Dependence of *Pfeifenton* (Pipe Tone) Frequency on Pipe Length, Orifice Diameter, and Gas Discharge Pressure

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Measured dependences of the *Pfeifenton* frequency on static flow pressure, orifice diameter, and pipe length are presented, based upon studies of air flowing through pipes terminated in various orifices. Frequency measurements were made of the vibrations inside the pipe. The *Pfeifentöne* are not a series of discrete single valued harmonics. Each covers a range of frequencies, any specific value of which is determined by the discharge flow-velocity or pressure. When the orifice diameter approaches zero the behavior of the *primary Pfeifenton* frequencies is as if they were produced by an open-closed organ pipe; when the orifice diameter approaches that of the pipe, the behavior is as if they were produced by an open-open organ pipe. A mechanism for the excitation of the *Pfeifentöne* is proposed.

INTRODUCTION

WHEN a pipe terminated in an orifice is attached to a large vessel containing gas, a spectrum of acoustic notes is produced inside the pipe as the gas pressure in the vessel is either raised or lowered. Most studies related to this phenomena were made during the last century.[1–7] The orifice is considered the location of the source of tones referred to variously as *Reibungstöne* (viscosity or friction tones),[6] *Spalttöne* (slit tones),[8] and jet tones[9]; the inside of the pipe is considered the location of the *Pfeifentöne* (pipe or whistle tones),[6] or the *sons des tuyaux* or *ton des tuyaux* (pipe sounds or pipe tones)[1,2]; and the pipe itself has been referred to as the tuyaux sonores (singing pipe).[1,2] The *Reibungstöne* have been suggested as the source of excitation of the *Pfeifentöne,*[6] although no satisfactory mechanism has been presented to account for this relation. Theory and experiments describing the general nature of *Reibungstöne* have been presented by several workers,[8,10–15] but no measurements of *Pfeifentöne* inside the pipe have been reported.

A number of characteristics of *Reibungs* and *Pfeifentöne* are reported:

(1) The frequency of the *Reibungstöne* is proportional to the velocity of the gas flow, not only when the gas flow is around a wire,[6] but also when the flow is through a rectangular slit.[7] That is, the frequency of the *Reibungstöne* is proportional to the square root of the pressure difference across the orifice.[4]

(2) An increase in the diameter of the discharge orifice causes a decrease in the frequency of the *Reibungstöne,*[7,9] but this effect is claimed to be only of minor magnitude.[4] It is also reported that the frequency a given pipe can produce is independent of the diameter of the discharge orifice.[1] The latter statement is shown below to be untrue.

(3) The *Pfeifentöne* are longitudinal vibrations of the gas column. For pipes of similar shape the *Pfeifenton* frequency is inversely proportional to the linear dimensions of the pipe.[1,2]

(4) The same pipe-orifice combination can produce sounds composed simultaneously of several pronounced frequencies.[1]

(5) The volume of the large reservoir (see Fig. 1) of air feeding the pipe has no effect on the phenomena.[1]

(6) Change in pipe length alters the spectrum of *Pfeifenton* harmonics produced by a variation of the gas-flow velocity, thus increasing the pipe length causes a series of lower frequencies to appear in the spectrum of harmonics. These appear at lower gas-flow discharge velocities. The higher frequencies are also altered. On the whole there is an increase in the number of

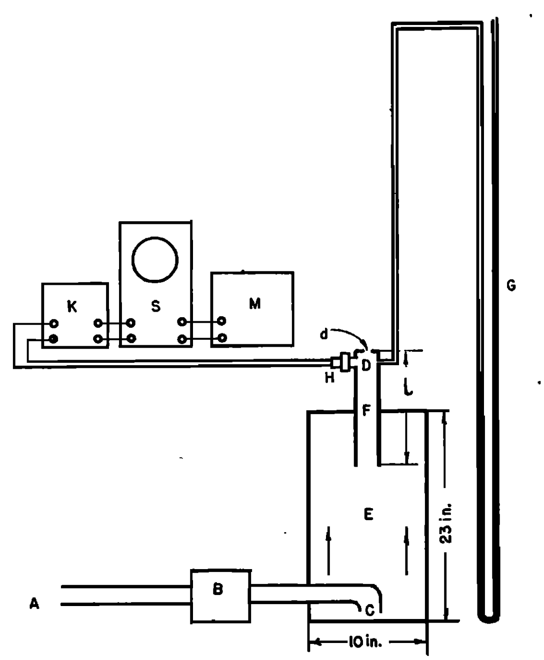

FIG. 1. Schematic arrangement of equipment.

