A TEXT-BOOK

ON

SOUND

BY

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MACMILLAN AND CO., LIMITED
ST. MARTIN'S STREET, LONDON
1926

PREFACE

In writing the following pages the aim has been to provide students with a text-book on Sound, embracing both its experimental and theoretical aspects.

To make it more widely useful, the mathematical portions are restricted to the elements of the calculus. Thus, when Fourier's Theorem or Differential Equations are introduced, the treatment is simple and the physical bearings of the problem are carefully discussed, so as to meet the needs of those readers having no previous acquaintance with such methods. All higher analysis is entirely excluded. Indeed, much of the work is intelligible to those not familiar with the calculus at all. For, in the parts where it is used, simpler alternative methods are often provided, chiefly for the sake of emphasising certain important physical aspects of the subject.

Experiments suitable either for laboratory exercise or lecture illustration are described in some detail, and distinguished by smaller type and numbered headings.

The various typical musical instruments are discussed more fully than usual, though always from the view-point of the physicist rather than that of the musician.

At the close of the book a number of original examples on the various chapters and sections are given to afford a gauge of the student's progress and grasp of the text. These include enunciations, proofs, numerical and descriptive examples, essay-writing, and actual manipulation in the laboratory. They are for the most part fairly straightforward, it being assumed that Pass or Honours candidates for Degrees or other Diplomas will further test themselves by working special problems from papers previously set at the particular examination they are taking.

Like every other modern work on Sound, the present text-book obviously owes much to the classical treatises of Helmholtz, Lord Rayleigh, and Tyndall. The excellent Continental courses on physics by Müller-Pouillet, Wüllner, and Jamin and Bouty also deserve mention. On special subjects a number of other works have been consulted with advantage, and references given in the text where necessary.

The endeavour has been made to bring the treatment up to date by insertion of the more important recent researches at home and abroad, the respective authorities being in each case quoted.

Thanks are hereby tendered to Messrs. Newton & Co. for permission to reproduce one of Prof. C. V. Boys' photographs of a bullet in flight; to Messrs. Taylor and Francis for a like favour with respect to any illustrations in the *Philosophical Magazine*; and to Prof. J. G. M'Kendrick, F.R.S., who kindly allowed some of the highly-interesting curves obtained from his Phonograph Recorder to appear in these pages.

To Mr. Ambrose Wilkinson, B.Sc., Lecturer in Physics at University College, Nottingham, special thanks are given for his valuable help in reading the proofs; but, as it can scarcely be expected that any single reader, however careful, would succeed in noting every inaccuracy, it is feared that some errors or obscurities still remain. Should such be found by any users of the book, their kindness in forwarding either corrections or suggestions would be heartily appreciated.

UNIVERSITY COLLEGE, NOTTINGHAM,
February 1908.

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CHAPTER I

INTRODUCTORY

1. THE word sound is commonly used in two different senses: (1) to denote the *sensation* perceived by means of the ear when the auditory nerves are excited; and (2) to denote the *external physical disturbance* which, under ordinary conditions, suitably excites the auditory nerves.

This usage will generally be followed here. It rarely leads to any ambiguity, the context generally showing in which of the two senses the word is employed. When necessary, for clearness' sake, the first or subjective sense will be represented by "the sensation of sound," and the second, or objective sense, by "sound waves," or other similar expressions.

It is a matter of common knowledge that the source of sound is always a body in a state of vibration, or rapid to-and-fro motion. This body may be a solid, as the string of a harp; or fluid, as the column of air in a wind instrument.

We may, therefore, define *Acoustics*, or the study of sound, as that branch of physics which deals with vibratory motion as perceived by the sense of hearing. It is usual, however, to include with this a few other closely allied phenomena.

2. Production of Sound.—But in order to produce sound it is not sufficient to have some body in a state of vibration as its source. We need also (1) some medium to receive and transmit this vibratory motion, otherwise neither the sensation of sound nor the external disturbance would be present. (2) It is imperative that the parts of the body in vibratory motion should have such shape, size, and motion as to cause a disturbance to advance through the air, and not such as to produce a local flow and reflow of the air simply. (3) Our ears enable us to perceive the sensation of sound only when affected by to-and-fro movements whose number per second lies between certain limits.

