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Ultrasonics

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ULTRASONICS

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Preface

During the last two or three decades, ultrasonic techniques have been developed so much that ultrasound can now be regarded as a significant branch of physics which has numerous applications in everyday life. This small book attempts to describe, in outline, the physics of the generation, propagation, attenuation, and detection of ultrasound (Chapters 2 to 4) and to indicate the principal ways in which physics is exploited for the benefit of mankind (Chapters 5 to 10).

This is intended to be an introductory text; it grew out of an article which my wife and I wrote for *Contemporary Physics* in 1976. At the end of the book there is a list of suggested further reading for anyone who wishes to study some particular part of the subject in more detail.

In the preparation of the present book I have been assisted by Mr J. L. Clark, Principal Teacher of Physics at Menzieshill High School in Dundee. In addition to making constructive criticism of the whole manuscript, Mr Clark also prepared the first draft of parts of chapter 1 for me. I am also grateful to the many authors, editors, industrialists, and publishers who have granted permission for the reproduction of their copyright material in tables or illustrations; the sources of these are indicated *in situ*. I am also grateful to Miss M.M. Benstead for re-drawing the diagrams for figures 5.5 and 7.30 and to Mr J.Q. Summers for some help in obtaining references on ophthalmology.

Dundee

A.P. Cracknell
July 1979

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1. Introduction

1.1. *Ultrasound*

By the term *ultrasound* we mean vibrations of a material medium which are similar to sound waves, but which have frequencies that are too high to be detected by an average human ear. The study and applications of these vibrations are called *ultrasonics*. In early days the term 'supersonics' was also used to include what we now describe as ultrasonics, but this term is now used only for *speeds* greater than the speed of 'ordinary' sound.

The upper frequency limit of human hearing varies from about 10 kHz to about 18 kHz. For any given person this threshold frequency decreases with increasing age. Towards the end of the nineteenth century Galton described the use of a small ultrasonic whistle to investigate the threshold frequency of hearing for humans.*

> On testing different persons, I found there was a remarkable falling off in the power of hearing high notes as age advanced. The persons themselves were quite unconscious of their deficiency so long as their sense of hearing low notes remained unimpaired. It is an only too amusing experiment to test a party of persons of various ages, including some rather elderly and self-satisfied personages. They are indignant at being thought deficient in the power of hearing, yet the experiment quickly shows that they are absolutely deaf to shrill notes which the younger persons hear acutely, and they commonly betray much dislike to the discovery. Every one has his limit, and the limit at which sounds become too shrill to be audible to any particular person can be rapidly determined by this little instrument.

Galton also studied the upper threshold frequency of hearing of various animals. There is no reason to suppose that this should be the same as for man (see fig. 1.1). The higher threshold frequency of birds is exploited in the construction of ultrasonic bird-scarers that are inaudible to man, while bats are known to use ultrasonic pulse-echo techniques 'to see in the dark' (see Chapter 6).

The spectrum of acoustic vibrations is illustrated in fig. 1.2. In many

*F. Galton, *Inquiries into Human Faculty and Development* (Macmillan, 1883).

