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# A PHOTOGRAPHIC STUDY OF SOUND PULSES BETWEEN CURVED WALLS AND SOUND AMPLIFICATION BY HORNS.

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SYNOPSIS.

*Photographic Study of Sound Pulses Passing between Walls Corresponding to Sections along a Straight Tube, a Crooked Tube, a Megaphone and a Conical Horn Receiver.*—Using the photographic method previously developed by the author, four pairs of brass plates, each of the proper section, were arranged radially about the axis of the sound-producing spark so as to provide the four passages to be studied. As the sound pulse progressed through these passages, instantaneous photographs registered its position at various stages. Six of these are reproduced. They clearly show that whenever a pulse moves at an angle to a wall there is reflection in exact accord with Huygen's construction. Sound pulses, therefore, do not glide around bends in tubes without appreciable reflection. In the case of a pulse emerging from the open end of a tube or horn, the per cent. of the energy reflected is small, while much of the energy of a pulse entering the large end of a conical horn is reflected back out of the end it entered.

*Sound amplification produced by four horn receivers* of different flares and with ratios of end areas varying from 7.8 to 256 was roughly measured outdoors and also in a special room with sound-absorbing walls, using both a Rayleigh disk and a Webster phonometer. The amplifying factors found were from three to twenty times less than would be expected from the simple condenser theory, which is clearly untenable. It is concluded that the amplification is a result of both resonance and condensation.

## PREVAILING THEORIES.

That the sound energy falling upon the ear or other form of sound receiver may be considerably increased by placing the receiver at the small end of a conical horn is a matter of common observation. The correct explanation of the amplifying action of the horn is quite another matter. In the opinion of the writer the complete explanation has not yet been given. Certain it is that the horn is not merely a condenser, nor is it merely a resonator. The former idea is the most common and the farthest from the truth. Doubtless many of us have thought of a conical horn as a sound condenser through which sound passes like liquid or shot through a funnel. Most textbooks that say anything at all about horns give substantially such an "explanation."

Quoting from one of the older books: "The reinforcing action of the ear trumpet has been attributed to the successive reflections of the sound waves, which multiplies their action on reaching the tympanum. But, as in the speaking trumpet, experiment has shown that the influence of the walls, and consequently the reflection of their inner surface, is very feeble, if any at all. The effect produced is in reality owing to the progressive diminution of the sections of the air surface which transmit the sound and which then transmit it with increasing energy towards the organ. This effect may be compared with that of a jet of water which issues from the orifice of a hose with much greater force than a body of water of equal diameter in the interior of the pump barrel." [1]

Quoting from one of the latest textbooks: "The ordinary speaking tubes connecting distant rooms in buildings depend not on regular reflection, but on the fact that the air particles next the inner surface of the tube vibrate most easily parallel with the surface; this causes the direction of vibration to be deflected by gradual bends in the tube, and consequently the wave runs along the tube without reflection. In ear trumpets, by the constraint of the smooth walls of the tube, the wave entering the wide end is gradually diminished in area till it emerges at the small end carrying all the energy that entered at the large end. Thus if the large end is 100 times that of the small end, *the energy per cubic centimeter* in the emergent wave is 100 times as great as in the wave which entered the trumpet, neglecting loss by friction, etc." [2] The redeeming word in this explanation is "etc."

Over against the notion that the horn is a condenser we have the statement that it is a resonator. "The effect of the horn is to reinforce the the vibrations which enter it due to the resonance properties of the air inclosed by the horn. . . . The horn is an air resonator . . . the response below the fundamental of the horn is very feeble." [3]

Quoting from the classic treatise of Lord Rayleigh: [4] "The case of progressive waves moving in a tube of variable section is also interesting. In its general form the problem would be one of great difficulty; but where the change of section is very gradual, so that no considerable alteration occurs within a great many wave lengths, the principle of energy will guide us to an approximate solution. It is not difficult to see that

[1] Guillemin, Application of Physical Forces, p. 114.

