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ABSTRACT

Effective ways to teach the science of acoustics to non-engineering students are presented and discussed. Topics include the physics of sound, sound wave phenomena, and noise control. (MLH)

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INTEREST AND MOTIVATION LEAD GOOD TEACHING

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INTEREST AND MOTIVATION LEAD GOOD TEACHING

A course in acoustics for engineers might satisfactorily start with a derivation of the wave equation and develop solutions for the various types of environments encountered in archetectural acoustics and noise control. The mathematical background of the engineer could permit him to visualize the various phenomena such as radiation, divergence, attenuation, reflection, and absorption of sound waves and give him satisfaction in the accuracy with which these phenomena can be described.

For the non-engineer, such a development would probably fail. Generally he would not have the mathematical background that would permit it, and the mathematical descriptions, accurate though they might be, would be relatively useless and probably could not convey to him a working picture of sound in action.

The non-engineer will never be required to design acoustical structures nor to perform noise control modifications of machinery or buildings; therefore, he doesn't need the laborious discipline required for such design activity.

Why then teach acoustics to the non-engineer? The answer is that everyone is influenced by acoustics from his first cry until the last breath he takes. Only the deaf are isolated from it and they long to share the experience.

Engineer and non-engineer alike must live and take part in that world filled with sound. His ears and his attitudes will react to these sounds. Sometimes this reaction may be beneficial, as with speech communication, fine music, audible alarm signals, etc. Sometimes the reaction will simply be annoyance; office noise distracts his attention, transmission of sound through walls reduces his privacy; and community noise may intrude and interfear with relaxation and sleep. Sometimes the reaction will be detrimental, as with factory noise, gun blasts, drag racing, etc. that may gradually (or suddenly) take away his hearing.

The non-engineering student, looking ahead to his future occupation and home life, will be interested in knowing what can be done to improve his environment. He would be interested in knowing qualitatively what effects and immediate remedies might be obtained without engineering analyses on his part, and in knowing how much that might cost him in terms of inconvenience and dollars.

The purpose of an acoustics course for the non-engineer then is to make clear the personal importance of acoustics and good hearing, to arouse his interest in his own and civic environmental betterment and safety, and to provide the information he needs to evaluate the balance of acoustical benefits and costs.

In order to convey this information in a lasting way that can be applied to new situations as they may arise long after the course is over, the fundamental operation of sound generators, of sound waves themselves, and of sound control devices must be made clear. This doesn't require a lot of mathematics. I would begin early in the course playing a number of recordings ranging from the weakest signals of interest, like the flight of a hungry mosquito to the loudest signals that could be reproduced effectively, including jet aircraft, riveting machines, forging hammers, drag races, rock music, etc. Many sounds could not be reproduced at full level, but they will still have a staggering impact and that will be heightened by knowing the real, live noise is twice or four times or ten times as loud. This beginning will give the class a common audible experience on which to draw.

From such an introduction even the non-engineering student might ask, "Why doesn't someone do something about noise?" Although doing something in an engineering way may be farthest from his mind, he will have caught the urgency of the matter and will be receptive to course material that will prepare him to influence not only his own environment, but that of the cummunity and the workplace.

Physics of Sound

The physics of sound can be taught as an interesting experience with lasting vitality by relying heavily on simple diagrams and analogies that relate the essential properties of acoustics to physical processes with which he is familiar.

At the outset it is important to convey the idea that every surface that vibrates, even air itself as it issues from a jet, compresses and rarifies the air next to it and sends out sound that travels away at somewhat over 1000 ft. per second. These waves may radiate in all directions, though as indicated schematically in Fig. 1, they may emerge in some directions more readily than in others and may eventually fall upon a listener's ear and produce the sensation of sound.

