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ON ACOUSTIC PRESSURE AND ACOUSTIC DILATATION

1. *Introductory. Apparatus.*—On a number of occasions, heretofore[1] I have endeavored to use the interferometer for the measurement of Mayer and Dvorak's phenomenon: but though the experiments seemed to be well designed and were made with care, they invariably resulted in failures. The present method, however, has been successful and led to a variety of results.

The apparatus is shown in Fig. 1, where B is a mercury manometer described elsewhere, the displacements being read off by the component rays LL' of the vertical interferometer. The mercury of the U-tube is shown at $m\ n\ m'$, above which are the glass plates g, g', the former being hermetically sealed, the latter loose, so that the air has free access. The closed air chamber R above m, receives the air waves from the plate of the telephone T by means of the quill tubes t hermetically sealed into the mouthpiece of the telephone, and t' sealed into the manometer. Finally t'' is a branch tube ending in a small stopcock C or similar device at one end, while the other communicates with tt'. Flexible rubber tube connectors may be used at pleasure, so long as the space bounded by the outer face of the telephone plate, the mercury surface m and the stopcock C is free from leaks.

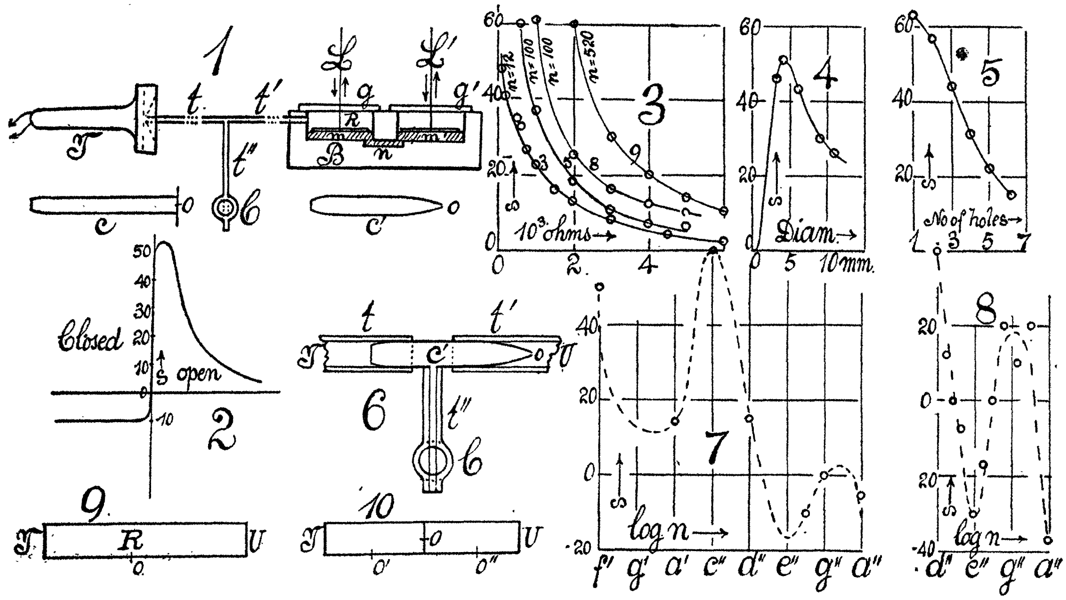
The cock C will eventually be replaced by the glass tubes c and c' (enlarged) perforated with minute orifices at O at one end and open at the other.

The telephone is energized by two storage cells and a small inductor with a mercury or

[1] Carnegie Publ., No. 149, part III., pp. 206–08, Washington, 1914, and subsequently. The phenomenon has been studied by Rayleigh, Kolacek, Lebedew, Wien, Geigel and others. As to hydrodynamic forces in pulsating media, the researches of Bjerknes and W. König should be mentioned.

other break. Large resistances are to be put in the telephone circuit so that the inductances are of secondary importance. The bore of the tubes *t*, *t′*, *c*, *c′* need not exceed 5 mm. Thus the chamber in *B*, about 6 cm. in diameter and 2 cm. deep, is the resonator (capacity 57 cm.^{3}) of the apparatus.

