch a programme designed to produce an ultrasonic array in which coupling resembled that of an immersion system. Experiments will now be described which use the schlieren method and "A scan" ultrasonic display to test the efficiency of the proposed array.

2.3.4 The Proposed Water Column Coupled Array

The water column coupled array is shown in figure 2.9. It comprises five ultrasonic probes, normal incidence compressional and "forward" and "backward facing" 40° and 70° shear wave probes. The normal incidence probe examines for horizontally oriented defects throughout the rail height. The 40° probes, which generate shear waves at 40° in the rail bolt holes. "Tache ovales" are detected by the 70° "backward facing" probe. Examination of the rail by this probe array is possible in a plane some 20 mm wide as indicated by figure 2.10.

The probe which was selected, common in all sections of the water box, is a 4 MHz 20 mm diameter well damped Meccasonics device. It was positioned to transmit compressional waves from a distance approximately one near zone from the rail surface. Theoretically this should occur at 280 mm. A practical measurement, carried out by colleagues within the laboratory, employed a beam profiling technique. This type of experiment, previously reported by J.T. McElroy[30] uses a steel ball which traverses across the path of the ultrasonic beam. Reflected signal amplitudes on the flaw detector screen are plotted for a number of probe to target distances. The zone pattern of
FIG. 2.9. THE WATER COLUMN COUPLED PROBE ARRAY.
the source shows irregularities within the Fresnel field, but as the distance from the source increases variations are reduced. At one "near field" distance, a transition point occurs, after which irregular variations within the signal are absent. This point occurred for this probe at 170 mm from the probe face. It may be seen that a discrepancy occurs between theoretical and measured near field distances. In practice the mechanical clamping of the edges of the piezoelectric plate may effectively reduce the wave source diameter, resulting in a decrease in the near zone distance. In practice the smaller value will be taken for the probe to rail spacing since it is obtained by a practical measurement.

The physical dimensions of the water boxes are determined by the requirement that reflections within each section should not obscure ultrasonic signals which require analysis. The optimum dimensions of the individual water boxes are in 2.3.5, determined by schlieren and "A scope" presentation. A membrane of polythene, a medium chosen for the close proximity of its acoustic impedance to that of water, supports a column of water.

2.3.5 Schlieren and "A scope" Examination of Water Boxes

Each individual element of the water column coupled array was inserted in turn into the schlieren system of figure 1.4. Here the experimental water tank, having glass sides, allowed the propagation of compressional waves in the water boxes to be seen.
2.3.5.1 The 70° Water Box

An experimental 70° water box is illustrated in 2.10 in which an incident compressional wave angle of 25° in water is selected to transmit shear waves at 70° in steel. It is shown here positioned on a "tache ovale" sensitivity block. This consists of a rail head in which a 6 mm diameter flat-bottomed hole has been drilled at an angle of 20° at which "tache ovales" typically are found to occur. Additionally reflections within the box will take place. In this design, the end to the left of the box is positioned to ensure that reflections do not produce "A scan" signals, within the time interval selected for inspection.

The effect of fitting sides to the box as shown in figure 2.11, has been examined by the following method.

The variable time delay of the schlieren electrical system was adjusted to bring the transmitted 4 MHz pulse into the field of view. The transmission of the pulse through this thin polythene membrane and its reflections within the box were photographed. The "A scope" display was recorded by displaying the transmitted and received rectified signals on the Tektronix oscilloscope, and photographing using polaroid film.

"Membranes" of polythene of thickness 0.16 mm were used later.

Schlieren photographs of the ultrasonic pulses propagating through the membrane and reflecting within the water box are shown in figure 2.12. The ultrasonic pulse was viewed through perspex windows, in addition to the glass tank windows.
FIG. 2.10.

a) 70° WATER BOX POSITIONED ON "TACHE OVALE" CALIBRATION BLOCK.

b) INCIDENT COMPRESSIONAL AND REFRACTED SHEAR WAVES.

FIG. 2.10. DESIGN FEATURES OF THE 70° WATER BOX.
FIG. 2.11.

a.) PERSPEX SIDES FITTED TO A 70° WATER BOX.

b.) END VIEW OF POSSIBLE INTERACTION OF PULSE WITH SIDES OF WATER BOX.

FIG. 2.11. 70° WATER BOX WITH PERSPEX SIDES FITTED.
FIG. 2.12

a) IDENTIFICATION OF OBJECTS IN SCHLIEREN FIELD.

b) INCIDENT PULSE.

c)  
d)  

e)  
f)  

FIG. 2.12. SCHLIEREN VISUALISATION OF THE REFLECTIONS WITHIN THE 70° WATER BOX.
Calculation of the times at which the "A scope" signals should occur were:

- Water Box internal reflection path: 206 μs
- "Tache Ovale" path: 220 μs
- Underside of calibration block: 247 μs

These were compared with the "A scope" display of figure 2.13.

The schlieren visualised reflections within the 70° water box of figure 2.12 show reflections in accordance with those theoretically predicted. "A scope" signal displays give a "tache ovale" generated signal of amplitude 20 dB greater than any other signals on the screen. When sides were fitted to the water box the signal to noise ratio was marginally decreased. It is interesting to observe that schlieren pulses may be visualised through two sheets of perspex, although the quality of the image is reduced. Schlieren literature indicates that a flatness of λ/10 is necessary for schlieren windows, for high quality work. When aluminium and steel sides were fitted in turn, the "A scan" signals for "tache ovale" detection were quite satisfactory.

2.3.5.2 The 40° Water Box

This water box is shown in figure 2.14. Its purpose was to examine the rail in the bolt hole region by obliquely incident shear waves.

The water box was manipulated along a rail head immersed in the schlieren tank to maximise the signal received from the bolt hole. "A scope" signals were recorded.
FIG. 2.13. 

(a) WITHOUT SIDES.

(b) PERSPEX SIDES FITTED, 4 mm. THICK.

FIG. 2.13. "A SCOPE PRESENTATION OF 'MAXIMISED' REFLECTIONS FOR A "TACHE OVALE" CALIBRATION HOLE, FOR THE 70° WATER BOX."
FIG. 2.14.

The 40° water box positioned on the rail, showing reflection of the "beam" within the box, and the fundamental reflection within the rail.
Calculations of the time at which the bolt hole signal should occur was made by means of the refraction law.

The "A scope" display is indicated in figure 2.15.

The bolt hole signal is shown to occur at 340 \( \mu s \) and corresponds closely to that calculated, 362\( \mu s \). An unpredicted reflection precedes the bolt hole signal and a possible cause may be due to re-radiation from the rail upper surface, since removal of the end of the box failed to eliminate this signal. Alternatively the rail upper fillet radius may be the source of this signal.

When an electronic gate is used to examine signals occurring within a given time interval, this unwanted signal could be discarded.

2.3.5.3 Water Boxes with "Normal" or "Near Normal" Incidence

The normal incidence probe is primarily intended for the detection of horizontal defects throughout the rail height. The suitability of single probes used in the "transmit and receive" mode or twin probes acting separately as "transmitter" and "receiver" is described in these experiments. Flaws in the form of flat bottomed holes drilled upwards into a rail head provided horizontally oriented reflectors. The twin probe device was designed as shown in figure 2.16 to produce beams which intersect at mid-rail height. The object of this design was to improve the sensitivity of detection of cracks at this location.

Using a single probe in the transmit and receive mode, schlieren pulses were examined visually and "A scope" signals recorded. Horizontally oriented flaws were in this way inspected at particular locations. The twin angled probe
A SCOPE SIGNAL AND POSSIBLE SOURCE OF UNEXPECTED SIGNAL IN THE 40° WATER BOX.
FIG. 2.16. SIDE VIEW OF TWIN TRANSDUCER ARRANGEMENT, CONSIDERED FOR THE DETECTION OF HORIZONTALLY ORIENTATED RAIL DEFECTS.
was similarly tested.

The "A scope" display for a single normal incidence probe positioned on a rail head with a horizontal reflector is shown in figure 2.17. Schlieren reflections observed visually and their probable generation mechanisms are shown in figure 2.18. Typical "A scope" indications are shown in figure 2.19 for the twin angled probe. The schlieren visualised reflections in water and their probable generation mechanisms are indicated in figure 2.20.

Since the twin probe has been designed to preferentially illuminate the mid-rail height position, flaws occurring at other locations will be less efficiently detected using this method. The mid-rail height is however a critical zone and this design might have been justified. The resolution of the twin probes for the head defects appears to be more dependent on the flaw detector than on single or double probe working. From the results, double probe working does not seem justified.

2.3.5.4 Water Box Membranes

There are several properties of membranes which require consideration, those considered here include:

(a) Mechanical Strength
(b) Resistance to impact
(c) Hygroscopic nature
(d) Electrochemical reaction
(e) Acoustic properties

As a result of an examination of a number of materials polythene was chosen. Experiments with thicker membranes proved satisfactory for which figure 2.21 portrays both
Signals produced from a "calibration" rail head with indication of the lateral position of the transducer with respect to the hole.

"Maximised" signal from flat bottomed hole for \( h_1 = 41 \text{ mm} \)

A scope rectified displays corresponding to the detection of a horizontal defect in the form of a flat bottomed hole.
FIG. 2.18. SKETCHES OF SCHLIEREN REFLECTIONS AND THEIR ESTIMATED SOURCES OF ORIGIN.
FIG. 2.19.

(a) HOLE DEPTH 24 mm., U.S.I.P. 10 SET. (RESOLUTION POSN. 2.)

(b) HOLE DEPTH 7.5 mm. USE. 1 SET.

FIG. 2.19. "A SCOPE RECTIFIED DISPLAYS FROM A FLAT BOTTOMED HOLE IN A RAIL HEAD, USING THE TWIN ANGLED PROBE."
FIG. 2.20. SKETCHES OF SCHLIEREN VISUALISED PULSES IN WATER AND THEIR PROBABLE SOURCES OF GENERATION FOR THE TWIN ANGLED PROBE.
FIG. 2.21. THE 70° WATER BOX WITH A THICK MEMBRANE FITTED.
"A scope" and schlieren effects for a polythene membrane of 1.6 mm thickness.

2.3.5.5 Conclusions of Water Column Array Experiments

(1) A feasibility study has been carried out into the use of a water column-coupled ultrasonic array for rail testing at speed. Examination of the static version has been made using both conventional "A scope" presentation and a schlieren visualisation technique.

(2) The basic design has proved suitable for the detection of cracks throughout the rail height.

(3) The new design with longer water path provides a system in which rapidly fluctuating signals are less likely to occur.

(4) Signals received by each probe will be suitable for analysis by electronic gating and processing systems.

(5) Ultrasonic probes of 23 mm diameter and 4 MHz nominal frequency have produced satisfactory results with water paths of 150 mm.

(6) The concept of using membranes to support water columns is possible without causing unwanted reflections on the "A scope" display.

(7) The overall dimensions of the array suggested by these experiments, will be of the order: length 0.7 m, width .06 m height 0.18 m.
The detection of "star cracks" at the rail bolt hole requires more detailed consideration. Long lengths of rail immersed in a water tank are currently being tested using these principles, by colleagues within this laboratory.
3. PHOTOELASTIC APPLICATIONS

3.1 Introduction

In the earlier work of chapter 1 the principles of photoelasticity were described. In this first series of applications the "crossed" plane polariscope was applied to the identification of waves and to the interaction of waves with cracks and boundaries within solid testpieces. The medium selected for testpieces was glass since the acoustic wave velocities resemble those in steel. This relationship is indicated by figure 3.1.

3.2 Visualisation by Continuous and Stroboscopic Light Sources

In ultrasonic testing pulsed wave excitation is now most frequently used. In an earlier rail testing system known as the "audigage", standing waves were generated in the rail in order to produce a resonant column. The presence of a defect in the path of the ultrasonic beam was indicated by a reduction in frequency of the audible warning generated. Figure 3.2 shows a standing wave generated by 4 MHz shear waves in quartz glass. Side lobes can be seen and measurement of the fringe spacing indicates two fringes per cycle as described by figure 1.12. It should be emphasised here that the term "fringe order" used in conventional photoelasticity, is used to indicate a level of stress. Here the terms "1st fringe", "2nd fringe", etc., are used to indicate the first and second bright zones produced by alternating voltage peaks. Stress values associated with these peaks are indicated by fractional fringe orders, as chapter 5 describes.

For the pulsed mode of operation, compressional and shear waves visualised by means of two pulsed light sources have been compared in quartz glass. In figure 3.3(a) compressional waves
Fig. 3.1 Frequency/wavelength relationship for some relevant materials used in the visualisation of acoustic waves.

<table>
<thead>
<tr>
<th>Medium</th>
<th>Frequency MHz</th>
<th>Wavelength mm</th>
<th>Compressional</th>
<th>Shear</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;Steel&quot;</td>
<td>2</td>
<td>2.95</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td>$C_c = 5900 \text{ m/s}$</td>
<td>$2\frac{1}{2}$</td>
<td>2.36</td>
<td>1.29</td>
<td></td>
</tr>
<tr>
<td>$C_s = 3230 \text{ m/s}$</td>
<td>4</td>
<td>1.5</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>1.18</td>
<td>0.65</td>
<td></td>
</tr>
<tr>
<td>Plate Glass (Lab. Specimens)</td>
<td>2</td>
<td>2.94</td>
<td>1.73</td>
<td></td>
</tr>
<tr>
<td>$C_c = 5900 \text{ m/s}$</td>
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<td></td>
<td></td>
</tr>
<tr>
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<td></td>
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<tr>
<td></td>
<td>5</td>
<td>0.69</td>
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<td></td>
</tr>
<tr>
<td>Fused Quartz</td>
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<td>2.94</td>
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<td>Lab. Specimens</td>
<td>$2\frac{1}{2}$</td>
<td>2.31</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$C_c = 5800 \text{ m/s}$</td>
<td>4</td>
<td>1.45</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$C_s = 3460 \text{ m/s}$</td>
<td>5</td>
<td>1.16</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
FIG. 3.2.

a) NO EXCITATION APPLIED TO PROBE.

b) EXCITATION VOLTAGE APPLIED.

FIG. 3.2. VISUALISATION OF CONTINUOUS WAVES IN QUARTZ GLASS IN THE CROSSED PLANE POLARISCOPE.
FIG. 3.3.

a.) 2½ MHz COMPRESSIONAL WAVES, STROBOTAC LIGHT SOURCE.

b.) 2 MHz COMPRESSIONAL WAVES, SPARK LIGHT SOURCE.

FIG. 3.3. COMPARISON OF COMPRESSIONAL WAVES IN QUARTZ GLASS, VIEWED IN THE CROSSED POLARISCOPE ILLUMINATED BY THE "STROBOTAC" AND THE SPARK LIGHT SOURCE.
viewed with the "strobotac" appeared blurred whereas in (b) clearly resolved individual half cycles are present. Obliquely incident shear waves seen by this high resolution system are displayed in figure 3.4(a)-(c). It will be essential in future work to view waves with this degree of resolution and sensitivity.

3.3 Identification of Acoustic Waves

Further work here will be concerned with three types of pulsed waves, namely compressional, shear and Rayleigh. In 1.6 it has been described that an incident compressional wave may produce, by reflection within a solid, both compressional and shear waves. For such a condition the two waves produced may be simultaneously visualised, thus providing a suitable condition for comparison of the wave properties. There are three principal methods by which this comparison may be made, namely;

(a) Measurement of velocity of propagation
(b) Measurement of wavelength
(c) Observation of the principal stress directions associated with the wave.

3.3.1 Production of two wave modes by reflection at a boundary in quartz glass

The electrical system of 1.4.2 was used to generate 2.5 MHz compressional waves into a quartz glass testpiece. Compressional waves incident at 40° to a quartz glass/air boundary, produce by reflection, both compressional and shear waves, shown in figure 3.6. The methods of identification, described in 3.3, may be applied to these two wave types.

3.3.2 Identification by Velocity of Propagation

The principles of the system used for stroboscopic photoelasticity, described in 1.3.2.3, show that by varying the time delay between the initiation of the transmitter pulse and
a) SHEAR WAVE PROPAGATING FROM RIGHT TO LEFT.

b) SHEAR WAVE AFTER REFLECTION FROM VERTICAL FACE. PROPAGATION DIRECTION FROM LEFT TO RIGHT.

c) SHEAR WAVE REFLECTION TAKING PLACE AT 40° FACE.

FIG. 3.4. OBLIQUELY INCIDENT 4 MHz SHEAR WAVES ILLUMINATED BY THE SPARK LIGHT SOURCE.
FIG. 3.5.

(a) COMPRESSIONAL AND SHEAR WAVES GENERATED IN GLASS.

(b) ANALYSER MARKINGS

FIG. 3.5. DIRECTION OF PROPAGATION OF COMPRESSIONAL AND SHEAR WAVES IN RELATION TO THE ANALYSER MARKINGS IN THE "CROSSED" PLANE POLARISCOPE.
the triggering of the spark light source, acoustic waves may be seen to propagate in transparent media. When a calibrated variable time delay is used then the distance travelled in a measured time gives the wave velocity. Since the compressional wave and shear wave velocities in glass, and steel, are in a ratio of about $2:1$, then it should be possible to distinguish these wave types by this method. It is more difficult to identify Rayleigh waves in this way since their velocity is only slightly less than that of shear waves. Nevertheless in the later work of 4.1.3 this means of identification can be seen to be a practical one for Rayleigh waves.

3.3.3 Identification by Wavelength Measurement

It has been shown in experiments with continuous waves, how an alternating voltage waveform applied to a probe will produce a fringe pattern in the transparent medium. For each half cycle of the acoustic wave one or more bright fringes may be produced, depending on the peak amplitude. At low amplitude only one bright fringe per half cycle is produced, giving two per complete wavelength. The brightness will be lower for lower amplitudes, but two per wavelength will still be visible, providing the stress level exceeds the minimum, or "threshold" level required for visualisation.

When several pulses are visualised in the transparent medium, it may be practical by direct comparison of fringe spacings to label waves "compressional" and "shear". When single isolated pulses are to be identified then twice the fringe spacing will give the wavelength. The wavelength/frequency relationship for steel and various types of glass used in this work is shown in figure 3.1.
3.3.4 **Identification by Directions of Principal Stress**

When adjustment of the variable time delay enables transmitted waves to be viewed close to a compressional wave probe face both compressional and shear waves may be seen to be generated. This condition is illustrated in Figure 3.5(a).

When these waves are viewed in a "crossed" plane polariscope in which the filters are slowly rotated, particular polariscope settings will give maximum and minimum intensities of both wave types. The precise location of these planes has been determined experimentally as follows.

Consider the arrangement of figure 3.5(a) in which compressional and shear waves were generated by a 2½ MHz compressional wave probe. These were simultaneously viewed in a "crossed" plane polariscope. The eye was focussed onto the central region of the leading wavefront in the compressional wave. The polaroid filters were rotated in synchronism and variations in the wave intensity at this point were observed. Using the analyser with markings at 10° intervals, sub-divided to 1°, as shown in figure 3.5(b) the plane of the analyser was measured with respect to the direction of the wave, for maximum and minimum intensities of the compressional wave. The same procedure was repeated for the shear wave at a central position on its leading wavefront.

Photographs were taken using a wide angle lens fitted to the M.P.P. technical camera.
FIG. 3.6. DIVISION OF A 2½ MHz COMPRESSIONAL WAVE INTO COMPRESSIONAL AND SHEAR AFTER REFLECTION FROM AN ANGLED FACE IN QUARTZ GLASS.
For the compressional wave propagating in the vertical plane, "extinction" of the wave occurs when the analyser in the "crossed" plane polariscopoe is set with its plane of polarisation at $0^\circ$ or $+90^\circ$ to the wave propagation direction. Maximum brightness occurs with the analyser set at $+45^\circ$ to the wave propagation direction.