[1] M. A. Masson, Compt. rend. 36, 257–260 (1853).
[2] See reference 1, pp. 1004–1008.
[3] William Thomson and J. P. Joule, Trans. Roy. Soc. (London) 143, 357–365 (1853).
[4] C. Sondhauss, Pogg. Ann. Phys. Chem. 91, 126–147 (1854).
[5] See reference 4, pp. 214–240.
[6] V. Strouhal, Weid. Ann. 5, 216–251 (1878).
[7] W. Kohlrausch, Pogg. Ann. Phys. Chem. 13, 545–569 (1881).
[8] F. Krüger and E. Schmidtke, Ann. Physik, 60, 701–714 (1919).
[9] E. G. Richardson, *Sound* (Longmans, Green and Company, New York, and Edward Arnold and Company, London, 1947).
[10] F. Krüger and H. Casper, Z. tech. Physik 11, 416–423 (1936).
[11] G. Burniston Brown, Proc. Phys. Soc. (London) 47, 703–732 (1935).
[12] G. Burniston Brown, Proc. Phys. Soc. (London) 49, 508–521 (1937).
[13] G. Burniston Brown, Proc. Phys. Soc. (London) 49, 493–507 (1937).
[14] Lord Rayleigh, *Theory of Sound, II* (Reprint, Dover Publications, New York, 1945), Vol. II, p. 412.
[15] F. Krüger, Ann. Physik 62.8, 673–690 (1920).