[2] A. L. Kimball, College Physics, Revised Edition, pp. 196–197.

[3] Dayton C. Miller, The Science of Musical Sounds, pp. 156 and 159.

[4] Lord Rayleigh, The Theory of Sound, Vol. II., p. 63.

in the case supposed there will be no sensible reflection of the wave at any part of its course, and that the energy of the motion must remain unchanged . . . from which it follows that as the waves advance the amplitude of vibration varies inversely as the square root of the section of the tube. In all other respects the type of vibration remains absolutely unchanged. From these results we may get a general idea of the action of an ear trumpet. It appears that according to the ordinary approximate equations there is no limit to the concentration of sound producible in a tube of gradually diminishing section."

In the light of the theory of reciprocity[1] it is difficult to harmonize the above statement with one by the same author a few pages later when speaking of the action of a trumpet. "From the theory of diffraction it appears that the sound will not fall off to any great extent in a lateral direction, unless the diameter of the large end exceed half a wave length. The ordinary explanation of the effect of a common ear trumpet, depending on a supposed concentration of the *rays* in an axial direction, is thus untenable."[2]

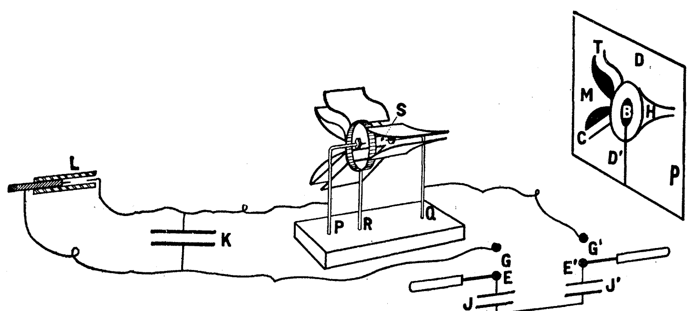



FIG. 1.

In view of such conflicting opinions, the writer decided to subject the question to experiment; by photographing sound waves passing through channels and by measuring the increase in intensity of a sound at a point when a conical horn is used as a "condenser."

## Photographic Method.

Figure 1 is intended to show only the general principles of the photographic method used. Details of the light gap, "camera" box, spark control, etc., may be found in some of the writer's earlier papers.[3]

[1] Ibid., Vol. I., p. 150.
[2] Ibid., Vol. II., p. 102.
[3] A New Method of Photographing Sound Waves, Phys. Rev., XXXV., Nov., 1912, p. 373.

$J$ and $J'$ are capacities, each of from one to five Leyden jars, averaging 525 cm. each, connected to the electrodes $E$ and $E'$ of an electric induction machine capable of producing sparks twenty to thirty centimeters long. The spark gaps $G$, $G'$, $S$ and $L$ are in series. When the capacity $J$, $J'$ is discharged through the gaps $G$, $G'$, sparks pass at both $S$ and $L$. The spark at $S$ takes place between platinum terminals at the ends of the brass rods $P$ and $Q$ and produces a sound wave. By properly adjusting the length of the light spark $L$ (1 to 3 cm.) and the capacity $K$ (six to twenty Leyden jars), the light spark can be retarded until the sound wave produced by the sound spark at $S$ has had time to travel a short distance radially outward from the axis of the sound spark. Then when the light spark occurs, it casts a shadow of the sound wave on the photographic dry plate $P$.[1] $B$ is the shadow of hard rubber buttons placed on the rods at each end of the sound spark gap to minimize the fogging of the dry plate by the light from the sound spark.

In order to study the passage of sound waves between walls and plates, several plates were cut from sheet brass, and shaped and disposed about the sound spark as shown in the figure. The plates were supported by soldering them at one corner to a narrow brass ring, the ring being placed beyond the end of the spark gap so as to interfere but little with the wave produced by the sound spark. The rod $R$, supporting the ring, and the rods $P$ and $Q$ were placed in line with the light gap so that they cast but one shadow on the dry plate.

