SCIENCE

VOL. LVIII AUGUST 31, 1923 NO. 1496

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SCIENCE: A Weekly Journal devoted to the Advancement of Science, edited by J. McKeen Cattell and published every Friday by

THE SCIENCE PRESS

Lancaster, Pa. **Garrison, N. Y.**

New York City: Grand Central Terminal.

Annual Subscription, $6.00. Single Copies, 15 Cts.

SCIENCE is the official organ of the American Association for the Advancement of Science. Information regarding membership in the association may be secured from the office of the permanent secretary, in the Smithsonian Institution Building, Washington, D. C.

Entered as second-class matter July 18, 1923, at the Post Office at Lancaster, Pa., under the Act of March 3, 1879.

ABSOLUTE MEASUREMENTS OF SOUND[1]

IT is now more than thirty years since it occurred to me to devise an instrument that should be capable of measuring the intensity or loudness of any sound at any point in space, should be self-contained and portable, and should give its indications in absolute measure. By this is meant that the units should be such as do not depend on time, place, or the instrument, so that, though the instrument be destroyed and the observer dead, if his writings were preserved another instrument could be constructed from the specifications and the same sound reproduced a hundred or a thousand years later. The difficulty comes from the fact that the forces and amounts of energy involved in connection even with very loud sounds are extremely small, as may be gathered from the statement that it would take approximately ten million cornets playing *fortissimo* to emit one horse-power of sound.

Before we can measure anything we must have a constant standard. In sound we must construct a standard which emits a sound of the simplest possible character, which we call a pure tone; it will be like that emitted under proper conditions by a tuning-fork, which is described by saying that the graph representing the change of pressure with the time shall be that simple curve known as the sinusoid or curve of sines. From this connection we say that the pressure is a harmonic function of the time. Unfortunately the pressure change is so small that at no point in a room, even when a person is speaking in a loud tone, does the pressure vary from the atmospheric pressure by more than a few millionths of an atmosphere. Thus we require a manometer millions of times as sensitive as an ordinary barometer, and, in addition, since the rhythmic changes occur, not once in an hour or day, but hundreds of times per second, if we wish the gauge to follow the rapid changes accurately, we have many mechanical difficulties.

The problem of a standard of emission has been solved by a number of persons, including Professor Ernst Mach and Professor Ludwig Boltzmann, and Dr. A. Zernov, of Petrograd, a pupil of the celebrated Peter Lebedeff. The problem of an absolute instrument for the reception and measurement of a pure

[1] An address before the Royal Institution of Great Britain, June 10, 1921, by the late Arthur Gordon Webster, D.Sc., LL.D., Hon.M.R.I., Professor of Physics, Clark University.

tone has been also successfully dealt with by a number of investigators, among whom may be mentioned Professor Max Wien, of wireless fame, the late Lord Rayleigh, and Lebedeff. But there remains a third step in the process, which is as important as the first and second. Given the invention of the proper standard source of sound, which I have named the "phone," because it is *vox et praeterea nihil,* and of a proper measuring instrument, which should evidently be called a phonometer, there still remains the question of the distribution of the sound in space between the phone and the phonometer. Any measurements made in an enclosed space will be influenced by reflections from the walls, and, even if we had a room of perfectly simple geometrical form, say cubical, and were able to make the instruments of emission and reception work automatically without the disturbing presence of an observer, it would still be impossible to specify the reflecting power of the walls without a great amount of experimentation and complicated theory. Nevertheless, this is exactly what was done by the late Professor Wallace C. Sabine, of Harvard University, who employed the human ear as the receiving instrument. Those who have made experiments upon the sensitiveness of the human ear for a standard sound will immediately doubt the possibility of making precise measurements by the same ear at different times, and particularly of comparing measurements made by one ear with those made by another. Nevertheless, Sabine attained wonderful success, and was able to impart his method to pupils who carried on his work successfully, so that he was able to create the science of architectural acoustics and to introduce a new profession. Still, the skill that required three or four months to attain by Sabine's method may be replaced by a few minutes' work with the phonometer.