For the shear wave "extinction" of the wave occurs when the analyser is set at $+45^\circ$ to the wave propagation direction. Maximum brightness occurs for analyser settings at $0^\circ$ or $+90^\circ$ to the wave propagation direction.

It will be seen from figure 3.5(a) that measurements are made at the wavefront centres, since for curved wavefronts "extinction" progresses along the wave with rotation of the filters. The results here agree with the earlier described theory. Small errors might be expected in measuring the "extinction" positions since residual stresses, of a type yet to be determined, existing in the glass, might impair the accuracy of results. For the purpose of this experiment accuracy has not been impaired by any residual stresses existing.

3.3.5 Identification of "Unknown" Waves

In order to test the validity of this system on waves of "unknown" types compressional and shear waves were stroboscopically "frozen" in quartz glass as indicated by Figure 3.6(a)-(f). The process of polariscopoe rotation to produce extinction was applied to each wave in turn, in the position indicated in (e), for its identification.

Figures 3.7 and 3.8 show 6 photographs as the plane of the polariscopoe was rotated through $100^\circ$. The leading set of waves were extinguished in figure 3.8(a) and the following set mid-way between 3.7(b) and (c).
FIG. 3.7.

(a) POLARISCOPE SETTING 50° TO THE VERTICAL PLANE
(30° w.r.t. COMPRESSIONAL WAVE, 20° w.r.t. SHEAR WAVE)

(b) POLARISCOPE SETTING 70° TO THE VERTICAL PLANE
(50° w.r.t. COMPRESSIONAL WAVE, 60° w.r.t. SHEAR WAVE)

(c) POLARISCOPE SETTING 90° TO THE VERTICAL PLANE
(70° w.r.t. COMPRESSIONAL WAVE, 60° w.r.t. SHEAR WAVE)

FIG. 3.7. VARIATION OF INTENSITY OF VISUALISED
COMPRESSIONAL AND SHEAR WAVES BY ROTATION
OF A "CROSSED" PLANE POLARISCOPE, STAGE I.
FIG. 3.8. VARIATION OF THE INTENSITY OF VISUALISED COMPRESSIONAL AND SHEAR WAVES BY ROTATION OF A "CROSSED" PLANE POLARISCOPE STAGE 2.
The polariscope settings for extinction of each wave may be obtained by the constructions of figure 3.9(a) - (c). These angles with respect to the wave surfaces correspond to 90° for the leading waves and between 40° and 60° for the following waves. The leading waves were "compressional" and the following waves "shear" based on these results.

It was possible to identify the two waves from the planes of the analyser which give "extinction" of them in the optical system. The shear waves are not completely extinguished since the angle settings shown are 40° and 60°. Photographs were produced using these settings in which the shear waves are judged by eye to be of equal intensity. The position for minimum intensity lies at an analyser setting between the two selected here.

For this experiment tracings were made from a photograph in order to determine wave propagation directions. For identification of a more routine nature some device is required to enable the wave planes to be measured. A simple transparent disc having marked "cross lines" may suffice. It must be positioned after the analyser, on the axis of the polariscope and must be rotatable with respect to the analyser.

An explanation of the occurrence of maximum and minimum light intensities occurring at particular angles for given wave types may be made by reference to the vectorial analysis of light intensities, when polarised light is transmitted through stressed transparent solids. In figure 3.10 the plane of polarisation of the polariser is represented by OY. The stressed model has one plane of principal stress represented by OE' and the other by OB'. Along these axes the plane polarised incident wave is resolved. These resolved components of OX, in phase at the
FIG. 3.9.

(a) WAVE ANGLES IN QUARTZ GLASS BLOCK.

(b) POLARISCOPE SETTINGS FOR WAVE NUMBER 1.

(c) POLARISCOPE SETTINGS FOR WAVE NUMBER 2.

FIG. 3.9. POLARISCOPE SETTINGS TO PRODUCE MAXIMUM AND MINIMUM LIGHT INTENSITIES FOR "UNKNOWN" WAVES PROPAGATING IN QUARTZ GLASS.
Fig. 3.10. Vectorial presentation of the resultant light amplitudes \( N_f - N_N \) produced by a crossed plane polariscope for particular settings of the plane of polarisation \( OA \) of the analyser.
entrance side of the specimen travel with different velocities. Consequently they will arrive at the exit side with a different phase relationship. When these two components are themselves resolved along the OY axis by the analyser their relative amplitudes, ON_1 and ON_2, are equal (since \( OX \cos 20^\circ \cos 70^\circ = OX \cos 70^\circ \cos 20^\circ \)) although they may have any phase relationship depending upon the specimen characteristics.

It can be seen that should the phase relationship be correct, (\( \lambda/2, 3\lambda/2 \), etc), maximum light will be transmitted by the analyser when these components ON_1 and ON_2 are a maximum.

Since \( ON_1 = ON_2 \)

and \( ON_1 = OX \cos \theta \cos (90-\theta) \)

they can be seen to be a maximum when \( \theta = 45^\circ \). Thus when \( \theta \) increases from zero, ON_1 progressively increases to give a maximum brightness when \( \theta = 45^\circ \) and progressively decreases between \( \theta = 45^\circ \) to \( \theta = 90^\circ \); at which point the brightness is a minimum.

When a compressional wave propagates in a medium along the vertical axis, the stress direction, coinciding with the direction of particle vibration, is likewise in the vertical axis. Hence the light intensity due to a compressional wave, according to the analysis of vectors, is a maximum when the plane of the analyser is set at 45° to the wave propagation direction. Consequently extinction occurs at 0°, 90°, etc.

For shear waves the vibration direction depends upon the polarisation direction which may occur in the horizontal or vertical planes, corresponding to Sh or Sv waves. When a shear wave propagates in the vertical plane and is vertically polarised its vibration direction is transverse in the plane
of the paper. The stress axes are at 45° to this plane. The maximum light intensity will be obtained with the analyser set at 0°, in the plane of wave propagation, or at 90° to that plane. Conversely "extinction" of the light intensity occurs at analyser settings of 45° to the wave propagation direction.

3.4 Particular Ultrasonic Testing Mechanisms

A selection of experiments is described in 3.4.1 to 3.4.3, which show some of the basic principles involved in ultrasonic testing. The objective in carrying out these experiments is twofold, first to obtain a better understanding of the mechanisms involved. The second objective is to produce for the British Railways N.D.T. Training School, a series of slides and photographs which will enable instructors to demonstrate more vividly the principles of ultrasonic testing.

3.4.1 Compressional Waves Incident Normally at a Crack

When compressional waves are incident normally at a horizontal crack, the "A scope" display may record the transmitted pulse, crack reflected pulse, and testpiece generated pulse. The interactions which occur within the testpiece are shown in figure 3.11(a)-(c). The three stages of the propagation of the pulse demonstrate reflection and diffraction of the wavefronts. In (c) it is interesting to observe diffracted waves of a "higher than nominal" frequency beneath the crack tip.

3.4.2 Shear Waves reflected at a Corner

When acoustic waves are incident at a solid/gas boundary, at each reflecting surface a mode conversion may be generated.

Figures 3.12 and 3.13 show a 4 MHz shear wave generated at approximately 40°, incident obliquely at the lower horizontal surface of a crown glass specimen. Mode conversions taking place are identified and reflection at the corner demonstrated.
FIG. 3.11.

(a) INCIDENT WAVE

(b) WAVE PASSING AND REFLECTING FROM CRACK.

(c) WAVE REFLECTING, PASSING AND DIFFRACTING AROUND CRACK.

FIG. 3.11. $2^{1/2}$ MHz COMPRESSional WAVES INTERACTING WITH A HORIZONTAL CRACK, SLIGHTLY UNDEREXPOSED PHOTOGRAPHICALLY.
FIG. 3.12.

(a) Shear waves reflected within a crown glass block containing a corner.

(b) Identification of waves in (a).

c) Identification of waves in (c).

d) Identification of waves in (c).

e) Identification of waves in (e).

(f) Identification of waves in (e).

FIG. 3.12. SHEAR WAVES REFLECTED WITHIN A CROWN GLASS BLOCK CONTAINING A CORNER.
FIG. 3.13. SHEAR WAVES REFLECTED AT A CORNER IN CROWN GLASS.
3.4.3 Compressional Waves Mode Converted by Reflection

For compressional waves incident obliquely at a solid/air boundary calculations have been made in 1.6.4. Here it was shown that providing the angle of incidence exceeds 70° the reflected shear wave angle is 33°. For incidence angles less than 70° the reflected shear wave angle may be calculated. In figure 3.14, 5 MHz incident compressional waves at a plate glass/air boundary are visualised to reflect shear waves at 34°, in addition to reflected compressional waves. This measured angle is in good agreement with that calculated.
FIG. 3.14. VISUALISATION OF MODE CONVERSION OF OBLIQUELY INCIDENT 5 MHz COMPRESSIONAL WAVES AT A GLASS/AIR BOUNDARY.
4. PHOTOELASTIC APPLICATIONS II

4.1 Generation of Rayleigh Waves by Ultrasonic Probes

This chapter describes the visualisation of Rayleigh waves generated by wedge probes and shows how copper wedge probes may be applied to the measurement of crack depth in rails.

4.1.1 Rayleigh Waves produced by a Perspex Wedge Probe

The principles of 1.6.3.6 describe the mode conversions which occur when using this method. The photographs of figure 4.1 show incident and reflected compressional waves in the wedge. Refracted compressional and mode converted Rayleigh waves occur in the testpiece. Waves reflected from the lower front corner of the wedge, called "wedge waves", marked "W" in 4.1(f), propagate from left to right.

The Rayleigh waves generated have not been found suitable for the main application here. A more suitable Rayleigh wave source is described in 4.1.2.

4.1.2 Rayleigh Waves Produced by a Copper Wedge Probe

The principles involved in the generation of Rayleigh Waves, by horizontally polarised incident shear waves, have been described in 1.6.3.6. The principles described outlined the possibility of the generation of waves in addition to the required Rayleigh waves. Since probes of this type are to be used later for the purpose of crack depth sizing, it was believed that a preliminary investigation into the waves produced in a glass testpiece would prove interesting.

By application of equation 1.12, an incident shear wave angle of $53^\circ$ was calculated. Photoelastically a total of five waves were observed in the glass testpiece.

These may be identified as Compressional $C_1$, shear $S_1$, shear $S_2$.
(a) "PARENT" COMPRESSIONAL WAVES IN PERSPEX AND WAVES IN THE CROWN GLASS TEST PIECE.

(b) IDENTIFICATION OF WAVES IN (a)

(c) INCIDENT AND REFLECTED COMPRESSIONAL WAVES IN PERSPEX, MORE WAVES IN THE CROWN GLASS TESTPIECE.

(d) IDENTIFICATION OF WAVES IN (e)

(e) PROPAGATION OF "PARENT" WAVES IN PERSPEX AND WAVES IN THE TESTPIECE

(f) IDENTIFICATION OF WAVES IN (e)

MAGN x 1/2

FIG. 4.1. 2 1/2 MHz RAYLEIGH WAVE PERSPEX WEDGE TRANSUCER, TRANSMITTING WAVES INTO A CROWN GLASS TESTPIECE.
FIG. 4.2.

(a) THREE DISCERNABLE WAVES IN THE TESTPIECE, AT A SHORT TIME DELAY.

(b) IDENTIFICATION OF WAVES IN (a)

(c) INDICATIONS OF FIVE WAVE TYPES IN THE GLASS TESTPIECE

Magn x $\frac{1}{2}$

(d) IDENTIFICATION OF WAVES IN (c)

FIG. 4.2. 4 MHz RAYLEIGH WAVE COPPER WEDGE TRANSDUCER.
and Rayleigh R. The fifth has been called a wedge reflection wave "W", being generated by reflection from the front face of the copper wedge in a direction left to right in the figure. Since more waves than might be expected are generated by this probe, closer examination by further experiments seemed justified. The propagation of these waves is shown in greater detail in figures 4.3 and 4.4. In 4.3(a) waves C₁, S₁, S₂, can be identified. As the time delay is increased the existence of the Rayleigh wave is clearly shown. In 4.4(a) the 10% difference in shear and Rayleigh wave velocities is evident as "S₂" and "R" separate. When the waves meet a boundary, figure 4.4(b), mode conversions occur. The Rayleigh wave reflects and propagates around it, compressional and shear waves are produced by the interaction.

The generation of four principal waves may be explained by considering the "parent" waves propagating in the wedge to be of two types. The shear wave piezoelectric plate generates both compressional and shear waves. The compressional component produces in the testpiece two waves, a compressional wave by refraction and a shear wave by mode conversion. In addition the shear wave in the wedge produces two waves, a shear wave by refraction and a Rayleigh wave by mode conversion. Calculations by means of the refraction law confirm the angles of propagation of the generated waves. Figure 4.5 indicates the waves which may be generated based on the acoustic wave velocities.

4.1.3 Crack Depth Measurement in Rails by Rayleigh Waves

4.1.3.1 Introduction

The requirement to monitor the progression of cracks in rail
FIG. 4.3, PHOTOLELASTIC VISUALISATION OF WAVES GENERATED BY A COPPER WEDGE "RAYLEIGH WAVE" PROBE INTO A GLASS TEST PIECE.
FIG. 4.4. REFLECTION AND MODE CONVERSION PROCESSES AT A VERTICAL BOUNDARY.
(a) VELOCITIES OF ACOUSTIC WAVES IN RAIL STEEL AND PLATE GLASS.

<table>
<thead>
<tr>
<th>MEDIUM</th>
<th>VELOCITY m/sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>COMPRESSATIONAL</td>
<td>SHEAR</td>
</tr>
<tr>
<td>RAIL STEEL</td>
<td>5800</td>
</tr>
<tr>
<td>PLATE GLASS</td>
<td>5900</td>
</tr>
</tbody>
</table>

(b) COMPRESSIONAL AND SHEAR WAVES INCIDENT AT $53^\circ$ IN A COPPER WEDGE.

FIG. 4.5. WAVES GENERATED AT A COPPER/STEEL BOUNDARY.
heads during fatigue has led to the development of the new technique employing Rayleigh waves. The principle of using the propagation time of waves which confine themselves to the surface of a testpiece was first tried here by R. Porter some five years ago. In those early experiments ultrasonic probes were used which rely on the perspex wedge principle. Another colleague C.R. Theumer began experiments with alternative wedge materials. Both copper and lead were tried. Unfortunately this work was not recorded, but it is believed that attenuation problems prohibited the use of lead for this purpose. A further series of experiments on notched rail heads during fatigue has been carried out by P. Johnson and D. Cook as recorded by internal memorandum IMPHYS/NDT 7226 May 1972. Here the copper wedge probe was introduced for practical measurements. For the experimental condition of a separate transmitter and receiver, only one received signal associated with the Rayleigh wave, was anticipated. For uncracked testpieces this was the case, but when a crack was introduced between the probes three received signals resulted. It was not possible at this stage to explain their origin and investigations using photoelastic visualisation seemed justifiable. Experiments which examined the transmitted waves and their interactions with notched glass testpieces were conducted.

4.1.3.2 Principle of Crack Depth Measurement
The determination of crack depth by surface waves relies upon the accurate measurement of propagation times of these waves between two ultrasonic probes. When two copper wedge Rayleigh wave probes are positioned at a fixed distance apart as in figure 4.6, expressions for a
FIG. 4.6. COPPER WEDGE PROBES GENERATING RAYLEIGH WAVES IN TESTPIECES.
pulse to travel from one piezoelectric plate to the other may be derived as follows:

Let \( C_R \) equal the velocity of Rayleigh waves in steel and \( C_S \) shear waves in copper. The total distance travelled in the two copper wedges is \( A \) and the separation of the probe index points is \( d \).

The time taken for Rayleigh wave propagation in the uncracked testpiece is \( d/C_R \). Hence an expression for the time taken for a Rayleigh wave to reach the receiving probe is:

\[
t_{\text{uncracked}} = A/C_S + d/C_R \tag{4.1}
\]

Should a vertical crack of depth \( b \) occur between the two probes, as in figure 4.6(b) then the total time taken would be:

\[
t_{\text{cracked}} = A/C_S + d/C_R + 2b/C_R \tag{4.2}
\]

The difference between the "cracked" and "uncracked" specimens wave propagation times is:

\[
t_{\text{cracked}} - t_{\text{uncracked}} = 2b/C_R \tag{4.3}
\]

It is this time difference, proportional to crack depth, which was used in these measurements. For this purpose a calibrated ultrasonic flaw detector may be used. Sketches of the unrectified "A scope" signals produced on the screen are shown for two specimens in figure 4.7(a) and (b). In (a) the specimen was uncracked and in (b) a surface-breaking vertically oriented crack was situated between the probes. The trace in (b) corresponded to a small crack, \( \leq 1 \text{mm} \). The leading edge of the pulse determined its time occurrence. Experiments described in 4.3.4 show how this simple trace pattern became more complicated as other wave types, generated by the probe,
FIG. 4.7. A SIMPLIFIED DISPLAY OF THE UNRECTIFIED SIGNALS PRODUCED BY SURFACE WAVES IN THE CRACK DEPTH MEASUREMENT RIG.
interact with larger vertical cracks.

4.1.3.3 Metal Wedge Transducers

The use of a metal wedge is reported by Viktorov to have several advantages when compared with plastic wedges.\(^{(26)}\)

These may be listed as follows:

(a) Simpler fabrication
(b) Reduced wear when in contact with the testpiece
(c) Improved acoustic impedance matching between the piezoelectric plate and the wedge and between the wedge and the steel testpiece as indicated in the following table.

<table>
<thead>
<tr>
<th>Medium</th>
<th>Shear Wave Vel, m/s.</th>
<th>Compressional Wave Vel, m/s.</th>
<th>Density, Kg/m(^3)</th>
<th>Acoustic Impedance, Kgm/m(^2)s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barium Titanate</td>
<td>6 050</td>
<td>5.77 \times 10(^3)</td>
<td>35 \times 10(^6)</td>
<td></td>
</tr>
<tr>
<td>Perspex</td>
<td>1 430</td>
<td>2 730</td>
<td>1.18 \times 10(^3)</td>
<td>1.7 \times 10(^6)</td>
</tr>
<tr>
<td>Copper</td>
<td>2 260</td>
<td>4 700</td>
<td>8.9 \times 10(^3)</td>
<td>20 \times 10(^6)</td>
</tr>
<tr>
<td>Steel</td>
<td>3 230</td>
<td>5 900</td>
<td>7.7 \times 10(^3)</td>
<td>22 \times 10(^6)</td>
</tr>
</tbody>
</table>

When two media in contact have similar acoustic impedances then efficient transmission of an acoustic wave may take place across the boundary. When the difference in the acoustic impedances is increased, reflection at the boundary increases and transmission through it is lowered. It can be seen from the table that the acoustic impedances of the piezoelectric plate, the copper wedge and the steel testpiece are all comparable, whereas those of perspex and plastic materials generally are much lower. Consequently
the efficiency of acoustic wave transmission is high for copper wedges coupled to steel testpieces and low for perspex wedges used for the same purpose.

One principal disadvantage of a metal wedge is its low attenuation of ultrasonic waves. This may result in an excessive transmitted pulse duration, caused by multiple reflections within the wedge. This restricts the use of these transducers to separate "transmitter" and "receiver" operation. Plastic wedges with their high attenuation may be used to advantage here since they allow "transceiver" mode working.

