THE MASTER HANDBOOK OF ACOUSTICS

BY F. ALTON EVEREST

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TAB TAB BOOKS Inc.
BLUE RIDGE SUMMIT, PA. 17214

FIRST EDITION

FIRST PRINTING

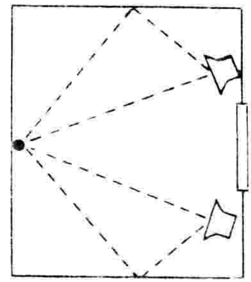
Printed in the United States of America

Library of Congress Cataloging in Publication Data

Everest, F. Alton (Frederick Alton), 1909-
The master handbook of acoustics.

Includes index.
1. Sound. 2. Electronics. I. Title.
QC225.15.E93 693.8'34 81-9212
ISBN 0-8306-0008-6 AACR2
ISBN 0-8306-1296-3 (pbk.)

Contents



Dedication

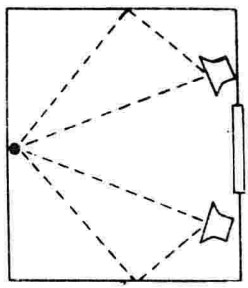
To Elva

Foreword

Directly or indirectly, all questions connected with this subject must come for decision to the ear, as the organ of hearing; and from it there can be no appeal. But we are not therefore to infer that all acoustical investigations are conducted with the unassisted ear. When once we have discovered the physical phenomena which constitute the foundation of sound, our explorations are in great measure transferred to another field lying within the dominion of the principles of Mechanics. Important laws are in this way arrived at, to which the sensations of the ear cannot but conform.

Lord Rayleigh in
The Theory of Sound
First Edition 1877
(Also in first American
edition, 1945.)
(courtesy of Dover
Publications Inc.).

Introduction



It is a hard fact of life that the intangibility of the acoustics link in the audio chain tends to obscure its vital importance. Hands on experience with microphones, amplifiers and loudspeakers lends a feeling of familiarity and comfort almost entirely lacking in our attitude toward the acoustical environment in which the microphone and loudspeaker function. There seems to be a great gulf in our understanding between the experience of listening to the music of Beethoven, Berlioz or the Bee Gees and fluctuating molecular densities in the air, and even less to the tickling of hair cells in the organ of Corti of the inner ear.

Yet acoustics, the science of sound, has two natures, physical and psychophysical. Sound as a disturbance in air is physical, sound as perceived by the ear is psychophysical. The old conundrum, "If a tree falls in the forest with no ear to hear it, is sound produced?", precisely distinguishes between sound as a stimulus and sound as a sensation. The study of sound as a physical stimulus alone is commonly viewed as a rather sterile subject of only academic interest. As a sensation, however, sound impinges on human experience and becomes of intense interest to us.

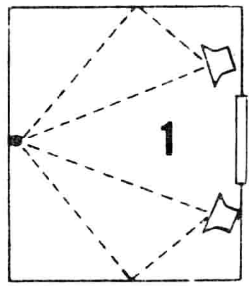
This book treats both the physical and psychophysical aspects of sound because the two are so inextricably interrelated. Whether the end product is a recording, a radio or television program or a live performance, the human ear-brain mechanism is intimately involved. In the electronic media, room acoustics is involved twice, once in the pickup and recording in the studio and again in reproduction in the home or classroom. Human ears listen and evaluate at both ends of the process.

By considering the dual aspect of sound, this book consistently considers the response of the human ear to various acoustical effects. Thus echoes affect intelligibility, room resonances affect quality of perceived sound and the combination of two or more acoustical signals can distort the sound heard, and so on. Some chapters treat sound phenomena as physical effects, but as a background for other chapters concentrating on one of the most amazing mechanisms in all nature, the human ear and the acoustic cortex of the human brain.

Of the many ways sound may be put to use, this book concentrates on sound as a medium of communication. The sound might be canned on film, tape or laser disk in analog or digital form, or it might be live. The information to be communicated may be for entertainment, instruction or just carrying on the multifaceted business of daily living. Whether professionals or amateurs are involved, whatever the medium or the purpose, the very word communication implies a junction or a joining, a sender and receiver, one or more persons at each end. If we recognize this personal aspect of the process and the existence of possible perceptual gaps and gulfs, we are in a better position to achieve true and accurate communication.

