XI. *On the Sympathetic Vibrations of Jets.*

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IN the year 1833 FELIX SAVART published a remarkable memoir* on the structure of liquid jets from circular orifices, in which he demonstrated the following facts :—

A vertical jet of liquid from a circular orifice presents in general two distinct portions—an upper continuous or rod-like portion, and a lower or troubled portion ; the relative lengths of these two regions being approximately the same in air as in a vacuum.

The lower or troubled portion consists of separate drops, as proved by the fact that objects may be viewed through it, even when the jet is composed of an opaque liquid like mercury.

The troubled portion of a jet which is not perfectly insulated from accidental vibrations, or from the vibrations produced by its impact against a solid body, presents swellings at regular intervals, these swellings (*ventres*) being the result of certain longitudinal and transverse changes of shape, of regular period, executed by each drop during its fall ; but a jet from a carefully insulated orifice does not exhibit these swellings, but only slight irregularities which continually change their position.

In the upper half of the first of these regular swellings the drops are not yet completely detached from the main stream, but only become so in the lower half.

A jet which is allowed to strike against a stretched membrane at a certain distance from the orifice, gives out a musical sound of definite pitch, or some sound related thereto ; its continuous portion at the same time becomes shortened, and resolution into drops occurs higher up in the stream.

The pitch of the characteristic sound depends neither on the nature nor the temperature of the liquid, but is determined solely by the velocity of the stream and the diameter of the orifice.

A jet which is exposed to the action of external vibrations may also have its continuous portion shortened, and may reproduce the impressed vibrations by impact against a membrane ; but the musical sounds which have this effect must either be related to the characteristic of the jet or not differ from it widely in pitch.

* Annal. de Chimie, vol. 53 (1833), p. 337, and POGGEND. Annal., vol. 29 (1833), p. 353, and vol. 33 (1834), pp. 451 and 520.

From his experiments SAVART concluded that periodic movements of the jet exist independently of communicated vibrations, and that these movements are not due to vibrations of the edges of the orifice, nor to friction of the liquid against these edges. He attributed them rather to periodic oscillations of the entire mass of fluid behind the orifice, and concluded that the vibrations excited by impact of the jet against any solid, when conducted back to the orifice, assist and intensify these normal vibrations. External vibrations act in a similar way, but such external vibrations may sometimes alter the normal period of the jet vibrations.

In a later paper * SAVART showed that the jet vibrations are preserved in the "nappe," or thin sheet of liquid formed when the jet strikes normally on a small surface.

In a paper published after his death† SAVART endeavoured to show, by some very beautiful experiments, that periodic oscillations of the mass of fluid behind the orifice did actually take place. Filling large glass tubes with water, and allowing the liquid to escape through circular openings in flat plates which closed their lower ends, he found that the tubes emitted musical sounds, the intensity of which passed alternately through certain maxima and minima as the level of the liquid sank within them. SAVART established the following law:—The pitch of the tone produced is independent of the diameter of the tube-reservoir, but varies directly as the square root of the height of the liquid therein, and inversely as the diameter of the orifice.

In the year 1852 SONDHAUSS ‡ imitated some of SAVART'S experiments with jets of air rendered visible by mixture with smoke. Using a circular orifice, and a pressure equal to one inch of water, he demonstrated that an air-jet, like a water-jet, presents a continuous and a troubled portion. In the experiment described the continuous portion was about one inch in length, and beyond this the jet showed protuberances analogous to those observed in liquid jets. SONDHAUSS also showed that an air-jet, projected against a surface, spreads out from the point of impact in the form of a "nappe." He does not appear to have observed the phenomenon of the sensitive air-jet, possibly because the pressure he employed was too high.

In 1853 MASSON § in an elaborate paper described an extended series of experiments on the tones produced by efflux of air. In some of these the jet was allowed to escape from a circular orifice into free air, and for this case he established the following laws :—

The flow of air through an orifice in a metallic plate is not continuous; it varies periodically, and the orifice is the seat of a vibratory movement which gives rise to sound when communicated to the external air :

* Annal. de Chimie, vol. 54 (1833), pp. 55 and 113; POGGEND. Annal., vol. 29 (1833), p. 356.

† POGGEND. Annal., vol. 90 (1853), p. 389; Comptes Rendus, vol. 37 (1853), p. 208; Phil. Mag., ser. 4, vol. 7 (1854), p. 186.

‡ POGGEND. Annal., vol. 85 (1852), p. 58.

§ Annal. de Chemie, ser. 3, vol. 40 (1854), p. 333; Phil. Mag., ser. 4, vol. 6 (1853), p. 449.

The number of vibrations of the air at the orifice varies directly as the square root of the pressure in the reservoir, or as the velocity of efflux; but is independent of the diameter of the orifice.

The first part of the law regulating the number of vibrations holds also for liquids, as pointed out by SAVART.

MASSON'S experiments were made with large orifices, and, with few exceptions, at comparatively high pressures. By calculation from his results he determined the rate of vibration corresponding to a pressure of 1 mm. of water to be $626\frac{1}{2}$ per second. In the great majority of his experiments the sounds of the jet were reinforced, as he supposed, by placing over the orifice tubes of various diameters and shapes.

About the same time SONDHAUSS,* apparently having no knowledge of MASSON'S work, also published experiments on sounds produced by the efflux of air. He found that a jet of air, at a pressure of 1 or 2 mm. of water, gave no sound; but a "rushing noise" was produced when the pressure was increased. At a pressure of from 5 to 30 mms. of water, a jet, although spontaneously emitting no sound, was capable of being thrown into vibration when an organ pipe was made to speak in its neighbourhood. The tone emitted by the jet was usually, but not always, an octave lower than that of the pipe. The pitch of the tone to which a jet would respond rose in general through the scale as the pressure was increased; but the jet was more powerfully affected by some tones than by others. SONDHAUSS expressly claimed the discovery of these sympathetic tones in air-jets.

He further found that an otherwise silent jet was caused to "sing" by placing in front of it an edge, a point, or an orifice in a plate. The pitch of the tone produced in this way, he concluded, varies directly as the velocity of efflux, and inversely as the distance between the orifice and receiving plate. He thought that the vibrations of the jet were due to friction of the air against the edges of the orifice, and compared the jet to a solid vibrating rod. His experiments were made with a number of orifices of various shapes.

In a note on this paper, MASSON † disputed the supposed analogy between the jet and a vibrating rod; and expressed the opinion that the vibrations of air jets arise at the orifice in the same way as those of liquid jets.

In 1865 SONDHAUSS ‡ obtained with water-jets results very similar to those previously obtained with air. He found that such jets could also be set in vibration by allowing them to strike against an edge or a plate. According to his observations the pitch of the tone produced rises with the velocity of efflux, but falls as the distance of the receiving plate from the orifice is increased. Here again, SONDHAUSS regarded the jet as an elastic rod, thrown into vibration by friction against the edges of the orifice.

* POGGEND. Annal., vol. 91 (1854), pp. 126 and 214.

† Annal. de Chimie, ser. 3, vol. 41 (1854), p. 176.

‡ POGGEND. Annal., vol. 124 (1865), pp. 1 and 235.

In 1866 KUNDT* obtained musical tones by the impact of two flames, or of an air-jet against a flame. He considered it a desirable condition that the flame and jet orifices should be of unequal size.

LECONTE in 1858, and BARRETT in 1867, discovered the now well-known "sensitive flame," which was investigated by BARRETT and TYNDALL.† In order to detect possible changes behind the orifice, which might account for the phenomenon, these physicists mixed smoke with the gas previous to ignition. No such changes were discovered; but they were thus led to observe that jets of unignited gas and air are also changed in form by sound, a fact strangely overlooked by SONDHAUSS. The changes occurring in such jets were found to be very similar to those induced by sound in liquid jets. BARRETT and TYNDALL stated that an ignited jet of gas—a flame—is sensitive to higher tones than an unignited jet at the same pressure, and that the effective tones are higher the smaller the orifice. They attributed the phenomenon to the resonance of the gas in the connecting tube.

In the course of these experiments it was noted that a sensitive flame sometimes *reproduces* the tone by which it is affected.

About this time also, TYNDALL‡ produced a new kind of "sensitive flame" by blowing a jet of air through a gas flame: and observed that the ordinary blowpipe flame could be brought into a sensitive condition. TYNDALL considered that the tones which visibly affect a sensitive flame must be of about the same pitch as those produced by friction of the gas against the orifice.

In a subsequent note BARRETT§ compared a flame at different pressures to a series of tuned reeds. He also made the interesting discovery that sensitive flames may be violently affected by vibrations far beyond the limit of audition.

In 1875 DECHARME|| not only produced tones by directing a jet of air against the surface of mercury, but observed that the latter was thereby thrown into vibration, as proved by the motions of a beam of light reflected from it.

The same experimenter also obtained musical tones by blowing air through a tube against a flame. Carbonic acid and pure oxygen, used instead of air, gave but feeble effects, and nitrogen hardly any. He attributed the action of carbonic acid to its decomposition by the flame.

More recently NEYRENEUF¶ has studied the phenomena of jets and flames. He observed that the "nappe" formed by the meeting of two flames, or of an air-jet and a flame, not only responded to, but also reproduced a limited range of tones uttered

* POGGEND. Annal., vol. 128 (1866), p. 610.

† Phil. Mag., ser. 4, vol. 33 (1867), pp. 92, 211, 287.

‡ Phil. Mag., ser. 4, vol. 33 (1867), p. 375.

§ Nature, vol. 16 (1877), p. 12.

|| POGGEND. Annal., Ergzgsb. 7 (1876), p. 176; Comptes Rendus, vol. 80 (1875), p. 1602, and vol. 81 (1875), p. 339; Phil. Mag., ser. 4, vol. 50 (1875), p. 496.

¶ Annal. de Chimie, ser. 5, vol. 25 (1882), p. 183.

in their neighbourhood. But very frequently the "nappe" emitted a harmonic of the exciting tone, instead of the tone itself.

In 1884 Lord RAYLEIGH* demonstrated the sensitiveness to sound of jets of coloured water in water, and also published some interesting drawings of the appearances of these and of vibrating sensitive flames when viewed intermittently.

The literature of sensitive flames is extensive, but it is not necessary to catalogue it here.

My attention was directed to this subject in the following way :—Happening to hold the flame of a BUNSEN burner in front of a small orifice in the end of a glass tube, from which a rapidly pulsatory jet of air issued, in such a way that the air-stream impinged on the flame, I noticed that a loud musical sound was produced, the pitch of which corresponded with the rapidity of the jet pulsations. So far there was little requiring explanation. But a feature of the phenomenon which strongly riveted my attention was this : that while the sound was of feeble intensity when the flame was *quite close* to the orifice, it increased in loudness as the lamp was withdrawn along the jet path, and reached its maximum with orifice and flame at a certain distance apart. Beyond this distance the sound rapidly degenerated into an unmusical roar.

In order to study this phenomenon more carefully, a small round hole was pierced in the diaphragm of an ordinary hand telephone, and the chamber behind the diaphragm placed in communication with a reservoir of air under gentle pressure, which previous experiment had shown to give the best result. The telephone being put into circuit with a battery and rheotome in a distant room, each motion of the diaphragm inwards naturally produced compression of the air in the chamber behind.

A small flame being placed in front of the orifice, it was found that not only musical vibrations, but also the more complex vibrations of speech, impressed upon the diaphragm, could be quite loudly reproduced. In fact, when the telephone was put in circuit with another telephone, or better with a battery and microphone in the distant room, speech loud enough to be heard over a small apartment could be readily produced. The words, however, were certainly lacking in distinctness.

A most natural assumption was, that the sounds heard resulted from the impact of a series of puffs of air against the flame. Accordingly I attempted to produce a greater volume of sound by increasing the number of jets. Several small round holes were pierced in the telephone diaphragm, and a separate flame placed in front of each of them. The experiment did not justify my anticipations ; for it soon appeared that by far the most effective jets were those that issued near the centre of the diaphragm, where the greatest motion existed ; an orifice near the circumference of the diaphragm yielding only feeble sounds. In fact it looked as if *motion of the orifice*, rather than compression of the air, was the chief agent in the phenomenon. This conclusion was

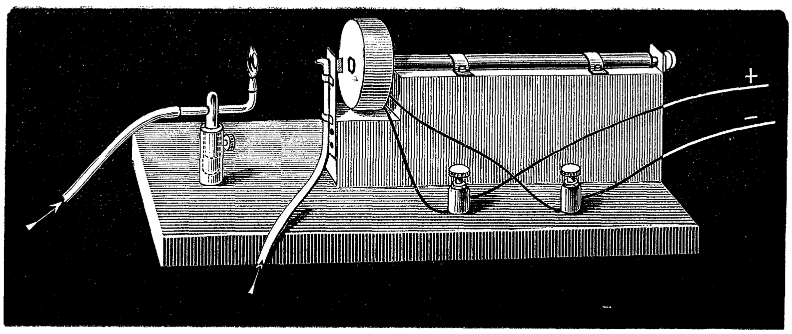
* Phil. Mag., ser. 5, vol. 17 (1884), p. 188.

speedily verified by attaching a light glass jet to a piece of soft iron, soldered to a brass spring, and letting the soft iron take the place of the telephone diaphragm. (Fig. 1.)