The writer was not very successful in photographing sound waves through transparent tubes and horns. The curvature of the walls of the tubes so interfered with the passage of the light through them that the waves could be photographed only at points along the axes of the tubes. The writer concluded, therefore, to curve some plates and so place them with respect to one another and to the sound spark axis that a vertical section at right angles to the spark axis would correspond to a longitudinal section of a tube or a horn. The shadow of plates so disposed, shown in Fig. 1, is the projection of such a section. Thus $C$ represents a longitudinal section of a straight cylindrical tube, $T$ a crooked tube, $M$ a megaphone, and $H$ a flared conical horn. For convenience they will be designated, respectively, straight tube, crooked tube, megaphone and horn. The spaces between the megaphone and the tubes on each side were closed to bring out more clearly their outlines. In the directions $D$ and $D'$ the wave was free to travel without interference from reflecting surfaces.

Except in so far as sound intensity affects sound velocity, it would appear that the shadow of a cylindrical sound pulse passing between plates

[1] Proc. Ind. Acad. Sci., 1915, p. 305.

curved and disposed as shown in the figure should represent a longitudinal section of a spherical pulse through tubes to whose longitudinal section the plate shadows correspond. Further, that the wave form in cylindrical tubes and horns for spherical pulses of the same radii as the cylindrical pulses would be obtained in the case of all but the crooked tube by rotating each system about its longitudinal axis.

It might be urged that we are dealing here with a sound pulse and not a sound wave. The writer[2] has shown that the velocity of such a pulse, except for points very near the spark axis, is the same as the velocity of a train of sound waves. Indeed, the pulse is more than a condensation only. In a study not yet published the writer has found that an electric spark produces both a condensation and a rarefaction and that the disturbed air shell near a spark is one wave length thick. But more to the point is the fact that the wave pictures show that the waves are exactly where we should expect them to be by Huygen's construction.

Figures 2 to 7, inclusive, show successive stages of an expanding spark wave, the average time interval between each of the six wave positions being about 0.00003 sec. Figure 3 is a double exposure, with a time interval of only 0.000006 sec. As would be expected, all six pictures show that the waves passed through the straight tube and megaphone without appreciable reflection, and that the megaphone wave suffered the greater attenuation. But on examining the waves through the crooked tube and through the horn we find convincing evidence that what has occurred is not just what some of us have been thinking would happen in such cases.

All the pictures show that there was energy reflection in every case except when the wave front was at right angles to the surface and the motion of the air parallel to the surface of the tube. In the case of the horn there was continuous reflection from one end to the other, even at the small end where the angle of the cone is very small. In the case of the crooked tube there were successive reflections. For the crooked tube, Fig. 6 and Fig. 7 show respectively an emerging and emerged wave much more attenuated than in the case of the straight tube of the same size. A considerable portion of the wave energy appears to be trapped inside the tube. However, it will be observed that the reflected waves in general were headed toward the outer end of the tube. This is not true, however, of the horn. Here the advancing wave shows unmistakable evidence of intensity increase or condensation, and that it emerged from the small end of the horn considerably amplified. But most of the energy was lost so far as the small end of the horn is concerned. The

[2] Proc. Ind. Acad. Sci., 1915, p. 299; 1918, p. 221. Phys. Rev., N.S., XVI., Nov., 1920, p. 449.

lost energy was contained in the reflected waves which, as the photographs show, headed the wrong way—"backing out" of the horn.

## INTENSITY MEASUREMENTS.

Some sound intensity measurements substantiated what the photographs clearly suggest, that the condensing power of a horn is not the quotient of the areas of the two ends, that it is not even of the same order of magnitude in the case of horns of considerable angle.