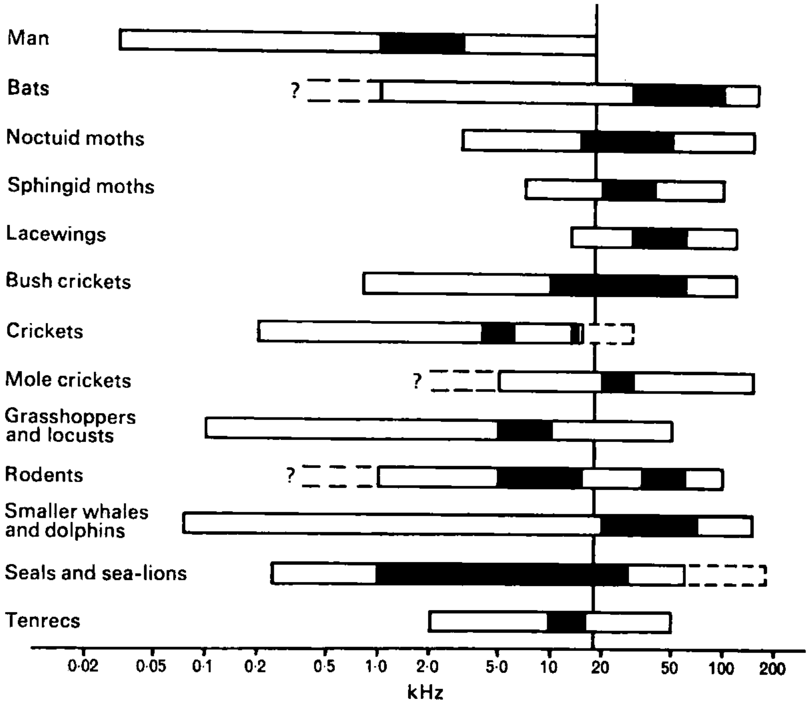

Fig. 1.1. The frequency range of hearing in man and approximate ranges for some groups of animals. The dark regions show the most sensitive frequencies. (From G. Sales and D. Pye, *Ultrasonic Communication by Animals* (Chapman and Hall, London, 1974)).

of the non-scientific and non-medical applications of ultrasound there would be no advantage in using very high frequencies; often the main consideration is simply to be out of the audible range so as to avoid discomfort to the workers, although the variation of the attenuation with frequency may also influence the choice of frequency that is used. In some of the scientific applications, however, it is important to use the highest available frequencies. At the present time any upper limit to ultrasonic frequencies is set by practical considerations rather than by theory. The term *microwave acoustics* is often used to describe the study of mechanical vibrations with frequencies which are so very high that they correspond to frequencies in the microwave range of the electromagnetic spectrum, say $\geqslant 10$ GHz, the vibrations themselves at these high frequencies being referred to as *microsound* or *praetersound* (fig. 1.2).

The early work on the upper limit of audibility of sound was performed using ultrasonic generators in the form of whistles (Galton whistles) which

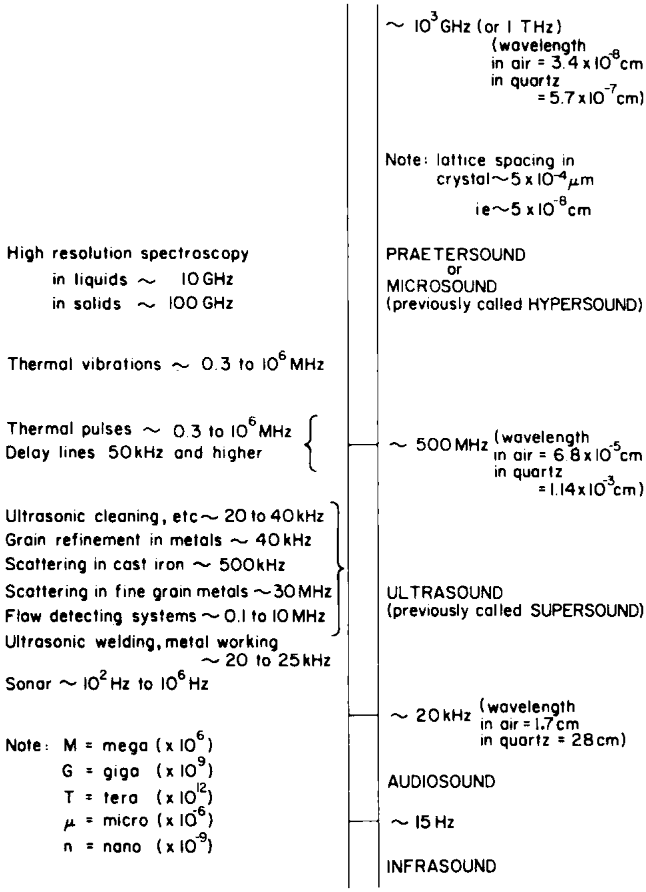

Fig. 1.2. Acoustic frequency scale (From R.W.B. Stephens, *Ultrasonics International 1975 Conference Proceedings*, p. 9, (IPC Science and Technology Press, Guildford, 1975)).

had clearly been developed from organ pipes (see Chapter 4). The detection of ultrasound in the early days was performed using sensitive flames. The development of modern ultrasonic generators and detectors, and the whole modern technology of ultrasonics, has resulted mainly, though not exclusively, from the exploitation of piezoelectricity (see Section 4.2), backed up by modern electronic techniques. Piezoelectricity was discovered by the Curie brothers in 1880. In this phenomenon, some materials when they are under some external mechanical stress develop an internal electric field, with charges of opposite sign appearing on opposite surfaces. In the following year Lippmann predicted the inverse effect, namely the appearance of a mechanical deformation of certain materials in external electric fields. However, it was not until after the 1914–18 War that piezoelectricity and its inverse effect were first successfully applied in the detection and generation of ultrasound (see Section 5.1). The original application was to the detection of enemy submarines.