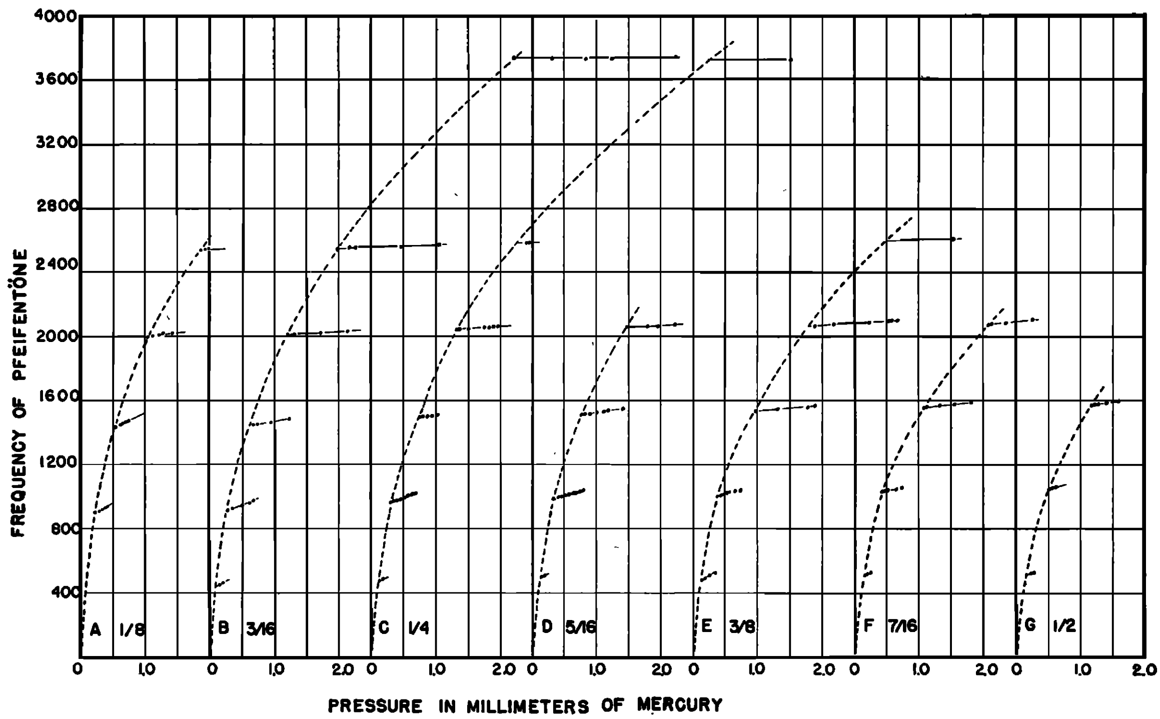

FIG. 2. Dependence of the *Pfeifenton* frequency on static flow pressure and orifice diameter. Orifice diameter for A is $\frac{1}{8}$ in.; B, $\frac{3}{16}$ in.; C, $\frac{1}{4}$ in.; D, $\frac{5}{16}$ in.; E, $\frac{3}{8}$ in.; F, $\frac{7}{16}$ in.; and G, $\frac{1}{2}$ in. In all cases the thickness of the orifice plate is $\frac{1}{16}$ in.; the geometrical length of the pipe, 11.762 in.; and the internal diameter of the pipe, 0.819 in.

harmonics that can be heard in the *Pfeifenton* spectrum of harmonics as the pipe length is increased.[6]

(7) Statements have been made, unaccompanied by experimental data, as to the relation between *Reibungstöne* and *Pfeifentöne*.[6] According to these, the pipe "sings out" best when the *Reibungston* produced at the edge of the orifice has the same frequency as one of the natural frequencies characteristic of the pipe-orifice geometry. The pipe, however, continues to respond with increase in the *Reibungston* frequency produced by an increase in the velocity of flow through the orifice. As the flow velocity increases, the natural *Reibungston* frequency reaches the next overtone of the pipe. The *Pfeifenton* then suddenly jumps into the next overtone. The discontinuous jumps in the *Pfeifenton* frequency will continue, as the velocity of flow through the orifice is made to increase. These discrete *Pfeifentöne* make up the *Pfeifenton* spectrum of harmonics.

The foregoing statements (Item 7) are not entirely correct or complete according to investigations reported in the present article. They are remarkable, however, in affording insight as to the relation of the two types of oscillation. They were made in the absence of the presentation of supporting experimental data, in an article dealing almost entirely with the conjugate phenomenon[9] where the stream of fluid passes around an obstacle, such as a wire (producing *Drahttöne* of wire tones), rather than *through* an orifice or slit.

Since instrumentation in acoustics during the previous century was poorly developed, investigators encountered extreme difficulties in research in this field.[4] This was true partly because of the variation in timbre and intensity of the tones studies and the difficulty in holding gas pressure constant, causing undesirable variations in frequency. It was especially difficult to determine which octave the sound was in. Many aspects of the phenomena therefore remain hidden. It is therefore not surprising to encounter discrepancies of experimental observation such as the following:

(1) The frequency of the components of the *Pfeifenton* spectrum will remain unchanged even through the flow pressure (flow velocity) varies between appreciable limits. Under these circumstances only the intensity of the sound increases or decreases with change of flow pressure.[1] In fact, a number of analytic relations have been proposed describing the sequence of tones obtained in the acoustic spectrum from a "singing pipe,"[2] presupposing that each component of the spectrum is a discrete single frequency. In contrast to this one finds[5] that appreciable and continuous changes in frequency occur in each component with change in pressure. This is apart from the large discontinuous jumps in frequency resulting from a change from one component to the next, caused by relatively larger changes in pressure.

(2) The different *Pfeifentöne* produced in the column of air in the pipe, by the gas flowing through the orifice, may be considered as the theoretical frequencies of either the open or the closed tube.[1] Nevertheless, it has also been reported that the whole column does not vibrate, only the part adjacent to the orifice. The length of this active part increases with lowering of frequency and decreases with rise of frequency, produced by a rise of pressure.[5]

Most of the results reported in the literature on *Pfeifentöne* and *Reibungstöne* have been obtained by placing a sharp edge or obstacle above the orifice. The obstacle tends to stabilize the tone and to increase the amplitude thus facilitating the determination of the frequency. The tones then fall into a class referred to as *Schneidentöne* (edge tones).[4–6,8–15] Masson,[1,2] who produced tones by the discharge of air through circular orifices, and Kohlrausch,[7] who produced tones by the discharge of air through rectangular slits, did not use sharp edges or obstacles to stabilize the oscillations. None of the results reported in the literature deal with measurements actually made on the vibrating column of air inside the pipe. Conditions inside the pipe always appear to have been inferred from measurements on the outside.

