Medical diagnosis, cleaning, drilling, non-destructive testing, and instrumentation and control are some of the many varied fields in which ultrasonic methods are used today. But, despite the far-reaching importance of the subject, little has been written for the person requiring a practical working knowledge of ultrasonics unclouded by all the theoretical details. This gap in the literature is filled by *Ultrasonics: Methods and Applications*.

The book starts with an easily understood summary of the necessary theory and goes on to explain how ultrasound is generated and received. The rest of the work discusses the various techniques and provides a study of the wide variety of applications of both low and high intensity ultrasonics. Throughout the book the use of mathematics has been kept to a minimum, but numerous references are provided for those who wish to study the subject in greater detail.

Physicists, chemists, electrical engineers, mechanical engineers, biologists, medical practitioners and students will find this book invaluable in providing a clear, concise, up-to-date account of the techniques and applications of ultrasonics.

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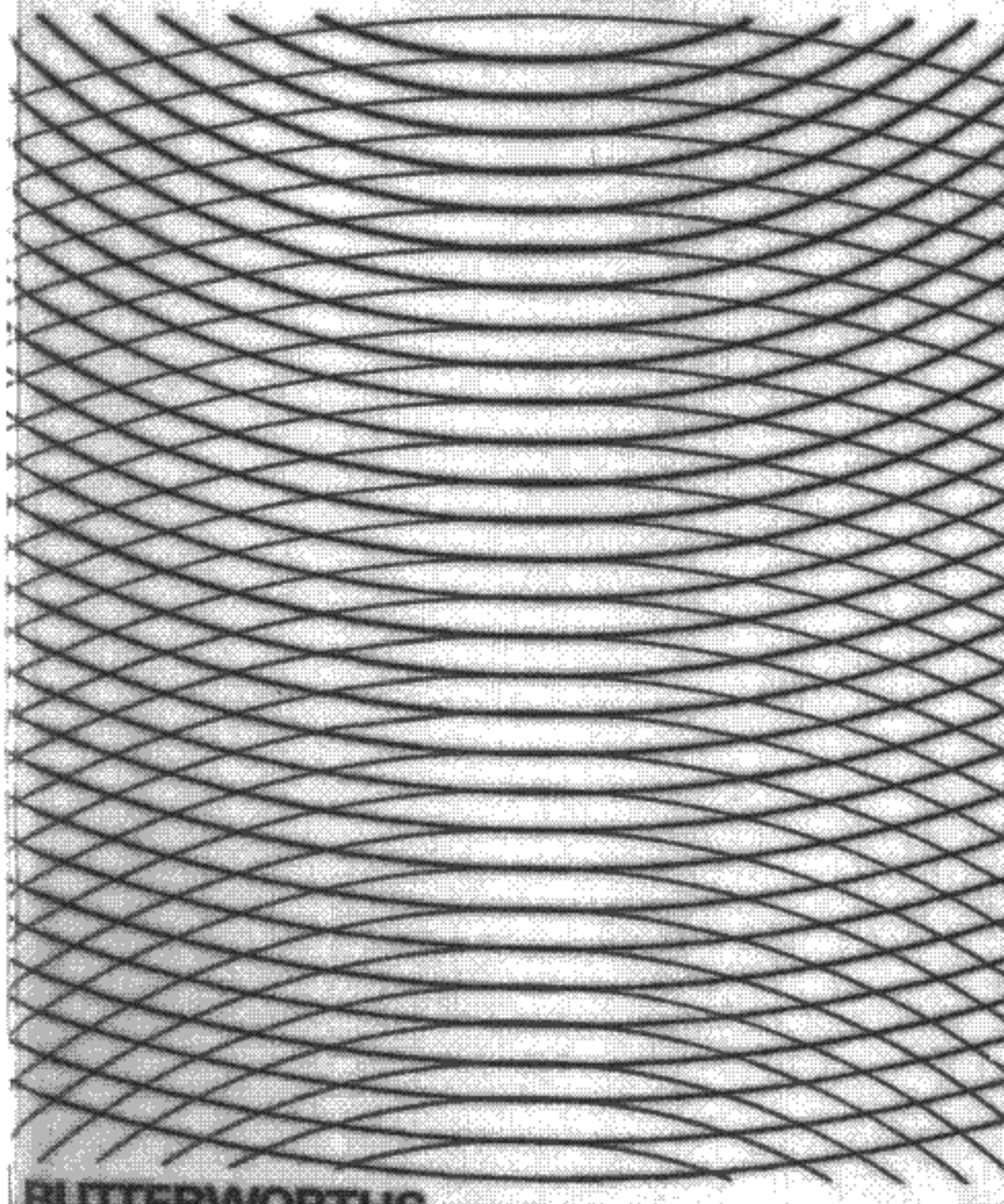
BLITZ

ULTRASONICS: METHODS AND APPLICATIONS

Bb

ULTRASONICS METHODS AND APPLICATIONS

JACK BLITZ



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ULTRASONICS:
METHODS AND APPLICATIONS

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JACK BLITZ
M.Sc., F.Inst.P., M.NDT.S.
Department of Physics
Brunel University

LONDON BUTTERWORTHS

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ENGLAND
Butterworth & Co (Publishers) Ltd
London: 88 Kingsway, WC2B 6AB

AUSTRALIA
Butterworth & Co (Australia) Ltd
Sydney: 586 Pacific Highway Chatswood, NSW 2067
Melbourne: 343 Little Collins Street, 3000
Brisbane: 240 Queen Street, 4000

CANADA
Butterworth & Co (Canada) Ltd
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Butterworth & Co (New Zealand) Ltd
Wellington: 26–28 Waring Taylor Street, 1
Auckland: 35 High Street, 1

SOUTH AFRICA
Butterworth & Co (South Africa) (Pty) Ltd
Durban: 152–154 Gale Street

First published 1971

ISBN 0 408 70212 5 Case
ISBN 0 408 70213 3 Limp
Reproduced by photo-lithography and made at the Pitman Press, Bath

PREFACE

This book is intended for the person who requires a working knowledge of ultrasonics but who may not have the necessary background in physics, mathematics, and electronics normally expected of readers of most existing works in the field. It is based on the author's *Fundamentals of Ultrasonics*, but the academic level has been lowered considerably and the scope has been extended to cover a wider range of practical applications.

It is hoped that the book will meet the requirements of engineers and scientists, at all levels, and also of medical practitioners.

The author wishes to thank the various sources of information acknowledged in the text and also Professor P. Feltham and Dr G. F. Lewin of Brunel University, Dr B. Brown of the University of Salford, Mr A. E. Crawford of Radyne Ltd, Messrs Dawe Instruments Ltd, Messrs Kerry Ultrasonics Ltd, and Messrs Westool Ltd for their kind co-operation.

Brunel University

J.B.

NOTES ON UNITS

To conform with present-day practice, SI units are used throughout this book and the following remarks may prove useful to those unfamiliar with them.

Mass, length, and time are expressed in the metric system in terms of the kilogram (kg), metre (m), and second (s). The unit of frequency is the hertz (Hz), which is equivalent to the cycle per second (c/s) in other systems of units. Multiples and submultiples of these units are related to one another by integral powers of 10^3 using the following prefixes:

pico (p) = 10^{-12}	kilo (k) = 10^3
nano (n) = 10^{-9}	mega (M) = 10^6
micro (μ) = 10^{-6}	giga (G) = 10^9
milli (m) = 10^{-3}	

For example,

1 ns (1 nanosecond) = 10^{-9} s
1 μm (1 micro-metre) = 10^{-6} m (i.e. 1 micron)
1 GHz (1 giga-hertz) = 10^9 Hz (i.e. 10^9 c/s)

CONTENTS

CHAPTER ONE

INTRODUCTION

1.1 General considerations

Ultrasonics, the study of sound propagated at frequencies beyond the range audible to people (i.e. above 18 MHz) is not a new subject. Galton was aware of the existence of ultrasound, and the whistle used by him in 1883 in his studies of the limits of the acoustic spectrum perceived by humans can be regarded as one of the first man-made ultrasonic transducers. Galton's instrument at that time appeared to have little other application except, perhaps, as a dog whistle.

In the three decades following Galton's work, ultrasonics remained a little-known curiosity; its development was hampered by the lack of progress in electrical technology. Thus, while the piezoelectric and magnetostrictive effects were known, they were not ultilised in the construction of useful ultrasonic instruments. As a result of the experiences of the 1914–1918 war, an interest in the subject developed and Langevin, in France, investigated the use of quartz transducers for transmitting and receiving ultrasonic waves, of relatively low frequencies, in water; they provided promising means for the detection of submarines and for under-water communication.

After the war, rapid developments took place in the fields of electronics and, in 1925, Pierce was using quartz and nickel transducers for generating and detecting ultrasound at frequencies extending into the mega-hertz range. By this time, Debye and Sears and also Lucas and Biquard, working independently of one another, had discovered the ultrasonic diffraction grating. The use of ultrasound to study the acoustical properties of liquids and gases then progressed steadily, and, by the 1930s, ultrasonic investigations into the properties of solids were being made. In 1934, Sokolov in the USSR published the first known work on ultrasonic flaw detection.

Between the two World Wars, a considerable amount of work was done on the development of high-intensity ultrasonic generators, including whistles, sirens, and electric spark-gap devices. An important year was 1927, when Hartmann and Trolle produced details of their ultrasonic whistle which proved capable of propagating ultrasonic waves having powers of up to 50 W in fluids. However, the scope of application remained limited until World War II provided new grounds for developments.

An excellent account of the early work done on the subject is to be found in Bergmann's *Ultrasonics*, which is generally recognised to be a classic in this field.

The use of the pulse methods derived from radar techniques enhanced the scope of ultrasonics considerably, and, in post-war years, it became widely applied in the non-destructive testing of materials, in medical diagnosis, and in various forms of instrumentation and control. Concurrently, the potentialities of high-intensity ultrasound, including cleaning, emulsification, drilling, and the various methods of processing materials, were realised.

In the 1960s, new materials and techniques were discovered and, with the developments of microwave propagation, it was found possible to generate ultrasonic waves at frequencies of up to 100 GHz. Applications of these ultra-high frequencies have already been shown to be of considerable importance in fundamental research in physics and in communication and computer technology.

Ultrasound is used in preference to audible sound in many applications for one or more of the following reasons:

1. It has directional properties — the higher the frequency, the greater the directivity. This is a main consideration in, for example, flaw detection and under-water signalling.
2. At the higher frequencies the wavelengths become correspondingly shorter and are comparable with, or even much less than, the dimensions of the samples of the material through which propagation takes place. This is important for the measurement of small thicknesses or for high-resolution flaw detection.
3. It is silent, which is advantageous for high-intensity applications. These applications can often be carried out more efficiently at audible frequencies, but the resulting noise may be intolerable and possibly injurious.

Ultrasonic applications are rigidly classified as being of either low or high intensity. At low intensities, ultrasound is used either as a means of investigating the properties of samples of materials or as a method of control. In most cases it is important that the material of propagation does not suffer any permanent change in its structural and chemical properties. Many low-intensity applications are made at very high frequencies, typically in the mega-hertz range, and the acoustic powers involved may range from a few microwatts to several tens of milliwatts.

At high intensities, ultrasound is generally used for changing the properties of the material through which it is passed. High-intensity applications are nearly always made at low frequencies, often just above the audible limit, and acoustic powers used here may extend from a few milliwatts to kilowatts.

This book is intended to serve as an elementary introduction; readers wishing to delve more deeply into the subject should consult the bibliography given below and, for more specific information, the references listed at the ends of each chapter.

1.2 Bibliography

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KRAUTKRAMER, J. and H., *Ultrasonic Testing of Materials*, Allen & Unwin, London (1969)
WELLS, P. N. T., *Physical Principles of Ultrasonic Diagnosis*, Academic Press, London (1969)

1.2.5 Current developments in ultrasonics

The following journals are recommended for up-to-date information on the subject.

Acustica, Germany (articles in English, French, and German)
IEEE Transactions on Sonics and Ultrasonics, USA
Journal of the Acoustical Society of America, USA
Soviet Physics: Acoustics (English translation), USA
Ultrasonics (Great Britain)

CHAPTER TWO

BASIC THEORY

2.1 General considerations

The only distinction between audible sound and ultrasound is that the latter cannot be detected by the human ear. The theory of ultrasonic propagation is thus exactly the same as that of audible sound, as to be found in any standard textbook on acoustics (see, for example, Stephens and Bate[1]). In this chapter, a simplified account is given of that theory related to the various phenomena and applications described in this book.

Sound is generated in a material as a result of some mechanical disturbance taking place within it. The disturbance may, for example, be a shock excitation, such as an explosion or the striking of a bell. On the other hand, the disturbance may take the form of continuous vibrations resulting, perhaps, from speech, the playing of a musical instrument, or the regular motion of a machine. In each case it can be shown that the source of sound is in a state of vibration.

2.2 Vibrations and waves

Vibrations are characterised by their *frequencies*, i.e. the number of complete periodic cycles undergone in unit time, e.g. one second. The unit of frequency is the *hertz* (Hz), and higher frequencies are expressed in kilo-hertz (1 kHz = 10^3Hz), mega-hertz (1 MHz = 10^6Hz), or giga-hertz (1 GHz = 10^9Hz).

Disturbances producing sound waves take place over continuous ranges or *bands* of frequencies, the widths of which depend on the nature of the source and the manner of its mounting (see Section 2.10). For continuous vibrations, the bandwidths are narrow and centred at a number of discrete frequencies, the values of which bear simple numerical relationships to one another (see Section 2.9). The lowest of these frequencies is called the *fundamental,* and the others are called *harmonics* or *partials*. The second harmonic has a frequency which is twice that of the fundamental, the third harmonic has one which is three times that of the fundamental, and so on. With shock excitation, however, the frequencies extend over a continuous and, perhaps, wide range.

For most ultrasonic applications, the source consists essentially of a plane surface oscillating with simple harmonic motion at a single frequency in a manner similar to that of a piston in the cylinder of an engine but with a much smaller amplitude and at a very much higher frequency. If the displacement of the source from its position of rest is measured at frequent intervals, e.g. every millionth or ten-millionth of a second, a graph similar to the one illustrated in Figure 2.1 is obtained.

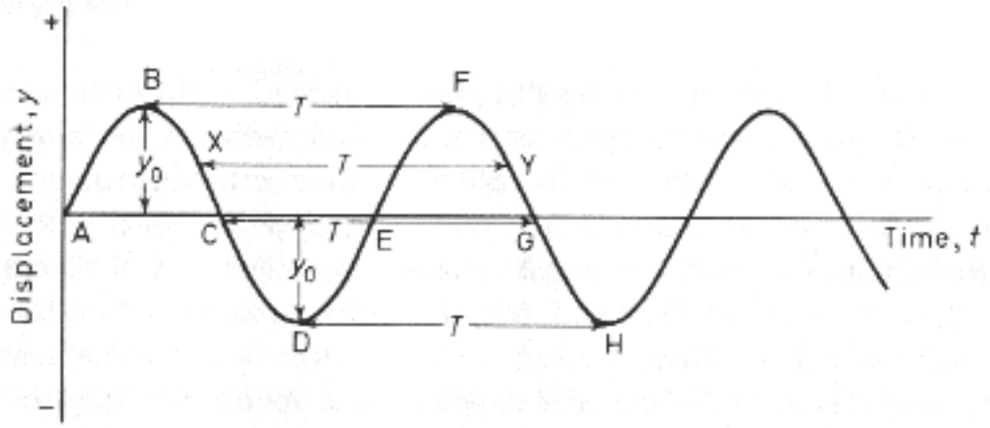

Figure 2.1 Variation of displacement y *with time* t *for an ultrasonic source*

The time taken for the source to execute one complete vibration is called the *period T*, which is represented on the graph of Figure 2.1 alternatively by the distance BF between two neighbouring peaks, the distance DH between two neighbouring troughs, or distances such as AE, CG, and XY. These distances are equal to one another and represent the separation of any two points closest together on the graph for which the phases of the vibrations are the same. It can readily be seen that the reciprocal of the time period T, measured in seconds, is equal to the frequency f, measured in hertz, i.e.

$$T = \frac{1}{f} \tag{2.1}$$

The shape of the curve is said to be sinusoidal and can be expressed mathematically as follows

$$y = y_0 \sin \frac{2\pi t}{T} = y_0 \sin 2\pi f t = y_0 \sin \omega t \tag{2.2}$$

where y represents the displacement at any time t, and ω is the angular frequency defined as

$$\omega = 2\pi f \tag{2.3}$$

Every half-cycle, the source is displaced alternately in opposite directions by a maximum amount y_0 called the *displacement amplitude.* The angle expressed alternatively as $2\pi t/T$, $2\pi ft$, or ωt in equation 2.2 is called the *phase angle* (measured in radians) and indicates the phase of vibration at a given time t. The change in phase angle corresponding to an elapse of a single time period T is equal to 2π (i.e. 360°).

The source transmits vibrational energy to the particles (e.g. atoms or molecules) of that part of the material in immediate contact with it. The energy then passes progressively through the material in the manner described below.

Figure 2.2 illustrates two parallel plates separated by the material of propagation. The left-hand plate acts as the source, which vibrates with simple harmonic motion, and the right-hand plate acts as the receiver. Imagine that the material is divided into a very large number of thin parallel-sided layers, each of equal thickness, as indicated by the letters A, B, C, . . ., X, Y, and Z. When the phase of the vibrations of the source is such that a displacement occurs, say, to the right by a given amount, the layer A is pushed in the same direction to suffer a similar displacement. The layer B is then displaced in turn, and the displacements are progressively transmitted from each layer to its neighbour until the final layer Z is reached, the displacement of which is suffered by the receiver. As the phase of vibration of the source changes, the magnitude of the displacement varies in the manner shown in Figure 2.1, taking alternative positive and negative values. Each layer and also the receiver experiences the same phenomenon.

Because it takes a small but finite time for the energy to pass from one layer to the next, the phase of vibration of each layer differs from that of its neighbour by a small but finite amount. The sound waves thus take a given time to pass from the source to the receiver. The velocity of the waves has a constant value for a particular material under specified physical conditions (e.g. constant temperature); this value depends on the elastic modulus and density of the material (see Section 4.1). If we consider some layer K (Figure 2.2) situated at a distance of, say, x from the source, the time taken for the sound to reach this layer is equal to x/c, where c is the velocity of sound in the material. Thus the phase of vibration of K at any time t is identical to that of the source at a previous time $t - x/c$, and the value y of the displacement is obtained by substituting this quantity for t in equation 2.2, i.e.

$$y = y_0 \sin \omega \left(t - \frac{x}{c}\right) \qquad (2.4)$$

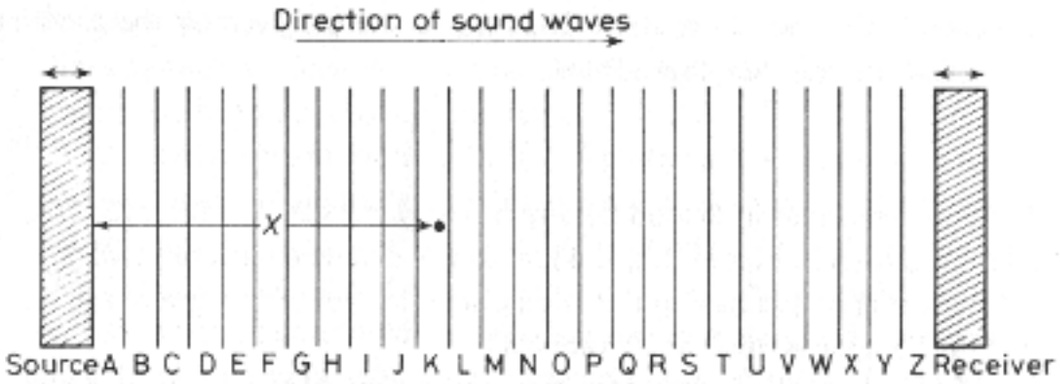

Figure 2.2 Division into layers of a material through which ultrasound is propagated

Equation 2.4 describes the propagation of *plane waves* from which no energy has been lost on the journey, i.e. there is no attenuation (see Section 2.13) to give rise to a reduction of the value of y_0.

If the thickness of each layer is regarded as being infinitesimally small, the displacement y at a distance x from the source may be regarded as being the same for all the particles in the layer. Then y is called the *particle displacement* and y_0 the *particle displacement amplitude.*

It must be made quite clear that it is the *energy* of the vibrations (i.e. the waves) and not the particles in the material which move from the

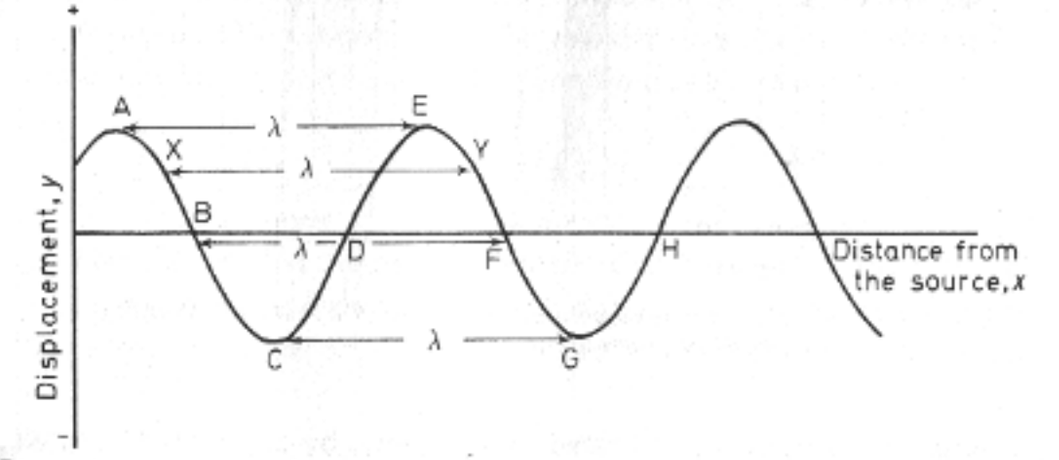

Figure 2.3 Variation of particle displacement y *with distance* x *from the source at a given time for plane waves*

source to the receiver. The particles themselves only vibrate about their mean positions with minute displacement amplitudes, typically of a small fraction of a millimetre.

Now consider the displacements at some *fixed* time t of all the particles lying on a straight line joining the source to the receiver. The quantity t in equation 2.4 is then constant, and the equation simply provides a sinusoidal relationship between y and x, as illustrated in Figure 2.3. While the source executes a complete cycle of vibration in

the time T, the sound waves travel a fixed distance, given by the product cT, called the wavelength λ. Thus

$$c = \frac{\lambda}{T} = \lambda f \qquad (2.5)$$

The wavelength, as indicated by any of the distances AE, BF, CG, DH, and XY shown in Figure 2.3, is equal to the distance between two neighbouring points having the same phase, i.e. for which the phase angle difference is 360° or 2π radians.

Up to now we have discussed the propagation of *longitudinal waves*, so called because the vibrations of the particles in the material take place in the direction of motion of the sound. The kind of longitudinal waves relevant to the study of ultrasonics is sometimes called *compressional waves* (or compression waves) because the imaginary layers in the materials of propagation are subjected to alternate compressional and tensile stresses by the waves. At any given time, the layers take on the appearance of Figure 2.4, where the centres of neighbouring compressed

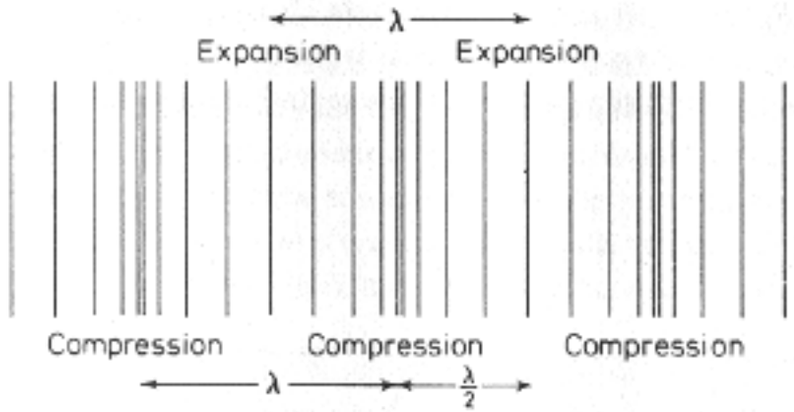

Figure 2.4 Appearance (exaggerated) of layers of a material in which longitudinal waves are propogated

or expanded regions are separated, respectively, by distances of one wavelength. The distance between the centre of a compression and that of the next expansion is one half-wavelength.

Another form of propagation is that of *transverse waves*, for which the vibrations of the particles in the material occur at right angles to the direction of wave motion. The imaginary layers shown in Figure 2.2 are then subjected to alternating shear stresses, and the resulting strains are directed parallel to their surfaces. The term *shear waves* is often used to describe this kind of transverse wave propagation. Shear waves can generally be passed through only solids, because liquids and gases do not usually support shear stresses. An exception to this rule, to be discussed

in Section 4.4, is the propagation of shear waves in highly viscous liquids, such as heavy lubricating oils, for very short distances, often only a small fraction of a millimetre.

Consideration so far has only been given to the motion of *plane waves*, which originate from vibrating plane sources and for which the wavefronts are plane surfaces parallel with the source. When the source has dimensions which are small compared with the wavelength, the waves may be considered to travel equally in all directions and the wavefronts are spheres having their common centre at the source, i.e. *spherical waves* are propagated. At large distances from the source, the curvatures of spherical wavefronts are small enough for the waves to be considered as being plane. It should be noted that most low-intensity applications involve the use of plane waves.

2.3 Wave characteristics

The principal characteristics of acoustic waves are: (a) particle displacement y, (b) particle velocity u, and (c) acoustic pressure (or stress) p.

The particle displacement has already been defined in the previous section. However, it is often more convenient to consider the *particle velocity* u, which is defined as the velocity of a vibrating particle in the medium (*not* of the waves) at a given time and location, i.e.

$$u = u_0 \sin \omega \left(t - \frac{x}{c}\right) \qquad (2.6)$$

where u_0 is called the *particle velocity amplitude.* Now the material carrying the sound waves is subjected to an alternating excess pressure or stress called the *acoustic pressure* (or *stress*) p, which varies as follows:

$$p = p_0 \sin \omega \left(t - \frac{x}{c}\right) \qquad (2.7)$$

Here p_0 is the *acoustic pressure* (or *stress*) *amplitude.*

2.4 Specific acoustic impedance

There is a similarity between the variations of sound wave characteristics and those of certain quantities used in electrical a.c. theory. Thus acoustic pressure may be regarded as being analogous to electrical voltage, particle velocity to electrical current, and particle displacement to electrical charge. Using the acoustic equivalent of Ohm's law, a

quantity known as the *specific acoustic impedance* Z_a, equivalent to electrical impedance, may be defined as

$$\frac{p}{u} = Z_a \tag{2.8}$$

Like electrical impedance, Z_a is, in general, a complex quantity but, for plane progressive waves, i.e. plane waves not reflected to form stationary waves (see Section 2.9), the imaginary component disappears leaving a real quantity (cf. electrical resistance). This real quantity can be shown to be equal to the product of the density ρ and the velocity c of sound for the material and is called the *characteristic impedance* R_a, i.e.

$$R_a = \rho c \tag{2.9}$$

The value of the characteristic impedance for a given material can be seen to depend only on its physical properties and thus to be independent of the wave characteristics and the frequency. Values of characteristic impedances for a number of familiar materials are given in Table 2.1.

Table 2.1 ACOUSTIC VELOCITIES AND CHARACTERISTIC IMPEDANCES FOR SOME COMMONLY USED MATERIALS AT ROOM TEMPERATURE

Material	*Longitudinal wave velocity, c* ($m\,s^{-1}$)	*Density, ρ* ($kg\,m^{-3}$)	*Characteristic impedance, ρc* ($kg\,m^{-2}s^{-1}$)
Aluminium	6 400	2 700	$1{\cdot}7 \times 10^7$
Brass	3 500	8 600	$3{\cdot}0 \times 10^7$
Copper	4 700	8 900	$4{\cdot}2 \times 10^7$
Gold	3 700	10 500	$3{\cdot}9 \times 10^7$
Iron	5 900	7 900	$4{\cdot}7 \times 10^7$
Lead	1 200	11 300	$1{\cdot}4 \times 10^7$
Nickel	5 600	8 900	$5{\cdot}0 \times 10^7$
Platinum	3 900	21 450	$8{\cdot}4 \times 10^7$
Silver	3 200	19 300	$6{\cdot}2 \times 10^7$
Steel	6 000	7 800	$4{\cdot}7 \times 10^7$
Barium titanate	5 000	5 400	$2{\cdot}7 \times 10^7$
Quartz	5 700	2 600	$1{\cdot}5 \times 10^7$
Nylon	2 700	1 140	$3{\cdot}0 \times 10^6$
Perspex (lucite)	2 700	1 200	$3{\cdot}2 \times 10^6$
Glycerol	1 900	1 260	$2{\cdot}4 \times 10^6$
Lubricating oil (typical values)	1 400	800	$1{\cdot}1 \times 10^6$
Olive oil	1 400	900	$1{\cdot}3 \times 10^6$
Water	1 500	1 000	$1{\cdot}5 \times 10^6$
Air	330	1·3	430
Hydrogen	1 300	0·90	110
Oxygen	320	1·4	450

2.5 Acoustic intensity

The power at any point in an acoustic field may be conveniently expressed in terms of the *intensity*, defined as the rate of flow of acoustical energy through unit area of an imaginary plane surface drawn about the point in question and orientated at right angles to the direction of wave-motion. The intensity I may be expressed in watts per square metre ($W\,m^{-2}$), and its relationships with other acoustical quantities are as follows:

$$I = \frac{p_0 u_0}{2} = \frac{u_0^2 \rho c}{2} = \frac{p_0^2}{2\rho c} \tag{2.10a}$$

Alternatively, I can be related to the root mean square (r.m.s.) values, the r.m.s. value being equal to $1/\sqrt{2}$ of the amplitude, i.e.

$$I = p_{\text{r.m.s.}} u_{\text{r.m.s.}} = u_{\text{r.m.s.}}^2 \rho c = \frac{p_{\text{r.m.s.}}^2}{\rho c} \tag{2.10b}$$

The intensity should remain constant at all points within unattenuated plane progressive waves (but see Section 2.14), but for spherical waves, it decreases inversely with the square of the distance from the source.

2.6 Pressure of radiation

It can be shown that, when some obstacle is placed in the path of sound waves, it experiences a steady direct pressure P, called the *pressure of radiation*. For plane progressive waves,

$$P = Ic \tag{2.11}$$

2.7 The decibel scale

In the study of ultrasonics, variations of intensity, acoustic pressure, etc., often take place in a logarithmic manner (see Sections 2.11 and 2.13) and measurements are made in comparison with some fixed standard. An intensity I may be expressed in relation to a reference intensity I_0 as follows:

$$\text{Intensity level} = 10 \log_{10} \frac{I}{I_0} \text{ decibels (dB)} \tag{2.12a}$$

It is usual to employ an a.c. voltmeter or a cathode ray oscilloscope for detection. These instruments measure a voltage which is proportional to

the acoustic pressure and, for this reason, the number of decibels change is obtained from pressure levels, i.e.

$$\text{Pressure level} = 20 \log_{10} \frac{p_{\text{r.m.s.}}}{p'_{\text{r.m.s.}}} \text{ dB} \qquad (2.12b)$$

where $p_{\text{r.m.s}}$ and $p'_{\text{r.m.s.}}$ are the r.m.s. acoustic pressures corresponding to I and I_0 respectively. The number 20 in equation 2.12b replaces 10 in equation 2.12a because the intensity is proportional to the square of the r.m.s. acoustic pressure. Thus the same number of decibels results in a given case whether intensity changes or pressure changes are measured.

2.8 Reflection and transmission at normal incidence at a plane boundary

When a beam of plane waves strikes a plane boundary separating two materials, some of the sound energy is transmitted forward and the remainder reflected backward (see Figure 2.5). The relative amounts

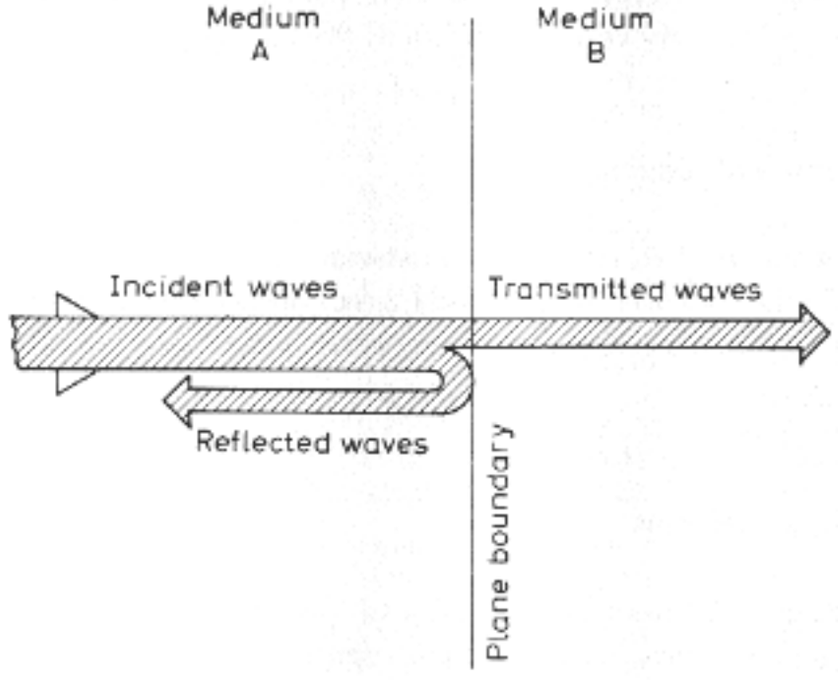

Figure 2.5 Reflection and transmission for normal incidence at a plane boundary

of reflected and transmitted intensities are expressed by the reflection and transmission coefficients, defined as follows:

$$\text{Reflection coefficient} = \frac{\text{Intensity of reflected waves at the boundary}}{\text{Intensity of incident waves at the boundary}} \qquad (2.13)$$

$$\text{Transmission coefficient} = \frac{\text{Intensity of transmitted waves at the boundary}}{\text{Intensity of incident waves at the boundary}} \qquad (2.14)$$

The coefficients may be expressed either as percentages or as decreases in the number of decibels. It can be shown (see, for example Blitz[2]) that:

$$\text{Reflection coefficient} = \frac{(R_1 - R_2)^2}{(R_1 + R_2)^2} \qquad (2.15)$$

$$\text{Transmission coefficient} = \frac{4R_1R_2}{(R_1 + R_2)^2} \qquad (2.16)$$

where R_1 and R_2 are the characteristic impedances (see equation 2.9) for the two materials. Using the values of the characteristic impedances given in Table 2.1, reflection and transmission coefficients can be calculated for pairs of different materials. The equations show that the transmission coefficient approaches unity and the reflection coefficient tends to zero when R_1 and R_2 have approximately similar values. The materials are then said to be well matched or coupled. On the other hand, when the two materials have substantially dissimilar characteristic impedances, e.g. for a solid or liquid in contact with a gas, the transmission and reflection coefficients tend to zero and 100 per cent, respectively. The materials are then said to be mismatched or poorly coupled.

A difficulty may arise when both the materials are solids. Unless their surfaces are ground flat to optical precision, contact occurs only in a few places and there is, effectively, a thin layer of fluid between them. If the fluid is a liquid for which the characteristic impedance is not too far removed from those of the solids and the thickness of the layer is much less than a wavelength, the value of the transmission coefficient is the same as if the two solids were in perfect contact. On the other hand, if the layer of fluid were a gas, as would be the case if the two materials were in air, the transmission coefficient is reduced almost to zero.

Substitutions of values of characteristic impedances, shown in Table 2.1, into equation 2.16 give 75 per cent for the transmission coefficient when a quartz crystal is placed in perfect contact with a steel block. In practice, however, there is a gap of an effective width of 1 μm when the surface of the steel is machined to a tolerance of this magnitude. At a frequency of 1 MHz, there is a reduction of transmission coefficient by only one or two per cent when the gap is filled with a liquid. On the other hand, if the gap were to contain air, the transmission coefficient would be reduced to about 4×10^{-9}, a decrease of more than 80 dB. This illustrates the importance of the use of a coupling fluid when transmitting or receiving sound waves in solids.

2.9 Stationary waves and resonance

When sound waves are reflected in the manner described in the previous section, the incident and reflected beams interfere with one another and a stationary (or standing) wave pattern is observed. If, after a single reflection, the acoustic pressure or particle velocity amplitudes A at various distances from the reflecting surface are measured, the amplitude variation depicted in Figure 2.6 is obtained. It is seen that the neighbouring maxima and minima, respectively, are one half-wavelength apart and

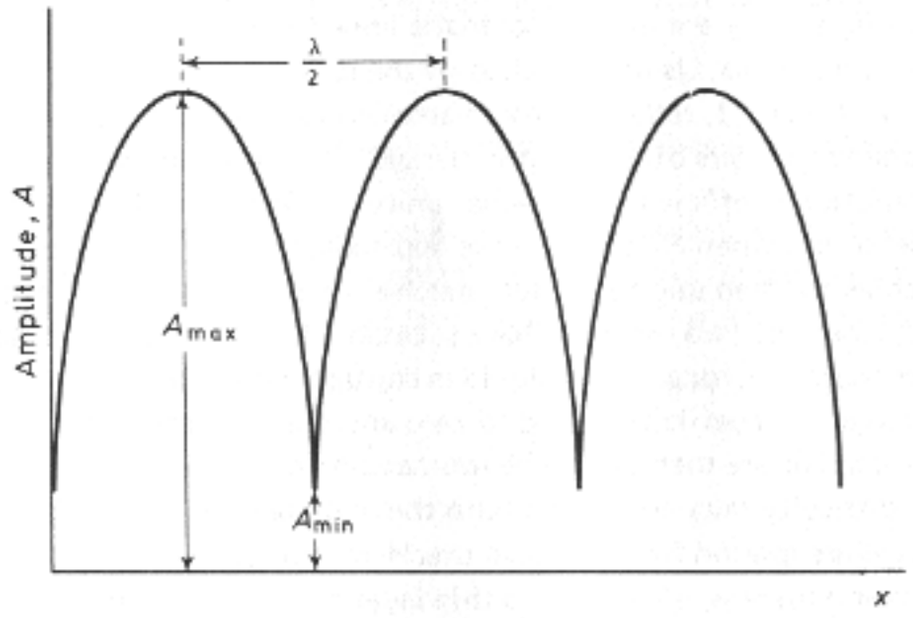

Figure 2.6 Variation of amplitude A with distance x from the source of a stationary wave system

that the distance between a maximum and its neighbouring minimum is a quarter-wavelength. The ratio of the amplitude at the maximum to that at the minimum is called the *stationary* (or *standing*) *wave ratio* (s.w.r), a quantity dependent on the reflection coefficient at the boundary and the attenuation coefficient (see Section 2.13) for the material.

In practice, measurements are usually made on materials having two parallel surfaces perpendicular to the direction of propagation. Multiple reflections at these surfaces take place, and, at certain frequencies, the amplitudes at the positions of the maxima may build up to very high values, especially where the standing wave ratio is high. Also, for high standing wave ratios, the amplitudes at the minima tend to zero. When this phenomenon is observed, it is said that the material is in a state of *resonance*. Figure 2.7 illustrates the resultant wave patterns at different times during a single cycle, for a high standing wave ratio.

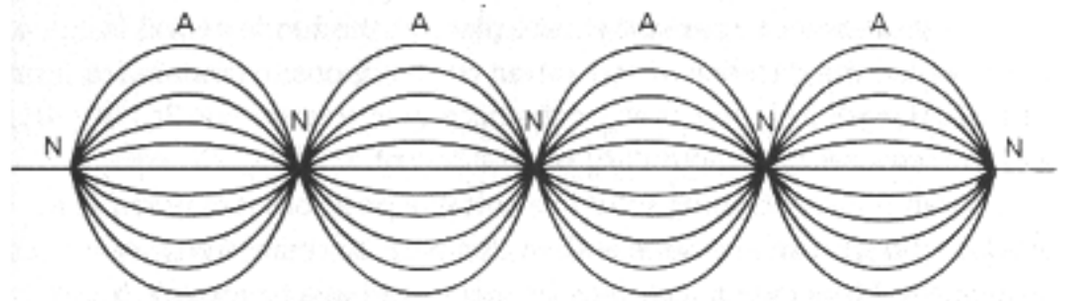

Figure 2.7 Envelope of stationary wave pattern showing nodes N and antinodes A

Two types of resonances resulting from stationary waves, namely half-wavelength and quarter-wavelength, are discussed below.

2.9.1 *Half-wavelength resonance*

Two situations can be considered:

1. *Parallel-sided material bounded at each end-surface by media having lower characteristic impedances* (e.g. a solid plate or bar in a liquid or gas): when the distance l between the boundaries is equal to one half-wavelength or a multiple number of half-wavelengths, particle displacement *antinodes*, particle velocity *antinodes*, and acoustic pressure *nodes* appear at the boundaries [see Figure 2.8(a)].

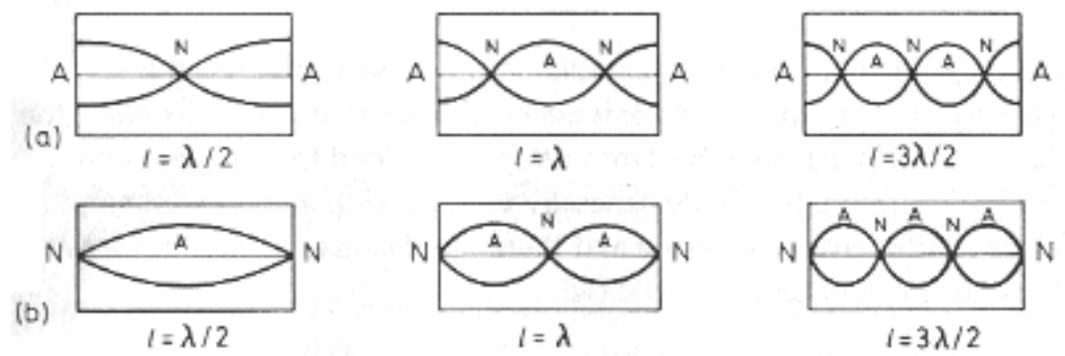

Figure 2.8 Half-wavelength resonance of body of length l, showing displacement nodes N and antinodes A: (a) material bounded on each side by a medium having a lower characteristic impedance; (b) material bounded on each side by a medium having a higher characteristic impedance

2. *Parallel-sided material bounded at each end-surface by media having higher characteristic impedances* (e.g. a liquid or a gas between two solids): in this case, particle displacement *nodes*, particle velocity *nodes*, and acoustic pressure *antinodes* occur at the boundaries [see Figure 2.8(b)].

In both instances, resonances take place at the fundamental frequency f_r, for which the distance of separation of the opposite boundaries is one half-wavelength $\lambda/2$, and at all of the harmonic frequencies $2f_r$, $3f_r$, $4f_r$, etc., corresponding to boundary separations of λ, $3\lambda/2$, 2λ, etc.

By clamping a vibrating solid in a suitable position, it is possible to produce a displacement node and, in this way, to remove any unwanted resonances. More energy can thus be made available to provide higher amplitudes of vibration at the required frequencies.

2.9.2 Quarter-wavelength resonance

If a solid (e.g. a bar or plate) is clamped to produce a node at one end (see Figure 2.9), leaving the other end free, quarter-wavelength resonance may be achieved. The resonance frequencies are f_r, $3f_r$, $5f_r$, etc., corresponding to the length of the solid being equal to $\lambda/4$, $3\lambda/4$, $5\lambda/4$, etc.,

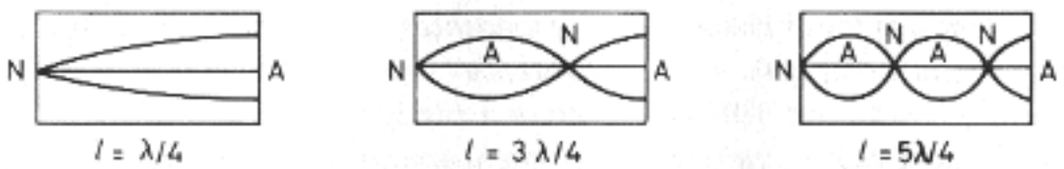

Figure 2.9 Quarter-wavelength resonance of body of length l, showing displacement nodes N and antinodes A

i.e. only odd harmonics are excited. It can be seen that when a bar, initially clamped at its centre, is clamped instead at one of its ends, the fundamental frequency becomes halved. Provided that it is not constrained, a resonating body generally vibrates with a maximum amplitude at its fundamental frequency and there is a decrease in amplitude as the order of the harmonic is increased.