Therefore, to produce sound sensations, it is necessary that our vibrating body should conform to this requirement also. These points are respectively illustrated by the following experiments:—

EXPT. 1. *A Medium Essential.*—To illustrate the necessity of a medium to convey sound from its source to the ear, hang a bell by india-rubber cords within a glass bulb fitted with a tap. Sound the bell in the bulb full of air with the tap open, and then with the tap closed, so as to indicate its loudness in each case. Next, exhaust the bulb as completely as possible by an air-pump. Detach the bulb when exhausted and shake so as to attempt to make the bell sound. No sound, or only an extremely feeble one is heard. While the bell is inaudibly shaking, open the tap so as to admit the air; the sound is very quickly restored. Contrast with this the case of an ordinary electric glow-lamp, whose incandescent filament sends light to us across the space within its bulb although it is practically devoid of air. Light, like sound, needs a medium for its propagation. But the medium essential to the propagation of light is the ether which we are at present unable to remove from any space.

EXPT. 2. *Importance of Sound Board.*—Fit up two steel wires each about 1 mm. diameter—one on a monochord, the other on the bars of two 56 lb. weights. The latter should have the same length between the bars that the former has between the bridges, and they should be tuned to the same pitch. It is desirable that the 56 lb. weights should not rest upon wood. They may both be on a level tiled floor, or slab of stone or slate. Or, the wire might be vertical, the upper weight being on an iron or stone bracket from a wall, and the lower one hanging freely. On plucking or bowing the wire on the 56 lb. weights, only a very feeble sound will be heard. But on plucking or bowing the wire on the monochord the sound is easily heard by an audience of a thousand persons.

It is thus seen that the wire whose ends are on the massive iron weights, although moving to and fro like the other, is yet unable to produce vigorous waves of sound in the air. But the precisely similar wire on the monochord passes over bridges which are moved by its vibrations. And the bridges in turn set the belly or upper board of the sound box in motion. It is true the motions of the bridges and belly are very small, but the shape of the latter forces the air near it to take up a vigorous vibratory motion which can advance to distant parts of a large room. Any mere local flow or reflow of the air, which is almost all that the wire on the weights could produce, is impossible in the case of the monochord sound box. Hence the distinction between the effects produced in the two cases.

EXPT. 3. *Right Frequency needed.*—Take a piece of steel about 1 m. long, 2 cm. wide, and 1 mm. thick. Clamp it firmly in a vice, allowing at first, say, 80 cm. to project. Pull this projecting end aside and let it go. It is seen to execute vibrations, but no sound is heard. Decrease the length of the projecting part, and again test the vibrations for audibility. Repeat the shortening and the test until the vibrations are audible as well as visible. This simple experiment shows that very slow vibrations are inadequate to produce an audible effect, although absolutely similar ones executed a greater number of times per second produce a distinct sound. We shall see later that vibrations executed too quickly fall beyond the limits of audition.

3. Noises and Musical Sounds.—All sounds may be divided roughly into two classes, noises and musical sounds. Noises are characterised by irregularity or suddenness, musical sounds by their comparatively smooth and even flow. But the line of demarcation between them cannot be sharply drawn. Throughout the irregularity of some noises may be perceived, now more and now less plainly, a persistent musical sound. On the other hand, very few musical sounds are entirely free from accompanying noises which disturb to some slight extent their regularity and smoothness. These differences can be illustrated better than defined. The following experiments afford typical examples :—

EXPT. 4. *Extreme Cases.*—(1) Drop from a height of 6 ft. a 2 lb. ball of iron upon a tin plate a foot square resting upon sawdust in a box on the floor. (2) Take a tuning-fork mounted upon its resonance box, and excite it gently with a carefully rosined bow. The first sound is unquestionably a noise, and the second just as surely a musical sound.

EXPT. 5. *Intermediate Cases.*—Pour water from a jug into a water bottle or tall jar until the bottle or jar is full. The sound produced by the falling water seems at first to be merely a confused noise. But, after a few seconds, it will be noticed that throughout the noise a sustained musical sound is also present. Moreover, the musical sound rises as the jar becomes nearer full, and this continuous rise makes it easier to detect. Bars of steel, bells, and gongs, when struck with another hard body, furnish examples of sounds in which noises and musical elements are both clearly present. The harder the hammer with which they are struck, the harsher and less musical will the sound usually be.