The source of sound was an organ pipe blown by air from a tank in which a constant pressure was maintained by an electrically driven compressor. Intensity measurements were made with both the Rayleigh Disk[1] and the Webster Phonometer.[2] The intensity was measured at a given point, without horn. Then the horn was placed in position and the intensity measured again — at the same point. The quotient of the latter intensity by the former is called the amplifying power or amplification. If called the condensing power it should be remembered that it includes the amplification due to resonance.

The chief difficulty encountered in these measurements was due to reflection from the walls of the room. In a room 25 × 35 feet, except for certain well-defined interference regions, the sound was about equally intense everywhere and was practically the same when the receiving horn faced the source as when turned in the opposite direction. Then, too, the intensity was practically independent of the direction of the axis of the sounding organ pipe with respect to the receiving horn, and it varied but little with change of distance between source and receiver.

The apparatus was then set up out doors as far as possible from buildings, trees, and objects that would act as reflectors. The two chief sources of trouble outside were ground reflection and varying air currents. However, fairly consistent intensity measurements were obtained.

The most reliable results were obtained when the apparatus was set up in a double-walled, constant temperaure room in the basement of the physics laboratory. The room was practically sound proof for sounds originating outside. To reduce the reverberation the walls were covered with the material which could be had quickest and without expense. Amongst other things there were several hundred large gunny sacks and a number of lap robes, blankets and comforters. The absorption was by no means all that could be desired. But it enabled the making of measurements in substantial agreement amongst themselves and with those made out doors, and sufficiently reliable to disprove the statement that a horn is a condenser.

[1] Rayleigh, Theory of Sound, Sec. 253b.

[2] Webster, Proc. Nat. Acad. of Sc., Vol. 5, May, 1919, p. 163. Ibid., July, 1919, p. 275.

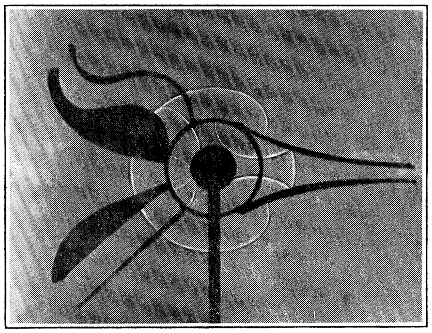


Fig. 2.

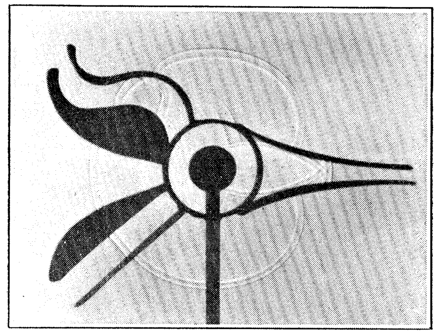


Fig. 3.

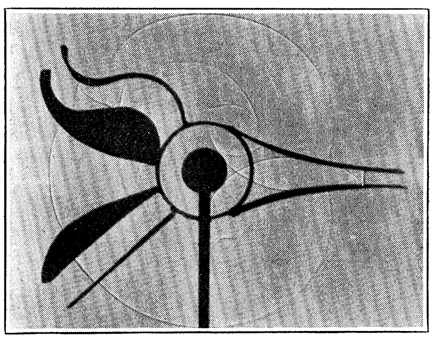
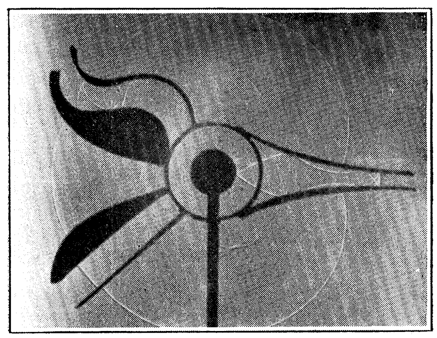


Fig. 4.