The various forms of sound illustrated by the recordings mentioned before, should include tones like the low frequency hum of a transformer and the high pitched screech of a jet aircraft compressor and may include the pure tone of an oscillator swept from the lowest audible frequency near 16 Hz to the upper frequency limit which, for various people with good hearing, will vary from 16 to 20 kilo Hz or a little higher. The sounds should also include broad band noise like that of a water fall or jet of air which contain a mixture of all frequencies. At this point a demonstration of the analysis of such a broadband noise with an octave band filter or narrower band filters to demonstrate the relative importance of sounds in various frequency bands and demonstrate that all bands of noise really are present to some degree in broadband noise. Here it would be instructive to demonstrate the sound of a change in level of 1, 5 and 10dB in level at a single frequency and to compare loudness of various frequencies at the same level as read on a sound level meter.

Some care should be used to be sure that the reproducing system is not severely limiting the sounds produced. This is an excellent point to make a sound level meter available to the students and have them participate making analyses of various noises and report the results.

Here it will be found that the sound produced by the speaker system is not uniform throughout the room. All students will not hear the same sounds unless they are permitted to move around and experience the variation. This may be their first exposure to room acoustics and the problems of sound reproduction and reinforcement common to all classrooms, auditoria, concert halls, and the like that will be studied as the course progresses.

The information from the analysis of some sounds may be plotted on a graph such as illustrated in Fig. 2 which shows some typical active band ~~spectra and~~ some familiar tonal noises superimposed. By hearing and seeing these spectra, a strong sensitivity for the quality of typical sounds is developed most rapidly.

At this point attention might be turned toward the ear and the hearing mechanism that has been serving the student almost without thought. It is a truly remarkable instrument having a physical appearance somewhat like that shown in cross section in Fig. 3.

The instructor here can elaborate on the remarkable structure of the ear and point out that the numerous sensory nerves located along the basilar membrane in the cochlea are excited by tones of various pitch and send signals to the brain. The brain determines the pitch by the location of the excited nerves and the loudness by the number of nerve impulses received per second. After exposure to loud sounds some nerves become depleted of energy; they respond less to incoming sound signals and the listener finds himself unable to hear as well as before. This decrease in sensitivity, or raising of the hearing threshold, is temporary for short and infrequent exposures, but after long exposure periods repeated daily over many years some nerves die and the listener experiences a permanent hearing loss that can never be regained.

To convey the remarkable dynamic range of the ear, and to emphasize the stress that intense sounds impose, a graph like Fig. 4 is helpful. It shows the hearing threshold for octave bands of noise for a typical healthy ear and shows also the upper limit of sound level above which the ear should not be exposed even for short periods of time. Note that the ear can receive sound pressures over a range of more than a million to one.

This is a good point to justify the use of decibel level notation as a means of avoiding large and cumbersome numbers. It is also a good point to introduce reference values for sound pressure level and intensity level and show how they relate.

The tremendous dynamic range of the ear can be visualized by imagining the ear as being analogous to a postage weighing scales that has a lowest sensitivity of one ounce. By defining one ounce as the reference value for the scales the weighing level in dB will start at zero for one ounce. The ear, being exposed to factory noise having a sound pressure level of 90dB would be as much above its limit of sensitivity as the postage scale weighing a one ton weight would be above its limit of sensitivity. Similarly riveting noise of 120dB at the ear would be equivalent to weighing a 30-ton tractor on the postage scales. The ear can be used to receive signals in this range for short periods satisfactorily and can after a short rest regain its original sensitivity. It is of little wonder, however, that factory noises do over-load and eventually reduce the ears sensitivity and cause permanent damage.

It is furthermore instructive to indicate that an exposure of the ear to an impulse from a shotgun or a forging hammer reaching as high as 150dB peak is in our analogy equivalent to weighing of a 100 ton jet airliner. Exposure to the impulse of 180dB which is near the level that will just not rupture a normal ear drum would be analogous to weighing of a 3,000 ton destroyer on the postage scale. This is the impulse that accompanied the discharge of some of the original air bag protective devices that were considered for reducing the risk of personal injury in a severe automobile collision.

From Fig. 4 it is clear that the ear is not equally sensitive to all frequences, being most sensitive in the mid frequency region near 3000 Hz. The "A" weighting network is a filter in the sound level meter that depresses the importance of the low frequencies and the very high frequencies in an approximation of the way the ear responds at low sound levels. The Fletcher-Munsen curves of equal loudness may be introduced here to show how the relative sensitivity of the ear changes and becomes flatter as the sound level is increased. This change can be demonstrated by listening to a full range recording played at increasing levels and observing the relative increase of base components.