I am deeply in debt to the scores of authors of technical and scientific papers referred to throughout this book. Surely, it is a great privilege to stand on such stalwart shoulders as the field of acoustics is reviewed. I am grateful to Martin Gallay of Gallay Communications, Inc., for permission to use material first appearing in Recording Engineer/Producer Magazine, principally in Chapters 5, 7, 10, and 12. As for the accuracy of the text, I assume full responsibility. My confidence in doing so, however, is strengthened considerably because of the checking of several key chapters by Robert S. Gales and Robert W. Young, former associates in underwater sound research who are now acoustical consultants in San Diego.

First, Some Fundamentals of Sound



It may be considered ironic to go back to 1866 for our introduction to some fundamentals of sound, but why not if by so doing we can avoid some of the ho-hum mathematics and hackneyed, opaque statements associated with most introductions to the science of sound? In 1866 a German by the name of Kundt published a paper describing an interesting experiment which has become firmly embedded in Physics 100 type courses around the world. Kundt's tube is nothing more than a glass or plastic tube with a source of sound at one end and a plug at the other as shown in Fig. 1-1. A dust-like powder is placed inside the tube. In the olden days lycopodium powder was found both suitable and readily available, but refined talc or finely ground cork will also perform satisfactorily.

The whole point of Kundt's tube (K-tube) is to make visible the effects of air-molecule movements which are invisible to the unaided eye. Sound requires an elastic medium for its propagation and air is elastic. If air molecules are moved out of position by an outside force, they tend to spring back to their original position if the force is removed. A vibrating diaphragm in the sound source compresses the adjacent air molecules when it moves outward and thins them out when it is retracted. If the diaphragm is vibrated continuously, this molecular compression and thinning out (rarefaction) is passed on to adjoining molecules. Although each molecule vibrates back and forth always close to home, it impacts others nearby and the energy transmitted via molecular collision constitutes the propagation of sound.

Figure 1-1 shows the piles of dust powder in the K-tube when the sound source is energized by an amplifier driven by a sine wave from an oscillator. By varying the oscillator frequency we note that the dust powder collects in orderly piles at certain frequencies. The powder concentrates where the molecular movement is minimum in the tube. With a little experimentation we discover that holding the oscillator frequency constant, the same effect can be achieved by varying the position of the plunger-plug. By cutting a couple of corners we conclude that the sound wave propagated down the tube and the wave reflected from the plug combine to form a standing wave, a sort of resonance, when the powder piles are highest and most agitated at the fringes.

When oscillator frequency or plunger position is changed for maximum effect on the powder, we sense that the sound in the K-tube and the distance between vibrating diaphragm and plug have arrived at some sort of important relationship. This relationship can be explained by reference to Fig. 1-1 again. The piles of powder occur at points of zero or minimum sound pressure (nodes), points A, C, E, etc. Between A and C zeros there is a peak (anti-node) of positive pressure at B where air molecules are compressed and crowded together (compression). A corresponding negative peak occurs at D where air molecules are thinned out (rarefaction). These dynamic positive and negative sound pressures fluctuate about the "zero" pressure which turns out to be, not a zero but the prevailing atmospheric pressure. Let one thing be clear, however: the fluctuations are highly exaggerated in Fig. 1-1. The pressure scale has a squiggle in it to indicate it has been shortened. In true scale, the sound pressure fluctuations on this sketch of, say, one unit are to be compared to something like a million units of atmospheric pressure. Even though minute, the sound pressure fluctuations of even weak sounds are readily detected by the ear and measured by meters.