The refraction and mode conversion processes which have been briefly described in 4.1,3 depend upon the appropriate values of the acoustic wave velocities. One interesting effect which will be seen later is the modification of the fundamental piezoelectric plate frequency by the media with which its faces are in contact. Krautkramer describes this effect as follows. "When a piezoelectric plate is located between two media which are both of lower acoustic impedance, or both of higher acoustic impedance than the piezoelectric plate, then it vibrates as a $\lambda/2$ resonator. Should one of the media be sonically softer and the other sonically harder than the plate, then it will oscillate only at $\lambda/4$ resonance. The characteristic frequency of the plate clamped in this way is one half that of the standard $\lambda/2$ resonator."

The Rayleigh wave probes used in this work were cemented to a copper wedge, the rear face was in contact with air. Consequently the waves transmitted into the testpiece were
theoretically, only one half of the fundamental piezoelectric free plate frequency of 4 MHz.

The sensitivity of the crack depth measurement is lowered by this frequency reduction. Rayleigh waves of frequency 2 MHz propagate in steel at a wavelength of 1.5 mm. In order to reduce the wavelength and so increase the sensitivity, piezoelectric plates might be used of higher fundamental frequency. Alternatively some form of rear face damping could be tried, in line with Krautkramer's criterion. Experimentation of this type will not be considered further here in this work.

4.1.3.3 Crack Depths in Notched Rail Heads during Fatigue

The testpieces of particular interest here were pieces of rail head material manufactured to B.S. Specification No. 11. In order to induce crack propagation at a particular location a small notch of depth 1 mm was machined in the rail head upper surface as indicated in figure 4.8(a). The notch width was such as to prevent transmitted Rayleigh waves from passing around the notch sides. Any waves reaching the receiver passed beneath the notch.

The rail head was inserted in an Amsler 2 fatigue machine and loaded at three points as indicated in figure 4.8(b). Rayleigh wave copper wedge probes were clamped to the rail surface at a distance of 20 mm on each side of the notch, coupled by grease at the copper/steel boundary.

In order to measure the propagation time of the Rayleigh waves, an ultrasonic set with a time calibrated "X" axis
FIG. 4.8. CRACK DEPTH MEASUREMENT ON A LOADED RAIL HEAD BY SURFACE WAVES.
was first used. An alternative arrangement used later transferred the "A scope" display to a Tektronix Type 547 oscilloscope. In these experiments a Lehfeldt MPT 10 flaw detector was operated in the separate transmit and receive mode and the display was monitored on the Tektronix Oscilloscope. The time base was first adjusted to view the overall trace pattern consisting of transmitted and received waves. By use of the time base expansion and adjustment of the variable time delay on the oscilloscope a more detailed examination of the received signals was made.

The application of an alternating stress to the specimens, ultimately induced cracks to propagate vertically downwards from the base of the notch. The received pulses were monitored as the cracks propagated. When a measurement of the depth beneath the surface was made, a dynamic or static load was applied to "open" the crack. A dynamic outer fibre bending stress, $\sigma = 200 \text{MN/m}^2$, or alternatively a static stress $= \sigma / 2$ was typical.

4.1.3.4 Analysis of Preliminary Results

The general display of transmitted and received signals is given in figure 4.9(a) and the received signal on an expanded time base in figure 4.9(b), both displays were produced on an un-notched testpiece. A comparison on the same time base for the received signals, obtained on un-notched and notched testpieces, is shown in figure 4.10(a) and (b) respectively.

The occurrence of three distinct received signals for notches of the order of 5 mm and above gave cause for concern. The last signal to occur was assumed to be due to the Rayleigh wave and was used for early crack depth
FIG. 4.9. “A SCOPE” UNRECTIFIED SIGNALS FOR COPPER WEDGE PROBES ON "SOUND" AND NOTCHED SPECIMENS.

(a) GENERAL DISPLAY OF TRANSMITTED AND RECEIVED SIGNALS

(b) SURFACE (RAYLEIGH) WAVE SIGNAL ON EXPANDED TIME BASE
(a) RAIL HEAD WITHOUT DEFECT, RAYLEIGH WAVE SIGNAL.

(b) RAIL HEAD WITH 5.6 mm NOTCH, TIME BASE AND DELAY AS IN (a).

FIG. 4.10. RECEIVED UNRECTIFIED 'SCOPE SIGNALS SHOWING THE EFFECT OF INSERTING A NOTCH BETWEEN THE TWO PROBES.
propagation experiments. Crack depths of 9 mm were required. The third signal was selected for crack depth measurement. When rail heads were subsequently broken, figure 4.11, results confirmed that the Rayleigh wave was the source of this signal. Further experiments were believed justified to explain more fully the received signal information.

4.1.3.5 Acoustic Wave Interactions with Artificial Cracks

Acoustic wave interactions have been divided into two parts. The first used notched steel testpieces to determine the notch depths at which increased duration of received signals occurred. The second examined the interaction of the generated waves within notched glass testpieces, to explain the origin of the triple signal "A scope" display.

4.1.3.5.1 Steel Testpieces with Small Notches

The depth of notches in rail heads included the following depths; 1 mm, 1.5 mm, 2.5 mm, 5.5 mm, 10 mm and 20 mm. The time base calibration of the oscilloscope corresponded to 1 cm for 1 mm of notch depth for the small notches and 1 cm for 2.5 mm of notch depth for large notches.

The received surface wave signal for the "no notch" and 1 mm notch condition is recorded in figure 4.12. Larger notch sizes of 1.5 mm and 2.5 mm affect the received signals as shown in figure 4.13. When the notch size reaches 5.5 mm the "triple" signals of figure 4.14(a) are produced. These are identified in 4.14(b).

The smallest notch used, 1 mm in depth, produces a change in the received signal shape and amplitude, figure 4.12(b). However the signal remains a single
FIG. 4.11. CROSS-SECTIONAL VIEWS OF RAIL HEADS SHOWING FATIGUE CRACKS.
FIG. 4.12. COMPARISON OF RECEIVED UNRECTIFIED "A SCOPE" SIGNALS FOR NOTCHED AND UN-NOTCHED RAIL HEADS.
FIG. 4.13. THE EFFECT OF INCREASING THE NOTCH SIZE
FOR SMALL NOTCHES ON THE RECEIVED UNRECTIFIED
"A SCOPE SIGNALS.

(a) 1.5 mm. NOTCH

(b) 2.5 mm. NOTCH
FIG. 4.14. TRIPLE SIGNAL "A SCOPE" DISPLAY PRODUCED BY THE TWIN COPPER WEDGE PROBE SYSTEM WHEN EXAMINING A 5.6 mm. DEPTH NOTCH.
continuous signal. The large negative-going trough has noticeably moved to the left, indicating that this signal is generated by a wave of higher velocity than the Rayleigh wave. Later work shows that this trough is generated by a shear wave. When the notch depth was increased to 1.5 mm, figure 4.13(a), the duration of the signal increases, but for a 2.5 mm crack separation into two separate signals were apparent, figure 4.13(b). Using a 5.5 mm depth notch positioned between the two wedge probes three separate received signals were formed.

Before proceeding with a programme of experiments with larger notches it was necessary to identify the causes of the "triple signal" display. Photoelastic visualisation was used for this purpose.

4.1.3.5.2 Notched Glass Testpieces

Notches were machined in rectangular plate glass specimens using a diamond saw. Adequate cooling liquid and a slow cutting rate were used to minimise thermal stresses which may be induced around the entrance and base of the notch. Three glass blocks with notches ranging in depth from 6 mm to 32 mm were examined in the photoelastic rig. One copper wedge probe was positioned with probe index point at 20 mm from the notch. With selected time delay settings the propagation of the four principal generated waves was examined. The effect of varying the notch depth on the interactions seen photoelastically was photographed. These are to be used later as a
basis for explanations of the "A scope" displays.

The interaction of waves with a 6 mm notch in glass is shown in figures 4.15 and 4.16. For notch depths increased to 16 mm and 32 mm, selected observed effects are recorded in figure 4.17.

In this discussion waves produced by reflection processes will be indicated by a "dash", as in $C_2'S$ meaning that the wave is compressional in nature and is generated by an incident shear wave.

The waves launched into the testpiece figure 4.15(a) are the same as those seen earlier in figure 4.3(a). In figure 4.15(c) the tip of the compressional wave $C_1$ strikes the crack producing two waves $C_2$ and $S_3$. In (e) these are seen to propagate further into the testpiece, whilst $S_1$ passes the notch tip. The second launched shear wave, $S_2$ and the Rayleigh wave, $R$, are seen here approaching the notch corner. "Wedge Waves" are seen to disperse spherically in a rearward direction.

With increased time delays further wave propagations are examined in figure 4.16(a) - (f). In (a), $S_2$ reflects at the notch corner generating a compressional wave $C'S_2$ and a shear wave $S_2'$.

In (e) $S_2$ has passed the notch and the Rayleigh wave has interacted within the notch corner to generate both compressional and shear waves in the manner previously described.
FIG. 4.15.

(a) WAVES LAUNCHED INTO NOTCHED GLASS BLOCK.

(b) IDENTIFICATION OF WAVES IN (a)

(c) INTERACTION OF C₁ WITH NOTCH

(d) IDENTIFICATION OF WAVES IN (c)

(e) PROPAGATION OF SPHERICAL WAVES, C₂, S₃

(f) IDENTIFICATION OF WAVES IN (e)

FIG. 4.15. EARLY STAGES OF THE INTERACTIONS BETWEEN ACOUSTIC WAVES AND A 6 mm. DEPTH NOTCH IN PLATE GLASS.
FIG. 4.16.

(a) REFLECTION OF $S_2$, STAGE 1.

(b) IDENTIFICATION OF WAVES IN (a)

(c) REFLECTION OF $S_2$, STAGE 2

(d) IDENTIFICATION OF WAVES IN (c)

(e) WAVES GENERATED BY REFLECTIONS AT THE NOTCH/UPPER SURFACE CORNER, AND THE NOTCH TIP

(f) IDENTIFICATION OF WAVES IN (e)

FIG. 4.16. LATER STAGES OF THE INTERACTIONS BETWEEN ACOUSTIC WAVES AND A 6 mm DEPTH NOTCH IN PLATE GLASS.
Figure 4.17(a) - (d) includes three selected interactions of particular interest, produced at notches of greater depth. In (a) the reflection of $C_1$ at the notch produces both compressional and shear waves which when diffracting around the base of the notch produce spherical waves. Eventually these can reach the upper surface of the block on the left hand side of the notch. In (c) a similar effect is shown on a larger notch at an earlier stage. Waves diffracting around the base of the notch in this case will reach the glass block upper surface at a point to the left of those in (a). In (e) the transformation of Rayleigh wave energy into a shear wave is illustrated. When the Rayleigh wave travels in a downwards direction to reach the bottom of the notch, part of its energy is converted into a shear wave, $S_R$. Some is reflected upwards along the right hand side of the notch, whilst the remainder travels around the notch tip and then upwards on the left hand side. The Rayleigh waves are not distinguishable in (e), but are when viewed in motion, by eye. The relative positions of the shear and Rayleigh waves are shown in (f).

Should a receiving probe be placed on the left hand side of the notch, "A Scope" signals may be produced by spherical waves of the type $S_2$ and $S_1$, in addition to the Rayleigh wave whose path is restricted to the surface of the notch or crack.
FIG. 4.17. SELECTED ACOUSTIC WAVE INTERACTIONS WITH LARGER NOTCHES IN PLATE GLASS.
The waves responsible for the multiple "A Scope" signals may be indicated by reference to figures 4.17(b) and 4.18. The latter is based on the observed interactions shown by the visualisation experiments and a knowledge of the wave velocities. Selected simplified sketches of visualisation observations are used in figure 4.18(a) - (d) and propagation paths, 4.18(e), to verify the causes of the first and third signals. The first signal is judged to originate from the transmitted shear wave \( S_2 \) which on reaching the notch partially reflects and partially diffracts around it. The diffracted part of the wave \( S_2 \) eventually reaches the receiving probe \( R_\chi \). The Rayleigh wave, "R" shown in (a), first travels along the horizontal surface and after interaction at the notch corner travels vertically downwards to generate a shear wave \( S_R \) at the notch tip. Part of the Rayleigh wave travels around the tip of the notch, but \( S_R \) travelling at approximately 10% greater velocity arrives next at the receiver \( R_\chi \). This gives the second received signal. The Rayleigh wave arrives later to give the third signal. The propagation times of the shear wave \( S_2 \) and Rayleigh wave \( R \) may be calculated from the wave velocities, and path lengths of the waves. This treatment using simplified wave trajectories gives a difference in propagation times of approximately 5 micro-seconds. The Rayleigh wave takes 19 microseconds approximately and the shear wave 14 microseconds. The propagation time of the \( S_R \) wave will be intermediate between that of the shear and Rayleigh, since for the first part of its journey it
FIG. 4.18.

(a) 1st TIME DELAY SETTING

(b) 2nd TIME DELAY SETTING

(c) 3rd TIME DELAY SETTING

(d) 4th TIME DELAY SETTING

(e) PROPAGATION PATHS OF 'R' AND 'S_2' WAVES

FIG. 4.18. MECHANISMS INVOLVED IN THE PRODUCTION OF A TRIPLE SIGNAL "A SCOPE DISPLAY OF FIGURE 4.10."
is a Rayleigh wave and for the second part it is a shear wave. The Rayleigh wave propagation time may later be compared with the general "A Scope" display of the transmitter and Rayleigh wave signals.

The Rayleigh waves in figure 4.18(d) will also produce by interaction at the notch/upper surface corners wave types 'C', 'S' and reflected 'R'. These have been omitted for simplicity since they do not affect the display over the time range considered.

4.1.3.5.1 Steel Testpieces with Large Notches

When larger notches in rail steel were used the information received was displayed in figures 4.19 and 4.20 (a) and (b). The time delay of the Rayleigh wave can be seen to be proportional to the depth of the notch.

The triple signals of figure 4.19(a) due to a 5 mm notch, are present for a notch length of 10 mm. When a 20 mm notch is used, attenuation of the Shear \( S_2 \) and Shear/Rayleigh \( S_R \) wave generated signals occur. The first of these is almost lost in the noise level but the Rayleigh wave signal remains clearly defined. Its frequency is approximately 2 MHz, half that of the nominal piezoelectric free plate frequency. As suggested in 4.1.3.3, this frequency reduction may be due to the different media, copper and air in contact with the plate, resulting in resonance at 2 MHz.
FIG. 4.19. "A SCOPE DISPLAY OF SIGNALS DUE TO A 5.6 mm NOTCH IN STEEL."
FIG. 4.20

(a) 10 mm NOTCH

(b) 20 mm NOTCH

FIG. 4.20 "A SCOPE DISPLAYS FOR LARGER NOTCHES"
4.1.3.6 Further Experiments to improve the Testing Method

In the earlier crack propagation work, certain fixed positions of the probes with respect to the notch and crack were determined. Using these probe positions, the "A Scope" display, though complex, enabled crack depths to be measured. Should the position of a transmitting probe be fixed and the receiver varied, as in figure 4.21(a), the "A Scope" display will differ from the fixed probe arrangement. The receiving probe, by moving relative to the notch, will view the acoustic waves from a different aspect. Consequently the three principal acoustic waves, shown earlier to be responsible for the three received pulses, will differ in their propagation times. Additionally, the amplitude of the signals might be expected to differ as the probe is scanned along the surface of the testpiece, searching out variations in acoustic wave intensity. By changing the probe locations, variations in "A Scope" signal amplitudes may be investigated in the search for an improved testing method.

If consideration is given to the arrangements of figure 4.21 (a) - (c), calculations of the propagation times of the waves "S₂", "Sₚ" and "R" may be made for the receiver positions indicated. These calculated times may be displayed graphically, as in (d) for selected positions of the receiver. The propagation time can be seen to increase linearly with probe movement for the Rayleigh wave R. For the shear wave S, and to a lesser degree the Shear/Rayleigh wave Sₚ, linearity is only achieved for receiver positions greater than Rₓ₂.
FIG. 4.21: THE VARIATION IN PROPAGATION TIMES OF THE THREE PRINCIPAL WAVES FOR PARTICULAR "RECEIVER" POSITIONS, USING A 10 mm DEPTH NOTCH.

(a) PATHS OF $S_2$ WAVE

(b) PATHS OF $S_n$ WAVE

(c) PATHS OF $R$ WAVE

(d) GRAPHICAL DISPLAY OF PROPAGATION TIMES
A series of practical experiments will now be described in which variations in probe positions will be seen to influence the time occurrence and amplitude of the received signal information.

4.1.3.6.1 Effect of Probe Spacing on Received "A Scope" Information

Using rail steel testpieces with various notch sizes, copper wedge probes were mounted at selected positions with respect to the notches. The "A Scope" display of received information was then recorded as the receiving probe position was varied and the transmitting probe remained fixed. The effect of a minimum probe spacing was later investigated using a range of notch sizes.

For a notch depth of 5.6 mm the probe arrangements and displays of received information are shown in figures 4.22 and 4.23.

For minimum probe separations figure 4.24 displays "A Scope" signals for notches ranging in depth from 5.6 mm to 20 mm.

With reference to figure 4.22 the "A Scope" signals shown in (b) are those which are now expected for experimental conditions of (a). As the receiver is moved nearer the notch the time occurrence of all received signals is reduced, as was predicted by the graphical display of figure 4.21(d). When the receiver is 10 mm distance from the notch, the time occurrence of all signals is reduced but a change in shape of the $S_R$ signal is
FIG. 4.22. EFFECT OF PROBE/NOTCH SEPARATION ON THE RECEIVED "SCOPE" SIGNALS FOR A 5.6 mm DEPTH NOTCH, LARGE SEPARATIONS.
FIG. 4.23. EFFECT OF PROBE/NOTCH SEPARATION ON THE RECEIVED "A SCOPE SIGNALS FOR A 5.6 mm. DEPTH NOTCH, (SMALL SEPARATIONS)
FIG. 4.24. RECEIVED "A" SCOPE SIGNALS WITH MINIMUM PROBE SEPARATION FOR A RANGE OF NOTCH DEPTHS.
apparent. This may result from two shear waves being produced by the Rayleigh wave interaction with the notch base. The generation of the first of these shear waves $S_R$ has been described in 4.1.3.5.2 and figure 4.17(e). As the Rayleigh wave travels around the notch base a second shear wave which may be called $S_{R2}$ could be produced at the point "Z" in figure 4.22(e). The time difference between these two shear waves would be sufficient to produce the change in shape of the $S_R$ wave signal. The receiver in the positions shown in figure 4.23(a) and (c) is better placed to detect the changes in shape of the $S_R$ wave. No credence may be given to the wave amplitudes since the coupling efficiency of the acoustic waves may produce considerable variations. However in these experiments attempts were made to optimise the displayed signals at each stage.

Experiments to investigate the effects of minimum probe separation have produced results of practical significance in future crack propagation work.

Conditions of minimum probe separation are for these experiments dependent upon the notch width, in this case 2 mm, but also upon the requirement to avoid direct acoustic coupling between the probes. In figure 4.24 the triple signal display is again evident for the small notch, as seen in (a). When the notch depth is increased to 10 mm, the $S_R$ wave reduces in amplitude but the $S_2$ wave merges with the signal noise level, leaving only two received signals. For a notch depth of 20 mm, the
depth of 20 mm, the $S_R$ wave has merged with the noise signal, leaving only the Rayleigh wave. These conditions of minimum probe separation may be worthy of further investigation in any future crack propagation work. Two points of particular interest to crack propagation monitoring emerge from figure 4.24. These are:

(a) the number of received signals decreases as the notch, or crack, increases in depth, probe separation being constant.

(b) when notch or crack depths are of the order of 20 mm then a single received signal, generated by the Rayleigh wave may be displayed, thus simplifying the signal interpretation and monitoring procedure.