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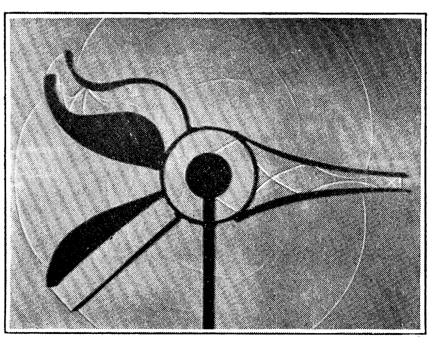

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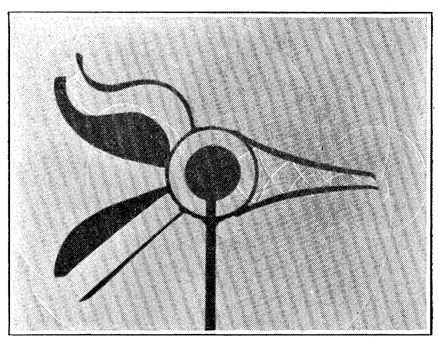

Fig. 7.

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Measurements were made with organ pipes of different pitch placed at different distances from the receiving apparatus. The horns used, four in number, were made of sheet zinc. All were thirty inches long when measured along the axis, and one and one quarter inches in diameter at the small end. The large end diameters were such that the ratios of the areas of the large and small ends were respectively 7.8, 33, 122, and 256.

Inasmuch as this experiment is to be repeated under wider and more favorable conditions than previously obtained, the writer will defer any extended publication and discussion of data. The following table, however, indicates the general character of the results:

| Distance between Source and Receiver. | Ratio of End Areas of Horns. | Amplifying Factor. | |
|---|---|---|---|
| | | By Rayleigh Disk. | By Webster Phonometer. |
| 8.0 feet | 7.8 | 3.1 | 2.9 |
| 8.0 " | 33.0 | 7.9 | 4.3 |
| 8.0 " | 122.0 | 11.9 | 6.0 |
| 8.0 " | 256.0 | 13.0 | 7.3 |
| 6.5 " | 7.8 | 2.6 | 2.0 |
| 6.5 " | 33.0 | 9.1 | 4.3 |
| 6.5 " | 122.0 | 10.3 | 6.0 |
| 6.5 " | 256.0 | 8.3 | 6.5 |

The author attaches no importance to the data in the above table from the standpoint of their absolute values. There is no question, however, as to the order of the quantities involved. This being true, the condensing power of horns is not even approximately what it has been represented to be by many writers. For instance, if the "condenser" theory were true, the amplifying power of the larger horn should be 256 (neglecting friction — small in this case). The average of the four values given in the table is 8.8. The highest amplification obtained was 13, about one twentieth the theoretical value.

It will be noted that the intensity ratios given by the Rayleigh disk run higher than those given by the Webster phonometer. This may be due to the fact that the Rayleigh disk was suspended in free air — without resonator or enclosure — while the vibrating disk of the phonometer was mounted at the end of a cylindrical resonator. At such limited distances between source and receiver and with a sound as intense as that produced by an organ pipe (frequency 256), the phonometer was so sensitive it could not be used when its resonator was in tune with the source. Therefore, the phonometer was not used as designed to be used, with both disk and resonator in unison with the sound to be measured. The disk only was so adjusted.

The resonance theory of horn amplification requires that some of the energy of an emerging wave be reflected back into the horn. Figures 2 to 7 show that in the case of a spark wave the amount of the energy reflected at the open end of a pipe or horn is too small to give any trace of a reflected wave.

## Conclusions.

1. The amplification of sound at the small end of a conical receiving horn is due to *both* resonance and condensation.

2. The amount of sound energy "condensed" at the small end of a conical horn receiver is but a small fraction of that demanded by the "condenser" theory. This theory is not tenable.