When the cock *C* is closed there is no appreciable effect until the telephone resounds harshly. In such a case there is marked dilatation in the resonator *R*, increasing with the intensity of vibration. The successive readings (*s′* fringes) are liable to be fluctuating, but the sign and mean value is definite.



FIGS. 1 TO 8

The displacements of the achromatic fringes corresponding to the head of mercury in *B* may be read off by a telescope provided with an ocular .1 mm. micrometer. It is perhaps advantageous to place the micrometer in the wide slit of the collimator, the fringes being parallel to the scale parts. To obviate the need of adjusting the inclination of the fringes (as this frequently changes), the slit holder should be revolvable around the axis of the collimator, the scale being parallel to the length of the slit and the fringes moving in the same direction across the white ribbon-like field. Fringes equal to a scale part in breadth are most convenient.

2. *Observations. Closed and Open Resonators.*—Spring interruptors dipping in mercury were first used, having frequencies of $n = 12$ and 100 per second, respectively.

Since for $s' - s_0 = s$ the head is $s\lambda/2$ (the displacement being *s* fringes of wave-length λ), this mean value, $s = 7$ fringes for the given intensity of vibration, is at once equivalent to $\Delta p = 2 \times 10^{-4}$ cm. of mercury, or to about 3×10^{-6} atmosphere. If but 500 ohms are put into the telephone circuit, however, appreciable deflection ceases.

Again, if the stopcock *C* is completely open no effect whatever is obtained. The bore of the small stopcock in this case need not exceed 2 or 3 mm. All the negative results which I obtained by other methods heretofore are thus explained.

3. *Resonator All but Closed.*—If now the plug of the cock *C* is rotated from the open position gradually until the opening is reduced to the merest crevice, the fringe deflection *s* will, on further slow rotation, be

found to increase from zero, with great rapidity to a positive maximum. The deflection then falls off with similar rapidity through zero to the negative value when the cock is again quite closed. I have indicated this result graphically in Fig. 2, in which the abscissas show the degree to which the cock has been opened and the ordinates the fringe deflections, s, obtained. The maximum pressure obtained in these initial experiments was the equivalent of about 50 fringes; *i.e.*, $\Delta p = 1.5 \times 10^{-3}$ cm. or about 2×10^{-5} atmosphere for a frequency of about 12 per second. At higher frequencies this datum is much increased.

These pressures are real: for on suddenly closing the cock at the maximum and breaking the current, they are retained until discharged on opening the cock.

4. *Pressure Depending on the Frequency and on the Intensity of Vibration.*—The maxima are observable for very considerable reductions of the intensity of vibration. In Fig. 3 curves 3, 5, I have given examples of the observed fringe displacement, s, when different resistances (given by the abscissas in 10^3 ohms) are put in the telephone circuit. In curve 3 the frequency is $n = 12$ per second. Curve 5 contains similar results when the frequency is $n = 100$ per second. The sensitiveness has obviously greatly increased and in a general way this is the case for higher frequencies.

5. *Fringe Deflection Varies as Current Intensity.*—The graphs, Fig. 3, are roughly hyperbolic, so that the equation $rs = C$ (r being the high resistance inserted into the telephone circuit) may be taken to apply within the errors of observation for resistance exceeding 1,000 ohms. So computed for convenience rs is 24×10^3 in series 3 and 36×10^3 in series 5. Hence at $r = 100$ ohms the pressure would have been 7×10^{-3} and 1.1×10^{-2} cm. of mercury. The instrument taken as a dynamometer is thus noteworthy, since its deflections would vary as the first power of the effective current or $i = i_0 s$. It is of interest, therefore, to ascertain how far the sensitiveness which can not here be estimated as above 10^{-4} amperes per fringe, may be increased.