The results with this arrangement were still more satisfactory than those previously obtained, and speech as well as musical and other sounds were reproduced of considerable loudness, if not always very distinctly. A singular fact also revealed itself, viz., that the effects were about the same whether the vibratory motions of the jet-tube took place in the direction of its length or transversely. It should be mentioned that certain desirable conditions of air pressure, size of jet orifice, and size and distance of flame had previously been ascertained by experiment.

At various times in the course of these experiments I had noticed that a flame against which an air-jet was playing under suitable conditions, was not only visibly affected by sounds, but that sometimes it seemed to *speak back* words uttered in its

Fig. 1.



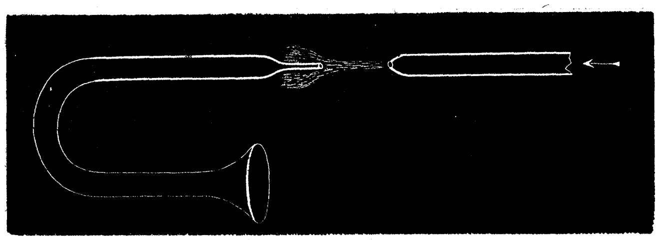
neighbourhood, the repeated sounds being comparable to a feeble echo from a near surface. It was also found that a vibrating body, such as a tuning fork, held near the jet orifice, caused the flame to emit the sound corresponding to its vibrations.

A jet of air, then, playing against a flame under proper conditions, formed a combination capable of reproducing, as sound, vibrations communicated to the air at the orifice, either from the air behind or external to the orifice, or from the jet tube or support.

But, very strangely, scarcely any but irregular blowing noises could be heard from a vibrating jet when the ear, or the end of a tube communicating with the ear and large enough to receive the whole mass of air in the jet, was held opposite to it, instead of the flame. Tubes of various sizes, with conical and cylindrical ends, and held at various distances, were tried without result, until finally it became evident that the changes in the jet, effective in producing sound, must be *relative* changes of different portions of it. This view was also suggested by the appearance of the flame in the preceding experiments. At the plane of contact of the jet with the flame, a peculiar ring of blue flame could be seen, and this ring evidently vibrated violently while the flame was emitting sound (fig. 1).

Accordingly, with the object of exploring every part of the jet, I took a hearing-tube with a *very small* opening in its end (about as large as the jet orifice), which could be applied to different points in the jet-path. With this arrangement the results were strikingly different. When the end of the hearing-tube was moved about in front of, and not too close to, the orifice from which a vibrating jet issued, the vibrations were distinctly audible over a wide area, and at points where the large hearing-tube gave absolutely no sound. When the hearing orifice was held at any point on the *axis* of the jet, the sound heard was much louder than at surrounding points in the same section, occasionally attaining a remarkable degree of intensity; and this intensity invariably reached its maximum at a certain distance from the jet orifice. When the hearing-tube was moved from this position *away* from the jet orifice, the sound first became confused, and then changed to an unmusical roar; but when it was moved towards the orifice the sound gradually died away, and nothing could be heard when the two orifices were close together. The diminution in loudness was also very rapid when the hearing orifice was moved from a point on the jet axis in any direction towards the circumference.

Fig. 2.



It now became of interest to discover the connexion between the point of maximum sound-intensity and the structure of the jet. To this end I made use of a well-known device for rendering visible the motions of air, viz., mixing it with smoke. Professor TYNDALL (*loc. cit.*) showed that when certain sounds were produced in the neighbourhood of a smoked air-jet at suitable pressure, the result was a shortening of the continuous column, the jet appearing to become confused, and to lose its rod-like character sooner than it would if undisturbed.

Experiments with smoked air soon threw some light on the phenomena above described. A jet of air charged with tobacco-smoke was allowed to escape at a pressure of about $\frac{1}{8}$th of an inch of water from an orifice, about $1\frac{1}{2}$ mm. in diameter, in the end of a glass tube. The atmosphere being perfectly still, and strict silence observed, the issuing stream was continuous and rod-like for a length of about 35 centims. This rod-like portion was slightly conical, the apex of the cone being at the jet orifice. Beyond this distance the jet expanded and rapidly became dissipated. Any continuous vibration of moderate pitch, impressed upon the orifice in any way, caused the continuous column to become shorter, and the jet to "break" or become confused at a distance from the orifice varying from 6 centims. to 1, according to the intensity of the vibrations.

On now introducing the small hearing orifice into the path of the jet, it was found that just beyond the breaking point an indistinct or harsh repetition of the disturbing sound was heard; that just at, or a little inside of, this point the repeated sound was clear and of maximum intensity; and that it died away as the hearing orifice was moved from this position, either towards the jet orifice or out of the line of the jet axis (fig. 2). Substituting a small flame for the hearing-tube, the greatest loudness and purity of tone were obtained when the flame was placed just within the breaking point; and on moving the flame the same changes in loudness and distinctness were noted as occurred with the hearing-tube.

In this experiment it was found most convenient to cement the jet-tube to the armature of an electromagnet, thrown into vibration by a battery and rheotome. The attention of the experimenter could then be fixed solely on the sounds proceeding from the jet.

This experiment was repeated many times, the jet being subjected to vibrations of varying pitch and intensity. The result was always the same. Whenever the jet "broke" in front of hearing orifice or flame, under the influence of a pure musical tone, either it gave forth no sound, or the sound heard was harsh and rattling in character. In the latter case the *rhythm* of the impressed vibrations was preserved, but the *quality* was lost.

In repeating these and similar experiments certain precautions should be observed, some of which have been pointed out by other experimenters in this direction.

The edges of the jet orifice, and of the receiving orifice, ought to be perfectly smooth and circular. Any irregularity in them tends to cause whistling or scraping noises in the hearing-tube, and also makes the jet more liable to "sing," in a manner presently to be described.

The air passage, from the reservoir to the orifice, should be wide and unobstructed. It is therefore better to control the outflow by regulating the pressure in the reservoir, rather than by any form of valve.

The air should be free from dust, and from suspended particles of water. Each little particle, as it passes the orifice, gives rise to a disturbance which grows as it travels along with the jet, and causes a crackling noise when it reaches the hearing orifice. Should the air be very dusty there will be a distinct gain by filtering it through a wide tube lightly packed with coarse cotton.

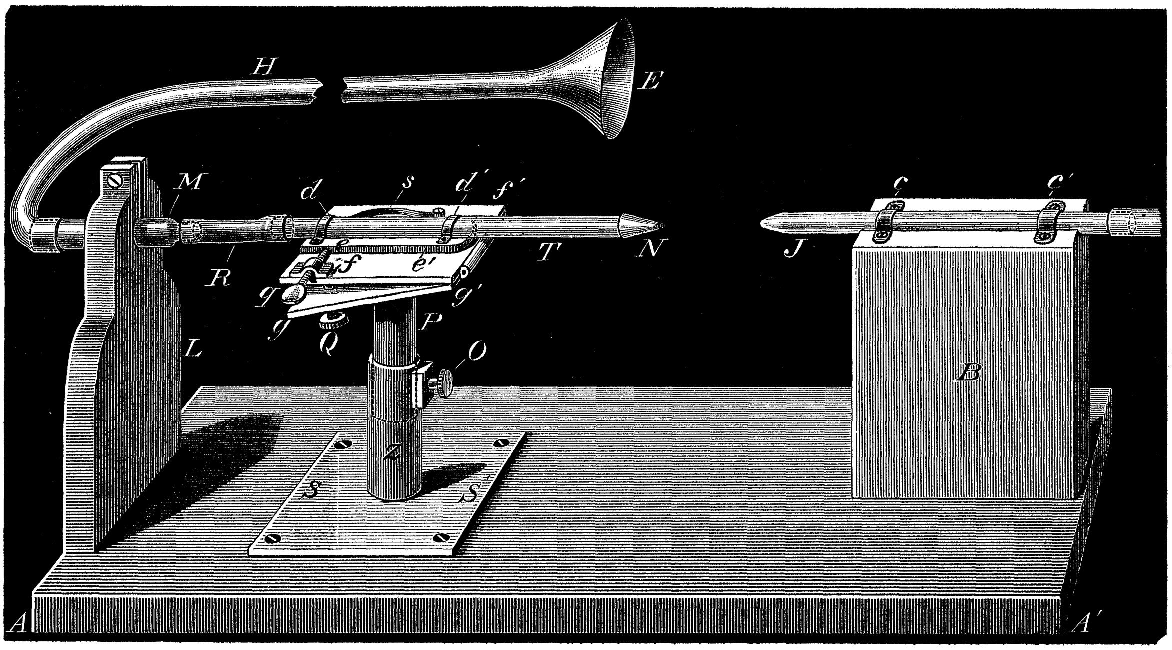
The apparatus actually necessary for these experiments is extremely simple. The air reservoir may take the shape of a bag made from a single sheet of thin vulcanized rubber cloth, five feet long by two feet broad, folded once and joined along its edges with rubber cement. Ordinary gas bags are much too stiff and heavy for the low pressures required, and elastic bags are quite useless. Into one corner is cemented one limb of a three-way stop-cock; of the remaining limbs one is connected to a laboratory blower, and the other leads to the jet by a wide rubber tube

Pressure is best applied to the bag, after it has been inflated by the blower, by means of a light board, on which weights may be placed. A fairly uniform pressure may thus be maintained for a considerable time when the jet is small.

For the preparation of the jet orifice a wide tube of fusible glass is selected, free from lead and of uniform thickness; this is carefully heated at one point with constant rotation, and drawn out. The constricted portion is then cut with a sharp file where it has the desired internal diameter, the edges of the orifice carefully ground off on a stone and finally slightly fused.

To facilitate the adjustment of the hearing-tube or flame, some form of apparatus like the following is desirable (fig. 3). On a wooden base, A A′, about 12 inches long by 4 inches broad, a vertical block B is mounted. The glass jet-tube J rests in a groove

Fig. 3.



on the top of B, and is held in position by two spring clips, $c\,c'$. The hearing tube, T, is a brass tube about $\frac{1}{4}$ of an inch in internal diameter, on the end of which nozzles, N, having orifices of different sizes, may be screwed. T is held in position by two stout clips, $d\,d'$, on a brass plate, $e\,e'$, about 2 inches long by $\frac{3}{4}$ of an inch wide, which is pivoted at e' on another brass plate, $f\,f'$, of nearly the same length but about 2 inches wide. A stout spring, s, presses the little plate $e\,e'$ firmly against the point of the screw q, which plays in a block on the plate $f\,f'$. The plate $f\,f'$ is hinged at one end to the similar plate $g\,g'$, soldered obliquely on the top of a brass pillar, P, which slides easily in the tube Z, and may be clamped in any position by the screw O. The tube Z is soldered to a brass plate, $s\,s'$, which may be screwed to the base board. A stout screw, Q, plays through the plate $g\,g'$, and the plate $f\,f'$ is firmly drawn down against its point by a spiral spring, not shown in the figure. Thus, by sliding P in the tube Z, the orifice may be brought approximately into position; after which a finer adjustment may be effected by turning screw Q, by which the orifice is moved up or down, or screw q, by which it is moved laterally. The tube T is connected by a piece of rubber-tubing, R, to the stout brass tube M, fixed permanently in the wooden upright, L. The end of the flexible rubber tube, H, provided with the ear-piece, E, is slipped over the tube M. The ear-piece may thus be applied to the ear without fear of disturbing the adjustment of N. The distance of the jet orifice from N may be varied by sliding the jet tube J to and fro in the groove in which it rests. J is connected by rubber-tubing to the reservoir.

For experiments with flames the tube T may be withdrawn, and a tube with burner, like that shown in fig. 1, may be substituted for it.

With this apparatus it is easy to repeat the above-described experiments, and to verify the following statements.