3. Sound pulses do *not* "glide around bends" in tubes and "slip" along slanting walls "without appreciable reflection." There is reflection at a surface whenever the molecules of air next the surface vibrate in any direction not parallel to that surface. Huygen's construction applies in every case.

4. Much of the energy of the waves reflected in a crooked tube of small angle may eventually emerge at the far end, but the several waves arrive at different times. Thus the form of the emerging wave may be widely different from that of the entering wave.

5. Much of the energy of a wave entering the large end of a conical horn is reflected and eventually *leaves the horn at the end it entered*. The wider the horn angle the greater the per cent. of energy thus "lost."

6. Of the energy of an emerging sound wave the per cent. reflected at the open end of a tube is small.

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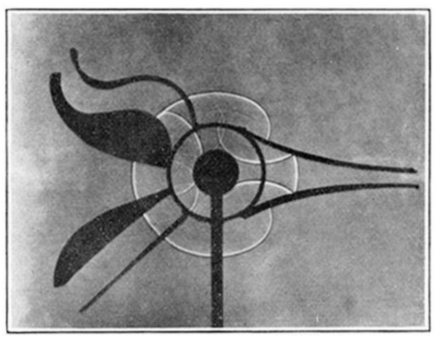
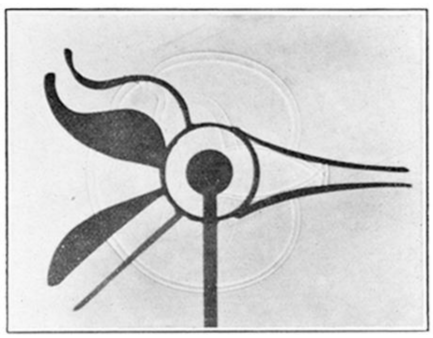


Fig. 2.



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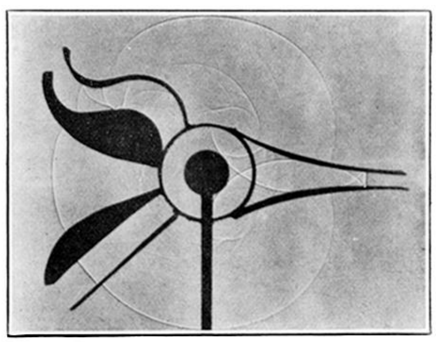

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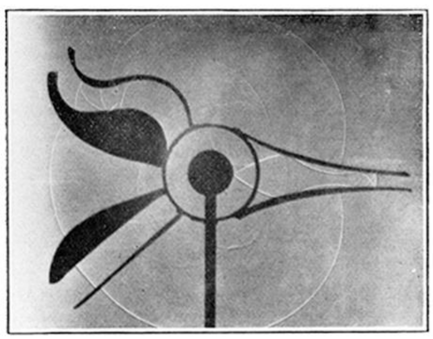

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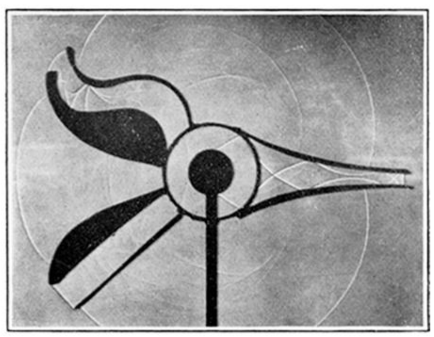

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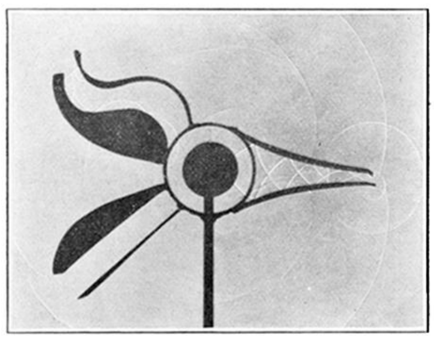

Fig. 7.