2.10 Quality of resonance

The amplitude of the vibrations of a resonating body depends, as stated previously, on the reflection coefficients at the boundaries and on the degree of attenuation within the material. Thus, when the reflection coefficients are high and the absorption coefficient low, the amplitude builds up to a high value. On the other hand, with high absorption and low reflection coefficients, the amplitude at resonance is comparatively low. The degree of resonance is indicated by a dimensionless number

called the Q (or *quality*) factor, a term familiar to electrical technologists, defined as follows:

$$Q = \frac{\text{Energy supplied per cycle}}{\text{Energy dissipated per cycle}} \qquad (2.17)$$

Here the energy is dissipated as a result of losses at the boundary, absorption, and losses due to the method of mounting.

When the frequency is increased above or reduced below its value at resonance, a decrease in amplitude takes place. Figure 2.10 illustrates

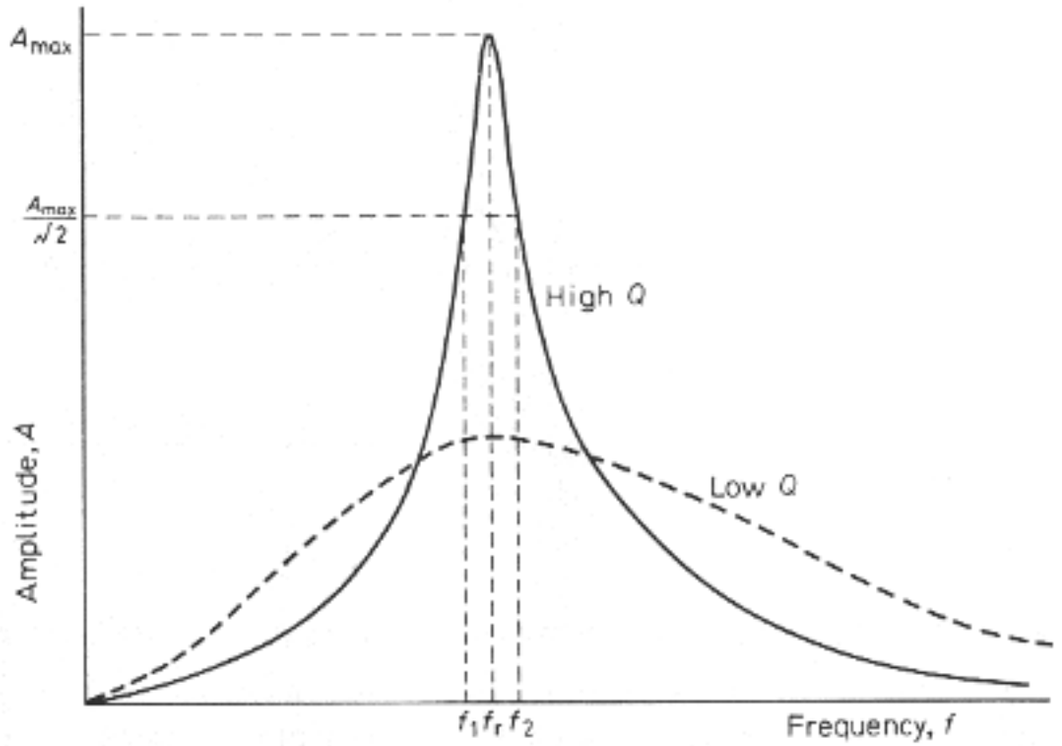

Figure 2.10 Frequency response curves showing relationships between amplitude A and frequency f

what are known as *frequency response curves*, which represent variations of velocity amplitude with frequency for a constant value of acoustic pressure amplitude. The narrower and higher curve indicates a high Q, and the broader and lower curve a low Q. An approximate value of Q can be obtained by reading off, from the curve, the values of the frequencies f_1 and f_2, on either side of the resonance frequency f_r, where the amplitude is reduced to $1/\sqrt{2}$ of its maximum value (i.e. about 3 dB). Then

$$Q \simeq \frac{f_r}{f_2 - f_1} \qquad (2.18)$$

This approximation is valid only where Q is greater than 3. The frequency difference $f_2 - f_1$ is called the *frequency bandwidth.*

2.11 Free vibrations

If a body is given a shock excitation, sound waves having frequencies which extend over a continuous wide band are generated. The amplitudes of these waves die down rapidly except at the resonance frequencies, where the vibrations are sustained for a longer time. Figure 2.11 illustrates the rate of decay of the vibrations at a given natural frequency.

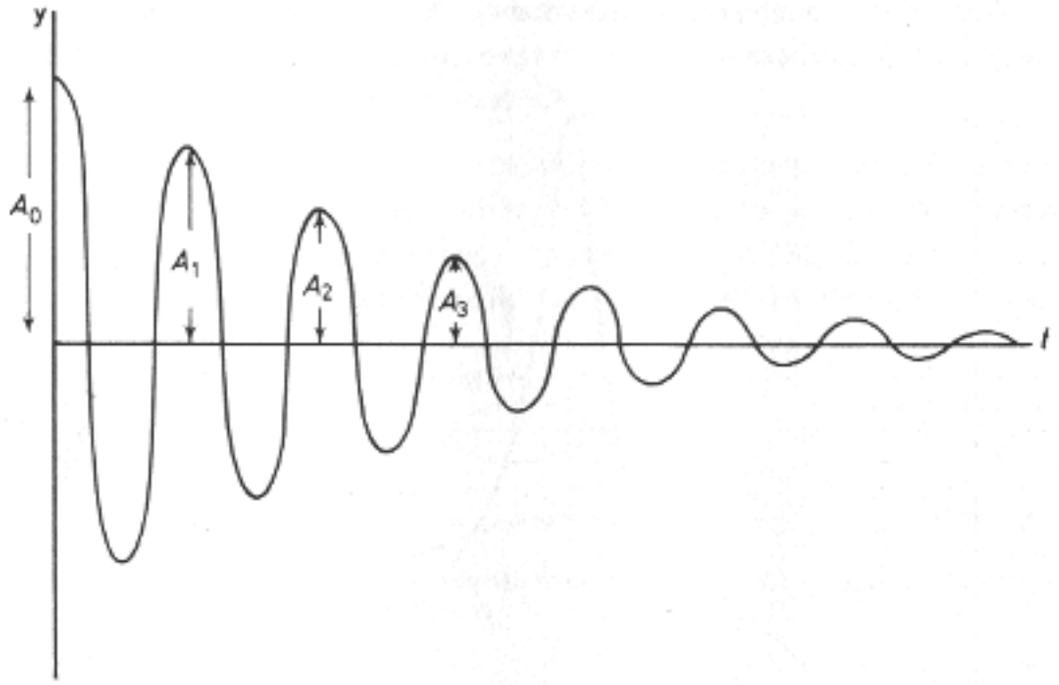

Figure 2.11 Decay of amplitude A *for free vibrations at a given resonance frequency*

The amplitude decreases with time in an exponential (logarithmic) manner by an amount depending on the reciprocal of the Q factor.

It is convenient to describe this rate of decay by the *damping coefficient* or *logarithmic decrement* (*log. dec.*) δ defined as follows:

$$\delta = \frac{2{\cdot}303}{n} \log_{10} \frac{A_0}{A_n} \qquad (2.19a)$$

Here A_0 represents the initial value of the amplitude and A_n its value after n complete oscillations. Using the decibel scale, the equivalent decrement D may be expressed as

$$D = \frac{20}{n} \log_{10} \frac{A_0}{A_n} \text{ dB/cycle} \qquad (2.19b)$$
$$= 8{\cdot}686\delta$$

(see also Section 2.13). It can also be shown that

$$\delta = \frac{\pi}{Q} \qquad (2.20)$$

2.12 Reflection and refraction of waves directed at an angle to a plane boundary separating two materials

Let a beam of plane longitudinal ultrasonic waves travelling in a material A be directed at an angle i to the normal at a plane boundary separating A from another material B (see Figure 2.12). At this boundary, longitudinal waves are reflected back into A at an equal angle i to the normal

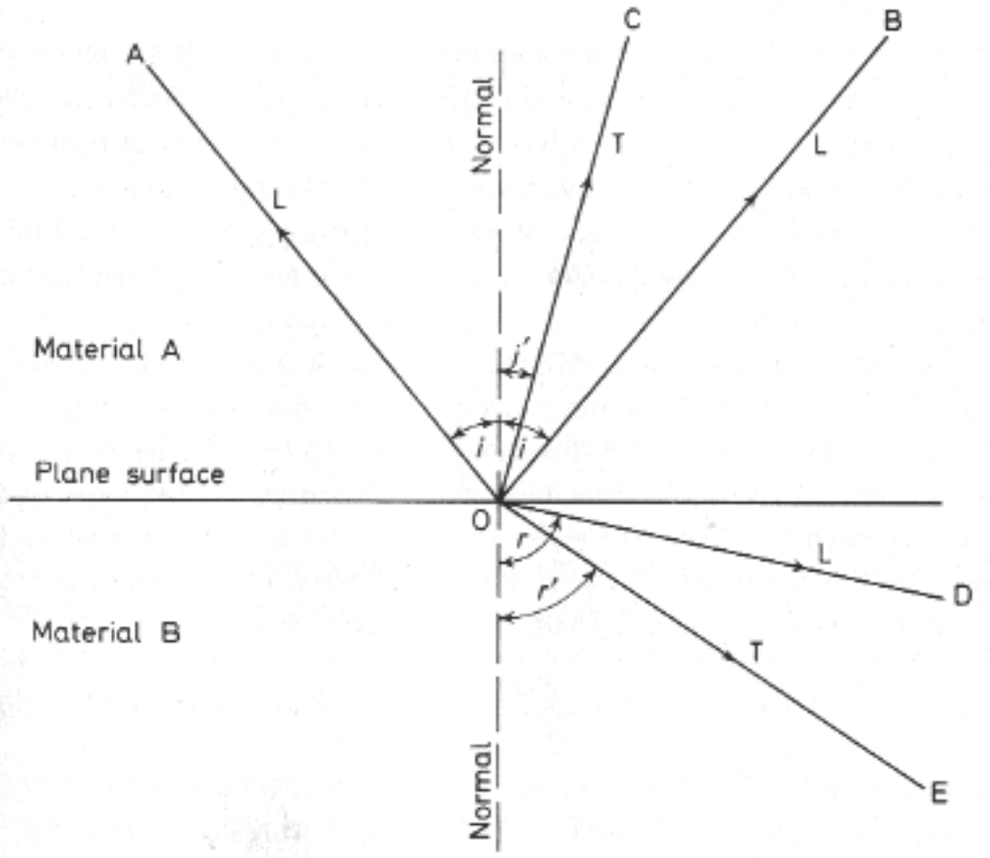

Figure 2.12 Double reflection and refraction of ultrasound at a boundary between two materials: L = longitudinal waves, T = transverse waves

but on its other side. If the material A is a solid, there will be an additional beam reflected at an angle i', smaller than i, to the normal. This second beam consists of shear (transverse) waves produced as a result of a phenomenon called *mode conversion* occurring at the surface (see, for example, Blitz[3]). The waves transmitted into material B are refracted at the surface, and a beam of longitudinal waves emerges at an angle r to the normal. Furthermore, if B is a solid, the phenomenon of mode conversion gives rise to the emergence of a beam of transverse waves at an angle r', smaller than r, to the normal.

In Figure 2.12, O represents the point of incidence on the boundary, AO the incident longitudinal beam, OB the reflected longitudinal beam, OC the reflected transverse beam, and OD and OE the respective refracted longitudinal and transverse beams.

The acoustic velocities for the various beams are related to one another in the following manner:

$$\frac{c_{1L}}{\sin i} = \frac{c_{1T}}{\sin i'} = \frac{c_{2L}}{\sin r} = \frac{c_{2T}}{\sin r'} \qquad (2.21)$$

The velocities of longitudinal waves in the media A and B are represented by c_{1L} and c_{2L}, respectively, and those of transverse waves by c_{1T} and c_{2T}, respectively. In Section 4.5 it is shown that the speed of transverse waves for a given solid is always less than that of longitudinal waves, typically by a factor of about one-half. Thus the angle r of refraction for longitudinal waves is always greater than the angle r' of refraction for transverse waves.

Consider now what happens when material A is a liquid and material B a solid. The longitudinal and transverse velocities in a solid are, in nearly all cases, greater than the speed of longitudinal waves in a liquid (see Tables 2.1 and 4.3). Thus, both r and r' are greater than i and both refracted beams will be bent away from the normal. It can therefore be seen that the angle i of incidence can be increased to a critical value i_{c1} for which r is equal to 90°. Then, from equation 2.21,

$$\frac{c_{1L}}{\sin i_{c1}} = c_{2L} \qquad (2.22)$$

because sin 90° = 1. On increasing i still further, only transverse wave propagation is possible in medium B. Mode conversion provides the usual method for generating shear waves in solids (see Section 5.5).

On increasing i still further, a second critical value i_{c2}, corresponding to $r' = 90°$, is reached. Thus,

$$\frac{c_{1L}}{\sin i_{c2}} = c_{2T} \qquad (2.23)$$

Here the refracted transverse beam travels along the boundary as *surface* or *Rayleigh waves* (see Section 4.5).

For propagation from water to steel, the values of i_{c1} and i_{c2}, as calculated from the data given in Tables 2.1 and 4.3, are approximately 14° and 30°, respectively.

Another effect of mode conversion occurs in ultrasonic flaw detection (see Section 6.2) where material A is a solid and B a fluid, e.g. air or water. The beam spreads out sideways as a result of diffraction (Section

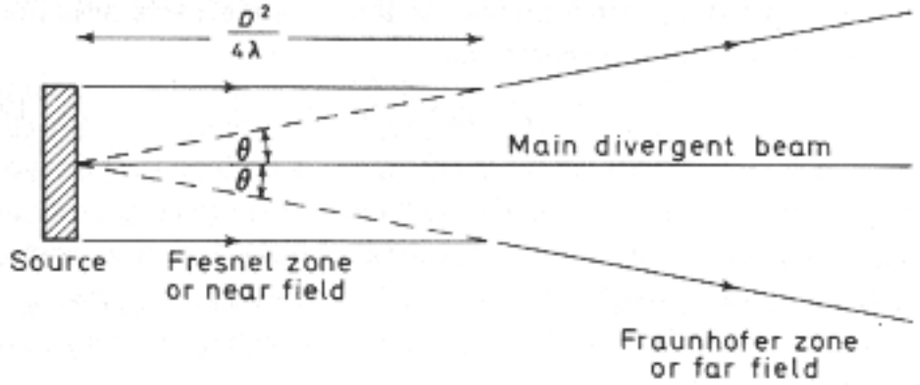

Figure 2.13 Diffraction of waves from a circular source vibrating in a piston-like manner

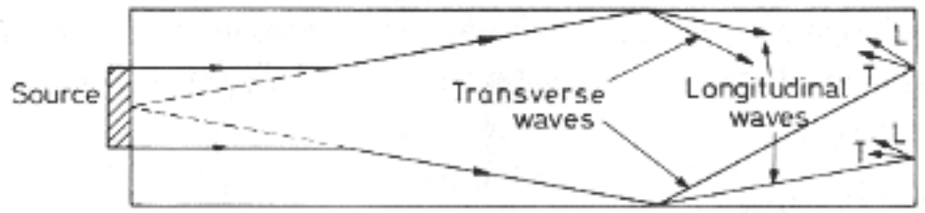

Figure 2.14 Mode conversion on reflection of diffracted waves at the lateral surfaces of a solid bar

2.14), and both longitudinal and transverse waves are reflected at the surfaces (see Figure 2.13). The transverse waves travel at a lower velocity and arrive at the receiver at a time later than the longitudinal waves, thus giving rise to the receipt of spurious signals (Figure 2.14).

2.13 Attenuation of plane waves

Ideally the intensity of a parallel beam of progressive plane waves should remain constant at all distances from the source. In practice this is not so because of the attenuation of ultrasound as it progresses through the medium. Assuming that there are no major discontinuities producing regular reflections, e.g. cracks, three causes of attenuation exist, namely diffraction, scattering, and absorption. Diffraction and scattering are properties of the shape and macroscopic structure of the material and they will be discussed in the following sections. Absorption, which is characteristic of the physical properties and microscopic structure of the material, is dealt with in Chapter 4.

Assuming that diffraction effects are constant, i.e. considering *either* the near field *or* the far field (Section 2.14), the amplitude A is found

to decrease in an exponential manner as the distance x in a direction away from the source is increased, i.e.

$$A = A_0 \exp(-\alpha x) \tag{2.24}$$

where A_0 is the amplitude where $x = 0$, and α is defined as the *attenuation* or *absorption coefficient* and may be expressed in *nepers* per unit distance (e.g. nepers mm^{-1}). It is often more convenient to consider attenuation per wavelength, i.e. $\alpha\lambda$. This is the same as the attenuation per cycle, defined in Section 2.11 as the logarithmic decrement δ, for free vibrations. Thus

$$\alpha\lambda = \delta = \frac{\pi}{Q} \tag{2.25}$$

It is also common practice to express attenuation in decibels per millimetre (dB mm^{-1}) or decibels per wavelength, and, from equation 2.19b, it can easily be seen that 1 neper is equivalent to 8·686 dB.

2.14 Diffraction

A parallel beam of plane waves originating from a source vibrating in a piston-like manner diverges after having travelled a specific distance d from the source. The value of d depends on the size of the source and the wavelength λ, and, for a circular source of diameter D, it can be shown that

$$d \triangleq \frac{D^2}{4\lambda} \tag{2.26}$$

The parallel portion of the beam is called the *near field* or the *Fresnel zone*, and the divergent part the *far field* or the *Fraunhofer zone*. The divergence, which appears to originate from the centre of the source, is called Fraunhofer diffraction (see Figure 2.13). Equation 2.26 shows that the directivity of the beam increases with the size of the source but decreases with wavelength, i.e. increases with frequency. Figure 2.14 illustrates what can happen when the length of a sample of the material is greater than the critical distance d. This phenomenon, also discussed in Section 2.12, presents difficulties in measurements of attenuation coefficients and in flaw detection.

The average intensity over any given cross-section in the Fresnel zone remains constant, assuming no absorption occurs, although cyclical intensity changes take place along any line in the direction of wave-motion (see Blitz[4]). In the Fraunhofer zone, the intensity decreases inversely with the square of the distance from the source in the same way as for a point source.

2.15 Scattering of ultrasound

It was shown by Lord Rayleigh that, if a large number of small particles of fairly uniform size is distributed homogeneously in a beam of sound, reflection takes place at each of the particles in a random manner, i.e. sound is scattered uniformly in all directions. A condition for this Rayleigh type of scattering is that the dimensions of the particles must be small compared with wavelength, i.e. the particle dimensions must be less than 0·1 times the wavelength.

The attenuation coefficient α is related to the mean particle diameter D and the frequency f as follows:

$$\alpha = Kf^4D^3 \tag{2.27}$$

where K is a constant for a particular material, depending on the ratio of the characteristic impedances of the suspended particles and the material through which the sound is propagated. This type of scattering may be observed with suspensions in gases (e.g. aerosols) and in liquids (e.g. emulsions). It also occurs in polycrystalline metals and in concretes (see Sections 4.6.1 and 6.7).

2.16 The Doppler effect

When relative motion takes place between the source and the receiver of sound waves, the frequency of the received signal will differ from that of the transmitted signal by an amount which depends on the velocities of the source and receiver. This is due to the Doppler effect, a phenomenon explained in general textbooks on acoustics (see, for example, Blitz[5]). The following cases are met with in the study of ultrasonics:

1. If the source is stationary and the receiver moves away from it with a velocity v, there is a decrease in frequency by an amount vf/c, where c is the speed of sound and f the frequency. When the receiver moves *towards* the source, there is an increase in frequency by this amount.
2. If the receiver is stationary and the source moves *away* from it with a velocity u, there is a *decrease* in frequency by an amount $uf/(c-u)$. On the other hand, when the source moves *towards* the receiver, there is an *increase* in frequency by an amount $uf/(c+u)$.

A well-known example in audio-acoustics is the apparent abrupt decrease in pitch of the note of the engine of a passing car.

3. A modification of example 2 occurs when the source and receiver, facing the same direction, are both stationary and an obstacle moves either towards or away from them with a velocity w. In this case, the mirror image of the source, owing to reflection at the surface of the obstacle, moves with a velocity $2w$. There is a *decrease* in frequency by an amount $2w/(c + 2w)$ when the reflector moves *away* from the source and an *increase* in frequency by an amount $2w/(c - 2w)$ when it moves *towards* it. This phenomenon as applied to electromagnetic waves is met with in radar techniques as, for example, used by the police in measuring the speed of a car suspected of exceeding the statutory limit.
4. When both the source and receiver, immersed in a fluid moving with a constant velocity, are stationary, the frequency remains constant but there is a change in the speed of sound equal to that component of the velocity of the fluid along the line joining the source and receiver.

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CHAPTER THREE

ULTRASONIC TRANSDUCERS

3.1 Introduction

Sound waves are generated or received by a *transducer*, i.e. any device which converts energy of one form to that of another. Our concern is with the transformation of ultrasonic energy to or from electrical, mechanical, or other forms of energy. A *reversible* transducer is one which will make the conversion in both directions with equal efficiencies.

In this chapter, the different types of transducer are classified as follows:

1. *Piezoelectric oscillators*, making use of the piezoelectric effect, which is reversible. The possible frequency range extends from 20 kHz to well over 10 GHz.
2. *Magnetostrictive oscillators*, employing the phenomenon of magnetostriction, which is also reversible. In most cases they are not used at frequencies higher than about 40 kHz, but the range can be extended without difficulty to over 100 kHz. Under certain circumstances, magnetostrictive transducers can be made to operate at mega-hertz and even giga-hertz frequencies.
3. *Mechanical transducers*, including purely mechanical oscillators (e.g. whistles and sirens) and radiometers, most of which are irreversible. They are used mainly for high-power applications, and the frequency range rarely extends beyond 50 kHz.
4. *Electromagnetic transducers*, which are sometimes employed for high-intensity applications at low frequencies, often in the audible range. They have been used on occasions for low-intensity work at frequencies of up to 50 kHz and, more rarely, as receivers at mega-hertz frequencies. They are reversible.
5. *Electrostatic transducers*, which may be used as generators at low intensities with an upper frequency limit of a few hundred kilo-hertz. They are reversible and may be used as receivers at frequencies as high as 100 MHz.
6. *Miscellaneous transducers*, which include thermal, chemical, and optical transducers.

Ultrasonic receivers may be considered to fall into one of the two following categories:

1. *Receivers terminating acoustic beams*: here the cross-section of the receiver embraces the whole or a large proportion of that of the beam and its dimensions may extend from several to a large number of wavelengths. The presence of the receiver materially affects the configuration of the acoustic field, e.g. to give rise to regular reflections of the beam.
2. *Receivers acting as probes*: ultrasonic probe receivers (not to be confused with the probes used for ultrasonic testing, which come under the category of receivers terminating acoustic beams) are employed for mapping out acoustic fields and for local intensity measurements. Their dimensions should be small enough not to upset the characteristics of the field, i.e. to be less than about one-tenth of a wavelength. For this reason, the use of probe receivers is generally restricted to lower frequencies (e.g. in the kilo-hertz range).

3.2 Piezoelectric transducers

3.2.1 General considerations

Piezoelectric transducers are made from materials displaying the piezoelectric effect, which was discovered by the brothers Pierre and Jacques Curie in 1880. The effect occurs naturally in certain single crystals possessing polar axes, such as quartz, tourmaline, lithium sulphate, cadmium sulphide, and zinc oxide.

Suppose that a material of this nature is cut in the form of a disc or slab, and an opposite pair of plane surfaces, orientated at right angles to a given axis, is coated with thin metallic films (e.g. of silver, gold, or aluminium) to form electrodes. If mechanical stresses are applied to the coated surfaces, equal and opposite electric charges will be induced on them and a voltage will be observed. This is the direct piezoelectric effect, and the crystalline axis perpendicular to the coated faces is the relevant polar axis. The converse effect is observed when a voltage is applied across the electrodes to produce an electric field. The crystal then suffers a mechanical strain.

These effects are associated with both compressions and shears, depending on the identity of the polar axis perpendicular to the electrodes. In quartz, for example, the principal polar axes are called the X- and Y-axes, of which there are three of each. The X-axes are orientated at angles of 120° apart, and for each X-axis there is a corresponding Y-axis

perpendicular to it. X-cut quartz crystals, for which the electrodes lie at right angles to an X-axis, are associated with compressions, and Y-cut quartz crystals with shears. The Z-axis, known as the optic axis and lying in the direction perpendicular to the planes containing the X- and Y-axes, is a non-polar axis for which the piezoelectric effect is not observed.

Figure 3.1 shows a part of a typical quartz crystal specimen. The Z-axis and one of the X-axes, with the corresponding Y-axis, are

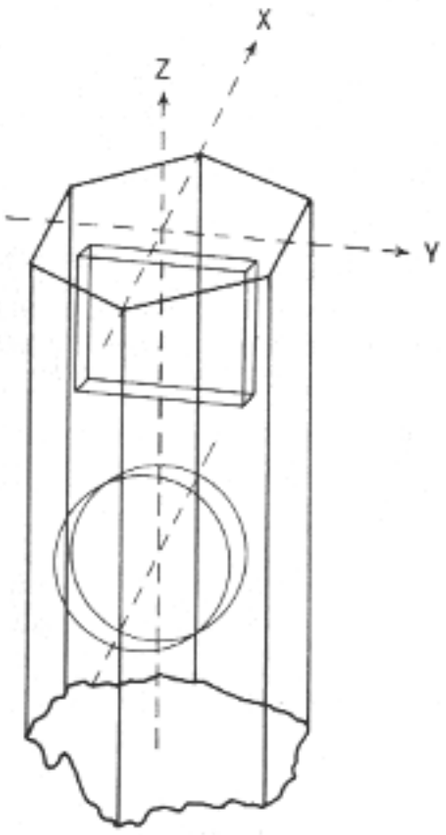

Figure 3.1 Axes of a quartz crystal, indicating X-cut rectangular and circular transducers

indicated, and outlines of X-cut transducers of rectangular and circular sections are given. Figures 3.2 and 3.3 illustrate the actions of the direct and converse effects for both compressional and shear types of transducers.

When an alternating voltage is applied across its electrodes, a piezoelectric transducer oscillates at the applied frequency with an amplitude of the order of 10^{-6} times its thickness. If, however, the transducer is excited at one of its resonance frequencies (see Section 2.9), the amplitude is considerably increased, e.g. to about 10^{-4} times the thickness at the fundamental frequency. The oscillations will be of

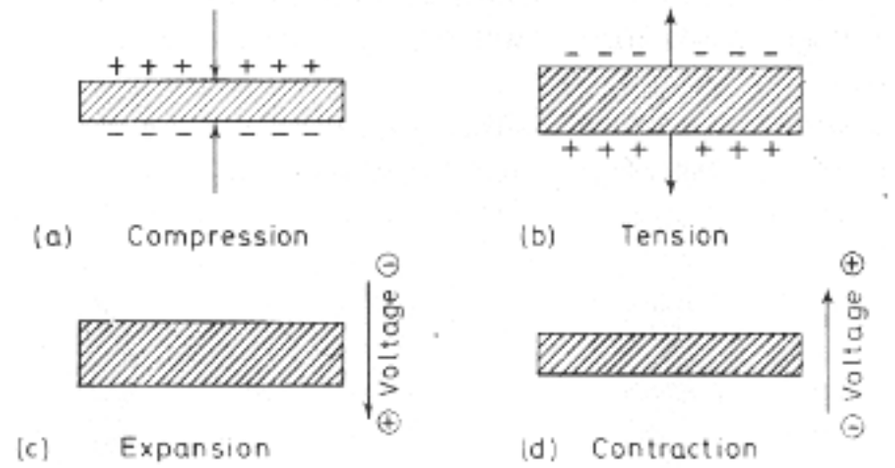

Figure 3.2 Piezoelectric effect for a compressional wave transducer: (a) charges induced on electrodes by a compressional stress; (b) charges induced on electrodes by a tensile stress; (c) expansion produced by a voltage in a given direction; (d) contraction produced when the voltage is reversed in direction

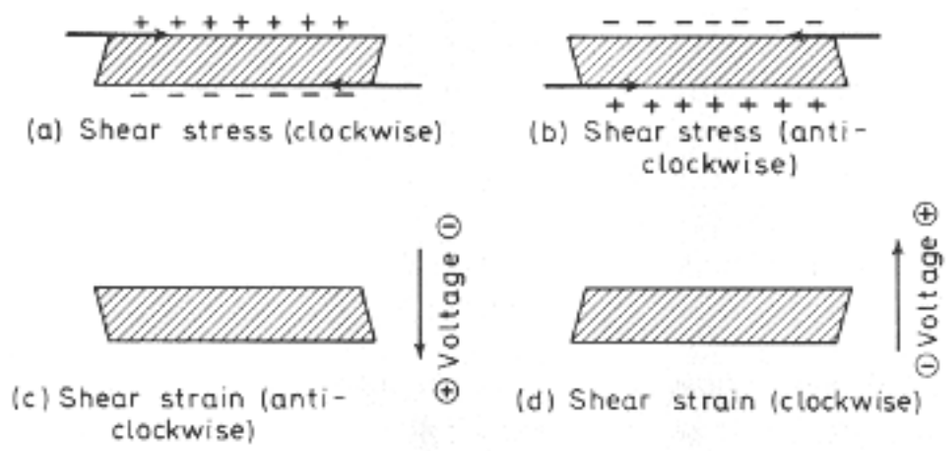

Figure 3.3 Peizoelectric effect for a shear wave transducer: (a) charges induced on electrodes by a shear stress in a given direction; (b) charges induced on electrodes when the shear stress is reversed in direction; (c) shear strain produced by a voltage in a given direction; (d) reversed shear strain produced by voltage in the opposite direction

either a compressional or a shear type, depending on the nature and the method of cut of the crystal. Thus longitudinal waves are generated by X-cut quartz crystals and transverse waves by Y-cut quartz crystals (but see Sections 2.12 and 5.5).

A piezoelectric transducer may also be used as a detector. Vibrations induced in it by the sound waves give rise to alternating charges appearing on the electrodes at the frequency of the vibrations. Maximum sensitivity occurs at a resonance frequency. In many applications, a single transducer can act simultaneously as both transmitter and receiver.

The piezoelectric effect can be induced artificially in certain materials which display a phenomenon known as *electrostriction*, which is analogous to magnetostriction (see Section 3.3). This effect may be observed in all dielectric materials, but its magnitude is negligible except in certain substances called ferroelectrics, which include barium titanate, lead zirconate titanate, lead meta-niobate, and sodium meta-niobate. If a slab of one of these materials is coated with electrodes on two opposite faces and a voltage applied, a mechanical strain, the magnitude of which is proportional to the square of the applied voltage, is produced. Because of the square-law relationship, the sense of the strain is independent of that of the field. Consequently, for example, an increase in thickness will remain an increase when the applied voltage is reversed in polarity. When an alternating voltage of sinusoidal form is applied to the electrodes, the frequency of vibrations is double the frequency of the voltage and the form of the oscillations is similar to that of a rectified but unsmoothed alternating current. To obtain a pure sinusoidal vibration, as shown in Figure 2.1, at the frequency of the applied voltage as obtained with naturally occurring piezoelectric materials, the transducer must be polarised by providing the electrodes with steady equal and opposite charges of a sufficiently high magnitude (cf. magnetostrictive transducers).

A permanent polarisation can be obtained by heating the material to a temperature above the Curie point, where the electrostrictive effect disappears, and then allowing it to cool in a strong direct electric field, typically of several hundred volts per millimetre. The orientation of this polarising field determines the direction of the polar axis. Thus, for longitudinal strains, the field is directed at right angles to the electrodes, and, for transverse strains, parallel with the electrodes. Provided that the exciting voltage is small compared with the initial polarising voltage, the oscillations will take place in a purely sinusoidal manner and the transducer is effectively piezoelectric.

Artificially induced piezoelectric transducers generally are not single crystals but of polycrystalline structure. They are made up of very large numbers of minute crystallites of the material bonded together, moulded to the required shape and size, and then baked in an oven. The final product is in the form of a ceramic. Because, prior to polarisation, these ceramic transducers are isotropic, they do not require to be cut with reference to any particular axis. Thus it is possible to shape them in any convenient form, e.g. a concave transducer capable of focusing ultrasound can be produced without difficulty. The piezoelectric properties of these transducers may be improved or otherwise adjusted by the additions of small quantities of other materials.

The piezoelectric effect is usually measured by what is called the *d coefficient*. Because the effect is reversible, this quantity may be expressed in one of two equivalent ways. For the first definition, suppose that the crystal is subjected to a mechanical stress whilst, at the same time, the electrodes are short-circuited by a wire. Charges induced on the electrodes by the stress will flow through the wire until the potential difference across the crystal is reduced to zero. If q is the value of the total charge flowing and F the force producing the stress, the d coefficient is given by the expression

$$d = \frac{q}{F} \text{ coulombs per newton (C N}^{-1}\text{)} \qquad (3.1)$$

Table 3.1 PRINCIPAL CHARACTERISTICS OF PIEZOELECTRIC MATERIALS USED AS LONGITUDINAL WAVE TRANSDUCERS*

Substance	*d coefficient*	*Electromechanical coupling coefficient, k*	*Upper Curie temperature, T_c*
	($C N^{-1} \times 10^{12}$)	(%)	(°C)
Quartz (X-cut)	2·3	11	550
Barium titanate	60 – 190	20 – 50	120 – 140
Lead zirconate titanate	80 – 320	23 – 76	350 – 490
Lead meta-niobate	85	42	550
Sodium meta-niobate	80 – 160	51 – 53	290 – 420
Lithium niobate	6	18	1 210
Lithium tantalate	8	31	660
Cadmium sulphide	10	34	
Zinc oxide	12	65	

* The values quoted in this table are approximate and those of d and k apply to room temperatures. The author is indebted to Mr R. F. Mitchell of the Mullard Research Laboratories for some of the information.

For the second definition, let a voltage V be applied across the crystal on which there is no applied load, e.g. if supported freely in a vacuum. If the resultant strain produces a displacement l of the surface, then

$$d = \frac{V}{l} \text{ volts per metre (V m}^{-1}\text{)} \qquad (3.2)$$

It is not difficult to show that the coulomb per newton is equivalent to the volt per metre.

Values of d coefficients for a number of commonly used piezoelectric materials are given in Table 3.1. The table also gives values of the electromechanical coupling coefficients k and the upper Curie temperatures T_c. The electromechanical coupling coefficient is defined, by convention, as the *square-root* of the ratio of the mechanical energy stored in the transducer to the electrical energy supplied to it. Both d

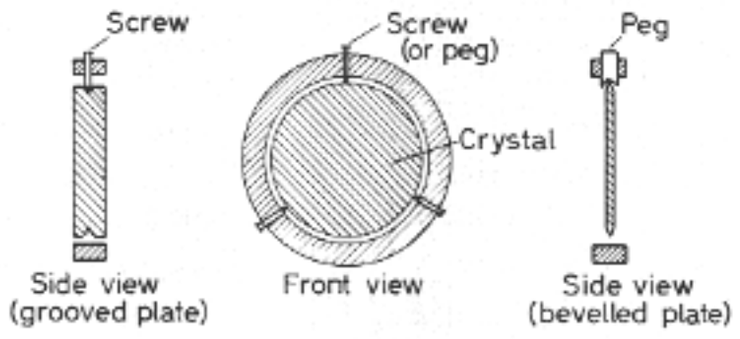

Figure 3.4 Nodal mountings for piezoelectric transducers, after Bechmann[1]

and k vary with temperature and reduce to zero at the Curie temperature, i.e. the temperature at which the piezoelectric effect vanishes. For single-crystal transducers there is usually only a single Curie temperature, but there may be more than one of these for ceramics. One form of barium titanate, for example, has Curie points at 120°C and 0°C and the piezoelectric effect is observed between these two temperatures.

The frequency response of a transducer depends on its Q factor (see Section 2.10). This may be expressed in relation to the characteristic impedances R_1 and R_2 of the material of the transducer and the medium of propagation, respectively, as follows:

$$Q = \frac{KR_1}{R_2} \qquad (3.3)$$

Here K is a dimensionless number having a value which depends on the absorption coefficient of the transducer material and the method by which the transducer is mounted. For the ideal case of a transducer made of a material having a negligible absorption coefficient (e.g. quartz)

and clamped accurately at its nodes (see Figure 3.4), K is equal to $\pi/2$. For a quartz transducer ($R_1 = 1{\cdot}5 \times 10^7$ kg m^{-2}s^{-1}) mounted nodally in hydrogen at standard pressure and temperature ($R_2 = 110$ kg m^{-2}s^{-1}), the value of Q is approximately equal to 2×10^5. On the other hand, a ceramic transducer (e.g. barium titanate) which has a high absorption coefficient and is held in position by a heavy spring (see Figure 3.5) has a very low value of K. If it were coupled to a solid, the Q factor would be nearly equal to unity.

Equation 2.18 shows how the Q factor of a resonator is related to its frequency bandwidth. At a frequency of 1 MHz, the bandwidth of the

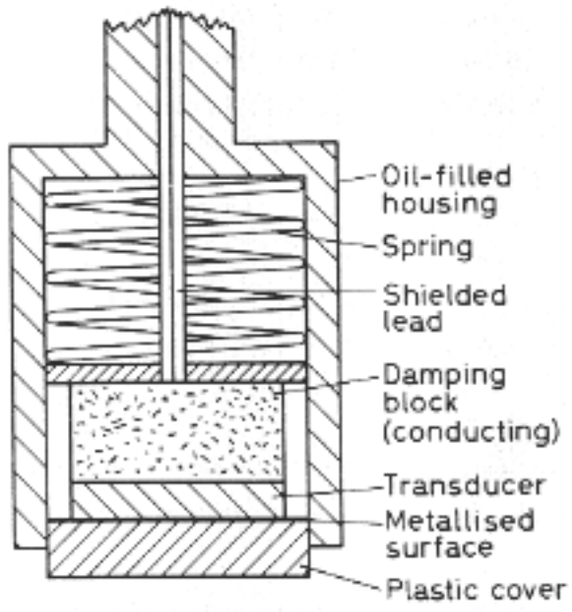

Figure 3.5 Heavily damped mounting of a ceramic transducer for pulsed operation in ultrasonic flaw detection

nodally mounted quartz crystal in hydrogen is only.5 kHz whereas that for the ceramic transducer coupled to a solid may be as high as 300 kHz. Thus ceramic transducers are especially suitable for the generation of short pulses, whereas quartz crystals are ideal for the propagation of continuous waves or long pulses for which frequency stability is an important consideration. The high absorption coefficients of the ceramic transducers also render them liable to overheating, with the consequent variation or even disappearance of the piezoelectric characteristics. Hence pulsed operation may be an essential requirement for the efficient working of these transducers, especially at high intensities.

Ceramic transducers generally have much higher d coefficients and electromechanical coupling coefficients than quartz crystals. Because, in addition, the ceramics have considerably lower electrical impedances

than quartz, they can be operated at much lower voltages. Quartz is an expensive material compared with the ceramics, but it has the advantage in that its chemical and physical properties are highly stable.

In most cases, piezoelectric transducers are operated as half-wavelength resonators (see Section 2.9), for which the thickness t is related to the resonance frequency f_r as follows:

$$t = \frac{c}{2nf_r} \tag{3.4}$$

where n is an integer describing the order of the excited harmonic and c is the velocity of sound in the transducer material. For most piezoelectric materials, the velocity of longitudinal waves is of the order of 5 000 m s^{-1}, and a transducer of thickness 10 mm will have a fundamental resonance frequency of about 250 kHz for compressional vibrations. Equation 3.4 shows that an increase in operating frequency is obtained by either decreasing the thickness, operating at a higher harmonic, or both.

High-frequency operation is limited to the thickness to which a transducer material can be cut without causing damage or giving rise to electrical breakdown across the electrodes. For quartz, the upper practicable fundamental frequency is in the region of 20 MHz, for which the crystal thickness is only about 0·14 mm. With ceramic transducers, the upper frequency limit is only about 10 MHz. The granular nature of the material inhibits the cutting of very thin slices of ceramics.

The excitement of the upper harmonics enables one to generate, in quartz, natural frequencies of several hundreds of mega-hertz. Because of the nature of the piezoelectric effect, only odd harmonics can be produced (see Blitz[2]). At very high frequencies, the wavelengths are extremely short and great care must be taken to ensure that the opposite surfaces of the transducer are accurately parallel with one another. For example, to produce waves at a frequency of 270 MHz with the 27th harmonic of a quartz crystal 0·28 mm thick, the corresponding wavelength is only about 2 μm. For the propagation of accurately plane waves, it is essential that the opposite surfaces are plane and parallel to a tolerance of around 0·2 μm, which is not feasible with ceramic transducers. In Section 3.2.3 it is shown how ultrasound of very high frequencies can be generated and received with the use of piezoelectric devices.

In theory, there is no lower frequency limit for the operation of piezoelectric transducers, but several practical difficulties occur. As mentioned earlier, quartz is expensive; the cost of a slab of this material

suitable for generating in its thickness mode at a fundamental frequency of 100 kHz (about 25 mm thick) may be several hundred pounds sterling (i.e. one thousand or so American dollars). If the propagation of a wide acoustic beam is not an important consideration, a quartz rod vibrating axially may suffice. However, ceramic transducer slabs capable of working at frequencies in the tens of kilo-hertz range are easily made and are relatively cheap. Unfortunately, because of their high absorption, they are somewhat inefficient in their use. This drawback, however, has been overcome by the use of sandwich transducers (see Section 3.2.4).

3.2.2 Coupling of piezoelectric transducers

For efficient coupling of ultrasound between the transducer and a solid, a suitable liquid must be provided to avoid an air gap which would give rise to a very high attenuation or even zero transmission (see Section 2.8). In the generation of longitudinal waves at normal temperatures, a film of oil or other suitable liquid is usually sufficient but, at low temperatures where most liquids solidify, it may be necessary to use a high-vacuum grease to prevent loss of continuity of characteristic impedance. For work at high temperatures, care must be taken to choose a couplant which does not evaporate.

For transverse wave propagation, the couplant should have enough strength to withstand the application of the shear stresses without collapsing. Sometimes a thin film of heavy oil or grease may serve this purpose, but it may be necessary to use an adhesive such as an epoxy resin. On some occasions Canada balsam or even nail varnish may provide good coupling for shear waves, depending on the temperature at which the measurements are to be made.

3.2.3 Ultra-high frequency (u.h.f.) piezoelectric transducers

The use of thin resonating piezoelectric slab transducers is no longer feasible at frequencies much above 500 MHz. However, with specially designed transducers it is possible to generate and receive ultrasound having frequencies exceeding 100 GHz. Furthermore, at such high frequencies, microwave techniques must be used for coupling the electrical signal to the transducer.

An early method of generating u.h.f. (or microwave) ultrasonics was to place one end of a single-crystal quartz rod inside an electromagnetic cavity resonator C_1 (see Figure 3.6). Its surface was excited at the required (non-resonance) frequency, e.g. 1 GHz, and waves were propagated along the rod. At first, the method could be used only for

producing ultrasound in single-crystal quartz because of the immense difficulty of coupling other materials to the free end of the rod. A similar electromagnetic cavity resonator C_2 at the other end of the rod acted as a receiver. Alternatively, a single cavity resonator would act as both transmitter and receiver of the waves reflected at the far end of the rod.

The method was later extended to measurements in other solids after an effective coupling technique was discovered. It then consisted of coating the free ends of the quartz rod and the solid specimen with thin films of indium, using a special high-vacuum technique. On placing the coated

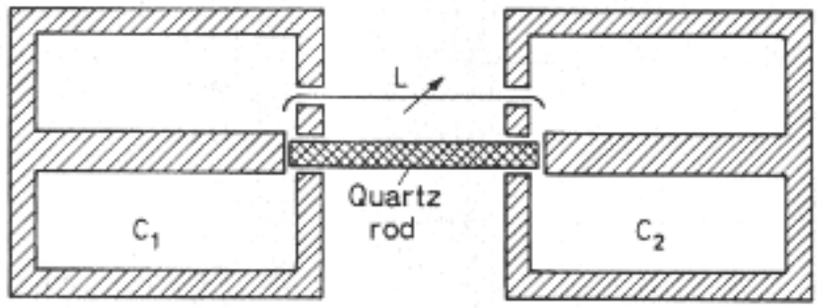

Figure 3.6 Location of quartz rod in electromagnetic cavity resonators for u.h.f. operation (L = variable electrical coupling), after Bömmel and Dransfield[3]

ends in contact under pressure in a vacuum at a temperature just below that of the melting point of indium, the surfaces fused together to provide a coupling with a transmission loss of not more than a few decibels.