In view of these changes it is suprising to find that the A-weighting network serves as a good representation of the way the ear has been found to be susceptable to hearing damage in the region of sound levels between 90dBA and 115dBA and has been adopted as the standard measure for evaluating industrial noise exposure.

Sound Wave Phenomena

Sound waves are invisible; they can be tracked and observed only be expensive instrumentation or arduous and painstaking measurements. The presence of sound can be shown easily by electronic means, but meters show only gross structure of sound and oscilloscopes generally show wave traces that represent variations in sound pressure at a point as a function of time. It is very difficult indeed to show the complexity of a whole sound field even in its simplest form.

But since sound is a wave phenomenon and there is similarity between waves of various kinds, much information can be gained from observing water waves. Drop a pebble into the smooth surface of a pond at daybreak and behold the way magnificant circles slowly expand, spread out and vanish. It's a breathtaking experience the first time you see it.

Although the actions of water waves are not quantitatively the same as those for sound waves in air, their similarities are many and their observation gives an intrinsic appreciation for the action of sound waves that can be provided in no other easily explorable way. Though water waves, like sound waves, carry energy and lose very little of it as they travel, we readily observe that circular waves decrease in amplitude as they expand, a beautiful demonstration of the important concept of divergence. The instructor then has the opportunity of relating divergence in the two dimensional water wave with that in a three dimensional sound wave. For some symmetrical sources, the water wave field represents a cross section through a sound wave field and an image of the latter can be imagined as a rotation of the water wave field about the chosen axis of symmetry.

Reaching into the experience of the student one can find familiar and interesting water wave fields. For example consider a log on a canoe being bobbed vertically up and down; nearly straight waves radiate from the sides and circular waves from each end as illustrated in Fig. 5a.

The waves from the sides proceed away with little loss in amplitude because they have little divergence whereas the circular waves at the ends diverge and decrease rapidly as did the waves from a pebble. After some distance, determined by the length and straightness of the log or canoe, even the side waves feed energy toward the end waves and begin to diverge also.

The instructor can use these experiences to develop the analogous sound fields from a line source (changing in diameter) or a plate source (changing in thickness) depending on the axis of symmetry chosen for rotation of the water wave field. Let the student try to determine the divergence for various parts of the sound fields developed.

If one should rock a canoe sideways instead of bobbing it up and down, the waves produced from the sides would be similar to those just considered, but the left and right sides would be out of phase 180°; one wave up at the same distance as the opposite wave is down. As seen in Fig. 5b the waves would not meet at the ends because they just cancel and no energy radiates in that direction. This radiation pattern is that of a dipole. It offers an excellent opportunity to extend the concept of a dipole and apply it to sound source and discuss the concept of phase.

A rotation of this wave pattern about an axis parallel to the canoe does not yield a real sound field pattern because there is not symmetry about that axis. The student might then be asked to consider what kind of sound field might be generated by a rotation about an axis at right angles.

I have deliberately discussed water waves in length here because they so effectively illustrate radiation from the most important types of sound sources. Much more can be done. Though a lake is not readily available as a laboratory tool, a ripple tank can be procured or assembled at a moderate cost and these same wave fields and many more reproduced in a small scale to illustrate sound propagation in rooms, in ducts, through noise control devices, yes and even the effect of wind and temperature gradients and air turbulence on acoustic signaling outdoors. Some typical sound fields that can be set up and studied by the student are illustrated in Fig. 6 and a photograph from one such set up is illustrated in Fig. 7.

Caution must be used as with all analogies, since water waves differ from sound waves in several respects. With imagination, these differences can be used to advantage.

Noise Control

A course in acoustics would be incomplete without discussion of noise control. Again it is not expected that the student would practice noise control except in an amateur way, perhaps in reducing noise in his own home, but he should gain a vivid picture of the important aspects of noise control so that he would recognize its need and value in his everyday world. He should know the value of buying quiet equipment, separating noisy and quiet operations, and the effective ways to control noise to his best advantage.