In this book we shall first be concerned with the physics of the production, propagation, attenuation, and detection of ultrasound (Chapters 2 to 4). After that we shall describe the general principles of the main present-day applications of ultrasonics in biology, medicine, technology and pure research in physical science. The wide range of these applications of ultrasound at the present time will become apparent as one reads through the book.

1.2. *Wave motion*

In this section we shall consider the propagation of waves in a material medium; this discussion will be equally relevant to ultrasound and to audible sound because, at this stage, the value of the frequency will not be restricted. In any event, the minimum frequency that may be classed as ultrasonic is neither fixed very precisely, nor is it a frequency at which any distinct change of wave properties suddenly occurs.

Let us consider a longitudinal progressive wave in which the particles of the medium move backwards and forwards along a *line* which is the same line as that in which the wave is travelling. It is, in effect, a one-dimensional wave. It may be referred to as a compressional wave, and an instantaneous picture of it is as fig. 1.3(*a*) and (*b*). The graph of the instantaneous value of the longitudinal displacement as a function of x is as shown in fig. 1.3(*c*), which should be treated with a little caution, lest it should obscure the fact that the wave is actually longitudinal.* In fig. 1.3(*c*) we have assumed, as is usual in a first approach, that the displacements are sinusoidal. This need not necessarily be the case but, for two reasons, sinusoidal, or simple harmonic, waves are the most important ones in practice. First, ultrasound is usually produced by the conversion of sinusoidal electromagnetic oscillations, of a single frequency, into ultrasonic waves. Secondly, any wave can always be Fourier-analysed into components which are pure sinusoidal waves.

Both fig. 1.3(*b*) and (*c*) represent instantaneous 'snapshots' of the medium taken at one instant of time t. At some later instant the particles

*Transverse ultrasonic waves may, of course, exist in certain circumstances, see Section 2.1.