Other techniques of generating and receiving microwave ultrasound involve sophisticated methods using piezoelectric semiconducting materials such as cadmium sulphide, zinc oxide, gallium arsenide, and gallium phosphide. A detailed description of these techniques is beyond the scope of a book of this nature and a summary of them is given elsewhere (Blitz[4]). One of the methods which has met with a considerable degree of success is to deposit, in a vacuum, a thin film of cadmium sulphide or other suitable piezoelectric material of thickness corresponding to the desired frequency of propagation to the surface of the medium. The deposition is carried out in such a way that the polar axis of the transducer material is properly lined up.

3.2.4 Piezoelectric sandwich transducers

High-intensity applications are often made at frequencies ranging from 40 kHz down to 20 kHz. To generate waves at the latter frequency with a piezoelectric ceramic requires that its thickness should exceed 100 mm.

A ceramic block of this thickness is not only relatively expensive but is highly absorbent. Because the absorbed acoustical energy is converted into heat, there is a rapid rise of temperature, even with pulsed operation, and the Curie temperature is soon reached, with a consequent disappearance of the piezoelectric effect. This trouble has been avoided with the use of sandwich transducers (see Figure 3.7).

A sandwich transducer consists of a comparatively thin piezoelectric plate located between two thicker metal plates to which it is clamped

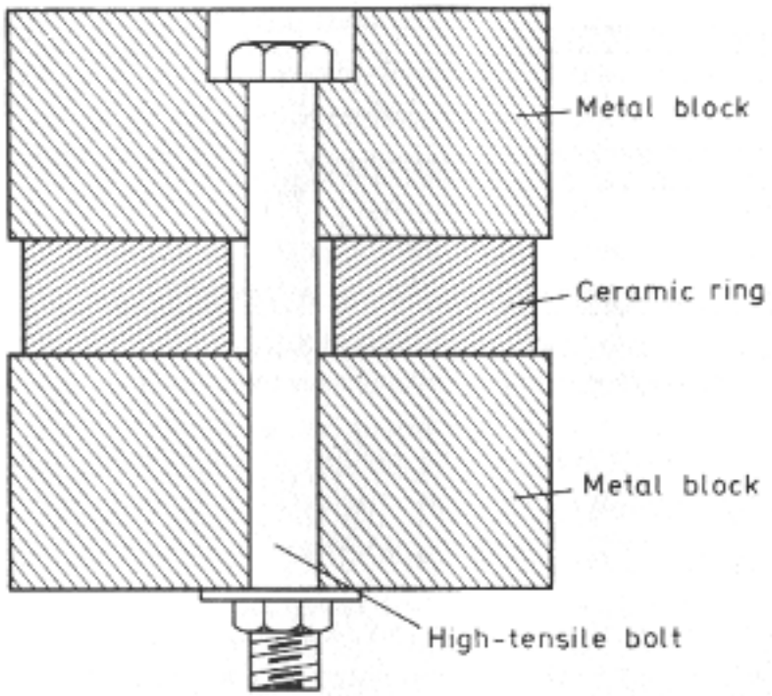

Figure 3.7 Sandwich transducer with mechanical bias

and cemented. The metal plates not only serve as electrodes but also increase the inertia of the vibrating system and thus reduce the resonance frequency. This frequency depends on the thicknesses of the metal plates and their characteristic impedances as well as on the thickness of the transducer material. A barium titanate plate 20 mm thick would normally have a fundamental resonance frequency of about 125 kHz. When such a plate is sandwiched between two metal plates of suitable thicknesses, this frequency may be reduced to 25 kHz. Acoustic outputs of several watts are common with this type of transducer arrangement.

Ceramic transducers have low tensile strengths and, when operated at high intensities, they are liable to fracture during the expansion phases

of their oscillations. On the other hand, they have high compressive strengths and damage can be prevented by compressing the sandwich permanently by means of a high-tensile bolt (see Figure 3.7); the transducer is said to be mechanically *biased*.

A description of sandwich transducers has been given by Hueter and Bolt[5] and by Berlincourt *et al.* (see Mason[6]).

3.2.5 Surface wave piezoelectric transducers

Surface waves can be generated by the use of mode conversion (see Section 2.12) with a longitudinal wave transducer as the primary source, but it is also possible to propagate them directly. The simplest way of

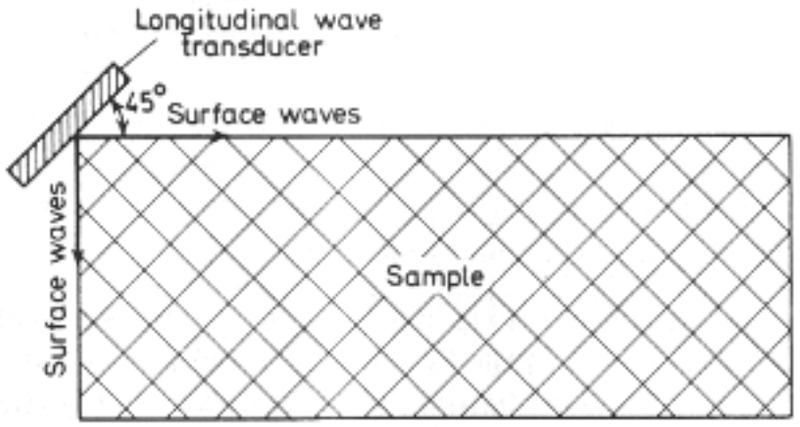

Figure 3.8 Generation of surface waves with a compressional wave transducer

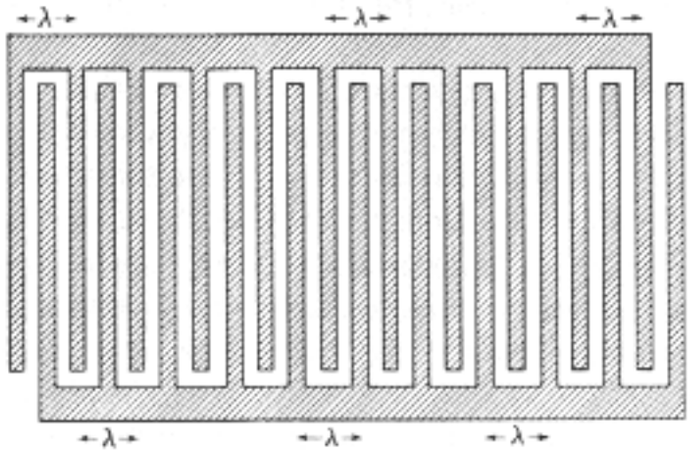

Figure 3.9 Arrangement of electrodes for a comb-type surface wave transducer

producing surface waves is to place an ordinary longitudinal wave transducer in contact with the edge of the material and inclined at an angle of 45° in the manner shown on Figure 3.8. The waves may be received in a similar manner. This method has been found to be highly satisfactory in, for example, the detection of surface flaws in materials.

A recently developed method of generating and receiving surface waves is to coat two electrodes in the form of interleaved combs on the surface of a piezoelectric material and to apply the exciting voltage at the required frequency across them (see Figure 3.9). In a typical case, for a frequency of 19 MHz with quartz, each comb had 11 teeth 40 μm in width, separated by the same distance apart. The distance of separation of the teeth of any one comb was equal to 160 μm, representing the wavelength for quartz at this frequency. This technique was developed for delay line applications, in which surface waves have the advantages of having low velocities and attenuations.

An account of the propagation of surface waves has been given by Viktorov[7].

3.2.6 Operation of piezoelectric transducers

For propagating continuous waves over a narrow frequency band, a quartz crystal mounted at its nodes (see Figure 3.4) provides an ideal source. However, electrical connections must be made to the electrodes and care must be taken to ensure that any additional damping caused by them is minimal. Nodal mounting is not always practicable, especially for very thin transducers or where contact with a solid medium has to be maintained. In these cases, the transducer is held in position by means of a light spring against a solid surface (the surface of the medium for a solid or the surface of a supporting platform for a fluid). In this instance, the solid surface (coated, if necessary, with a conducting substance) provides one electrical contact with the transducer electrode; the other is provided by the spring, which should be as light as possible to minimise damping. The impedances of the exciting and receiving electrical circuits should be correctly matched to the electrical impedance of the transducer to provide maximum efficiency.

For pulsed wave operation it is essential that the pulses are kept sufficiently short to prevent their overlapping and to ensure that stationary waves are not set up in the material of the medium. As stated earlier, where it is required to produce very short pulses and where a

narrow frequency band is not needed, it is best to use a transducer material, such as a ceramic, which provides high internal damping and to mount it to give high external damping. Figure 3.5 illustrates a typical method of housing a longitudinal wave ceramic transducer. The transducer is backed by a block of a material having a very high acoustic absorption coefficient but, at the same time, of sufficiently large electrical conductivity to provide contact with that transducer surface remote from the material of propagation. A mixture of tungsten powder and Araldite is ideal for this purpose. Further damping is provided by a heavy spring which also ensures good mechanical contact with the test material. A fairly high direct voltage (typically from 300 V to 600 V) of instantaneous duration is applied periodically to the transducer electrodes at the required pulse repetition frequency (usually between 50 s^{-1} and 1000 s^{-1}). At each electrical impulse, the transducer experiences a high initial strain after which it oscillates over about two or three cycles during which time the amplitude dies down rapidly (see Figure 2.11). Thus, for a transducer operating at a frequency of 6 MHz to produce pulses each of three wavelengths, the pulse duration is about only 0·5 μs for propagation into most metals. The pulse-length (PL) in seconds is approximately related to the frequency bandwidth as follows:

$$PL = \frac{1{\cdot}3}{\text{Frequency bandwidth}} \qquad (3.5)$$

For certain applications, usually in research laboratories, where it is important for the bandwidth to be as narrow as possible, e.g. for the measurement of attenuation, which varies with frequency, the use of much longer pulses is necessary. In this case, the transducer is excited by a radiofrequency oscillator at the required resonance frequency of the transducer and the pulse length is controlled electronically. Crystal transducers, having much lower absorption coefficients, are then employed.

3.2.7 Piezoelectric probe receivers

Piezoelectric probe receivers are used principally for measuring intensities in different parts of ultrasonic beams in fluids, mainly in investigating the configurations of acoustic fields, e.g. for determining the intensity distributions in front of transmitting transducers. The requirements of their design are that the dimensions of the sensitive element should be small compared with the wavelength (typically less than one-tenth), that the frequency response be constant over the

whole of the required range, and that the sensitivity of the piezoelectric element be constant for all directions.

Ideally, for an omnidirectional response, the receiver should be spherical in shape. Romanenko (see Rozenberg[8]) has described the construction of 'micro-miniature' sensitive barium titanate receiving transducers in the shape of spherical shells of outside diameters as low as

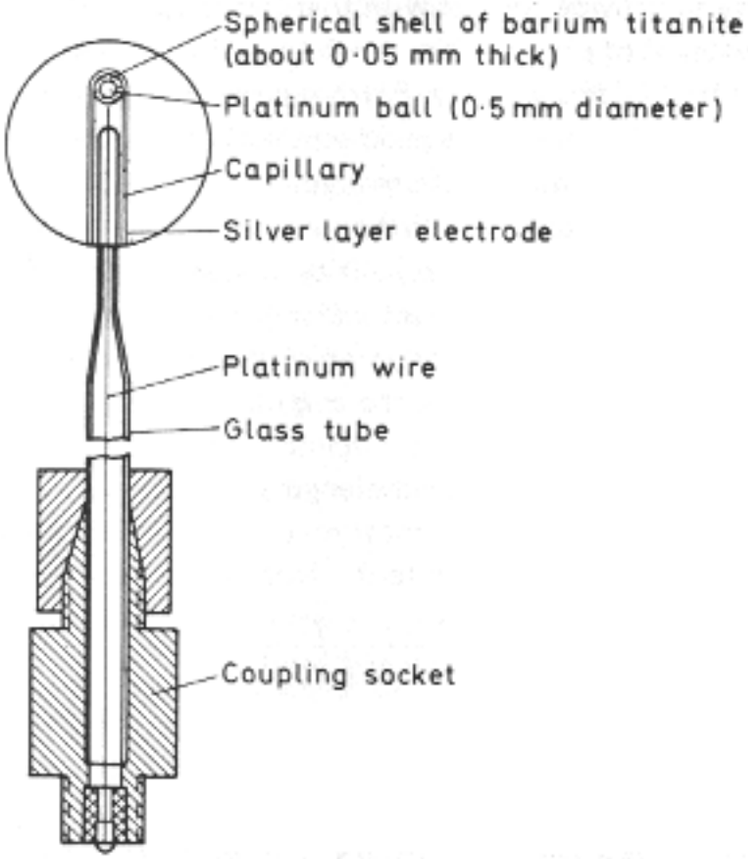

Figure 3.10 Design of 'micro-miniature' spherical receiver. From Rozenburg[8], courtesy Plenum Press

0·1 mm and thicknesses 0·05 mm (see Figure 3.10), which in liquids could be used satisfactorily at frequencies of up to 5 MHz.

Cylindrical transducers, in the forms of tubes, are more easily constructed and are quite suitable if one is concerned only with measurements in a single plane. They are capable of vibrating in a number of different modes, i.e. radial, length, and wall-thickness, and there is usually enough overlap between these modes to give rise to a fairly flat response over a wide band of frequencies. Ceramic tubes of outside diameter 1·5 mm, length 1·5 mm, and wall thickness 0·3 mm are easily obtained commercially and can be used to measure intensities at frequencies of up to 100 kHz in liquids and 25 kHz in gases, without disturbing the acoustic fields.

3.3 Magnetostrictive transducers

Magnetostrictive transducers are generally made of ferromagnetic materials, i.e. certain metals, such as nickel, cobalt, and iron, which can easily be magnetised and which display *magnetostriction* or the *Joule effect*. When a bar or rod of one of these materials is placed in a magnetic field, it suffers a change in length, either an increase or decrease, depending on the nature of the material and the strength of the field. Whether the strain is a positive or negative one is independent of the sense of the field (cf. electrostriction – see Section 3.2.1). Thus, when the magnetic field is reversed in direction, there is no change in the sense of the strain, i.e. an increase in length remains an increase. Figure 3.11 shows how the mechanical strain varies with the magnitude

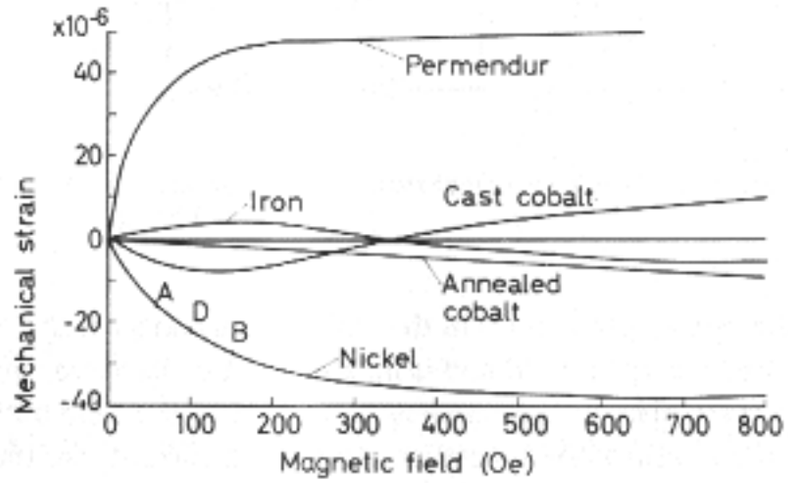

Figure 3.11 Relationship between mechanical strain and applied magnetic field strength due to magnetostriction, after Carlin[9]

of the field strength for a few ferromagnetic materials. It is seen that, in general, the variation is not a linear one. In practice one finds that nickel is the most satisfactory material for magnetostrictive transducers. It has an electromechanical coupling coefficient of 31 per cent and a Curie temperature of 358°C. Permendur, an alloy, has a Curie point of about 900°C but the electromechanical coupling coefficient is low.

The magnetostrictive effect can also be observed in certain non-metals known as ferrites. They have the advantage that, being poor electrical conductors, they are not overheated by eddy currents which are induced by the alternating currents exciting the periodic magnetic field. However, because of their poor mechanical properties, they are not often used in the design of ultrasonic transducers.

There is a converse magnetostrictive effect, known as the *Villari effect*, for which a mechanical stress applied to a ferromagnetic rod lying in a magnetic field gives rise to a change in the magnetic flux density.

Magnetostrictive transducers are often made in the forms of rods surrounded by coil windings (see Figure 3.12). An alternating current through the coil induces an alternating magnetic field of the same frequency; this gives rise to longitudinal oscillations of the rod.

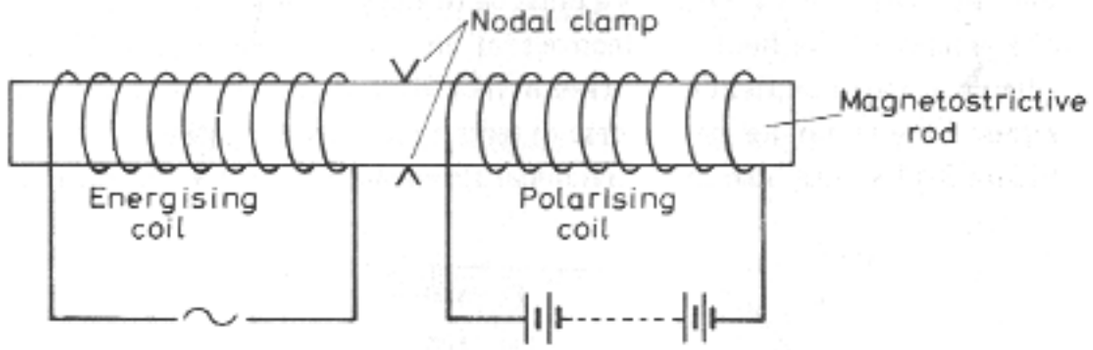

Figure 3.12 Method of exciting a magnetostrictive transducer in the form of a rod

Because the value of the strain in the rod depends only on the magnitude of the applied magnetic field and is independent of its sense, these oscillations take place at a frequency twice that of the field and take on the form of an unsmoothed rectified alternating current, i.e. the vibrations are of low amplitude and contain many unwanted frequencies. As in the case of ceramic transducers (see Section 3.2.1), this disadvantage is overcome by polarisation. It is not usually possible to obtain a high polarising field by permanent magnetisation, and a steady direct field of suitable magnitude is provided by passing a direct current through another coil wound round the transducer. Thus, instead of the oscillations taking place about the origin of the curve of Figure 3.11, they occur about some other point, say D. Provided that the amplitude of the applied alternating field is low enough for changes to take place along an approximately linear portion of the curve between, say, A and B and, in any case, is less than the value of the polarising field, the oscillations are purely sinusoidal and occur at the applied frequency.

As with piezoelectric transducers, maximum efficiency of the oscillations is obtained at the fundamental resonance frequency f_r (see Section 2.9). The effects of harmonics are minimised by nodal mounting (see Figure 3.12).

The resonance frequency varies inversely with the length of the transducer rod. For example, a nickel rod 125 mm in length has a fundamental resonance frequency of 20 kHz, at which high intensities are possible. The frequency is increased by decreasing the length, but, at the same time, there is a lowering of intensity for a rod of given cross-sectional dimensions resulting from the reduction in size of the vibrating mass. The output from this type of transducer becomes vanishingly small at frequencies much higher than 100 kHz. However, magnetostrictive transducers are used mainly for high-intensity applications and the use of frequencies higher than about 20 kHz is not common.

A disadvantage of using rod-shaped oscillators lies in the fact that there is a considerable leakage of magnetic flux. For high-intensity

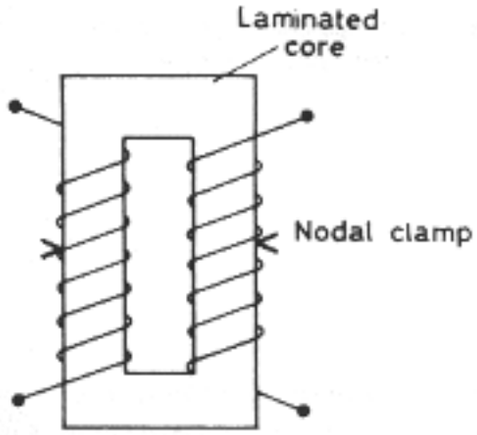

Figure 3.13 Window-type transducer

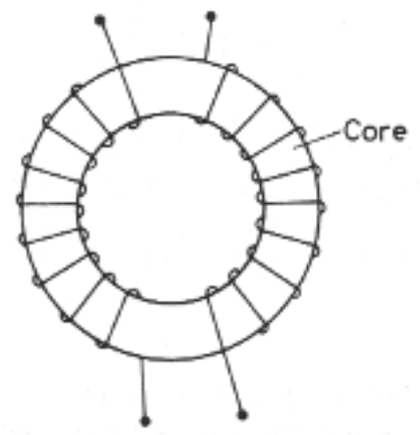

Figure 3.14 Ring-type transducer

applications, it is common to use transducers designed to form closed magnetic circuits (see Figures 3.13 and 3.14). The window-type transducer illustrated in Figure 3.13 is clamped nodally, and its vibrations are longitudinal. The ring-type transducer, however, vibrates in a radial manner (see Figure 3.14) so that ultrasonic energy is focused at the centre where, consequently, the acoustic intensity may be very high.

In Section 4.6.3 it is explained that ferromagnetic materials absorb ultrasound as a result of hysteresis and also of the induction of eddy currents. Both these phenomena give rise to a considerable amount of heating. There are a number of ferromagnetic materials having low hysteresis losses, but, unfortunately, their magnetostrictive properties are poor. However, eddy current losses may be reduced by using laminated stacks consisting of alternating sheets of the metal and of some insulating material such as mica. It is important to cool the transducer during its operation, otherwise the rise in temperature brought

about by hysteresis and eddy currents may produce a reduction, or even disappearance, of the magnetostrictive properties.

An increased intensity, distributed over a smaller area, can also be obtained with both rod and window types of transducers by using what is known as a *velocity transformer*. This consists of a tapered coupling rod (see Figure 3.15) and provides an increase in the value of the particle velocity at the end remote from the transducer. For maximum

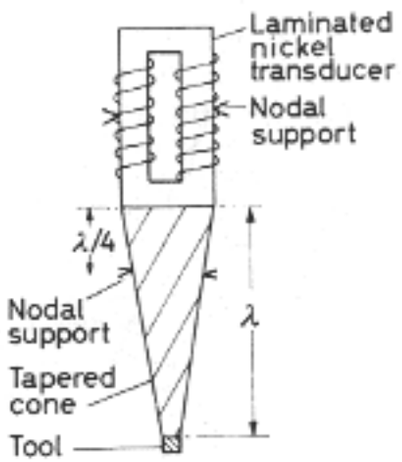

Figure 3.15 Use of tapered coupling rod with the ultrasonic drill

efficiency, the transformer is designed to resonate by making it one wavelength long and supporting it at a nodal point, i.e. at a distance of a quarter-wavelength from the transducer. The diagram illustrates the application of the velocity transformer to the construction of the ultrasonic drill (see Section 7.7).

A method of coupling magnetostrictive transducers to liquids is described in Section 7.6 in connection with ultrasonic cleaning applications. The section also contains a brief comparison of the properties of magnetostrictive and ceramic transducers as used for this type of work.

Magnetostrictive oscillators are reversible and thus can be used as receivers. An example of a magnetostrictive probe receiver is illustrated in Figure 3.16. It consists of a nickel rod held vertically in a fluid in which ultrasound is radiated in an upward direction. The rod is contained in a plastic tube so that only the free end is exposed to the waves which are then transmitted along its length. A current is induced by the Villari effect in the pick-up coil placed near the upper end of the rod. Another coil carrying a direct current provides the polarising field. The formation of stationary waves is prevented by placing an absorbent material at the top of the rod.

Mention should be made of the use of nickel film transducers for producing and receiving ultrasound of very high frequencies ranging from 100 MHz to 100 GHz in solids. A thin film of nickel, of thickness corresponding to one half-wavelength at the resonant frequency, is

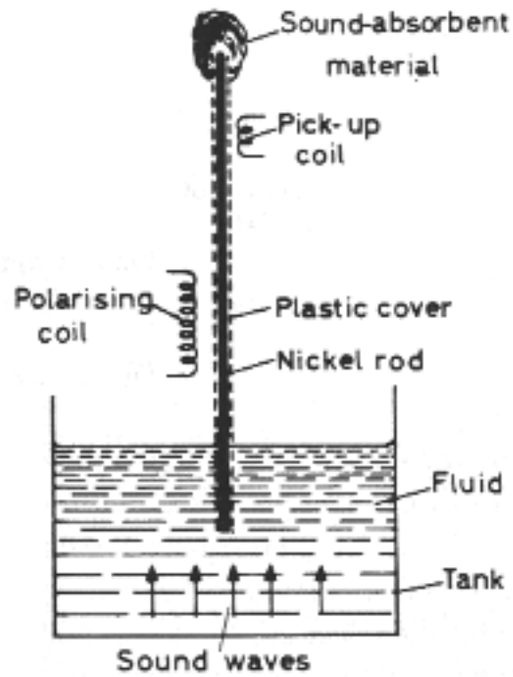

Figure 3.16 Magnetostrictive probe microphone for liquids

deposited on the end-surface of the specimen into which sound is to be passed. The rod is located with its plated end inside a microwave electromagnetic cavity resonator, excited at the required frequency. The receiver may consist of a similar film coated on the opposite surface of the specimen and also located in a cavity resonator. Alternatively, using a reflection method, a single nickel film can act as both source and receiver. The method is similar to that used with u.h.f. piezoelectric transducers (see Figure 3.6) except that a polarising magnetic field is necessary. On the other hand, no coupling material is required and no special technique is necessary for coating the nickel film.

3.4 Mechanical transducers

Mechanical ultrasonic generators are now used almost exclusively for high-intensity propagation in liquids and gases at frequencies of up to about 25 kHz and exist mainly in the forms of whistles and sirens. They

are generally more powerful and less expensive than piezoelectric and magnetostrictive transducers, but their applications are more limited in scope.

Ultrasonic whistles are of two types, namely the *cavity resonator*, used mainly for gases, and the *wedge resonator*, employed for both gases and liquids. The cavity resonator exists in two forms. The first, called the *Galton whistle* (see Figure 3.17) consists of a cylinder terminated

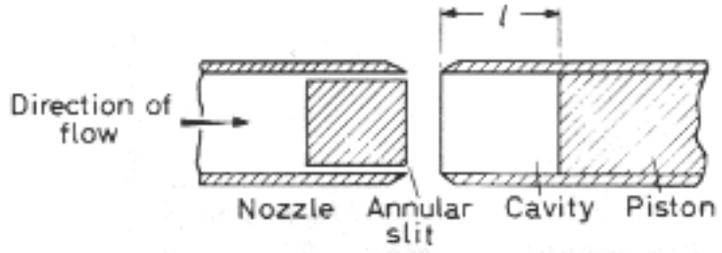

Figure 3.17 Galton whistle

by the end-surface of a piston which can be adjusted in position to provide resonance at the required frequency, i.e. for which the length *l* of the cavity is one quarter-wavelength. The fluid, usually a gas, flows through an annular slit at high speed and strikes the rim of the tube where vortices appear and produce edge-tones. The frequency of the edge-tones depends on the velocity of the fluid which can be adjusted until the cavity resonates. For air, at a frequency of 20 kHz, fundamental resonance takes place for a cavity length of approximately 4 mm. It is difficult to excite pure tone resonances at frequencies of much higher than this.

The second type of cavity resonator is the *Hartmann generator*, similar in design to the Galton whistle, except that the annular slit is replaced by a conical nozzle (see Figure 3.18). The fluid is forced

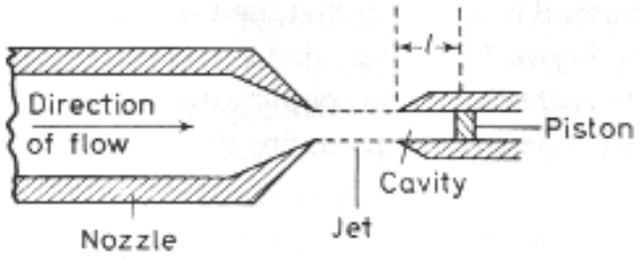

Figure 3.18 Hartmann generator

through the nozzle and emerges at a supersonic velocity to produce shock waves, which cause the cavity to be excited at a high intensity. Resonance is achieved by adjusting the fluid velocity. This device is

much more powerful than the Galton whistle, and, at a frequency of 20 kHz, it is possible in air to produce up to 50 W of acoustical energy.

The *wedge resonator* consists of a rectangular plate with wedge-shaped edges, similar to a razor blade, mounted on nodal supports and placed in a fluid jet stream like that used for the Hartmann generator (see Figure 3.19). The wedge is set up into flexural vibrations having an

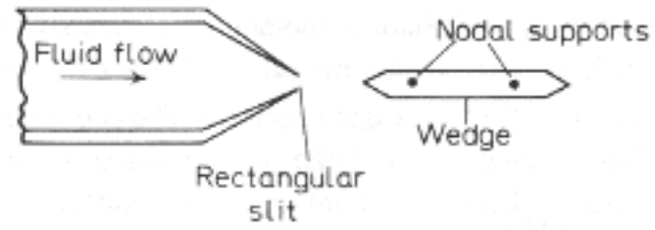

Figure 3.19 Side view of arrangement for wedge resonator

intensity comparable with that attained by the Hartmann generator. This type of transducer is especially suitable for use with liquids and is employed extensively to produce emulsions, especially in the food and cosmetic industries (see Section 7.3). Operating frequencies are, again, of the order of 20 kHz.

Sirens also are used for generating high-energy ultrasound in fluids, In its basic form, the siren consists of a disc (the rotor) in which are cut a number of identical holes spaced evenly around the circumference of a circle slightly smaller than the disc. The rotor turns concentrically in front of a similar disc (the stator), which is kept at rest whilst fluid jets are directed through the holes. The frequency of the emitted ultrasound is equal to the frequency of interruption of the jet flow, as the holes move relatively to one another, and is given by the product of the number of holes in the rotor and the speed of revolution. Thus a siren with a rotor having 100 perforations and revolving at a speed of 12 000 rev/min (200 s^{-1}) emits sound waves of a frequency of 20 kHz. The tone emitted by the siren is not a pure one but this is unimportant for the applications for which it is used. One advantage of this instrument is that the frequency can be varied in a continuous manner simply by altering the speed of rotation.

The use of mechanical receivers has been restricted to measurements of intensities in liquids and gases. However, indirect measurements can be made of intensities in solids by coupling the solid to a liquid in which the receiver is situated and calculating the decrease in intensity at the solid–liquid interface, using equation 2.16. The two principal types of mechanical receivers are the *Rayleigh disc* and the *radiometer.*

The Rayleigh disc consists of a thin circular disc suspended vertically in the ultrasonic field by means of a torsion fibre. Initially the disc is positioned, in the absence of sound waves, with its plane surfaces parallel with the direction of propagation. The sound waves then exert a couple on the disc, which rotates until brought to rest in a steady position as a result of an opposing couple exerted by the suspension. The angle of rotation required to reach the state of equilibrium depends on the particle velocity and, hence, the acoustic intensity.

A *radiometer* is a device which measures directly the pressure of radiation, a quantity which is proportional to the acoustic intensity (see Section 2.6). The simplest form of radiometer is a tiny solid sphere suspended in the sound field. It is deflected horizontally in the direction of propagation when the ultrasound is present. The device is calibrated by subjecting it to known fluid pressures and then measuring the resulting displacements. Other types of radiometer exist in the forms of radiation balances (see Figures 3.20 and 3.21) for which the pressures

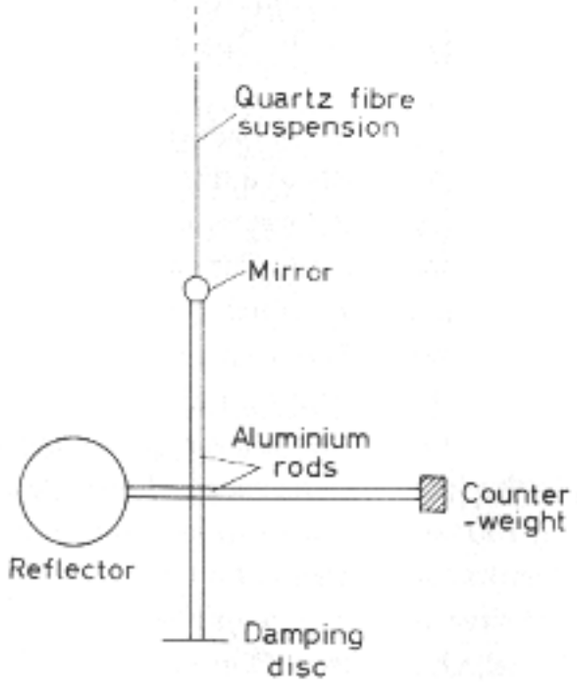

Figure 3.20 Torsion balance radiometer

of radiation are exerted on plane surfaces of bodies of negligible weight. The torsion balance radiometer is designed for waves travelling in a horizontal direction and the common balance type for vertically directed waves, but the use of a 45° reflector can readily render horizontal waves vertical and vice versa. Sensitivity of detection is

greatest when the degree of mismatch of characteristic impedance between the material and the reflector attached to the balance is a maximum. For fluid media, this condition may be achieved by making the reflecting element from two thin sheets of a light solid material, such as mica, with an air space in between.

The Rayleigh disc and torsion balance radiometers are employed as probe receivers, and it is essential that their dimensions be small compared with wavelength, otherwise the acoustic field is disturbed by the

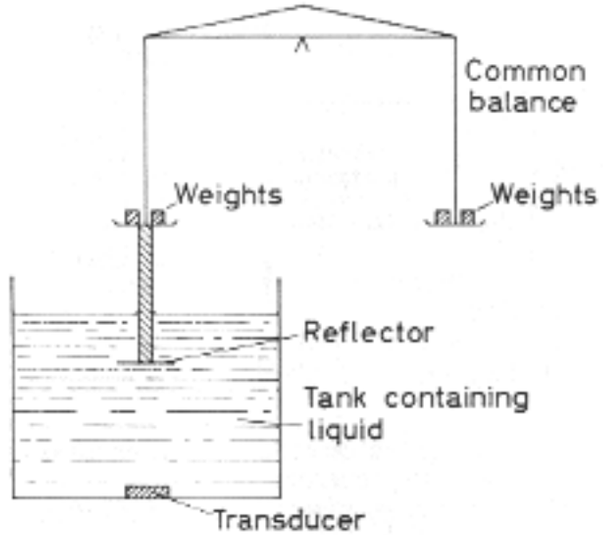

Figure 3.21 Common balance radiometer

receiver. This sets an upper frequency limit of about 60 kHz to their operation. The common balance type of radiometer may, however, act as the terminal of the acoustic path and its upper frequency limit is determined only by its sensitivity. It has been used to measure intensities in liquids at frequencies in the mega-hertz range (see Wells[10]).

3.5 Electromagnetic transducers

Electromagnetic types of transducers are commonly used at audible frequencies in the forms of loudspeakers and microphones, but their applications at ultrasonic frequencies are somewhat limited because of the rapid increase of inertial effects with frequency above the audible range. However, with modern techniques of depositing thin metal films, this disadvantage has been overcome, and lightweight electromagnetic

transducers have been used for some low-intensity ultrasonic measurements in poorly conducting solids and liquids. A disadvantage of the method is that the constant application of a steady magnetic field is required.

A device used successfully by Giacomini (see Mason[11]) for internal friction measurements (see Section 5.4) at frequencies of up to about 50 kHz or so is illustrated in Figure 3.22. A bar of poorly conducting

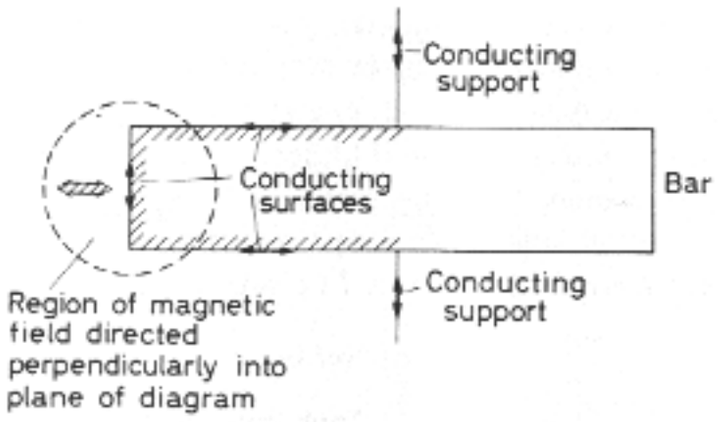

Figure 3.22 Giacomini's electromagnetic method for exciting a bar of poorly conducting solid material into ultrasonic vibration

solid is coated with a thin conducting strip of negligible mass over opposite halves of the upper and lower surfaces and the end-face. It is supported horizontally at the nodal positions by electrically conducting wires, and the coated end is subjected to a horizontal magnetic field at right angles to the axis. When an alternating current is passed through the conducting strip, the bar vibrates longitudinally, in accordance with Fleming's left-hand rule of electromagnetism.

Because electromagnetic transducers are reversible, vibrations in the bar are picked up by the conducting strip which, in the presence of a steady magnetic field, will have induced in it an alternating e.m.f. in accordance with Fleming's right-hand rule of electromagnetism. This e.m.f. is related to the acoustic intensity. Thus the device can be used as both a transmitter and a receiver of ultrasound.

More recently, Filipczynski[12] designed an electromagnetic receiver for measuring intensities of pulsed ultrasonic waves in poorly conducting liquids at lower mega-hertz frequencies (see Figure 3.23). An aluminium film in the form of a continuous and winding narrow strip is

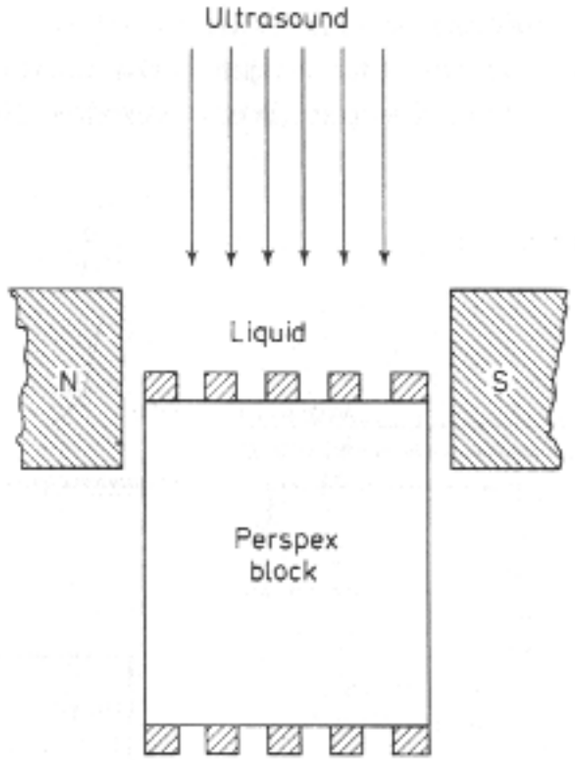

Figure 3.23 Filipczynski's electromagnetic transducer for intensity measurements in poorly conducting liquids

evaporated on to a perspex block so as to provide a coil of negligible mass. The block is then immersed in the liquid and located inside a gap between the pole-pieces of a permanent magnet which supplies a steady magnetic field of high intensity. Ultrasonic waves pass from the liquid into the block, giving rise to oscillations of the aluminium coil which induce in it an e.m.f. related to the intensity in the block. The intensity in the liquid could be calculated by allowing for reflection and transmission at the perspex–liquid interface in accordance with equations 2.15 and 2.16.

3.6 Electrostatic transducers

An electrostatic transducer consists essentially of two parallel plates of a conducting material placed close to one another to form an electrical

capacitor. One plate is fixed and the other is free to vibrate in a direction at right angles to the surface of the plates. A high resistance of the order of a megohm is placed in series with the capacitor and a direct potential difference of several hundred volts maintains steady charges on the plates (see Figure 3.24). The device is reversible in its action and may be used as either a transmitter or a receiver.

For operation as a transmitter, a signal at the desired frequency, having an output voltage of amplitude not exceeding the direct potential

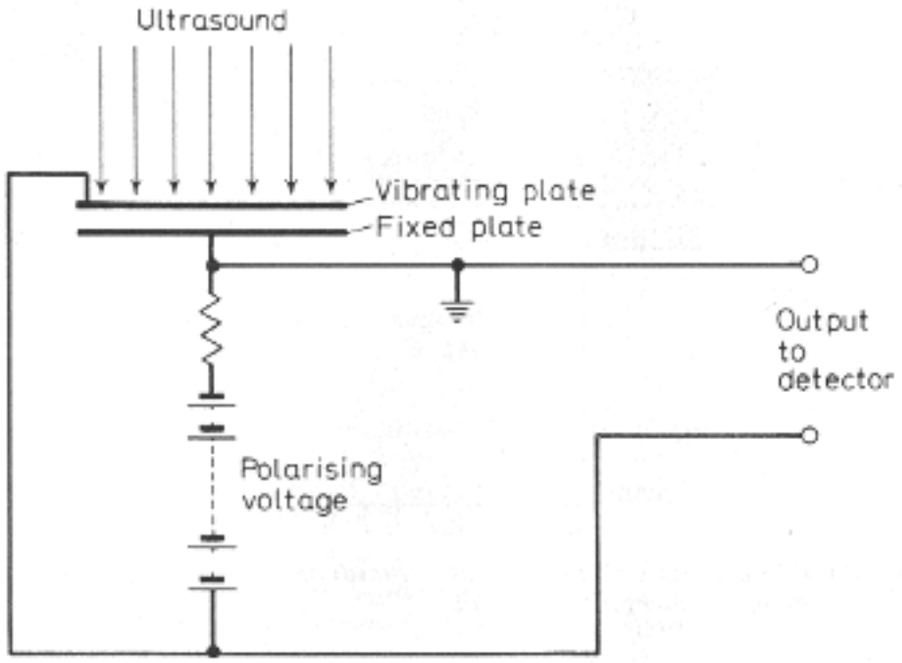

Figure 3.24 Principles of the electrostatic type of transducer

difference, is fed to the plates. The resultant periodic variation of the charges induces vibrations of the movable plate. For use as a receiver, the movable plate is placed in position to receive the sound waves and its consequent vibrations give rise to periodic variations of the electrical capacitance of the transducer. This, in turn, produces an alternating current which flows through the high resistance; the resulting alternating voltage appearing across this resistance is related to the intensity of the received sound.

The electrostatic transducer in the form of the condenser microphone has long been used at audible frequencies. It has the advantage that the moving system, i.e. the diaphragm, is extremely light, so inertial effects are negligible and the sensitivity remains constant over a wide frequency

range. It can be used for gases and liquids as both a receiver and a transmitter at frequencies of up to about 300 kHz, and, because it is a non-resonance device, it can be used without any appreciable change of sensitivity at all frequencies within its range of operation.

The upper frequency limit is determined by the increasing inertia of the diaphragm, by the comparatively low sensitivity of the device, and by the fact that its output can easily be shunted to earth by the capacitance of the lead connecting it to the detecting circuit. The last

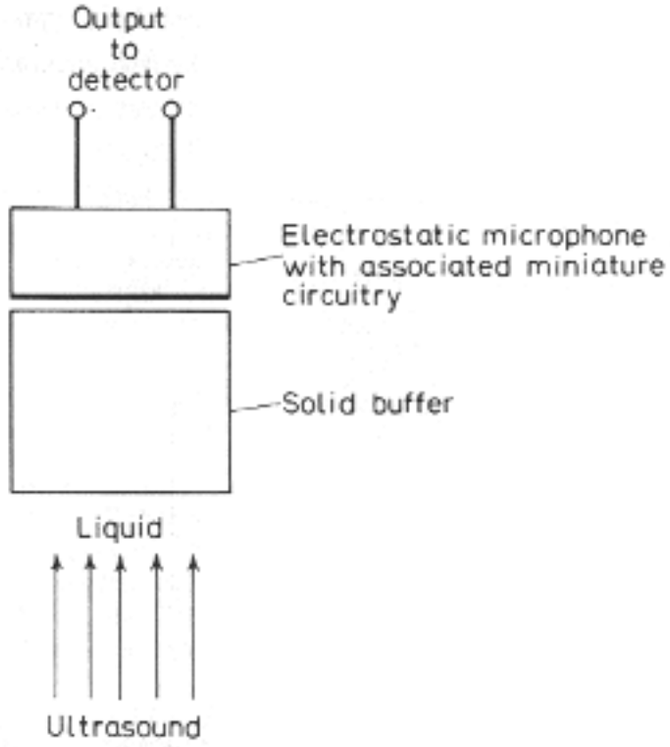

Figure 3.25 Electrostatic transducer used for measuring intensities at mega-hertz frequencies in liquids

two disadvantages may be overcome by the use of recently developed miniaturised circuits placed in direct contact with the fixed plate. This provides an amplified output of low resistive impedance which is easily detected, even at high frequencies.