The analogy of Fig. 8 illustrates the interrelation of the fundamental aspects of noise control. A source of noise, both sound and vibration, is represented by a river racing down a mountain side.

In this analogy, noise control is like stopping or reducing the flow of the river. Many sources of noise cannot be prevented from generating noise and still perform their function any more than a river can be stopped and still drain the mountainside. But as it is possible to build a dam which will separate the river from the point in question, it is possible to construct an enclosure to isolate a sound source, or to use flexible vibration mounts to isolate a vibrating machine. In either instance the flow of noise can be interrupted. However, since isolation does not destroy noise nor stop its production, noise will almost instantly collect between the source and the isolator just as water over a long time collects behind a dam unless some auxilliary means of dissipation is provided. For water the dissipation may be evaporation or soaking into the ground or a diversion channel. For sound the dissipation may be naturally existing absorption but usually additional absorptive materials must be added, as for example, on the inside walls of the enclosure so that the sound will be converted into heat after a few reflections without any serious increase in level inside the enclosure.

For vibration, the dissipative medium is structural damping added in the form of damping tape or more complicated structures that yield as they deform, thereby converting vibrational energy into heat.

With this analogy it is hardly necessary to say that if there is a hole in the dam, water will go through and defeat the purpose regardless of how high the dam may be built. Similarly also even one solid member bridging across a flexible vibration isolator will destroy its isolation almost completely.

Simple as it is, this analogy represents the heart of all noise control. Once understood, it is then clear why sound can leak from one room to another through a connecting duct or through a concealed opening behind perimeter heating units or through the porous acoustical tile ceiling and over a partition where there are not suitable barriers in the space above the ceiling. It is clear also why a vibrating compressor mounted on soft springs still vibrates the building when left with solid connections through piping or rigid electrical attachments.

To demonstrate audibly the importance of vibration isolation, one needs only to listen to a tuning fork vibrating with quite visible amplitudes at the ends of its tines. Very little sound is generated because the tines are small compared with a wave length of sound at the frequency of vibration so they create little oscillating pressure. The air slips easily around the tines as they vibrate.

Then place the stem of the tuning fork in contact with a large sounding board like a table and the radiated sound will increase greatly. Even though the amplitude of the stem is much smaller than that of the tines, when it drives a large radiating surface, that surface can effectively exert pressure against the air and that pressure will radiate away as sound. This and many other demonstrations like it with various sources of vibration can be presented to the student to show in an unforgettable way the essentials of vibration isolation as fundamental part of noise control.

The noise control concepts taught by these analogies can be illustrated by simple schematic diagrams such as shown in Fig. 9. The most direct noise control measure is to reduce the amplitude of vibration of the noise radiator. Often its amplitude is determined by its function and can't be lowered. Sometimes, the effective radiating area can be reduced by a simple redesign or effectively reduced by piercing the radiator with holes that are closer together than half a wavelength of the troublesome sound. Finally, if a prime source of vibration is itself small, then noise reduction can be achieved by separating the source from large radiating surfaces.

Some devices do not submit to these kinds of noise reduction at the source, but may permit the use of a barrier, a partial enclosure or a full enclosure to reduce the noise at the operator's position as indicated in Fig. 10. Here the wave field is indicated schematically. Of course the sounds from a noisy machine do not have simple wave fronts as depicted here since a machine may have many noise sources and numerous radiating surfaces. But waves in the middle of the audible range near 1000 kz have a wavelength of about 1 ft. and might look significantly like those shown. In appearance they look much like the water waves encountered at the beginning of our discussion and to be sure one may set up models like these in a ripple tank and show the relative amounts of wave shielding provided by scale models of structures like these over a range of frequencies scaled to the models.

The effects of both acoustic and vibration isolation and the effects of sound absorption and vibration damping can be shown also by simple ripple tank modeling.

Laboratory Experiments

Though the interaction of the source, the transmission path, and the receiver can be shown with great visibility by modeling and illustrated by analogies, laboratory experiments should not be neglected.