The received signals resulting from these notches and the observations made, should be applicable to cracks of similar depths, since the early observations of the triple signal "A Scope" display was made on cracked testpieces. The only minor difference in the display may occur at particular probe spacings when the duration of the $S_R$ wave is increased for certain conditions. When cracks of comparable depth are similarly measured, the $S_R$ wave should not expand in time, since the base of a fatigue crack is considerably less than a notch and will not generate a second $S_R$ wave.

4.1.4 Conclusions of Crack Depth Measurements

1. A shear wave piezoelectric device mounted in a copper wedge may be used to generate Rayleigh waves in steel or glass testpieces. In addition three other waves may appear in the testpiece. Compressional and shear waves originate from a "parent"
compressional wave in the wedge. Shear and Rayleigh waves originate from a "parent" shear wave. These waves can be identified by a photoelastic visualisation system.

2. The depth of surface-breaking cracks may be measured or monitored by using two copper wedge Rayleigh wave probes, one operating as a transmitter and the other as a receiver. The time taken for a Rayleigh wave to travel between the probes may be used to indicate the depth of the crack.

3. It is essential that a static or dynamic stress is applied to "open" a fatigue crack before a crack depth measurement is made.

4. The crack length should exceed the surface wave beam width to ensure the surface wave propagates beneath the crack rather than around its sides.

5. Good correlation between measured and actual crack depths has been achieved for cracks ranging in depth from 2.5 mm to 9 mm, for cracks having a single origin of fracture.

6. A minimum crack depth detectable is theoretically of the order of one wavelength. Cracks less than one wavelength, i.e. 1.5 mm at 2 MHz, may be reliably detected using this method. A crack depth of two wavelengths seems the minimum which may be measured in practice.

Maximum crack depths which might be measured will be limited by the attenuation of the Rayleigh waves in the medium of the testpiece. Work currently underway suggests that measurement of crack depths to 25 mm is possible in rail steel. This value may not be the upper limit.
7. The display of received "A Scope" information varies considerably with the spacing of the probes. It is particularly dependent on probe spacing for the larger crack depths measured here.

8. The technique of using the minimum practical probe spacing will in some experiments have advantages in signal interpretation. It is suggested that in future work this technique could be used to advantage.

4.2 Residual Stress Measurement in Rails by Normal Incidence Shear Waves

4.2.1 Introduction
This work relies upon the birefringence of certain transparent materials in order that the acoustic stress waves may be visualised. A technique exists which relies upon the stress birefringence of metals to calculate the residual stresses existing within them. This technique is currently being investigated in this laboratory with respect to rail steels. The general principle has however already been comprehensively reported\(^{(31)}\), and is frequently described as the "sing around" method for residual stress measurement.

The residual stresses which may exist within long lengths of welded rail can cause the rails to buckle, hence a derailment could occur. Should a technique be available which would measure the residual stresses of welded rail "in situ", then some re-assurance of the rail condition would be available.

4.2.2 Principles
The technique to be used here briefly comprises the measurement
of velocity of shear waves, chosen due to their vibration
directionality, in the rail web in two mutually perpendicular
directions. In a simplified stress distribution, these are
along the rail length, in the plane of the tensile or
compressive stress, and perpendicular to that plane. In
practice an ultrasonic shear wave transducer is connected
onto the rail web, with suitable couplant and applied pressure
\( \frac{l}{U^*} \)
to transmit shear waves into the rail steel in a manner similar
to that shown in figure 4.25. The shear wave is allowed to
"reverberate" several times within the web. The resulting
echoes are, for experimental purposes only, displayed on an
oscilloscope screen. The \( n \)th echo is selected to re-trigger
the transmitter, previous echoes are "gated out". The rate at
which the transmitter is re-triggered depends upon the time
taken for the \( n \)th signal to reappear. The re-triggering rate
may be measured in terms of a frequency, commonly referred to
as a "sing around" frequency, \( f_{sa} \), since it is proportional
to the transition time of the acoustic waves in the specimen.

Having determined this frequency in the plane parallel to the
residual stress the transducer may now be re-positioned in a
plane perpendicular to the stress. Subsequently a corresponding
frequency for this plane is recorded. Calibration of the system
in terms of the rate of frequency change, \( \frac{df_{sa}}{dt} \), with stress,
similar to the graph of figure 4.26 is required to verify the
system linearity and reproducibility.

One problem experienced in this laboratory is the purchase of a
satisfactory shear wave transducer. One typical criticism of
some commercially available transducers is their production of
significant compressional waves in addition to the required
FIG. 4.25.

(a) SHEAR WAVE TRANSDUCER COUPLED TO GLASS TESTPIECE.

(b) "A SCAN" DISPLAY OF REFLECTIONS OBTAINED CONDITIONS AS IN (a)

FIG. 4.25. "A SCOPE" DISPLAY OF THE REFLECTIONS PRODUCED WITHIN A 25 mm. THICK CROWN GLASS TESTPIECE FOR A NORMAL INCIDENCE SHEAR WAVE TRANSDUCER.
FIG. 4.26. STRESS/FREQUENCY RELATIONSHIP FOR SHEAR WAVE POLARISATION BOTH PARALLEL AND PERPENDICULAR TO THE PLANE OF THE APPLIED STRESS, FOR RAIL WEB SPECIMENS.

\[ \frac{d\sigma}{dF} = 7.2 \times 10^6 \text{N/m}^2/\text{Hz} \]

\[ \frac{d\sigma}{dF} = 3.44 \times 10^6 \text{N/m}^2/\text{Hz} \]
shear wave. In some transducers a front face wear plate is fitted which causes reverberations to occur within it. These reverberations may produce interference effects seen in the "A Scope" display. The seriousness of this effect in some cases has been seen to be dependent upon the $n^{th}$ signal selected. It may be more serious for example when the 8th reflection is used and less serious when the 3rd is used. This interference, in the form of an alternating wave of low amplitude, precedes the main R.F. reflection causing early triggering of the electronic gate.

4.2.3 Normal Incidence Shear Waves viewed in the Plane Polariscope

Since shear waves are of interest here the analyser settings of the plane polariscope coincided with the plane of propagation of the centre of the shear waves. The waves transmitted by certain commercial shear wave transducers were examined.

Figure 4.27 shows the visualised waves transmitted by two shear wave transducers of frequency 1.5 MHz and 4 MHz. Coupling to the glass testpiece was by "aroclor" liquid and an applied load. The 4 MHz transducer, manufactured by Baugh & Weedon by request, is again shown in figures 4.28(a) - (d). The probe to testpiece coupling is similarly achieved. This experiment shows the effect of driving the transducer at a higher transmitter pulse energy level. Pulse reflections within the crown glass block are also demonstrated.

When the probe shown in figure 4.27(a) was used by colleagues within this laboratory for experiments on the "sing around" equipment some practical difficulties were experienced.
FIG. 4.27. SELECTION OF A TRANSDUCER FOR THE "SING AROUND" RESIDUAL STRESS MEASURING TECHNIQUE.

(a) MECCASONICS 1/2 MHz PROBE (U.S.E. 1. PULSE ENERGY 3.)

(b) WAVE IDENTIFICATION OF (a.)

(c) BAUGH AND WEEDON 4 MHz PROBE (U.S.E. PULSE ENERGY 1.)

(d) WAVE IDENTIFICATION OF (c.)

MAGNIFICATION x1
FIG. 4.28. "SING AROUND" SHEAR WAVE TRANSDUCER TRANSMITTING WAVES INTO A CROWN GLASS TESTPIECE, USING AROCLOR COUPLING LIQUID AND AN APPLIED LOAD.
Visualisation of the waves transmitted showed additional waves leading the main shear waves. These are believed to be shear waves originating from the transducer edges. This may have caused the triggering problems experienced. Experiments with the Baugh and Weedon transducer shows the effect of two particular pulse voltage levels derived from the Krautkramer U.S.E.1 transmitter. Figure 4.27(c) shows, at pulse energy "1", clearly resolved shear waves only leaving the transducer face. When the pulse voltage is increased to position "3", figure 4.28(a), merging of the shear wave half cycles occurs but also additional waves preceding the shear are produced. Propagation of these waves within the thickness of this crown glass block shows more clearly that other waves are generated. Of these one is identified as shear and the other as compressional, due to their velocity difference. These are shown in figure 4.28(d).

It is appreciated that the number of waves seen and the energy contained by them will critically depend upon the transmitter waveform. When comparing the two commercial transducers it is evident that a strong shear wave is produced by the Baugh and Weedon type at pulse energy "1", without producing unwanted waves. When using this transducer in the "sing around" equipment more consistent and interference-free results were produced. It should be pointed out that this may be due in part to the "machining away" of an araldite front wear plate leaving the rectangular piezoelectric element almost exposed. This resulted in the elimination of wearplate reverberations. This transducer is certainly the most suitable of all those tried for stress measurement by the "sing around" process.
4.3 Examination of Rail Ends by Ultrasonic Waves

4.3.1 Compressional Waves Normally Incident

In practice the use of normal incidence compressional waves at the rail end is restricted to the search for horizontal defects. Angled defects are detected by oblique incidence shear waves. There are however a number of interesting effects, which will take place in practice, as the normal incidence probe scans the region of the bolt hole.

Experiments will now be described in which interactions occur between compressional waves and a glass model of the rail-end.

A glass model was selected for this experiment which has large machined slots at 45° to the vertical axis. The 5 MHz compressional wave probe was grease coupled to the glass model at a position to give a maximum rectified signal from the upper surface of the number one hole. Probe excitation was derived from the U.S.E.1 and an auto transformer. Observations of particular interest were photographed.

The incident and reflected waves are displayed in figures 4.29, 4.30 and 4.31. Identification of principal waves is made at each stage of the reflection process.

These figures show isoclinics, in the testpiece, produced by the machining of the hole and cracks. It is possible that these may be removed by a prolonged annealing process.

In figure 4.27(a) the waves transmitted by the 5 MHz probe can be seen to be of two types. The principal compressional waves \( C_1 \), "ringing" slightly are leading, whilst the slower shear wave, \( S_1 \) can be seen mid-way between the probe and the bolt
FIG. 4.29. 5 MHz WAVES GENERATED BY A COMPRESSIONAL WAVE PROBE INTERACT WITH A GLASS MODEL RAIL-END.

(a) INCIDENT WAVES

(b) IDENTIFICATION OF INCIDENT WAVES.

(c) REFLECTIONS OF THE COMPRESSIONAL WAVE 1st TIME DELAY.

(d) IDENTIFICATION OF WAVES IN (c).

MAGN x 3/9
hole. \( C_1 \) is the wave generated from the probe by design. \( S_1 \) is generated by the transverse motion of the piezoelectric plate. The production of shear waves by this means has previously been described in which shear waves were generated at the probe edges giving two shear wavefronts. The shear wave shown now, in figure 4.27(a), differs from that seen earlier in that it has a single wavefront, suggesting a single origin is responsible. Since the probes used are the same, the difference in pulse voltage levels, positions "1" and "3" respectively may be the cause. At the higher pulse voltage level the piezoelectric plate vibration may be slightly modified. However the shear wave \( S_1 \) does not at normal gain settings produce a problem in ultrasonic testing.

As the waves progress, \( C_1 \) first meets the 20 mm long "A" crack. This notation describes the crack location. It is used in practice by the British Rail Civil Engineering departments and is as illustrated in figure 4.29(b). The reflection process here generates two waves, \( C_2 \) by reflection and \( S_2 \) by mode conversion. Part of \( C_1 \) diffracts around the crack to produce a compressional wave in its shadow. A wave in this position is aptly described by Krautkramer as a "shadow" wave, being situated in the "shadow" of the crack. \(^{(26)}\)

When the compressional wave meets the hole two waves are produced by reflection. \( C_3 \) leads a shear wave \( S_3 \) produced by angular incidence of the principal compressional wave at the hole.

The shape of these reflected waves may be compared with that drawn for a spherical wave reflected from a convex spherical surface, in optics. There it is shown how the curvature of
the wave with respect to that of the reflector can produce an oblique incidence condition. This condition for acoustic waves can cause the conversion of the wave from compressional to shear and vice versa, as indicated in 1.6.4. When the centre of the compressional wave meets the hole upper surface, normal incidence occurs and no conversion takes place. Hence \( S_3 \) can be seen on close inspection to be divided into two halves, having reflected obliquely.

The 10 mm long 'C' crack is the next obstacle to the incoming waves. The effects produced here are similar to those of the "A" crack. \( C_4 \) and \( S_4 \) are generated by reflection and \( C_1 \) passes and diffracts around the crack.

When further time delays are introduced figure 4.30(a) - (d) \( C_2 \) and \( S_2 \) are seen to separate. Similarly the distance between \( C_3 \) and \( S_3' \) and \( C_4 \) and \( S_4 \) also increase. The compressional wave \( C_1 \) reflects from the side of the hole to give \( S_5 \), whilst later cycles of this wave packet, \( C_1 \) follow later. In (c) wave propagations continue. Finally in figure 4.31(a) the reflected compressional wave \( C_3 \) returns towards the probe and provides the method of the detection of the hole on the "A Scan" display.

The shear waves \( S_3 \) and \( S_4 \) appear particularly bright here, perhaps because their orientation, together with their intensity, is particularly favoured by this plane polariscope. \( S_3 \) shows a spherical wave, of academic interest, to the right of the 10 mm crack, produced by diffraction around this obstacle.

It is interesting to see here the considerable number of waves which may result from a single incoming compressional wave.

A similar display of the observed effects for obliquely incident shear waves will now be described within a testpiece having
FIG. 4.30.

(a) REFLECTIONS AND MODE CONVERSIONS, 2nd TIME DELAY

(b) IDENTIFICATION OF WAVES IN
(a.)

(c) FURTHER INTERACTIONS
3rd. TIME DELAY.

(d) IDENTIFICATION OF WAVES IN
(c.)

MAGN. x \( \frac{2}{3} \)

FIG. 4.30. WAVES PRODUCED AT LATER TIMES WITHIN THE GLASS RAIL- END.
(a) 4th TIME DELAY.

(b) IDENTIFICATION OF WAVES IN (a)

MAGN. x $\frac{2}{3}$

FIG. 4.31. FINAL SELECTED TIME DELAY SHOWING ACOUSTIC WAVES INTERATING WITH THE CRACKED HOLE.
small cracks at the rail bolt hole.

4.3.2 Shear Waves Obliquely Incident

In this experiment the manner in which obliquely incident shear waves interact with a bolt hole having small notches was displayed. The objective was to explore the mechanisms occurring at the boundaries of this relevant complex shape. The knowledge so gained will be used in its practical application to bolt hole crack sizing, which is suggested in "Future Work".

The glass model rail, having small machined notches at the bolt hole, was inserted in the "crossed" plane polariscope. A shear wave wedge probe producing waves at 40° in plate glass, was positioned to give a maximised "A Scan" signal from a 4 mm notch in the "A" position. Photographs were taken to record the various stages of wave propagation within the model.

Photographs and identification of the incident and reflected waves are given in figures 4.32(a) – (d) and 4.33(a) – (d).

There are two weak scattered waves, $C_{H1}$ and $C_{H2}$ shown in figure 4.32(a), which are produced by reflection from the hole of an incident compressional wave $C_1$. The reflection of $C_1$ from the rail end gives $C_1$ propagating from left to right across the model. A strong shear wave $S_1$ approaches the hole. It exhibits the forked effect in its wave-front. The generation of this wave shape suggests that a complex source is responsible.

In figure 4.32(c) the shear wave reflects from the hole to produce both compressional and shear waves, $C_2$ and $S_2$. Weak compressional waves $C_1^1$ and $C_1^{11}$ reflect from the rail end. Propagation of other "weak" waves continues.
FIG. 4.32.

(a) INCIDENT SHEAR WAVE AND WEAKER COMPRESSIONAL WAVES.

(b) IDENTIFICATION OF WAVES IN WEAKER COMPRESSIONAL WAVES.

(c) SHEAR WAVE APPROACHES 4 mm.

(d) IDENTIFICATION OF WAVES IN NOTCH AND REFLECTS FROM HOLE.

FIG. 4.32. REFLECTIONS OF OBLIQUELY INCIDENT WAVES, GENERATED BY A SHEAR WAVE WEDGE PROBE AT A BOLT HOLE HAVING NOTCHES OF DEPTH 4 mm. AND 2 mm.
Fig. 4.33. Reflections at an early stage (a) and at a later stage (c). Identification of waves in stage 1° (b) and another stage (d). Reflections at the bolt hole and 4 mm notch for a probe positioned for a maximum "A scope notch signal."
Two stages of reflection of the shear wave from the 4 mm notch are shown in figure 4.33(a) and (c). In (a) one part of the incident wave passes the crack, partly diffracting around it to produce a wave in its shadow. The centre of $S_1$ reflects from the notch to give a compressional wave $C_3$ followed by a stronger shear wave $S_3$. This shear wave returns towards the probe, its propagation being further demonstrated in (c). Shear wave $S_3$ does provide the means of detection of a "star" crack in this position at the rail bolt hole.
5. MEASUREMENT OF STRESSES ASSOCIATED WITH ACOUSTIC WAVES

5.1 Introduction

The visualisation of acoustic waves previously described here has been produced by the use of a "crossed" plane polariscope. The work now to be described will first show how this basic instrument can be converted to allow examination of glass models by circularly polarised light.

There are certain advantages to be gained by using a circular polariscope in this work. First any isoclinics present will be removed and second the light intensity produced by the wave will be independent of the settings of the linear polarisers, providing the crossed condition is maintained. There are in addition some disadvantages. Since the stroboscopic light source used here is not monochromatic, then light propagating through the model will not be truly circularly polarised. Absorption of light by the quarter wave plates will reduce the light intensities of the waves in comparison with those seen in a plane polariscope.

Stress measurements associated with acoustic waves will be developed from the measurement of static stresses in a loaded cantilever beam to the dynamic stresses associated with acoustic waves. An approximate method, using a Coker compensating wedge (33) and an accurate method known as "Tardy" compensation will be used for static stresses (34). The small dynamic stresses associated with acoustic waves will necessitate the use of the Tardy method only. A further method known as "Senarmont" compensation (35) would also be applicable to acoustic wave stress measurement but will not be described in this work.
5.2 The "Standard" or "Crossed" Circular Polariscope

The circular polariscope consists basically of four elements, two polarising filters, the polariser and analyser and two quarter wave plates. The way in which these elements are combined is shown in figure 5.1.

When a beam of unpolarised light falls on the polariser it is converted to plane polarised light. The first quarter wave plate, Qp, splits the wave into two mutually perpendicular components of equal amplitude. The light emerging from Qp is therefore circularly polarised.

The second quarter wave plate Qa converts the circularly polarised beam into a plane polarised one. Its plane of vibration is the same as that of the light from the polariser. Since the analyser is "crossed" with respect to the analyser, no light penetrates through it.

5.2.1 The Effect of a Birefringent Crystal Plate in a Circular Polariscope

When a birefringent crystal plate is interposed in the field of a circular polariscope the effects produced are described by Frocht. When the incident circularly polarised beam of light falls normally on the plate the light is divided into two mutually perpendicular components of equal amplitude and differing in phase by 90°. This effect is independent of the directions of principal planes within the plate. The rectangular components enter the plate with an angular phase difference of $\pi/2$ or linear phase difference of $\lambda/4$. In passing through the plate they receive an additional phase difference of $\Delta p$ which is determined by the thickness of the plate and the wavelength $\lambda$ of the light used. The effect of
FIG. 5.1.

FIG. 5.1. THE "STANDARD" OR "CROSSED" CIRCULAR POLARISCOPE.
particular plate thicknesses on the optical transformations occurring in a circular polariscope is considered in 5.2.2 to 5.2.4.