6. *Pin Hole Sound Leaks.*—Pin holes less than a mm. in diameter seem more like a provision for light waves, than for sound waves often several feet long; but one may recall the phenomenon of sensitive flames.

It is so difficult to make the fine adjustment for maximum conditions with stopcocks that their replacement by the devices given in c and c', Fig. 1, is far preferable. Here c is a quill tube, to one end of which a small sheet of very thin copper foil has been fastened with cement. The sound leak at O is then punctured with the finest cambric needle. The other end (somewhat reduced) is thrust into a connector of rubber tubing *at* t''. In case of c' the tube has been drawn out to a very fine point. This is then broken or ground off until the critical diameter (.04 cm.) is reached. Both methods worked about equally well but in the case c several holes side by side or holes of different sizes may be tried out. Such results are shown in Fig 4, which exhibits the deflection (s fringes, ordinates) for different diameters of hole in mm. (abscissas), when 1,000 ohms were put in the telephone circuit. It will be seen that the optimum .4 mm. in diameter is quite sharp. The finest size of needle is needed.

An example of results obtained with the sound leak c when different resistances are in circuit, is given in Fig. 3, curve 8. The value of rs; viz.,

s	51	25	16	12	10	5	fringes
$10^{-3}r$	1	2	3	4	5	10	ohms
$10^{-3}rs$	51	50	48	48	50	50	

is much more constant than hitherto and reaches 50×10^{-3}. Hence at 100 ohms the pressure increment should be $\Delta p = 1.5 \times 10^{-2}$ cm. of mercury.

Figure 5 finally indicates that the multiplication of pinholes, all of the same diameter (.04 cm.) is similarly disadvantageous. The deflection for four holes is scarcely half as large as for one.

If with the current on, a drop of water is placed on the hole O in c, Fig. 1, the pressure is long retained whether the current is thereafter broken or not. It is gradually dissipated, however, as the joint at the telephone plate is rarely quite tight; and when the telephone sounds, pressure increments may even become negative, as above. If most of the water is removed by bibulous paper a moderate fairly constant pressure is usually observed for some time, until (doubtless with the breaking of the film across the hole) the maximum is suddenly again attained.

7. *Inside and Outside Stimulation.*—When the tube c' is inserted within the rubber connectors t, t' in the absence of vents, there is much undesirable pressure disturbance at the outset, which is but very slowly dissipated. Moreover the closed space can not be opened again at pleasure without similar commotion. I, therefore, used the apparatus, Fig. 6, in preference, in which the pinhole tube c' is provided with a branch tube t'' and cock C. The rubber tube t leads to the telephone (beyond T) and the tube t' to the mercury U-tube (beyond U). If C is open, c' may be inserted or withdrawn with facility. If C is closed the resonator R is closed, as in the above case.

Using the mercury interruptor (frequency c) with 2,000 ohms in circuit the deflection of the closed region was invariably negative. The deflection is peculiar, moreover, inasmuch as it is a slow growth within a minute or more, to a maximum. On breaking the current the deflection dies off in the same slow fluctuating way. If the cock C is opened, the zero is instantaneously recovered. In other words the dilation is due to a loss of gas within the closed region, which loss is but slowly restored after the telephone ceases to vibrate.

If the cock C, Fig. 2, is opened at the critical point, or if it is replaced by the tube c, the deflection is again positive. The action of c thus exceeds that of c', probably because the pinhole in c happens to be nearer the critical size than in c'.

The question next at issue is the influence of pitch upon the dilatation of the closed resonator R. An electric siren (§ 8) was here used with 2,000 ohms in the telephone circuit. The results appeared about as follows:

g' to b'	c''	d'' to e''	f''	g''	pitch
—5	—25	maximum estimated at —200	—35	0	fringes

There is thus an enormous maximum dilatation somewhere in the range of frequency d'', e'', which from the hovering character of the deflection is not further determinable. This amounts to a pressure decrement of $\Delta p = -6 \times 10^{-3}$ cm. of mercury with 2,000 ohms in the telephone circuit. At 100 ohms it would have been about a millimeter of mercury.