When an electrostatic transducer is used with solids, the setting of an upper frequency limit by the inertia of the vibrating plate does not arise because the end-surface of the solid can serve as this plate; this surface must be covered with a metallic film if the solid is a poor conductor. Electrostatic transducers have been used for detecting ultrasound at frequencies of up to 100 MHz in solids. By using a solid as a buffer,

the device can be used for measuring intensities at mega-hertz frequencies in liquids (see Figure 3.25) if reflections at the interface are allowed for.

3.7 Miscellaneous transducers

Other methods of generating and receiving ultrasound involve the uses of thermal, chemical, and optical devices, and a short account of them is given elsewhere[13]. The observations of chemical changes in materials irradiated with ultrasound have sometimes provided a means of detection. Also it is possible to generate ultrasonic waves in a transparent

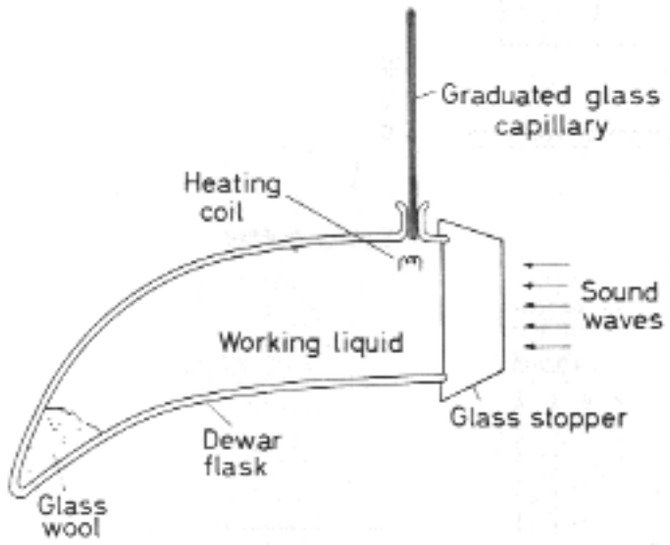

Figure 3.26 Device for measuring ultrasonic energy absorbed by a liquid, after Mikhailov and Shutilov[14]

medium by the crossing of two laser beams originating from a common source. In general, however, chemical and optical transducers are not often used.

On the other hand, there are a number of applications which make use of thermal transducers. One thermal type of transmitter is the spark-gap generator, which radiates ultrasound as a result of periodic temperature changes taking place when a high alternating voltage of a given frequency is discharged across a gap in a circuit.

The hot-wire microphone, originally developed during the 1914–1918 war, is a receiving thermal transducer. It consists of a thin wire, of the order of 25 μm (0·001 in) diameter, usually made from platinum and heated to just below redness. When sound waves strike the wire, it cools down by an amount directly dependent on the intensity. This is indicated by a decrease in its electrical resistance. The hot-wire microphone has been used successfully for gases at frequencies of up to 600 kHz but has not proved suitable for liquids because of its low sensitivity due to convection losses.

Ultrasonic intensities can also be measured from the rise in temperature within the beam. An instrument designed for this purpose and applied to high-intensity measurements is illustrated in Figure 3.26. The heat produced by the ultrasound is absorbed by the liquid in the flask, which is thermally insulated. The liquid consequently expands, and there is a rise in the level of the liquid in the graduated capillary tube, which is calibrated by supplying a measured amount of heat from the heating coil. The shape of the flask is designed to prevent waves reflected at the walls passing back into the acoustic field. The waves transmitted through the liquid are finally absorbed by the glass wool placed at the end of the vessel. Acoustic powers of from 50 mW to 30 W can be measured to an accuracy of better than 10 per cent with this device.

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CHAPTER FOUR

THE PROPAGATION OF ULTRASOUND IN MATERIALS

4.1 General considerations

Ultrasound travels through a uniform material at a constant speed provided that the deformations produced in it by the action of the waves are purely elastic, i.e. the acoustic intensity is low. The velocity c of the sound depends on the density ρ and the modulus E of elasticity appropriate to the type of deformation produced by the waves, i.e.

$$c = \sqrt{\frac{E}{\rho}} \tag{4.1}$$

The elastic modulus E used in the above equation does not have the same value as the one determined by ordinary statical measurements. In the latter case, the body is deformed relatively slowly with the temperature remaining constant and it is the *isothermal* elastic modulus which is measured. When sound passes through a substance, the resulting deformations alternate at a rapid rate, even at low frequencies. During the compression phase of a cycle, the temperature rises, and, during the expansion phase, it falls. Heat should flow from the regions of compression to those of rarefaction, but, before enough time has elapsed for this to happen, the sound waves will have moved a sufficient distance for a reversal in phase to have occurred, i.e. compressions will have become rarefactions and vice versa. Thus no time would become available for heat exchanges to occur across any temperature gradients set up by the waves and it can be said that these exchanges are adiabatic. The symbol E in equation 4.1 then represents the *adiabatic* elastic modulus. This has a higher value than that of the corresponding isothermal modulus. For liquids and solids, the difference between the two quantities is usually very small, but, for gases, this difference is considerable (see Section 4.2).

At high intensities, the velocity of sound may be somewhat greater than that predicted by equation 4.1 and its value, which depends on the wave amplitude, is given by a more complicated expression. However, when one measures the speed of sound in order to determine the value of the elastic modulus, the intensity is kept sufficiently low for equation 4.1 to be applicable. The study of the acoustical properties of a material stressed beyond its elastic limit is a highly specialised one and is not likely to concern the reader.

Also of importance is the absorption of sound waves by a material. There are a number of different ways in which this can occur, and they will be dealt with briefly in this chapter.

4.2 Propagation in gases

Gases will support only compressional and tensile stresses but not shear stresses, and it is thus possible to pass only longitudinal waves through them. The applications of these types of stresses give rise to a change in volume, and the appropriate elastic modulus is the bulk modulus K. For the so-called permanent gases, e.g. oxygen, hydrogen, and nitrogen, which condense at very low temperatures and obey Boyle's law to a high degree of precision, K is equal to the hydrostatic pressure P for isothermal conditions and the product γP for adiabatic conditions. Here γ represents the ratio, for the gas, of the specific heat at constant pressure to the specific heat at constant volume. It has a value which usually lies between 1·3 and 1·7, depending on the nature and physical state of the gas. Equation 4.1 can thus be rewritten as

$$c = \sqrt{\frac{\gamma P}{\rho}} \tag{4.2}$$

This equation applies to a high degree of approximation to most gases, except for some heavy organic vapours, for which the speed of sound may be somewhat higher. It can be shown that, for an ideal gas, i.e. one obeying Boyle's law, the speed of sound varies with the temperature t (in degrees Celsius) as follows:

$$\frac{c}{c_0} = \sqrt{\left(1 + \frac{t}{273}\right)} \tag{4.3}$$

c and c_0 represent the acoustic velocities at temperatures t and 0°C, respectively. Thus, if one measures the velocity at a given temperature, its value at 0°C can be easily calculated. Acoustic velocity measurements can thus provide a method of temperature determination. Values of c_0 for a number of gases are given in Table 4.1.

Except at very high or very low pressures, the velocity of sound in a gas remains constant when the pressure is changed.

The acoustic velocity in a mixture of two gases varies linearly with the degree of concentration, by weight, of each component. Thus, for a mixture of oxygen ($c_0 = 330\ \mathrm{m\,s^{-1}}$) and nitrogen ($c_0 = 310\ \mathrm{m\,s^{-1}}$) present in equal masses, the velocity at 0°C is $320\ \mathrm{m\,s^{-1}}$, i.e.

Table 4.1 VELOCITIES OF SOUND FOR SOME COMMON GASES AT 0°C AND ATMOSPHERIC PRESSURE

Gas	*Velocity, c_0* ($m\,s^{-1}$)
Air	330
Argon	320
Carbon dioxide	260
Helium	970
Hydrogen	1 300
Neon	430
Nitrogen	330
Oxygen	310

½(330 + 310) $m\,s^{-1}$. Thus velocity measurements can provide a means of measuring relative concentrations in mixtures of gases.

Sound waves are absorbed in gases as a result of the following three phenomena: (a) viscosity, (b) thermal conduction, and (c) thermal relaxation. Absorption due to *viscosity* and *thermal conduction* takes place in all gases. The absorption coefficient increases with the square of the frequency, but its value does not become appreciably high, for laboratory purposes, until the frequency rises above a few hundred kilohertz. The total absorption resulting from both these phenomena is called the *classical absorption* (because the relevant theory is derived from a consideration of purely classical physics) and typical values of the corresponding absorption coefficients are 0·12 dB mm^{-1} for air, 0·15 dB mm^{-1} for oxygen, and 0·21 dB mm^{-1} for nitrogen at a frequency of 1 MHz.

Absorption resulting from *thermal relaxation* may occur in all except monatomic gases, such as argon and neon. A proper account of this phenomenon is beyond the scope of an elementary work of this nature, and the reader who is interested is referred elsewhere (e.g. Blitz[1]). It is sufficient to state here that thermal relaxation results from exchanges of energy between the various atoms contained within each gas molecule; these exchanges affect the specific heat of the gas. The corresponding absorption coefficient is obtained by subtracting the value of the classical absorption coefficient, at the frequency concerned, from the measured absorption coefficient. Figure 4.1 shows the relationship between the absorption per wavelength ($a\lambda$) (see Section 2.13) and frequency. At a frequency called the *relaxation frequency* f_0 the curve reaches a peak. Below the relaxation frequency, a increases with the square of the frequency. The figure also shows that the velocity of

sound v varies with frequency. At low frequencies it has a constant value c, but, as the relaxation frequency is approached, the velocity increases and then levels off to a higher constant value at a frequency above f_0. This higher velocity is a few per cent greater than the velocity c at lower frequencies. The variation of acoustic velocity with frequency is called *dispersion.*

At atmospheric pressure, the relaxation frequencies for most of the so-called ideal gases usually lie in the mega-hertz range, but, for some of

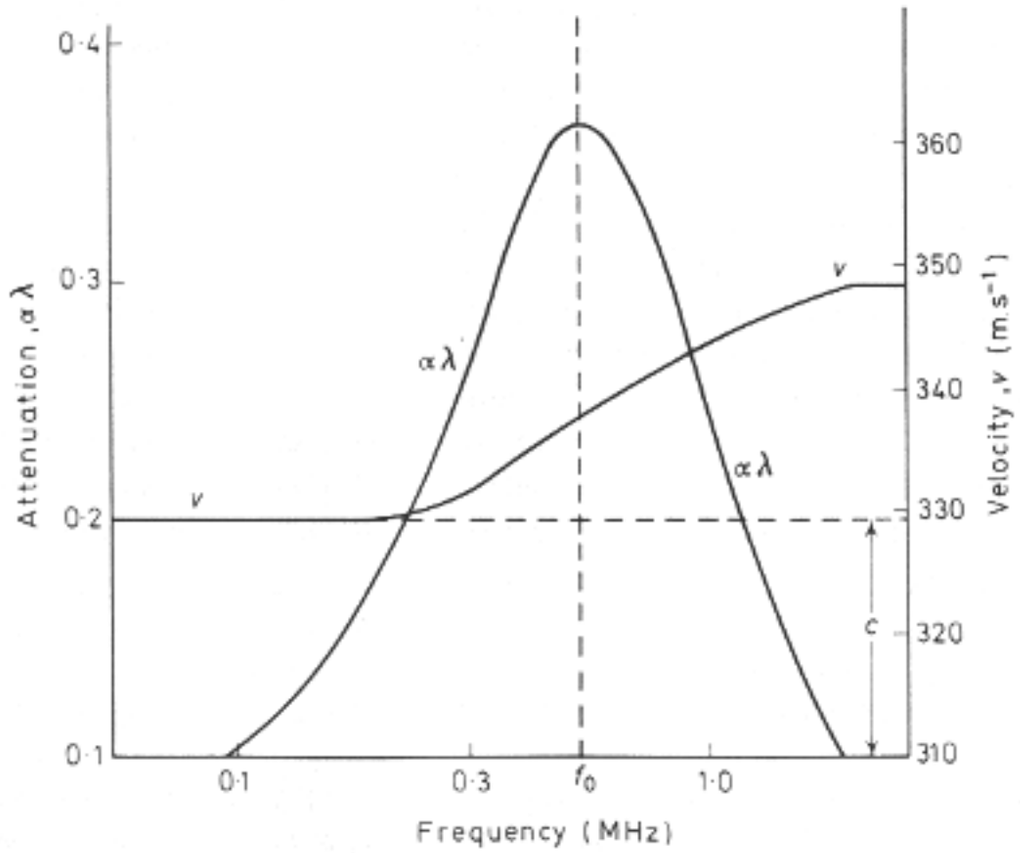

Figure 4.1 Typical variation, due to thermal relaxation, of absorption per wavelength αλ and velocity of sound v with frequency

the heavier gases and vapours, they may be somewhat lower, e.g. for carbon dioxide there is a relaxation at 15 kHz at s.t.p. Gases may possess more than one relaxation frequency, and the curve in Figure 4.1 then becomes somewhat more complex.

In practice, attenuation in gases becomes very high at mega-hertz frequencies, and the practical upper limit for measurements rarely exceeds 5 MHz. Consequently, it is not always possible to measure a

required relaxation frequency at atmospheric pressure. However, the relaxation frequency varies linearly with pressure, as follows:

$$\frac{f_1}{f_2} = \frac{P_1}{P_2} \tag{4.4}$$

where f_1 and f_2 are the relaxation frequencies corresponding to gas pressures P_1 and P_2. Thus, if the pressure is reduced to a suitable value, a relaxation peak may be observed and the relaxation frequency corresponding to atmospheric pressure can easily be deduced from equation 4.4. Another advantage of the application of this equation is that a continuous variation of both absorption and acoustic velocity with pressure can be investigated. Curves similar to those shown in Figure 4.1 can be obtained without the necessity of varying frequency. This is important with the use of high-Q quartz crystal transducers which can be operated only at single frequencies.

Absorption coefficients and relaxation frequencies can change dramatically when impurities, even in minute quantities, are introduced into a gas. For example, the introduction of 1 per cent by weight of water vapour into carbon dioxide will increase one of the relaxation frequencies from about 15 kHz to more than 2 MHz, with a corresponding change of absorption coefficient. In suitable cases, the measurement of relaxation frequency can be a highly sensitive method of determining the degree of concentration of impurities present in small quantities (e.g. parts per million).

4.3 Propagation of longitudinal waves in liquids

In common with gases, liquids collapse under the action of shear stresses. With heavy liquids, the time taken for the collapse to take place may be somewhat longer and it may be possible to pass shear waves through them for limited distances (see Section 4.4). However, the passage of shear waves through liquids is an exceptional phenomenon and, in general, it may be taken here that only longitudinal wave propagation is possible in liquids.

For longitudinal wave propagation, the relevant elastic modulus applicable to equation 4.1 is the bulk modulus K and the difference between its isothermal and adiabatic values is usually negligible. The velocity c of sound is given by the expression

$$c = \sqrt{\frac{K}{\rho}} \tag{4.5}$$

where ρ is the density of the liquid. Values of c for a number of commonly used liquids are given in Table 4.2. The velocity of sound varies with temperature but not in the simple manner as with gases; in most cases, it *decreases* as the temperature rises, but, for water under normal conditions, there is first an increase with temperature, rising to a peak at 73°C at atmospheric pressure, then a decrease. In general, the velocity of sound in a liquid rises when there is an increase in pressure.

Table 4.2 VELOCITIES OF SOUND FOR SOME COMMON LIQUIDS AT 20°C AND ATMOSPHERIC PRESSURE

Liquid	*Velocity, c* ($m\,s^{-1}$)
Acetone	1 200
Benzene	1 320
Carbon tetrachloride	950
Castor oil	1 500
Chlorobenzene	1 320
Ethyl alcohol	1 200
Glycerol (pure)	1 940
Methyl alcohol	1 120
Nitrobenzene	1 480
Olive oil	1 440
Toluene	1 320
Water	1 490

When two liquids are mixed together, the variation of the acoustic velocity with the degree of concentration is not always a simple one, even when no chemical reaction takes place between the components. When two unassociated liquids are mixed together, the variation is linear, as occurring with gases, but, if one or both of the liquids are associated, there is, in most cases, first a decrease in velocity with concentration until a minimum is reached and then a linear increase. If, however, one of the liquids is water, which is associated, the curve shows a maximum. Figure 4.2 illustrates variations of the velocity of sound with concentration for ethyl alcohol–carbon tetrachloride and ethyl alcohol–water mixtures at different temperatures. It will be seen from this figure that the velocity in a 17 per cent concentration of ethyl alcohol in carbon tetrachloride remains constant for all temperatures. This is a useful consideration in the design of liquid delay lines.

Classical absorption due to viscosity and thermal conduction takes place in liquids as well as in gases, but the thermal conduction effects are usually negligible. In some liquids, especially organic ones, thermal relaxation may be observed. In other liquids, including water, absorption

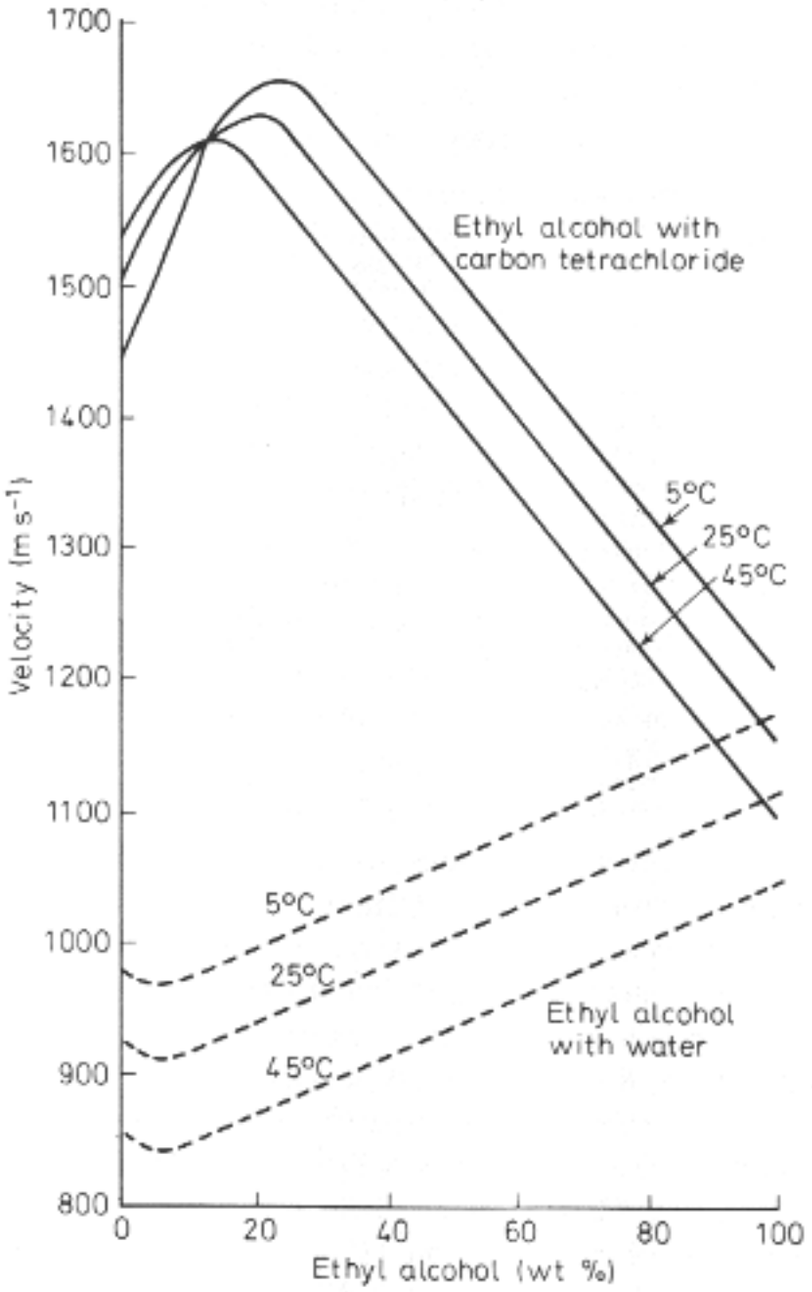

Figure 4.2 Relationships between the velocity of sound and concentration at different temperatures for mixtures of ethyl alcohol with carbon tetrachloride (continuous lines) and of ethyl alcohol with water (broken lines), after Derenzini and Giacomini[2]

occurs as a result of *structural relaxation*, sometimes known as *bulk viscosity*. This, again, gives rise to absorption peaks and dispersion in the manner previously shown (see Figure 4.1). It is not feasible here even to attempt any explanation of this phenomenon, and the interested reader is referred elsewhere (e.g. Blitz[3]).

4.4 Propagation of shear waves in liquids

Although the propagation of shear (transverse) waves in liquids is an exceptional phenomenon and is of less importance than the propagation of longitudinal waves, it is, nevertheless, of great interest.

As stated earlier, liquids will take a finite amount of time to collapse under the action of shear stresses, and shear wave propagation may be possible even though the range of penetration may be less than 1 μm. For liquids having low viscosities (i.e. 'light' liquids) the shear wave velocity c_T is given by the expression

$$c_T = \sqrt{\frac{2\eta\omega}{\rho}} \tag{4.6}$$

where η is the coefficient of viscosity, ρ the density of the liquid, and ω the angular frequency. The absorption coefficient a is given by

$$a = \sqrt{\frac{\omega\rho}{2\eta}} \tag{4.7}$$

It is seen that, the higher the viscosity (i.e. the heavier the liquid), the greater the velocity of sound and the lower the absorption. Furthermore, both the velocity and the attenuation increase with frequency. Typically, for a frequency of 1 MHz with water at room temperature, for which $\eta \triangleq 1$ centipoise (10^{-3} N m^{-2} s), the approximate values of c_T and a are 3·5 m s^{-1} and 1·8 x 10^3 neper mm^{-1} (1·5 x 10^4 dB mm^{-1}), respectively. Thus an intensity drop of 100 dB takes place after the ultrasound has travelled a distance of only 2·6 μm, corresponding to a time interval of less than 1 μs. With more-viscous fluids, the velocity will be correspondingly higher but the range of penetration will be reduced, perhaps to as little as 10^{-3} μm. However, this may well be of the same order of magnitude as the thickness of a film of lubricating oil, and the technique of shear wave propagation lends itself to investigations into the properties of this type of material.

For a very heavy liquid, the time of collapse under the action of a shear stress is much longer and account must now be taken of the shear modulus G for this kind of substance. G is related to the viscosity

coefficient η by the following equation:

$$G = \frac{\eta}{\tau} \tag{4.8}$$

where τ is called the *relaxation time*, which depends on the time taken for the liquid to collapse under the action of the shear. The corresponding shear wave velocity c_T is the same as that for solids, namely

$$c_T = \sqrt{\frac{G}{\rho}} \tag{4.9}$$

Liquids which relax slowly are referred to as being *viscoelastic* or *non-Newtonian*, and their relaxation times may range from as low as 10^{-6} s for castor oil to many years or even centuries for glasses, which are in reality supercooled liquids.

4.5 Propagation in solids

Sound can be transmitted through solids in several ways, depending on the shape, size, and nature of the material and also on the type of wave excitation. Solids will usually withstand shear stresses, and it is thus possible to pass transverse waves as well as longitudinal waves through them. The differences between their adiabatic and isothermal elastic moduli are very small.

For a solid in the shape of a bar, rod, or wire, for which the cross-sectional dimensions are assumed to be small compared with the wavelength, the velocity c_R of longitudinal waves is given by the equation

$$c_R = \sqrt{\frac{Y}{\rho}} \tag{4.10}$$

where Y is the Young's modulus and ρ the density of the solid. It is assumed that the beam of sound extends over the whole cross-section of the rod and there is no reaction to the applied stress at the lateral boundaries. Equation 4.10 is no longer applicable when the cross-sectional dimensions exceed about one-tenth of a wavelength because the material will then act as a waveguide and other considerations must be taken into account in determining the velocity of sound. This sets an upper frequency limit for the propagation of sound waves with an easily calculated velocity in rods and wires, e.g. about 50 kHz for a steel rod 10 mm in diameter and 500 kHz for a steel wire 1 mm in diameter. Thus, when used for delay line applications at mega-hertz frequencies, wires must have diameters of small fractions of millimetres.

The propagation of alternating shears along a rod or wire usually takes the form of *torsional waves* for which the vibrations are directed around arcs of circles concentric with the axis. The corresponding velocity c_T is given by

$$c_T = \sqrt{\frac{G}{\rho}} \tag{4.11}$$

where G is the shear modulus.

Most applications involving velocity measurements, either directly or indirectly, are made on materials in bulk form. The operating frequency is chosen for the cross-sectional dimensions of the sample to occupy at least several wavelengths. Furthermore, the lateral boundaries of the beam should be contained within the material. Frequencies for which conditions intermediary between those of a rod and bulk material apply should be avoided if a simple expression for the velocity of sound is required.

When longitudinal waves pass through a material in bulk form, the reactions of the non-radiated part of the material on the lateral boundaries of the beam of sound must be considered. These reactions produce shear stresses in addition to the compressional stresses associated with the waves. The acoustic velocity c_L will thus be a function of both the bulk modulus K and the shear modulus G, i.e.

$$c_L = \sqrt{\frac{K + \frac{4}{3}G}{\rho}} \tag{4.12a}$$

If one makes use of the relations connecting the principal elastic constants, equation 4.12a may be rewritten in the following form, which is more familiar to engineers:

$$c_L = \sqrt{\frac{Y(1-\sigma)}{(1+\sigma)(1-2\sigma)}} \tag{4.12b}$$

where σ is Poisson's ratio for the material.

For pure shear wave propagation in bulk solids, the velocity of sound is given by equation 4.11. Values of acoustic velocities for various solids are shown in Table 4.3, where it is seen that the transverse wave velocities are very roughly equal to about half the corresponding longitudinal wave velocities. The longitudinal wave velocities in rods are somewhat less than those in bulk materials. It should be made clear that these are only average values, because they are affected by the previous histories of the materials, e.g. whether they are annealed, work-hardened, rolled, or drawn.

Equations 4.10–4.12b assume that the material in question is isotropic, i.e. its physical properties, such as elasticity, thermal conductivity, and electrical resistivity, remain the same for all directions. This

is generally true for unstressed polycrystalline and amorphous solids but not so for materials existing in the forms of single crystals. Furthermore, the equations are not necessarily applicable to pre-stressed materials, such as rolled or extruded metals, where anisotropy is introduced by the pre-stressing process. The velocities of sound in anisotropic materials vary with direction, and the expressions for them are somewhat complicated. For further details, the reader is referred to Mason[4].

Table 4.3 VELOCITIES OF SOUND FOR SOME METALS IN POLYCRYSTALLINE FORM AT 20°C AND ATMOSPHERIC PRESSURE

Metal	*Velocity*		
	Longitudinal waves in rods, c_R ($m\,s^{-1}$)	*Longitudinal waves in bulk materials,* c_L ($m\,s^{-1}$)	*Shear and torsional waves,* c_T ($m\,s^{-1}$)
Aluminium (worked)	5 100	6 400	3 100
Copper	3 700	4 700	2 260
Gold	2 000	3 200	1 200
Iron	5 200	5 900	3 200
Lead	1 200	2 300	790
Nickel	4 800	5 600	2 900
Platinum	2 800	3 900	1 700
Silver	2 700	3 700	1 600
Steel (mild)	5 200	6 000	2 900
Tin	2 700	3 300	1 700

Also of importance is the propagation of acoustic waves across the surfaces of solids, i.e. *surface waves*, the theory of which is somewhat involved. In the study of ultrasonics, one is usually interested in the *Rayleigh* type of surface waves, for which the particle vibrations take place in those planes at right angles to the surface and orientated in the direction of propagation, in a manner to some extent similar to that occurring with waves on liquid surfaces. The vibrations have two components of motion, one transverse and the other longitudinal. The phase of each of these modes of vibration varies at different rates, and a given particle, in its vibration, will generally follow an elliptical path. The equation for the velocity of Rayleigh waves is a complex one (see, for example, Blitz[5]); the value of this velocity can be shown to be approximately 0·9 times that for shear waves in the material concerned. The depth of penetration of Rayleigh waves below the surface is very small, and the geometry of the beam can be considered to be two dimensional. The attenuation is consequently much lower than that experienced by bulk waves in the same material. Rayleigh waves are

reflected at discontinuities on the surface, e.g. corners and cracks, and, for this reason, they are sometimes used for surface flaw detection. Another type of surface waves, in which the vibrations take place in the plane of the surface but in the direction perpendicular to that of the beam, is known as *Love waves*. Love waves are employed extensively by seismologists but have little application in the study of ultrasonics.

It was stated previously that Rayleigh waves penetrate only a short distance below the surface. If, however, the solid is in the form of a thin plate, there is complete penetration and flexural vibrations take place to give rise to what are known as *Lamb waves* (see, for example, Filipczynski, Pawlowski, and Wehr[6]). Lamb waves provide a useful tool for the detection of laminar defects just below the surfaces of solid materials.

A detailed account of Rayleigh and Lamb waves has been given by Viktorov[7].

4.6 Attenuation in solids

Attenuation of sound waves in solids may be caused by a number of factors, the most important of which are as follows:

1. Losses characteristic of polycrystalline and non-homogeneous materials,
2. Absorption due to imperfections of the crystalline lattices,
3. Absorption resulting from ferromagnetic and ferroelectric phenomena,
4. Absorption caused by interactions of sound waves with free electrons,
5. Absorption caused by interactions of sound waves with thermal lattice vibrations.

These phenomena are discussed briefly below, but, for a more detailed account, the reader is referred elsewhere (Blitz[5]).

4.6.1 Losses characteristic of polycrystalline and non-homogeneous materials

Practically all metals used in the construction of the commodities of everyday life are polycrystalline in their structure. Polycrystalline solids are made up of very large numbers of grains, having microscopic dimensions, of the material. Each of these grains is itself a single crystal and thus, in general, anisotropic. However, because the grains are

orientated at random and because they exist in very large numbers, the solid as a whole, from statistical considerations, displays isotropic properties. Now if a straight line is drawn through the material, the physical properties, e.g. elastic moduli, of the material change abruptly at each grain boundary owing to the variations of orientation of the crystalline axes of the grains. Thus sound waves travelling along that line will suffer abrupt changes in their velocities, often by more than 20 per cent, with corresponding changes in their characteristic impedances, and reflections will take place at each grain boundary. Where, as is usual, the wavelength is large compared with the mean dimension of the grains, reflection will not be regular but will take the form of scattering equally in all directions, i.e. Rayleigh scattering as described in Section 2.15. The waves will thus be attenuated in accordance with equation 2.27 for which the value of K will depend on the degree of anisotropy of the individual grains.

For most polycrystalline metals, the value of the mean grain size is sufficiently low for no appreciable degree of attenuation to appear at frequencies much less than 1 MHz. However, the attenuation coefficient then increases very rapidly with frequency, because of the fourth-power law, and, except for extremely fine-grained materials, it is practically impossible to pass ultrasound through polycrystalline metals at frequencies above 10 MHz. For coarse-grained metals, the upper limit may be only 1 MHz. Thus, if a beam of ultrasound of frequency 2 MHz is attenuated by 10 dB as a result of Rayleigh scattering, the attenuation is increased to 160 dB when the frequency is raised to 4 MHz. With most commercial ultrasonic equipment, this is sufficient to render the waves undetectable. In Section 6.7 it is shown how Rayleigh scattering provides a means of estimating grain sizes in metals.

In non-homogeneous materials, such as concrete, Rayleigh scattering takes place because of the presence of aggregate. The velocities of sound in concretes are generally much lower than those in metals, typically by a factor of one-half, and the sizes of the aggregates are considerably larger than those of metallic grains. For this reason, measurements on concretes are made at frequencies of around 100 kHz. Attenuation measurements provide a means of determining aggregate sizes in concretes and, together with velocity measurements, provide valuable information about the quality of the product.

Another cause of attenuation in polycrystalline materials is friction occurring at the grain boundaries. In this case, the attenuation coefficient can be shown to be proportional to the first power of the

frequency but independent of the grain size. Provided that the other causes of attenuation are negligible, the total attenuation coefficient a for a polycrystalline metal may be expressed as follows:

$$a = Af + Bf^4 \qquad (4.13)$$

where f is the frequency and A and B are constants for a given sample of material and type of waves, i.e. longitudinal or transverse.

Attenuation in polycrystalline substances may also be caused by thermal conduction effects. Because of the abrupt changes in elastic modulus along the direction of the sound waves at the grain boundaries, the strain suffered by each grain is different from that suffered by its neighbour, for a given stress. Consequently, the temperature variations per cycle differ from grain to grain and temperature gradients are set up in addition to those associated with the wave motion. The regular cooling–heating cycles are thus upset, and a general rise in temperature, perhaps very small, takes place. The energy required to supply this rise in temperature is taken from the sound waves which consequently suffer attenuation.

This phenomenon is called the *thermoelastic effect* and is not generally observed in polycrystalline metals at frequencies above 100 kHz. It should be noted that a similar effect has been attributed to absorption in single-crystal dielectric materials at frequencies in the upper mega-hertz and giga-hertz range.

4.6.2 Absorption due to imperfections of the crystalline lattice

Under normal circumstances, most solids, which includes all metals, are crystalline in nature. The atoms inside the crystals are arranged in a regular pattern called a *lattice*, each atom being located at defined distances from its neighbours, corresponding to specified physical conditions, e.g. constant temperature and pressure. For a perfect crystal, the regular lattice structure is broken only at the boundary. However, most crystals contain defects in the forms of impurity atoms, vacancies in the lattice structure, and dislocations, i.e. discontinuities in the lattice structure. Each of these defects may be responsible for ultrasonic absorption as a result of their taking energy from the waves.

Of greatest interest is the absorption resulting from the interaction of sound waves with dislocations. Dislocations can be introduced into a material by fatigue, cold-working, or rough treatment, and, in general, the higher the density of the dislocations, the greater the hardness of the material. Ultrasonic attenuation measurements may, in some cases,

provide a means of studying these dislocations. Figure 4.3 illustrates the results of experiments carried out by Bordoni[8] on attenuation in copper samples at a frequency of 30 kHz at different temperatures, using the internal friction method (see Section 5.4). In its original state, the attenuation in the sample was small (curve A), but, after cold-working, there was a considerable increase (curve B), and, on annealing, a marked decrease in attenuation was observed (curve C). The peaks indicate that the absorption process is a relaxation one similar to that caused by thermal relaxation in gases. The value of the absorption coefficient at the peak depends on the dislocation density, but the

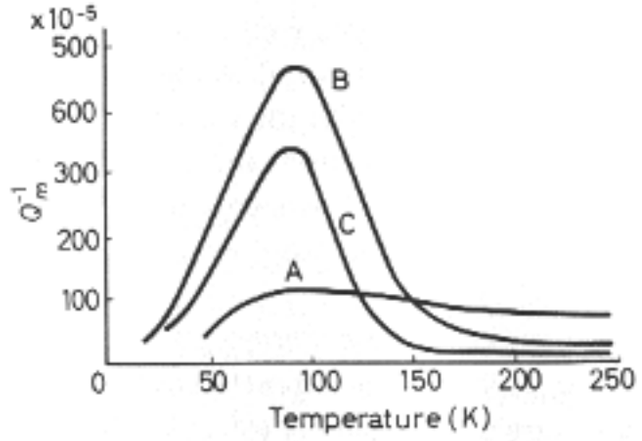

Figure 4.3 Attenuation in copper at 30 MHz as a function of temperature, after Bordoni[8]

position of the peak depends on the nature of the dislocations. There are a number of ways in which dislocations can give rise to ultrasonic absorption, and the reader is referred to Mason[9] for a detailed account.

4.6.3 Absorption resulting from ferromagnetic and ferroelectric phenomena

In Sections 3.2 and 3.3 it was stated that ferroelectric and ferromagnetic materials display, respectively, the phenomena of electrostriction and magnetostriction. These materials are made up of large numbers of what are called 'domains', i.e. elementary regions each behaving as an electrified or magnetised body having a unique polarisation. When ultrasonic waves pass, for example, through a domain of a ferromagnetic material, the domain suffers periodic stresses and, because of the converse magnetostrictive (Villari) effect, changes take place in its intensity of magnetisation. The domains thus suffer magnetic hysteresis during each cycle, and energy taken from the acoustic beam is converted into heat,

so giving rise to attenuation. A similar phenomenon takes place with ferroelectric materials, in the domains of which electric hysteresis takes place.

An additional loss of energy occurring in ferromagnetic materials is the induction of minute eddy currents in the domains, as a result of the hysteresis.

The losses discussed above provide important considerations in the designs of magnetostrictive and electrostrictive (i.e. piezoelectric ceramic) transducers in which much energy is converted into heat during their operation.

4.6.4 Absorption caused by the interactions of ultrasound with free electrons

If ultrasound of a sufficiently high frequency is passed through a single crystal of a pure metal at a very low temperature, e.g. less than −253°C (20 K), attenuation resulting from interactions with free (conduction) electrons may take place. This attenuation increases when the temperature is reduced still further. Frequencies at which the phenomenon can be observed lie usually in the middle and upper mega-hertz range, where the acoustic wavelength is of the same order of magnitude as the mean free path of the electrons at the temperature concerned. The absorption coefficient can be varied by the application of a suitable magnetic field.

An interesting phenomenon occurs with certain metals known as superconductors (e.g. lead, tin, and niobium) for which the electrical resistance is abruptly reduced to zero at the transition temperature, usually within a few degrees of the absolute zero (−273°C). The attenuation is sharply reduced to zero at the onset of superconductivity but can be made to reappear by the application of a magnetic field of sufficiently high value, which destroys the superconductivity.

Electronic attenuation has also been shown to occur at low temperatures in heavily doped single crystals of semiconductors such as germanium and silicon.

4.6.5 Absorption caused by interactions of ultrasonic waves with thermal lattice vibrations

If high-frequency ultrasound (e.g. above 100 MHz) is passed through a single crystal of a pure insulating or intrinsic semiconducting material, free from lattice defects, at room temperature, a high attenuation may be observed. This would result from the interaction of the sound waves

with the thermal vibrations of the atoms forming the crystalline lattice. This attenuation increases with the square of the frequency, and, with a few exceptions, notably quartz, yttrium iron garnet (YIG), and ruby, propagation at microwave frequencies is virtually impossible at room temperatures. However, on reduction of the temperature, the amplitude of the lattice vibrations is reduced, and, at very low temperatures, the attenuation due to this phenomenon is small. The effect is difficult to observe in metals because of the additional attenuation resulting from the interaction of the sound waves with the free electrons (see Section 4.6.4).

4.6.6 Miscellaneous causes of attenuation

Other causes of attenuation in solids include thermal relaxation in plastics and rubberlike materials, structural relaxation in glasses, nuclear magnetic resonance, paramagnetic resonance, and intervalley scattering, a phenomenon observed in some semiconducting single crystals.

4.7 Ultrasonic amplification in solids

In 1961, Hutson, McFee, and White[10] published results of an experiment in which they succeeded in amplifying ultrasound passing through a

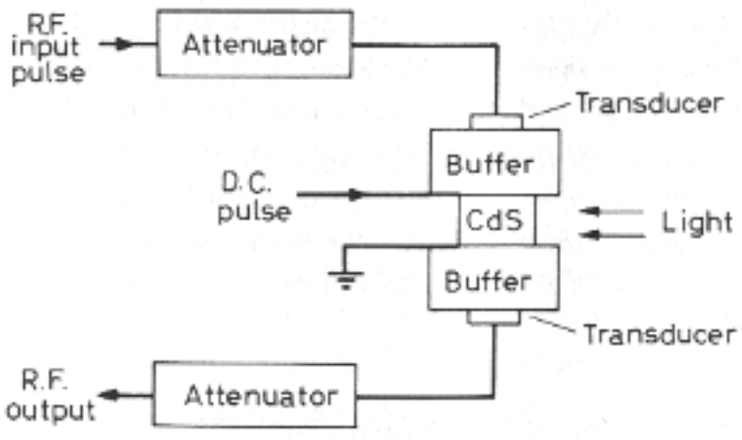

Figure 4.4 Block diagram of the arrangement used by Hutson, McFee, and White[10] for amplification in cadmium sulphide

single crystal of cadmium sulphide, a piezoelectric semiconductor. The sample, in the form of a block (see Figure 4.4) plated on two opposite faces with electrodes, was placed in close contact between two fused quartz buffers and exposed to illumination. Two identical shear wave transducers, one acting as a transmitter and the other as a receiver, were bonded to the outer surfaces of the buffers. Pulsed shear waves were propagated through the sample, simultaneously and in phase with d.c. pulses of the same length and pulse repetition frequency, and, provided that the d.c. pulse amplitude was sufficiently high, amplification of the ultrasound was observed. This amounted to 24 dB at a frequency of 15 MHz and over 30 dB at 45 MHz.

The method has since been exploited extensively and has valuable application in the field of telecommunications. Recent work has involved the use of surface waves in view of their low attenuation compared with bulk waves.

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CHAPTER FIVE

LOW-INTENSITY TECHNIQUES

5.1 Introduction

5.1.1 General considerations

Ultrasound is regarded as being of low intensity when no permanent changes take place in the properties of the material of propagation, an essential condition for any non-destructive testing technique. The acoustic powers are generally very low and rarely exceed a few tens of milliwatts.

The principal methods used for low-intensity applications are as follows:

1. Pulse methods,
2. Progressive continuous wave methods,
3. Stationary wave or resonance methods (including acoustic interferometry and damping capacity techniques),
4. Mode conversion and total reflection methods,
5. Optical methods (including Schlieren and diffraction techniques),
6. Reverberation methods,
7. Impedance methods.

The methods involve, either directly or indirectly, measurements of acoustic velocities and attenuations. In many instances, a single instrument provides both these measurements, often simultaneously.

The choice of frequency is determined, for example, by the size of the sample of the material, by the kind of information required from the measurements, and by the optimum requirements for sensitivity. In practice, most low-intensity applications are made within the frequency range from 0·5 MHz to 10 MHz.

5.1.2 Measurements in gases

Gases are characterised by their relatively high absorption coefficients and low characteristic impedances. Their absorption coefficients increase considerably with frequency and become very high at mega-hertz frequencies (see Section 4.2). For this reason and also because of the poor mismatch of characteristic impedance with solid transducer materials, it is virtually impossible to pass ultrasound through gases at frequencies higher than about 5 MHz.

Until the 1950s the only feasible method of measuring the acoustic velocities and absorption coefficients in gases at mega-hertz frequencies was the acoustic interferometer, using a quartz crystal transducer. This is an exacting instrument requiring careful mounting and adjusting of the transducers and reflector, because of the very short wavelengths and poor transmission from the source to the gas, even under conditions of resonance. With the development of ceramic transducers, higher acoustic outputs have become possible and the less exacting pulse technique can be used.

The disadvantage of using piezoelectric transducers for gases is that the frequency is fixed, because only resonance operation is practicable owing to their high Q factors. However, as discussed in Section 4.2, in the investigation of relaxational phenomena, a variation in pressure produces the same effect as a variation in frequency. With the use of electrostatic transducers (see Section 3.6), continuous frequency changes are possible but, unfortunately, there is an upper frequency limit of less than 300 kHz.

For applications to large quantities of gases, e.g. control types of experiments in free air, for which the use of a parallel beam is not important, it is feasible to work at frequencies in the lower kilo-hertz range. In this case, use can be made of mechanical, magnetostrictive, and ceramic transducers, from which comparatively high acoustic outputs can be obtained.

Further difficulties with measurements in gases arise from the introduction of impurities, which can affect the results seriously. For example, in certain circumstances (see Section 4.2), the introduction of 1 per cent water vapour to a gas might increase the measured value of the attenuation by as much as 400 per cent. It is thus essential that the interferometer chamber be leak-proof and also that the gas under examination is not contaminated by any of the materials used in the equipment, e.g. vacuum grease and mercury. This is not a very easy aim to achieve because some means must be found for moving the reflector relative to the source. Any mechanical connection to the reflector might have to pass through a gas-tight gland, itself a serious source of leakage, but the difficulty has been overcome by the skilful use of expanding bellows. On the other hand, the problem does not arise with the use of the multiple echo pulse technique for which the source and reflector can

be kept stationary. This last method may not, however, be suitable for measurements with highly attenuating gases.

5.1.3 Measurements in liquids

Because the mismatch of characteristic impedances is not serious, the transmission of ultrasound from a solid transducer to a liquid medium presents little difficulty. Furthermore, absorption coefficients in liquids are generally somewhat lower than those in gases and work at higher frequencies is possible, e.g. up to several hundred mega-hertz.