5.2.2 A Plate Thickness Producing a Phase Difference of one Wavelength

The motion of two mutually perpendicular transverse waves may be represented by $H$ and $V$, eq. 5.2. Here the phase difference between them is $\lambda/4$. Should either wave change in phase by $\pm \lambda$, then the relative positions of the $H$ and $V$ components will remain unchanged. In figure 5.3(a) the light emerging from the plate will be unchanged from that entering it, ignoring absorption. The direction of rotation of the circular polarised light on leaving the plate will be either clockwise or anticlockwise, being of the same rotation as it was on entering the plate.

When a polariscope is set for extinction, as in figure 5.3(a), the field will remain dark after such a plate described above is interposed in the polariscope.

5.2.3 A Plate Thickness Producing a Phase Difference of one half Wavelength

If reference is again made to figure 5.2, it may be seen that a phase change of $\pm \lambda/2$ in either component would change the lead from "$H$" to "$V$". This would result in a change in the direction of rotation of the incident circular wave.

An anticlockwise circular wave incident on the plate will emerge as a clockwise wave, as shown in figure 5.3(b). Similarly a clockwise incident wave will emerge as an anticlockwise one.

The combined effect of the plate M and the quarter wave plate Qp is equivalent to a single quarter wave plate of opposite sign, producing opposite rotation, to that of Qp.
FIG. 5.2.

FIG. 5.2. TWO MUTUALLY PERPENDICULAR TRANSVERSE WAVES WITH PHASE DIFFERENCE $\lambda/4$
FIG. 5.3.

a.) SIMPLE CRYSTAL PLATE PRODUCING AN INTEGRAL NUMBER OF WAVELENGTHS OF RETARDATION.

CIRCULARLY POLARISED LIGHT, ROTATION AS $C_1$.

PLANE POLARISED LIGHT, VIBRATIONS AS ANALYSER.

NO LIGHT GETS THROUGH

CRYSTAL PLATE PRODUCING RETARDATION OF AN INTEGRAL NUMBER OF WAVELENGTHS.

b.) CRYSTAL PLATE PRODUCING RETARDATION OF AN ODD NUMBER OF HALF WAVELENGTHS.

FIG. 5.3. OPTICAL TRANSFORMATIONS IN A STANDARD OR CIRCULAR POLARISCOPE PRODUCED BY SIMPLE CRYSTAL PLATES OF DIFFERENT THICKNESSES.
When using a standard circular polariscope set for extinction, the quarter wave plate at the analyser $Q_a$ produces a rotation of opposite sign to that of the quarter wave plate $Q_p$ at the polariser. The circular polarisation produced by the plate $M$ is therefore intensified by polarisation $Q_a$.

It may be shown that the effect of a half wave plate set at $45^\circ$ relative to an incident plane polarised beam, is to turn the polarisation of the incident wave through $90^\circ$. In a standard circular polariscope this would give a bright field. Similarly a half wave plate inserted in a circular polariscope of any setting, changes the intensity of the emerging light at the analyser from maximum brightness to darkness and vice versa.

5.2.4 A Plate Thickness producing an Arbitrary Phase Difference

It can be seen by reference to figure 5.4(a) that light emerges from a plate, giving an arbitrary phase difference with an elliptical polarisation, $C_2$. This is due to the sum of clockwise and anticlockwise circular motions $C_3$ and $C_4$. One of these, $C_3$, is extinguished by the analyser the other penetrates through it.

This condition of an arbitrary phase difference existing in a simple crystal plate is analogous to the conditions existing in a glass model temporarily strained by the action of acoustic waves. The phase differences resulting from the waves used here will be of various magnitudes, but in general will be small compared with those due to $\lambda/4$ and $\lambda/2$ crystal plates.

The conclusions concerning the phase differences due to crystal plates may also be derived from the intensity of illumination of a beam emerging from a circular polariscope. The derivation of the intensity equations are given in the reference due to
FIG. 5.4. ARBITRARY RETARDATIONS DUE TO CRYSTAL PLATES.

a) ARBITRARY RETARDATION DUE TO CRYSTAL PLATE.

b) DOUBLY REFRACTING PLATE OF VARIABLE THICKNESS.
Frocht. The intensity $I$ of the light emerging from a circular polariscope set for extinction is given by

$$I = I_1 \sin^2 \frac{a_p}{2} \quad (5.1)$$

where $a_p$ is the phase difference introduced by a birefringent crystal plate and $I_1$ the intensity of the incident circular wave.

When $a_p = 2m\pi$

then $I = 0$

where $m$ is any integer. This includes the condition of introducing a plate thickness of one wavelength as in 5.2.1.1.

When $a_p = (2m+1)\pi$

then $I = I_1$, a maximum intensity occurs.

This includes the condition of introducing a plate thickness of one half wavelength, as in 5.2.1.2, or an odd number of half wavelengths.

Summarising these effects, for zero phase difference or a whole number of wavelengths minimum intensity is transmitted by the analyser. When the phase difference is an odd number of half wavelengths maximum intensity is transmitted by the analyser.

5.2.5 A Doubly Refracting Plate of Variable Thickness in the Standard Polariscope

In figure 5.4(b) is shown a doubly refracting plate whose thickness varies according to the law

$$t = cy \quad (5.2)$$

in which $c$ is a constant. The optic axis of the plate is assumed to be perpendicular to the axis of propagation of the light beam. The thickness of the plate may be considered to consist of small steps as shown. The effect of interposing such a plate in the standard polariscope may be considered as follows.
Let "t" be the required thickness of the plate to cause retardation of one wavelength between the components of the incident circularly polarised beam. Where the thickness of the plate is t or mt, m being an integer, in a polariscope set for a dark field, then at all such points the field would appear dark. At points in the plate at which the thickness is different from mt, brightness occurs. A maximum brightness occurs where retardations are one half wavelength or any number of half wavelengths. The image of the plate of variable thickness would consist of straight, parallel, equidistant black bands separated by bright bands, for circularly polarised monochromatic light. The colour of the bright bands depends upon that of the light source.

If white light is used, or a source emitting a broad spectrum, then interactions of the fundamental colours takes place. Repeated cycles of straight, parallel, coloured bands, or isochromatics are produced.

A tapered wedge-shaped device will be used later to enable an approximate value of the stresses existing in a stressed cantilever beam to be quickly determined.

5.3 Temporary Double Refraction in the Circular Polariscope

The above description of retardations has been made with reference to simple crystal plates in which double refraction is a permanent optical property. In photoelasticity, testpiece materials are used which, in an unstressed state are isotropic and only when stressed show anisotropy. This property of such materials, celluloid, bakelite and araldite has been discussed earlier with respect to their action upon plane polarised light. The beam of plane polarised
light incident normally upon the stressed model resolves into two components according to the law of vectorial resolution. When circularly polarised light is incident on such a model, the light is resolved into two components which are 90° out of phase. In both cases the components are perpendicular to one another, travel with different velocities and arrive out of phase.

As the stresses acting upon a model are gradually increased from zero to maximum, each point in the model produces a definite number of optical cycles. This effect is shown in figure 5.5(a).

If the retardation, \( R \), produced by loading a testpiece is \( N \), then \( N \) represents the fringe order at a given point. The fringe order may be a fractional number and generally will vary from point to point. Early experiments have shown that the retardation produced by temporary double refraction can be directly proportional to applied loads. It is believed that this will also be so with the stress levels used here.

5.4 Application of the Stress-Optic Law to Stressed Testpieces

The stress-optic law, described in 5.1.2.8 shows for two dimensional testpieces, stressed within the elastic limit, the relative retardation between the light wave components travelling through them. This retardation, \( R \), the stress-optical coefficient \( C \), plate thickness \( t \), and principal stresses \( p \) and \( q \) are related by equation (1.2)

\[
R = C(p-q)t
\]

This may be applied to a testpiece in pure compression as follows:

A two dimensional testpiece subjected to a pure compression, as shown in figure 5.5(b) is placed in the field of a standard circular
FIG. 5.5.

a) VARIATION IN INTENSITY OF STRESS PATTERN WITH APPLIED LOAD.

b) A TEST PIECE SUBJECTED TO A PURE COMPRESSION.

FIG. 5.5. THE VARIATION IN INTENSITY OF ILLUMINATION OF A TEST PIECE SUBJECTED TO AN ALTERNATING LOAD.
polariscope. The plane of the applied stress is made perpendicular to the direction of propagation of the light beam. When \( \sigma_x = p \) and \( \sigma_y = q \), these may be substituted in the stress-optic law. For this case of pure compression \( \sigma_x = 0 \), and,

\[
R = Ct(p-q)t = -Ct\sigma_y
\]

showing that the retardation is proportional to stress. For a model in pure tension, \( \sigma_y = -q \) and the retardation would be obtained from,

\[
R = Ct(q)
\]

When the testpiece is free from stress it will appear dark. As the stress is increased the image becomes brighter and reaches a maximum brightness when

\[
R = \lambda/2
\]

Darkness is restored when \( R = \lambda \). Further increases in stress will produce conditions of brightness and darkness for \( R = 3\lambda/2 \) and \( 2\lambda \) respectively, producing the variation in intensities as shown in figure 5.5(a).

5.5 "Setting Up" the Standard Circular Polariscope

The standard circular polariscope, shown in figure 5.1, consists of an arrangement of linear polarisers and quarter wave plates set at particular orientations. A method for the identification of the "planes of polarisation" of the linear polarisers has been described in 1.4.1. The "fast" and "slow" axes of the quarter wave plates, if not known, must also be identified. A method for their identification is described in 5.5.1.

5.5.1 Identification of the Axes of Quarter Wave Plates

Unpolarised light was made to reflect from the surface of a plane mirror as shown in figure 5.6. The reflected light then passed through a quarter wave plate and a linear polarising filter.
FIG. 5.6. IDENTIFICATION OF THE "FAST" AND "SLOW" AXES OF A $\lambda_4$ PLATE, USING THE PRINCIPLES OF A PLANE POLARISCOPE.
The plane of polarisation of the filter was fixed and in the figure this has been made to coincide with the vertical axis. The quarter wave plate was rotated and the variation in the appearance of the light transmitted through the quarter wave plate and linear polariser observed. As the quarter wave plate only was rotated, two positions were found at which the transmitted light appeared blue. This plane identified the slow axis of the quarter wave plate to lie at $45^\circ$ to the plane of polarisation of the linear polariser. Two positions were found at which the transmitted light appeared a reddish-blue. This plane identified the fast axis of the quarter wave plate. These axes were determined within $\pm 1^\circ$ using this method.

When the fast axis is determined some absorption of the lower wavelength blue light occurs. Similarly when the slow axis is determined some absorption of the higher wavelength red light occurs. These effects are as those produced by a birefringent crystal plate in the "crossed" plane polariscope.

5.6 Visualisation of Acoustic Waves using a "Standard" Circular Polariscope

The experimental procedure used here was similar to that of earlier work with the plane polariscope. The arrangement of figure 5.1 was used to show both compressional waves and obliquely incident shear waves in a quartz glass block. The resulting visualisation of the waves may be seen in figure 5.7(a) and (b). Quartz glass was chosen for this experiment due to its high stress optical coefficient. Similar experiments with plate glass were less successful.
Fig. 5.7. Acoustic waves visualised in the "plane" and "standard" circular polariscopes.

(a) Plane polariscop. 2½ MHz, 15 mm dia. probe (photographed with wide angle lens, 125 mm x 100 mm sheet film.)

(b) Circular polariscop. 2 MHz, 10 mm dia. probe (photographed with 35 mm film, normal lens) magn. x1.
Although the polariscope was set for a dark "field", the background of the quartz glass block has a "grey" appearance. It is believed that this is due to dispersion within the testpiece. When viewing by eye compressional waves visualised in the circular polariscope, it is interesting to observe that adjacent "fractional fringes", corresponding to successive half cycles, appear in slightly different colours. When a negative-going voltage is applied to the transducer the first and third fringes appear white, whilst the second and fourth appear a blueish white. When direction of the excitation voltage is reversed, the colours of the fringes reverse in order of appearance. The colours of the fringes appear to be indicative of the stress type existing. "White" may be tensile and "blue" compressive. The direction of electrical polarisation of the ceramic element and the polarity of its connection will also influence these observations. These relationships will be investigated in later work.

The two examples shown in figure 5.7 are to be used for stress measurement experiments. In addition the stress waves travelling in a plate glass testpiece will be examined. First the stresses in an araldite testpiece subjected to static loading will be measured in order to develop the principles involved. The methods by which this may be achieved will now be described.

5.7 Methods for the Measurement of Fractional Fringe Orders

In order to measure acoustic wave stresses the relative retardations associated with them must be determined. These relative retardations expressed in terms of a "fractional fringe order", abbreviated in some cases later to \( F \), may be substituted in the photoelastic equations in order to calculate stresses.
a.) STRESSED ELEMENTS A AND B

b.) OPTICALLY EFFECTIVE STRESS ON ELEMENT.

FIG. 5.8. THE PRINCIPLE OF COMPENSATION BY SUPERPOSITION OF STRESSED ELEMENTS.
There are several methods for the measurement of fractional fringe orders as indicated by the references given earlier. An approximate result may be achieved by the use of a compensating bar of birefringent material known as a Coker compensator. More accurate results can be obtained by using compensation due to Tardy or Senarmont. The approximate method and that due to Tardy will now be described.

5.7.1 Approximate fringe order Measurement by means of a Tension or Compression Bar or Birefringent Material

A point in a testpiece at which the normal stresses are equal in all directions, is defined as an isotropic point. At such points \( p = q \), and \( p-q = 0 \). Since the difference in the principal stresses determines the phase difference, then at isotropic points the phase difference is zero and extinction occurs in the standard circular polariscope.

An approximate method for the determination of \( p-q \) has been developed by Coker which relies upon this principle. A pure tension or compression stress is superimposed over an arbitrary stress system, to convert that system into one which is optically equivalent to an isotropic point.

In figure 5.9(a) the element "A" is subjected to a pure tensile stress \( p \). The element "B", of the same material and thickness as "A", is subjected to a tensile stress \( q \) in a direction perpendicular to that of \( p \). "B" is then placed in front of, or after "A". The total retardation produced by the two elements is the same as that which would be produced by a single element subjected to both \( p \) and \( q \). When \( p \) and \( q \) are equal, then the condition of an isotropic point exists. A measure of the stress existing in "A" can be made by adjusting the stress in "B" until an isotropic point is produced. The stress \( q \) which is necessary to
produce extinction is then a measure of the stress \( p \).

When the stress \( p \) to be measured is tensile, it may also be compensated by superimposing a compressive stress \( q \) over it. Now the stresses \( p \) and \( q \) would need to be parallel to each other in order to produce a single point of zero stress.

5.7.1.1 The Application of a Tapered Tension Bar to the Measurement of Fractional Fringe Orders

For this measurement of fringe order a tension bar was used in the form of a tapered araldite wedge. This wedge had "frozen" into it isochromatics, or fringes, corresponding to the first three orders of stress. Its appearance in the standard circular polariscope is shown in figure 5.9(a).

The production of a wedge of this type, carried out by colleagues in the Track Group, here at Derby, is by the following method. A rectangular beam of araldite is stressed to produce a uniform tensile stress of the required order as shown in figure 5.9(b). The loading is performed at the softening point of araldite, approximately 125° C. The temperature is reduced slowly, whilst maintaining the applied load until room temperature is reached. The beam is then sliced diagonally as in figure 5.9(c) to produce two wedges, the surfaces of which may then be polished. One of these wedges may be used to give an approximate value of the fringe order over the range for which it has been stressed. Compression wedges may be made by a similar technique but compressive loading is more difficult. Araldite testpieces and compensators are normally stored at 50° C to prevent the absorption of moisture which may induce time-edge stresses.
FIG. 5.9.

(a.) TAPERED "STRESS FROZEN" WEDGE

(b.) ARALDITE BEAM IN TENSION

(c.) CUTTING THE BEAM TO PRODUCE TWO WEDGES FOR STRESS FREEZING PROCESS.
The "stress freezing" process was first carried out by Filon and Harris in 1923 on flint glass\(^{(37)}\). From these experiments it was concluded, according to Heywood, that the material consisted of at least two phases with each phase possessing different properties. On heating the stressed material one phase becomes viscous and transfers its share of the load onto the other elastic phase. On cooling the viscous phase sets in a distorted position so that when the applied load is removed little recovery in its shape can take place. Both phases become stressed, in a manner dependent upon the applied stress. Due to the different optical properties and proportions of the two phases present, a differential optical effect is observed in the polariscope, revealing fringes. This di-phasic nature of materials is described in the literature in which the behaviour of glass and plastic materials is compared.

The stresses at the surface of the cantilever may be described as "free boundary stresses". Boundaries free from external shear and normal stresses are referred to as "free boundaries". For a rectangular element bordering on such boundaries, figure 5.10(a), the faces of it are principal planes. The directions of principal stresses at such points are either tangential or normal to the boundary. The normal stress is assumed to be zero. From this it follows that points lying on free boundaries have only one principal stress, its direction is tangential to the boundary. Since the stress pattern shows \((p-q)\) at each point, should either of them be zero, which occurs at a free boundary, then the numerical value of either \(p\) or \(q\) may be measured.
If reference is again made to figure 5.10(a) it may be seen that the directions of the boundary stresses may be determined by superimposing the tension compensator either normally or tangentially at the boundary. Since the wedge is under tension it can compensate directly for compression. To compensate for tension it must be turned through $90^\circ$.

5.7.2 Measurement of Fringe Orders in a Stressed Araldite Cantilever by Tension Compensator

The araldite cantilever beam was subjected to a load of $0.100\ \text{kg}$ at a distance of $7.0 \times 10^{-2}\ \text{m}$ from the fixed end. Examination first in the plane polariscope was carried out to determine the direction of applied stress. Quarter wave plates were then inserted to convert the polariscope to a "standard" circular type and the isochromatics produced by the load were viewed.

A tensile compensating wedge of araldite was then superimposed at the fixed and of the beam, at a position and in a direction which would optically compensate for the maximum tensile stress at the upper horizontal surface. The wedge was moved in a vertical manner until the black zero order fringe lay astride the upper horizontal free boundary.

The cantilever, in the plane and circular polariscopes, is shown in figures 5.10(b) and (c), by illustration, and 5.11(a)(b) and (c) by photograph. It may be seen that the isoclinic line of figure 5.11(a) is perpendicular to the direction of application of the load. Compensation of the stress at the fixed end of the beam occurs at a fringe order of slightly less than one fringe, for a load of $0.1\ \text{kg}$, shown in figure 5.11(b).

Since this method gives only an approximate measure of the fringe order no attempt will be made for the present to convert
a.) Compensation of compressive and tensile stresses at a free boundary.

b.) Loaded cantilever beam.

3rd ORDER
2nd ORDER
1st ORDER

ARALDITE TENSION COMPENSATOR

ZERO ORDER FRINGE AT UPPER SURFACE

C.) Compensation by tapered Araldite wedge.

**FIG. 5.10:** Identification of stress type and compensation by a tapered tensile compensator.
FIG. 5.11. (a) PLANE POLARISCOPE, 0° ISOCLINIC

(b) COMPENSATION BY A WEDGE COMPENSATOR.

FIG. 5.11. IDENTIFICATION OF STRESS DIRECTION AND "COMPENSATION" IN "PLANE" AND "CIRCULAR" POLARISCOPE.
fringe orders into stress values. This will be carried out in 5.7.5.

5.7.3 Calculation of Stress in a Loaded Cantilever Beam

The calculation of stress in a loaded cantilever beam may be made with a knowledge of the cantilever parameters and either the applied load or the deflection at the point of loading.

The action of bending forces on a beam of rectangular cross section is described by Shigley\(^{(38)}\). When a cantilever beam is acted upon by forces as shown in figure 5.12(a) fibres in the top plane are in tension whilst those in the bottom plane are in compression. On a plane \(N_1 - N_2\) fibres remain at their original length. This plane is called the neutral plane representing points of zero stress.