The slow growth of relatively enormous pressure decrements here recorded is so surprising that further experiments are needed. To begin with one may ask whether the telephone plate, held as usual by strong screw pressure between annular plates of hard rubber, is adequately airtight. I therefore removed the telephone and sealed all these parts with cement, thoroughly.

On replacing the telephone with the adjustment as in Fig. 6, the behavior had in fact changed, the negative pressure being of the small value indicated in §2, without growth in the lapse of time. In other words the presence of the pinhole c' within the closed region was now ineffective.

We may summarize these early results for the particular frequencies used, as in Figs. 9 and 10. In an air region R, closed on one side by a vibrating telephone plate T and on the other by a quiet plate U, the pressures are distributed as if there is a maximum at T and a minimum at U. If the region R, Fig. 9, communicates with the atmosphere by a pinhole O of the critical diameter, the pressure within R is raised as a whole by the amount which the pinhole air valve will withstand. Again if the closed region T U, Fig. 10, contains a pinhole valve O within only, it does not differ essentially from the corresponding case in Fig. 9; but if an additional very fine leak O' is supplied on the T side, Fig. 10, the U side gradually develops a large pressure decrement; whereas if the pinhole is supplied on the U side, this develops the usual pressure increment. In the former case air leaks out of O' diffusively; in the latter it leaks into O''.

After many trials, however, only in one case did I succeed in obtaining pressure decrements with pinholes, screw cocks, etc.; this when lost could not be recaptured; but all the present and following results in acoustic dilatation were strikingly reproduced by putting a new telephone with unsealed plate in circuit.

With the apparatus, Fig. 1, and the cock C opened at the critical point, a diapason c'' blown in the vicinity of the cock was easily identified and the octave c''' even three times as active (15 fringes). In another adjustment, the shrill overtone gave nearly 100 fringes. There is some misgiving in interpreting these data, as the open mouth of the pipe must usually be closed to the mouth of the cock; but as the overtone was still appreciably effective six inches to a foot away, the results are probably trustworthy.

8. *Effect of Resonance.*—While a parallel relation of the maximum pressure to the frequency of the telephone note has been shown to exist, it is obvious that the best conditions for high maxima will occur under conditions of resonance between the natural R and the T vibrations (Fig. 1) or their harmonics. I, therefore, used the same small induction coil with two storage cells, but with a commutator-like current-breaker, controlled by a small electric motor with a variable resistance in circuit (electric siren). By gradually decreasing this resistance all chromatic intervals between about f' and a'' were obtainable. The speed of the motor, however, fluctuated slightly, while intervals within a semitone often produced large pressure differences. Thus the determinations of the intervals of a somewhat flickering pitch in all chromatics is quite difficult, even for a musical ear. A series of organ pipes within the given range seemed to offer the best standards of comparison, as it was necessary to turn rapidly from one series of observations to another.

In this way the graphs given in Figs. 7, 8, were worked out, the curves showing the fringe displacement s to the logarithmic frequency n of the telephone. In Fig. 7, to limit the deflections within the range of the ocular, about 2,000 ohms were put in circuit. Three maxima and three minima (one positive and two negative) are indicated. The maximum below f' could not be reached. The strong one at c'' was well marked and approachable from both sides. The small one near g'', though easily observed by continuously changing the pitch, was difficult to record.

The latter, however, is particularly interesting as it introduces the strong pressure decrements at a''. I, therefore, reexamined it in Fig. 8 with less resistance (1,000 ohms) in circuit and the results came out more clearly. The deep minimum at a'' deserves further investigation, as it precedes a probably very high maximum at the near c'''. At least this may be inferred from the stimulation produced by an organ pipe used on the outside of the apparatus, §7. Something better than the electrical siren used will have to be devised; but apart from this the results are very definite.