A jet of air at moderate pressure (below 10 mms. of water), from an orifice 1 to $1\frac{1}{2}$ mm. in diameter, forms a continuous column for a certain distance, beyond which it becomes confused and breaks up.

Any impulse, such as a tap on the jet-support or a short and sharp sound, causes a minute disturbance to start from the orifice. This disturbance increases as it progresses, and finally causes the jet to break. By directing the jet against a flame, or against a hearing orifice, it is readily perceived that such disturbances travel along the jet-path with a velocity which is not that of sound in air. In fact, the sound heard in the ear-piece resembles an echo of the disturbing sound.

The disturbances produced by sounds of different pitch travel along the jet-path with the same velocity. This is evident, since otherwise distinct reproduction of the complex vibrations of speech at a distance from the orifice would be impossible. This velocity is much less than that of sound in air, and is probably the mean velocity of the jet stream.

A vibrating air-jet, playing into free air, gives rise to very feeble sounds; but these sounds are much intensified when the stream impinges on any arrangement which serves to divide it into two parts. Of such arrangements, a surface pierced with a small orifice is the best, the orifice being placed in the jet axis.

A jet of air at low pressures responds to and reproduces only sounds of low pitch. Sounds above a certain pitch, which varies with the pressure, either do not affect it or are only faintly reproduced.

At pressures between 10 and 12 mms. of water the jet reproduces all the tones of the speaking voice, and those usually employed in music, with the exception of very shrill or hissing sounds. When the pressure in the reservoir equals about 13 mms. of water, hissing sounds are well reproduced, while sounds of very low pitch become fainter. At higher pressures, up to about 25 mms. of water, shrill or hissing noises produce very intense disturbances, while ordinary speech tones have but little effect. But at these pressures sounds of high pitch frequently cause the jet to emit lower sounds, of which they are harmonics.

In general, a pressure of about 12 mms. of water will be found most suitable for reproducing speech or music. Under this condition the jet is very sensitive to disturbances of all kinds, and will reproduce speech, singing, and irregular sounds included under the term " noises."

It must be understood that the pressures here given are only suitable for jets about 1 mm. in diameter. When the diameter is only a small fraction of a millimeter the above limits may be greatly exceeded, since the velocity of efflux no longer depends solely on the pressure.

A jet escaping from a perfectly circular orifice into free air does not vibrate spontaneously so as to produce a musical sound. But musical vibrations may be excited in it by the passage of the air on its way to the orifice through a resonant cavity or through any irregular constriction.

An air-jet impinging on any obstacle, such as a flame, frequently vibrates spontaneously if the obstacle is at sufficient distance and of such a nature as to diffuse the disturbances produced by impact, or throw them back on the orifice.* This constitutes one of the chief drawbacks to the use of a flame as a means of converting the jet vibrations into sound. The disturbances excited in the surrounding air by the impact of the jet upon it are so intense as to react easily upon the stream as it escapes from the orifice. When, therefore, the jet is thrown into any state of vibration it tends to continue in the same state, even after the exciting sound has ceased.

A jet of air usually responds most energetically to some particular tone or set of related tones. Such a particular tone may be called its fundamental. The practical inconvenience arising from this may be diminished by increasing the air pressure, until the jet fundamental is higher than any of the tones to be reproduced.

The influence of reflected vibrations in disturbing the jet may be well shown as follows:—Let one end of a short piece of rubber-tubing be brought close to the orifice of a silent jet playing against a hearing-tube, but not in such a way as to obstruct it. The jet will remain silent. But if the other end of the tube be held near the hearing orifice the jet will begin to " sing," and will continue singing so long as the tube is held in this position. The tone produced, while depending mainly on the jet, is not independent of the resonance of the tube, since a change in the length or diameter of the latter frequently alters the pitch. It is noteworthy that the arrangements used by SONDHAUSS and MASSON in their experiments were precisely such as would cause disturbances produced by the jet, either by impact or otherwise, to be thrown back on the orifice. This may account for some of the irregular and apparently anomalous results obtained by them.

* Lord RAYLEIGH (Phil. Mag., ser. 5, vol. 17 (1884), p. 189) suggested that the musical sound, sometimes obtained when an air-jet is directed against a flame, results from the tendency of any regular cycle in the mode of disintegration of the jet to propagate itself, when a connexion exists between the orifice and the body on which it strikes, as in SAVART'S experiments with water-jets.

In experimenting with flames it is well to observe the following precautions. The flame should be short: the gas should escape at very low pressure from a circular orifice about the size of the jet orifice. If the burner orifice is small, and the gas pressure high, the flame itself may become a source of vibrations ; and these vibrations, intensified by the impact of air upon it, may be thrown back on the jet orifice.

The loudest sounds are obtained by directing the jet below the apex of the blue flame-zone. In this region the gas has not yet been mixed with the surrounding air, and the intensity of its combustion will therefore depend on the supply derived from the jet. It is remarkable that vibrations are very feebly reproduced when pure oxygen is substituted for air in the jet. In this case the blue flame ring formed by impact becomes very small, the combustion of the oxygen becomes localized, and the necessary condition of the separation of the jet into two portions is probably not fulfilled.

The flame ought to be of sufficient size to apparently absorb the jet. A complete blue flame ring will then appear, the plane of which intersects the angle between the jet and the flame. The centre of this ring will then appear dark, and very little light will be given out.

The best distance of flame or hearing-tube from the jet orifice must be determined by trial. The adjustment is, however, a matter of a few seconds' manipulation, and may easily be effected with eye and ear as guides. When it is desired to reproduce accurately a series of sounds, the distance should be such that the jet will not "break" in front of the hearing orifice or flame, under the influence of the most intense vibration to which it is to be subjected.

When a flame and an air-jet meet at right angles, sounds may also result from vibrations impressed on the flame orifice. The properties of flames are in general parallel to those of gaseous jets. Without going into details, the chief differences may be summarised as follows :

A flame behaves as a more rigid body than an unignited jet, and, except in the so-called "sensitive" state, *i.e.*, at high pressure, it is not easily affected by aërial sound vibrations.

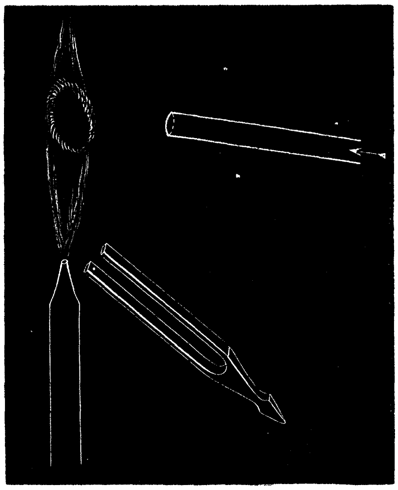
The pressure necessary to make a flame respond to any given range of tones is higher than that required for an air-jet from the same orifice. In these two relations, therefore, a flame is intermediate between a gaseous and a liquid jet.

Except at high pressures, when it is approaching the sensitive state, a vibrating flame from a circular orifice does not emit sound. But its vibration may always be rendered audible by blowing air against it. The best result is obtained when a stream of air at gentle pressure is directed from a *wide* tube just below the apex of the blue zone (fig. 4).

The phenomenon of interference is strikingly shown when vibrations of slightly different pitches are impressed on the flame and air-jet orifices respectively.

Having now briefly described the more prominent characteristics of vibrating gaseous jets, I propose to give a few experiments which may be of value when the nature of the changes occurring within them comes under discussion. This subject is one of some difficulty. No complete theory of jets has been worked out, and I have searched through the literature of the subject without finding anything that would materially assist in explaining their peculiar properties.* We have here to deal with extremely rapid motions of a fluid which is invisible, and the evidence under such circumstances must be mainly indirect. Many obscure points will, however, become clear when the very similar phenomena of liquid jets are considered.

Fig. 4.



Let an orifice in the end of a capillary tube, which is connected with a small water manometer, be moved about in the path of a jet of air. The plane of the orifice being always kept at right angles to the jet, it will be found that the velocity of the air along the axis of the stream diminishes continuously from the jet orifice to the breaking point. This fall in velocity is at first slow, but becomes very rapid when the manometer orifice reaches the point where the jet begins to expand.

* [August 26, 1886.—Since writing the above, my attention has been directed to two papers by Lord RAYLEIGH (Proc. Lond. Math. Soc., vol. 10 (1878), p. 4, and vol. 11 (1879), p. 1), in which the explanation of the normal tones, at least, of air-jets, is doubtless to be found.

In the first of these papers it is shown mathematically that in the case of a cylindrical jet of fluid moving in still fluid (supposed frictionless) disturbances impressed upon the jet give rise to waves which move forward with the velocity of the jet, and increase in amplitude very rapidly with the time; and that the instability of the jet increases without limit with the pitch of the disturbances.

The second paper deals, amongst other topics, with cases of jets of frictionless fluid under certain hypothetical conditions which approximate to those of the actual jets which come under experiment. It is shown that the instability of the jet, so far from increasing without limit with the pitch of the disturbances, soon reaches a maximum; and that for disturbances of still shorter wave-length than those which are most effective this instability is finally exchanged for actual stability.

It is to be hoped that the distinguished author of these papers may himself discuss their full bearing on the facts here recorded.]

Further, let the manometer orifice be moved from any point on the axis of the jet towards the circumference; a fall in velocity may again be noted which is steep near the jet axis, but becomes slower as the circumference is approached.

A similar change may be noticed just at or even inside the jet orifice; but here the fall is more steep than at external points.

Now let the manometer orifice be fixed at different points along the jet axis, and let the jet be subjected to any continuous musical vibrations by which it is affected. The vibration of the jet will then be attended by a diminution of mean velocity along the axis, which is almost imperceptible close to the jet orifice, but becomes sensible at a distance depending on the intensity of the vibration. If the vibration be gradually increased so as to cause the breaking point to approach the manometer orifice, the rate of fall becomes gradually greater; and if the jet "break" a little in front of the orifice the manometer may indicate no excess of pressure.

Finally, let the manometer orifice be placed at a distance from the axis of the jet, and very near its circumference, and let the jet be continuously vibrated as before. It will then be found that changes in the mean velocity, similarly dependent on the intensity of the vibration and the distance from the orifice, occur along the outer part of the jet, but *opposite* in character to those along its axis, for vibration of the jet now causes *increase* of pressure in the manometer.

It may sometimes happen that greater increase of pressure will be noticed at some points on the circumference of any section of the jet than at others. But by rotating the jet tube it can be seen that this depends on some want of symmetry about the orifice or of the tube behind it, and not on the direction of the sound. A jet which shows this peculiarity may also present in any section *two* (possibly more) points of maximum sound intensity when examined by a hearing-tube, indicating probably a tendency to divide or branch.

The same changes may be shown in a simpler way as follows:—Cut out of thin writing paper a small disc about a quarter of an inch in diameter, on the end of a slender slip of paper, which may serve as a handle, and let this be fixed by the stem at some distance in front of a jet, in such a way that the stream impinges on the centre of the disc. The latter will then naturally appear to be repelled, but will be kept in position by the stem, which acts as a kind of spring. Any sound will now cause the disc to move *towards* the orifice, showing a diminution of pressure against its face.

Now remove the disc and substitute for it a small flat *ring* of paper, on the end of a slender stem, the internal diameter of the ring being about 6 mms., and its external diameter about 12 mms.; and let this be so held at some distance from the orifice that the central portions of the jet pass through the ring, while the extreme outer portions strike its face. The ring will also appear to be slightly repelled while the jet is steady; but any vibration impressed upon the jet will cause it to move further *away* from the orifice, showing an increase of pressure against its face.

The motions of both disc and ring increase with the intensity of the sound, so long as they are within the breaking point.

What relation subsists between the diminution in pressure along the axis of a vibrating jet and the intensity of the disturbing sound is as yet unknown. But it is by no means improbable that, when discovered, it may supply a means of directly comparing the intensities of sounds of different pitches.

The conclusion to be drawn is, I think, that any impulse of the nature of sound, or of any other nature, causes a disturbed transverse layer to start from the orifice of an air-jet; that this layer increases in area as it advances with the jet, the ratio of the pressure at its centre to the pressure at its circumference becoming continually smaller; and that the impact of a succession of these disturbances against a hearing orifice or a flame gives rise to a sound whose constituent vibrations are copies of the disturbing vibrations.

The foregoing experiments supply an explanation of the fact that very little sound results when a vibrating jet plays into free air or into a large hearing-tube. Under these circumstances the diminutions in velocity along the jet axis, due to its vibrations, are balanced by the excesses along its outer portions, an almost complete interference ensuing when the jet breaks. But this interference is prevented when the jet strikes upon an edge or a perforated plate, in fact upon any arrangement which divides the stream into two parts, and sound is the result. A flame probably acts in this way; for inspection shows that while it is emitting sound there is no combustion at the centre of the plane of impact, but very active combustion at the circumference.