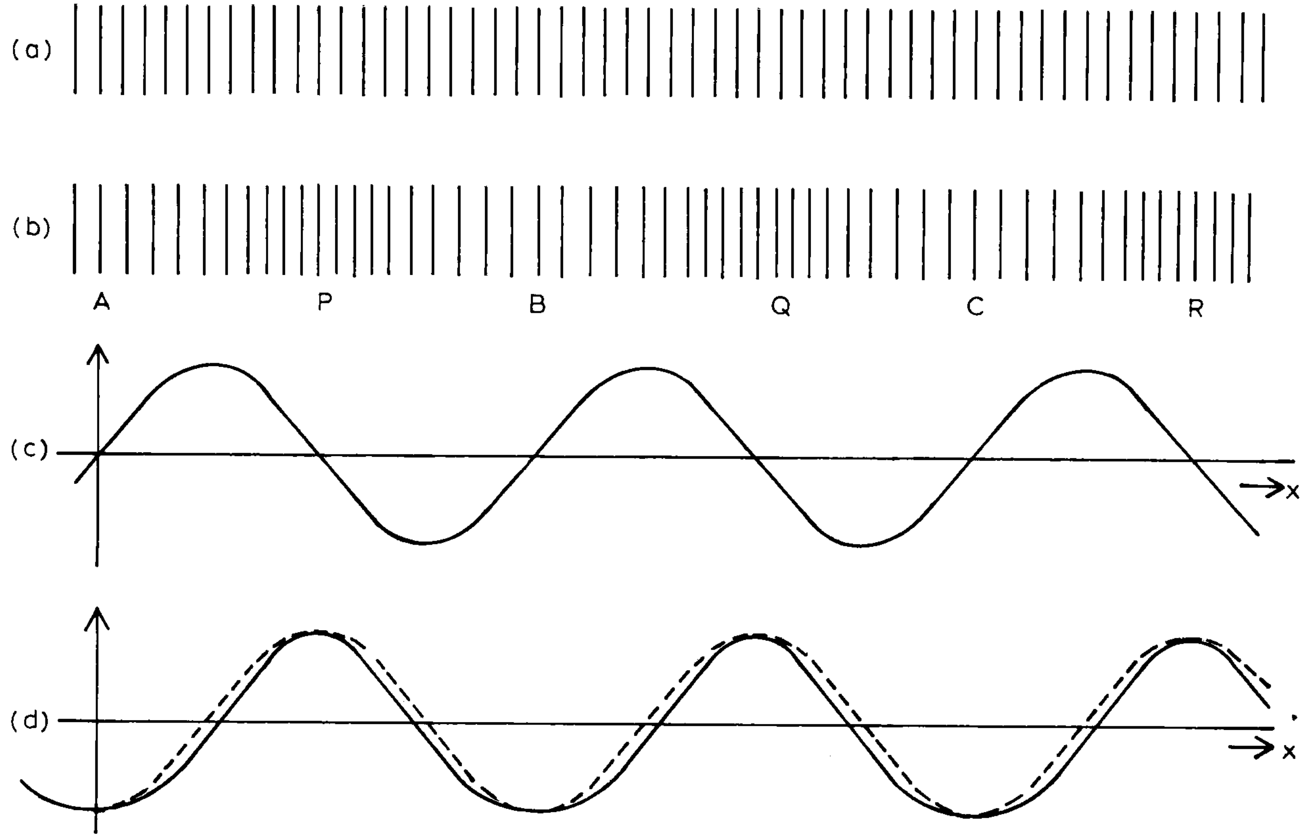

Fig. 1.3. Schematic illustration of longitudinal wave, (*a*) equally spaced planes in the absence of wave, (*b*) displaced positions of same planes at one instant during passage of wave, A, B, C are regions of rarefaction, P, Q, R are regions of compression (*c*) graph of instantaneous displacements, (*d*) graph of excess pressure (continuous curve)–the broken curve represents the excess pressure as a function of equilibrium positions of the particles.

of the medium will have rearranged themselves, while the compressions and rarefactions will have travelled a certain distance from, say, left to right, in the diagram. The individual particles of the medium are oscillating about their equilibrium positions without there being any net movement of the medium as a whole—one does not, for example, experience a wind blowing when listening to an orchestra or a choir!

The pressure in a region of compression is greater than the pressure would be in the medium in the absence of the wave. Thus one could plot a graph of the excess pressure $p(x, t)$, at a fixed time, as a function of x along the path of the wave (see fig. 1.3(*d*)).

The *displacement* of a particle is its distance from its equilibrium position; this is a function both of the equilibrium position x and of the time t and so can be written $u(x, t)$. For a sinusoidal wave as in fig. 1.3(*c*), each particle participating in the wave motion is vibrating with simple harmonic motion about its own equilibrium position. The amplitude a of the wave is the maximum value of the displacement, and the *wavelength* λ is the distance between any two consecutive particles which are vibrating in phase.

The expression for the particle displacement $u(x, t)$, as a function of x and t, can be written

$$u(x, t) = a \sin\left(\frac{2\pi t}{T} - \frac{2\pi x}{\lambda}\right), \tag{1.1}$$

where λ is the wavelength. The time T required for one complete cycle of a particle's motion is called the *period* of the oscillation. This is related to the *frequency* ν of the oscillation by

$$\nu = 1/T. \tag{1.2}$$

The angular frequency ω is defined by

$$\omega = 2\pi\nu. \tag{1.3}$$

Equation (1.1) can be rewritten in a number of ways. In terms of the frequency $\nu(= 1/T)$, instead of the period T, it becomes

$$u(x, t) = a \sin\left(2\pi\nu t - \frac{2\pi x}{\lambda}\right) = a \sin 2\pi\left(\nu t - \frac{x}{\lambda}\right). \tag{1.4}$$

c, the speed of the wave, is related to λ and ν since during a single period of a *particle's* motion the travelling *wave* will advance by one wavelength. Thus

$$c = \lambda/T = \nu\lambda. \tag{1.5}$$

In Table 1.1. we give values of λ, for various frequencies ν, for

Table 1.1. Some examples of ultrasonic wavelengths.

Frequency	Wavelength		
	(for $c = 1000\ \mathrm{m\,s^{-1}}$)	(for $c = 3000\ \mathrm{m\,s^{-1}}$)	(for electromagnetic radiation)
20 kHz = 2×10^4 Hz	5 cm	15 cm	1.5×10^4 m
100 kHz = 10^5 Hz	1 cm	3 cm	3×10^3 m
1 MHz = 10^6 Hz	1 mm	3 mm	300 m
50 MHz = 5×10^7 Hz	20 μm	60 μm	6 m
1 GHz = 10^9 Hz	1 μm	3 μm	30 cm

ultrasonic speeds of $1000\,\text{m s}^{-1}$ and $3000\,\text{m s}^{-1}$, which are typical speeds in a liquid and in a solid (see Table 2.1). For comparison we also give the corresponding wavelengths for electromagnetic radiation of the same frequencies.