Sound itself is a very objective fact of life familiar to all. The part which the air medium plays in propagating sound, however, is very abstract because it involves invisible air molecules. Smoke particles, which can be seen with the aid of a low-power, darkfield microscope, are small enough to act much like air particles as we look into the propagation of sound. By injecting some smoke into our K-tube we can see how air molecules act as they are set in vibration by passing sound waves. The illuminated smoke particles, normally appearing as tiny white dots, appear as lines under the influence of sound as seen in Fig. 1-2. The length of each white

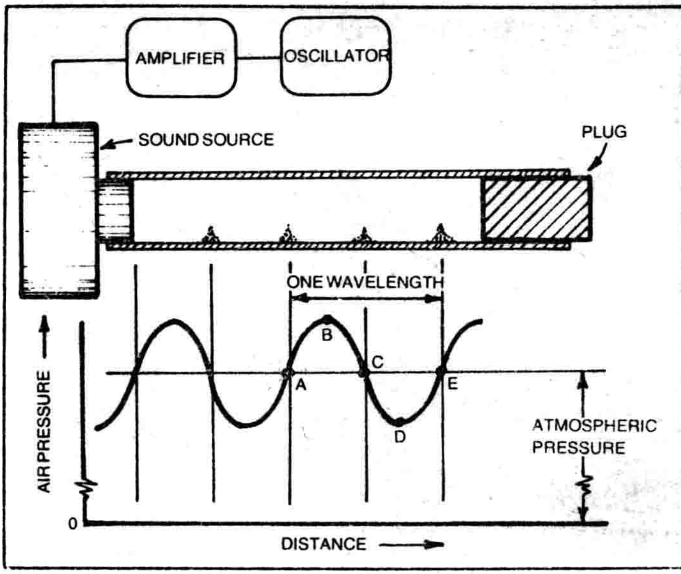


Fig. 1-1. In the Kundt's tube the wave traveling to the right from the source and the wave reflected from the end plug come into coincidence at certain frequencies. This results in a standing wave which has nodes of zero pressure and anti-nodes of high pressure. Bits of cork in the tube collect at the nodes where air particle motion is a minimum. By measuring the distance between nodes and knowing the frequency of the sound, the velocity of sound may be determined.

line is the peak-to-peak amplitude of vibration of that particular smoke particle. For a very loud sound this would be only about 4 thousandths of an inch (0.1 mm).

Energy is required to arrange the powder particles in the K-tube of Fig. 1-1 into neat piles. The reality of sound energy is dramatically illustrated in the ancient experiment shown in Figs. 1-3 A&B. At the focal point of the parabolic reflector is an ultrasonic whistle, called a Galton whistle after its inventor, blown by compressed air and capable of producing intense sound. Although out of the range of the human ear, any dogs around would be greatly agitated at such an uncomfortably loud sound. From the parabolic reflector come plane waves which are reflected from the glass surface establishing a standing wave condition. Using narrow tweezers to avoid disturbing the sound field, thin slices of cork may be inserted at nodal points, resulting in the stack of cork chips shown which have no visible means of support. The force of the sound wave is supporting the cork chips through the violent up and down dance of the air molecules.

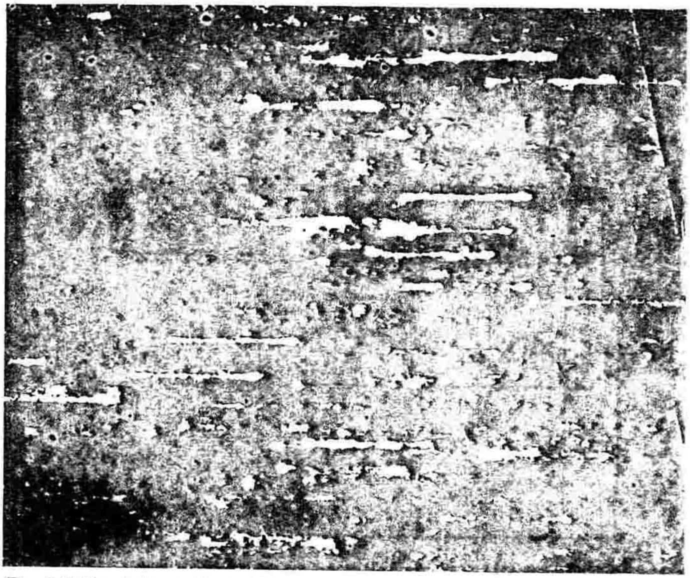


Fig. 1-2. Smoke particles in a Kundt's tube viewed with a microscope appear as white spots with the sound turned off and as white lines with the sound turned on as they follow the same motion as the air particles when sound is propagated (from Alexander Wood's *Acoustics*, Reference 1).