This region of active combustion under the best conditions takes the form of a ring, and the explanation of the loud sounds proceeding from it is to be found in rapid changes in the rate of combustion. The occurrence of such changes may be easily proved. Let a fine slip of very thin platinum foil be attached by brazing to two stout copper rods, and let the foil be bent and inserted in the flame in such a way that it coincides with the blue flame-ring, and is raised to incandescence. If now the copper rods be connected in circuit with a battery and telephone, both of low resistance, the changes occurring in the temperature of the flame-ring when the jet is vibrated will be communicated to the little platinum slip, causing corresponding changes in its resistance; hence will necessarily result corresponding changes in the electric circuit, so that the sound or other disturbance acting on the jet will be feebly reproduced in the telephone.

Another simple experiment may suitably find mention here. If a plate of platinum foil be raised to incandescence either by a battery current or by a noiseless blow-pipe flame, and if an air-jet at proper distance be projected against the incandescent surface (of course on the opposite side from the blow-pipe), any vibration or disturbance imparted to the jet orifice will be heard as sound from the plate, and this sound will be louder the higher the temperature to which the plate is raised. This must, of course, be due, either to expansions and contractions of the plate, caused by the varying impact of the cool jet; or possibly to the ring-shaped waves of air (if they may be so called) leaving the incandescent surface with a higher temperature and of greater volume than they possessed when approaching it.

The foregoing experiments obviously admit of many variations, which it is unnecessary to mention here.

A remarkable fact is that the vibrations set up in a jet by sound seem to be independent of the direction of the sound, and copy only its form. It is quite true that powerful impulses, such as those produced by a vibrating tuning-fork held close to the orifice, will cause the jet to divide or branch, and the direction of this branching will depend on the position of the tuning fork. But, so far as I have observed, *small* disturbances of the gas at the orifice exert the same influence, from whatever direction they may arrive.

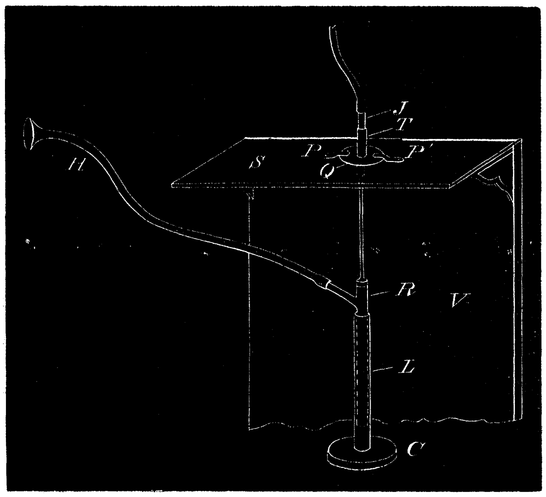
Such disturbances may be other than of a mechanical nature. Thus electric strains at the orifice may act as disturbances to the jet. A very effective way to demonstrate this, is to include a battery and a microphone or rheotome in the primary circuit of an induction coil, and to connect either of the secondary terminals with a brass-jet nozzle, mounted on the end of an insulating ebonite or glass tube; while the remaining secondary terminal is either grounded or attached to a conductor held close to the jet orifice. On talking to the microphone the words spoken may be heard from the jet in the usual way. Also by coating a glass jet tube inside and outside with platinum near the orifice, but not *at* the orifice, and connecting these coatings with the induction coil secondary terminals, we can get an arrangement capable of taking the place of the ordinary receiving telephone.

It would not serve the purpose of this paper to describe at length the great number of experiments made with jets of air and other gases. Most of them have only a secondary interest. One other fact, however, is worthy of notice. It is not only at the orifice that jets are easily affected. In fact it is easy, especially by mechanical means, to produce disturbances at a distance from the orifice. But the intensity of the effect on the jet diminishes as the distance of the point of application of the disturbance from the orifice increases.

At a very early stage in this investigation the question naturally presented itself: Would jets of water and other liquids exhibit the same properties as gaseous jets? Referring to the historical notice at the beginning of this paper, it will be seen that much more had been done in the way of reliable experiment with liquid than with gaseous jets; probably because the phenomena of such jets appeal to two senses, sight and hearing, and are therefore more easily studied. A few simple experiments sufficed to show that all the results obtained with gaseous jets may also be obtained with liquid jets, and in a more marked and satisfactory way.

As even the lightest known liquid has a very high density compared with air, we should naturally not expect liquid jets to exhibit the same *sensitiveness* to sound that gaseous jets do. Nor do they in fact; while to purely mechanical disturbances they are as sensitive, if not more so. To produce powerful effects by sound on liquid jets, it is therefore necessary to supply a lever, by means of which aërial sound-waves may act on the orifice at greater mechanical advantage. Such a lever is afforded by rigidly attaching the jet-tube to a sound-board which offers a large surface to the air. In many cases, indeed, the support or table on which the jet apparatus rests will answer all purposes; but generally it is better to attach the jet tube to a pine-board, about a quarter of an inch thick, and having a surface of about one square foot. A board of this thickness is preferable to a thinner one, since it is not so apt to play the part of a resonator, while it is equally effective in collecting sound impulses from air. Provided its surfaces are free, it is of little consequence how it is supported; but it may be conveniently attached to props at the four corners. It is also a matter of indifference whether the jet tube is parallel or perpendicular to, or forms any angle with, the sound-board.

Fig. 5.



The apparatus shown in fig. 5 is sufficient for all ordinary experiments. The sound-board, S, is screwed to two brackets, projecting from the stout vertical board, V. The latter is supported on leaden or india-rubber feet in such a way that the sound-board projects over a sink or trough.

The jet tube, J, fits in a slotted brass tube, T, which is soldered in the centre of a circular brass plate, Q, about two inches in diameter. This plate is pressed flat against the sound-board by two stout springs, P and P′. A hole in the sound-board, about three-quarters of an inch in diameter, allows the jet tube to project through it, and to be moved a little sideways. The jet tube can thus be easily changed.

The receiving surface is formed by a thin rubber membrane, stretched over the end of a brass tube, R, about $\frac{3}{8}$ths of an inch in internal diameter; this tube is provided with a lateral branch, inclined slightly upwards, to which the hearing tube, H, is attached. The tube, R, slides smoothly up and down within the slightly larger tube, L, fixed on a heavy leaden base, C. This arrangement allows the distance of the membrane from the jet orifice to be easily varied. The receiving surface ought to have a motion of at least 8 or 10 inches.

The water supply can be drawn from any kind of reservoir, capable of being fixed at different heights, and connected with the jet tube by soft black rubber-tubing. But water may also be drawn from the mains, when the pressure in the latter is tolerably constant. In crowded or noisy neighbourhoods a jet so supplied is exposed to many accidental vibrations; but these vibrations, as well as the disturbances always produced when the pressure is regulated by an ordinary tap, may be deadened by connecting the latter with the jet tube through a coiled rubber tube immersed in a vessel of water. A narrow vertical tube or a mercury gauge connected with the supply-pipe may serve to indicate the pressure.

Glass jet tubes are easily prepared in the way already described for air-jets; but care should be taken to make the drawn-out ends as obtuse as possible. What is practically an orifice in a thin plate may be obtained by heating in a blow-pipe flame the squarely cut end of a tube of uniform thickness, with constant rotation, until it has contracted so as to form an orifice much smaller than required, and then, while the glass is still soft, blowing somewhat forcibly into the opposite end.

Care should be taken to remove air-bubbles as completely as possible from the supply tube. A large bubble will frequently lodge in some bend at a distance from the orifice, and by its oscillation keep the jet violently disturbed.

The fundamental properties of jets may now be illustrated as follows:—Having mounted in the sound-board a jet tube with an orifice about 7 mms. in diameter, let the reservoir be lowered so as to cause water to escape at a pressure of 15 cms. The jet will then form a continuous column for a short distance, beyond which it becomes troubled and breaks into drops. As the pressure is raised the length of the continuous column gradually increases, until the pressure approaches 160 cms., when this portion of the jet gradually loses its rod-like character, and becomes violently disturbed. Before this point is reached, if the orifice is not perfectly circular the surface of the continuous column will appear corrugated or beaded.

Even at a pressure of 15 cms. the jet will sluggishly respond to ordinary voice sounds (which are always complex), or to taps on the sound-board or support; but will remain quite indifferent to simple musical tones of moderate pitch, and to shrill or hissing noises. The visible effect of any disturbance of brief duration will be a momentary shortening of the continuous column, after which the jet resumes its normal appearance. If the source of disturbance be a continuous musical sound of sufficiently low pitch, the shortening of the clear column will persist as long as the sound lasts, and will bear some relation to its intensity.

As the pressure is increased by raising the reservoir the range of tones to which the jet responds, and by which its continuous portion is shortened, is gradually extended, embracing notes of successively higher pitch; while it is still affected by all the lower tones. At a pressure of about 45 cms. of water it will respond to low whistled tones, and finally at a pressure of about 15 decimeters it will be affected by all the tones occurring in the human voice, and usually employed in music, with the exception of hissing sounds. At a somewhat higher pressure it will also be visibly affected by hissing noises.

These effects are not confined to jets of the size mentioned, but are exhibited by much larger and much smaller ones. But the pressure required to produce any given range of sensitiveness increases with the size of the jet, approximately in accordance with SAVART's law. It is not easy, however, except by very careful construction of the orifice, to get jets of more than 1 to $1\frac{1}{4}$ mm. in diameter to respond to sounds of very high pitch, without, at the same time, a great deal of accidental disturbance. A large jet also requires very careful insulation. On the other hand, jets of as small diameter as ·12 mm. are well adapted to show the influence of pressure on sensitiveness. But for such jets the pressure necessary to produce sensitiveness to any given tone does not even approximately follow SAVART's law, being higher than indicated by theory. Small orifices are also useless when sounds are to be produced by impact of the jet, and are very liable to become plugged by little particles of dust, unless the liquid supplied is carefully filtered.

Now, let the hearing-tube, illustrated in fig. 5, be held in the path of the jet, so that the steam impinges on the centre of the membrane, and let the jet be subjected to any continuous vibration by which it is affected, while the ear-piece of the hearing-tube is held to the ear. The following may be noted:—When the membrane is held close under the jet orifice, no sound will be audible in the ear-piece; but as the receiving-tube is gradually withdrawn along the jet path, a sound will be heard corresponding in pitch and quality to the disturbing sound—provided, of course, that the jet is at such pressure as to be capable of responding to all the higher tones to which the disturbing sound may owe its timbre. The intensity of this sound grows as the distance between jet orifice and membrane is increased. Finally, while the jet is still continuous above the membrane, a point of maximum intensity and purity of tone will be reached; and if the membrane be carried beyond this point the sound heard will at first increase in loudness, becoming harsh in character at the same time, and at a still lower point will degenerate into an unmusical roar. In the latter case the jet will be seen to break above the membrane.

Although the jet in this experiment will respond to and reproduce all tones lower than the highest by which it is visibly affected, it will not reproduce all with equal intensity, but will be most powerfully affected by some one tone or set of tones, as pointed out by SAVART. The highest of the proper tones of the jets is usually a fourth or a fifth lower than the highest which it is capable of reproducing. It is worthy of notice that jets from orifices not perfectly circular show this preference for certain tones more than strictly cylindrical jets; and it may possibly be that this preference is invariably the result of some irregularity in the orifice. The inconvenience arising from it when speech or music is to be reproduced, is practically entirely removed by increasing the pressure until the jet responds to a note of 4000 double vibrations per second, or to the highest tone easily whistled. In speech at least tones of such extreme pitch are always very feeble, and even if the jet break above the membrane when such a note is loudly sounded, it will probably not do so under the influence of spoken words.

Between the musical tones of the ordinary speaking voice, which correspond roughly with the tones of the pianoforte, and sibillant or hissing sounds, there appears to be a considerable interval. And if a jet be at such pressure as to reproduce all the tones of the piano, a much higher pressure will be required to make it respond to hissing noises. But when this point is just reached *small* jets are still sensitive to all lower sounds. Accordingly with small jets, the vibrations of which may be rendered audible in a manner presently to be described, this is the pressure best adapted for reproducing speech, music, and other sounds of all kinds. Moreover, at such pressure the tendency to reinforce particular tones is entirely lost.