Difficulties can arise with measurements in electrically conducting liquids, such as tap-water, and extreme care must be taken to ensure that the liquid does not provide a short circuit across the electrodes of the transducer. One way of doing this is to mount the transducer on to the outside of the containing vessel so that the sound enters the liquid through the walls. This method may suffer from transmission losses at the liquid–container boundary and from the possibility that the walls

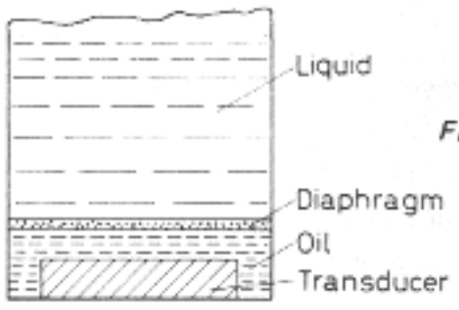


Figure 5.1 Arrangement for a transducer radiating into an electrically conducting liquid

of the vessel may not be exactly parallel or homogeneous in structure. Another way is to contain the transducer in an insulating oil separated from the conducting liquid by a rubber diaphragm (see Figure 5.1). The characteristic impedance of the type of rubber used for this purpose (known as ρc rubber) is very close to that of water and of many other liquids, so that transmission losses are minimised. In practice, the water-tight probe of a commercial ultrasonic flaw detector can often serve the same purpose (see Figure 3.5). The protecting cover is made from a material, such as PVC, which also has a characteristic impedance close to that of water. A third method is to separate the transducer and liquid by an almost non-absorbent solid buffer, such as fused quartz. Figure 5.8 shows how this method is applied to the phase comparison

technique, which is particularly suitable for highly attenuating liquids where acoustic path lengths are short.

A large choice of measurements over a wide frequency range is available for both contained liquids and free liquids (e.g. sea-water).

5.1.4 Measurements in solids

Measurements can be made in solids over a wide range of frequencies, extending to more than 100 GHz. However, the majority of them are made on polycrystalline materials for which there is an upper frequency limit of about 10 MHz, as determined by the effects of Rayleigh scattering. This limit may be exceeded for amorphous materials, such as fused silica and other kinds of glasses. The most widely used measuring technique for solids is the pulse method.

In nearly all cases, a vibrating resonance type of transducer is used for transmitting and receiving, and a satisfactory means of coupling it to the solid sample must be achieved for good matching of characteristic impedances. As discussed in Section 2.8, when a transducer or transducer assembly (i.e. probe) is placed in contact with a solid, there is always a thin air-gap between the neighbouring surfaces unless they are ground to optical flatness (an expensive and time-consuming process). The air-gap must therefore be filled with a suitable liquid. If moderate transmission losses are not important, the immersion technique, for which the transducer and solid sample are immersed in some liquid and separated by a fixed distance, is highly suitable (see Figure 6.2).

5.2 Pulse methods

Basically, the pulse method consists of the generation of short regular pulses of ultrasonic waves in the test sample, the time taken for them to pass through a measured distance being measured. This method is limited in scope by the accuracy of measuring very short periods of time, and, until comparatively recently, it could be used only for field work, e.g. measuring acoustic velocities in atmospheric air and sea-water. However, with the advancement of modern electronic techniques, in which time intervals of less than 10^{-12} s can be measured accurately, the pulse method can now be used for determining acoustic velocities and attenuations in very short samples of material; the shortness of the sample is determined by the lowest limit of wavelength and, hence, by

the highest limit of frequency. In single crystals at low temperatures, it is possible to generate ultrasound at frequencies as high as 100 GHz, for which the corresponding wavelength is of the order of 50 nm (i.e. 5×10^{-8} m). Measurements on samples of only a few millimetres thick, requiring frequencies of some tens of mega-hertz, are now quite common.

The application of ultrasonic pulse technique was brought about by the development of radar. It was first used by Sproule in Great Britain and by Firestone in the USA during the 1939–1945 war for flaw detection in solids, but its application has been rapidly extended to other types of measurements in all kinds of materials.

The basic technique, which is still the one most commonly used, is called the *pulse echo method* (see Figure 5.2). At regular intervals (usually between 50 and 1000 times per second), a trigger excites simultaneously both the time-base and the pulse generator. The time-base control is connected to the X plates of the cathode ray oscilloscope; its function is to move the electron beam from left to right in a given very short time (anything between 1 μs and 1 ms) and then to return it to its original position almost instantaneously. In the absence of any signal being applied to the Y plates, a bright horizontal trace appears on the screen. The pulse generator causes a d.c. signal of several hundred volts and of negligible duration to be applied to a piezoelectric transducer and to excite it at its natural frequencies (see Section 3.2.1). The transducer then emits a very short pulse of ultrasound consisting of a few wavelengths, decreasing in amplitude [see Figure 5.5(a)] into the material under test. At the same time, the signal passes through the tuned amplifier to the Y plates of the oscilloscope and a large peak A appears at the left-hand extremity of the screen. The emitted ultrasonic pulse is reflected at the opposite boundary of the test sample and arrives back at the transducer, which now functions as a receiver. The electrical signal, provided by the receiving transducer as a result of its excitation by the acoustic pulse, is amplified and then rectified so that a d.c. signal appears across the Y plates of the oscilloscope.

Because the amplifier is tuned, only signals having a frequency equal to one of the natural frequencies of the transducer, usually the fundamental, are detected by the oscilloscope. During the time taken for the ultrasound to complete one return passage through the material, the electron beam in the oscilloscope will have moved a given distance to the right and the signal corresponding to the received pulse will be indicated by a smaller peak B (see Figure 5.2). The distance of separation

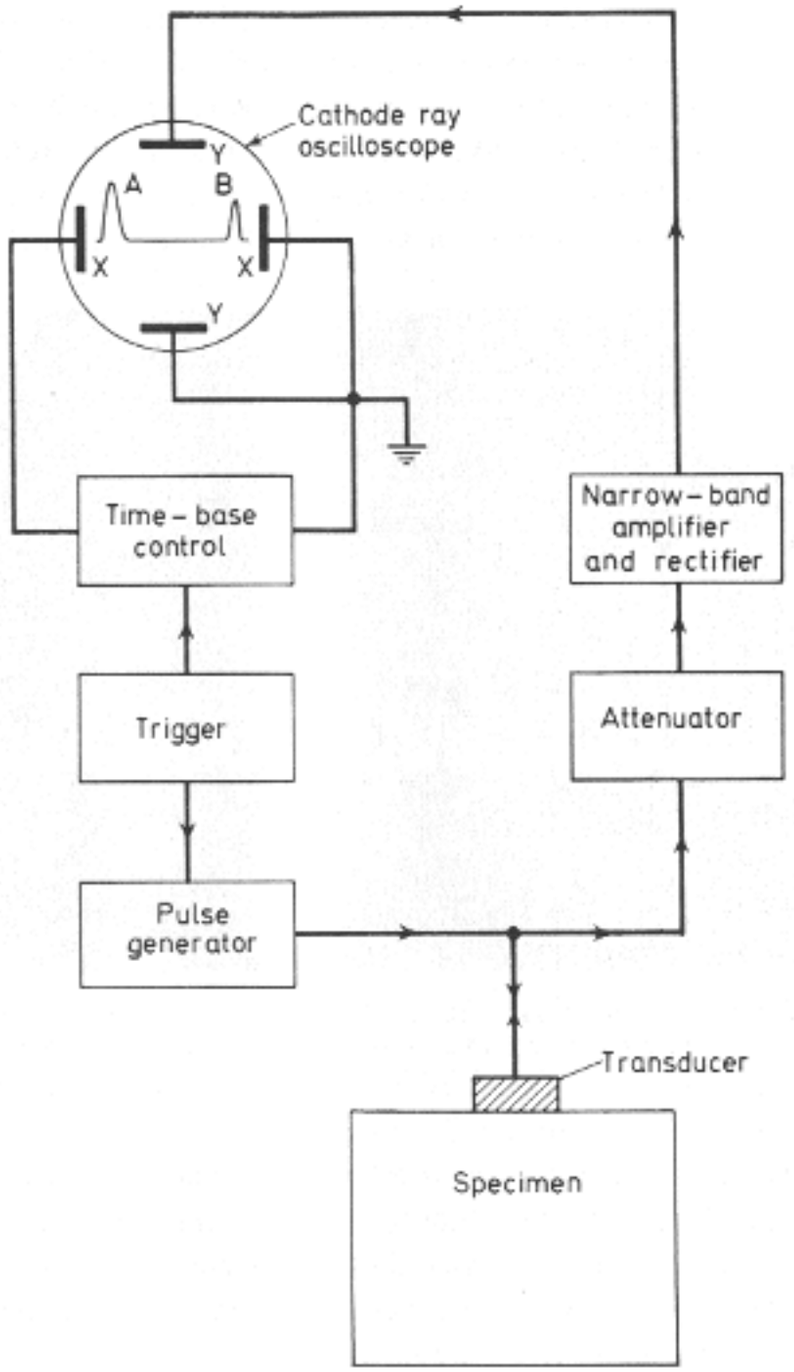


Figure 5.2 Simplified block diagram of equipment used for the basic pulse echo technique

of A from B depends on this time and on the calibration of the time-base. Because the time-base repetition frequency is synchronised with the pulse repetition frequency, the peaks A and B appear to be stationary.

The velocity of sound in the medium is obtained by dividing the measured value of the acoustic path length by the time of travel, as determined from the time-base of the oscilloscope, which can be calibrated in one of two ways. The first is to feed a signal from a standard frequency source to the Y plates of the oscilloscope. The second, which is to be preferred, is to send ultrasonic pulses through a material in which the

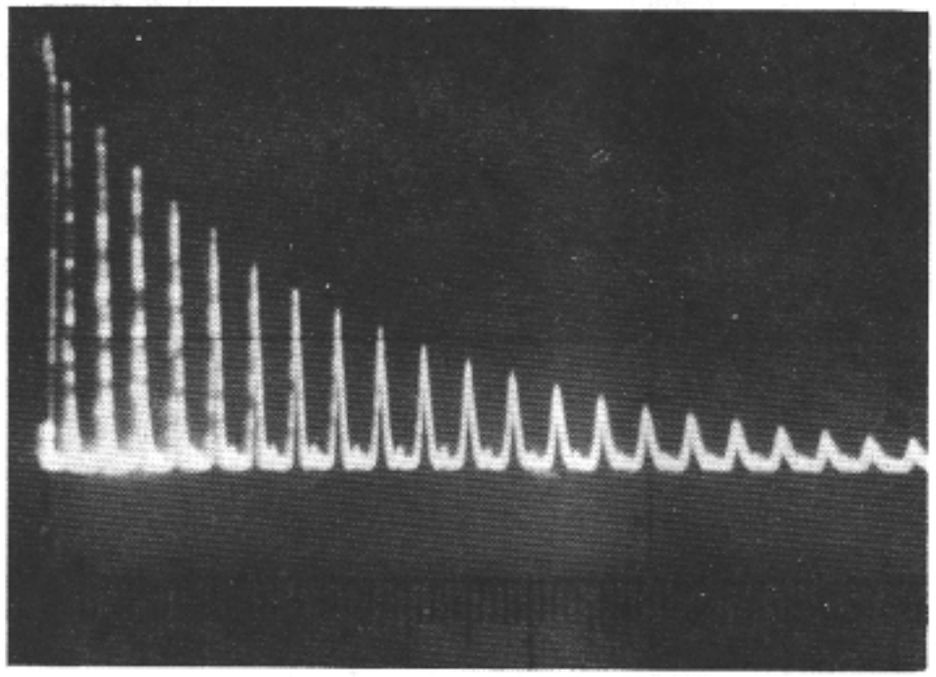


Figure 5.3 Appearance of traces on oscilloscope screen with the multiple pulse echo method: satellite peaks caused by lateral reflections of diffracted waves can be seen

speed of sound is known and to note the positions of the peaks A and B. It is more satisfactory to use a liquid, kept at a constant temperature, as the medium for calibration; a reflecting surface, which is kept parallel to the transducer surface, can be moved in a precise manner to any required position. A material used for this sort of calibration is usually called a *delay line*.

In the delay line method, the two transducers, one in contact with the medium and the other with the delay line, are connected in parallel with one another so that the pulse from each can be propagated simultaneously through the two materials. Two peaks, corresponding to B, one for the liquid and the other for the test material, appear on

the screen. The position of the reflector for the delay line is adjusted until the peaks coincide with one another. The determination is simplified by placing attenuators in series with the transducers and adjusting them until the peaks are the same height when they approach coincidence.

The absorption coefficient of a material can be measured by the *multiple echo method* for which the oscilloscope time-base is contracted until several peaks of decreasing heights, corresponding to multiple reflections at the end-boundaries of the material, appear on the screen (see Figure 5.3). Provided that the surfaces are accurately parallel with one another, the attenuation coefficient can be measured from the logarithmic decrement of the peak heights. The usual method is to

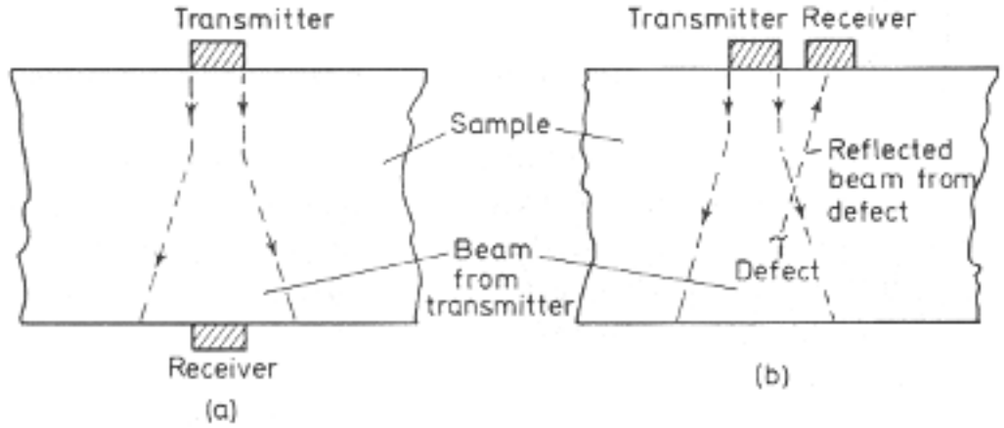


Figure 5.4 Locations of transmitting and receiving transducers for use with the double-probe method: (a) transmission technique; (b) reflection technique, as used for flaw detection

connect a calibrated attenuator in series with the transducer and to note the level of one of the peaks (e.g. the third). The vertical control is adjusted until this level coincides with a horizontal line drawn on a graticule placed in front of the screen. The setting of the attenuator is then adjusted until a peak corresponding to an earlier deflection (e.g. the second) falls to this level. The attenuation is then given by the number of decibels change in the setting of the attenuator divided by the acoustic path length (i.e. twice the length of the sample). Greater sensitivity may be obtained by comparing peaks of widely differing orders (e.g. the twenty-second and the second), provided that they both correspond to reflections taking place in either the near field or the far field. In the latter case, allowance must be made for attenuation caused by the spreading of the beam (see Section 2.14).

When it is desired to study the waveforms of the received pulses, the rectifier is switched out of the circuit.

It is sometimes advantageous, e.g. for highly attenuating materials or for certain flaw-detection applications, to use separate transmitting and receiving transducers (see Figure 5.4), i.e. the double-probe method as opposed to the single-probe method just described. The peak A will thus not appear on the oscilloscope screen, but, if an initial peak is required, e.g. to act as a zero time mark, the circuit should be modified to allow for a signal to be fed to the Y plates at the instant of excitation of the transmitting transducer.

For some applications, e.g. measurements of absorption and velocity dispersion, which are frequency dependent, a long pulse of

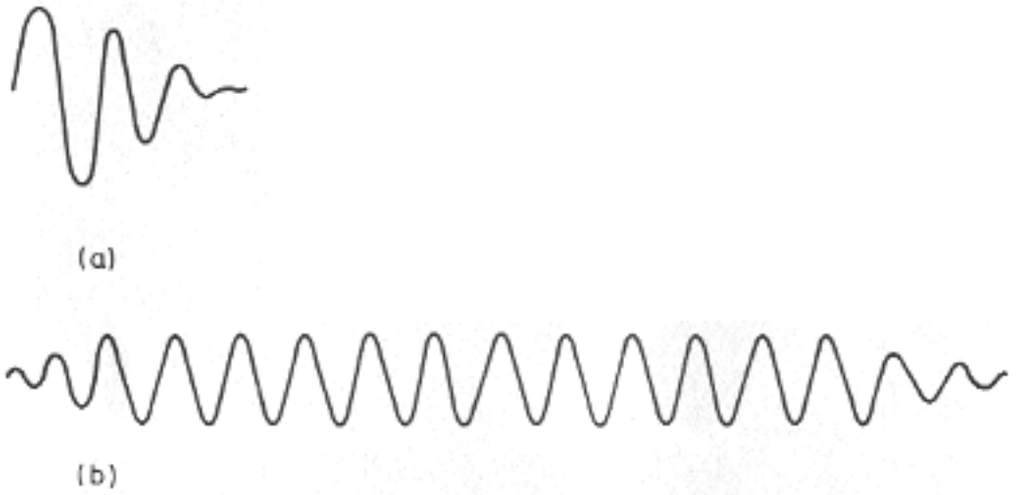


Figure 5.5 Waveforms of pulses excited by (a) the application of a high-amplitude d.c. signal to a heavily damped piezoelectric oscillator, and (b) a radiofrequency signal applied to a transducer for a finite time at the required frequency

constant amplitude is required. In this case, the vibrations of the transducer are controlled by a radiofrequency oscillator and the pulse length is controlled by an electronic pulse generator or a gating device connected to the circuit. Figure 5.5 shows a comparison between the waveform of the long pulse resulting from this kind of excitation and the short pulse characteristic of a heavily damped ceramic transducer excited by a high-amplitude d.c. signal of short duration.

The basic pulse echo method described above, if carefully applied, can measure the velocity of sound with an accuracy of about 1 part in 10^3. However, a device used by Williams and Lamb[1] provides an accuracy of better than 1 part in 10^4. This makes use of a null method in which two identical quartz crystal transducers T and R are located at opposite ends of the sample (Figure 5.6). The transducers are damped sufficiently to provide a flat response over a required limited range of frequencies. The pulse repetition frequency is adjusted for the second pulse to leave

the transmitter T when the first arrives back from the receiver R after a single reflection. Interference takes place between the two pulses, and the wave frequency is adjusted until the combined signal amplitude is a minimum. In order to observe this phenomenon, the signals fed to the Y plates of the oscilloscope are not rectified. The pulse repetition frequency is then equal to the reciprocal of the time taken for the

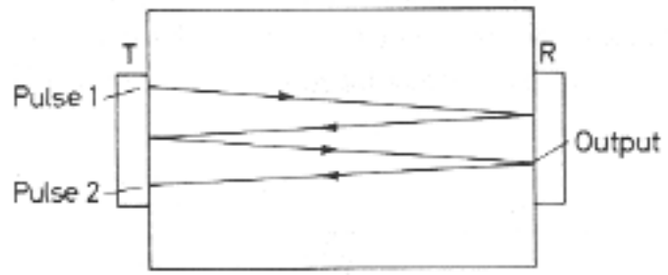


Figure 5.6 Method used by Williams and Lamb[1] for velocity measurements

pulses to complete one return passage through the sample, and the velocity can be calculated if the thickness of the sample is known.

Another technique, described by McSkimin[2,3] is the 'sing-around' method devised by Holbrook (see Figure 5.7). This is a pulse transmission

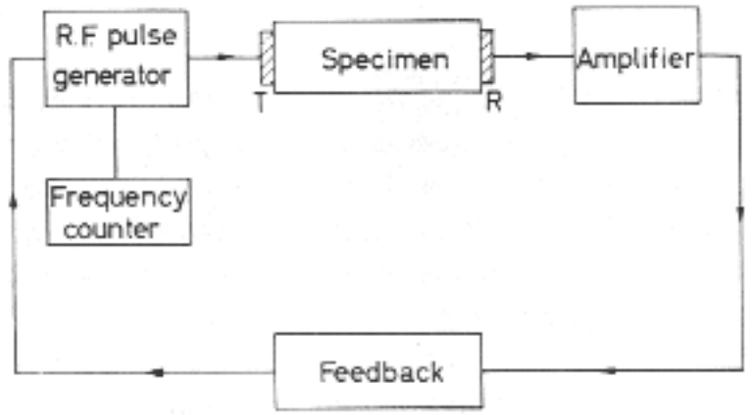


Figure 5.7 Block diagram for the 'sing-around' method, after McSkimin[2,3]

device for which short pulses from the transmitter T pass through the material and are picked up by the receiver R. The receipt of each pulse by R activates the pulse generator to cause another pulse to be transmitted by T. The pulse repetition frequency is thus determined by the time taken for the pulses to pass through the material. The velocity is again determined if the thickness of the sample is known, after due allowance has been made for any time delays characteristic of the electronic circuitry. The accuracy of this method is comparable with that attained by Williams and Lamb.

A technique which is especially suitable for measurements with small samples of liquid, e.g. for rare or highly absorbent materials or where accurate temperature control is required, is the *phase comparison method*. One version, described by McSkimin[2, 3], is illustrated schematically in Figure 5.8. The liquid is contained within a fused silica spacer ring sandwiched between two fused silica rods. Fairly long pulses from a quartz crystal transducer are propagated through one of the rods, and the reflected pulses from opposite surfaces of the liquid interfere with one another. On changes of wave frequency, the amplitude varies

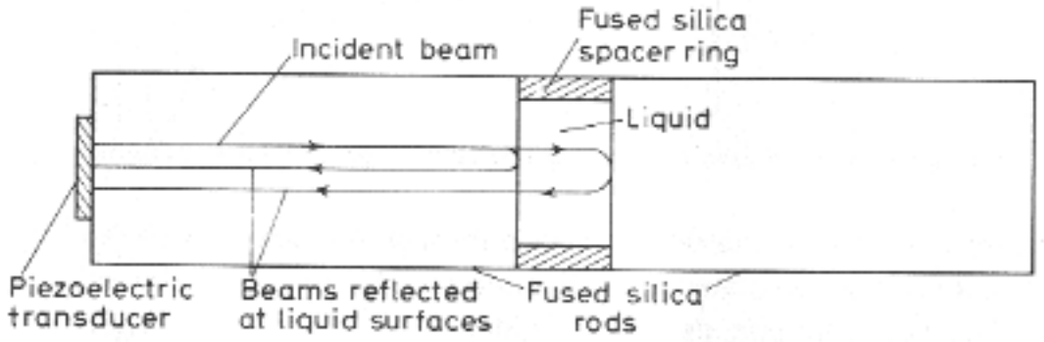


Figure 5.8 Phase comparison method for measurements in liquids, after McSkimin[2, 3]

through maxima and minima, and the variation in frequency corresponding to two successive minima is equal to the reciprocal of the time taken for the return passage of the pulse through the liquid after reflection at the remote surface. The acoustic velocity can then be calculated from a knowledge of the thickness of the liquid sample; a degree of accuracy of up to 1 part in 10^4 is possible.

The method can also be used for determining the absorption coefficient of the liquid by measuring the amplitudes of the pulses reflected at both surfaces, after allowance has been made for the characteristic impedances of the liquid and silica buffer (see equations 2.15 and 2.16). In this case, the pulses should be short enough to eliminate any interferences.

5.3 Progressive continuous wave methods

For progressive continuous wave methods the transmitting transducer is excited at constant amplitude and over a very narrow band at the required frequency so as to generate continuous waves in the sample.

The waves are detected by a receiving transducer situated at a measured distance from the source. This method is suitable only when the attenuation in the material is high or when some damping device is

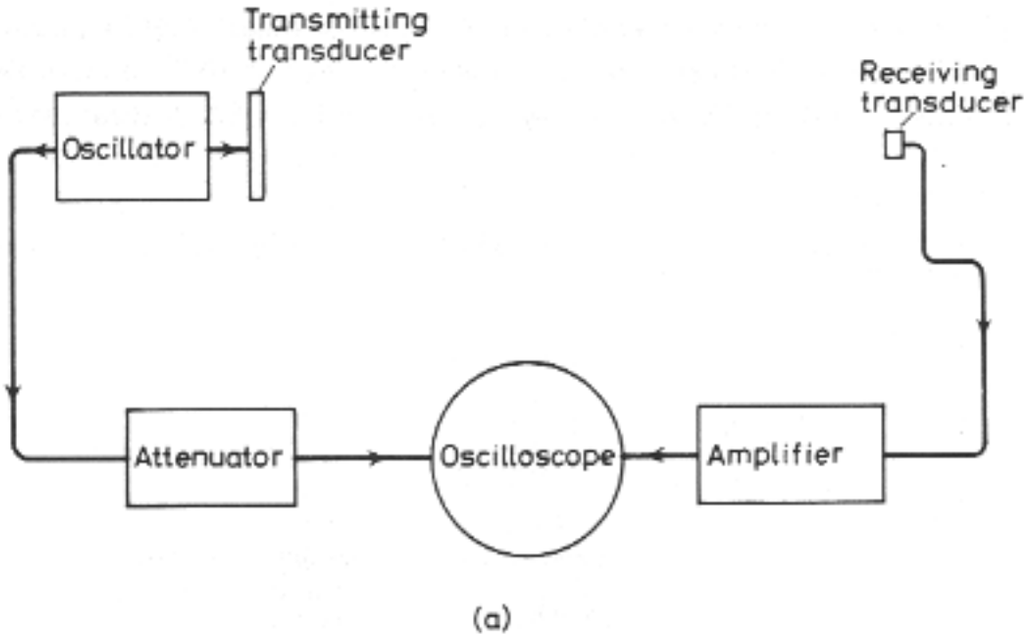


Figure 5.9 Continuous progressive wave method: (a) typical arrangement; (b) appearance of traces on oscilloscope screen

placed at the remote end of the sample to prevent any reflections from taking place and the consequent formation of stationary waves.

A typical arrangement is illustrated in Figure 5.9(a). Signals at a given frequency are fed from a continuous wave oscillator to the transmitting transducer and, at the same time, to the Y_1 plates of a double-beam cathode ray oscilloscope. This latter signal provides a reference trace on the oscilloscope screen [Figure 5.9(b)]. The sound waves picked up by

the receiving transducer are converted to an alternating voltage of the same frequency and waveform and are fed to the Y_2 plates of the oscilloscope to provide a second trace. When the receiver is moved away from or towards the source, this second trace moves relatively to the reference trace. The wavelength is determined by measuring the displacement of the receiver which gives a phase difference of 360° between the two traces, and the frequency may be obtained from the calibration of

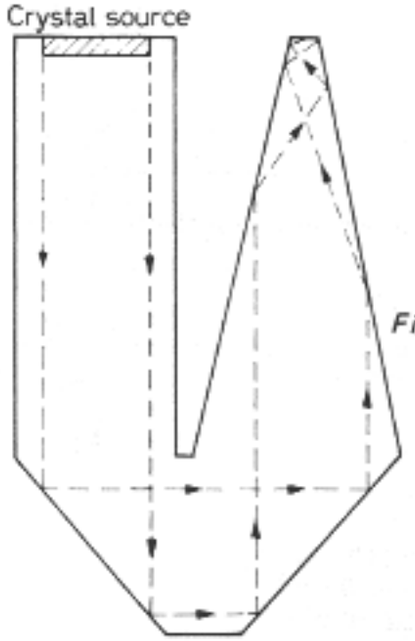


Figure 5.10 Tank designed by Biquard to prevent the formation of stationary waves in a liquid

Dotted lines represent ultrasonic rays

the time-base. The attenuation is measured from the decrease in amplitude of the second trace as the receiver is moved away from the source.

The method can also be used for materials having a low absorption coefficient at low frequencies, where the application of a probe receiver is feasible (see, for example, Section 3.2.7). For fluids, the containing vessel should be designed in such a way that there is no interference due to reflections at the walls or far end. This can be achieved by the use of a suitable absorbent material or by shaping the vessel in such a way that the waves suffer multiple lateral reflections and are absorbed finally by the walls (see Figure 5.10). For solid rods and wires, the receiver may be located at the side of the specimen and the position varied by sliding it. The far end of the rod may be damped by using plasticene or some other suitable absorbent.

5.4 Stationary wave or resonance methods (the acoustic interferometer)

With resonance methods, stationary waves are set up in the sample and either the acoustic path length or the frequency is varied until resonance takes place in the material, i.e. the thickness is either an exact number of half-wavelengths or an odd number of quarter-wavelengths, depending on the type of resonance occurring (see Section 2.9).

For measurements in liquids and gases, a single reversible transducer and a parallel solid reflecting surface are immersed in the medium (see Figure 5.11). The reflector, controlled in position by some kind of

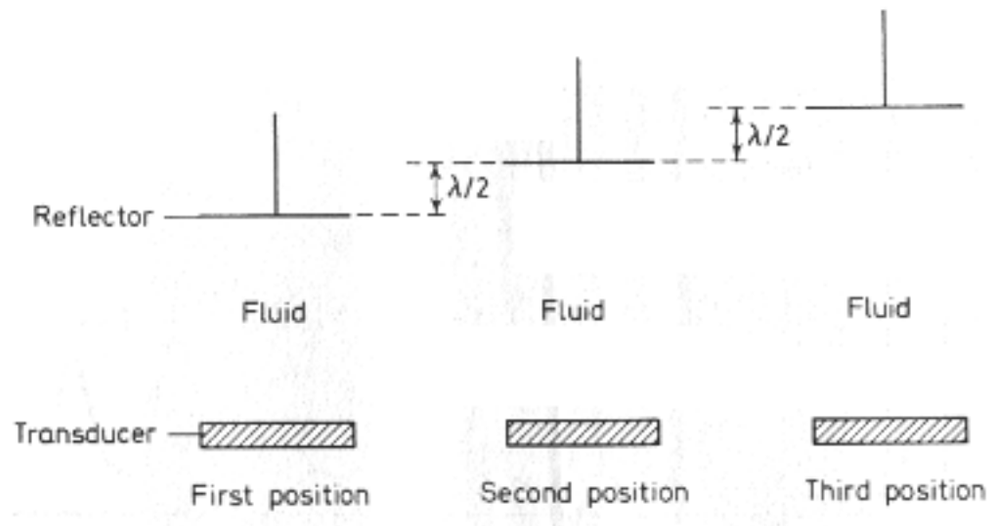


Figure 5.11 Basic design of acoustic interferometer used for fluids, showing three consecutive positions for resonance

micrometric device, is moved until a state of resonance is obtained. The transducer is mounted for minimum damping (see, for example, Figure 3.4), and an electronic detector connected to it will indicate the amplitude of its vibrations. The signal received by the detector is observed for different positions of the reflector and peaks will indicate resonance. The peaks decrease in amplitude as the distance from the source is increased, and they are separated from one another by a distance of one half-wavelength. For low attenuation, the resonance peaks are sharp and the decrease in amplitude with distance is small, but, with high attenuation, the peaks are broad and die down rapidly. The method of measuring attenuation is somewhat involved, but, where this is low, an approximate value is given by the peak decrement. Figure 5.12 shows a plot of the root mean square current through the transducer against the position of the reflector for a liquid sample.

It is important, especially for gases where the wavelength may be as short as 0·3 mm at a frequency of 1 MHz, that the surfaces of the source and reflector are accurately parallel with one another otherwise false readings may be obtained. The effects of non-parallelism and also of diffraction may give rise to the appearance of unwanted additional peaks. One method of checking parallelism is to obtain resonance and to adjust the orientation of the reflector and also its position relative to the source until the observed signal is a maximum.

For measurements in solids, the end-surfaces of the sample should be accurately parallel to one another. The transducer is mounted on one of

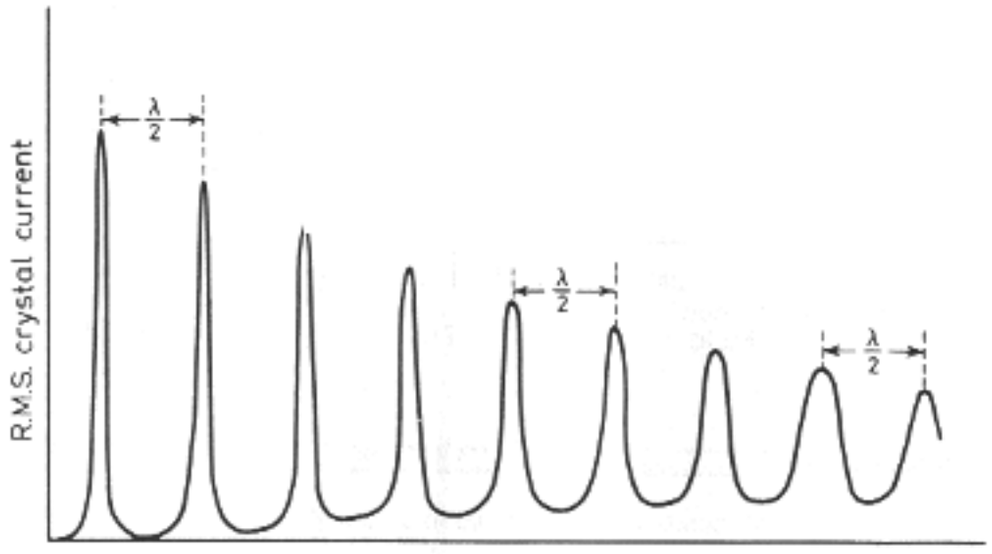
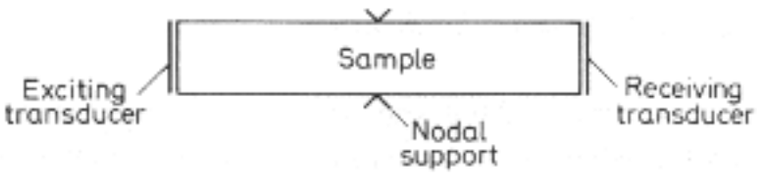


Figure 5.12 Resonance peaks obtained with the acoustic interferometer

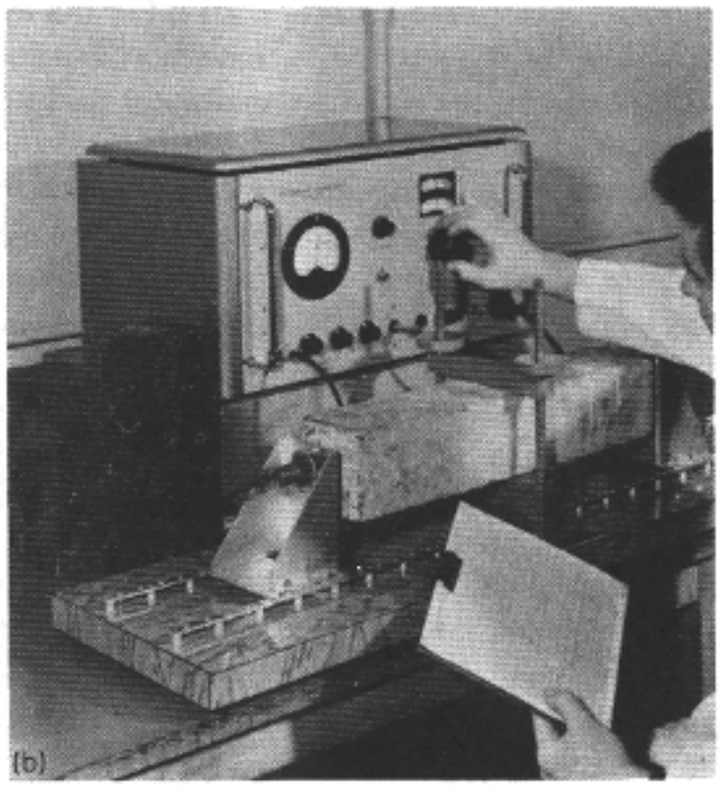
these surfaces and the opposite one acts as the reflector. It is not possible to change the acoustic path length, and, instead, the frequency is varied. The observed resonance frequencies are harmonics of the fundamental, for which the thickness is one half-wavelength, and this is equal to the difference in frequency between two adjacent harmonics.

The attenuation coefficient for a solid may be determined by the application of stationary waves by the use of the *damping capacity* or *internal friction* method, especially suitable for frequencies of up to 50 kHz. The solid, in the form of a bar, is clamped lightly at its mid-point and set into vibration at its fundamental natural frequency by means of a suitably designed transducer. The rate of decay of the vibrations is noted, and the attenuation coefficient thus determined (see Sections 2.11 and 2.13). A method, originated by Bordoni, is illustrated in Figure

5.13(a). The rod, typically from 50 mm to 100 mm in length, is mounted at its mid-point between two knife-edge supports or three needle points, located at angles of 120° apart, and is excited electrostatically at one end (see Section 3.6). For this purpose, the end-surface of the rod must be metal plated if the material is a poor electrical conductor. The



(a)



(b)

Figure 5.13 Damping capacity technique: (a) diagrammmatic representation; (b) application to testing of concrete. Courtesy Dawe Instruments Ltd

electrostatic transducer is given an impulse of high amplitude, and the rod executes free damped oscillations which are detected by a similar electrostatic transducer located at its other end. The absorption coefficient is determined by counting electronically the number n of vibrations required for the amplitude to fall below the fraction 1/e (i.e. 1/2·71828) of its initial amplitude. Equation 2.19a shows that $n = 1/\delta = 1/\alpha\lambda$.

A similar device originated by Giacomini using electromagnetic excitation is described in Section 3.5. Figure 5.13(b) shows how the damping capacity method is used for testing the properties of concrete samples.

5.5 Mode conversion and total reflection methods

The total reflection method (i.e. the ultrasonic goniometer) may be used for measuring the velocities of both longitudinal and transverse waves in isotropic solid specimens when only a single plane surface is accessible. It employs the principles of the reflection and refraction of ultrasound at a plane boundary, as discussed in Section 2.12. For this method, the solid is immersed with its plane boundary uppermost in a liquid. Material A in Figure 2.12 represents the liquid and material B the solid. Pulsed ultrasonic waves are transmitted from a piezoelectric transducer immersed in the liquid along the direction AO at an angle i to the normal and the reflected waves following the path OB are picked up by a similar transducer, suitably placed, acting as a receiver. A peak representing the received reflected pulse is displayed on the screen of an oscilloscope.

The two transducers are rotated simultaneously in such a way that both the equal incident and reflected angles i to the normal, for longitudinal waves, remain the same. The angle of incidence is increased until there is an abrupt increase in the height of the received trace. This indicates that the incident angle has reached the first critical value i_{c1}. The velocity c_{2L} of longitudinal waves in the solid is related to the velocity c_{1L} of longitudinal waves in the liquid by equation 2.22. If c_{1L} is known, c_{2L} can thus be calculated from the measurement of i_{c1}. To determine the velocity c_{2T} of transverse waves in the solid, the angle i is increased still further until it has reached its second critical value i_{c2}, for which there is another abrupt increase in the height of the observed trace. The value of c_{2T} is then given by equation 2.23.

Best results are obtained if the observed acoustic path length remains entirely within the near field (see Section 2.14). For this reason one should work at frequencies exceeding 2 MHz, with transducer diameters of at least 10 mm.

A sensitive method, devised by Rollins[4], for measuring shear wave velocities with a single transducer consists of immersing the material in water with a vertical stainless steel reflecting surface in contact with it at right angles (Figure 5.14). The transducer is rotated about the axis formed by the vertical line of intersection of the surfaces of the sample and the reflector until the second critical angle is reached, as indicated by a sharp increase in the signal strength. When this happens,

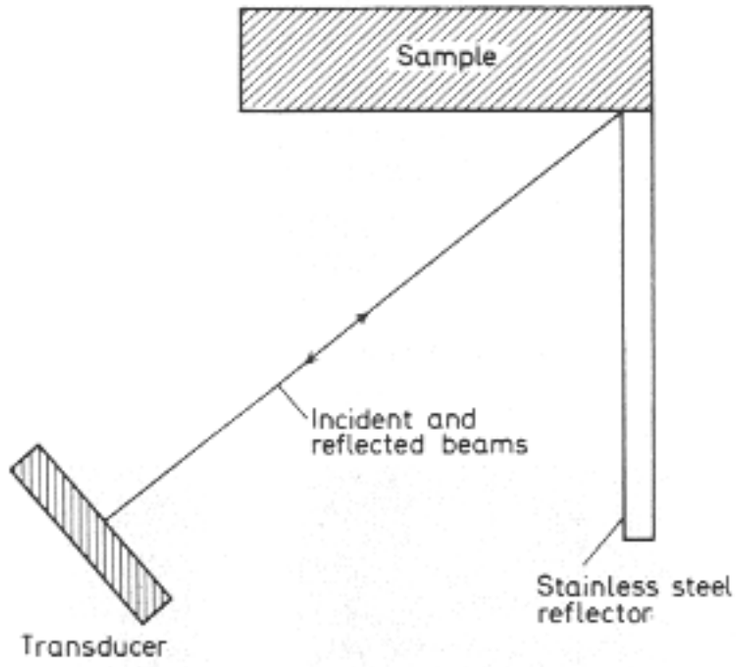


Figure 5.14 Diagrammatic representation of Rollin's goniometer

surface waves refracted along the surface of the sample are immediately reflected back by the stainless steel surface and reconverted into longitudinal waves which travel back to the transducer.

5.6 Optical methods

5.6.1 The optical diffraction method

The optical diffraction method may be used for measurements in transparent liquids and solids. When sound waves pass through a transparent material, periodic variations take place in the refractive index, this being a maximum in the regions of compression and a minimum in the regions of expansion. These variations produce a coarse optical diffraction grating having a spacing equal to the ultrasonic wavelength. The grating moves with the velocity of sound, but, because this is negligible compared with the velocity of light in the material (typically $1{\cdot}5 \times 10^3$ m s^{-1} as compared with 2×10^8 m s^{-1}), the grating may be considered to be stationary with respect to the light passing through it.

A beam of light, originating from a monochromatic source (e.g. a mercury discharge tube placed behind a suitable filter or a sodium lamp) and passing through a narrow slit, is rendered parallel by locating the latter at the focal point of a converging optical lens (see Figure 5.15).

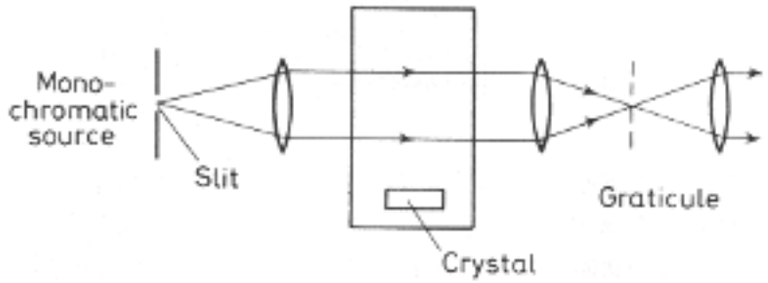


Figure 5.15 Typical arrangement for the optical diffraction method

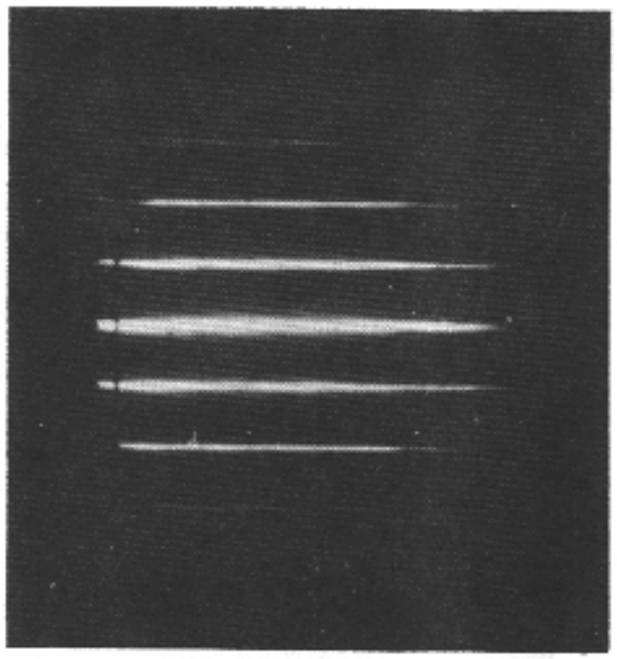


Figure 5.16 Images of a sodium slit source obtained with the optical diffraction method

The parallel monochromatic beam passes through the medium, as shown, and is brought to a focus in the focal plane of the telescope. In the absence of ultrasound, only a single image of the slit is observed, but, when propagation takes place, several equally spaced parallel images of the slit are observed (see Figure 5.16) as a result of diffraction. The distance of separation of neighbouring images, which can be measured by means of the graticule in the eyepiece of the telescope, varies in

inverse proportion to the spacing of the grating, i.e. the wavelength. The graticule is calibrated either by means of a preliminary measurement with a liquid in which the velocity of sound is known or by employing a coarse optical grating of known spacing (e.g. 40 lines per millimetre). The velocity of sound is determined by multiplying the measured value of the wavelength by the frequency of the source.