FREQUENCY

In Fig. 1-1 the diaphragm of the sound source is driven back and forth by the amplifier. Each round trip of the diaphragm, from neutral position to maximum deflection in one direction, back to neutral and on to a maximum position in the opposite direction and back to neutral, constitutes one cycle of diaphragm travel and one cycle of sound is produced (A to E). The number of these cycles in one second is called the frequency of the sound. In honor of an early experimenter with electromagnetic radiation, one cycle per second is called one hertz (symbol, Hz). One thousand cycles per second is called one kilohertz (kHz), and so on. Today we have electronic frequency counters which are capable of toting up every positive loop in a given length of time (commonly 1 or 0.1 second) and register the total on a readout display.

WAVELENGTH

The wavelength of a sound is the distance a sound wave travels in one cycle, or 1 Hz. This is indicated in Fig. 1-1 as the distance between alternate zero (or neutral point) crossings, such as A and E. It is the same distance between adjacent positive peaks or adjacent negative peaks or the distance between any two corresponding points of a given cycle. It is quite evident in studying Fig. 1-1 that frequency and wavelength are related. This relationship also involves the speed of sound:

$$\lambda = \frac{c}{f} \tag{1-1}$$

where, λ = wavelength of sound in feet (or meters),
c = speed of sound, feet per second (or meters per second) and
f = frequency, hertz or cycles per second.

The K-tube of Fig. 1-1 now becomes a research instrument. How fast does sound travel? is the question to be answered. The K-tube is fired up and the distance between alternate piles of powder is scaled off (e.g., A to E) and found to be about 2¼ inches. Without an electronic frequency meter an estimate of the frequency is read off the oscillator dial as about 6,000 Hz. From the above equation the speed of sound is found to be (6,000) (2.25/12) = 1125 feet per second. Such precision shouldn't happen in such a crude device! The accepted value of speed of sound at air temperature 68°F (20°C) is actually 1127 feet per second.

It is interesting that for audible sounds within the range of our ears the wavelengths also fall within a familiar range. Taking the speed of sound as 1127 ft. per sec., wavelengths of typical audible frequencies are as follows:

Frequency	**Wavelength**	
	inches	**centimeters**
20 Hz	676.2	1,717.5
1 kHz	13.5	34.4
8 kHz	1.7	4.3
20 kHz	0.68	1.7

Later we shall see how the fact that bass sounds having wavelengths comparable to room dimensions create some very special problems.

THE SIMPLE SINUSOID

The sound source diaphragm moving in and out produces sound pressure fluctuations of the shape shown in Fig. 1-1. This is called a sine wave. The sine form is directly related to what is called simple harmonic motion. A weight vibrating on a spring displays such motion. The piston in an automobile engine is connected to the crankshaft by a connecting rod. The crankshaft going around and around and the piston up and down beautifully illuminate the inherent relationship between rotary motion and linear simple harmonic motion. The piston position (neglecting connecting rod angle) plotted against time produces a sine wave. It is a very basic type of mechanical motion and it yields an equally basic waveshape in sound and electronics.