It is a great experience for the student to map out sound levels around a source and see that the levels vary widely close to a machine as the microphone approaches various individual sources. Measured in a free field, the sound level will drop off with distance and it is interesting to identify a certain rate of divergence with the size or shape of source. In a reverberant room there may be little observable divergence before entering the reverberant field as shown in Fig. 11.

I have purposefully not detailed these experiments because they must be tailored to the equipment and facilities available. However, the lack of an anechoic chamber should be no hinderence to making free field measurements. The outdoors serves well for such experiments on calm summer days and can be even more anechoic in the winter over ground covered with a foot or so of soft snow.

A hardwalled office without furniture, books, draperies or rug makes a respectable reverberation room for a wide variety of experiments related to building acoustics as well as factory spaces and can be used for measuring quantitatively the total amount of sound radiated by a sound source and the amount of noise reduction obtained with various machine modifications that theory and model studies might have suggested.

Summary

Acoustics is an interesting subject in its own right. With a generous augmentation from recordings, analogies and, laboratory experiements, it can be an exciting experience. Since it affects each of us intimately every day, it holds significance for everyone, but its teaching should take on

a particularly student-centered flare for the non-engineer. Its importance in the home, at work, and in the political arena makes it an essential part of the overall awareness everyone needs in our modern society.

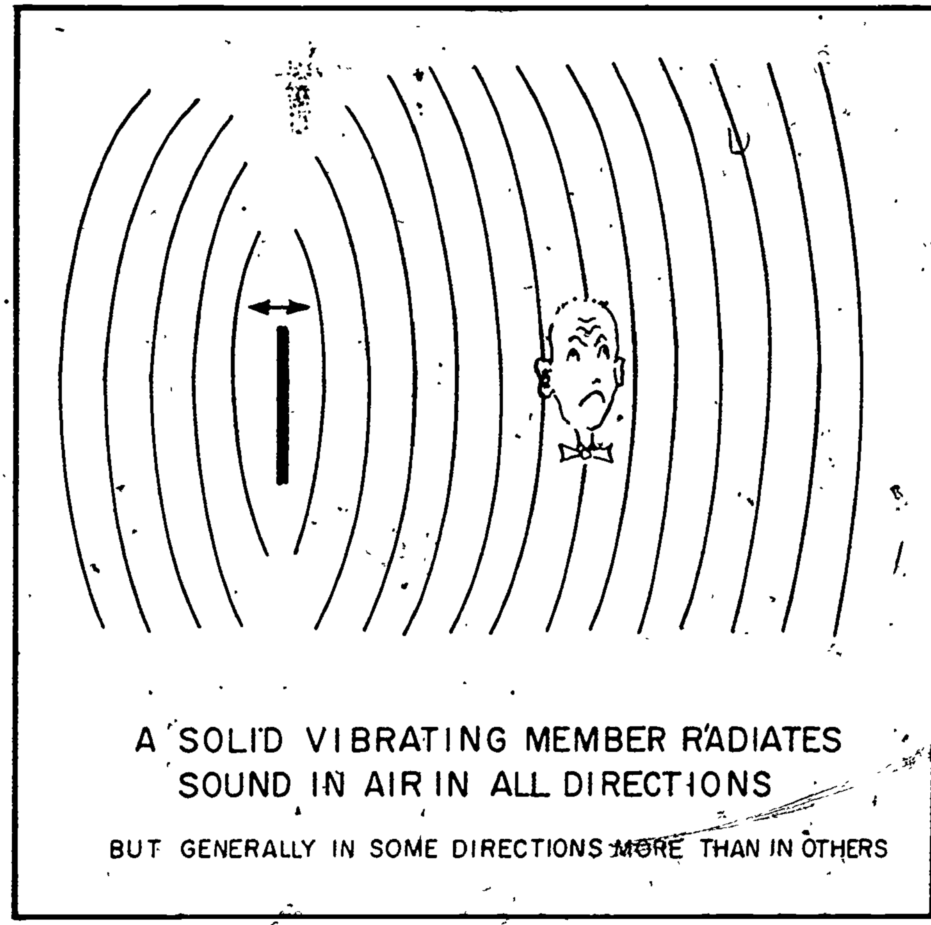
A SOLID VIBRATING MEMBER RADIATES
SOUND IN AIR IN ALL DIRECTIONS
BUT GENERALLY IN SOME DIRECTIONS MORE THAN IN OTHERS