In order to avoid the influence of disturbing objects, the observer should take the phonometer to an infinite distance, which is manifestly impossible. The method employed was to get rid of all objects, except a reflecting plane covered with a surface the coefficient of reflection of which could be measured. For this purpose the teeing ground of a suitable golf course was used. With the present instrument it can be determined in a few minutes, if there is no wind.

In 1890 I proposed to use a diaphragm made of paper, which should be placed, shielded on one side, at the point where the sound was to be measured. In order that the effect of the sound should not be distorted, the membrane, instead of having to do any work, as in the case of the diaphragm of the phonograph in digging up the wax, or in that of the microphone in compressing the carbon, was to be perfectly free, but was to carry a small plane mirror cemented on at its center. In close juxtaposition and parallel with this was the plane side of a lens which, viewed in the light from a sodium flame, was to give Newton's rings or interference fringes. Of course, when the sound falls upon the diaphragm the fringes vibrate rapidly and disappear from sight.

By the introduction of a Michelson optical interferometer, two of the difficulties of this instrument were overcome—namely, (1) that of adjusting the lens so that it would not strike the vibrating mirror, since the mirrors in the interferometer could be as far apart as one pleased; and (2), more important still, it permitted the use of fringes in white light, so that it was possible to use gas, incandescent, or arc light with excellent effect. A further improvement was introduced by the use of a thin plate of mica for the diaphragm.

To obtain the sensitiveness necessary to measure sounds of ordinary intensity, the property of resonance is employed twice—*i.e.,* a system of two degrees of freedom is used. First, the plate resounds to a sound more strongly as it is tuned more nearly to it; and second, a resonator that can also be tuned is put behind the plate. The sound entering by the hole in the resonator is magnified by the tuning, and acts upon the plate, which is also tuned. A graph can be plotted in which one coordinate represents the stiffness of the plate, or rather what may be called the mistuning, which is the stiffness lessened by the product of the mass by the square of the frequency. The other coordinate represents the corresponding quantity for the resonator, the stiffness of which depends simply on the volume into which the air is compressed, while the effective mass depends on the dimensions of the whole, and its damping on the sound radiated from the mouth. It is then found that the tuning should not be such as to make the representative point occur at the middle of the figure, making both mistunings zero, but that both mistunings should be of the same sign and a certain magnitude, depending on the coefficients of damping of the two degrees of freedom of the coupled system. The mathematical theory is precisely that of a wireless receiver. The ultimate sensitiveness depends on the smallness of the damping of the plate.

The apparatus as it was built several years ago was mounted upon a heavy bronze stand, covered at the back by a heavy bronze cover to keep out the sound, while the three shafts turning the screws of the interferometer adjustment protruded through sound-tight fittings. Upon the front of the instrument a properly tuned resonator was attached, and at the side was a small incandescent lamp with a straight, horizontal filament, an image of which was projected by a lens upon the first mirror of the interferometer. Upon this was focused a telescope, giving in the reticule an image of the horizontal, straight filament, crossed by the vertical interference fringes seen with white light. In order to get these the plate must be in the proper position within a few hundred-thousandths of an inch. The objective of the tuning-fork was carried by a tuning-fork which oscillated vertically, tuned to the pitch of the pure tone to be examined, and this, combined with the horizontal motion of the fringes, resulted in a figure of colored fringes in the form of an ellipse. On slightly mistuning the fork, the ellipse could be made to go through all its phases, and when it was reduced to an inclined straight line its inclination was read off on a tangent scale. The amplitude of the compression of the air in the sound was then directly proportional to the scale-reading.

While the interferometer is still used for calibration, the movement of the diaphragm is recorded for actual measurements by a thin steel torsion strip carrying a concave mirror. A lamp with a vertical, straight filament is viewed through a telescope into which the small mirror focuses the image of the filament on the reticule, and a magnification of from 1,200 to 1,500 is used, so that the sensitiveness is about the same as with the interferometer.