The stress in the outer fibres at a distance \(y\) from the neutral plane is given by equation 5.5

\[
\sigma = \pm \frac{My}{I}
\]

where \(M\) is the bending moment of the section

and \(I\) is the moment of inertia

For the rectangular section of the cantilever \(I = \frac{td^3}{12}\)

where \(t\) is the thickness and \(d\) the depth of the beam.

Applying the stress equation to the araldite cantilever beam, for which \(t = 2.61 \times 10^{-3}\) m, \(d = 5.88 \times 10^{-3}\) m, \(l = 7.0 \times 10^{-2}\) m, and \(y = 2.94 \times 10^{-3}\) m, the stress may be calculated for given loads \(F\) from equation 5.6

\[
\sigma = F \times 4.0 \times 10^3\ \text{N/m}^2
\]
FIG. 5.12.

a.) THE ACTION OF AN APPLIED LOAD ON A CANTILEVER BEAM.

b.) STRESSES AT POINT A. FOR AN ARALDITE BEAM.

FIG. 5.12. THEORETICAL STRESSES AT THE UPPER HORIZONTAL SURFACE, POSITION "A" OF A LOADED CANTILEVER BEAM.
A range of loads from 0.02 kg to 0.100 kg were applied during these experiments. The corresponding theoretical stresses induced at the point A on the cantilever are shown graphically in figure 5.12(b).

The theory relies upon a number of conditions. This beam has a much smaller \( \frac{l}{d} \) ratio than theory suggests is desirable. An alternative theoretical method which relies upon a measurement of the deflection at the point of application of the load will now be described.

The beam was loaded incrementally with 0.020 kg to 0.100 kg and the deflection produced at each load was measured with a clock gauge. Using equation 5.4 from Ryder\(^{39}\) the stress values were calculated using the measured deflections tabulated below.

A second measurement of the beam deflection was made using a cathetometer. The calculated stresses using these deflections are included in the figure for comparison. It is believed that these measurements should be more accurate since no contact is made between the beam and the measuring device.

<table>
<thead>
<tr>
<th>Load kg</th>
<th>0.020</th>
<th>0.050</th>
<th>0.087</th>
<th>0.100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deflection x.mm</td>
<td>0.128</td>
<td>0.458</td>
<td>0.790</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Using Ryder's equations the stress may be calculated as follows

\[
\sigma = \frac{3 E \times y}{l^2} \quad (5.7)
\]

Where \( E \) is the modulus of elasticity
\( \times \) is the deflection at the point of application of the load
\( y \) is the distance from the neutral axis to the point of stress measurement
\( l \) is the length of the beam.
For this araldite cantilever the equation simplifies to:

\[ \sigma = 5.6 \times 10^5 \, \text{N/m}^2 \]  

(5.8)

Results from this equation are plotted with the previous theoretical results of Figure 5.12.

5.7.4 Tardy Compensation

This method uses rotation of the analyser alone in a standard circular polariscope to determine the fractional fringe order existing. It may be used to determine the fractional fringe order relative to the nearest integral or half order isochromatic line. In general photoelastic work using araldite testpieces the magnitude of stresses existing frequently necessitates the measurement of several orders of fringe, i.e. \( n = 4, 5, 6 \), for example. In work on acoustic waves in glass only fractional fringe orders, of the order of 1/10 of a fringe, are relevant.

When the fringe order is required at point A, figure 5.11, first the directions of the principal stress axes should be determined at that point. If not known, this may be achieved by examination of the model in the plane polariscope. The position of the isoclinic line will be parallel to the direction of the applied stress. The planes of polarisation of the polariser and analyser should then be arranged parallel and perpendicular to the principal stress axes at "A". Quarter wave plates are then inserted into the polariscope with their axes set at 45° to the linear polarising filters. The first quarter wave plate with its fast axis at +45° to the polariser, the second with its slow axis at +45° to the polariser. Quarter wave plates are "crossed" with respect to each other, linear polarisers are "crossed" with respect to each other. The arrangement is that of the standard
or "crossed" circular polariscope.

When the light source is monochromatic the integral orders of interference, retardation of 0, \( \lambda, 2\lambda \), etc., is shown in black. When a spark light source is used, isochromatics may appear coloured, depending upon the stress levels induced.

Should the analyser only now be rotated, the isochromatic at point "A", for example, is made extinct at a particular analyser setting. The angle of rotation required to reduce a bright fringe to a black fringe, or zero stress condition, is proportional to the order of interference between "A" and one of the adjacent isochromatics.

Considering isochromatics of the zero order and first order, since these are particularly relevant, fractional fringe orders may be measured as follows. Consider an analyser rotated clockwise by 10° to produce extinction. Extinction at the point "A" is achieved by transferring extinction from the zero order fringe to position "A". Interference at "A" is given by equation 5.9.

\[
n = 0 + \frac{\text{angle of rotation}}{180^\circ} \tag{5.9}
\]

or

\[
n = 0.056
\]

For an anticlockwise rotation of the analyser to produce extinction at "A", "extinction" would have moved from the 1st order isochromatic, to the lower order region of "A". The angle of rotation would in this case have been \((180-10)^\circ\) and the corresponding order at "A" would be obtained from equation 5.10.

\[
n = 1 - \frac{170}{180} = 0.056 \tag{5.10}
\]
This method of stress measurement was first applied to a loaded cantilever beam for which the stress at the fixed end was determined. When the principle had been established by comparison with calculated results of 5.7.3, the principle was then applied to acoustic waves.

5.7.4.1 Tardy Compensation—applied to a Cantilever Beam

The araldite cantilever beam was positioned horizontally in the field of the "crossed" circular polariscope and a load applied at the position "B". The plane of polarisation of the analyser was set vertically to coincide with the direction of the applied stress at the point "A". Photographs of the fringe pattern for small loads were taken. The analyser was then rotated in the Tardy manner until the stress at "A" was optically reduced to zero. The amount of rotation of the analyser, or the compensation required, was measured. The effect of inserting a bright spectral filter into the optical system was also investigated. The choice of the violet spectral filter was made since its insertion produced the optimum resolution, when compared with other filters transmitting suitable light wavelengths.

The process of compensating for stress by rotation of the analyser is shown diagramatically in figure 5.13 and by means of colour photographs in 5.14.

Figure 5.15 shows the compensation required for stresses induced by loads of 0.020 kg and 0.100 kg. The anticlockwise rotations, expressed in terms of fractional fringe orders, are shown using "white" and "violet" light sources.
FIG. 5.13. TARDY COMPENSATION "TO REDUCE TO ZERO" OR "COMPENSATE" A TENSILE STRESS AT THE UPPER HORIZONTAL SURFACE OF A CANTILEVER.
FIG. 5.14.

(a) ANALYSER SET IN THE VERTICAL AXIS.

(b) ANALYSER ROTATED ANTICLOCKWISE FOR PARTIAL COMPENSATION OF "FIXED END" STRESS

MAGN x 1.4.

FIG. 5.14. TARDY COMPENSATION FOR FRACTIONAL FRINGE ORDERS IN AN ARALDITE CANTILEVER STRESSED BY A LOAD OF 0.1 kg AT "B"
FIG. 5.15.

THE VARIATION OF FRACTIONAL FRINGE ORDER AND STRESS WITH LOAD ON A STRESSED CANTILEVER BEAM BY TARDY COMPENSATION.
It can be seen from figure 5.13(a) that the neutral axis, the unstrained layer in the beam, appears black, indicative of the zero order fringe. Hence with the analyser in the vertical plane in this fringe appears along the centre-line of the beam.

When an anticlockwise rotation of the analyser is made, the black fringe moves towards the upper horizontal surface. This process is shown in (c) and (d). Hence the stress at "A", which is tensile, is being compensated by an anticlockwise analyser rotation. Complete compensation is being achieved in (d) and (e). Similarly the compressive stress at "C", on the lower horizontal surface at the root, may be compensated by a clockwise analyser rotation.

It may be summarised that tensile stresses are compensated by anticlockwise rotation and compressive stresses by clockwise rotation of the analyser for experimental arrangements of this type.

The colour prints show the conditions of no compensation and partial compensation of the tensile fringe. Further anticlockwise rotation in addition to that of figure 5.14(b) will be required for complete compensation at position "A" at the fixed end. Figure 5.15 shows the fractional fringe order increases linearly with the applied load over the range shown. The insertion of a violet spectral filter may be seen to have little effect on the measured fringe orders and does restrict the optical wavelength range, thus enabling a better estimation of the stress optical coefficient to be obtained. Measurements of the low values of fractional fringe orders in acoustic waves
is made in 5.9.1., using both white and violet light.

5.7.5 Conversion of cantilever Fringe Orders into Stresses

Fringe orders may be converted into stresses by use of equation 5.3, and the relationship between the fringe order $N$ and relative retardation $R$; $N = \frac{R}{\lambda}$, giving:

$$ (p-q) = FNt^{-1} $$

where $(p-q)$ is the difference in principal stresses and $t$ the model thickness. The fringe stress coefficient $F$ and stress optical coefficient $C$ are related by $F = \frac{\lambda}{C}$. For araldite materials most work has been carried out in stress analysis at the wavelength of sodium light or mercury light. Consequently values of $F$ and $C$ are only available at these particular wavelengths. In order to calculate these properties at other wavelengths the equation relating to photoelastic dispersion may be used. However material constants must be known. Heywood quotes 7.5% lower values of "F" at 546 nm than for 589 nm. Assuming a linear decrease in $F$ with $\lambda$ for the cantilever material, Araldite CT.200, a value of $F$ at the light wavelengths used in this polariscope can be determined.

In order to estimate the wavelength of light which is relevant in the circular polariscope, three factors require consideration. These are the spectral distribution of the tungsten electrode spark light source, the transmission characteristic of the violet spectral filter and the optical response of the eye of the observer.

These three characteristic curves are shown in figure 5.16(a) to (c) (40) (41) (42). The first estimate of the wavelength of measurement may be obtained by taking the product of the filter response and photopic response. This gives the relationship of figure 5.17(a). From the photopic response curve the part
FIG. 5.16.

a) TUNGSTEN SPARK LIGHT SOURCE SPECTRAL DISTRIBUTION.

b) VIOLET SPECTRAL FILTER.

c) THE PHOTOPIC RESPONSE OF THE EYE OF THE OBSERVER.

FIG. 5.16. SPECTRAL DISTRIBUTION FOR THE LIGHT SOURCE, % TRANSMISSION OF THE OPTICAL FILTER AND THE PHOTOPIC RESPONSE OF THE EYE OF THE OBSERVER.
of importance is the shaded area, corresponding to part of the pass band of the spectral filter. In order to select a value of the light wavelength to be used for stress measurement, the product of "photopic response" and "% transmission of the filter" may be the best method of selection. A plot of this product is shown in figure 5.17. Using this criterion an operating wavelength of 470 n.m. may be selected.

A further factor to be considered is the spectral response of the light source. In figure 5.16(a) the spectral response of the tungsten spark light source shows its variation in intensity with wavelength. The product of the three variables shown in figure 5.16 has been plotted against wavelength in figure 5.17(b). From this relationship the best estimate of the operating wavelength is 470 n.m. This value will be used in stress calculations as follows.

For a wavelength of 470 n.m. the value of F may be derived by extrapolation of the F/\(\lambda\) graph of figure 5.18(a). The value of F selected is 2.62 N/m fringe. Substituting in equation 5.3 gives:

\[
(p - q) = 1.0 \times 10^3 \text{ N N/m}^2
\]  

(5.11)

stresses so calculated for the stressed cantilever are shown in figure 5.18(b). Since the principal stress q at the boundary is zero, then the value of the principle stress p, tensile at the point considered, will be indicated by the equation.

5.7.6 Comparison of Theoretical and Photoelastically Measured Cantilever Stresses

In order to compare the theoretical and measured cantilever stresses, figures 5.11(b) and 5.18(b) should be examined.
FIG. 5.17. SELECTION OF THE OPERATING WAVELENGTH OF THE STANDARD CIRCULAR POLARISCOPE USING A TUNGSTEN SPARK LIGHT SOURCE.

a.) PRODUCT OF EYE AND FILTER CHARACTERISTICS, WITH WAVELENGTH.

b.) PRODUCT OF EYE, FILTER & PHOTOGRAPHIC PLATE CHARACTERISTICS.
a.) VARIATION OF FRINGE STRESS COEFFICIENT WITH WAVELENGTH FOR ARALDITE CT 200

b.) MEASURED STRESSES.

FIG. 5.18. CANTILEVER MATERIAL PROPERTIES AND MEASURED STRESSES BY PHOTOELASTICITY.
Stresses calculated on the basis of the deflection of the cantilever compare more favourably with photoelastic results than those calculated only on the magnitude of the applied load. This may be due to the ratio of length "1" to depth "d" of this beam, which is not as large as suggested by the theory described by Shigley and Ryder. 

For an applied load of .100 kg at a distance of $7.0 \times 10^{-2} \, \text{m}$ from the fixed end of the beam, a calculated stress, based on beam deflection, of $0.615 \, \text{kN/m}^2$ results. This compares reasonably well with a measured stress of $0.80 \, \text{kN/m}^2$. It is now believed that a beam of different geometry may have enhanced the accuracy of the measurements. In spite of this the order of the stresses has been indicated by photoelasticity.

5.8 Acoustic Wave Fractional Fringe Orders by Tardy Compensation

If consideration is given first to the visualisation of compressional waves, previously shown in the plane polariscope, bright fractional fringes were produced for each half cycle, against the dark background of the testpiece. When the circular polariscope is used, the undisturbed background appears grey and contrast is reduced.

Incident 2 MHz compressional waves examined in a circular polariscope are shown in figures 5.19 and 5.20. In the monochrome photographs of figure 5.19 the first and third fractional fringes are dark whilst the second and fourth are bright. It is thus showing a difference in sign of the compressions and rarefactions. Colour prints of figure 5.20 show, blue and white fringes of alternate half cycles.

When the wave fronts reflect from the base of the plate glass block, a bright fractional fringe leads, concurring with the principle of
FIG. 5.19

(a.) INCIDENT WAVES, COMPRESSSIONAL AND SHEAR

(b.) REFLECTED WAVES.

MAGN. x2

FIG 5.19 PHASE CHANGE BY REFLECTION, FROM A PLATE GLASS/AIR BOUNDARY, OF WAVES GENERATED BY A 2 MHz COMPRESSIONAL WAVE PROBE IN MONOCHROME.
FIG. 5.20. REFLECTION OF NORMALLY INCIDENT COMPRESSIONAL WAVES AT A GLASS/AIR BOUNDARY SHOWING PHASE REVERSAL BY COLOUR PHOTOGRAPHY.
phase reversal at a boundary of this type.

When shear waves are examined the first, second, third and fourth fractional fringes all appear bright. Their intensity, judged by eye, decreases with the oscillatory motion. It will be shown in the experiments to follow shortly on shear waves, that "compensation" of adjacent fringes is achieved by opposite directions of rotation of the analyser in the Tardy method.

The effects described for both compressional and shear waves will undoubtedly be related to the stresses producing these fringes. The manner in which they produce the observed effects will now be investigated.

5.8.1 Identification of the Stresses due to Compressional Waves

In section 5.7.4.1 relating to the stresses in a cantilever beam a description was given of the rotation directions of the analyser for compensation of tensile and compressive stresses. This principle may be applied to acoustic waves in a similar way in order to identify the stresses associated with particular fractional fringes. In conventional photoelasticity it is usual for the polarised light to pass through the whole of the model thickness. In acoustic wave investigations the optical path intercepted by the acoustic wave will be relevant. This must be considered for each stress measurement.

Using the Tardy method compressional waves were visualised in quartz glass. A negative-going excitation voltage of 640 volts was applied to the probe. The analyser was set with its plane of polarisation in the vertical axis coinciding with the direction of wave propagation, and the appearance of the fringes due to the acoustic wave stresses was noted. The analyser only was then rotated, first in an anticlockwise direction and then in
clockwise direction and the effect on the brightness of the first four fringes was observed.

The effect of reversing the polarity of the excitation voltage to give a positive-going pulse was later investigated.

The appearance of the waves for particular settings of the analyser is indicated in figure 5.21 for a negative-going excitation voltage. When the voltage polarity is reversed, the direction of rotation of the analyser to produce compensation is reversed for each of the fringes considered.

The first fractional fringe here is compensated by an anti-clockwise rotation of the analyser. The direction of rotation indicates a tensile stress for the first half cycle of the stress waves. In colour photographs this is indicated by a white fringe as in figure 5.20(b). The polarity of the electrical connections to the piezoelectric plate will influence this effect. The stress associated with the second half cycle is compressive, being compensated by a clockwise rotation of the analyser. In figure 5.20(b) this is displayed as a blue fringe, although here this occurs after phase reversal.

The third and fourth cycles result from tensile and compressive stress waves respectively, indicated again by analyser rotation.

5.8.2 Identification of Stresses due to Shear Waves

The identification of stresses in shear waves has been made using a similar technique to that described above. In this case obliquely incident shear waves in quartz glass were the subject of the experiment.
FIG. 5.21.

(a) THE FIRST TWO FRINGES OF COMPRESSIONAL WAVES.

(b) ANALYSER PLANE OF POLARISATION FOR (a)

(c) COMPENSATION OF THE 1st FRINGE.

(d) ANALYSER PLANE OF POLARISATION FOR (c)

(e) COMPENSATION OF THE 2nd FRINGE.

(f) ANALYSER PLANE OF POLARISATION FOR (e)

FIG. 5.21. IDENTIFICATION OF STRESSES IN THE FRINGES ASSOCIATED WITH COMPRESSIONAL WAVES BY TARDY COMPENSATION.
The ultrasonic probe used here was of special manufacture, designed to generate shear waves at 40° in plate glass, by means of a perspex mode conversion wedge. Due to the higher shear wave velocity of quartz glass, it may be calculated using the refraction law that shear waves transmitted by this probe will propagate at 45° in quartz glass. The direction of propagation is particularly important, as described in "Tardy compensation", since the planes of polarisation of the linear polarisers must be aligned parallel and perpendicular to the planes of the principal stresses.

The shear wave probe was grease coupled to the quartz glass testpiece and inserted into the field of a "standard" circular polariscope. The planes of polarisation of the linear polarisers were originally set in the horizontal and vertical axes. Since the planes of principal stress associated with shear waves occurs at 45° to the wavefront, the filters and λ/4 plates were rotated clockwise by 45°. The propagation of the shear waves occurs at 45° to the vertical axis requiring a further 45° of clockwise rotation of all elements in the polariscope. (For a shear wave propagation direction of 40° all elements of the polariscope would need to be rotated by 85°. Since these shear waves propagate at 45° the original positions of the filters would be correct.)

With the polariscope so arranged the probe was electrically driven by a negative-going voltage of 500 volts. The analyser only was rotated to optically compensate for the first and second fringes. The rotation direction was noted for each half cycle of the stress wave.
FIG. 5.22

a.) THE FIRST TWO FRINGES OF 45° SHEAR WAVES.

b.) ANALYSER SETTING FOR (a.)

c.) COMPENSATION OF THE 1st.F. FRINGE.

d.) ANALYSER SETTING FOR (c.)

e.) COMPENSATION OF THE 2nd.F. FRINGE.

f.) ANALYSER SETTING FOR (e.)

FIG. 5.22 IDENTIFICATION OF STRESSES IN THE FRINGES ASSOCIATED WITH OBLIQUELY INCIDENT SHEAR WAVES BY TARDY COMPENSATION.
The compensation of shear wave stresses, produced by a negative-going voltage, is indicated in figure 5.22 for 2.5 MHz shear waves propagating at 45° in quartz glass. For the particular probe used, the first fringe is compensated by an anticlockwise rotation of the analyser, shown in (c) and (d). The second fringe is compensated by a clockwise rotation, shown in (e) and (f).