Fig. 1

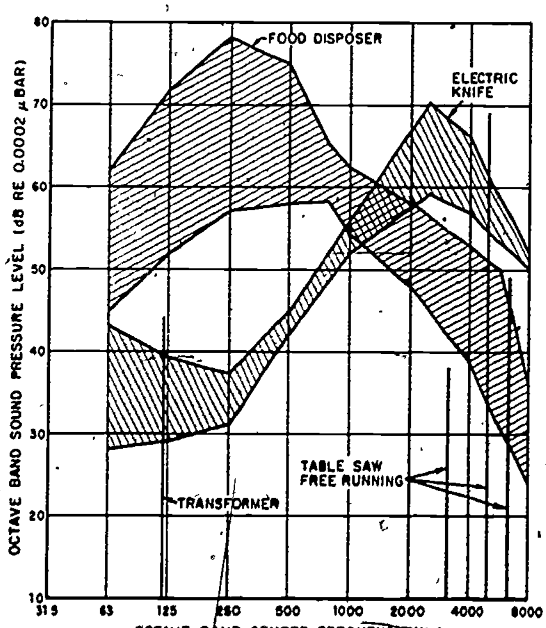
FOOD DISPOSER
ELECTRIC
KNIFE
TABLE SAW
FREE RUNNING
TRANSFORMER
OCTAVE BAND SOUND PRESSURE LEVEL (dB RE 0.0002 μBAR)
80
70
60
50
40
30
20
10
31.5
63
125
250
500
1000
2000
4000
8000
OCTAVE BAND CENTER FREQUENCY (Hz)