An advantage of this method is that velocities can be determined in comparatively small samples of materials. Once the optical system is set up, measurements can be made on different samples in fairly rapid succession if the arrangement devised by the author is used (see Figure 5.17). The liquid is contained in an accurately parallel-sided glass cell

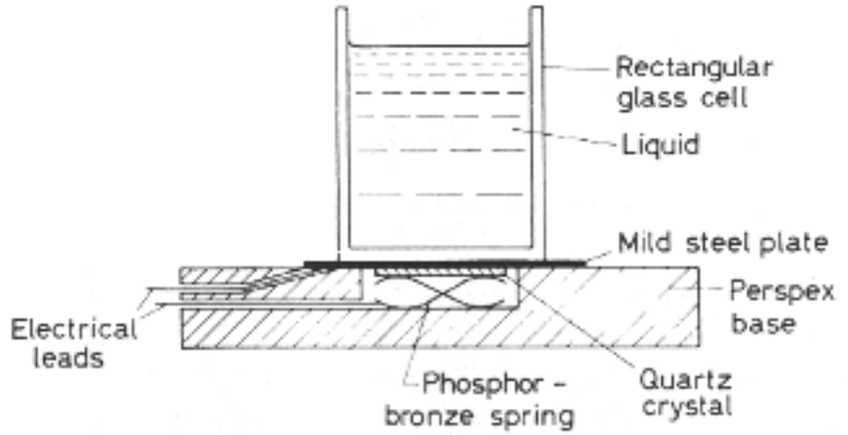


Figure 5.17 Arrangement used by the author for diffraction measurements

placed on top of a steel plate in good acoustical contact with a quartz transducer. A thin film of oil ensures matching of the base of the cell with the plate.

The sensitivity of the method depends on the fineness of the ultrasonic grating (i.e. the shorter the wavelength, the finer the grating). If the grating is too coarse, the images formed by the diffracted light beams are too close together for proper resolution. For liquids, the lowest practicable frequency is about 10 MHz for which a quartz crystal source is necessary. This frequency corresponds to a wavelength of approximately 0·15 mm for which the equivalent optical grating spacing is about 7 lines per millimetre. The upper frequency limit is determined by the absorption coefficient of the material.

The method is unsuitable for gases because of the low degree of contrast in refractive index between the compressed and rarefied regions of the waves.

A proper explanation of the phenomenon of optical diffraction is to be found in textbooks dealing with physical optics (see, for example, Longhurst[5]).

5.6.2 *The Schlieren method*

The Schlieren method provides an effective way of visualising ultrasonic beams, but it is not normally regarded as a means of measuring sound velocities or attenuations. A typical arrangement for this method is illustrated in Figure 5.18. A slit S is illuminated by a source of monochromatic light, and its image is focused on to a wire W, parallel to the

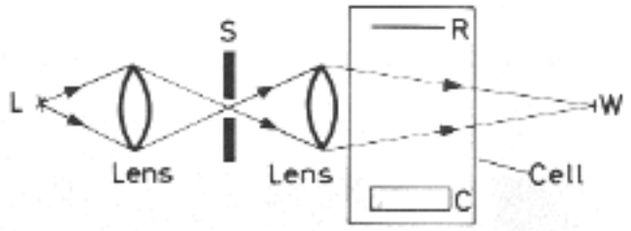


Figure 5.18 Use of the Schlieren technique for ultrasonic waves in a liquid

slit, by means of a lens. The acoustic field is located, as shown, between the lens and the wire, and the telescope is focused on to the wire. In the absence of ultrasound, the wire completely obscures the image of the slit. When the waves are propagated, the medium suffers local periodic variations in refractive index as mentioned in Section 5.6.1 and the optical beam is diverted to avoid the wire. Consequently, a series of light and dark parallel optical fringes, corresponding to the regions of compression and expansion, respectively, may be observed. With progressive waves, it is necessary for the source of light to be flashed on and off at the ultrasonic frequency, i.e. to act as a stroboscope, for a stationary pattern to be observed. With standing waves, however, the stationary pattern is already present and stroboscopic illumination is unnecessary. Any distortion of the acoustic field, e.g. diffraction, gives rise to a corresponding distortion of the observed pattern.

An easily assembled and inexpensive Schlieren system suitable for visualising ultrasound in liquids has been described by Bronson[6].

5.7 Reverberation methods

The use of the reverberation method at audible frequencies in the application of acoustics to the design of buildings is well known. It has

now been extended to the upper kilo-hertz range for measurements of absorption coefficients in liquids.

In an application by Karpovich[7], the liquid under test is contained in a spherical or cylindrical vessel (see Figure 5.19). A transmitting transducer T and a receiving transducer R are cemented to the outer surface of the wall of the vessel. Ultrasonic waves from the transmitter undergo multiple reflections in all directions at the walls of the container, and the sound field rapidly becomes diffuse. A steady state is reached for which the same quantity of sound energy enters the liquid as is

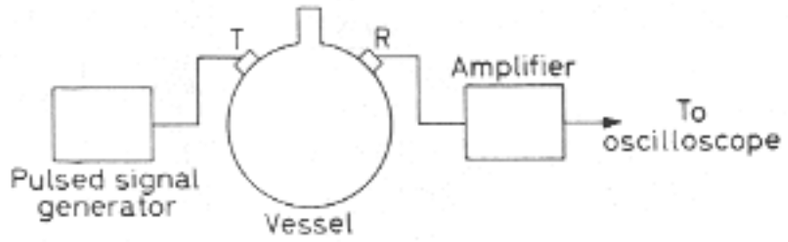


Figure 5.19 Reverberation method, after Karpovich[7]

dissipated as a result of absorption. When the transmitting signal is switched off, the amplitude of the signal picked up by the receiver decays exponentially and the absorption coefficient can be calculated from the logarithmic decrement of this decay (see equation 2.25). A preliminary measurement must be made with the vessel empty to allow for any absorption by the material of its walls. The transmitter is, in practice, excited at regular intervals by means of square-shaped pulses, and the output of the receiver is amplified logarithmically and fed to the Y plates of a storage oscilloscope, the time-base of which is synchronised with the pulse trigger. A straight line having a negative gradient, from which the attenuation coefficient can be calculated, appears on the screen.

5.8 Impedance methods

It was stated in Section 4.4 that, when a shear stress is applied to a liquid, a finite time elapses, quite often of the order of 10^{-6} s, before it collapses and, during this short time, it is possible for the resulting disturbance to be propagated for a short distance, say 0·1 mm, through the liquid.

Velocities and absorption coefficients for shear waves in liquids cannot be measured in the conventional manner, but it is possible to determine these quantities by means of the impedance method which

involves the measurements of the real and imaginary components of the impedance of the transducer, often a Y-cut quartz crystal. The impedance is affected by the loading of the transducer by the material of propagation. Fuller details of the method are given elsewhere (Blitz[8]).

Mason and McSkimin (see Hueter and Bolt[9]) used an impedance method, suitable for mega-hertz frequencies, which employs shear wave reflections. The apparatus consists of two identical fused quartz bars (Figure 5.20) with their end-faces inclined at an angle θ to the horizontal.

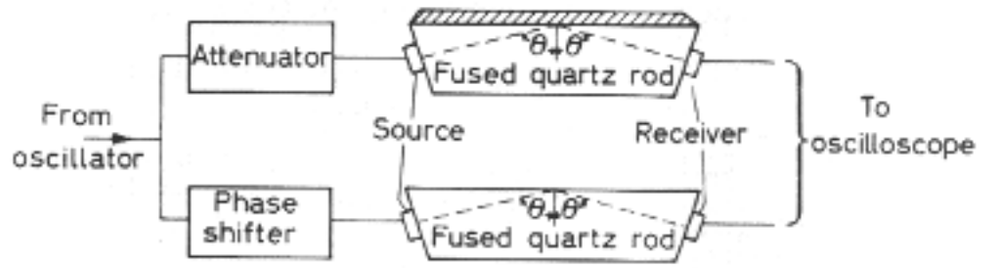


Figure 5.20 Shear wave reflection method of Mason and McSkimin

Similar Y-cut quartz crystals are mounted on these end-faces so that shear waves polarised in a direction parallel with the upper surface are totally reflected, as shown. The magnitude of the angle of incidence θ to this surface is sufficiently high that no longitudinal waves can be transmitted as a result of mode conversion. The magnitudes of the received signals for each bar are compared, and balance is obtained by adjustment of an attenuator and a phase shifter. A thick layer of the viscous liquid under test is placed on the top surface of one of the bars, and the balance is restored by further adjustments of the attenuator and phase shifter. From these adjustments and a knowledge of the characteristic impedance of the fused quartz for shear waves, the shear wave propagation constants for the liquid can be calculated.

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CHAPTER SIX

LOW-INTENSITY ULTRASONIC APPLICATIONS

6.1 General considerations

Applications of low-intensity ultrasound are generally based on the techniques of measuring velocities and attenuations described in the previous chapter. In most cases, it is essential that the method employed is a non-destructive one, i.e. no permanent changes must take place in the properties of the material of propagation. Low-intensity ultrasonic techniques have now been developed to a stage at which there are thousands of different applications, but it is possible here only to describe briefly some of the more important ones. For further information, the reader is recommended to consult the bibliography given in Chapter 1 and the references provided at the end of this chapter.

6.1.1 Applications involving velocity measurements

The velocity of sound in a material depends on the elastic constants and density of that material, as shown in equation 4.1. Thus direct measurements of velocity determine the elastic constants provided that the density can be evaluated by another method, e.g. by measuring the volume and weighing or by using a hydrometer.

Both the elastic constants and the density vary with temperature, concentration, nature of alloy, structure, and so on, and a measurement of the velocity may yield information about one of these quantities provided that the others remain constant or can be measured independently.

The most important of the applications of velocity measurements are flaw detection, thickness gauging, and various types of control devices. In these applications, the acoustic velocity in the material is already known and it is the acoustic path length which is determined by timing the passage of ultrasound.

6.1.2 Applications involving attenuation measurements

Applications involving attenuation measurements usually employ the resonance and pulse techniques. The resonance technique is often applied to the measurement of absorption in a solid bar using Bordoni's internal friction method, described in Section 5.4, at frequencies of up to about

50 kHz; this procedure enables one to investigate the dislocation density, which governs the degree of hardness of the material. When a specimen is annealed, the dislocation density is low, but it may be increased by work-hardening, i.e. the specimen becomes harder but more brittle when the number of dislocations is increased (see Section 4.6.2).

Attenuation measurements with the pulse technique are often used for determining grain sizes in metals, usually at lower mega-hertz frequencies. Scattering at grain boundaries in a polycrystalline specimen causes the ultrasound to be attenuated (see Section 4.6.1), and, at a given frequency, the attenuation coefficient is proportional to the average volume of the grains in that specimen. Thus a coarse-grained material will attenuate ultrasound to a higher degree than a fine-grained material. The attenuation also varies with the fourth power of the frequency, and this sets an upper limit to the frequency range for which the method is usable. This limit varies from 2 MHz for coarse-grained materials to 10 MHz for fine-grained materials. The lower limit is set by the fact that this type of scattering, known as Rayleigh scattering, becomes negligible at frequencies of much less than 0·5 MHz. The scattering technique can also be used at lower frequencies, e.g. 200–500 kHz for investigating the structures of fine concrete mixtures.

Attenuation measurements also indicate the presence of gross defects and the existence of distributed porosity in materials. In these cases, it is usual, because of the high value of attenuation, to use a transmission method.

6.2 Ultrasonic flaw detection

The idea of using ultrasound to detect flaws in materials was put forward by Sokolov in the USSR as early as 1934. However, the method he used consisted of a crude image converter and it did not prove to be of great value. Not much progress was made in this field until the development of the ultrasonic pulse technique.

In general, the basic pulse method described in Section 5.2, with longitudinal wave propagation at mega-hertz frequencies, is used. It is customary to employ the single-probe pulse echo method, making use of a reversible transducer. This method is feasible when the opposite surfaces of the material under test are reasonably parallel with one another and the line of the defect is roughly parallel with these surfaces,

provided that it is not too near a surface or another defect. In the absence of any defect, two peaks A and B (see Figure 6.1) appear on the screen of the oscilloscope. The peak A indicates the time of transmission of the pulse and the peak B the time of its receipt after a single reflection at the opposite surface of the specimen, i.e. the *bottom echo*.

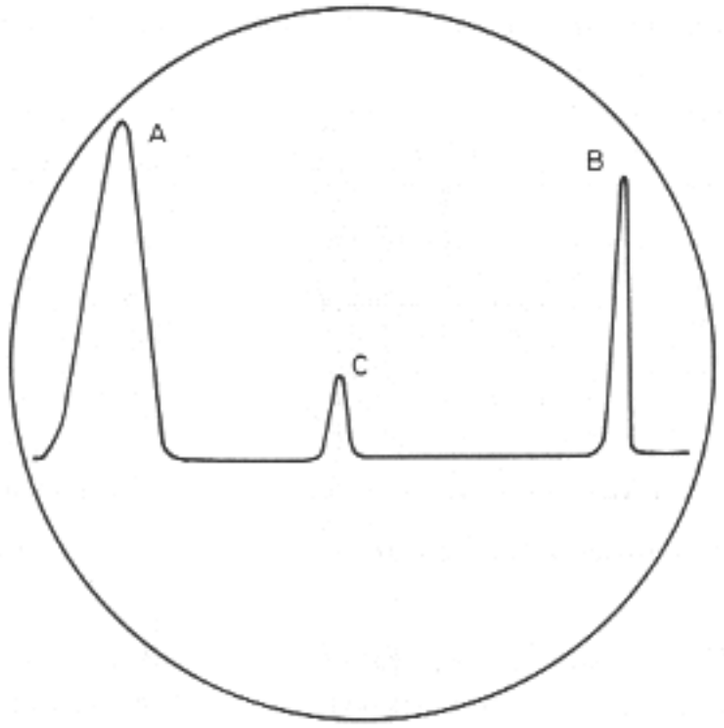

Figure 6.1 Appearance of peaks on the oscilloscope screen of an ultrasonic flaw detector

The presence of a defect gives rise to a discontinuity of characteristic impedance in the material, and reflection of part or all of the incident waves takes place, resulting in the appearance of another peak, C. The horizontal distance AC across the screen indicates the position of the defect, and the height of the peak C is determined by the intensity of the ultrasound reflected back to the transducer, i.e. it indicates, to some extent, the size of the defect. As one would expect, the peak B diminishes in height when a defect is present, and this diminution can sometimes serve as a better indication of the nature of the defect than the height of the peak C. For example, when the defect is orientated at an angle to the top surface of the sample, much of the sound reflected by it is lost.

Defects in various parts of the material are located by moving the transducer probe (see Section 3.2.6 and Figure 3.5) over the top of the

surface, a method known as *scanning*. It is customary to slide the probe over the surface, using an oil couplant which also acts as a lubricant. For automatic scanning, it is usually more desirable to use an immersion technique in which there is no direct contact of the probe with the surface and which has the advantage that there is no variation in the loading on the transducer as a result of manual pressure. Heights of the peaks, corresponding to reflections, are thus constant for a given

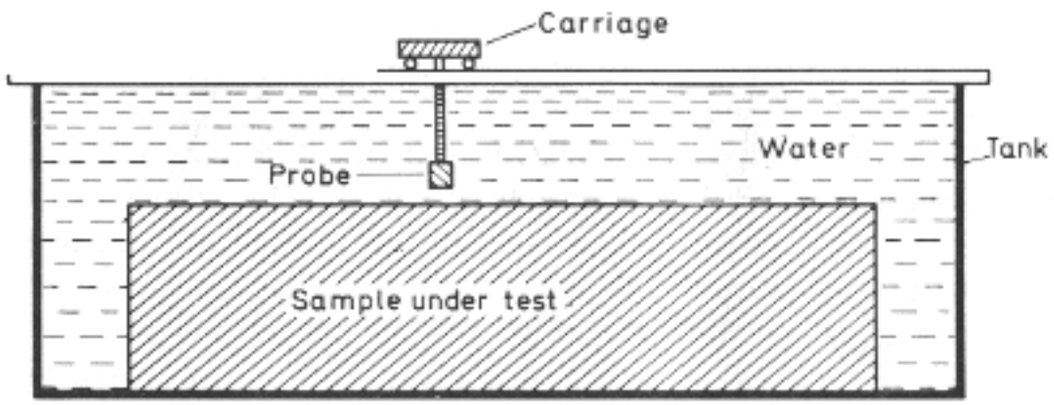

Figure 6.2 Arrangement of probe and test sample for immersion scanning

intensity. The sample and the probe are both immersed in a liquid, usually water, and separated from one another by a fixed vertical distance (see Figure 6.2). The probe, or the sample, is moved mechanically with the vertical distance of separation remaining constant until a complete scan is made. In the observation of the oscilloscope trace, allowance must be made for signals reflected from the top surface of the test sample. To take fullest advantage of the time-scale of the oscilloscope, the time-base is delayed to such an extent that the only peaks appearing on the screen are those corresponding to pulses reflected at points located between the upper and lower surfaces of the sample, i.e. referring to Figure 6.1, the peak A will now represent reflections from the upper surface, B reflections from the lower surface, and C reflections from a defect.

The degree of resolution of a signal from a defect may be reduced for two main reasons. First, it is not possible with a single probe to locate any defect in what is called the *dead zone*, which may extend to several millimetres distance from that surface in contact with the transducer. Its existence arises from the fact that the high direct voltage, often of the order of 300 V or more, required to excite the transducer, provides, when fed to the Y plates of the oscilloscope, a very large peak at the

commencement of the trace which appears on the screen. It may take as long as 1 μs, during which time the pulse will have travelled about 5–6 mm (about ¼ in), before the amplitude of this peak has virtually decreased to zero. The dead zone can be eliminated by using the immersion technique.

Another cause of decrease in resolution is the fact that it is not possible to distinguish two defects from one another or a single defect from a surface when the distance of separation is less than one pulse length. This second difficulty becomes less serious as the distance from the source increases, because the peak amplitudes and widths decrease as a result of attenuation.

However, both these troubles may be overcome by the use of the two-probe technique, requiring separate transmission and receiving probes which can be placed side by side [see Figure 5.4(b)]. Care must be taken

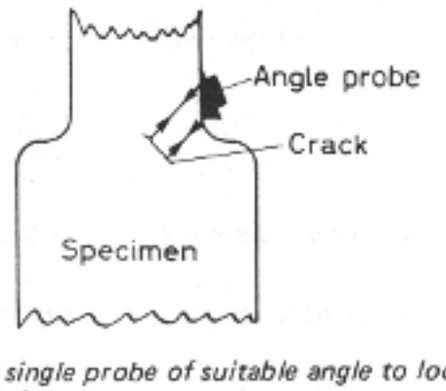

Figure 6.3 Use of a single probe of suitable angle to locate an awkwardly placed defect

to avoid any direct pick-up from the transmitting probe by the receiving probe as a result of electrical coupling or acoustical coupling (e.g. through the generationpf surface waves).

When the defect does not lie in a direction parallel with the surface, it is better to use an angle probe, consisting of a transducer mounted on a plastic wedge. If the wedge has a suitable angle, the beam is incident normally to the surface of the defect and a taller peak representing the flaw echo is observed. Figure 6.3 shows how the position of an awkwardly situated crack can be detected with the use of a single probe of suitable angle.

There are certain applications, such as the detection of defects orientated at right angles to the surface, e.g. flaws in butt welds, for which a technique known as *forward scanning* is employed. Using an angle probe with a wedge of suitable angle, it is possible by the method of mode conversion (see Section 2.12) to propagate transverse waves at

a shallow angle to the surface into the material. Longitudinal waves are not transmitted into the material but are reflected back into the wedge. This device is called a *shear wave probe.* Figure 6.4 illustrates a design of a shear wave probe in which the longitudinal waves reflected in this way are completely attenuated after multiple reflections and are thus prevented from entering the material. Figure 6.5 shows how the forward

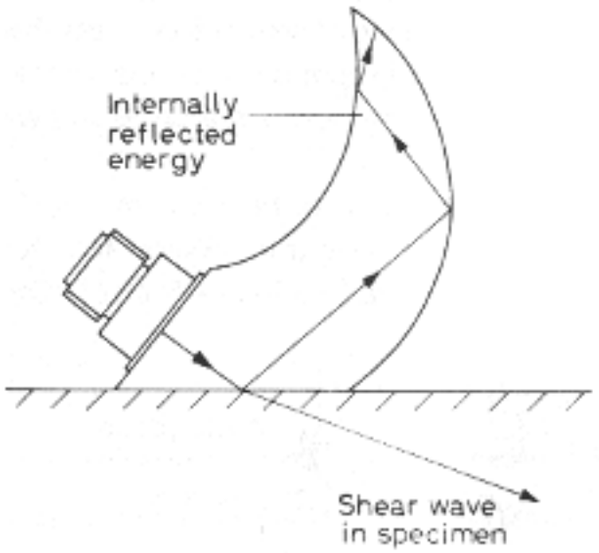

Figure 6.4 Design of shear wave probe, after Sproule and Wells[1]

scanning technique employing two probes is applied to the location of defects in butt welds.

Laminations near the surface of a material may be detected by the Lamb wave technique (see Section 4.5) based on the discovery by Lamb that a plate can resonate at any one of a very large number of frequencies. Now the material of the sample between the lamination and the

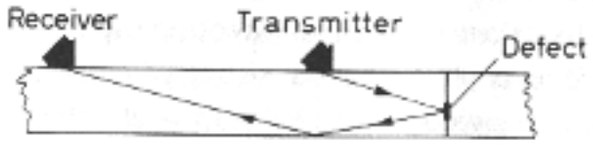

Figure 6.5 Use of shear wave probes to locate a defect in a butt weld

surface does, in effect, constitute a plate. Figure 6.6 shows how pulsed surface waves can excite the vibrations at a laminar defect and cause a signal to be observed on the screen of an oscilloscope forming part of an ordinary commercial ultrasonic flaw detector. Surface waves can be excited either by means of a shear wave probe of suitable angle, using mode conversion, or by placing an ordinary longitudinal wave probe on the edge of the sample (see Section 3.2.5.).

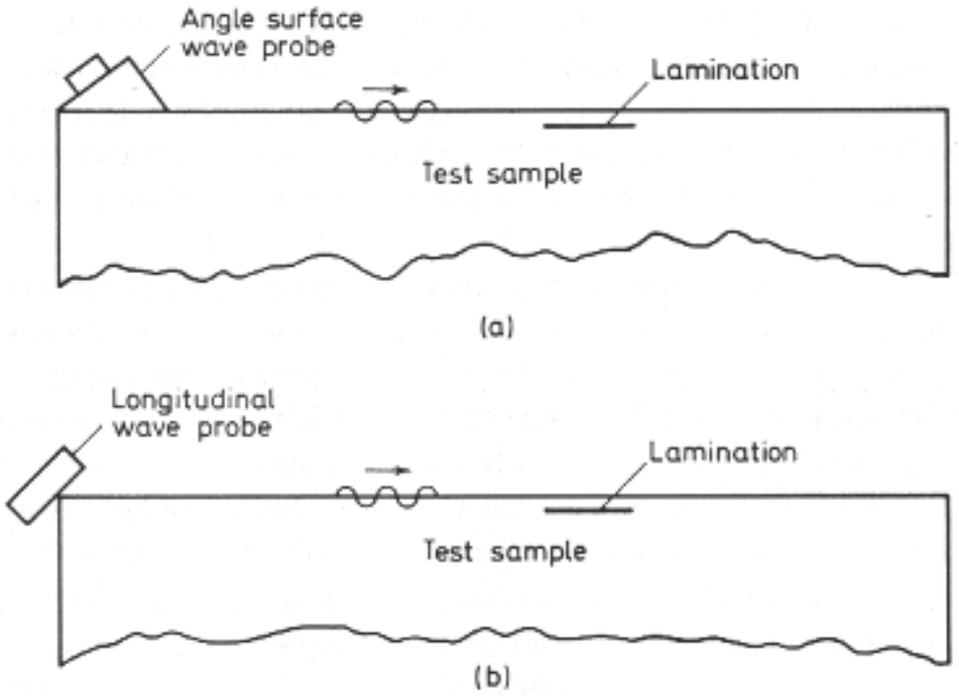

Figure 6.6 Application of Lamb waves to the detection of sub-surface laminations: (a) and (b) alternative methods of propagation; (c) cathode ray oscilloscope display (A = transmission peak, B = peak due to reflection at edge, C = peak due to Lamb waves)

Mention should be made of the *pulse transmission* (or *shadow*) technique of flaw detection for which two probes are located opposite one another, as shown in Figure 5.4(a). It is often used for testing highly attenuating materials, for which the echo method would be unsuitable because of the doubling of the acoustic path length. The transmission technique does not indicate the position of a defect but only whether or not it is present. It will however, give some idea of the magnitude of the defect from the degree of attenuation of the received signal.

Preston[2] has shown how the transmission method has been used in the study of defects in rubber–metal bonds by measuring the attenuation and relating this to the transmission coefficient for a perfect rubber–steel bond immersed in water. The value of this coefficient would be reduced by an air-gap caused by the lack of bonding between the rubber and the steel, and an observation of this reduction from the decrease in height of the oscilloscope trace would indicate the extent of this defect.

When ultrasonic flaw detection techniques are applied, a considerable amount of skill is required on the part of the operator. He must be suitably trained in order to be able to identify various types of defects from the shapes and sizes of the traces observed on the screen. Care must be taken to ensure that a particular peak corresponds to a defect and is not a spurious indication such as one obtained, for example, from the spreading of the beam and subsequent reflection at the sides of the sample, possibly with mode conversion (see Section 2.12 and Figure 2.14).

In many cases, the nature of the detected flaw can be interpreted from a previous history of the material, e.g. the existence of blow-holes and slag inclusions in steel, resulting from the technique used in the foundry, or the production of cracks due to a faulty rolling process. Depending on the future use of the material, certain defects may be tolerated, e.g. in regions where negligible stresses are likely to be exerted, whilst others are sufficiently important for rejection. A minor crack in a given region in a sample may be harmless whereas a larger crack cannot be tolerated. Test-blocks have been made to assist the operator in his decision whether or not to pass a component for service. These blocks are drilled with flat-bottomed holes of different diameters, and, in the designer's specification for a component, the height of a peak observed on the oscilloscope screen, resulting from reflections from a crack of a given size, is compared with that due to reflections at the remote end of a flat-bottomed hole drilled in a test-block made from the same material.

Thus a crack of the largest tolerable size may be stated to reflect a signal of the same amplitude as that from the bottom of a hole of, say, 1·5 mm diameter located at the same depth. Alternatively, it may be stated that the amplitude of the signal must not be greater than a given number of decibels compared with that reflected from a specified hole. Figure 6.7 illustrates a typical test-block with holes of a given diameter but of different depths.

Ultrasonic flaw detection is a technique which can be rapidly carried out and does not involve the use of dangerous ionizing radiations such as those produced from x-ray tubes and radioactive isotopes. Sometimes,

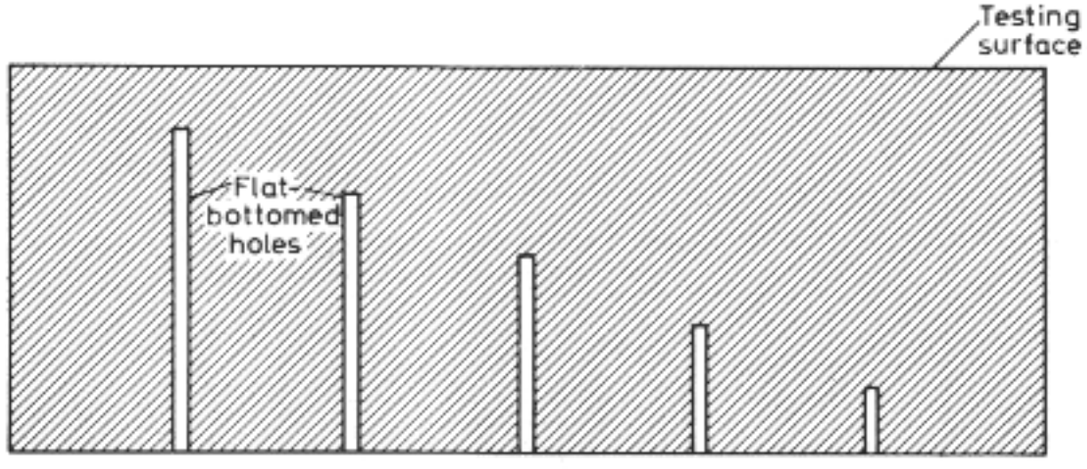

Figure 6.7 Design of a test-block for longitudinal waves, showing flat-bottomed holes of different depths

however, ultrasonic testing is carried out in addition to other forms of testing. For example, x-rays may be used on a component to indicate whether or not defects are present and to give an indication as to their location. Ultrasonic testing is then applied to investigate the exact positions of the flaws and, perhaps, to present fuller details of their nature.

6.3 Scanning techniques in ultrasonic testing

Three different methods of scanning are employed in ultrasonic testing, namely the A-, B-, and C-scans.

6.3.1 A-scan method

With the A-scan, a time-base is connected to the X plates of the oscilloscope and the output from the probe fed to the Y plates. The probe is moved over the surface in a systematic manner as shown, for

example, in Figure 6.8. The position of the trace in the horizontal direction gives the location of any defect or other discontinuity, and the height of the trace indicates the intensity of the beam arriving back to the probe after reflection. This is the method described in the previous section and the one most commonly used in flaw detection. A permanent record of the scan can be obtained by feeding the output signal to a pen recorder, the motion of which is synchronised with that of the probe. In this way, the scan can be carried out automatically and a later examination of the trace can yield information about the extent

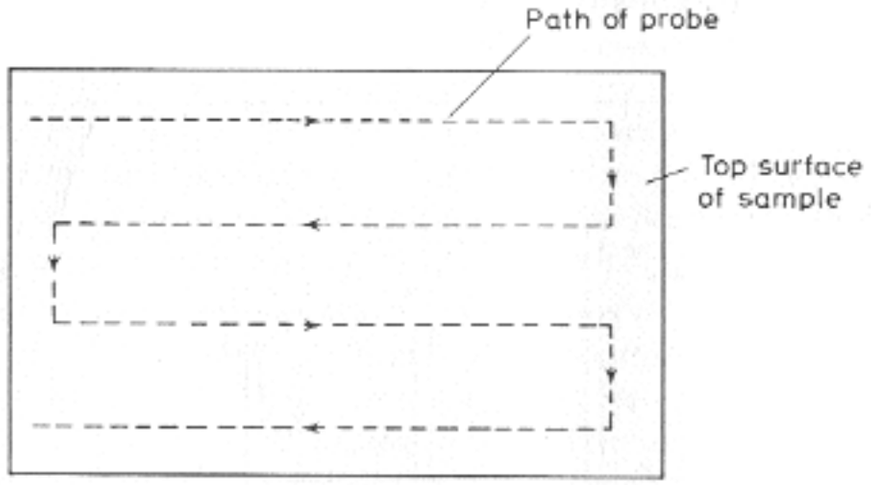

Figure 6.8 Motion of probe over the surface of a test sample for an A-scan

and position of any defect. An alarm device can be fitted to the equipment so that, when a flaw echo of intensity higher than a predetermined value is received, an audible or visual warning can be given.

6.3.2 B-scan method

With the B-scan technique, the location of a probe along a given line of a scan is indicated by the horizontal position of a spot on the cathode ray tube. The time-base is connected across the Y plates so that any vertical deflection of the spot from the base line indicates the depth of a defect or other discontinuity giving rise to reflection. The output of the transducer resulting from received reflections modulates the cathode beam intensity so that the amplitude of the reflected waves is proportional to the intensity of the spot appearing on the screen. If a storage oscilloscope is used, lines corresponding to contours of internal structure formed by the defects and discontinuities appear on the screen. A permanent record may be obtained by photographing the trace with an exposure having a duration equal to that of the scan (see Figure 6.9).

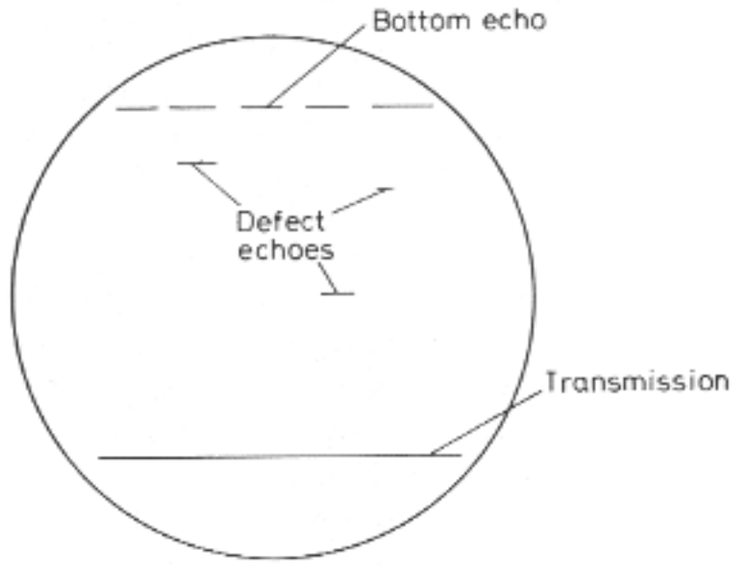

Figure 6.9 Appearance of the trace on the screen of a cathode ray oscilloscope for a B-scan used for flaw detection

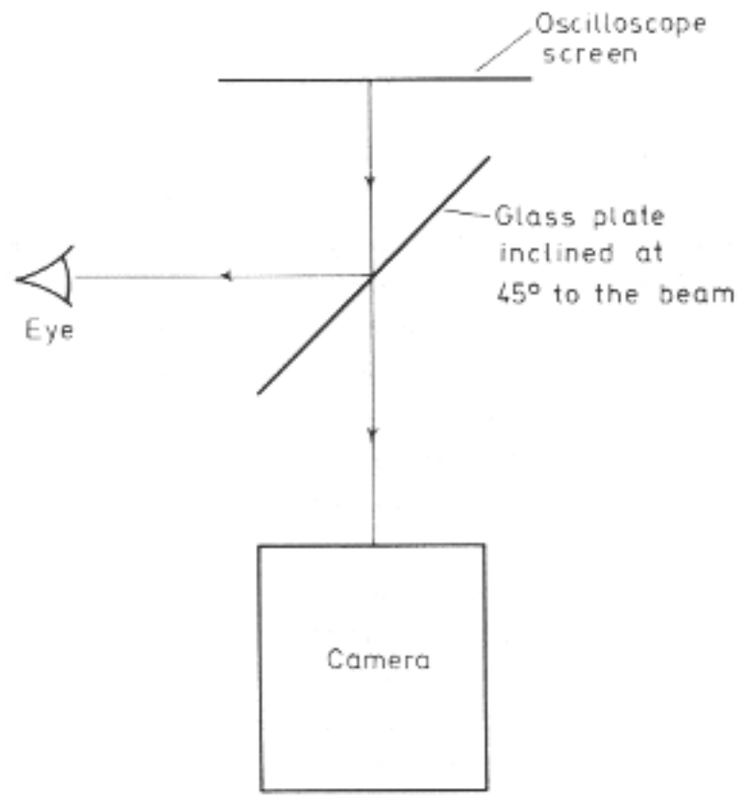

Figure 6.10 Arrangement for simultaneous viewing and photography of an oscilloscope screen for a C-scan

6.3.3 C-scan method

With the C-scan, the position of the spot on the screen of the oscilloscope corresponds to that of the probe. The probe, sometimes mounted on a carriage, can be moved along two directions at right angles to one another. The motion along one direction controls the voltage across the X plates of the oscilloscope, and the motion along the other direction controls the voltage across the Y plates. The amplitude of the reflected signal governs the intensity of the electron beam and, hence, the spot on the oscilloscope screen in the same manner as for the B-scan. The position of any defect or discontinuity which gives rise to reflection is not indicated by this method. Thus, if one uses a storage oscilloscope or if the screen of an ordinary oscilloscope is photographed for the duration of the scan, an image of the internal structure of the sample, similar in appearance to an x-radiograph, is observed. Figure 6.10 shows an arrangement for a C-scan, using a storage oscilloscope, which permits the image to be observed visually during the exposure of the photographic plate; the viewing is best done in a darkened room.

6.4 Ultrasonic imaging

An imaging technique which, by now, has become well established is the C-scan method discussed in the previous section. In this section, other ultrasonic imaging methods are briefly described.

One method of imaging is to immerse the solid sample in a liquid, to achieve the most efficient degree of coupling, and to irradiate it with ultrasound. Using an acoustic lens, an image is formed in the same way as a visual image with an optical lens. Internal structures of optically opaque objects can thus be examined.

Basically, an acoustic lens is designed in a similar fashion to an optical lens. However, it must be remembered that, in optics, a beam is refracted towards the normal when it passes from an optically less dense to an optically denser medium. In acoustics, the converse is applicable and a converging lens must have either one or two concave surfaces if it is placed in an acoustically less dense medium (i.e. a medium having a lower velocity of sound). Figure 6.11 illustrates the action of a typical ultrasonic converging lens made, say, of Perspex and placed in water.

The degree of resolution of an ultrasonic imaging system will increase as the wavelength is decreased, i.e. as the frequency is increased. However, there is an upper limit of about 10 MHz which is determined by the increase in the absorption coefficient with frequency for water.

The earliest ultrasonic imaging methods were devised in about 1934 by Sokolov. The object was immersed in water in the path of a vertical ultrasonic beam. An acoustic lens was located above the object in such a position that the image was formed on the liquid surface. This image appeared in the form of surface disturbances which were visualised by oblique illumination.

During World War II, Pohlmann, in Germany, devised a method for the inspection of shell cases: an ultrasonic image of an object was

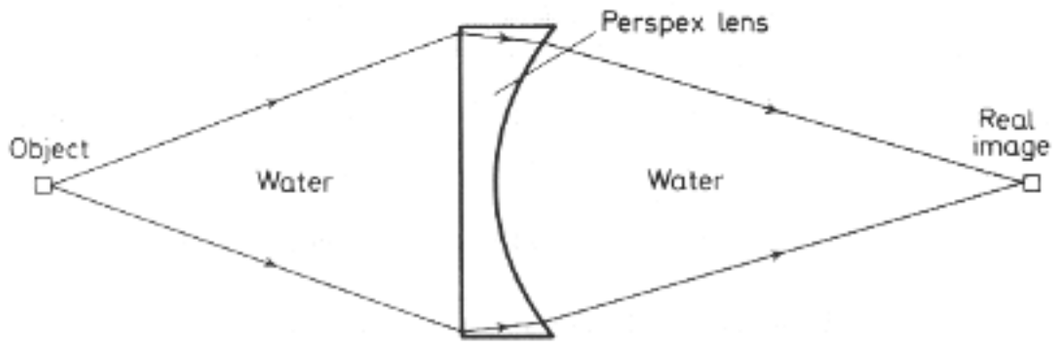

Figure 6.11 Design of a converging ultrasonic lens

formed in a thin cell which contained a large number of minute aluminium discs of diameters small compared with the wavelength (see Hueter and Bolt[3]). In the absence of any sound waves, the discs were orientated with their surfaces parallel to the direction of sound. When the ultrasound was radiated, they behaved as Rayleigh discs (see Section 3.4), each having rotated by an amount dependent on the acoustic intensity. On the cell being illuminated, a visual image of any internal defects appeared.

With the method of Smyth, Poynton, and Sayers[4,5] (see Figure 6.12), the object O is immersed in a tank of water and irradiated by the quartz crystal C at a given frequency. Images of points forming the object are focused by the acoustic lens L to the corresponding points on the quartz plate Q which forms the end-surface of the cathode ray tube T, replacing the usual fluorescent screen. Waves incident at points on Q induce, piezoelectrically, localised electrical charges of magnitude proportional to the amplitude of the beam. At the same time, Q is bombarded by a narrow beam of cathode rays which moves over the surface, in the same way as a television scanner, and secondary electrons are

given off to be collected by the anode A. The anode current is amplified and fed to a modulator connected to the cathode of a conventional cathode ray oscilloscope. The scanning in the two cathode ray tubes is synchronised to give a visual image on the screen of the conventional tube. The resolution is poor compared with that of an optically formed image. For water at the practical upper frequency limit of 10 MHz, the ultrasonic wavelength is 0·15 mm. The wavelength of light varies from 4×10^{-4} mm for violet to 8×10^{-4} mm for red. The degree of resolution varies inversely with wavelength, and the resolving power of the ultrasonic imaging system is about 300 times worse than that of a comparable

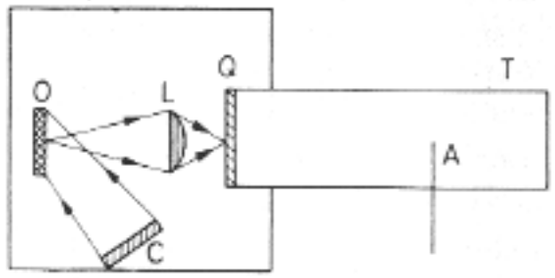

Figure 6.12 Ultrasonic image converter used by Smyth, Poynton, and Sayers[4,5]

optical system. However, optical waves cannot penetrate opaque solid materials. Better resolution can, of course, be obtained with the use of x-rays, but x-ray techniques, besides being time consuming in their application, provide radiation hazards.

Because of the upper frequency limitation, the degree of resolution of ultrasonic image converters is restricted, but, if the image contains information concerning phase as well as amplitude, more detail of the interior of the object (e.g. the shapes and sizes of defects) becomes available. This can be achieved by means of the newly developed technique of *ultrasonic holography.*

Holography is a method used in optics to provide an accurate three-dimensional image of a given object. It is carried out in two stages. In the first stage, a permanent record in the form of a two-dimensional pattern of optical fringes, called the *hologram*, is obtained on a photographic plate. In the second stage, the image is formed from the hologram.

With the optical technique, a coherent monochromatic beam (i.e. a very long train of light waves having a single frequency as obtained from a laser source) is incident partly at a mirror and partly at the object under examination (see Figure 6.13). Interference takes place, at the photographic plate, of light reflected at the mirror (the reference

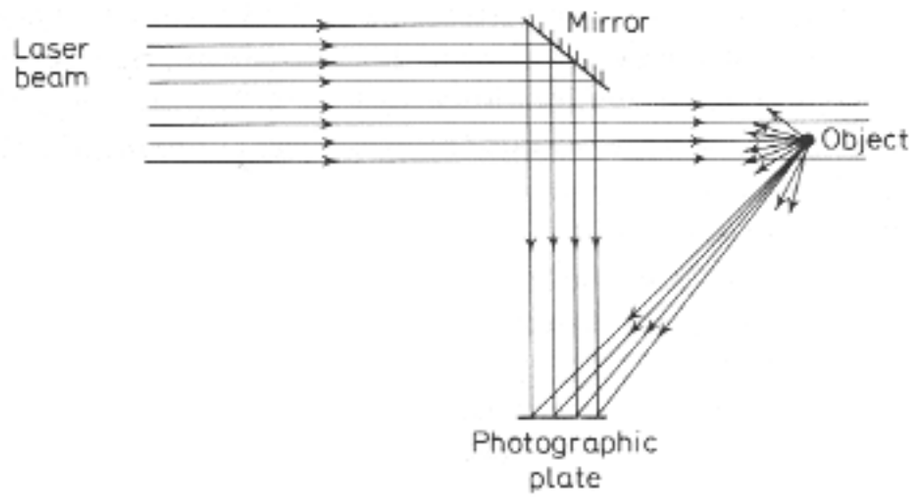

Figure 6.13 Production of an optical hologram

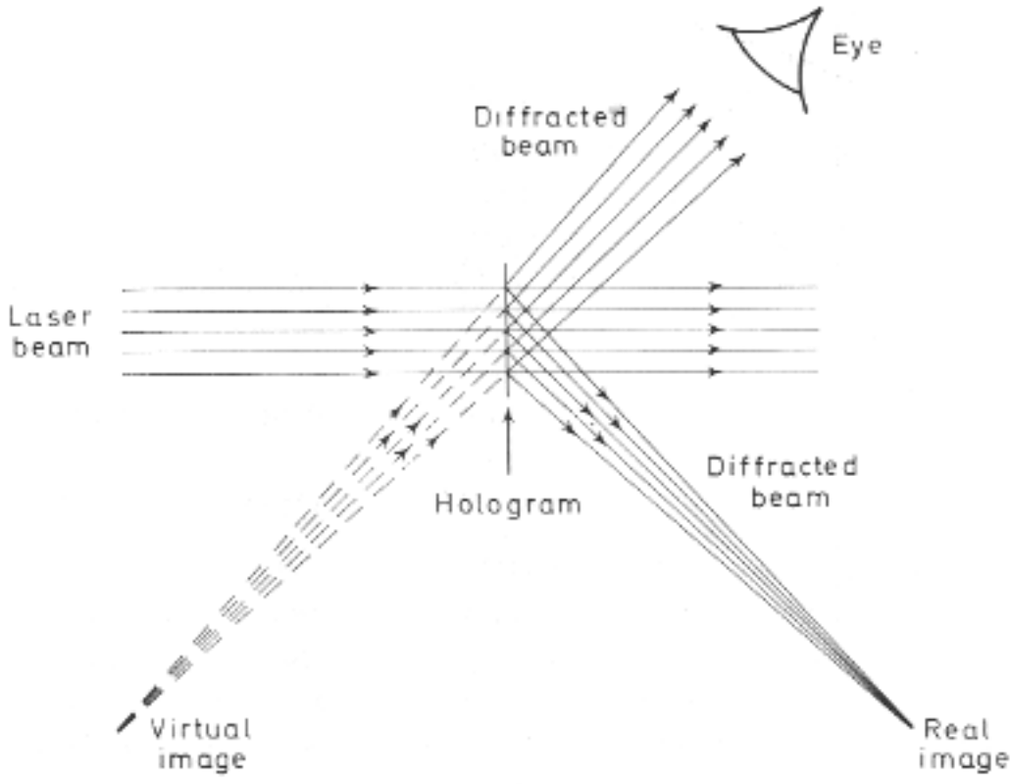

Figure 6.14 Formation of real and virtual images from an optical hologram

beam) with light scattered from the illuminated object. The plate is developed after exposure and a complicated system of optical fringes (the hologram) appears on the surface. Figure 6.14 shows how two three-dimensional images, one real and the other virtual, are obtained from the hologram as a result of its diffraction of the laser beam. The virtual image can be observed with the naked eye; this image is in three dimensions and is entirely free from aberrations.