When the excitation voltage polarity was reversed the direction of rotation of the analyser was reversed for each fringe in order to compensate.

In figure 1.13 the effect of shear stress directions viewed in the plane polariscope is described.

It can be seen that a positive-going shear stress will give maximum light through the analyser for an analyser set in an anticlockwise position relative to the stress direction. A minimum light intensity will be achieved for a clockwise rotation. Hence the anticlockwise rotation shown in figure 5.22(d) compensates for a "negative-going" shear stress of (c) associated with the first fringe. The clockwise rotation of (f) compensates for the "positive going" shear stress of (e) associated with the second fringe.

5.8.4 Fractional Fringe orders due to 2 MHz Compressional Waves in Plate Glass

A normal incidence 2 MHz compressional wave probe was grease coupled to a 19 mm thick plate glass testpiece which was inserted in the field of a "standard" circular polariscope. The maximum excitation voltage available from the Kelvin ultrasonic set was used to excite the probe. Compressional waves visualised in the glass testpiece were arranged to occur at a particular point in the glass by means of the variable
(a) 2 MHz COMPRESSIONAL WAVES IN PLATE GLASS.

(b) STRESSES OF THE FIRST HALF CYCLE (TENSILE)

FIG. 5.23 VARIATION IN FRACTIONAL FRINGE ORDERS ASSOCIATED WITH THE FIRST HALF CYCLE OF 2 MHz COMPRESSIONAL WAVES IN PLATE GLASS WITH PROBE EXITATION VOLTAGE.
time delay.

The method of Tardy compensation was used to measure the maximum tensile and maximum compressive stresses in the centre of the first two wave fronts at a distance of 20 mm from the probe. This process was carried out for various excitation voltages by inserting an attenuator between the transmitter and the ultrasonic probe. Measurements were made as the voltage was increased and decreased over a voltage range of approximately-200 volts to -650 volts. From the rotation, in degrees, required for compensation the fractional fringe order was calculated for a range of excitation voltages. Photographs of the waves were taken on 35 mm high speed Ectachrome Film.

Compressional waves generated in plate glass are sketched in figure 5.23(a). The variation in the fractional fringe order with voltage is plotted for the first half cycle in figure 5.23(b). Similar information is shown in figure 5.24 for the second half cycle of the compressional wave.

The relationship between the fractional fringe order, F.F.O., and voltage is linear over the voltage range used here, for the first two cycles of the compressional wave. By comparing the two graphs it can be seen that higher fringe orders are produced in the second half cycle than the first for a given excitation voltage. This observation will be confirmed in later experiments. As a measure of sensitivity, the voltage required to produce one fringe is suggested, although in practice one fringe will not be reached in experiments with acoustic waves here. One tenth of a fringe is a more realistic and typical value. For the first half cycle 9 100 volts/fringe are required whereas for the second half cycle the value is 6 200 volts/fringe.
FIG. 5-24. VARIATION IN FRACTIONAL FRINGE ORDERS ASSOCIATED WITH THE SECOND HALF CYCLE OF 2 MHz COMPRESSIONAL WAVES IN PLATE GLASS, WITH PROBE EXCITATION VOLTAGE.

SE/A = 6200 VOLTS/FRINGE ORDER

* VOLTAGE INCREASE
X VOLTAGE DECREASE
The waves visualised in the circular polariscope appear generally weaker than when viewed in the plane polariscope. The next series of experiments will use quartz glass which has a higher stress-optical coefficient than plate glass. Waves visualised in this medium will be brighter for a given excitation voltage.

5.8.4 Fractional Fringe Orders due to 2 MHz Compressional Waves in Quartz Glass

The experimental procedure used here is similar to that of the previous experiment. The testpiece was in the form of a wedge-shaped quartz block 32 mm thick. Waves were "frozen" for fringe order measurement at a distance of 20 mm from the probe face. Photographs were taken to show the effect of "compensation" on the appearance of the first wavefront.

The compressional waves are shown in the standard circular polariscope for particular analyser settings, in figure 5.25(a) and (b).

The variation of F.F.O. with excitation voltage is shown for the first two fringes on figure 5.26. For the first fringe, the reciprocal of the slope of the line, $1/m = 8$ gives 6 400 volts/fringe, whilst for the second fringe 5 250 volts/fringe are required.

The photographs display the typical appearance of the waves viewed in circularly polarised light and in addition give the "compensated" condition of the first fringe. The rotation of the analyser responsible for producing these two optical conditions is used for calculation of the F.F.O.
FIG. 5.25. TARDY COMPENSATION APPLIED TO THE 1st HALF CYCLE OF 2 MHz COMPRESSIONAL WAVES, IN QUARTZ GLASS.
FIG. 5.26. FRACTIONAL FRINGE ORDERS IN QUARTZ GLASS, ASSOCIATED WITH THE FIRST TWO HALF CYCLES OF 2 MHz COMPRESSIONAL WAVES, FOR VARIOUS EXCITATION VOLTAGES, AT A WAVE PROPAGATION DISTANCE OF 20 mm.
The graphs show again a higher sensitivity for the second fringe than for the first. This may be due to the second half cycle of the voltage excitation being of greater magnitude than the first. This effect has been observed previously using a different electrical system. With the present electrical system only one half cycle of the voltage pulse is apparent when displayed on the oscilloscope, probably due to the electrical impedance difference between the ultrasonic set and the probe.

The higher sensitivity obtained using quartz glass is demonstrated by the lower value of \( S = \frac{1}{m} \). For the second fringe 5 250 volts/fringe may be compared with 6 200 volts/fringe in the case of plate glass. The divergence of the beam, to be discussed later, will affect the measurements of the F.F.O. For the fixed distance of 20 mm in each experiment, coinciding approximately with the extent of the near field, it is believed that a fair comparison is being made.

5.8.5 The Fractional Fringe Orders Associated with Obliquely Incident Shear Waves

Shear waves obliquely incident at 45° in quartz glass were used for this experiment. The optical system was arranged as in 5.8.3. Excitation of the transducer was by a negative-going pulse of peak value approximately 500 volts. Graphs of voltage against fringe orders were plotted for the first two fringes. Photographs of the shear waves in the "standard" circular polariscope and in an optically compensated form for the first fringe, were taken.
The effect of compensation on obliquely incident shear waves is shown in figure 5.27(a) and (b). Graphical information is displayed in figure 5.28(a) and (b). For the first half cycle a sensitivity of 4,020 volts/ fringe is calculated and the second half cycle requires 3,333 volts/ fringe.

The sensitivity of these obliquely incident shear waves is the highest observed so far. The second half cycle is again of higher magnitude than the first.

The observation of a higher magnitude of applied voltage in the second half cycle has been reported by Redwood, discussed further in 5.9.2.1. This would undoubtedly result in a higher induced stress associated with the second half cycle of the wave.

5.8.6 The Effect of Beam Divergence on the Measurement of Fractional Fringe Orders

The measurements of fractional fringe orders made so far have been related to a particular position occupied by an acoustic wave at a given time. In propagating through the glass block, divergence of the wave will occur in a theoretically predictable manner. In fused quartz using the compressional wave probe described, the near field may be obtained from figure 5.29(a). After the near field boundary has been reached, divergence of the wave occurs as shown in figure 5.29(b). Measurements for normal incidence compressional waves have been made at a position before any significant divergence takes place. In order to demonstrate the variation in fringe order values which may occur with distance an experiment was carried out as follows.
FIG. 5.27. SHEAR WAVES PROPAGATING AT 45° IN QUARTZ GLASS, SHOWING THE EFFECT OF TARDY COMPENSATION ON THE FIRST HALF CYCLE.
FIG. 5-28. FRACTIONAL FRINGES OF SHEAR WAVES INCIDENT AT 45° IN QUARTZ GLASS.
FIG. 5.29. THE NEAR FIELD AND BEAM DIVERGENCE RELATIONSHIPS FOR PROBES OF VARIOUS DIAMETERS GENERATING 2 MHz COMPRESSIONAL WAVES IN QUARTZ GLASS.
The variation in fringe orders with distance was measured for waves generated by a 10 mm diameter compressional wave probe, grease coupled to a quartz glass block. Variation in the variable time delay caused the wave to be viewed at particular positions as indicated in figure 5.30(a). Changes in optical path length are shown in figure 5.30(b). Tardy compensation gave a measure of the fractional fringe orders associated with the first half cycle of the wave. These values were plotted for each wave position. As the wave propagates through the quartz glass testpiece its fractional fringe order varies as indicated in figure 5.30(c).

A linear variation in fringe order with distance is shown by the graph. From this line an equation relating the fractional fringe order, for the first fringe, with distance may be derived as follows,

$$F.F.O. = -0.0021 r + \text{const.} \quad (5.12)$$

where F.F.O. is the fractional fringe order for the first half cycle and "r" is the distance travelled by the compressional wave from the probe face. The value of the constant will be that of the F.F.O. at the instant when the wave first enters the test-piece.

With reference to the slope of the graph, figure 5.30(c), the anticipated relationship between stress and distance travelled by the wave may be described as follows. The relationship between the wave energy, E, amplitude and stress is:

$$E \propto (\text{Amplitude})^2 \propto (\text{Stress})^2$$

(5.13)

As the wave propagates, the energy at a point within it decreases inversely with the square of the distance,

$$E \propto \frac{1}{r^2}$$

obeying the inverse square law. This means that the stress per unit area decreases inversely as distance r, and
FIG. 5.30. THE EFFECT OF BEAM DIVERGENCE ON THE MEASUREMENT OF FRACTIONAL FRINGE ORDERS OF ACOUSTIC WAVES IN QUARTZ GLASS FOR A PROBE EXCITATION OF 640 VOLTS.
From figure 5.30(b) it can be seen that the optical effect is therefore independent of r. From this reasoning the graph of F.F.O. against r, should be a horizontal line, providing the light travels through exactly the same part of the wave for each measurement.

The magnitude of the negative slope of the line indicates how important the point of measurement will be in this work. At distances of 10 mm and less from the probe face, little variation in the width of the wavefront occurs. Beyond the near field the wave diverges at about 21°. This effectively increases the optical path affected by stress, of the circularly polarised light in the testpiece. Variations in optical path length, illustrated in figure 5.30(b), show at 10 mm from the probe the optical path length is 10 mm, whereas at 40 mm it has increased to 20 mm. It will be seen later that the rate of decrease of measured stress in the wave, with distance $d\sigma/ds$, will be more rapid than $d\text{FFO}/ds$, since stress in photoelastic work is inversely proportional to the optical path length in the testpiece. It can be seen that reference to the "divergence" and "near field" characteristics of probes used will be most important and careful selection of the point of measurement must be observed. These observations will apply equally to shear waves and a plot of the "beam" shape will be required before shear stress measurements can be made.

5.9 Conversion of Fractional Fringe Orders into Stresses for Acoustic Waves

The calculation of stresses associated with acoustic waves will be confined to the particular examples of normal incidence compressional waves and 45° obliquely incident shear waves, both visualised in quartz glass. The methods involved in the conversion of F.F.O.
values into stresses will be applicable to other testpieces and probes when the general principles are observed.

If reference is made to the photoelasticity equations it will be seen that the wavelength of the light must be known and the stress-optical coefficient for that wavelength must be available. Work by Jog (44) has shown how "C" varies with wavelength over the range 225 n.m to 650 n.m. This graph is reproduced in figure 5.31. It shows a definite dispersion of the stress optical coefficient, "C" increases with decreasing wavelength. A comparison with the stress-optical coefficient of plate glass may be made by reference to figure 5.31(b). The point of selection of the operating wavelength for this work will be made by reference to figure 5.17. For a wavelength of 470 n.m values of "C" for quartz and plate glass are 21.7 N/m fringe and 28.6 N/m fringe respectively.

5.9.1 The Effect of a Violet Spectral Filter on Measurements of Fractional Fringe Orders

In order to limit the range of wavelengths transmitted by the quarter wave plates of the standard circular polariscope, experiments were carried out using a violet spectral filter. This filter was chosen from the range of Ilford spectral filters since using this particular one the acoustic waves were most clearly seen.

The filter was inserted in the optical system between the light source and the Fresnel lens. Using Tardy compensation, fractional fringe orders were measured using a range of excitation voltages for both compressional waves and obliquely incident shear waves.

The fractional fringe orders produced by the first and second half cycles of a normally incident compressional wave are shown
FIG. 5.31. VARIATION OF STRESS - OPTICAL COEFFICIENT WITH WAVELENGTH FOR QUARTZ AND PLATE GLASS.
in figure 5.32(a) and (b). When shear waves are incident at 45° in quartz glass the fractional fringe orders produced by the first half cycle of the wave are shown in figure 5.33(a) and (b). In (a) measurements are shown without a spectral filter and in (b) results are produced using a filter in the optical system.

When comparing the results of figure 5.32 with those of figure 5.26, it can be seen that for the first fringe the "sensitivities" are similar. The measurements with the filter in this example show a slightly increased scatter. When the results for the second fringe are compared, those made with the filter are slightly lower.

Figure 5.33 shows good agreement for measurements made with unfiltered and filtered light for obliquely incident shear waves.

From these measurements the results indicate that all the previous readings of fractional fringe orders without a spectral filter may be used to obtain values of stress, using the value of 470 n.m. as the operating wavelength. The accuracy of the measurements has not been impaired by the use of the optical filter. Figure 5.34 shows the variation of the fringe-stress coefficient with λ and the values for quartz and plate glass at the wavelength selected; data to be used in stress calculations.

5.9.2 Stress Values Associated with Compressional and Shear Waves

5.9.2.1 Compressional Waves

When applying equation 1.2 to compressional waves propagating in plate glass, the fringe stress
FIG. 5.32. FRACTIONAL FRINGE ORDERS IN QUARTZ GLASS, GENERATED BY COMPRESSIONAL WAVES USING A VIOLET BRIGHT SPECTRAL FILTER IN THE LIGHT SOURCE.
FIG. 5.33. FRACTIONAL FRINGE ORDERS FOR 45° INCIDENT SHEAR WAVES, USING A BROAD SPECTRUM AND A FILTERED LIGHT SOURCE.

(a) WITHOUT FILTER, 1st. 1/2 CYCLE

(b) WITH VIOLET BRIGHT SPECTRAL FILTER 1st. 1/2 CYCLE.
FIG. 5.34. VARIATION OF FRINGE STRESS COEFFICIENT WITH WAVELENGTH FOR QUARTZ GLASS AND PLATE GLASS.
coefficient $F = 28.6 \text{ N/m fringe}$ is substituted, the equation simplifies to:

$$p - q = 28.6 \frac{\text{N}}{\text{m}^2}$$  \hspace{1cm} (5.14)

When a point in the wave propagation at 20 mm is selected at which the optical path length is 15 mm, then the peak stress $p$, since $q = 0$, will be given by:

$$p = 1910 \frac{\text{N}}{\text{m}^2}$$  \hspace{1cm} (5.15)

For the first half cycle of the wave, a fringe order of 0.056, figure 5.23(a), at -500 volts excitation of the probe gives a tensile stress of 107.0 N/m$^2$. For the second half cycle a fringe order of 0.08, figure 5.24(b), for the same excitation voltage gives a compressive stress of 153.0 N/m$^2$.

For compressional waves in quartz glass insertion in equation 1.2 of the fringe stress coefficient of 21.9 N/m fringe and $t = 15 \times 10^{-3}$ m at a propagation distance of $20 \times 10^{-3}$ m, gives a stress $p$ calculable from equation 5.16.

$$p = 1460 \frac{\text{N}}{\text{m}^2}$$  \hspace{1cm} (5.16)

For the first half cycle of the wave, a fringe order of 0.078, figure 5.26(a), at -500 volts, gives a tensile stress of 114.0 N/m$^2$. For the second half cycle a fringe order of 0.098, figure 5.26(b), at -500 volts, gives a compressive stress of 143.0 N/m$^2$.

It is interesting to observe that the stress measured for the first half cycle of each wave is approximately equal in each type of glass. A further similarity in stress values occurs for the second half cycle. This may be due to the similar boundary conditions existing in each experiment, since (pc) plate glass \(\rightarrow\) (pc) quartz. Comparing the stresses of the first and second cycles in a particular medium,
quartz for example, a further point of interest may be observed. The compressive stress of the second half cycle is of 20% greater magnitude than the tensile stress of the first half cycle. In plate glass this difference in stresses is of the order of 40%. 

The generation of short duration ultrasonic pulses has been reported by Redwood\(^{(43)}\). He described how the electrical characteristics of the transmitter and probe and the relevant acoustic impedances can affect the generated ultrasonic pulse. He shows that the voltage of the second half cycle can be 10% higher than that of the first, thus explaining to some extent the stress differences found here.

5.9.2.2 The Variation of Stress, Associated with a Compressional Wave, with Increasing Propagation in a Quartz Glass

For the calculation of stresses to be carried out here the information of figure 5.33 will be important. First an excitation voltage of \(-640\) V. has been selected. Consequently the stress at 20 mm propagation will be greater than that indicated earlier for \(-500\) volts excitation. The following table has been compiled of the variation with distance of the stress associated with the first half cycle of a compressional wave propagating in quartz glass. Measured fractional fringe orders were inserted into equation 5.16. for this purpose.
<table>
<thead>
<tr>
<th>Excitation Voltage</th>
<th>Stress Type</th>
<th>Distance from probe mm</th>
<th>Optical Thickness ( t ) (m)</th>
<th>Fringe Order</th>
<th>Stress ( \sigma ) N/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>-640 V. Tensile</td>
<td>5</td>
<td>10 x 10⁻³</td>
<td>.128</td>
<td>187.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>&quot;</td>
<td>.117</td>
<td>170.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>&quot;</td>
<td>.108</td>
<td>158.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>&quot;</td>
<td>.097</td>
<td>142.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>&quot;</td>
<td>.088</td>
<td>129.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>&quot;</td>
<td>.078</td>
<td>114.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>35</td>
<td>&quot;</td>
<td>.068</td>
<td>99.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>&quot;</td>
<td>.058</td>
<td>86.5</td>
<td></td>
</tr>
</tbody>
</table>

A linear variation of stress with distance travelled by the wave is indicated by figure 5.35. An equation based on experimental work, relating the tensile stress \( \sigma \) for the first half cycle of the wave, with distance travelled \( r \) in quartz glass is as follows

\[
p = -29 r + \text{const.} \tag{5.17}
\]

where the value of the constant is that stress associated with the wave at the instant of entering the quartz glass.

### 5.9.2.3 Shear Waves Obliquely Incident

For these measurements a perspex wedge shear wave probe was selected in which incident compressional waves propagated at 31° in perspex. The shear waves generated in quartz glass travelled at 45° to the vertical axis in the manner shown in figure 5.36.

The first objective was to determine by calculation the optical path length of the circularly polarised light acted upon by the acoustic wave. The compressional wave in perspex generated by a 20 mm 2.5 MHz source, was calculated to have a near field \( N \) of 9.2 x 10⁻³ m, the ultrasonic
FIG. 5.35. VARIATION OF TENSILE STRESS, ASSOCIATED WITH THE FIRST HALF CYCLE OF A COMPRESSIONAL WAVE, PROPAGATING IN QUARTZ GLASS MEASURED BY TARDY COMPENSATION.
FIG. 5.36.

(a.) EXPERIMENTAL ARRANGEMENT

(b.) PLANE OF POLARISATION OF ANALYSER FOR COMPENSATION OF 1st.FRINGE.

(c.) PLANE OF POLARISATION OF ANALYSER FOR COMPENSATION OF 2nd.FFRINGE.