Fig. 2

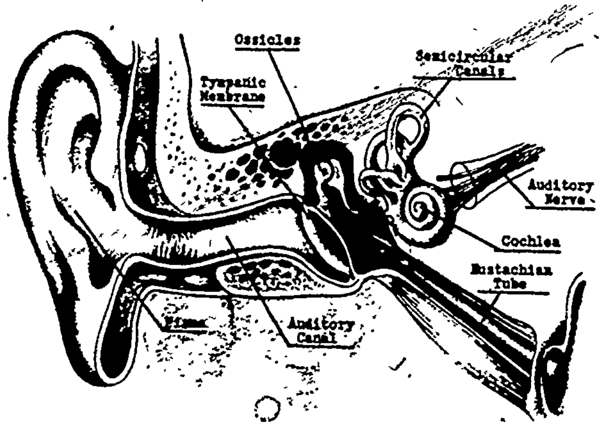

Fig. 3

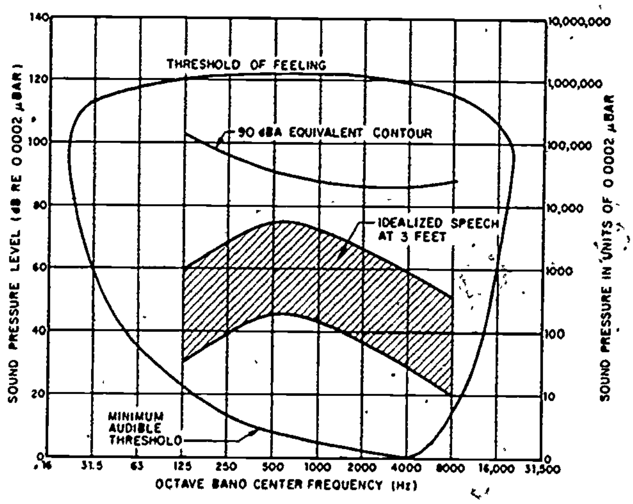

Fig. 4

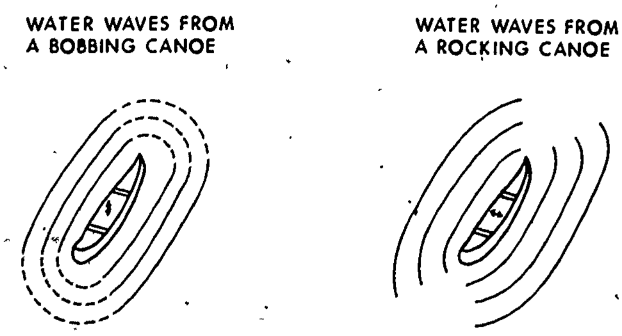

Fig. 5

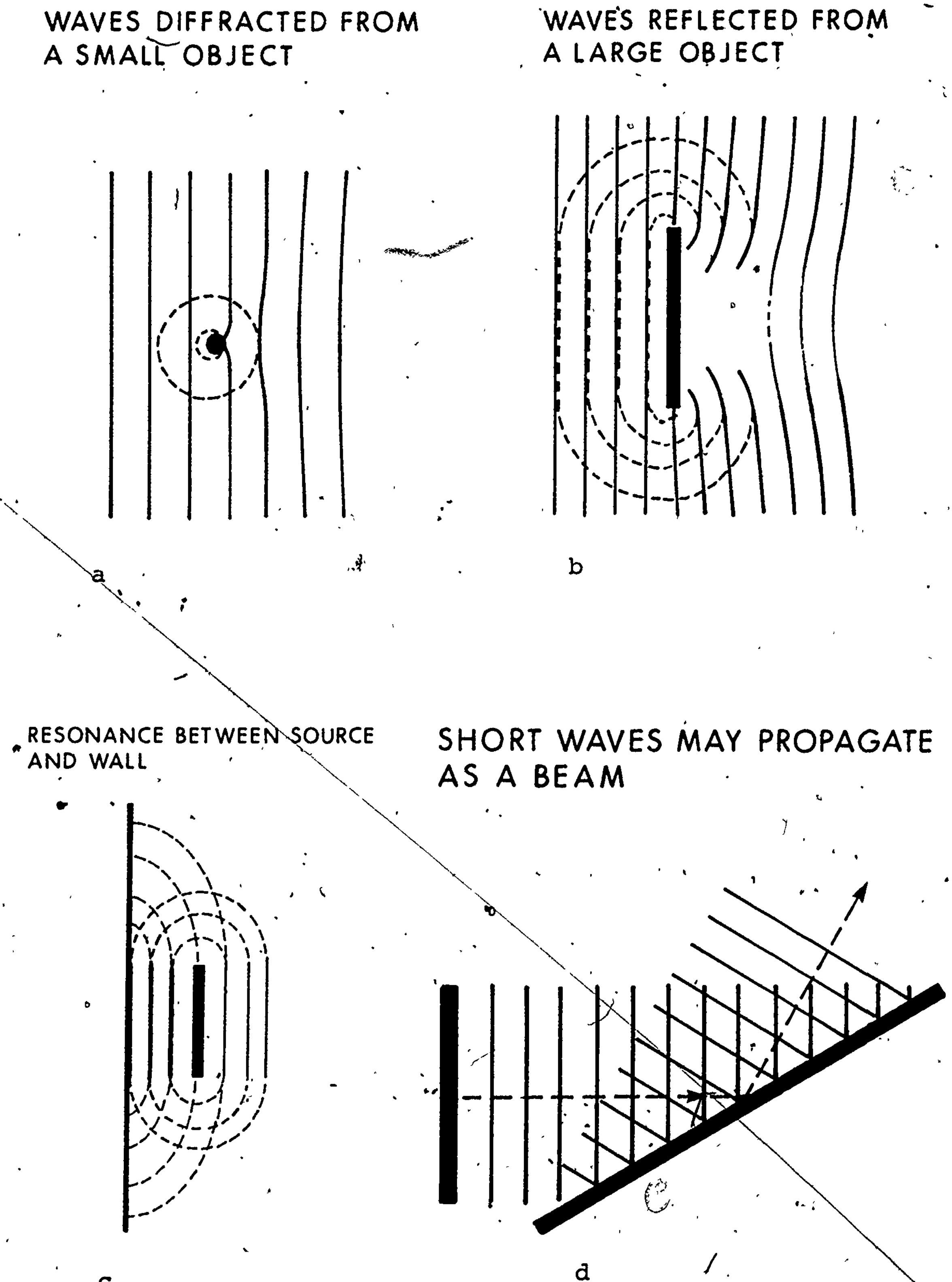
WAVES DIFFRACTED FROM A SMALL OBJECT
a
WAVES REFLECTED FROM A LARGE OBJECT
b
RESONANCE BETWEEN SOURCE AND WALL
c
SHORT WAVES MAY PROPAGATE AS A BEAM
d