Results presented in this paper have been obtained almost entirely without sharp edges or obstacles placed above the orifice. It is, therefore, believed that complication of the phenomena has been minimized. Pressure and frequency measurements have always been made inside the pipe. The gas used was air.

APPARATUS

The dependence was determined of the *Pfeifenton* frequency produced in the pipe *F*, Fig. 1, (by the flow of air discharging through the orifice *D*) on the pressure in *F*, and on the orifice diameter *d*. Compressed air from the reservoir passed through *A*, the pressure regulator *B*, and into the stilling tank *E*. It then diffused upward, passing through *F* and *D*, into the free atmosphere. The static pressure difference across the orifice was determined by the manometer *G* filled with butyl phthalate.

The frequencies of the *Pfeifentöne* in *F* were determined by the pressure pick-up *H* and associated circuits *K*, the oscilloscope *S*, and the precision audio-oscillator *M*. The pressure signal from the pressure pick-up *H* was impressed on the *Y* axis of the oscilloscope; that from the oscillator *M*, on the *X* axis. The *Pfeifenton* frequency was determined from the Lissajous figures produced on the oscilloscope. Since frequently the *Pfeifentöne* were superimposed on a considerable amount of natural turbulence in the stream, considerable skill was often required in interpreting the Lissajous figures.

Dimensions of the stilling tank and the diameter of *F*, which remained constant throughout all runs, are shown. The length of *F* was varied by adding or taking away sections of pipe. The diamerer *d* of the orifices varied from $\frac{1}{8}$ to $\frac{1}{2}$ in. in steps of $\frac{1}{16}$ in. All of the orifice plates were $\frac{1}{16}$ in. thick

DEPENDENCE OF *PFEIFENTON* FREQUENCY ON STATIC FLOW PRESSURE AND ORIFICE DIAMETER

Figure 2 (*A–G*) shows the dependence of the *Pfeifenton* frequency on static flow pressure for seven orifice diameters varying from $\frac{1}{8}$ to $\frac{1}{2}$ in., in steps of $\frac{1}{16}$ in. The geometrical length of the pipe is 11.762 in. and the diameter 0.819 in. All figures show a similar trend in the location of the discrete ranges of *Pfeifenton* frequency. For all ranges, an increase of static pressure causes an increase in the *Pfeifenton* frequency. In general, for each orifice diameter, as the static pressure is raised there appears a sequence of harmonics, each made up of a continuous range of frequencies. The