With ultrasonic holography, an optical hologram is prepared using a technique different from the method just described but the method of viewing the final image is the same.

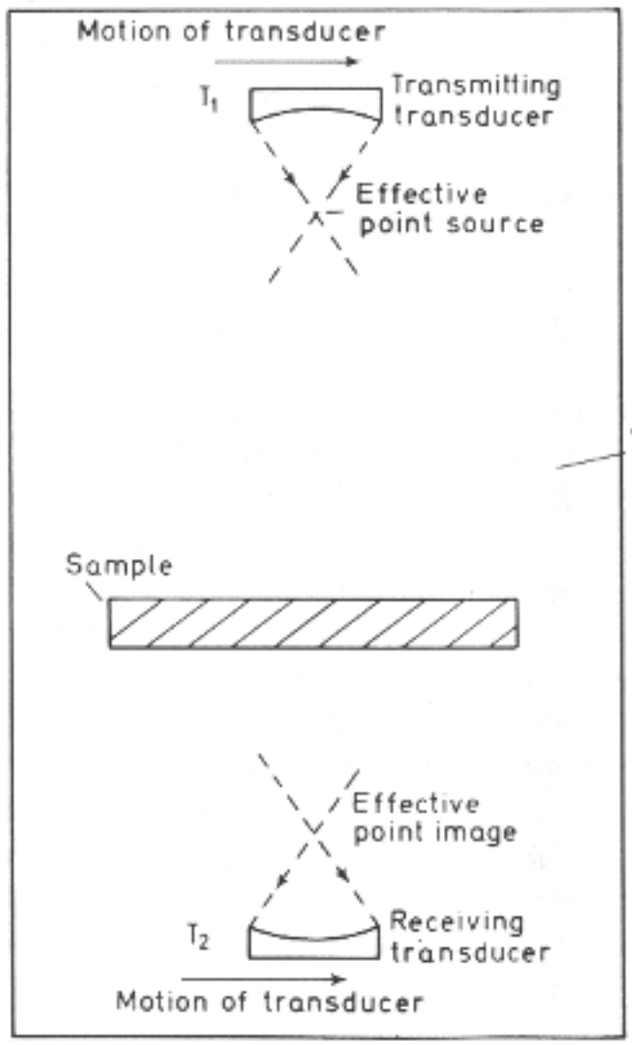

Figure 6.15 Ultrasonic holographic system used by Aldridge, Clare, and Shepherd[6]

Several systems have been tried out for the production of ultrasonic holograms, and one of the most promising has been devised by Aldridge, Clare, and Shepherd[6]. With their method, the sample is contained in a water bath and located between two ceramic transducers T_1 and T_2 (see

Figure 6.15), T_1 being the transmitter and T_2 the receiver. The transducers are both of the focusing kind in order that point images of point objects can be obtained. The whole surface of the sample is scanned with ultrasonic pulses by the two transducers moving simultaneously, a fixed distance of separation being maintained. Because the coherence of the ultrasonic beams produced in the conventional manner is easily established, it is possible to provide the reference beam electronically. This is done by adding an electrical signal of the same frequency as that of the exciting transducer T_1 to the electrical signal produced by the receiving transducer T_2. The resultant of these two signals is connected to an intensity plot on a fascimile recorder, which is scanned simultaneously with the sample. The scanning process takes several minutes. The recording is then photographed and reduced in size by a factor equal to the ratio of the speed of light in air (the medium for optical viewing) to the speed of ultrasound in water (the medium for ultrasonic scanning); this factor has a value of about 300. Viewing is then carried out using conventional optical holography.

In the present stage in the development of this technique, it often requires a great deal of imagination to be able to relate the image obtained by ultrasonic holography to its actual appearance, and more realistic pictures have been obtained using the C-scan technique. However, one is really concerned with the information received rather than the visual appearance of the image, and this can be closely related, in the light of previous experience of the operator, to the nature of defects and other structural changes in the interior of the sample.

6.5 Ultrasonic propagation in stressed materials

6.5.1 Measurements of mechanical stresses

If a material is subjected to an external mechanical stress, changes in its elastic properties may take place and the relationships between stresses and strains become non-linear, involving what are described as third-order elastic constants (see, for example, Smith[7] or Blitz[8]). One would thus expect to observe variations of the acoustic velocities when stresses of different magnitudes are applied. Shahbender[9] described how it is possible to measure the values of these stresses from the changes of acoustic velocities in isotropic materials, using the pulse technique.

Initially, Shahbender obtained calibration curves for the material under test (see Figure 6.16) for which the percentage change in the

velocity of sound was plotted as a function of the applied stress. The curves in the figure apply where a stress is exerted in, say, the z direction and longitudinal waves and two separate beams of shear waves are propagated in the x direction. The shear waves are polarised in the y and z directions, respectively. For isotropic materials, the two beams of shear waves would normally travel at the same velocity, but the introduction of any anisotropy may cause them to move at different velocities.

To determine the stress, the phase difference ϕ between the two shear wave components of the received pulse and the value of the

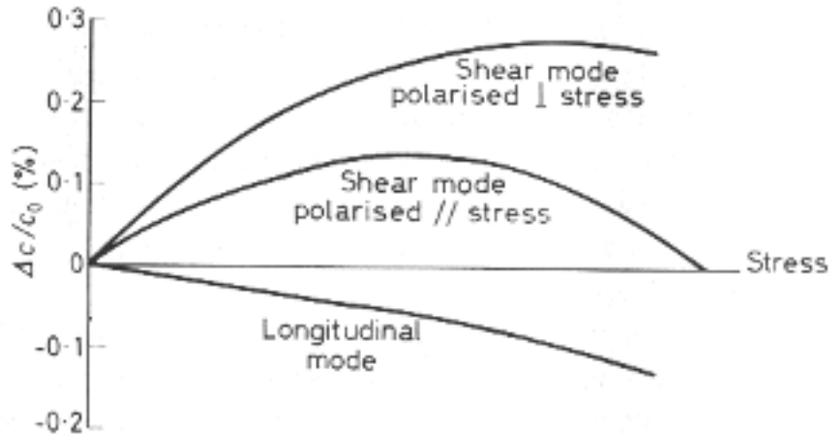

Figure 6.16 Variations of acoustic velocity with applied stress, after Shahbender[9]

longitudinal wave velocity (to determine the acoustic path length) are measured. The value of the stress is obtained from the calibration curve using the relationship

$$\phi = \frac{\omega l}{c_0}\left[\left(\frac{\Delta c}{c_0}\right)_n - \left(\frac{\Delta c}{c_0}\right)_p\right] \qquad (6.1)$$

where ω is the angular frequency and l the acoustic path length; c_0 is the shear wave velocity in the unstrained medium (the same for all polarisations) and the suffices n and p represent polarisations in the directions normal and parallel, respectively, to the direction of stress in the strained medium; Δc is the velocity change.

6.5.2 Acoustic emission

Another phenomenon observed in a solid under the action of externally applied loads is the plastic deformations which take place at discontinuities in its structure. They may give rise to a pile-up and final breaking away of dislocations. This mechanical disturbance may be

sufficiently intense for the propagation of acoustic waves, having a frequency range which depends on the nature of the discontinuities but which could lie within the limits from, say, 30 kHz to 1 MHz. Dunegan and Harris[10] have described experiments carried out within the frequency range 30–150 kHz to detect interior cracks and to investigate how dislocations and cracks grow in size as the loading increases.

6.6 Ultrasonic thickness gauging

Ultrasonic thickness measuring can be achieved with the use of either the pulse or the resonance technique, as described below.

With the pulse technique, equipment similar to that used for flaw detection is employed, in conjunction with a variable delay line (see Section 5.2). Simultaneous propagation of pulses is made through the sample and the delay line, which may be, for example, either a length of nickel wire on which the position of a magnetostrictive exciting coil can be adjusted or a liquid terminated by a reflector (single-probe method) or by another transducer (double-probe method). Two separate traces corresponding to the received signals are observed on the screen, and the delay line is then adjusted in length until the peaks coincide in position. The thickness of the specimen is obtained by noting the length of the delay line, usually with some micrometer device, when coincidence is observed. The delay line is calibrated by measurements in materials of known thicknesses for which the acoustic velocities are known.

With the resonance technique (see Section 5.4) a single wide-band frequency transducer may be used. This can be a piezoelectric crystal mounted for heavy damping and operated well below its fundamental resonance frequency. The frequency of the exciting oscillator is adjusted until the sample resonates, as indicated by a sharp increase of the current through the transducer. Alternatively, the oscillator exciting the transducer can be made to sweep through the whole of the required frequency range at regular intervals and the output from the transducer fed to the Y plates of an oscilloscope, the X plates of which are controlled by the frequency sweep. Peaks appearing on the oscilloscope screen can give direct indications of thicknesses, by taking into account the fact that the material has a thickness of an integral number of half-wavelengths for each position of resonance.

An important advantage of the ultrasonic method of thickness gauging is that access to only one of the surfaces is necessary. This is

advantageous for the assessment of the internal corrosion of pipes. The thickness of a ship's hull can be measured as a test for external corrosion from inside the ship whilst it is at sea, thus avoiding the expensive, time-consuming, and less reliable process of taking sample borings of the hull whilst the ship is in dry dock. Measurements of the depths of fat on bodies of live animals is another profitable application of ultrasonic thickness gauging; this has proved to be extremely valuable in the rearing of pigs for bacon.

6.7 Estimation of grain sizes in polycrystalline materials

In Section 4.6.1 it was stated that ultrasound is scattered in a polycrystalline material by the individual grains forming its structure and that, if the wavelength is large compared with the mean grain diameter,

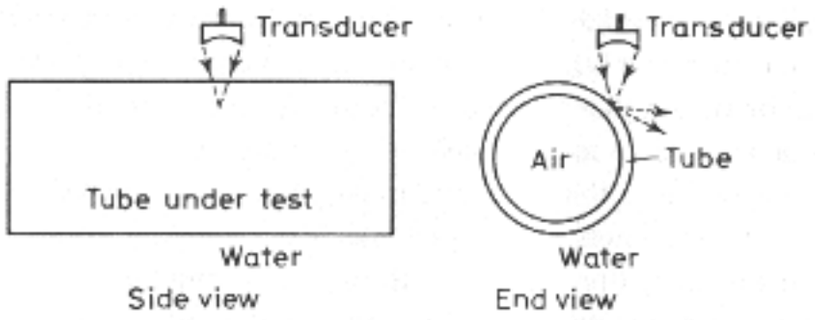

Figure 6.17 Location of transducer and tube in water tank for grain size investigations, after Aldridge[11]

the resulting attenuation at a given frequency is proportional to the cube of the diameter (see also equation 2.27). It was also stated that this phenomenon may be used to determine or compare mean grain sizes in different samples of material.

Aldridge[11] has devised a method by which not only the mean grain sizes but also the grain size distribution may be determined rapidly in thin stainless steel tubes. He used the pulse method in which a concave ceramic transducer of frequency 10 MHz was focused on to the tube surface over an area of 0·3 mm diameter at a distance of about 10 mm from it. The tube was immersed in water with the transducer fixed in position, and a helical scan was made over the whole of its surface by rotating the tube as it moved in an axial direction (see Figure 6.17). The tube was plugged at each end to keep its inside free from liquid and thus to prevent any penetration of ultrasound. The point of focus of

the transducer was positioned in such a way that waves reflected in a regular manner did not arrive back at the transducer and that only scattered radiation was received.

Because the grain size distribution was not uniform, the amplitude of the received pulses varied with position of the tube. The signals from these pulses were fed to a 100-channel analyser, and scatter distribution curves were obtained (see Figure 6.18). The peak heights and shapes of the curves indicated, respectively, the mean grain sizes and grain size distribution. Calibration was made from samples having their grain sizes and distributions determined by conventional visual methods.

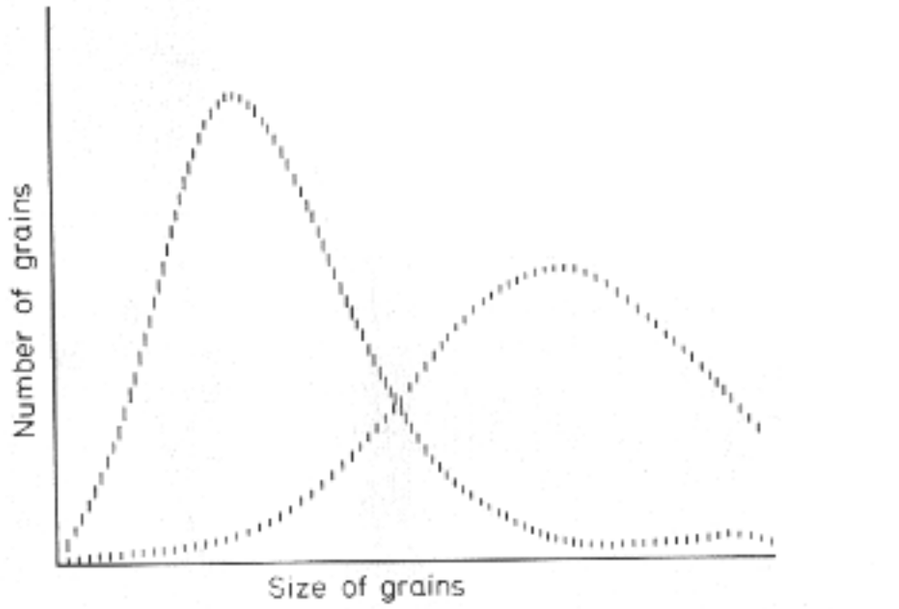

Figure 6.18 Grain size distributions for two different samples of stainless steel tubes of similar dimensions obtained from ultrasonic scatter measurements, after Aldridge[11]

6.8 Ultrasonic sensing

Ultrasound has been used in air, in other gases, and in liquids for the sensing of objects. An obstacle placed between transmitting and receiving transducers or between a reversible transducer and a reflector interrupts the beam, with the result that there is a change in the amplitude of the received signal. In gases, most applications are made at the lower frequencies where attenuation is small. The frequency used should not be too low otherwise audible sound is emitted and, furthermore, a reduction in the directivity of the beam will be experienced (see

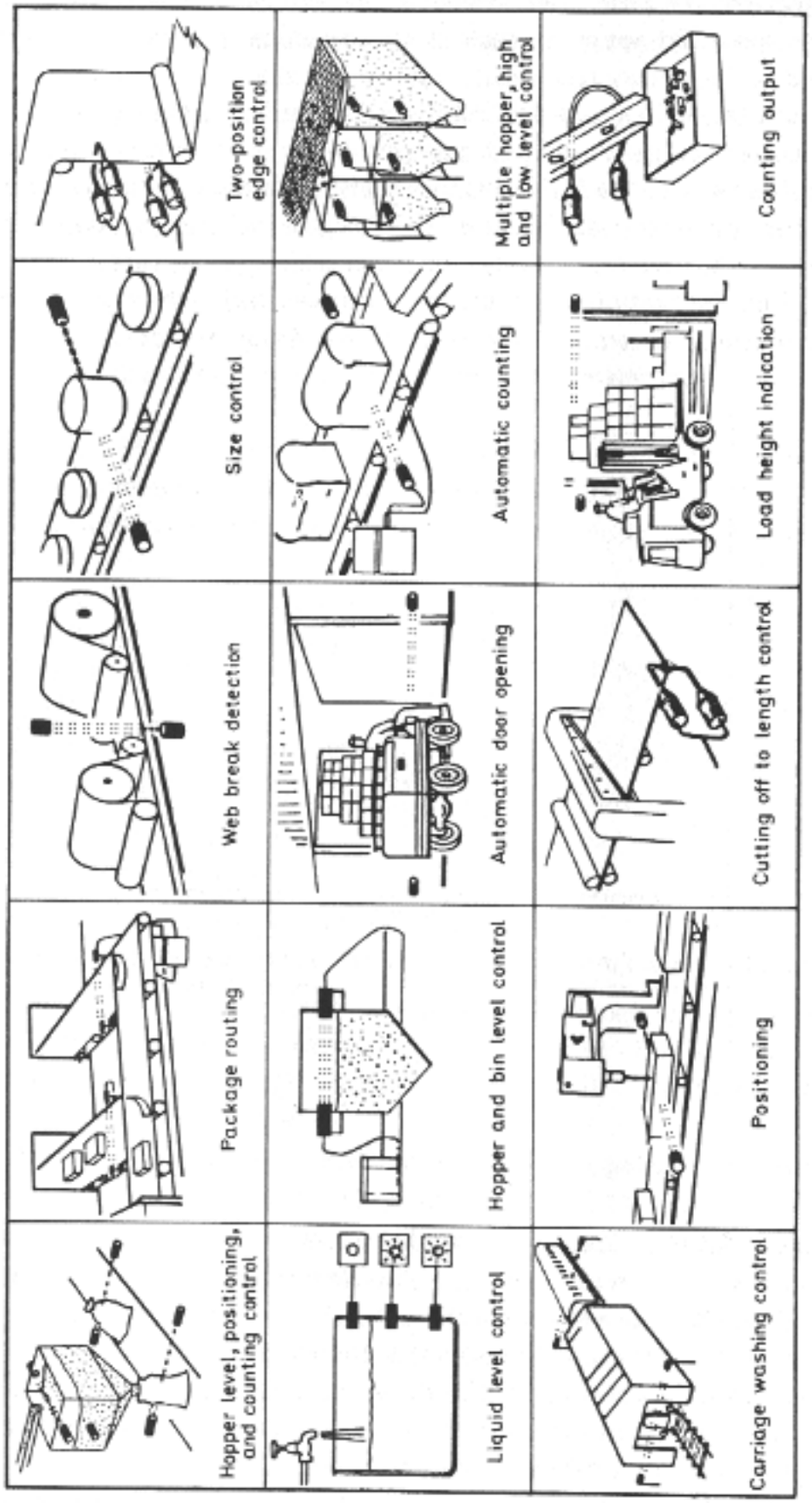

Figure 6.19 Various ultrasonic sensing applications. Courtesy Westool Ltd

Section 2.14). The optimum frequency for applications in air is in the region of 40 kHz. Ceramic transducers have proved useful for this purpose.

With a double-probe sensing device, the beam travels from the transmitting to the receiving transducer in a straight line. This device has many applications (see Figure 6.19), including the level control of hopper bins, the counting of components on a conveyor belt, and the positioning of components for work. It has also been used for detecting unwanted intruders in offices and warehouses: the interruption of the beam triggers off an alarm as a result of the reduction of the signal picked up by the receiver.

Applications of the single-probe device include the detection of obstacles for the guidance of blind persons, for whom the apparatus can be incorporated in a hand-held instrument the size of a pocket torch. In a system devised by Kay[12], the frequency is modulated, i.e. made to vary periodically with time, and the reflected waves received by the transducer may have a different frequency from those transmitted at the time of receipt. This frequency difference, which depends on the time taken for the waves to complete a return passage and, hence, on the distance of the obstacle, is made audible and detected by the user through an earphone. In this way, he can judge the position of an obstacle. He will also have some idea of the nature of the obstacle from the intensity of the reflected waves; a hard object has a greater reflection coefficient than a soft one. The device is highly directional, and, with suitable practice, the user should have little difficulty in finding his way along a busy thoroughfare.

One of the earliest ultrasonic sensing methods dates back to the 1914–1918 war, when ultrasound was used by Langevin for the location of submarines, other craft, and various underwater obstructions; the technique, known as *sonar*, was also used for signalling. A mosaic of quartz crystals 2 mm thick was placed between two steel plates, each 30 mm thick, to form a sandwich transducer of some 250 mm diameter, with a resonance frequency of about 38 kHz, and serving as the transmitter. A similar arrangement was used as the receiver. The transmitter was pulsed at regular intervals by the discharge of a capacitor across the electrodes with the aid of contacts on wheels operated by an electric motor (see Bergmann[13]). The same type of transducer was used for signalling between ships, for which continuous waves were modulated by the operation of a key (for Morse transmission) or by a telephone transmitter (for speech communication).

Later applications using the modern type of electronically operated pulse equipment, described earlier, include the sounding of an ocean bed, from which its profile can be mapped out by means of an automatic pen recorder, and the location of shoals of fish. This second application may reveal also the size of the shoal and even the species of the fish from the characteristics of the received trace.

6.9 Ultrasonic control

Ultrasound has been used for various control applications, such as measurements of pressure, concentration, and temperature.

Pacey[14] has devised a method by which the pressure in a vacuum system can be measured from a determination of the degree of damping of a quartz crystal placed in the system. A quartz crystal is mounted with minimum loading at the supports. When the pressure of the surrounding gas is increased, the damping of the crystal is also increased and there is a reduction in the amplitude of its vibrations. Changes in the reading of a calibrated meter connected to the excited crystal indicate the pressure.

A similar type of device may be used to determine the thickness of metal plating in a vacuum coating chamber. As the thickness of the coating is increased, there is an increase in the degree of damping of the crystal. The method can also be used for level detection (see Figure 6.19). The crystal is placed in a tank containing a liquid. When the liquid level rises to submerge the transducer, there is an increase in the damping; when the level falls below that of the transducer, the damping is decreased. Suitable switching devices actuated by the change of loading on the crystal can control the opening and closing of valves and thus control the level of the liquid.

Figure 6.20 illustrates a method due to Sliwinski and Walasiak[15] of controlling the concentration in a solution by monitoring the velocity of sound in it. Continuous ultrasonic waves at a frequency of about 10 MHz are passed through the liquid, and a beam of monochromatic light is directed at right angles to the ultrasound. The light is diffracted (see Section 5.6.1), and slits are positioned to receive the first-order diffracted beams on each side of the main beam. The angle of diffraction depends on the velocity of sound and, hence, on the concentration.

A solution of the desired concentration is placed in the vessel, and the slits are positioned so that slit 1 receives one of the diffracted beams when the concentration is a little too strong and slit 2 receives the other

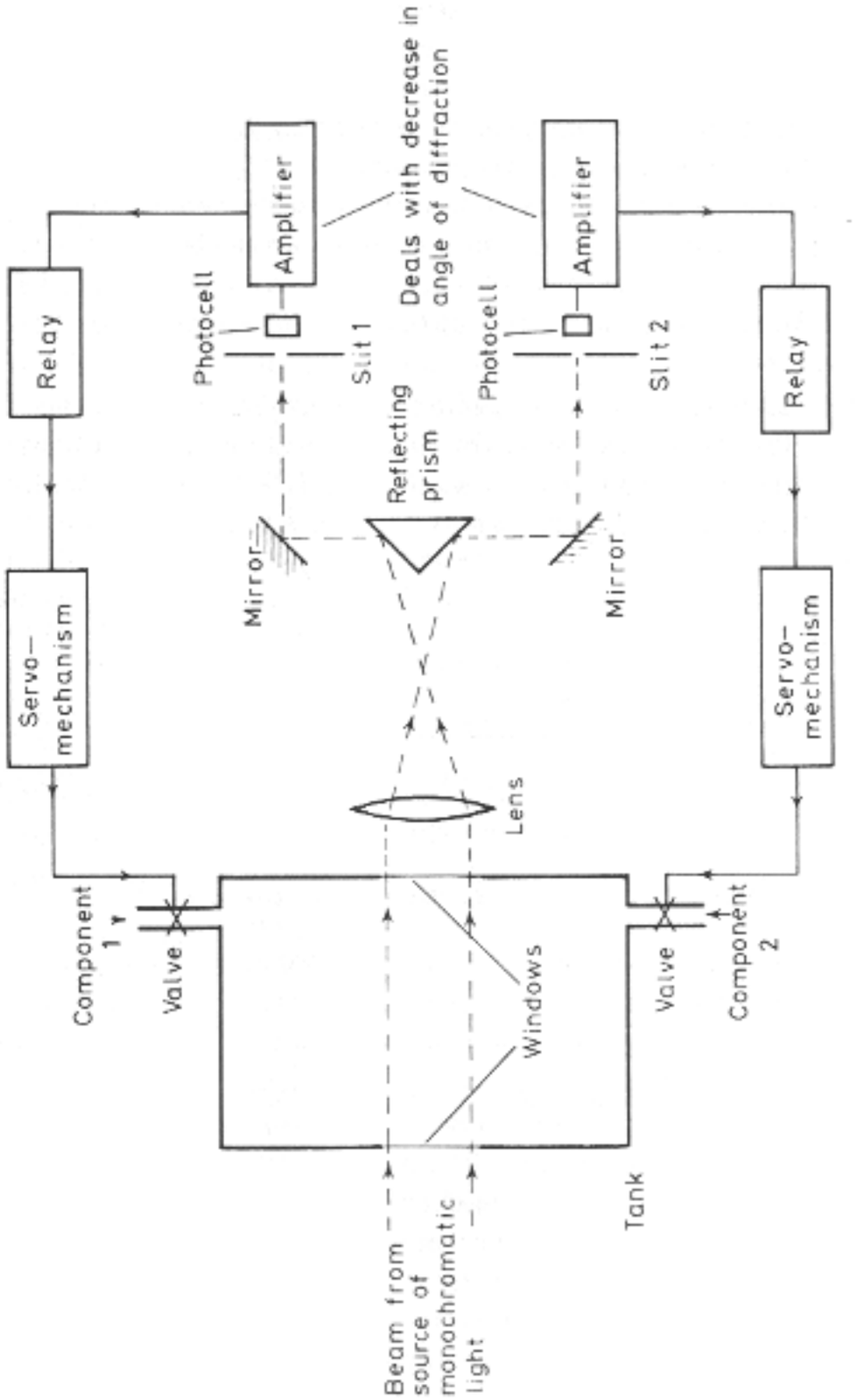

Figure 6.20 Ultrasonic method of controlling the concentration of a solution, after Sliwinski and Walasiak[15]

beam when the concentration is a little too weak, in accordance with the laid-down tolerance. Photocells are placed behind the slits, and relays are operated in such a way that a valve admitting one of the components of the solution is opened when slit 1 is illuminated and a valve admitting the other component is opened when slit 2 is illuminated. The valves close when the photocells are no longer excited. In this way, the concentration is maintained at a constant value.

By measuring the acoustic velocity with a suitable method (see Chapter 5), the temperature of a body or enclosure can be determined provided that the manner of variation of velocity with temperature for the material is known. An accuracy of better than 1 per cent can often be attained.

Bell[16] has shown how the temperature of a furnace, molten metal, or nuclear reactor core can be determined by measuring the resonance frequency of a solid rod acting as a sensing element. This sensor, in the form of a rod or wire, is made from a refractory material either one or

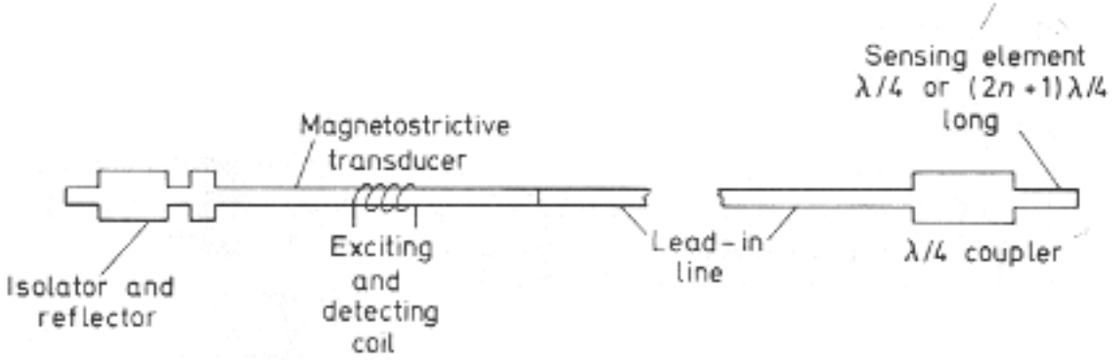

Figure 6.21 Solid acoustic thermometer, after Bell [16]

three quarter-wavelengths long. It is joined to a quarter-wavelength coupling rod of larger diameter to provide a mismatch of mechanical impedance (i.e. the product of the acoustic characteristic impedance and area of cross-section) at the node. This gives the sensor a higher Q factor so that it vibrates with high amplitude only over a narrow band at the resonance frequency (see Figure 6.21). Where possible, the sensing element and coupling rod can be machined from the same piece of material. The coupling rod is connected by a long rod or wire to a magnetostrictive transducer, to the far end of which are fitted wider-diameter rods to isolate reflected waves.

Pulses of, say, 40 oscillations are propagated with a frequency which can be varied within suitable limits. The pulses are long enough for the formation of standing waves in the sensing element. Resonances at the natural frequency can be observed on the screen of a cathode ray

oscilloscope. These resonance pulses can be distinguished without difficulty from those reflected from other discontinuities in the acoustic line, because of the high Q factor of the sensing element.

Mobsby[17] used this device with a quarter-wavelength sensing element made of ruthenium, which has a melting point of 2310°C. The element was 10 mm long and resonated at a frequency of 136 kHz, which fell to 120 kHz at 1700°C, giving an average sensitivity of 20 Hz $^{\circ}C^{-1}$ at the higher temperature limit. The accuracy of the thermometer depends on the Q factor of the sensing element and may be as good as 0·1 per cent.

Of recent innovation is the *ultrasonic leak detector*, which has been used for both pressure and vacuum systems. When a gas passes through a small orifice, sound waves are propagated by the resulting disturbance. It has been found that virtually all small leaks emit ultrasound having frequencies close to 40 kHz. A small portable detector consisting of a ceramic transducer with a horn connected to a transistorised amplifier and detecting meter, having a frequency response covering the range 36—44 kHz, is now commercially available[18].

6.10 Ultrasonic delay lines

Delay lines are devices for storing electrical signals for finite lengths of time, e.g. in computers to store information to be extracted at a later stage of a calculation. Much success has been achieved by applying

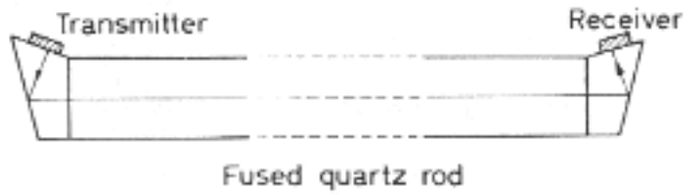

Figure 6.22 Ultrasonic delay line using shear waves after mode conversion, after May [19]

ultrasound for this purpose. Electrical signals are fed to a transducer and converted to ultrasonic waves which travel a given distance through the material acting as a delay line, the length of which depends on the velocity of sound in it and the required time of delay. At the end of the acoustic path, a transducer converts the sound back to an electrical signal.

The simplest form of ultrasonic delay line consists of a crystal transducer radiating into a column of liquid (e.g. mercury contained in

a tube) and terminated at the opposite end by a reflector. The delay time depends on the length of the liquid column, e.g. the position of the reflector relative to the transducer. Solid delay lines are often more convenient to use. For short delay times, e.g. of the order of a microsecond, the transducers may be placed at opposite ends of a solid block or rod, a few centimetres in length. The delay time can be increased by the use of shear waves, which have velocities of the order of one-half those of longitudinal waves in the same material. Figure 6.22 shows how shear waves are produced by mode conversion, propagated along a fused

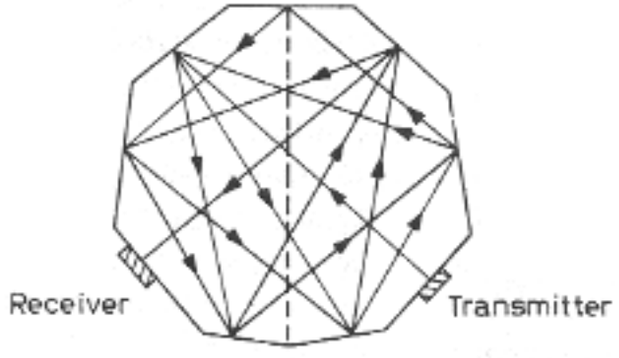

Figure 6.23 Polygon delay line, after Arenberg[20]

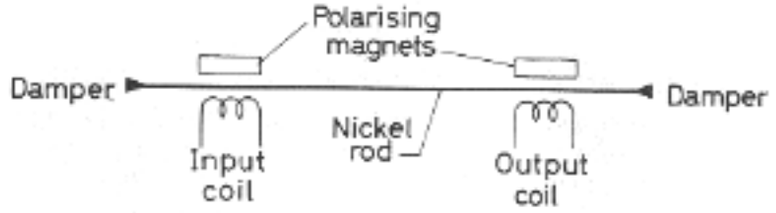

Figure 6.24 Magnetostrictive delay line

quartz or silica rod, and reconverted back into longitudinal waves before arriving at the receiving transducer. Longer delay paths, of the order of a few milliseconds, can be obtained by multiple reflections in polygons made of low-loss materials such as fused quartz (see Figure 6.23). By using a magnetostrictive delay line, such as a nickel rod with coils, the delay time can be made continuously variable by altering the relative positions of the coils (Figure 6.24).

Latest developments in ultrasonic delay lines involve the use of surface waves for which both velocities and absorption coefficients are much less than for bulk waves for a given material. A surface wave delay line may consist of a piezoelectric material medium with comb-type

transducers (see Section 3.2.5 and Figure 3.9). The line can be made variable in length if the receiving comb assembly is coated to the underside of a thin piece of suitable material which can be slid along the surface either towards or away from the fixed transmitting comb.

Useful accounts of ultrasonic delay lines have been given by Eveleth[21] and by Roderigue[22]. The account by the latter author is of interest because it concerns the use of microwave frequencies *at room temperatures.*

6.11 Applications of ultrasonics to fluid flow

In Section 4.4 it was shown that the attenuation of shear waves in a viscous liquid at a given frequency decreases with increasing viscosity. The damping of the vibrations of a shear wave transducer placed in such a liquid is thus related to the coefficient of viscosity η of that liquid. One method of measuring η consists of the periodic application of pulses to a Y-cut crystal or, at a lower frequency, a torsionally vibrating rod immersed in the liquid. The pulse repetition frequency is governed by the degree of damping in the following manner. When, after excitation of the first pulse, the amplitude of the transducer falls to a predetermined level, another pulse is triggered off. Hence the pulse repetition frequency increases with damping and, if the device is calibrated with a liquid having a known coefficient of viscosity, provides a measure of viscosity.

The velocity of flow of a liquid in a pipe can be measured by the application of the Doppler principle (Section 2.16). In the simplest application, using the pulse technique, two reversible transducers operating typically at a mega-hertz frequency are placed in the liquid so that the line joining them is parallel with the direction of flow. Initially one of these transducers acts as a transmitter and the other as a receiver, but, at regular short intervals, they are switched over to reverse their functions. The acoustic velocities are $c + w$ along the direction of flow and $c - w$ in the opposite direction, where c represents the velocity of sound and w the velocity of the flow of liquid. The received signals are fed to an oscilloscope, on the screen of which two peaks are observed, corresponding to the velocities $c + w$ and $c - w$. Because the frequency of switching from one transducer to the other is high, the peaks are observed simultaneously. The distance between the peaks depends on the difference between the times t_1 and t_2 for the waves to travel in their respective directions. Thus, if d represents the distance of separation of the transducers, it can easily be seen that

$$t_1 - t_2 = \frac{d}{c - w} - \frac{d}{c + w} \tag{6.2}$$

i.e.

$$w \simeq \frac{c^2(t_1 - t_2)}{2d} \tag{6.3}$$

where w is small compared with c.

This does not apply when the bore of the tube is narrow, because of the interruption of the liquid flow by the transducers. The flow becomes unimpeded if the transducers are located on plastic wedges bonded to the outer wall of the pipe, as shown in Figure 6.25. The ultrasound then travels along a line inclined at some angle θ to the axis of the tube. The relative positions of the transducers depend on the velocity of flow, and

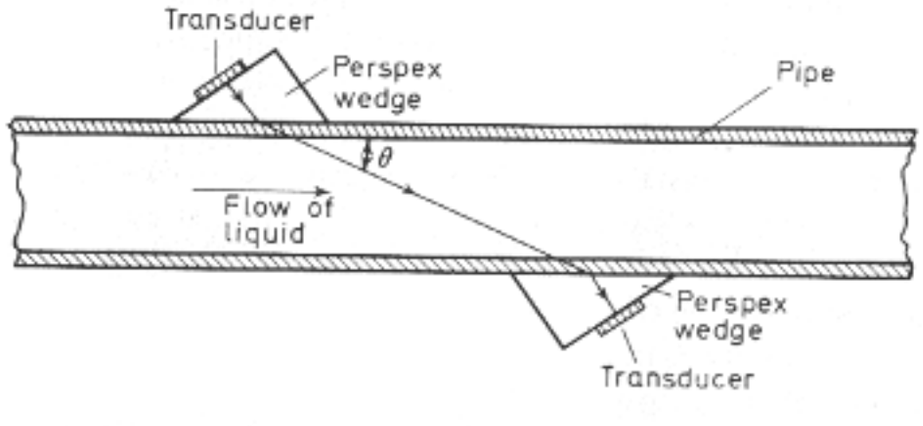

Figure 6.25 Arrangement of transducers for measuring the velocity of a liquid flowing through a narrow tube, using the Doppler effect

w in equation 6.2 is then replaced by $w \cos\theta$, the component of the velocity of the liquid in the direction of the sound, i.e.

$$t_1 - t_2 = \frac{d}{c - w\cos\theta} - \frac{d}{c + w\cos\theta} \tag{6.4}$$

i.e.

$$w \simeq \frac{c^2(t_1 - t_2)}{2d\cos\theta} \tag{6.5}$$

where w is small compared with c.

The angle of the wedge should not be too great otherwise total reflection may occur at the interface of the inner surface of the tube and the liquid. This difficulty may be overcome where the tube is made either of the same material as the wedge or of a thin metal of thickness less than one-tenth of a wavelength (see Section 2.8). In the latter case, the nature of the material of the tube has no effect on the transmission

of the waves. Alternatively, a short length of this kind of tube having the same diameter as that of the parent tube may be interposed without disturbing the flow of the liquid.

6.12 Applications of ultrasonics to medical diagnosis

The techniques used in flaw detection have been extended with much success to medical diagnosis. The characteristic impedances and absorption coefficients of different parts of the human body, such as muscles, bones, layers of fat, etc., vary sufficiently to enable reflections and attenuations to be observed using the methods described in Sections 6.2, 6.3, and 6.4. The acoustic properties of healthy and malignant tissues have been found to differ by a sufficient extent to make possible, in a number of cases, an early diagnosis of cancer. The uses of miniature transducers have enabled practitioners to conduct certain ophthalmic and dental examinations ultrasonically. In all diagnoses, care must be taken to ensure that the intensities are sufficiently low to prevent harmful effects to the body occurring as a result of overheating and cavitation. Frequencies used for medical examinations range from 1 MHz to 10 MHz

Spectacular advances in medical diagnosis have been made with the use of the C-scan technique described in Section 6.3.3, and clear 'pictures' have been obtained of the foetus in an expectant mother at different stages of pregnancy, and of malignant growths, damage, and inflammations for various organs such as the breast, the liver, and the brain. Thickness measurement techniques have been used for measuring dimensions in foetal, bladder, and liver examinations.

Doppler methods have been used for the measurement of the velocity of blood flow and of the motion of the mitral valve of the heart. The latter can be determined by the frequency shift caused by a moving reflector, as explained in Section 2.16.

The developments of the use of ultrasound in medical diagnosis are far-reaching, and lack of space prevents the further discussion of their details in this chapter. An excellent account of the subject has been given by Wells[23].

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CHAPTER SEVEN

HIGH-INTENSITY ULTRASONICS

7.1 General considerations

In general, it may be said that ultrasound has a high intensity when the applied acoustic stress is sufficiently great for it to be no longer linear with the resultant strain, in contradiction to Hooke's law. The corresponding acoustic power may be of the order of watts and, in some cases, may be as high as several kilowatts, as compared with powers of the order of milliwatts or microwatts for low intensities. The changes brought about by high-intensity ultrasound are often permanent.

In this chapter, the principles of the various high-intensity phenomena and devices are explained and an account of their applications is given. Fuller details, together with a comprehensive list of references, have been provided by Brown and Goodman[1].

7.2 Cavitation

Many of the applications of high-intensity ultrasonics concerning liquids often involve the use of cavitation. This phenomenon may be observed in boiling water and also in sea-water in the vicinity of the rotating propeller of a ship. Cavitation takes place in a liquid when it is subjected to rapidly alternating pressures of high amplitude. It can thus be brought about by the use of sound of sufficiently high intensity.

Imagine that sound travels through a small region in a liquid. During the positive half-cycle of the waves, the liquid in the region is compressed, and, during the negative half-cycle, it expands. When the acoustic pressure amplitude is greater than the hydrostatic pressure, the molecules of the liquid are wrenched apart and voids are created. The voids, which contain only the vapour of the liquid, expand during the negative part of the pressure cycle and then collapse abruptly. This collapse takes place almost instantaneously with the release of energy at an enormous rate, giving rise to the propagation of shock waves. Local temperature increases of some tens or hundreds of thousands of degrees are consequently attained for very short periods at the frequency of the wave propagation. The action just described is called *true* or *vapour cavitation*, which is observed in liquids free from bubbles.

When bubbles are already present in a liquid, cavitation can occur at much lower intensities than before because it is no longer necessary for the acoustic pressure amplitude to exceed the hydrostatic pressure in order to create voids. *Gaseous* or *pseudo-cavitation* is then said to occur. Pseudo-cavitation can also be induced in bubble-free liquids by the introduction of suitable nuclei to assist the formation of voids. Examples of these nuclei are solid particles suspended in the liquid, and defects introduced into its structure, e.g. by neutron bombardment.

The onset of cavitation is usually indicated by a hissing sound called *cavitation noise.* For true cavitation, the noise results from sharp cracks occurring when the liquid is torn apart internally; this noise can be very intense. The minimum acoustic intensity (or acoustic pressure amplitude) required to produce cavitation is called the *cavitation threshold* or, alternatively, the threshold intensity (or pressure). The amount of energy

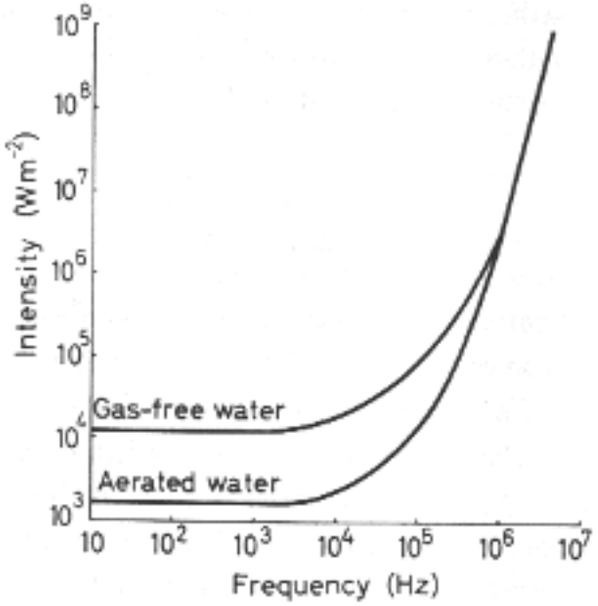

Figure 7.1 Variation of threshold intensity with frequency for water at room temperature, after Esche (see Hueter and Bolt[2])

released by cavitation may be determined by observing the loss of weight from erosion, due to cavitation, of metal foils suspended in the liquid. This can also be done by evaluating the chemical changes brought about by the process, e.g. the amount of chlorine liberated by a quantity of carbon tetrachloride dissolved in the liquid.