At much higher pressures the sensitiveness of small jets to hissing noises becomes pronounced, but the capacity to reproduce lower tones gradually disappears, the deeper tones being the first to lose effect.

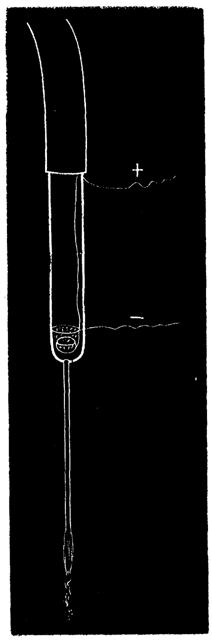
The connexion between the spontaneous vibration of a jet and its impact on some solid, is well seen as follows. While the jet is undisturbed by external sounds let the hearing-tube, or a branch from it, be brought near to the sound-board, the open, trumpet-shaped end being held quite close to it. The receiving-tube being introduced into the path of the jet near the orifice, no effect will be produced. But if the membrane be gradually drawn away from the orifice a point will be reached at which the jet will begin to "sing," at first faintly, afterwards more loudly. The singing will continue so long as the same state of affairs is maintained, but will cease when the ear-piece is withdrawn from the sound-board. Even when no special means are used to make the jet self-disturbing, the impact vibrations communicated from the membrane to the sound-board through the intervening air may be sufficient to keep the jet in vibration. If the locality be very quiet the point at which this occurs may even be reached, and the jet remain silent; but any accidental noise or vibration may disturb this state of quietude, and cause the jet to sing.

It is evidently true for liquid as for gaseous jets that all sound disturbances are propagated along the jet-path with the same velocity.

Only a highly practised ear can distinguish between the disturbing sounds and the echo-like reproduction by the jet when both are within range of hearing. In order, therefore, to form an adequate idea of the intensity of sound that may arise from the jet impact, and the marvellous accuracy with which impressed vibrations are amplified and reproduced, it is absolutely necessary that the source of these impressed vibrations should be at a distance from the experimenter. Vibrations may be very simply conveyed to a jet along the wire or cord of a "lover's telegraph." A thin cord is attached at one end directly to the support of the jet, or to the tube itself, and at the other to the centre of a parchment drum, which may be carried to a considerable distance. The connecting cord being stretched, an assistant may be directed to speak or sing to the distant drum. Or for the air-jet attached to the armature of a telephone magnet, shown in fig. 1, we may substitute a water jet, directed against a suitably placed membrane.

When spoken words are reproduced in these and similar ways, if the pressure in the reservoir be allowed to fall below that required for distinct speech, the characteristic quality of the speaker's voice, which is largely due to overtones, will first be lost; at still lower pressure, certain sounds and syllables will be missed, and the words will become unintelligible. On the other hand, if the pressure be somewhat above the necessary limit, a peculiar nasal quality will be added to the voice, due probably to the greater reinforcement of vibrations of high pitch. At still higher pressure the reproduction will become feeble, and crackling noises, due to minute air-bubbles in the liquid and other accidental causes, will become painfully loud in the ear-piece.

Fig. 6.



When the jet liquid is a non-conductor vibration may also be excited in it by electrical disturbances at the orifice. The jet-tube (fig. 6) is best made of glass. The orifice having been formed, the tube is thoroughly cleansed, and coated outside near the orifice with bichloride of platinum solution mixed with mucilage, dried, and heated to redness in the flame of a lamp, until metallic platinum is burnt into its surface, which can be effected without destroying the shape of the orifice. A fine platinum wire wound round the platinized portion of the tube forms one terminal of a secondary telephonic circuit, and a slip of platinum foil within the tube forms the other. The primary circuit may include a microphone or a rheotome, and a battery. The vibratory changes in the potential of the two secondary terminals of the circuit, caused by vibrations impressed on the microphone or rheotome, excite disturbances in the jet, which may be reproduced as sound. When, for example, words are spoken to the microphone, these words are accurately repeated in the ear-piece connected with the hearing membrane on which the jet plays.

The action in this case may depend on changes in the surface tension of the liquid at the orifice, accompanying the electrical changes. Distilled water, alcohol, ether, petroleum, &c., may be used as the jet liquid. Small quantities of saline substances in solution, and especially any slight trace of mineral acid, effectively destroy the sensitiveness of water, by increasing its conductivity.

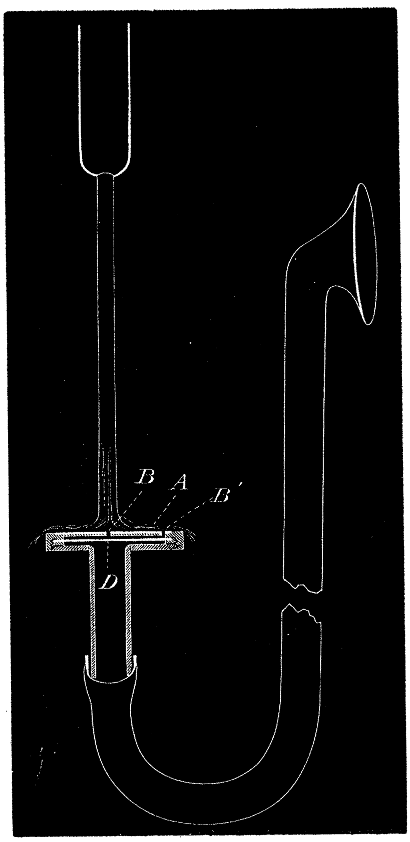
This method may be variously modified. For example either the outer or the inner electrode may be dispensed with, and the corresponding secondary terminal joined to earth.

A striking difference must have been noticed between the methods by which gaseous and liquid jets are made to excite vibrations in air. Whereas very little sound results from the impact of an air-jet on a membrane, very loud sounds are produced by the impact of a liquid jet. This might seem to indicate a difference in the character of the motions excited by vibration in jets of the two kinds of fluid. Nevertheless, it can be shown that changes occur in the normal velocity of the central portions of a vibrating liquid jet, and that these are sufficient to excite sound. Let the jet strike upon a stout brass plate, A (fig. 7), pierced with a small orifice, B, which leads to a small flat chamber, of which the brass plate forms one side. The opposite side of this chamber is formed of a thin metal diaphragm, D, through which the pulses generated in the chamber are communicated to the hearing-tube. Just as in the case of the air-jet, the loudest sounds are heard when this orifice receives the central portion of the liquid jet. Feebler sounds are produced from the compact of surrounding portions of the stream, or the jet-nappe. The chamber between A and D should of course be entirely filled with liquid; a second aperture, B′, allows the contained air to escape.

One of the most effective and most interesting methods of studying the vibrations of a liquid jet consists in including a portion either of the continuous column, or of the jet-nappe, in circuit with a battery and a telephone, by which means its vibrations become audible in the telephone. This method may be used with jets of all sizes, but most advantageously with very small ones; and as by its means something may be learnt of the changes occurring within the stream, I purpose to describe it at some length. By making use of small jets we get rid of the necessity for "insulating" the jet orifice; for the disturbances produced by impact are then so feeble as to be practically without effect. The jet is received on a smooth hard surface, which is scarcely capable of communicating disturbance to the surrounding air.

Before describing the method it is well to recall one of SAVART's observations. In one of his papers (*loc. cit.*) he describes the phenomenon of the "nappe." When a jet of water strikes normally on a small flat surface it spreads out as an exceedingly thin film in free air, in shape somewhat resembling an umbrella. This film is bounded by a kind of fringe, where it resolves itself into drops. It was regarded by SAVART as a modification of the continuous column of the jet, and he showed that the jet vibrations are preserved in it. The fringe by which it is surrounded he regarded as analogous to the troubled region.

Fig. 7.



When the jet is allowed to strike upon a large flat surface the appearances are slightly different. The liquid radiates from the point of impact, forming a thin circular film, having the jet at its centre. The film adheres closely to the surface, when this is capable of being wetted by it, and is bounded by a region in which the liquid is piled up, forming a layer many times thicker than the film. In this adherent film also the vibrations impressed upon the jet are preserved.

The electric current may be passed through any portion of the continuous column or of the nappe. It is obviously necessary that the fluid constituting the jet should have a certain degree of electrical conductivity. Many saline substances in solution will confer the requisite conductivity on water; but those substances are to be preferred which do not yield solid insoluble products by electrolysis. The most suitable liquid is distilled water acidified with $\frac{1}{300}$th of its volume of pure sulphuric acid, especially free from lead. This amount of sulphuric acid cannot be much exceeded without impairing the sensitiveness of the jet, probably by increasing the viscosity of the liquid.

By means of a battery, a telephone, and a couple of platinum electrodes, we can examine every part of a jet of this acidulated water; and the method is so delicate that changes can be detected in every point from the orifice to the discontinuous portion.

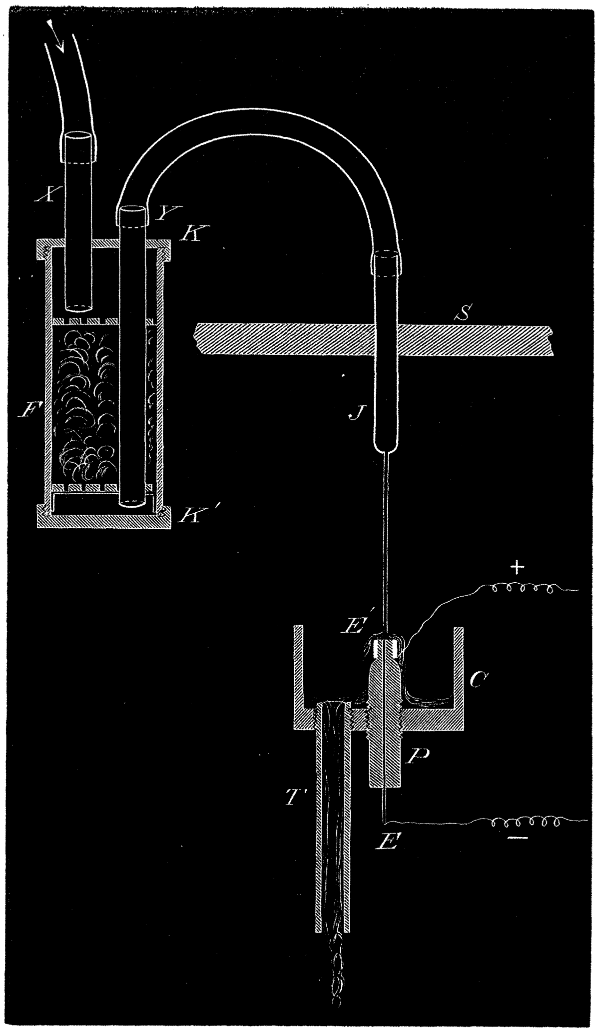
That vibratory changes are initiated in the jet stream at its origin, and during its passage through the orifice, may be proved by connecting the inner and outer electrodes of a jet tube similar to that shown in fig. 6 with the terminals of a circuit including a telephone and a battery of a few elements. Vibrations impressed on the jet orifice will then be transmitted to the telephone; and if the jet tube be mounted in a proper sound-board the most complex sounds may be reproduced. But the reproduction, although admirably distinct, is always feeble, as might naturally be expected. The pressure necessary for distinct articulation is not so high as that required when the electrodes are placed at a distance from the orifice. From this we may infer that very rapid vibrations may exist in the liquid at the orifice, which are only propagated along the jet when the stream attains a certain velocity.

Very similar results are obtained if the jet nozzle be made of platinum, and the jet be allowed to strike upon the rounded end of a platinum rod placed at a little distance from the orifice. The current may be passed in either direction between nozzle and rod. The best sounds are obtained in the telephone when the end of the rod is a little beyond the "vena contracta."

It is evidently impossible to include any length of the jet at a distance from the orifice in a circuit, without transforming it into a nappe; and I have therefore taken advantage of the fact that so far as vibrations are concerned the nappe has all the properties of the jet stream itself. The nappe formed by the impact of a steady jet against an extended flat surface is of about the same diameter, whatever may be the distance of the surface from the orifice, so long as it is formed from the continuous portion; but the intensity of the disturbances transmitted to it from the orifice increases with the distance, as for the jet itself. The simplest way of passing a current through it consists in allowing the jet to strike normally upon the exposed end of a platinum wire imbedded in an insulator, such as ebonite, which is impervious to, and unaffected by, the liquid employed. The jet spreads out from the point of impact as a nappe, which comes in contact with a platinum ring imbedded in the same surface. The wire and ring are made to serve as electrodes.