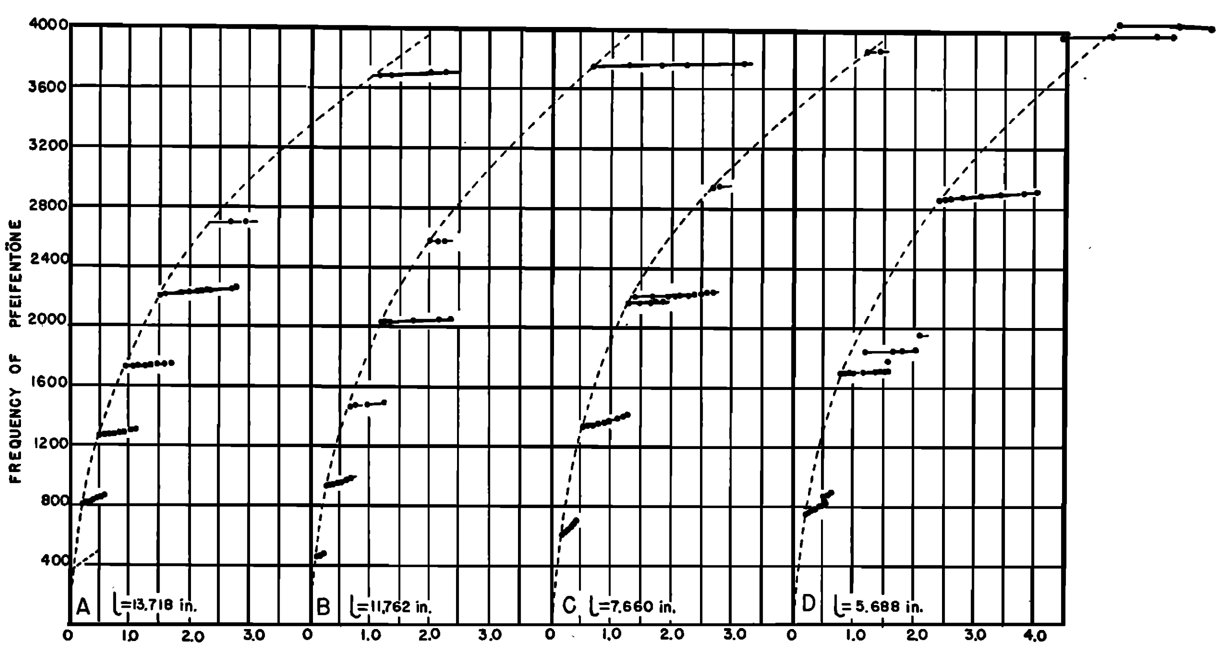

FIG. 3. Dependence of the *Pfeifenton* frequency on static flow pressure and pipelength. Pipelength for A is 13.718 in.; B, 11.762 in.; C, 7.660 in.; and D, 5.688 in. In all cases the thickness of the orifice is $\frac{1}{16}$ in.; the diameter of the orifice, $\frac{3}{16}$ in.; and the internal diameter of the pipe, 0.819 in.

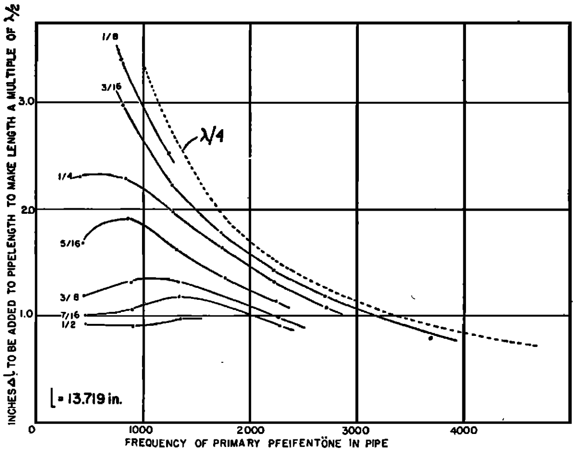

FIG. 4. Comparison of the length of the pipe-orifice combination, producing the *primary Pfeifentöne*, with that of an open-open organ pipe that will produce the same acoustic frequencies as the *primary Pfeifentöne*. The ordinate shows the length Δl that must be added to the effective length of the pipe (actual length 13.718 in. and effective length 13.965 in. in the present case) to produce, in an open-open pipe, the same acoustic frequency as that of the *primary Pfeifentöne* produced by the pipe-orifice combination. This is shown for a range of orifice diameters from $\frac{1}{8}$ to $\frac{1}{2}$ in. in steps of $\frac{1}{16}$ in.

sequence begins with a fundamental and is followed by overtones.

Occasionally one of the harmonics will be absent. This is true of the fundamental in Fig. 2A. The reason for their absence is not known, but appears to lie in the nature of the dynamics of the flow, and to some extent in the sharpness of the edges of the orifice. It is found that *Pfeifentöne* do not appear as readily when the orifice edges are slightly nicked and partly beveled.

Pfeifentöne and the vibrations observed in open organ pipes have several similar characteristics. In the organ pipe, with a gradual increase in the static pressure of flow between jumps in frequency, a continuous increase in the frequency of vibration occurs.[16] It is a self-generated oscillating flow superimposed on the continuous flow of air. This type of behavior is found also for *Pfeifentöne*. Fig. 2, for example, shows that the permissible and continuous range of *Pfeifenton* frequency for the harmonic in the vicinity of 1000 cps is approximately 60 cps. The specific value of the *Pfeifenton* frequency in the range of a particular harmonic therefore depends upon the static flow pressure. Both the permissible range and the sensitivity of the *Pfeifenton* frequency to changes of static flow pressure decrease as one goes to higher harmonics. The latter is shown by the decrease in slope of the line segments in Fig. 2.