At first the only method of tuning was the clumsy one of changing the mass of the diaphragm by adding small pieces of wax. This was not capable of continuous variation. Now the diaphragm has been discarded and replaced by a rigid disc supported by three steel wires in tension. The disc is made of mica or aluminium, and is carried by a little steel spider containing three clamps to hold the wire. The tension is regulated by three steel pegs, one of which is controlled by a micrometer screw. The disc is placed in the circular hole through which the sound enters the resonator. This has the advantage of reducing damping very largely, and thus of increasing the sensitiveness enormously. The instrument now competes with the human ear, and can be tuned over two octaves or more.

This sensitiveness can be demonstrated by projecting the colored interference fringes on a screen and singing faintly in a remote part of the room, when the fringes will disappear. Using the telescope end of the apparatus, the instrument will indicate the sound of a tuning-fork when one can scarcely hear it. It is obvious that the disc may be made the diaphragm of a telephone and thus increase its sensitiveness. In fact, Professor King has used such a telephone to record wireless messages with great success. He has also invented another sort of tunable diaphragm composed of a stretched steel membrane with compressed air behind it, which enables it to be tuned continuously, but over a smaller range.

I now come to the source of sound—the phone. This has been reduced to a reversed form of the phonometer. The disc is driven by an interrupted or alternating current by means of electromagnets, and tuned like the phonometer. Its excursion is measured by a powerful microscope, and the emission of sound is known in absolute measure. It is now driven by a triode valve tube, in the manner suggested by Professor W. H. Eccles, of Finsbury Technical College, London, for a tuning-fork. This has been worked out for me by Dr. Eckhardt at the Bureau of Standards in Washington.

The third part of the investigation involves a determination of the coefficient of reflection of the ground. The phone is set at a convenient height, and the phonometer at a convenient distance. Either is then moved along at a constant height and the varying deflections of the phonometer are read while the sound remains the same. Interference sets in between the direct sound and its image reflected in the ground, and the existence of a minimum is obvious to the most naïve observer by the ear alone. The reflection of either grass or gravel was found to be about 95 per cent., while, with a most carefully deadened room, the walls of which were covered with thick felt, there was perhaps 20 per cent. reflection. The whole measurement at both ends and the transmission checks up with an accuracy of about 2 per cent.

With this apparatus all sorts of acoustical experiments may be performed. By attaching to the phonometer a long glass tube or antenna, it has been possible to explore all sorts of places, such as the field within a horn or tube lined with an absorbent substance. The transmission of sound through fabrics, walls and telephone booths may also be quickly examined. The instrument is used by psychologists and by telephone and acoustic engineers, and is of interest to navigators. An interesting by-product is an instrument for showing the direction of an acoustic signal in the fog. It has been called a phonotrope, on the analogy of heliotrope, which turns to the sun. It consists of two equal horns which bring the sound to the opposite sides of the disc. When the whistle blows, the band of light spreads out, and on turning the instrument it closes to zero when the sound is directly ahead. Thus at several miles the direction is given to within two or three degrees.

Finally, let us consider that mystery of sound, the violin, which has been studied by Professor Barton, of Nottingham, and Professor Raman, at Calcutta. This may be described by the engineer as a box of curious shape, made of a curious substance, wood, of variable thickness, with two holes of strange figure to let the sound out of the resonating box. The latter is actuated by a curious substance, catgut, made of the intestines of a sheep, and set in vibration by another curious substance, the tail of a horse. Yet from this wonderful box we get the most ravishing sounds, which affect profoundly the emotions of the most civilized. Yet the physicist reduces all musical instruments to combinations of resonators with strings, membranes, bars, plates and horns. The mathematical theory of strings was given by Euler two hundred years ago, of bars and plates less than a hundred years, of resonators by Helmholtz and Rayleigh, and I have recently added a theory of horns which, while only approximate, works well in practice, and investigations are now being carried out by such methods on vowels and the violin.