Figure 7.1 shows how the threshold intensity varies with frequency. Curves for aerated water and for gas-free water, are shown. As one would expect, the threshold is considerably lower for aerated water than for

gas-free water. The threshold remains fairly constant at low frequencies, but it rises rapidly for frequencies higher than about 10 kHz. This rise is attributed to the fact that, at higher frequencies, there may not be enough time between cycles to allow for sufficient growth of the bubbles for cavitation to occur.

Cavitation may be suppressed by subjecting the liquid to an increased hydrostatic pressure so as to raise the threshold intensity. A decrease in threshold intensity takes place when the time of exposure to ultrasound is increased, this being due to a finite time elapsing between the start of acoustic excitation and the onset of cavitation. Thus, when pulsed waves are generated in the liquid, the threshold intensity is reduced on the lengths of the pulses being increased.

The intensity of cavitation increases with temperature as a result of the production of further cavitation nuclei due to heating. However, a

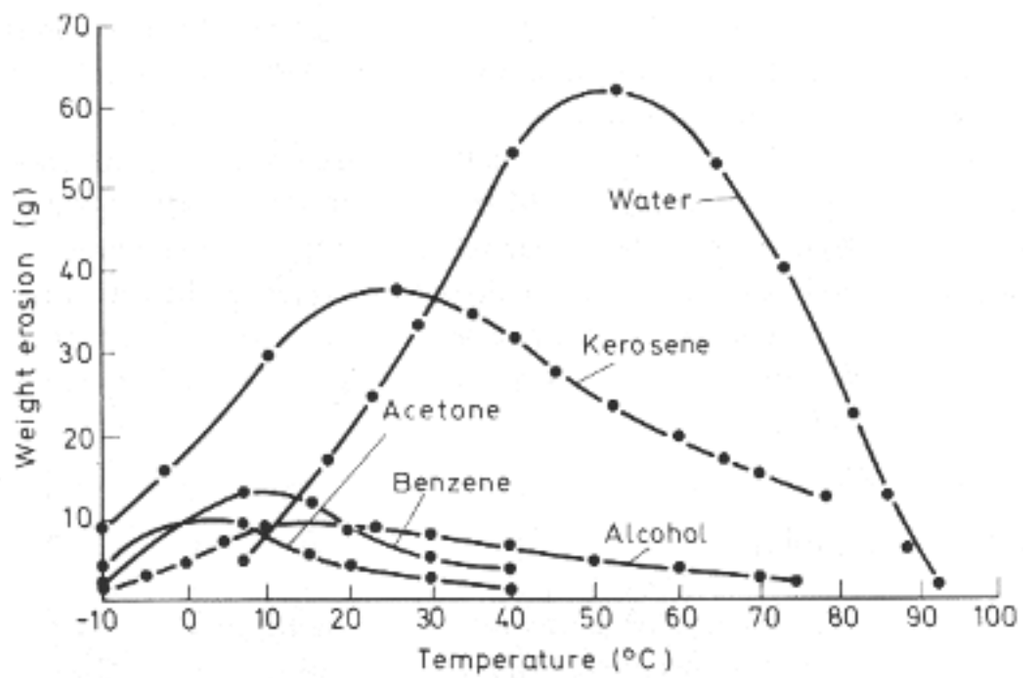

Figure 7.2 Cavitational erosion as a function of temperature for aluminium in various liquids, after Brown and Goodman[1]

rise in temperature also brings about a lowering of the surface tension of the liquid and an increase in its saturation vapour pressure, both of which affect cavitation. The energy released by cavitation will generally at first increase with temperature, then pass through a peak, and finally decrease as the temperature is increased still further. Figure 7.2 illustrates results of measurements of cavitational erosion as a function of temperature for a number of liquids. Thus, to produce maximum cavitational

effects in a given liquid, one should operate at a temperature corresponding to the peak on the curve. This is not always feasible because the piezoelectric or magnetostrictive effect of the transducer may decrease considerably if the temperature is raised too high.

Water, because of its comparatively high surface tension, is a very effective medium for cavitation. It can be made still more effective by the addition of about 10 per cent alcohol, which results in a considerable increase in the saturated vapour pressure but a decrease in surface tension. However, the beneficial effect caused by the rise in vapour pressure more than compensates for any losses due to the fall in surface tension.

Cavitation may be accompanied by a weak emission of light, a phenomenon known as *sonoluminescence*, from which a continuous spectrum can be observed. This probably arises from the incandescence of the vapour in the bubbles as a result of local increases in temperature of thousands of degrees. Another possible cause of the phenomenon is the production of electrical discharges across the bubbles as a result of ionisation produced by cavitation.

The various effects of cavitation and their applications are discussed in some of the following sections of this chapter. One chooses a low operating frequency to obtain the maximum effect, but the lowest practicable limit is about 18 kHz. Below this frequency, the sound is audible, and, because of the very high intensity required to produce cavitation, conditions for the operator and others in the vicinity are both unpleasant and harmful.

7.3 Emulsification

An important application of ultrasonically induced cavitation is the emulsification of two immiscible liquids such as oil and water. Oil is injected into the water, which is then excited ultrasonically to produce cavitation. As a result, very fine droplets of oil are forced with high energies into the body of the water and the minute particles of oil rapidly disperse to form a highly stable emulsion. The name *homogenisation* is often applied to this process.

Emulsification can also occur as a direct consequence of agitation alone, even in the absence of cavitation. An example of this is the mixing together of two liquids having widely differing densities, e.g. water and mercury. However, the emulsion so formed is not very stable and the liquids separate after a very short time.

The production of emulsions by ultrasonically induced cavitation has extensive application in industry, where it is often found to be more effective than by the method of mechanical agitation or stirring. Ultrasonic techniques are advantageous because there is less mechanical wear of the equipment and no unwanted air bubbles are introduced. There is no need to raise the temperature, an advantage where heating might otherwise affect the quality of the product, and no time is wasted in waiting for the emulsion to cool down.

Applications of ultrasonically induced homogenisation are numerous. In the food industry, the method is used in the preparation of dairy products, sauces and gravies, mayonnaises and salad creams, and syntheti creams. In the frozen-foods industry, the sauces prepared by ultrasonic homogenisation will withstand repeated freezing and thawing because

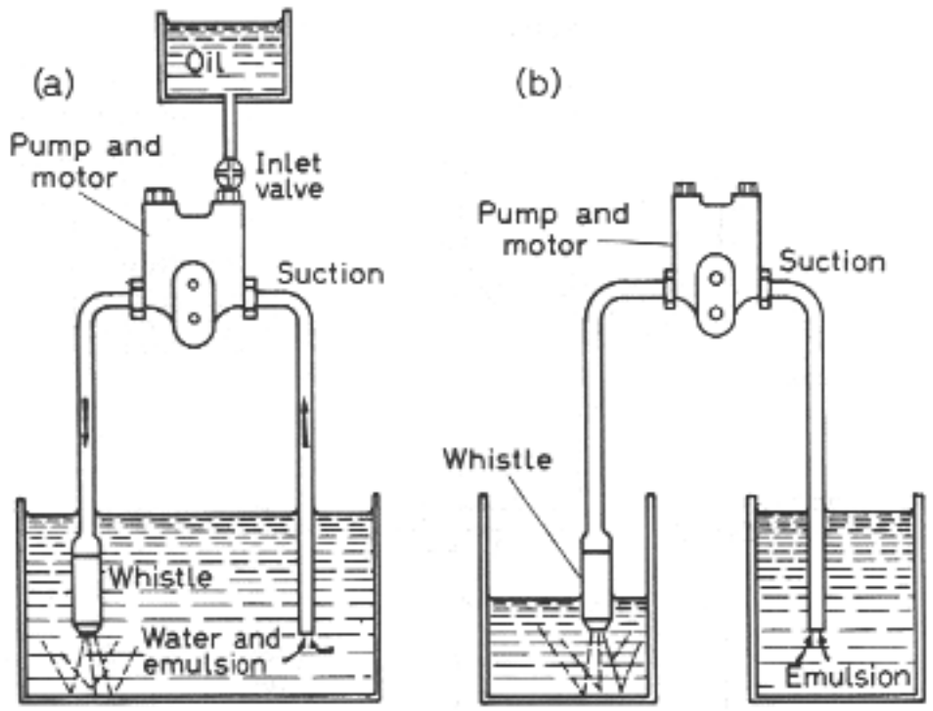

Figure 7.3 Production of emulsions using the resonant wedge whistle, after Crawford[3]: (a) initial stage; (b) final stage

of the high stability of the emulsion. The phenomenon is applied also to the preparation of pharmaceutical products, including antibiotic preparations, and to cosmetics, paints, and polishes.

The resonant wedge whistle, described in Section 3.4, is often used for the production of emulsions. Figure 7.3 illustrates a method of preparing an oil–water emulsion with this device. First of all, an emulsion is formed ultrasonically as the oil is introduced into the water [Figure 7.3(a)], and then the mixture is refined by circulation. Finally,

the oil supply is disconnected and the emulsion is forced through the whistle into the second container to produce an even fine suspension. The diameters of the suspended particles may be as little as 2 μm.

7.4 Ultrasonic atomisation

As early as 1927, Wood and Loomis showed that when a beam of intense ultrasound emerging from a transducer immersed in a liquid is directed upwards, a fine mist appears above the surface. The density of the mist depends on the intensity of the waves, and the size of the droplets is related to the frequency and to the surface tension of the liquid. Surface waves are propagated as a result of the disturbance, and their wavelength is determined by these quantities. It has been shown that the diameters of the droplets are approximately equal to a little

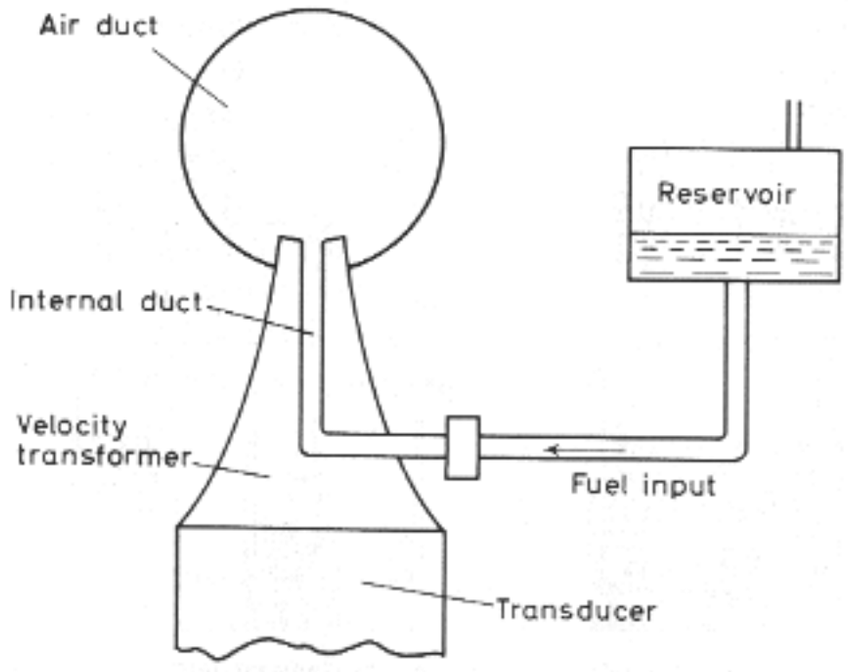

Figure 7.4 Equipment for ultrasonic atomisation, after Brown and Goodman[1]

less than the half-wavelength of the surface waves. This suggests that the droplets are formed by the ejection of the wave peaks.

Frequencies used for ultrasonic atomisation range from about 40 kHz to several mega-hertz, depending on the required size of the droplets, which may extend from 100 μm to 10 μm. Applications have been made to inhalation therapy and also to the design of oil burners. In the latter case, one can dispense with the small, easily blocked, orifices which are

required for conventional oil burners. In any case, blockages which do occur can be cleared by the action of the ultrasound. Figure 7.4 illustrates the properties of a device used by Mullard Equipment Ltd for ultrasonic atomisation.

7.5 Effects of ultrasound on suspensions

When ultrasound passes through a fluid in which particles are suspended, the pressure of radiation (see Section 2.6) pushes the particles along the direction of propagation. In a stationary wave system, however, the motion takes place from the antinodes to the nodes of acoustic pressure, where the particles coagulate and fall, when heavy enough to overcome both the viscosity and the hydrostatic upthrust of the fluid. When the particles are in the form of a gas, the bubbles coalesce at the nodes and then rise to the surface.

Applications of these effects include the dispersion of fog and smoke and also the degassing of molten glass, molten metals, liquid foodstuffs (prior to vacuum packing), and beer (prior to bottling). For the degassing of bottled liquids, ultrasound at a frequency of about 20 kHz is generated to produce stationary waves. The coalesced bubbles rise to the neck of the bottle and into the air, after which the stopper is fitted.

The effects just described are caused by agitation alone and, in no way, are due to cavitation. It so happens that, if the intensity is high enough in a liquid for cavitation to take place, the particles may break up and form an emulsion.

7.6 Ultrasonic cleaning

Ultrasonic cleaning is a process which can involve both agitation and cavitation. Most applications, including the cleaning of large components, are carried out in the low frequency range, from 18 kHz to 40 kHz, in which cavitation is most active. However, with delicate articles, which are easily damaged, higher frequencies within the range from 100 kHz to 1 MHz, where cavitation is virtually absent, are used.

The transducer is often attached to the outside of the cleaning tank to prevent any damage to itself by cavitation erosion.

Cleaning at low frequencies is normally carried out with ceramic and magnetostrictive transducers, the former, nowadays, being included in a

sandwich assembly (see Section 3.2.4). Ceramic transducers are excited by moderately high direct voltages, typically about 1·5 kV, in the form of pulses, and care must be taken in their design to eliminate the possibility of thermal shocks (which may give rise to depolarisation) and electrical shocks (which might cause damage). The characteristic impedances of ceramic transducers are fairly well matched to those of the cleaning fluids, and a high output power is thus possible.

Magnetostrictive transducers require only comparatively low voltages for their operation but take high currents. However, because they are made of heavy metals, their characteristic impedances are high compared with those of the cleaning fluids, their power outputs are relatively lower, and they are generally less efficient than ceramic transducers. On the other hand, they are very robust compared with the brittle ceramics and there is much less chance of accidental damage. Furthermore, magnetostrictive transducers have high Curie temperatures, ranging from 360°C for nickel to about 900°C for permendur, and will withstand high temperatures without depolarisation.

The design of magnetostrictive transducers has now been improved to provide better matching with cleaning fluids by spacing apart the laminations so as to reduce the overall density of the vibrating system and thus the effective characteristic impedance. Output efficiencies of the latest designs compare favourably with those of ceramic transducers.

The ideal cleaning fluid should possess the following properties:

1. Low surface tension for cavitation at lower levels.
2. High saturation vapour pressure for higher cavitation energy.
3. Good wetting properties to provide better contact with the component to be cleaned.
4. Low viscosity to provide rapid penetration into the soil.
5. Ability to react chemically with the soil.
6. Ability to hold the soil in dispersion to prevent recontamination.

Trichloroethylene and cyclohexane have proved to be satisfactory for most purposes, but manufacturers have now developed new solutions with a view to satisfying the above-mentioned requirements in the most efficient manner.

Figure 7.5 shows a typical cleaning bath for small-scale operation, and Figure 7.6 illustrates a method of cleaning a large number of components, using a conveyor belt arrangement.

Ultrasonic cleaning is not only a rapid and easy process but is also less liable to cause damage to components than the more-conventional

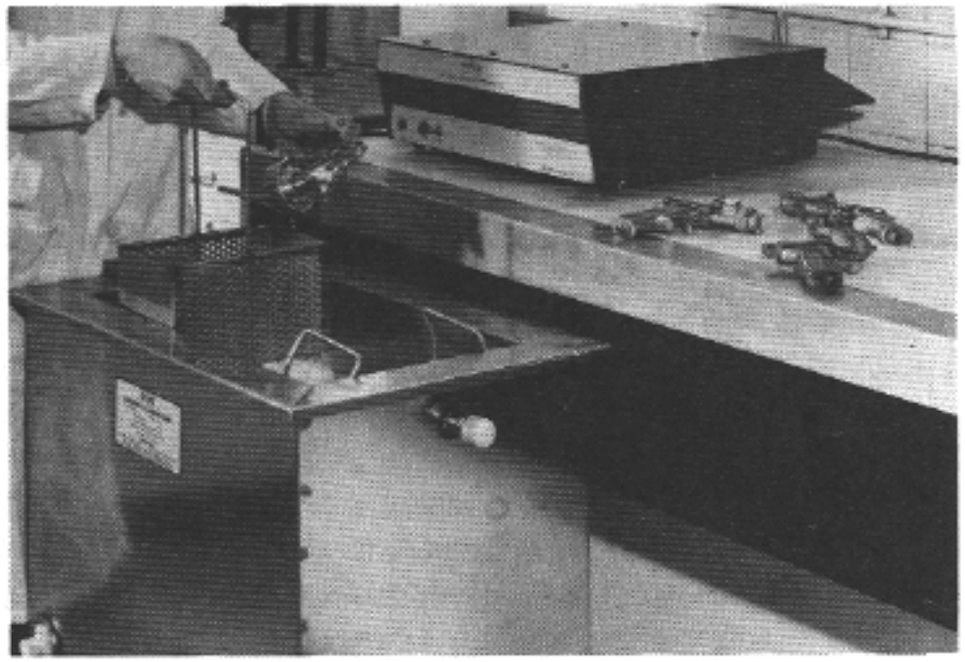

Figure 7.5 Ultrasonic cleaning tank for small-scale operation. Courtesy Dawe Instruments Ltd

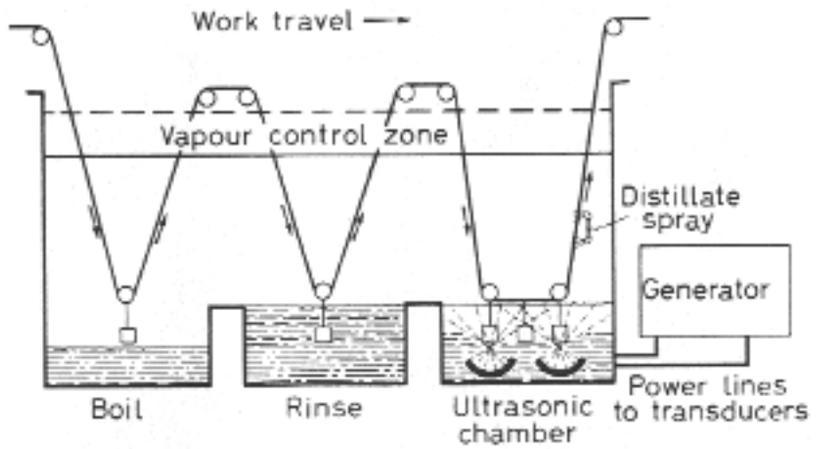

Figure 7.6 Conveyor belt arrangement for large-scale ultrasonic cleaning[3]

methods. Applications include the removal, without scratching, of lapping paste from lenses after grinding, the cleaning of grease and swarf from small orifices in engine components, the removal of oil, dust, grease, soluble flux residues, buffering compounds, and processing soils from semiconductor devices, printed circuits, and jewellery, the removal of tarnish from metal surfaces, and the removal of blood, etc., from surgical instruments. The method, however, has not proved satisfactory for the laundering of clothes, mainly because of the damping effect of textiles on the ultrasonic waves. Furthermore, it does not appear to have competed very successfully with the conventional methods in the field of automatic dishwashing.

7.7 Applications to solids

When high-intensity ultrasound is passed through a solid, strains which exceed the elastic limit may be produced. The material might then suffer plastic deformations which increase in magnitude with each

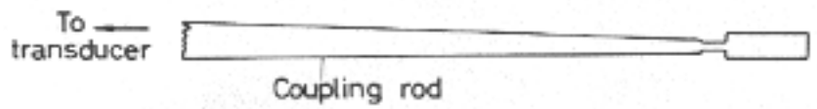

Figure 7.7 Application of ultrasonics to fatigue testing

cycle and eventually give rise to fracture. As a result, ultrasonics has found application to fatigue testing, and an arrangement designed for this purpose is illustrated in Figure 7.7. Ultrasonic fatigue testing is carried out at frequencies of the order of 20 kHz using acoustic powers of up to 200 W, and the time taken for a complete test may be a matter

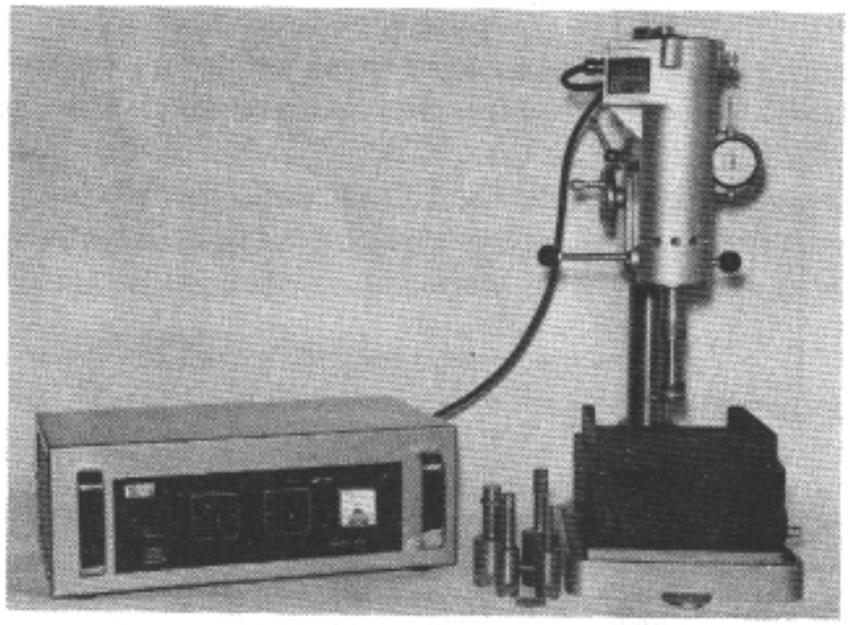

Figure 7.8 Ultrasonic drill with various coupling rods. Courtesy Kerry Ultrasonics Ltd

of only a few hours as compared with several weeks with conventional methods carried out at frequencies of less than 100 Hz.

An important application to solids is the ultrasonic drill, which is widely used. The action of the drill is reciprocal, like that of the pneumatic road-drill, and holes of any desired shape may be cut in a suitable material. Figure 3.15 (Chapter 3) illustrates the principles of the device, which consists of a tapered rod firmly attached at its broad end

to a magnetostrictive transducer. A cutting tool is screwed tightly into the narrow end. The rod, which is of resonant length, acts as a velocity transformer (see Section 3.3). The tool need be made of only a soft material, such as mild steel, because the actual cutting is performed by an abrasive slurry, e.g. boron carbide, silicon carbide, or aluminium carbide in suspension. The slurry is applied between the work and the tool, and it is continually renewed during the cutting process. The method has been found to be highly advantageous for the drilling of hard and brittle materials, such as glass, ceramics, tungsten carbide, and germanium. It has been applied extensively to such processes as the cutting of wire-drawing dies, semiconductor micro-electronic devices, and jewels for watch bearings. Figure 7.8 illustrates a typical commercial ultrasonic drill together with a selection of coupling rods.

7.8 Metallurgical applications

Much success has been achieved by the applications of high-intensity ultrasound to the treatment and working of metals. As well as drilling

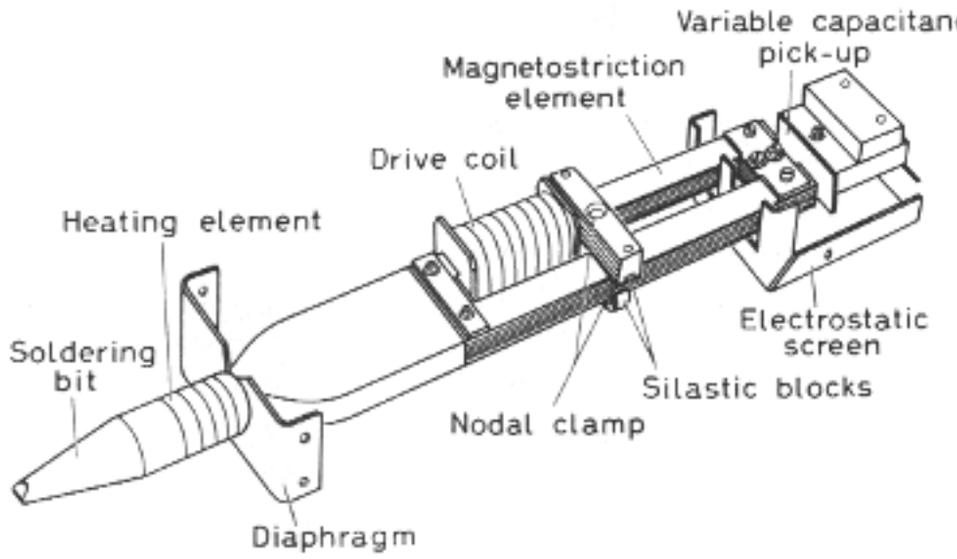

Figure 7.9 Ultrasonic soldering iron.

and fatigue testing, as discussed in the previous section, the applications include the treatment of melts, soldering, and welding.

When a molten metal is cooled, it is essential that all gas bubbles are removed prior to its reaching the solid state. Degassing can be achieved by irradiating the melt with high-intensity ultrasound (see Section 7.5). If cooling occurs under normal conditions, crystals begin to form at the

temperature of solidification. The crystals grow to sizes which depend on the rate of cooling and the types of impurities, if any, present in the metal. Ultrasonic cavitation causes the breaking up of the crystals, and the solid which is finally formed has then a much finer grain structure than it would have if cooling were to take place with the melt undisturbed.

The ultrasonic soldering of metals can be effected without the use of any flux, and troubles arising from the introduction of corrosive substances are thus eliminated. An ultrasonic soldering iron somewhat similar in design to the ultrasonic drill was introduced some years ago and is illustrated in Figure 7.9. The essential difference between the two instruments is that the soldering iron has an electrically heated bit in the position occupied by the tool at the end of the ultrasonic drill. The vibrations of the bit produce cavitation in the solder, thus cleaning the surface of the work and removing oxide coatings. An excellent adhesion of the solder to the metal surface will then take place.

Another instrument for soldering is the ultrasonic tinning bath, which is used for small parts and wires. It consists of a metal bath containing molten solder in which ultrasonic cavitation is produced by the action of a high-power transducer.

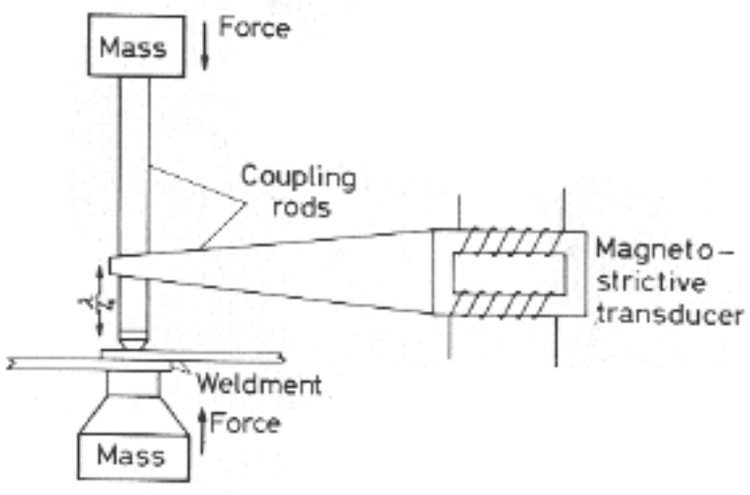

Figure 7.10 Ultrasonic welding method, after Jones and Powers[4]

Until the discovery of fluxes suitable for aluminium, the use of ultrasonics provided the only really effective way of soldering this metal. Ultrasonic soldering has proved itself to be highly efficient for 'micro-joints', and soldered joints have been made with 0·05 mm (0·002 in) diameter gold wire on gold-plated silicon and also on aluminium foil 0·15 mm (0·006 in) thick.

Another application of high-intensity ultrasonics is that of welding. The ultrasonic welding of metals can be performed at room temperatures without the need for any special surface preparation, and practically no deformation of the work takes place. The physical mechanisms involved in this process are not fully understood, but it is probable that molecular diffusion takes place across the surfaces in contact with one another. When the technique was first developed in about 1955, it was thought that it would embrace a wide range of applications, but, for metals, its scope has been limited to the welding of thin metal sheets and foils. Figure 7.10 illustrates a typical arrangement using a magnetostrictive transducer working at a frequency of 25 kHz. It can be seen that the process takes place under the action of transverse waves. This is in contrast to the vibrations acting normally to the contacting surfaces for the welding of plastics materials (see Section 7.11). Devices of this kind have proved to be useful for spot and seam welding.

7.9 Chemical effects

One of the effects of cavitation in a liquid is the promotion of chemical reactions. This is caused by the electrolytic action brought about by the appearance of equal and opposite free electrical charges at opposite ends of the bubbles, the enormous local increases of pressure and temperature when the bubbles collapse, and the release of energy from the bubbles when resonating with the ultrasonic waves.

Ordinary tap-water electrolyses as a result of cavitation, and, if certain substances are dissolved in it, either oxidation or reduction may occur, depending on the nature of the dissolved substance. A well-known example is the electrolytic separation of the K and I ions when crystals of potassium iodide (KI) are dissolved in water. The K ions are then oxidised, and free iodine is produced.

Because of the very slow rates of reaction, the chemical changes brought about by ultrasound have very little practical application. However, it has been found that ultrasonics have accelerated by a considerable extent those chemical changes initiated by other means. Ultrasonics has also been applied with success to polymerisation processes and molecular rearrangements.

A successful application of ultrasonics to chemical actions has been made to alkylation processes, which require vigorous agitation during the reactions. Figure 7.11 illustrates one type of arrangement where the

required reaction takes place in a focused ultrasonic field. Another application is one made to the process of electroplating. Bubbles appearing at the electrodes are dispersed by ultrasound, thus giving rise to an increase in the speed of the process. The quality of the plating is also improved, as a result of the removal from the surface by cavitation of

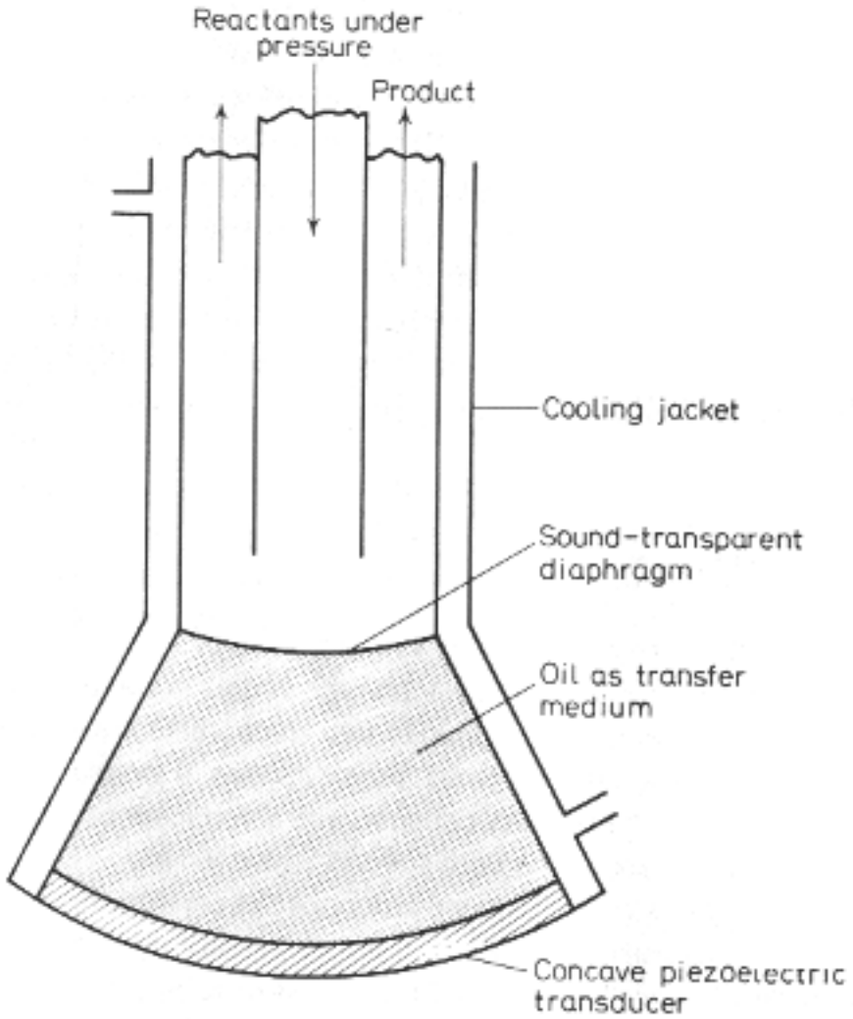

Figure 7.11 Alkylation process using ultrasonics, after Brown and Goodman[1]

any contamination. Still another chemical application, which has proved itself to be highly successful, is the maturing of wines and spirits. By irradiation of the liquid with ultrasound, maturing times can be reduced from several months to only a week or so.

7.10 Biological effects and medical applications

If high-intensity ultrasound is passed through organic tissue, changes will take place as a result of the occurrence of some of the phenomena

discussed earlier in this chapter. Experiments have shown, for example, that small animals may sometimes be killed or injured by these effects.

It has been known for a long time that cavitation destroys and breaks down living cells and extracts their contents, and ultrasound now provides a highly satisfactory medium for this purpose. One application,

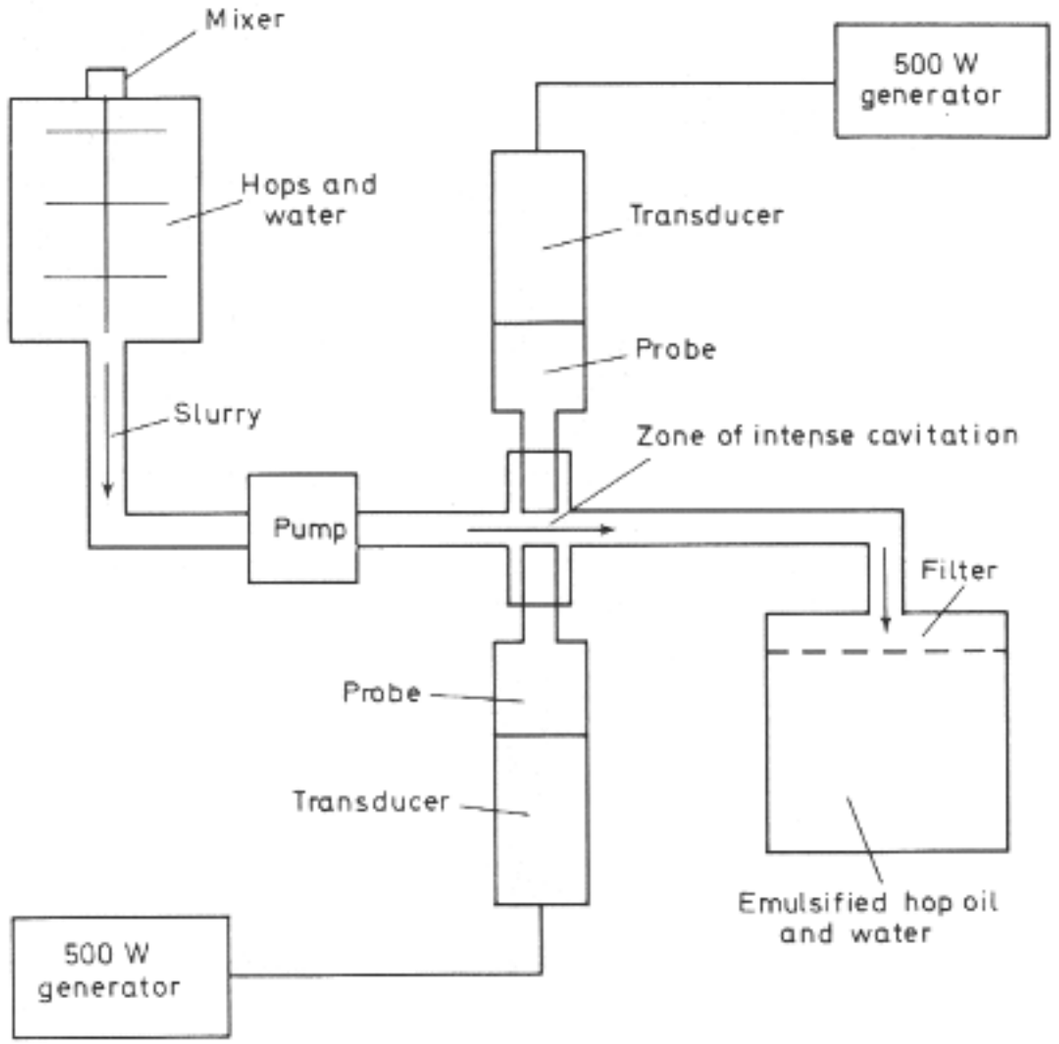

Figure 7.12 Ultrasonic hop extraction process[1]*. Courtesy Mullard Equipment Ltd*

which is made in the brewing industry, is the extraction of hops. The hops, mixed with water, are pumped through a region under the action of intense cavitation (see Figure 7.12). The contents of the hops are extracted, and an emulsion is subsequently formed. The solid residue is then filtered away. By this method, which can be applied at normal temperatures, the rate of extraction is greater than that obtained by the more-conventional methods, which demand that the hops be stored for some time while awaiting processing. Using the ultrasonic technique, the emulsion can be kept almost indefinitely without any loss in quality.

The quality is actually improved because the process does not require any boiling, which is essential for the older methods of hop extraction.

High-intensity ultrasound is often used for sterilisation. Applications have been made to the sterilisation of milk, but, unfortunately, the

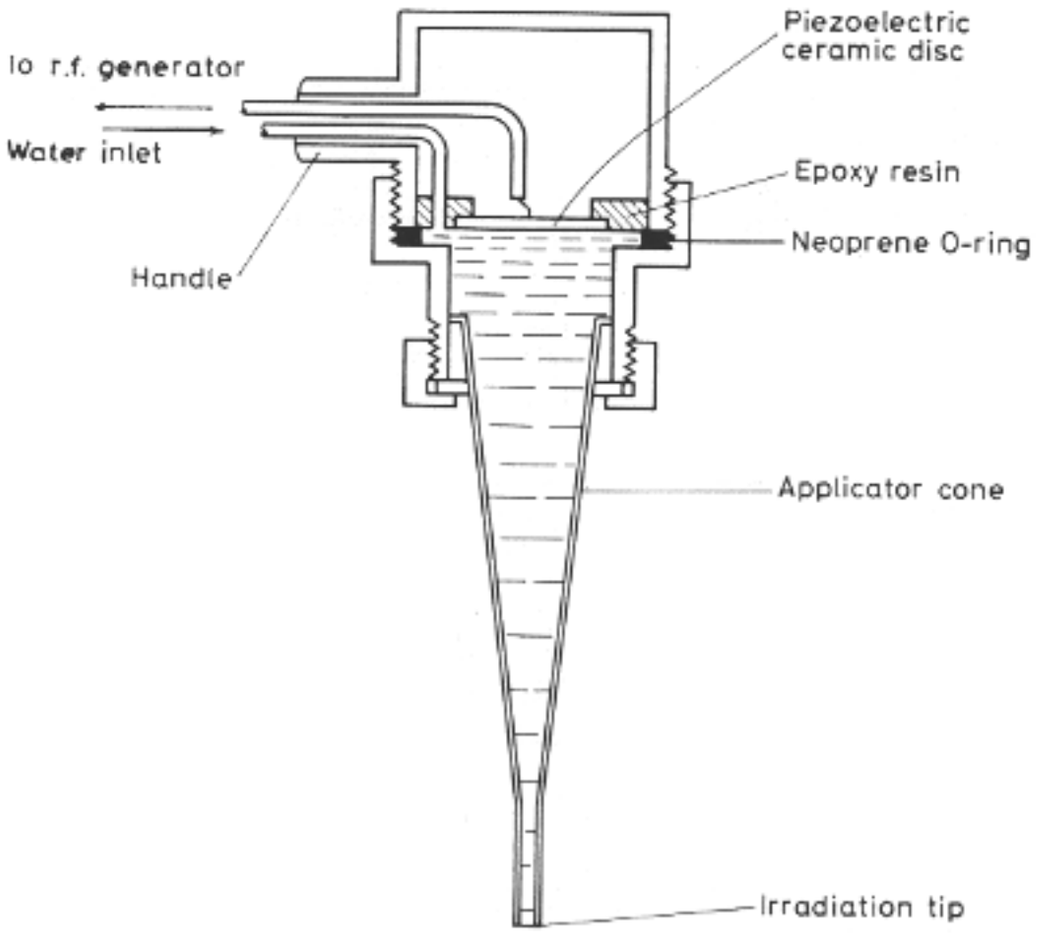

Figure 7.13 Arrangement of transducer and acoustic lens for ultrasonic neurosurgery, after Crawford (see Brown and Gordon[5])

flavour is somewhat impaired, probably owing to some chemical reaction taking place. Another use of ultrasonics is the tenderising of meat by the breaking down of its fibres.

Mention should be made of the adverse effects of ultrasound on human beings. Care must be taken in ultrasonic medical diagnosis to restrict the intensity level to well below the limit above which cellular damage to and disruptive effects on chromosomes may occur. Airborne ultrasound of high intensity can also have a harmful effect on life. For example, persons operating high-power ultrasonic equipment for long periods have been subjected to fatigue and nausea, even at frequencies far

removed from the audible range. In fact, high-intensity ultrasound has been successfully employed in the scaring away of birds.

Medical applications of high-intensity ultrasound are somewhat limited. For quite a long time, the heating effects have been utilised for the treatment of muscular ailments such as lumbago. Because of the necessity of focusing the waves into selected zones, to avoid damage to sensitive tissues, frequencies in the mega-hertz range are often used. Recent advances have been made in ultrasonic surgery, especially in the fields of neurology and otology, and a considerable degree of success in the treatment of Ménière's disease, an affliction of the ear, has been achieved.

Figure 7.13 illustrates a transducer, described by Crawford (see Brown and Gordon[5]) designed for neurosurgery. A piezoelectric transducer operating at a lower mega-hertz frequency is coupled to a tuned metal plate and then to a focusing polystyrene lens. A cone filled with degassed water and mounted over the lens couples the converging beam through a membrane and coupling fluid to the patient's scalp.

The ultrasonic drill, working in a reciprocal manner (see Section 7.7), has been applied to dentistry. Its principal advantages are simplicity in cutting and the fact that the action is painless. On the other hand, however, a continuous supply of slurry is required, much heat is generated, and it is found that the cutting action is not wholly satisfactory for soft material such as decay. When first introduced, the device was considered to have a promising future, but interest in it then diminished. Recently, however, improvements have taken place and the interest has since been renewed in view of the possibility of applying ultrasound to the actuatior of high-speed rotary drills.

Fuller accounts of ultrasonic applications to biology and medicine are given by Brown and Gordon[6].

7.11 Ultrasonic welding of plastics and fibres

Following the discovery of the possibility of welding metals by ultrasonic methods, extensive developments have been made in the welding together of plastics materials. Success has been achieved with orientated polyesters, polyethylenes, polystyrenes, polyamides, vinyls, polypropenes, polycarbonates, and a number of fluorocarbons. On the other hand, some plastics, including Teflon, do not lend themselves to this treatment. The physical properties of the welding process, although not

yet fully understood, are evidently not the same as those governing the welding together of metals. The welding of plastics takes place under the action of longitudinal vibrations, as opposed to shear vibrations for the welding of metals. The effect of ultrasound is probably to clean the touching surfaces, flatten them to provide a more efficient means of contact, and then give rise to diffusion from one material to the other. Provided that this can be allowed by the molecular structures of the two materials, bonding then occurs.

The welding process is achieved by the direct application of the tip of a velocity transformer connected at its broad end to a high-power and low-frequency (e.g. 20 kHz) transducer, an arrangement used in the ultrasonic drill (see Section 7.7). The time taken for the process is considerably longer than that required for metals, but the joint strengths are very high, usually much higher than those which can be achieved, if at all, by other methods.

This method has been extended to the welding together of man-made fibres, including nylon, acrylic, and polypropylene, as well as mixtures of man-made and natural fibres, e.g. nylon and wool. Tensile strengths of the joints have been considerably higher than those obtainable by other methods. Furthermore, a much better joint can be achieved ultrasonically. An account of the ultrasonic welding of threads has been given by Crawford[7].

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