Fig. 6

Fig. 7 Reflection from a rigid cylinder in a Ripple Tank.

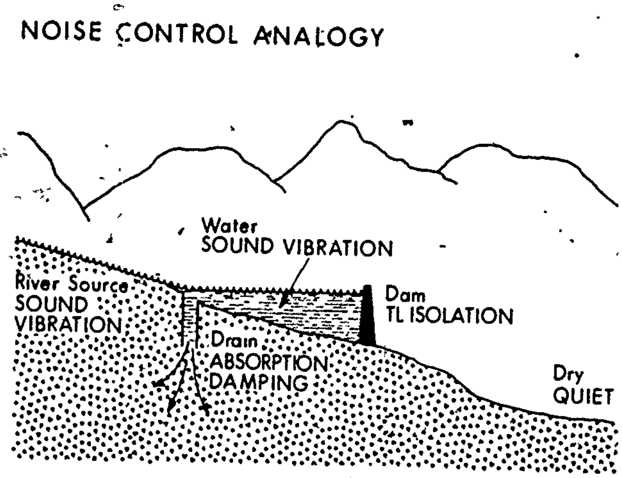

Fig. 8

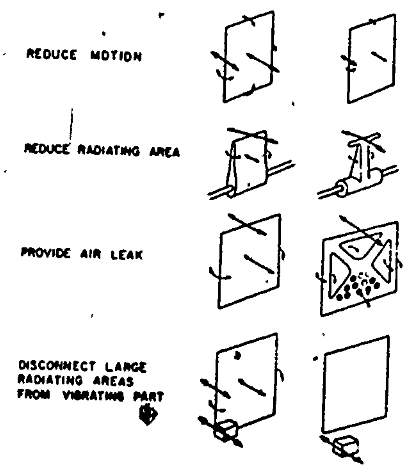

Fig. 9

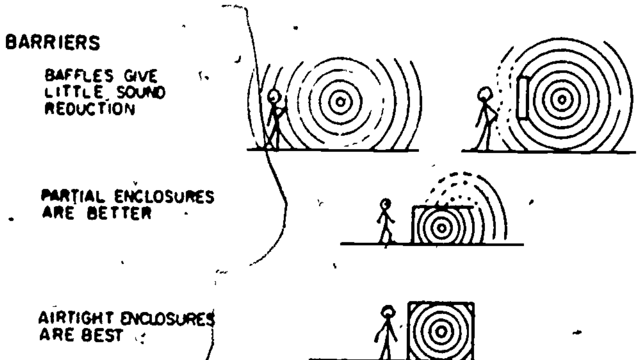

Fig. 10

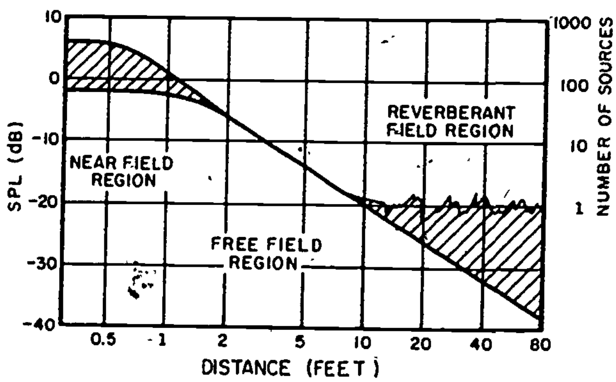

Fig. 11