A very simple form of apparatus is shown in section in fig. 8. The jet tube, J, is mounted in the sound-board, S. The receiving surface is formed by the end of an ebonite plug, P. A platinum wire, E, passes water-tight through this plug, its exposed upper end forming the inner electrode of the "Transmitter." The outer electrode, E′, consists of a little tube of platinum foil which surrounds the wire, E, but is insulated from it by the ebonite. After it has been fitted on, the top of the ebonite plug is turned off so as to present a smooth continuous surface, slightly convex. Fine platinum wires welded to E and E′, serve to connect them with the terminals of the circuit.

Fig. 8.



The plug, P, is fitted into a small ebonite cup, C, by which it is supported, and into which the jet liquid flows; the liquid is thence carried off by the tube, T, to a vessel in which it collects and from which it may be returned to the supply reservoir. The cup, C, may be supported on any kind of adjustable stand.

An indispensable adjunct to any apparatus for experimenting with small jets is the filter, F. This may consist of an ebonite cylinder, of about the size shown, closed above and below by the screw caps, K and K′. Through the upper cap pass two tubes, X and Y. The tube Y (from the bottom of the filter) is connected to the jet tube by a piece of *black* india-rubber tubing, and the tube X, is similarly connected with the reservoir. Two perforated discs of ebonite are fitted within the cylinder, and the space between them lightly packed with coarse cotton, which has been previously treated with caustic potash, and thoroughly washed with dilute sulphuric acid and water. This filter serves to hold back bubbles of air and little particles of dirt which might stop up the orifice.

The strength of battery to be used with this "Jet Transmitter" will depend chiefly on the nature of the jet fluid. With the solution of sulphuric acid above recommended, and platinum electrodes, the resistance of the film, and the polarization resistance at the contact of the liquid and electrodes are so great that a battery of high electromotive force is required. But for the same reason the resistance of battery and line is of little consequence, and a large number of elements of small surface may be used. About twenty little zinc-carbon cells charged with a solution of sal ammoniac answer well, but this number may be exceeded with advantage. Such a battery does not sensibly polarize when connected through the film. The strength of battery cannot however be indefinitely increased; for a point is soon reached at which noises in the telephone, due to the escape of electrolytic gas-bubbles from the electrodes, completely drown the sounds due to vibratory changes of the jet. But long before this occurs, sounds of all kinds are loudly reproduced.

As I have before stated, this instrument may be adapted to jets of various sizes, the dimensions and distance apart of the electrodes being regulated by the diameter of the nappe. I have had them constructed with jets only $\frac{1}{7}$th of a millimeter in diameter, discharging about 6 c.c. of liquid per minute under a pressure of about 45 centims. Even such small jets are capable of transmitting speech loudly and distinctly; but it is difficult to get from them a good nappe, the liquid having a great tendency to accumulate on the electrodes instead of flowing evenly away. When the nappe is very small, the electrodes may therefore advantageously be formed by the exposed ends of two fine platinum wires.

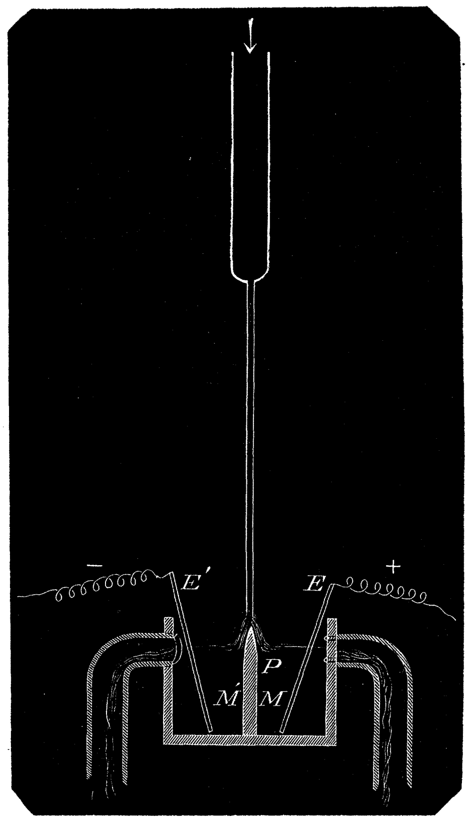
With these small instruments it is easy to demonstrate all the principal properties of jets; the absence of spontaneous vibrations, the dependence of the pitch of the fundamental tone and of range of sensitiveness on the diameter of the orifice and the pressure, the growth of disturbances along the jet path, &c.

There are two ways in which the jet may be supposed to act on the electric current. It is a fact of observation that the diameter of a vibrating jet at any point is constantly varying; and we may suppose the successive protuberances and constrictions which it exhibits, and which appear in the nappe as waves radiating from the point of impact, to interpose a continually changing resistance in the circuit; or again, the interruptions to the electric flow may take place at the contact of the liquid with the electrodes, being due to changes in the character of the motion, rectilinear or rotatory, of the liquid particles. Probably, as I hope to show, the effect is a compound one, due to both causes.

That the first of these hypotheses is amply sufficient to account for the observed phenomena is readily proved. It is not difficult to arrange a jet-transmitter so that no part of the jet or the jet film comes in contact with the electrodes.

Thus the jet, or the nappe, may make contact between two masses of liquid in which the electrodes are immersed. This is easily effected by allowing it to strike upon the sharp edge of an insulating (ebonite) partition, P (fig. 9), which separates the two masses of liquid, M and M′. At the edge of the partition the jet divides into two streams through which the electric circuit is completed. The electrodes E and E′ are small platinum plates immersed in M and M′.

Fig. 9.



Making due allowance for the increased resistance necessarily thrown into the circuit, this form of transmitter is very effective. Many other forms of this apparatus have been tried, but it is not necessary to describe them here.

If any further proof be needed, I may give the following. Du Bois Raymond has shown that the polarization at the contact of amalgamated zinc with a saturated zinc-sulphate solution is practically nil. I have therefore constructed a transmitter, having amalgamated zinc electrodes, and a jet of saturated zinc-sulphate solution. This transmitter was perfectly effective, the most striking feature about it being that very small battery power was required, a single Leclanché element being sufficient.

Nevertheless it is highly probable that "polarization" plays some part in the action. In the ordinary jet transmitter, this polarization of the electrodes, when they are small, is exceedingly intense. If, while the jet is playing, the current be sent between them for a few seconds, and the battery be then suddenly cut out of the circuit, the jet will continue to transmit vibrations to the telephone with gradually increasing feebleness for a minute or even longer. No such effect can be obtained of course with the transmitter having zinc electrodes and a jet of zinc sulphate solution.

Owing to this intense polarization it is quite impossible to measure the resistance of the nappe by any of the usual methods, which might be interesting as enabling us to estimate the thickness of the film. A small transmitter inserted in a WHEATSTONE Bridge will show an apparent resistance, varying with its dimensions and the strength of current, from 1,000 to 1,500,000 ohms. This resistance is also extremely variable, even for the same battery and transmitter: it seems to be influenced by the direction of the current between the electrodes only when these are of unequal size.

Now it is well known that part at least of the resistance included under the term "polarization," is dependent on the state of rest or motion of the liquid at the surfaces of the electrodes; and if changes occur in the motion, rectilinear or rotatory, of the jet particles, such changes might certainly influence this mechanical polarization, and thereby affect the strength of the current. I have already given one experiment which shows that vibrations induce changes in the relative velocity of the particles along the axis of the jet. The following experiment furnishes an additional proof. Just as the impact of a vibrating air-jet, playing in air against an orifice, may excite sound, so the impact of a water jet playing against electrodes immersed in water, may excite electrical undulations. In fact if both jet tube and electrodes of a polarizing transmitter be immersed in a vessel containing the same fluid with which the jet is supplied, the transmitter will not cease to operate, provided that the electrodes are brought much closer to the orifice: for the continuous portion of the jet now becomes much shortened, owing to friction against the surrounding fluid. The diagram (fig. 10) represents the most striking form of the experiment.

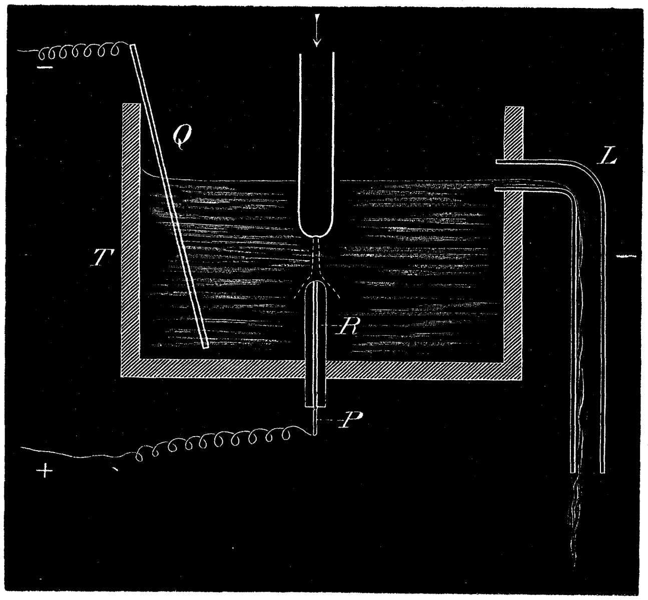
The jet plays against the exposed end of a fine platinum wire, P, firmly embedded in the centre of a small ebonite rod, R, which passes through the bottom of the trough T. A side tube, L, carries off the overflow from the trough. The end of the wire P, and a small platinum plate Q immersed in the liquid of the trough, form the electrodes between which the current is passed (in either direction). The telephonic effects with this arrangement are exactly similar in kind to those obtained from an air-jet with a small hearing orifice. The loudest sounds are heard when P is placed in the axis of the jet at a certain distance from the orifice; and the reproduction grows fainter as the electrode P is moved from this position, either towards the orifice or laterally.

The telephonic effects are feeble, but such as they are they cannot be attributed to the interposition of varying liquid resistances between the conductors.

Under these conditions, in fact, a liquid jet becomes comparable to a jet of air.

If the jet liquid be coloured the analogy becomes strikingly evident. At low pressures the continuous part of the stream of coloured liquid is elongated and unsteady, being easily swayed about by currents in the surrounding liquid : and where it becomes discontinuous it either branches or forms a divergent cone. In this condition it is not sensitive to sounds of high pitch ; but a musical tone of low pitch, or a gentle tap on the supporting sound-board, causes it to break quite close to the orifice. As the pressure is increased the breaking point first recedes from and then approaches the orifice ; and when the velocity is so great that the jet visibly responds to high tones, the continuous portion, even of a jet 1 mm. in diameter, is little more than a centimeter in length. At the breaking point the liquid then spreads out as a divergent cone, quite similar to the conical brush seen on the end of a smoked air-jet.

Fig. 10.



We have seen that very little sound results from the impact of a vibrating air-jet against a membrane : and precisely the same is true for a jet of water when both jet and membrane are submerged. But the telephonic experiment last described shows that increased effects result when the receiving surface is so small as only to be affected by changes occurring in the neighbourhood of the jet axis.

The analogy may be pushed further. If the velocity of the stream at different points be measured by introducing into its path a capillary tube connected with a vertical tube containing either mercury or water, which may serve as a manometer, a progressive fall in velocity will be indicated as the manometer orifice is moved away from the jet orifice and along the axis ; and a similar fall in velocity as the manometer orifice is moved from any point on the jet axis radially towards the circumference. The diminution in the latter case is steeper near the orifice than at a distance from it.

Again, if the manometer orifice be placed at any point in the jet axis, and if the jet be thrown into vibration, a diminution of mean velocity will be indicated, which increases alike with the intensity of the impressed vibrations and the distance from the jet orifice ; and becomes most pronounced when the disturbances are sufficient to make the jet break in front of the manometer orifice. These changes are precisely similar to those noticed in vibrating air-jets.

It is interesting to contrast with these the conditions of motion in a water jet projected into air. Using a manometer with a very small orifice in the manner already described, it is easy to show that the velocity of the jet particles at the orifice, and for some distance outside of it, is greatest along the axis, and diminishes from this outwards. At a distance from the orifice, however, a similar change is by no means so evident, partly because most large jets, which can alone be studied in this way, are usually so unsteady that it is not easy to keep the manometer orifice constantly in one position with respect to the stream ; but chiefly, no doubt, because, owing to the viscosity of the liquid, the motion of the particles tends to become uniform low down in the stream. Nevertheless I have little doubt that such a fall in velocity occurs throughout the continuous portion of the jet.