1.3. *Energy, momentum and pressure in an ultrasonic wave*

The *intensity* of a wave is the rate at which energy is transferred across a unit area normal to the direction of propagation of the wave, that is the power transferred per unit area. Appropriate units are therefore $\text{J s}^{-1}\text{m}^{-2} = \text{W m}^{-2}$.

Consider one particle, of mass m, of the medium through which such a wave is travelling. The particle's instantaneous velocity is found by differentiating eqn. (1.4)

$$v(x, t) = \frac{\partial u(x, t)}{\partial t} = a2\pi\nu \cos 2\pi\left(\nu t - \frac{x}{\lambda}\right). \tag{1.6}$$

The maximum value of this velocity is therefore

$$v_{\text{max}} = a2\pi\nu = a\omega. \tag{1.7}$$

The energy E of the particle will, in general, be partly potential energy E_p and partly kinetic energy E_k, so

$$E = E_p + E_k. \tag{1.8}$$

Consider the instant when the particle is passing through its equilibrium position. The potential energy is zero and its velocity has its maximum value. The total energy then is therefore equal to the kinetic energy, thus

$$E = \tfrac{1}{2}mv_{\text{max}}^2 = \tfrac{1}{2}ma^2\omega^2. \tag{1.9}$$

If the medium has a density ρ, then a volume V of the medium will have a mass ρV and will contain $\rho V/m$ particles. The total energy contained in a volume V is therefore given by

$$\text{total energy in volume } V = \tfrac{1}{2}ma^2\omega^2 \frac{\rho V}{m} = \tfrac{1}{2}a^2\omega^2\rho V. \tag{1.10}$$

The total energy of all the particles in unit volume is called the *energy density* E and is therefore given by

$$E = \tfrac{1}{2}a^2\omega^2\rho. \tag{1.11}$$

This energy is being transferred by the wave at a speed c. Consider a cuboid of length l and cross-sectional area A, the energy in which is to be transferred across plane X (fig. 1.4). The energy contained in the cuboid,

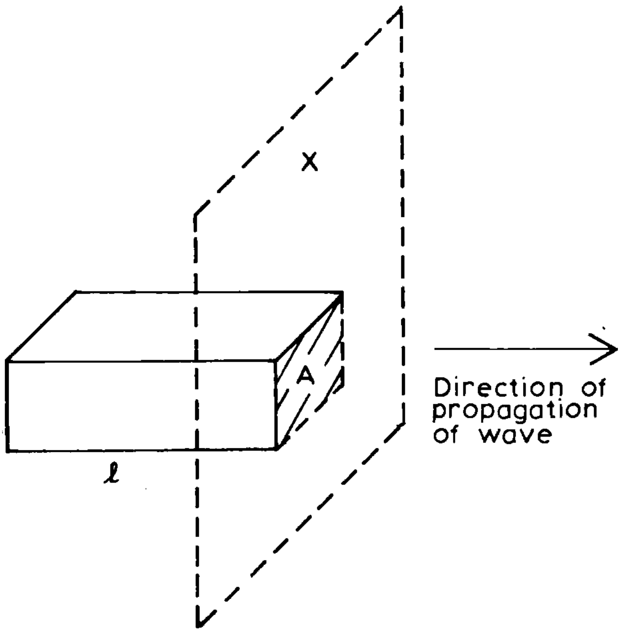

Fig. 1.4.

which is $\frac{1}{2}a^2\omega^2\rho lA$, will cross the plane X in a time given by l/c. Hence the power P transferred is given by

$$P = \frac{\frac{1}{2}a^2\omega^2\rho lAc}{l} = \tfrac{1}{2}a^2\omega^2\rho Ac. \tag{1.12}$$

The power transferred across unit area, that is the intensity I, is therefore given by

$$I = \tfrac{1}{2}a^2\omega^2\rho c. \tag{1.13}$$

Having seen that a travelling ultrasonic wave transports energy, it is natural to expect that it also carries momentum. It is also natural to expect that if such a wave impinges on a surface and is reflected or absorbed by the surface, there will be a pressure exerted on that surface. Such a pressure can, indeed, be detected experimentally. One might call this pressure the *radiation pressure* but, in fact, there are two different definitions of radiation pressure. One, the *Rayleigh radiation pressure*, is taken to be the difference between the time average of the pressure at a point in a fluid through which a beam of sound, or ultrasound, passes and the pressure which would have existed in a fluid of the *same mean density* at rest. The other, the *Langevin radiation pressure*, is defined as the difference between the pressure at a wall and the pressure in the medium, at rest, behind the wall. Much as one would like to treat the transport of momentum and the phenomenon of radiation pressure quantitatively, the theory in both cases is rather too complicated for this book (see Further Reading).