FIG. 5.36. STRESS MEASUREMENT FOR THE FIRST TWO HALF CYCLES OF AN OBLIQUELY INCIDENT SHEAR WAVE IN QUARTZ GLASS.
wavelength of $1.09 \times 10^{-3}$ m. The calculated divergence of the wave occurs at approximately $4^\circ$. This low angle of divergence does not affect the source diameter for shear waves originating at the perspex/quartz boundary.

Calculation of the length of the near field in quartz for shear waves using a source diameter of 20 mm and wavelength of $1.5 \times 10^{-3}$ m gives $N^\nu = 67 \times 10^{-3}$ m. The fractional fringe orders indicated in 5.8.5 have been measured at a distance of $20 \times 10^{-3}$ m from the perspex/quartz boundary and are within the near field of the source. Consequently the optical path length of the circularly polarised light will be $20 \times 10^{-3}$ m, equal to the source diameter.

The values of stress existing in the first two half cycles of the obliquely incident shear wave may be calculated by the insertion of $C = \lambda/p$ into equation (1.2) giving $p - q = FN/t$. The optical path length $"t"$ is in this case 20 mm. The equation then simplifies to:

\[ p - q = 11.0 \times 10^3 \text{ N/m}^2 \] (5.18)

Selecting fringe orders from figure 5.28 for a probe voltage excitation of -500 volts, the relevant F.F.O's for the first and second half cycle are 0.14 and 0.15 respectively. Conversion of these into stresses gives 154 N/m$^2$ and 165 N/m$^2$.

When the stresses associated with these obliquely incident shear waves are compared with compressional waves, at the same propagation distance, higher levels are indicated. For the first half cycle the ratio is 1.35:1 and for the second 1.53:1. A further comparison of interest would be to
measure stresses in shear waves and compressional waves, in which both wave types are generated normally to the probe/testpiece boundary. This may be carried out in future work.

For normally incident shear waves, providing the emitted power levels were standardised, stresses may be expected to be higher than that for compressional waves in the ratio of the wavelengths, i.e. 1.54:1.

5.9.3 Relationship between Acoustic Wave Stresses and the Conventional "A Scope" Ultrasonic Display

It is believed that a useful comparison may be made between the measured acoustic stresses and the logarithmic "A scope" display of stress wave amplitudes. For this purpose a series of experiments was carried out in which stresses of waves reflected from glass/air and glass/plasticine boundaries were compared with "A scope" indications.

Tardy compensation was used to measure fractional fringe orders associated with 5 MHz compressional waves, transmitted by a 10 mm diameter probe excited by a negative pulse of 500 volts peak. For the quartz glass/air boundary condition the time delay was varied to produce a reflected wave at a selected position in the glass block. The F.F.O. was determined. Plasticine was then firmly fixed at the glass boundary and a second measurement performed on the reflected wave. These experimental conditions are illustrated in figure 5.37. A comparison of the amplitude of the first reflected "A scope" signal was noted for the two boundary conditions, the displays are shown in figure 5.38.
FIG. 5.37.

a.) INCIDENT WAVE, 15 mm. FROM PROBE. 
    FACE. (LIGHT BEAM NORMAL TO PAPER)

b.) INCIDENT WAVE WITHIN 
    "NEAR FIELD" OPTICAL 
    PATH LENGTH 10 mm.

c.) REFLECTED WAVE, HAVING TRAVELLED 65 mm, 
    GLASS/AIR BOUNDARY.

d.) OPTICAL PATH LENGTH 
    FOR (c), 20 mm.

e.) REFLECTED WAVE FROM GLASS/PLASTICINE BOUNDARY, 
    OPTICAL PATH AS (c)

FIG. 5.37. EXPERIMENTAL CONDITIONS WITHIN QUARTZ GLASS BLOCK FOR ACOUSTIC WAVE STRESS AND "A SCOPE" CORRELATION.
a.) QUARTZ GLASS/AIR BOUNDARY.

b.) QUARTZ GLASS/PLASTICINE BOUNDARY.
In addition, for comparison, the reflection coefficients for the two boundary conditions were calculated using the acoustic impedances of the boundary media.

In the "A scope" displays it can be seen that the plasticine has produced a decrease in amplitude of 2 db.

The measured F.F.O's are as follows:-

Reflected wave 1st fringe .105 glass/air boundary

" " 2nd " .105 " " "
" " 1st " .085 glass/plasticine boundary
" " 2nd " .083 " " "

Conversion of these fractional fringe orders, "N" into stresses may be made by application of equation \( p - q = 21.9 \text{ N.m}^{-1} \text{ N/m}^2 \)

In the case of the reflected wave the optical path length, equal to "t" in this equation, is 20 mm, (see figure 5.41(d)). Hence the equation simplifies to \( 1.95 \times 10^3 \text{ N}. \text{ N/m}^2 \). Stresses for the reflected waves are then: 205 N/m\(^2\) (glass/air boundary) and 166 N/m\(^2\) (glass/plasticine boundary).

The ratio of these two measured stresses, 1.24:1, is then equivalent to the ratio of the "A scan" signal amplitudes of 2 db, a voltage ratio of 1.259:1.

The Reflection coefficients, "R", may be calculated for plane waves from equation 5.19

\[
R = \frac{W_2 - W_1}{W_2 + W_1}
\]  

where \( W_1 \) is the acoustic impedance of the medium containing the incident wave

\( W_2 \) is the acoustic impedance of the medium containing the transmitted wave.
For quartz glass, $W_1 = 17 \text{ kg/m}^2\text{S}$

" air $W_2 = 0.000398 \text{ kg/m}^2\text{S}$

" plasticine $W_2 = 2.37 \text{ kg/m}^2\text{S}$

When the boundary media are glass and air, $R_{g/a}$ is $-100\%$ approximately. When the boundary media are glass and plasticine $R_{g/p}$ is $-75.3\%$.

The close relationship between the ratio of stresses and the "A scope" signal amplitudes is encouraging. It provides a useful comparison between stress measurements and the conventional method of display. From these results a theoretical relationship between stress and logarithmic amplitude measurements has been shown. This may be expressed in the form:

$$\frac{\sigma_1}{\sigma_2} = K \log_{10} \frac{A_1}{A_2}$$  \hspace{1cm} (5.20)

Calculations of the reflection coefficients $R_{g/a}$ and $R_{g/p}$ have shown them to differ by approximately $25\%$. The negative sign of these coefficients is indicative of a change of phase on reflection, which occurs when the second medium is acoustically softer than the first.

The three methods of obtaining comparative signal amplitudes show good agreement. The optical and logarithmic measurements are confirmed by the calculated sound pressure levels of the reflected wave, for each boundary condition.

6. SUMMARY OF CONCLUSIONS, FUTURE WORK, REFERENCES.

6.1 Summary of Conclusions

(1) Visualisation systems have been developed based on schlieren and photoelastic principles. Each system has shown both continuous waves and pulsed waves propagating in transparent media.
(2) The schlieren system, which uses the Debye-Sears parallel light optical arrangement, has confined its application to acoustic waves propagating in water.

(3) Electrical systems for the generation of continuous and pulsed waves have been described.

(4) The effects of reflection, refraction, diffraction and transmission of continuous and pulsed waves in water have been demonstrated.

(5) The Fresnel and Fraunhöfer relationships for selected probes transmitting into water have been displayed.

(6) For 3 MHz compressional waves in water the effect of the source diameter in generating plane and spherical wavefronts has been clearly shown.

(7) For pulsed waves at 3 MHz in water, resolution of the individual half cycles has been obtained using a commercial stroboscope.

(8) The principles of photoelasticity have been described in which the effect of birefringent and anisotropic materials are compared in plane and circular polariscopes.

(9) A detailed description of the method of construction of a plane polariscope having a large field of view has been given.

(10) The electrical systems required for the photoelastic visualisation of continuous and pulsed waves have been outlined.
(11) The construction of a "standard" or "crossed" circular polariscope has been described in detail. The method included the identification of the "fast" and "slow" axes of quarter wave plates.

(12) The suitability of various types of flashing light source for viewing dynamic effects have been investigated. A comparison has been made between the General Radio "Strobotac" and a laboratory-built spark light source in schlieren and photoelastic systems.

(13) Enhanced sensitivity and resolution has resulted when the spark light source was used on both visualisation systems.

(14) The possible health hazard, due to X-ray emission, from a thyratron valve operating at 15 kV in the spark source, has not shown the requirement for personnel to be graded "classified" with respect to X-radiation. Should the use of the spark light source exceed 15 hours per week, then personal monitors may need to be worn.

(15) An account of acoustic wave types and their generation is given. The interaction of various waves with boundaries, relevant to ultrasonic examination is described.

(16) The principal application of the schlieren apparatus has been in the design of a water column-coupled probe array for ultrasonic testing at speed from a moving vehicle. An examination of a static version of the array has been made using the ultrasonic "A scope" analysis and schlieren visualisation. The basic design of the array has proved suitable for the detection of cracks throughout the rail height.
The new design, with long water path, provided a system with less likelihood of rapidly fluctuating signals, due to variation in water coupling film thickness.

Signals received by each individual probe appeared suitable for analysis by electronic gating and processing systems.

Ultrasonic transducers of 23 mm diameter and 4 MHz nominal frequency have produced satisfactory "A scope" displays with water path ranges of approximately 150 mm.

The concept of membranes to contain water columns has proved practicable, without causing unwanted reflections within the water boxes.

The overall dimensions of the array will be governed by the requirement to have "fore" and "aft" looking probes of both the 40° and 70° type. It is estimated that the length will be 700 mm, width 60 mm and height 180 mm.

A plane polariscope with spark light source has been used with a converging light optical system to visualise three principal acoustic waves. These waves have been classified as compressional, shear and Rayleigh waves.

The plane polariscope has been used to identify these waves by three methods, namely:

a) Velocity of wave propagation
b) Wavelength measurement, or wavelength comparison
c) Determination of the directions of principal stresses associated with the waves.
(24) The technique of stroboscopic photoelasticity has been employed to study phenomena particularly relevant to ultrasonic testing. These have so far included
a) the interaction of ultrasonic waves with defects of particular orientations.
b) interactions with the boundaries of components of various geometries.
c) the conversion of acoustic waves from one mode to another by both refraction and reflection processes.

(25) The generation of Rayleigh waves by wedge transducers using various wedge materials has been examined. When the wedge material was transparent, such as perspex, propagation of the wave within the wedge was also visualised. Additional waves produced by the refraction mode conversion process have been identified. More efficient generation of Rayleigh waves was achieved by using a copper wedge transducer than by a perspex wedge transducer.

(26) Visualisation of shear waves generated by "oblique" and "normal" incidence has been carried out. When "oblique" incidence was used a compressional wave invariably preceded the shear. The problems involved in the generation of "normal" incidence shear waves have received some attention, namely:
 a) coupling of the shear waves into the testpiece
 b) the production of additional unwanted waves.
 These problems have been related to a residual stress measuring technique, currently being investigated within this laboratory.
The examination of a particularly relevant British Railways problem, the detection of "star cracks" at the rail bolt hole has received some attention. The detection of these cracks, oriented in a glass model rail at $45^\circ$ to the vertical plane, has been examined using shear waves generated in glass at $40^\circ$ to a normal to the rail head. The detection of the hole by a standard "A scope" display was compared with photoelastic examination of the mechanisms producing detection. Unexpected mode conversions of the incident shear wave occurred at the hole. Both compressional and shear waves resulted, the latter produced the means of detection.

The mechanisms of detection of "star cracks" has been investigated by using plate glass models in which cracks were machined. Cracks, in these experiments, ranged from 2 mm to 20 mm in length.

The problem of sizing for bolt hole cracks may in the future be investigated using this technique. Investigation of the "db drop" method, currently used by British Rail Civil Engineers on high manganese rail steel, should be possible using the visualisation apparatus.

The optical design of the photoelastic system would be improved by using a parallel light beam through the working section. For the large models currently used this would require large diameter lenses of high quality. These may prove costly depending upon the source of supply. This modification would produce a system in which viewing by eye is easier. In addition the sensitivity would be more consistent over the whole field of view, an important factor when large models are used.
A method for the measurement of the depth of surface-breaking cracks using Rayleigh waves has received detailed attention.

A shear wave piezoelectric device mounted in a copper wedge has been used to generate Rayleigh waves in steel and glass testpieces. In addition three other waves have been produced in the testpiece. Compressional and shear waves originate from a "parent" compressional wave in the wedge. Shear and Rayleigh waves originate from a "parent" shear wave. These waves have been identified by a photoelastic visualisation system.

The depth of surface-breaking cracks has been measured and monitored by using two copper wedge Rayleigh wave probes, one operated as a transmitter and the other as a receiver. The time taken for a Rayleigh wave to travel between the probes has been used to indicate the depth of the crack.

It is essential that a static or dynamic stress is applied to "open" a fatigue crack before a crack length measurement is made.

The crack length should exceed the surface wave beam width to ensure the surface wave propagates beneath the crack rather than around its sides.

Good correlation between measured and actual crack depths has been achieved for cracks ranging in depth from 2.5 mm to 9 mm, for cracks having a single origin of fracture.
(37) A minimum crack depth detectable is theoretically of the order of one wavelength. From the "A scope" displays a crack depth of two wavelengths seems the minimum which may be measured in practice. However very small cracks can be detected due to a change in the shape of the surface wave signal. Maximum crack depths which might be measured will be limited by the attenuation of the Rayleigh waves in the medium of the testpiece. Work currently underway suggests measurement of propagation of crack depths to 25 mm is possible in rail steel. This value may not be the upper limit.

(38) The display of received "A scope" information varies considerably with the spacing of the probes. It is particularly dependent on probe spacing for the larger crack depths measured here.

(39) The technique of using the minimum practical probe spacing will in some experiments have advantages in signal interpretation. It is suggested that in future work this technique could be used to advantage.

(40) A method has been described for "setting up" a "standard" circular polariscope for the determination of stresses in acoustic waves by Tardy compensation.

(41) The development of stress measurement from that in a statically loaded araldite beam to the dynamic stresses of acoustic waves has been made. Results of static stress measurements made photoelastically have been confirmed by theoretical calculations.
Identification of stress types associated with each half cycle of a compressional wave have been determined for a probe excited electrically with a known voltage polarity. Reversal of the polarity of the probe excitation voltage resulted in a reversal of the stress type in particular half cycle of the wave.

Identification of stress types associated with each half cycle of a shear wave have similarly been determined. "Positive-going" and "Negative-going" shear stresses have been shown to be associated with a particular voltage polarity for a selected probe. A reversal of the stress type resulted when the polarity of the voltage excitation was reversed.

In this instance, using a 2 MHz 10 mm diameter probe, for compressional waves propagating in a quartz glass block the experimentally determined stresses have been found to decrease linearly, with distance \( r \), for which a law has been derived of the form \( p = - 29 \, r + \text{const} \).

When stresses of 40° shear waves and 0° compressional waves are compared, higher stresses are found in the shear waves. The ratio \( \sigma_s / \sigma_c \) is approximately in the ratio of the wavelengths for these wave types.

A method has been devised for the comparison of acoustic wave stresses with the conventional ultrasonic "A scope" display. Confirmation of the experimental results has been made by calculation of relevant reflection coefficients.
The work described here has resulted in a quantification of the stresses associated with acoustic waves of compressional and shear types, which previously was not possible. This development may be applied to the study of stresses of waves produced by reflections within testpieces. The method has been outlined for waves simply reflected at a glass/air boundary, but could be extended to more complex geometries of rail bolt holes.

A series of slides showing the various wave types and their interaction with boundaries has been prepared for the British Railways N.D.T. School. These slides were taken by the Senior Instructor to Angola in 1974 when invited to lecture on ultrasonic rail testing. Since the students spoke only Portuguese, it was believed that visual aids were essential to produce an efficient teaching programme. These slides, it is reported, were well received by the students.

6.2 Future Work

6.2.1 Apparatus

Should there be a requirement to further investigate ultrasonic probe array characteristics in water boxes, a schlieren system using mirrors should be used. For a 300 mm field of view, schlieren mirrors would at present cost £250 each.

The photoelastic polariscopes may be improved for viewing by modifications to the optical system. A high quality large diameter lens, which produces a parallel light beam through the polariscope, would improve viewing by eye. An alternative arrangement for viewing might employ a closed circuit television camera. A vidicon tube of higher sensitivity than that currently available may be required in the camera, due to
the attenuation of the light by the polaroid filters.

The spark light source currently used has a glass thyratron valve. Improvements in the rigidity and compactness of the source and brightness of the spark would result by constructing a similar device using a ceramic thyratron valve.

6.2.2 Experimental Work

The photoelastic work has included a study of a range of ultrasonic probes. It is believed that this type of experimental work will find further applications. The design of probes for crack detection in rails will shortly continue, comparing the efficiency of shear wave probes of particular angles for rail bolt hole crack detection. A similar investigation for ultrasonic coach probes, obtained from various manufacturers, is currently underway.

The problem of defect sizing is being approached by using focussed shear wave probes of special design. Such probes are not available from manufacturers since their efficient design is quite complex. The waves generated by prototype probes of this type may be visualised in suitable glass testpieces, enabling design features and the effect of modifications to be clearly seen.

The measurement of the depth of surface-breaking cracks has been reported here. The probes used have proved efficient for this particular application, but cannot be used in the transmit/receive mode. A new type of liquid wedge Rayleigh wave probe is being manufactured to specification and should be evaluated on the photoelastic rig.
Wave interactions with testpiece boundaries is an important part of ultrasonic testing. The interaction of waves with the geometrical shapes found in railway axles does in certain cases produce unexpected "A scan" displays. A study of waves propagating in two dimensional models of axle shapes would prove beneficial, both as a teaching aid and as an aid in ultrasonic signal interpretation.

Work on acoustic wave stress measurement could be applied both in Engineering and Medical ultrasonics. Quality control of probes might be achieved by measurement of the stress produced by waves in glass. The Tardy method could be applied when known electrical voltages were applied to the probe. Installation of such a system might be made by probe manufacturers within the Railway organisation and by external suppliers.

Different types of stress associated with the individual half cycles of compressional and shear wave have been observed and measured. The interaction of certain types of stress wave, tensile or compressive in the case of compressional waves, with cracks in particular stressed areas has not been investigated. This would undoubtedly produce academic interest, the practical benefits are not yet fully appreciated.

The sizing of cracks associated with rail bolt holes is currently made by the "db drop" method. Considerable debate has recently taken place regarding the efficiency of this method. The accuracy and reliability of crack sizing, in this particular railway application should be effectively investigated by the photoelastic visualisation apparatus.
The interaction of ultrasonic waves with spheroidal defects can be visualised photoelastically using glass testpieces with spheroidal defects incurred during manufacture. Such defects may be obtained in a range of sizes and may be compared with those occurring in various types of weld. The application to defect sizing in weld testing may prove beneficial.

During the investigations with Rayleigh waves the transmitted wave frequency was shown to be approximately one half that of fundamental frequency of the piezoelectric plate. A lower transmitted frequency resulted in a reduced sensitivity of the ultrasonic system. The relationship between the damping media, in contact with piezoelectric plate, and the frequency of waves transmitted could prove worthwhile, for probes which rely upon the wedge principle.

In the field of medical ultrasonics it is believed that some concern has been expressed about the magnitude of stress waves used in ultrasonic diagnosis. It might be envisaged that visualisation media acoustically resembling human tissue could be selected, enabling stress measurements relevant to ultrasonic diagnosis to be made. It is believed that the human eye, being acoustically consistent throughout, might be acoustically "matched" by certain birefringent jellies. Hence such a jelly may prove a suitable visualisation medium in which to carry out stress measurements.

6.3 References