Since sounding bodies are in a state of vibration, and musical sounds are characterised by their regularity and smoothness, it seems natural to infer that they are produced by *regular* or periodic vibrations. We shall afterwards see distinct proof that this is the case. Noises, on the other hand, are produced by *irregular* or non-periodic vibrations. We shall, henceforth, be concerned almost solely with musical sounds, noises being practically dismissed with this brief notice.

4. Propagation of Sound.—Let us now examine the general nature of the process by which sound advances from its source to the ear or other recipient. The medium of this advance is usually the air, and this will serve our present purpose, as the essentials with which we are now concerned are the same whatever the medium. The features in question may be illustrated as follows:—

EXPT. 6. *Air Waves.*—Arrange a pipe AB, about 6 feet long and 4 inches diameter, with a glass funnel F and a lighted candle C in a line with it at one end. At the end remote from the funnel introduce into the pipe two watch-glasses, one containing strong hydrochloric acid and the other ammonium hydrate, so as to produce dense white fumes. Or, instead of producing fumes in this way, the smoke from smouldering brown paper will serve. Near the end containing the fumes or smoke make a sharp report by clapping together smartly two blocks of wood or two books. When everything is rightly adjusted the candle

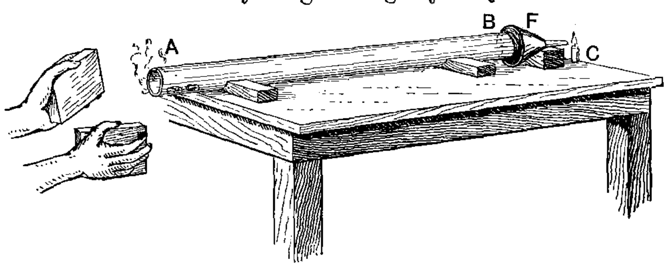

FIG. 1.—AIR WAVES.

flame is seen to duck at each clap. But, although abundant fumes may be evolved within the tube at the end next the source of sound, no trace of fume is seen to issue at the end next the candle.

Hence we conclude that when sound passes from one point to another it is not the medium of its propagation which advances. On the contrary, the parts of this medium make only quite small excursions to and fro. And it is this state of minute to-and-fro motion that advances. Thus the medium as a whole, after the disturbance has passed, is practically where it was to begin with. Illustrations of this advance of a state of motion through a medium which does not itself appreciably advance may easily be multiplied. The following will repay consideration:—

EXPT. 7. *Water Waves.*—Obtain a trough about 6 feet long, 8 inches wide, and 6 inches deep. Let this be placed level and about half-filled with water. Next float upon the water about six pieces of cork, each about 7 inches square and a quarter of an inch thick, and each carrying a straw mast and a paper flag. Agitate the water at one end by alternately depressing and raising a block of wood. The disturbed state of the water thus produced at one end is shown by the floats to advance to the other, the flags, one by one, nodding as the waves pass them. On carefully watching this phenomenon it will be observed that the corks move not only up and down, but also exhibit a little movement lengthwise of the trough. But if the agitation is slight they do not leave their place

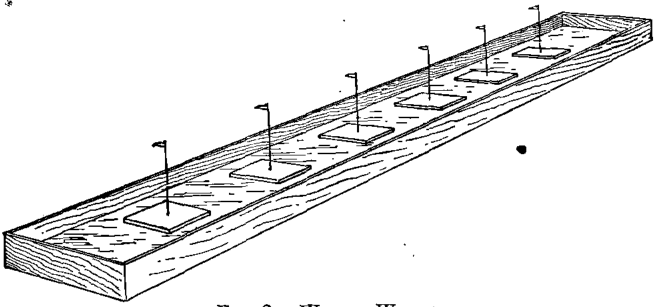

FIG. 2.—WATER WAVES.

entirely to advance with the wave. The motion of the water at any point is really round and round in a closed loop in a vertical plane.

EXPT. 8. *Rope Waves.*—Obtain a solid india-rubber cord, about half an inch in diameter, and about 20 or 30 feet long. Fix one end on a hook or staple in a wall, and take the other end in the hand. On shaking sidewise the end held in the hand a series of corresponding displacements will be seen to pass along the cord to the farther end. Here the motion of the separate parts of the cord is clearly not one of advance, but only a to-and-fro motion sideways or *transversely.* But this state of motion advances, each part of the rope executing in turn the motion that a neighbouring part executed a little before.

EXPT. 9. *Spring Waves.*—The apparatus shown in Fig. 3 affords a valuable illustration of the phenomena now under discussion, and although more elaborate than those