In order to detect changes in velocity along the axis of the jet, and to get rid of the acceleration due to gravity, the jet must be projected horizontally : and here the curvature of the path described introduces a new element of difficulty in the observations. But as the result of many experiments it may, I think, be stated that there is a distinct retardation of the axial portions of the jet at a distance from the orifice.

Finally, it is quite impossible to say definitely that vibration of the jet causes a diminution in the mean velocity along the axis, within its continuous portion, or that it does not. Any such change must be slight, and would of course be mainly attributable to friction of the jet against the surrounding air. That this friction is not wholly to be neglected may be shown by allowing a water jet to fall through a horizontal flame from a small orifice, near its base (fig. 11). When the flame is at a sufficient distance from the jet orifice, vibrations impressed upon the jet will cause it to emit sounds even when it is still within the continuous portion. These sounds are no doubt due to the jet carrying along with it a layer of air, which is projected against the flame.

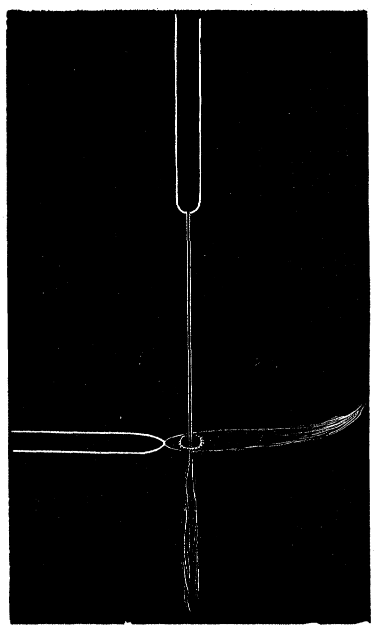
I have now given a brief description of the chief properties of jets as observed by myself and others. Nothing like a complete account of the experiments made has been attempted ; simply those have been selected which throw any new light on the subject.

It does not appear, so far, that the phenomena admit of any obvious explanation, properly so called. At the very outset we are met by the difficulty that the motions taking place within a fluid jet, even when it is not subjected to vibration, have been only partially investigated. In what follows, therefore, I shall simply indicate a few points that seem to me to have been overlooked or not sufficiently dwelt upon in treating of these phenomena hitherto, and point out certain analogies which may at least serve as guides to further experiment, even if they answer no other purpose.

Briefly stated, the facts to be accounted for are the following :—

An impulse given to the fluid at a jet orifice, or to the orifice itself, gives rise to some kind of disturbance which probably moves forward with the mean velocity of the stream, and therefore involves always the originally disturbed particles, or those immediately adjoining them. If the velocity were different for different disturbances, accurate reproduction of complex sounds at a distance from the orifice would be impossible.

Fig. 11.



The disturbance produced by an impulse in the direction of the jet, or by a sound impulse, is circular and symmetrical with respect to the jet axis, and retains its symmetrical form throughout. This is not the case when the impulse is mechanical, and in a direction inclined to the jet axis, or when the orifice is not perfectly circular. These conclusions are arrived at by inspection of instantaneous photographs of jets disturbed by sounds and by vibrating tuning-forks, &c.

A sound vibration of a simple nature conveyed to the jet orifice causes disturbance of a certain length of the column, which disturbance takes the form of a swelling and a contraction. Both swelling and contraction become more pronounced as the fluid travels away from the orifice; but at any given distance within the continuous portion successive sections of the jet represent the form of the impressed vibration. This statement, however, requires qualification; for a jet of given size and at any particular pressure, can reproduce at a distance from the orifice only a certain range of tones. But the upper limit of this range is not sharply defined, the tones lying in its neighbourhood losing their effect gradually; and it is by no means certain that, other conditions being equal, it is the same for different gases, or for different liquids.

At a distance from the orifice, depending on the intensity of the original disturbance, the constricted portion of the jet gives way, a break in the stream being the result. A succession of vibrations impressed upon the orifice therefore cause the stream to resolve itself into drops.

When the impressed vibrations are complex the length of the column corresponding to each presents minor constrictions and expansions, sometimes of very complicated outline. Breaks in the stream occur first at intervals corresponding to these lengths: the detached portions tending further to resolve themselves at a greater distance from the orifice.

The formation and growth of the swellings and contractions are attended by corresponding changes in the velocities of the axial particles of the jet. These changes may be characterised as accelerations and retardations of the velocity measured along the jet path.

When a jet escapes into a fluid which offers a sensible resistance to its motion, its axial particles suffer a gradual retardation. But this retardation is greater when the jet is disturbed by vibrations than when it is in its normal condition.

Such are the phenomena; how far are they explained by theories hitherto accepted? In view of the striking parallelism of the properties of gaseous and of liquid jets, it will hardly be considered inadmissible to assume that the most satisfactory explanation will be that which refers both to the same origin. In the two kinds of jets we have the same tendency to vibrate at some definite rate; the same growth of vibratory changes along the jet path; similar phenomena of discontinuity manifested at a certain distance from the orifice; and similar changes in the motion of the particles of fluid along the axis.

SAVART and SONDHAUSS have occupied themselves chiefly with the origin of normal vibrations: PLATEAU alone explained not only their origin but also their growth. Now, simple inspection of the table given by SAVART of tones generated in a tube reservoir by efflux of water from an orifice in its lower end, shows that these tones are much higher in pitch than those which would result from the impact of the jet against a stretched membrane. Vibrations originating in this way cannot therefore account for the normal jet vibrations, which are invariably connected with impact.

With regard to SONDHAUSS's idea, viz., that the jet is comparable to a solid rod thrown into vibration by friction against the orifice, it must be admitted that the analogy was not wholly without foundation. If spontaneous vibrations be excited in an air-jet in the manner I have described, it will usually be found that the pitch of the tone rises as the hearing orifice is moved towards the jet orifice. But this does not go on indefinitely; for after the tone has risen through an interval of about a third, it suddenly returns to its original pitch, again rises, again falls, and so on, until the impact disturbances become too feeble to re-act upon the fluid at the orifice. The analogy, therefore, is incomplete; and, moreover, does not take into account the peculiar changes in the motion of the jet fluid.

So peculiar are these changes, that the term "vibration" as applied to them seems to me entirely misleading. By this term is, commonly at least, signified a kind of motion, in which each particle of the vibrating body executes oscillations about a mean position, whether of rest or of steady motion, to which it tends to return when its motion is interfered with. But in a sounding jet the motions are not of this kind. Any vibration impressed on the orifice, produces a disturbance which tends to grow always in a definite direction; and when the motions are interfered with, the particles do not return to their original positions.

PLATEAU * on the other hand referred the normal vibrations of a jet to quite a different origin. Regarding the jet as a stationary cylinder of liquid, he proved experimentally that under the influence of the "forces of figure" alone, it would break up into shorter cylinders, the length and diameter of which would bear to each other a constant ratio. Each cylinder would further tend to assume a spherical form, by diminishing in length and increasing in diameter. Such changes must necessarily be attended by growing constrictions between successive cylinders; and, finally, disruption must occur at these points, a succession of drops being detached from the stream. At the moment of its liberation, each drop would be in a state of tension or elongation, and thereafter would execute oscillations about its form of stable equilibrium—the sphere. These oscillations always reaching the same phase at a definite distance from the orifice, would give rise to the appearance of the "ventres" or swellings, noticed by SAVART in the discontinuous part of a liquid jet. The tendency to divide would of course exist in the liquid cylinder from the moment of its formation; but when the impulses due to the impact of the successive drops upon an obstacle are conveyed back to the orifice, they materially assist this tendency, and the stream consequently resolves itself into drops nearer to the orifice.

The normal vibrations of a liquid jet are thus completely and satisfactorily accounted for; and PLATEAU by an ingenious train of reasoning, showed also that division might even occur at other than the normal points, thus explaining SAVART's observation, that a jet could vibrate under the influence of tones about one-fifth higher, and an octave lower, than its normal. Moreover, Lord RAYLEIGH in a later paper † has pointed out that theoretically the lower limit of effective tones is not well defined, thus bringing PLATEAU's theory into closer agreement with the facts described in this paper.

Now, while it is impossible to deny to this theory the merits of simplicity, of firm experimental foundation, and of being in harmony with facts previously known, there are, I think, cogent reasons why it cannot be held to account for the new phenomena described above. In the first place it is a fact of experience, already noticed by

* Phil. Mag. ser. 4, vol. 12 (1856), p. 286, and vol. 14 (1857), pp. 1 and 431.

† Proc. Roy. Soc., vol. 29 (1879), p. 71, and vol. 34 (1882), p. 130.

SAVART and MAGNUS,* and easily verified by means of the "Jet Transmitter," that a jet from a perfectly circular orifice, carefully protected from vibrations, does not spontaneously divide in a regular manner. On the contrary, rhythmical division only takes place under the influence of external vibrations, or of the disturbances produced by impact, or when the orifice is irregular. It was quite natural that this should have been denied by PLATEAU; for it can be readily understood from the experiments given above, that perfect insulation of a large jet from the vibrations of any solid body on which it strikes, by means of which solid body the musical character of its vibrations could alone be ascertained, is extremely difficult. With small jets, however, such as can be used in the transmitter, this insulation is comparatively easy. Now, experiment shows that the electrodes may be placed even in the *discontinuous* part of a small well-insulated jet, and yet no musical vibrations be excited in the telephone. When we consider that the electrical method is so delicate, that the effects of communicated vibrations are by it perceptible even at the orifice, it is difficult to believe that spontaneous rhythmical divisions could exist without manifesting themselves lower down.

In the second place, the "forces of figure" which cause the resolution of a liquid cylinder at rest, cannot be considered as solely operative in bringing about the changes which take place in a jet vibrating under the influence of sounds lower in pitch than its normal. Experience shows that whatever may be the rate of the impressed vibrations, within the prescribed limits, and however complex their character, all produce disturbances which grow equally along the jet. As I understand PLATEAU's theory, developed by Lord RAYLEIGH, this would not be the case with disturbances growing under the influence of surface tension alone. The forces of figure, then, either must act in some definite way in both cases; or, if in the latter, they are entirely subordinate to, and controlled by, the impressed forces, some further condition than the mere form of the jet must be taken into account to explain the difference. In fact, their sole action seems to be that they fix an upper and ill-defined limit to the rate of vibration of the jet. With all vibrations below this limit they do not in any way interfere.

The conclusion to be drawn is rather that a jet, at least in its upper part, is *not* comparable to a liquid cylinder at rest. I shall show reason for believing that it may become so at a distance from the orifice; and also that the resemblance may be more pronounced in large jets than in small ones.

It is at once obvious that PLATEAU's theory is quite inapplicable to gaseous jets,† the phenomena of which are strictly parallel to those of liquid jets, and identical with those of a liquid jet playing within a mass of similar liquid, in which the "forces of figure" are necessarily entirely abolished. An examination of some instantaneous shadow-photographs of vibrating jets of air, rendered slightly opaque by smoke, has proved to me that these jets also present swellings and contractions precisely

* POGGEN. Annal., vol. 95 (1885), p. 1, and vol. 106 (1859), p. 1.

† See note on Lord RAYLEIGH's mathematical papers.

similar to those seen in liquid jets, and that these changes grow along the jet-path. I have only been able so far to observe this drop-like appearance in jets at low pressure, and even then the outline is somewhat obscured by trails of smoke detached from the stream. I hope, however, to succeed in getting good photographs of jets at high velocities. The practical difficulties in the way can no doubt be overcome.

It seems to me that the true key to an explanation of the vibratory phenomena of both liquid and gaseous jets is to be found in the fact that the velocity of the stream issuing from a circular orifice is not equal at all points, but diminishes from the centre, or jet axis, outwards. When the efflux takes place from a straight circular tube (and even such a jet is "sensitive") this may be caused by adhesion of the fluid to the sides of the tube, or by friction; but when the jet issues from a hole in a thin plate it is no doubt chiefly due to the convergence of the stream lines towards the orifice. This will tend to cause retardation of the normal velocity of the outer layers of fluid: indeed *at* the orifice the outermost layer of a liquid must be in a state of absolute rest. The fall in velocity from the centre of the stream outwards must evidently be more steep in small jets than in large ones; and as I have pointed out, it is precisely the former which give the most accurate reproduction of impressed vibrations.

The normal jet, then, as it leaves the orifice is composed of an infinite number of cylindrical streams, the velocity of each being uniform in any section of it, but varying in some inverse ratio with its diameter. We thus have in the jet the characteristics of the forward motion of a vortex ring; and the motions of a jet may be considered to be the resultants of the motions of an infinite number of parallel and coaxial vortex rings, moving forward with the same velocity.