Data already obtained and to be presented in a later paper indicates that the dotted line in each case describes the dependence of the frequency of the *Reibungstöne* on static flow pressure. The frequency of *Reibungstöne* has been shown in the literature to increase smoothly with rise of pressure.[6,7] Here the discontinuous ranges of *Pfeifenton* frequency apparently arise because of the coupling effect of the vibrating column of air in the pipe with the *Reibungstöne*.

Most of the results shown in Fig. 2 are the superposition of experimental data taken at widely different times, in several cases more than a month apart. They indicate a high degree of reproducibility.

DEPENDENCE OF THE *PFEIFENTON* FREQUENCY ON STATIC FLOW PRESSURE AND PIPELENGTH

Figure 3 (A–D) shows the dependence of the *Pfeifenton* frequency, produced in the pipe by the air discharging through the orifice, on the static pressure in the pipe for four different pipe lengths varying from 5.685 to 13.718 in. The diameter of the discharge orifice was kept constant at $\frac{3}{16}$ in., and the diameter of the pipe remain the same as before. A comparison of the curves show that

(1) the frequency interval between adjacent harmonics increases as the pipelength decreases in the same sense as for organ pipes;

(2) the permissible range of frequency for several of the harmonics is even greater than in the previous set of figures, amounting to at least 10 percent of the mean frequency of the harmonic;

(3) for the shorter tubes some of the permissible ranges of frequency occur as doublets or triplets.

DEPENDENCE OF THE PRIMARY *PFEIFENTON* FREQUENCY ON ORIFICE DIAMETER AND PIPELENGTH

There is still an uncertainty as to which frequency, if any, in the continuous range of frequencies comprising

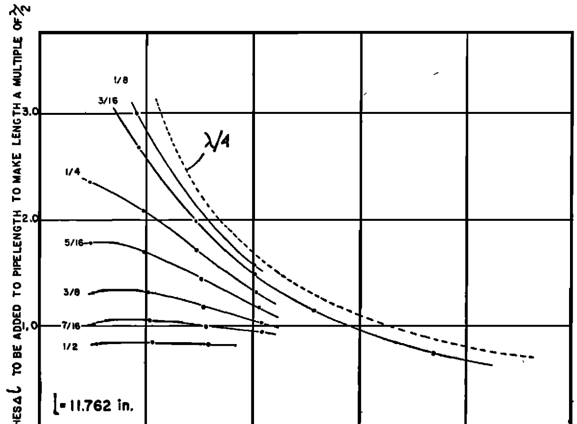

FIG. 5. Comparison of the length of the pipe-orifice combination, producing the *primary Pfeifentöne*, with that of an open-open organ pipe that will produce the same acoustic frequencies as the *primary Pfeifentöne*. The ordinate shows the length Δl that must be added to the effective length of the pipe (actual length 11.762 in. and effective length 12.008 in. in the present case) to produce, in an open-open pipe, the same acoustic frequency as that of the *primary Pfeifentöne* produced by the pipe-orifice combination. This is shown for a range of orifice diameters from $\frac{1}{8}$ to $\frac{1}{2}$ in. in steps of $\frac{1}{16}$ in.

[16] G. Burniston Brown, Nature 141, 11–13 (1938).

a given *Pfeifenton* harmonic is most simply related to the geometry, alone, of the system. Some evidence may be found to help one make a choice. This is based on the thought that there is one frequency, of the frequency range comprising a given harmonic, at which the *Reibungston* and the *Pfeifenton* are equal and also at which both have the same value that each would have in the absence of any mutual interaction of one on the other. It is this frequency that is believed to be most easily related to the geometry of the system. Evidence indicates that this frequency, hereafter referred to as the *primary Pfeifenton*, is the one associated with the low pressure end of each complete line segment in the figures. Evidence in the literature has been summarized in the Introduction (Items 1, 3, and 7) under "· · · characteristics of *Reibungs* and *Pfeifentöne* · · ·."

The geometrical length of the pipe is found to be far from a multiple of any of the *primary Pfeifenton* wavelengths. In most cases the disagreement is very great. A correction in length should be added to the open end of the pipe.[9,17] Even in the case of a cylindrical pipe with a clean-cut end, the antinode does not coincide with the end of the pipe. The effective length is always greater than its geometrical length. For a cylindrical pipe the end correction is approximately independent of the wavelength. It is usually taken as $0.6R$, where R is the radius of cross section of the pipe.