2. The propagation of ultrasound

2.1. *Propagation in an isotropic medium*

Since ultrasound is, essentially, of the same nature as audible sound, the theory of its propagation is similar to that for audible sound. In this section we shall restrict ourselves to isotropic media. For the present purpose, 'isotropic' means that the magnitude of the ultrasonic velocity is the same for all possible directions of propagation in the medium. Isotropic media include gases, liquids, non-crystalline solids and polycrystalline solids. It should be noted that whereas cubic crystals are isotropic in some of their properties they are not isotropic as far as the propagation of sound or ultrasound is concerned. We shall consider the propagation of ultrasound in crystals in Chapter 9.

The three conventional elastic moduli for an isotropic material are the Young modulus E, the bulk modulus K, and the shear modulus G.

The Young modulus is defined in terms of the stretching of long thin wires or rods (fig. 2.1(a)) with

$$\text{stress} = \frac{\text{stretching tension}}{\text{area of cross-section}} = \frac{F}{A} \tag{2.1}$$

and

$$\text{strain} = \frac{\text{increase in length}}{\text{original length}} = \frac{\delta L}{L} \tag{2.2}$$

so that

$$E = \frac{\text{stress}}{\text{strain}} = \frac{F/A}{\delta L/L} = \frac{FL}{A\delta L}. \tag{2.3}$$

The bulk modulus is concerned with the compression of a material under a (uniform) hydrostatic pressure p (fig. 2.1(b)) when

$$\text{stress} = \text{pressure} = p \tag{2.4}$$

and

$$\text{strain} = \frac{\text{increase in volume}}{\text{original volume}} = -\frac{\delta V}{V} \tag{2.5}$$

so that

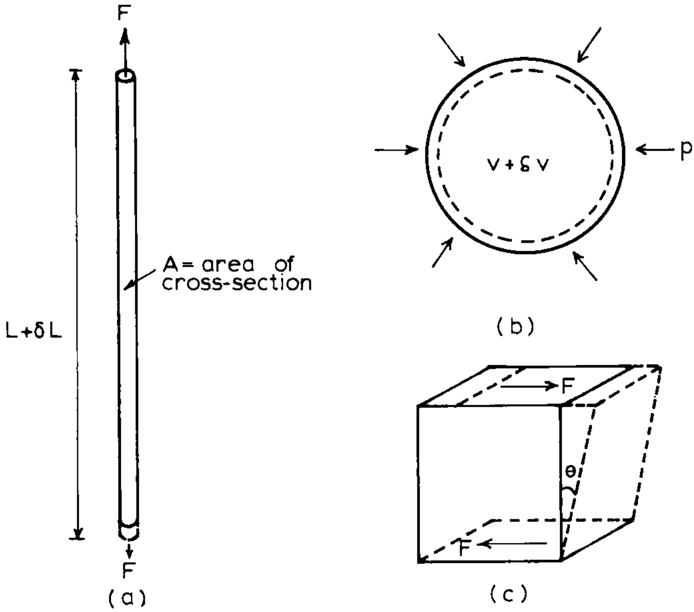

Fig. 2.1. Diagrams to illustrate the definitions of (*a*) the Young modulus, (*b*) the bulk modulus, and (*c*) the shear modulus.

$$K = \frac{\text{stress}}{\text{strain}} = \frac{p}{-\delta V/V} = -\frac{pV}{\delta V}. \tag{2.6}$$

Finally, for the shear modulus (fig. 2.1(*c*))

$$\text{stress} = \frac{\text{shearing force}}{\text{area}} = \frac{F}{A} \tag{2.7}$$

and

$$\text{strain} = \text{angle of shear} = \theta \tag{2.8}$$

so that

$$G = \frac{F/A}{\theta} = \frac{F}{A\theta}. \tag{2.9}$$

We shall assume that a medium is behaving in a linear manner so that moduli of elasticity are constants for any given material; that is, the stress is assumed to be sufficiently small that Hooke's law is obeyed.

For a solid these three moduli of elasticity are usually considered independent although it is possible to obtain relationships among them by introducing Poisson's ratio. Which particular modulus is relevant will depend on the system in which the waves are propagating; both longitudinal (compressional) waves and transverse (shear) waves may occur. The Young modulus applies only to solids. If a *steady* stress is applied to a