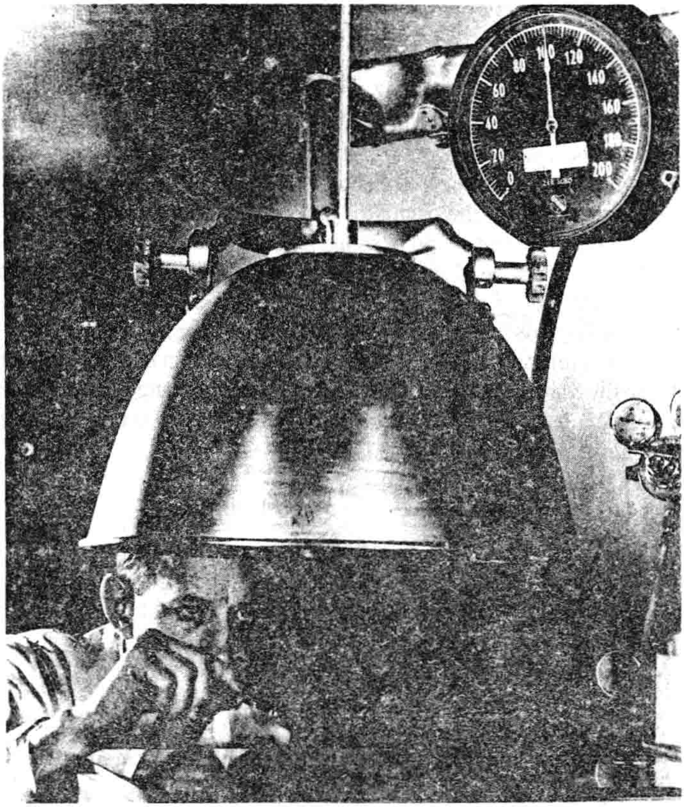


Fig. 1-3A. The Galton whistle blown by compressed air demonstrates the force of sound waves as slices of cork are levitated. A standing wave system is set up between the parabolic reflector with the ultrasonic whistle at the focal point and the plate glass surface (courtesy of Moody Institute of Science).

Fig. 1-3B. Close-up view of Fig. 1-3A (courtesy of Moody Institute of Science).

COMPLEX WAVES

Speech and music waveshapes depart radically from the simple sine form. A very interesting fact, however, is that no matter how complex the wave, if it is periodic, it can be reduced to sine components. The obverse of this is that any complex wave can, theoretically at least, be synthesized from sine waves of different frequencies, different amplitudes, and different time relationships (phase). A friend of Napolean named Fourier initiated thinking in this surprising direction. This can be viewed as either a simplification or complication of the situation; certainly it is a great simplification in regard to concept, but sometimes complex in application to specific speech or musical sounds. As we are interested primarily in basic concept, let us see how even a very complex wave can be reduced to simple sinusoidal components.

HARMONICS

A simple sine wave of a given amplitude and frequency f_1 is shown in Fig. 1-4A. In Fig. 1-4B is another sine wave of half the amplitude and twice the frequency (f_2). Combining A and B the waveshape of Fig. 1-4C is obtained. In Fig. 1-4D another sine wave of half the amplitude of A and three times its frequency (f_3) is shown. Adding this to the $f_1 + f_2$ wave of C, Fig. 1-4E is obtained. The simple sine wave of Fig. 1-4A has been progressively distorted as other sine waves have been added to it. Whether these are acoustic waves or electronic signals the process can be reversed. The distorted wave of Fig. 1-4E can be disassembled, as it were, to the simple f_1, f_2, and f_3 sine components by either acoustical or electronic filters. For example, passing the wave of Fig. 1-4E through a filter passing only f_1 and rejecting f_2 and f_3, the original f_1 sine wave emerges in pristine condition.

Applying names, the sine wave of lowest frequency (f_1) of Fig. 1-4A is called the ***fundamental***, the one of twice the frequency (f_2) of Fig. 1-4B is called the ***second harmonic*** and the one of three times the frequency (f_3) of Fig. 1-4D is the ***third harmonic***. The fourth harmonic, the fifth harmonic, etc., are, of course, four and five times the frequency of the fundamental, and so on. Curiously, even though the waveshape is dramatically changed by shifting time relationships, tne ear is relatively insensitive to such time changes although quite sensitive to harmonic amplitude content.

PHASE

All three components, f_1, f_2, and f_3, start from zero together. This is called an in-phase condition. In some cases the time relationships between harmonics or between harmonics and the fundamental are quite different than this. Remember how one revolution of the crankshaft of the automobile engine (360°) was equated with one cycle of simple harmonic motion of the piston? The up and down position of the piston spread out in time traces a sine wave such as that in Fig. 1-5. One complete sine wave cycle represents 360° of rotation. If another sine wave of identical frequency is delayed 90°, its time relationship to the first one is a quarter wave late. A half wave delay would be 180°, etc. For the 360° delay the wave at the bottom of Fig. 1-5 falls in step with the top one, reaching positive peaks and negative peaks simultaneously, the in-phase condition.