When the effective length of the pipe, equal to the sum of the geometrical length and $0.6R$, is now used in the calculations, there again is no appreciable improvement. The effective length of the pipe is far from being a multiple of the observed *primary Pfeifenton* wavelengths. An explanation for this discrepancy lies in the diameter of the orifices. Several of the orifice diameters are comparable to that of the pipe, but most are not. The different pipe-orifice geometries studied therefore differ in varying degrees from that of a purely open-open organ pipe.

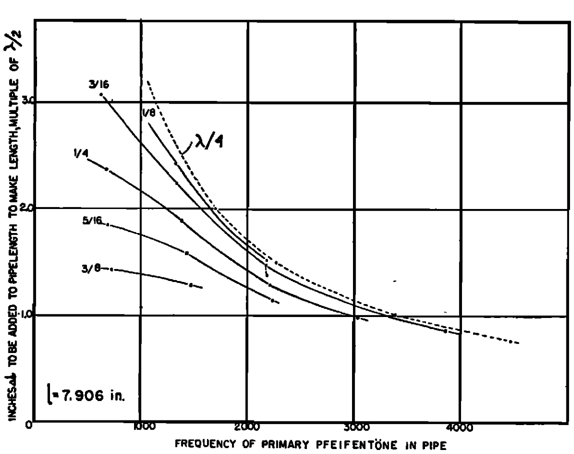

FIG. 6. Comparison of the length of the pipe-orifice combination, producing the *primary Pfeifentöne*, with that of an open-open organ pipe that will produce the same acoustic frequencies as the *primary Pfeifentöne*. The ordinate shows the length Δl that must be added to the effective length of the pipe (actual length 7.660 in. and effective length 7.906 in. in the present case) to produce, in an open-open pipe, the same acoustic frequency as that of the *primary Pfeifentöne* produced by the pipe-orifice combination. The is shown for a range of orifice diameters from $\frac{1}{8}$ to $\frac{1}{2}$ in. in steps of $\frac{1}{16}$ in.

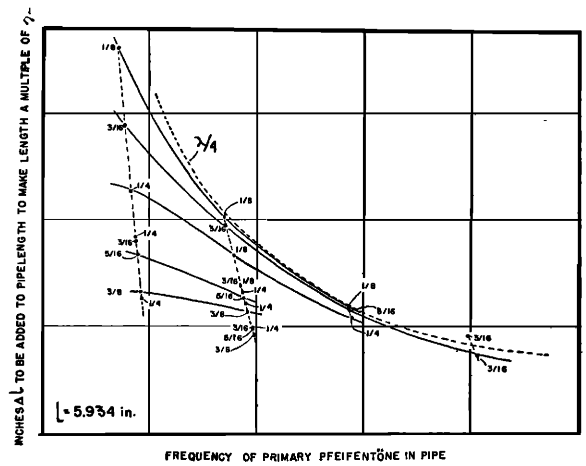

FIG. 7. Comparison of the length of the pipe-orifice combination, producing the *primary Pfeifentöne*, with that of an open-open organ pipe that will produce the same acoustic frequencies as the *primary Pfeifentöne*. The ordinate shows the length Δl that must be added to the effective length of the pipe (actual length 5.688 in. and effective length 5.934 in. in the present case) to produce, in an open-open pipe, the same acoustic frequency as that of the *primary Pfeifentöne* produced by the pipe-orifice combination. This is shown for a range of orifice diameters from $\frac{1}{8}$ to $\frac{1}{2}$ in. in steps of $\frac{1}{16}$ in.

It is desired now to come to a generalization of the effect of orifice-pipe geometry on *Pfeifenton* wavelength. To do this the increment in length Δl (new end correction) will be calculated that must be added to the effective length of the pipe $(l+0.6R)$, to produce an open-open pipe resonating at the same acoustic wavelength as the orifice-pipe geometry in Fig. 1. In the limit, as the orifice-diameter approaches that of the pipe, Δl will approach zero. The new end correction Δl may be calculated from

$$f=\frac{n}{2}\frac{c}{(l+\Delta l+0.6R)},$$

where n is the number of the harmonic; c, the velocity of sound; and f, the frequency of the *Pfeifenton*. All quantities in the equation are known except Δl, the velocity of sound being known quite accurately since the temperature of the air in the pipe was determined within ±0.10°C. The calculated values of Δl for the geometrical pipe lengths 13.719, 11.762, 7.660, and 5.688 in. are shown in Figs. 4–7. The range of orifice-diameters is the same as before. Each figure shows the dependence of the new end correction Δl on the frequency of the *primary Pfeifenton* for the same sequence of orifice-diameters.