ARTHUR GORDON WEBSTER

SCIENCE AND PHILOSOPHY IN VIRGIL

RELIGIOUS superstition once borrowed such a large portion from the works of Virgil, though it was accomplished in a way as inexplicable as it was unwarranted, that we are apt, from the standpoint of science, to dismiss him altogether as a source from which to gather anything useful in the history of scientific thought. It is no wonder, however, that the ardent early fathers of the Christian church found in the fourth Ecologue an indication, pregnant with prophecy, conscious or unconscious on the part of the poet, of the coming of Christ and the regeneration of the world, a return to its golden age. Other interpretations have of course been made of the lines, but the ready credulity of a budding faith had every temptation to accede to the conviction that Virgil was a herald of the approaching light of the world. But the reputation Virgil had in the Middle Ages partook of that of a man of science. He was a wizard, the happy man who knew the causes of things,

Felix qui potuit rerum cognoscere causas.[1]
How blest the sage! whose soul can pierce each cause
Of changeful Nature, and her wondrous laws.

As a matter of fact this was no boast of Virgil, it was only his sigh that he did not understand them all and it is difficult to see, in spite of Comparetti's monumental work,[2] what could have given the mind of the middle ages that respect for Virgil as a man of science, of which we find so many traces in the authors of the pre-Renaissance. For them he was not so much the necromancer of verse, recognized by a later and an earlier age, as a wizard of knowledge in natural science. The lines however which precede[3] the one above, so often quoted, give us a glimpse of the kind of things he had in mind when he longed for a knowledge of their causes.

> The muses [he declares] . . . will show me the paths of heaven and the stars, the various eclipses of the sun and the changes of the moon, whence comes the quaking in the earth, by what force the sea swells high on the rocky shores and again sinks back upon itself, why the winter sun rushes on to plunge beneath the ocean wave, what it is lengthens out the tedious nights, but if I could not draw nigh to these parts of Nature the cold blood would gather round my heart.

That is, as I take it, for Sotheby certainly goes astray here, if he could not imagine some rational explanation of these things he would stand terror stricken in the presence of God. That is the reason, it seems to me, he exclaims, "fortunate indeed is he who perceives the causes of things."

In Virgil, as in all ancient writers, we get a far franker acceptation than we do to-day, a much plainer indication of the all pervading pantheism in the fundamental beliefs of men. It is probably as widespread to-day, but it is hidden beneath a reticence which the mystic faith of Christ, quite in contrast to the ancient pagan tendencies, imposes on its communicants. Still it peeps out now and then, not in science alone where it has the support of physics, but in religious pedagogy with the maxim that God is everywhere. The haruspices and the augurs thought or, in Virgil's day, pretended to think that the birds bore the impress of the will of the gods on their in-

1 Georgicon II. 490. I use Sotheby's translation here, but the classics are immortal because they have a message for each generation, otherwise they would have perished. Only from the text can the modern critic judge if the references from it are valid for the scientific thought of this generation. There can be no doubt Virgil is here referring to Lucretius whose De Rerum Natura was his model in youth.

2 Virgilio Nel Medio Evo, per Domenico Comparetti, Fierenze, 1896.

3 Me vero primum dulces ante omnia Musae,
quarum sacra fero ingenti percussus amore,
accipiant caelique vias et sidera monstrent,
defectus solis varios lunaeque labores;
unde tremor terris, qua vi maria alta tumescant
obicibus ruptis rursusque in se ipsa residant,
quid tantum Oceano properent se tinguere soles
hiberni, vel quae tardis mora noctibus obstet,
sin has ne possim naturae accedere partis
frigidus obstiterit circum praecordia sanguis:

But, most beloved, ye Muses! at whose fane
Tranced by deep zeal I consecrate my strain,
Me first accept! and to my search unfold
Heaven and her host in beautious order roll'd;
Th' eclipse that dims the golden orb of day,
And the moon labouring through her changeful way;
Whence rocks the earth, by what vast force the main
Now bursts its barriers, now subsides again;
Why wintry suns in ocean swiftly fade,
Or what delays night's slow-descending shade.
But if chill blood, long lingering in my vein,
From Nature's secret lore my search restrain,