Adjusting the siren for the maximum c'', the sensitiveness with different resistances in circuit (2,000–9,000 ohms) was determined. The curve is shown in series 9, Fig. 3, and is the highest thus far obtained. The equation, $rs =$ constant, does not fit so well here, a result inseparable from the slightly fluctuating note; for this makes a big difference in the maximum. The mean value is about $rs = 80 \times 10^3$. Referred to a circuit resistance of 100 ohms this is equivalent to a deflection of 800 fringes and a pressure of $\Delta p = .024$ cm. of mercury.

An auxiliary telephone placed in circuit with that of T, Fig. 1, affords no suggestion of these occurrences. Its notes rather increase in strength regularly with the pitch. Yet if the note should happen to be near e'', the other telephone would show no deflection.

Finally the use of the pin hole vent as a *probe* to detect the distribution of compression in organ pipes has been very fruitful; but these results will have to be omitted here.

9. *Reversal of Poles of Telephone Changes Sign of Fringe Deflection.*—An earlier detection of this result would have saved me much mystification. Not expecting it, I did not look for it; but it seems that a reversal of the telephone current (so to speak) reverses the fringe deflection, symmetrically. It is merely necessary to add a switch to the telephone circuit to prove this. Moreover for a given position of the switch and in the proper order of frequency, pressure increments pass continuously into pressure decrements (Fig. 7).

To test the case further, I used the motor interruptor, making a survey for frequencies between g' and a'' with the switch reversed and the sealed telephone. The new curve corresponded very fully to the curve, Fig. 7, except that maxima and minima had been exchanged. Thus the apparatus regarded as a dynamometer would, with a proper selection of frequency, give both quantity and sign of the impulsive currents in the telephone.

Since the resonating region R is vented by the pinhole, the positions of equilibrium of the quiet and of the vibrating plate are ineffective. Hence it is necessary to assume that the vibrations of the plate are here not symmetrical; or that, for instance, the impulse corresponding to the break of current at the interruptor is of excessive importance.

A closed region may be filled with an excess of compressed wavefront successions, provided means are at hand for the supply of the extra air needed and the energy dissipated; conversely, the closed region may be filled with an excess of rarified wavefront successions if the outflow of superfluous air is possible. In both cases the vent must be so small as to leave the region virtually closed. A ray of light imprisoned in a chamber closed with perfect mirrors might be considered as analogously circumstanced.

10. *Removal of Pressure Decrements Associated with Pressure Increments.*—Marked pressure decrements occur near the minima at c'' and a'' in case of the prolonged tests in §8. One may, therefore, suspect that (as in §7), the decrements result from an insufficiently tight joint at the telephone plate. The telephone with sealed plate was, therefore, carried through the chromatic series of notes from f' to a''. It is needless to give the data here, because they resembled Figs. 7 and 8 in character, except (as was anticipated) that there were no pressure decrements at the minima. In fact the maxima (below f' at c'', g'' and above a'') came out more sharply than in Figs. 7, 8 and the now positive minima (near g', d'', a'') equally so. It seems as if the ordinary overtones in the key of C were in question.

Replacing the sealed telephone by the usual apparatus with clamped plate, the results of Figs. 7, 8 with marked dilatations at the minima were reproduced at once, except that the maxima (a', c'', a'') were in the key of A, in accordance with the increased volume.

Finally I tested the above telephone with sealed plate again and found that pressure decrements at the minima associated with pressure increments at the maxima (as in Figs. 7, 8) had reappeared. These relations were exchanged on reversing the current. I suspect, therefore, that the potent influence is the mode of vibration (modified by sealing) of the telephone plate itself. About this I shall have something to say in the near future, showing that each inductive impulse is followed by shock waves in the plate, of relatively very high frequency compared with the frequency of induction, just as an anvil rings after each blow of the hammer.

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