This comparison of the jet with a series of vortex rings is not entirely fanciful, for experiment shows that when a jet and a vortex ring are projected from similar orifices, the outline of the jet at successive points along its path shows precisely the same shapes that are successively assumed by the vortex ring. For example, all sections of a jet from a circular orifice are circular, provided that there is nothing to interfere with the free motion of the fluid behind the orifice. With the same proviso, the smoke ring from a circular aperture remains always circular. If a jet orifice be elliptical, and the pressure not too high, successive sections of the jet as we proceed from the orifice will be alternately circular and elliptical, and the major axes of successive ellipses will be at right angles to each other. Now these succeeding shapes also characterize the well known vibrations of a smoke ring projected from an elliptical aperture. These analogies might easily be multiplied. Again, if the aperture in a smoke ring box be an elongated rectangle, a suitable tap on the diaphragm will frequently cause the projected ring to break up into two divergent rings, thus imitating the division of a vibrating jet into two streams; a phenomenon which, when occurring under the influence of sound vibrations, I believe to be invariably due to some irregularity at or behind the orifice.

Now, in a perfect fluid the system of rings composing the jet would continue indefinitely: in the actual jet two forces tend to their destruction, viz., internal friction, or the viscosity of the fluid, and friction against the surrounding medium. In liquid jets in air the first of these is mainly operative; but when the jet is surrounded by a fluid of its own kind, the second is most effective.

In the first case (of a liquid jet in air) internal friction must bring about a gradual equalization of the velocities of the liquid particles, and at a distance from the orifice the jet will therefore approach the condition of a liquid cylinder at rest. As it does so it will gradually come under the operation of the "forces of figure," will divide, and ultimately resolve itself into drops. Owing to minute variations in the motions of the jet fluid the divisions will be somewhat irregular, but in the main they must tend to assume a rhythmical character, as pointed out by PLATEAU.

The point at which discontinuity becomes apparent cannot, however, depend solely on the viscosity of the liquid, but must also depend on its superficial tension, which determines the *rapidity* of drop formation. If this theory is correct, it should be found then, that those liquids which are most mobile, and have the lowest surface tension, yield the longest continuous jets. Now experiments made by SAVART have already shown this to be the case, although he connected the continuity of a jet with the compressibility of the liquid. Causing jets of ether, alcohol, and water to escape from a circular orifice 3 mms. in diameter, and under a pressure equal to 50 cms. of the liquid, he found the continuous columns to be 90, 85, and 70 cms. in length respectively. The compressibility of the liquids are to each other as 131·35 : 94·95 : 47·85, in accordance with SAVART's theory. On the other hand, the coefficients of internal friction are ·59213; 1·3754 and 1·1858 for these liquids respectively (HELMHOLTZ and PITROWSKI), and the superficial tensions in contact with air 1·88, 2·5 and 7·3 milligrams per millimetre. SAVART's observations are, therefore, equally in harmony with the theory here proposed. Thus, while water and alcohol do not differ widely in viscosity, drops are sooner detached from a jet of the former liquid since it has the greater superficial tension.

Both superficial tension and viscosity diminish with rise of temperature; we should, therefore, expect to find that, other conditions being equal, a jet of hot liquid preserves its continuity through a greater distance than a jet of the same liquid cold. This I have found to be the case. In one experiment the continuous part of a jet of distilled water at 10° C. was about 17 cms. in length; but increased to about 20 cms. when the water was heated to 70° C.*

When a gaseous or liquid jet plays within a mass of fluid of the same kind, and when accordingly "forces of figure" do not exist, the analogy to a system of smoke-rings in air is much more evident. The action of internal friction in equalizing the velocities at different points in any section is now insignificant; but the jet rapidly

* Lord RAYLEIGH (Phil. Mag., ser. 5, vol. 17 (1884), p. 192) has already pointed out the remarkable influence of viscosity, modified by changes in temperature, on the "flaring" pressure and sensitiveness of a liquid jet in liquid.

loses energy by setting up rotatory or other motions in the surrounding medium. The rate of this loss depends on the velocity of the jet; and since the outer layers are most retarded, it is attended by increased vorticity. Now, at very low pressures, the fall in velocity from the axis outward is not steep, and the jet, therefore, travels as a nearly uniform stream to a considerable distance. Up to a certain point the length of the continuous stream increases with the pressure; and where discontinuity occurs the jet appears to dissipate rather than to break up in any regular manner. The continuous column of a smoke jet in air may thus extend to 12 inches, and of a coloured water jet in water to 4 or 5 inches, when the orifice is from 1 to $1\frac{1}{2}$ mm. in diameter. If the jet in this condition be disturbed by a gentle tap on the supports, a break appears close to the orifice, and behind the break a portion of the fluid appears to be thrown off from the main stream. In the mass thus detached distinct rotatory motions may be seen similar to those observed in a smoke ring when it has nearly reached the end of its career, and is almost stationary.

The production of vortex rings by interrupting the flow of a water jet in water, has already been noticed by OBERBECK.*

When the pressure is increased to a point at which the jet answers to tones of high pitch, the appearance changes. The nearly cylindrical part becomes much shorter, and beyond this the jet expands rapidly in the form of an aigrette, or divergent brush. The motion may then be compared to that of a smoke ring which travels with nearly uniform diameter for a certain distance, but which expands rapidly when its velocity has been considerably reduced by the surrounding air.

I have mentioned above that when a vibrating jet of air is directed into the trumpet-shaped end of a hearing-tube, its vibrations are almost quite inaudible; but that relatively loud sounds are produced when the hearing orifice is very small and placed in the jet axis. A phenomenon strictly parallel to this may be noticed with vortex rings in air. Let a ring, for convenience rendered visible by smoke, be projected into a large funnel connected by a tube with the ear, and the only sound resulting from its impact within the funnel will be a kind of rushing noise. But let it be projected against a *small* orifice in the end of the hearing-tube, and a sharp click will be heard when the ring strikes the orifice. This click will be loudest when produced from the centre of the ring, and faintest, although still sharp and clear, when produced from its circumference. The analogy is thus complete. These effects may be obtained from the ring so long as it continues to move.

Now, assuming that a jet is composed of an infinite number of circular vortex filaments, vibrations impressed upon the orifice may be supposed to act somewhat in the following way. The vorticity of the jet, as we have seen, is the result of the unequal velocities of the layers composing it. Any disturbance, therefore, which alters the rate or distribution of velocities at the orifice, must also change the vorticity of the jet. To take a simple case, let the vibratory motions of the orifice

* Annal Phys. Chem., ser. 2, vol. 2, pp. 1-17.

take place in the direction of the jet, and let the (liquid) jet play into free air. The motions of the orifice being rapid, and the liquid mobile, the velocity of the stream through the centre may be supposed to remain constant. During a forward motion of the orifice we shall then have acceleration, and during a backward motion retardation, of the velocities of the outer layers of the jet. The first change necessarily implies expansion and diminished vorticity, the second contraction and increased vorticity. If we imagine the motions of the orifice to be produced by two rapidly succeeding impulses in opposite directions, the result will be the formation of two vortex rings of unequal size and strength, which will accordingly begin to act upon each other in a known manner. The foremost ring will go on expanding, its velocity at the same time diminishing, while the hindmost ring will contract, its velocity at the same time increasing. This action will continue until either the constricted portion of the jet gives way, or the vortical motions are destroyed by internal friction, and the forces of figure gain the upper hand.

The growth of an expansion and contraction are thus accounted for, if we suppose that the action of neighbouring parts of the jet on the two vortices is small in comparison with their mutual action. Moreover, as this mutual action of two rings varies inversely as some power of the distance between them higher than the second, changes once started at the orifice must increase very rapidly with the time.

Now it is evident that the portion of the jet which has passed through the orifice during the time that this has taken to execute a complex vibration, must present swellings and contractions at successive points proportional to the varying velocity of the orifice; and in this case, for the sake of simplicity, we may imagine as many pairs of unequal vortex rings to be developed in the jet as there are simple vibrations in the impressed complex vibration. The larger rings will then grow at the expense of all smaller rings; and the result will be that the changes in the jet will go on increasing until disruption occurs at a distance from the orifice.

Since the expansions and contractions of the rings are attended respectively by diminution and increase of their velocites, both rotatory and translatory, there must be corresponding variations in the velocities, measured along the jet-path, of the particles of fluid involved in them. Leaving out of consideration the motion of translation of each ring, the motions of the central and circumferential particles are in opposite directions, and the sum of the velocities in one direction must be equal to the sum of the velocities in the opposite direction. The changes produced by vibration must therefore be apparent at every point of a jet; but since the stream lines of a vortex ring are crowded together near its centre, these changes must be most intense along the jet axis, and most feeble along its outer portions. Again, when the rings are destroyed, either by friction or by directing the jet into a trumpet-shaped tube, the opposing external and internal velocities neutralise each other in the main. On the other hand, when the jet strikes upon any object, such as a perforated plate, which divides each ring into two parts, this interference must be more or less incomplete.

When a jet of liquid escapes into a medium which offers little resistance to its motion, no change, or at any rate only a slight change, can be produced by vibration in the *mean* velocity along its axis. For here the accelerations are balanced by the retardations; and as these changes succeed each other very rapidly, they are incapable of affecting the sluggishly moving manometer, although quite capable of acting on the highly sensitive mechanism of the ear. When, however, the jet plays within a medium which sensibly resists it, the case is different. Even in its normal state the stream gradually parts with its energy to the surrounding fluid, and therefore expands while its velocity diminishes. But when it is thrown into vibration, owing to the greater surface exposed to the medium by the swellings and contractions, the loss of energy and consequent expansion become more rapid; and hence results a diminution of mean volocity. For the same reason, we have in the outer layers, or in the medium immediately adjoining, an increase of mean velocity when the jet is thrown into vibration.

It has been assumed so far that the disturbances communicated to the jet are of the nature of impulses. But the same reasoning can be extended to cases in which the motions of the orifice are undulations, even of such long period that one whole vibration cannot be included in the continuous part of the jet. For here each infinitely thin section of the jet can be regarded as an independent ring or system of rings, which grows or contracts at the expense of adjacent sections.

I have also assumed that the motions of the orifice take place in the direction of the jet. But it is evident that lateral impulses may also alter the vorticity of the stream, and the disturbances will then not be symmetrical. Want of symmetry is not apparent when a jet is disturbed by sounds produced at some distance, whatever their direction; but it is very evident in the photographs of liquid jets thrown into vibration by tuning forks applied to the support. The planes of the rings in the jets, and the transverse diameters of the drops into which it is resolved, are seen not to be always perpendicular to the axis.

It hardly needs to be pointed out that impulses communicated to the fluid either behind or external to the orifice, may cause disturbances precisely similar to those resulting from motions of the orifice itself. Experimentally we know that vortex rings must be produced in this way.

The properties of a jet may undoubtedly be profoundly modified by the viscosity or surface tension of the fluid. When the fluid is highly viscous an impulse communicated to the orifice will tend to produce acceleration or retardation of the whole layer of fluid included within it; and even if the fluid is only moderately viscous, the inequalities of motion constituting vorticity, in virtue of which the initial disturbances tend to grow, must rapidly disappear. On the other hand, the surface tension of a liquid may be conceived to accelerate, to a certain extent, the growth of the vibratory changes. We have an extreme case of this kind of action in jets of mercury, which are not only highly sensitive, but break very easily under the influence of sound. This may be seen by letting the jet fall into a basin of mercury, and including it in circuit with a battery and coil. Viewing it in a dark room, sparks will then appear wherever breaks occur, and may frequently be seen quite close to the orifice when the jet is disturbed by moderately loud sounds. The vibrations of a mercury jet become much more regular when it is surrounded by water.

In the foregoing I have given the outlines of a new theory of jet vibrations. Treading on somewhat unfamiliar ground, I have endeavoured to base it, as far as possible, on purely experimental considerations. It would be useless to deny that there are many points in which the theory, taken as a whole, is deficient; and my hope is that others, who have made a special study of vortex motion, may be able to supply what is wanting. The strongest claim to attention that can be urged for it is certainly that it refers the otherwise very similar phenomena of gaseous and liquid jets to conditions of motion which may be experimentally demonstrated in fluids of both kinds. Whether or not the theory can stand the test of mathematical treatment remains to be seen. But even should it ultimately prove to have no more solid foundation than analogy, the experimental part of the inquiry which has led to it may still have some value as a contribution to our knowledge of an exceedingly interesting, if somewhat obscure, class of phenomena. Many lines of thought and experiment are already suggested, and on some of these I hope to report at an early date.