[17] A. E. Bate. Phil. Mag. 24, 453–458 (1937).

All figures (4–7) for the different pipe lengths have the same characteristic appearance. The position of each point, however, is extremely sensitive to errors in the measurement of air-flow temperature and frequency. Within experimental error and for the given pipe diameter, one may conclude therefore that the end correction Δl *is independent of pipe length and depends chiefly upon orifice diameter*. The dotted curve in each figure has been calculated and represents a length of pipe Δl equal to a quarter wavelength. All experimental curves fall below this, but do approach it asymptotically as the orifice-diameter approaches zero.

The asymptotic approach of the experimental curves to the quarter wavelength curve in Figs. 4–7 leads to the following generalizations:

(1) As the diameter of the orifice approaches that of the pipe, the values of the ferquencies of the *primary Pfeifentöne*, excited in the column of air moving rapidly through the pipe, tend to approach those of an open-open organ pipe. In all four figures the increment Δl is seen to decrease as the orifice diameter increases. In the limit, when Δl equals zero, the pipe-orifice combination will behave as an open-open organ pipe.

(2) As the diameter of the orifice approaches zero, the values of the frequencies of the *primary Pfeifentöne* tend to approach those of an open-closed organ pipe. The $\frac{1}{8}$-in. orifice-diameter curves in all four figures come very close to the quarter wavelength curve. This indicates that if a quarter wavelength is added to the effective length of the present pipe the new open-open pipe will resonate at approximately the same frequency as the experimental pipe-orifice combination having the $\frac{1}{8}$-in. orifice.

(3) For gradations of orifice diameter between the foregoing extremes, the *primary Pfeifentöne* frequencies appear to take on values between an open-closed and a completely open-open organ pipe, as if produced by an organ pipe having corresponding gradations of geometry.

As the pipe becomes shorter, the *Pfeifentöne* take on an anomalous character. Instead of appearing as single linear frequency ranges in the figures, they break up into doublets and triplets. For example, there are the doublets composed of the *primary Pfeifentöne* at 2160 and 2190 cps in Fig. 3C, and at 765 and 885 cps, and at 3970 and 4065 cps in Fig. 3D. A triplet composed of the *primary Pfeifentöne* 1710, 1855, and 1965 cps is shown in Fig. 3D.

When the end correction Δl for each of the *primary Pfeifentöne* of a doublet or triplet is plotted as in Fig. 7, all of the points fall on precisely the same curve as that produced by a variation of orifice diameter alone. Thus, precisely the same variation of end-correction, with *Pfeifenton* frequency, is obtained whether the variation is produced by change of orifice-diameter or by a frequency jump from one member of a doublet, or triplet, to another.

Consider, for example, the curve in Fig. 7 for a $\frac{3}{16}$-in. orifice-diameter. The points on this curve correspond to the *primary Pfeifenton* of the lowest frequency-member of each doublet or triplet in Fig. 3D. This curve also has the same shape as in Figs. 4–6 for the same orifice diameter ($\frac{3}{16}$ in.). The upper member of the fundamental *Pfeifenton* doublet in Fig. 3D, on the other hand, lies far below the curve in Fig. 7, at an end correction of 1.84; the other members of the *Pfeifenton* triplet lie at 1.44 and 0.97; and the other member of the highest *Pfeifenton* doublet, at 0.92.

All these points in Fig. 7 are seen to fall on precisely the same nearly vertical lines as do those obtained for the other orifice-diameters. An isolated minor instance of the reversal of the gereral order in the doublets is seen in Fig. 7 at frequencies 3970 and 4065 cps. This explains why the dotted curve in Fig. 3D is drawn through the *primary Pfeifenton* of the upper member of the doublet rather than the lower.

MECHANISM FOR EXCITATION OF THE *PFEIFENTÖNE*

There is evidence to indicate that the *Pfeifentöne* may be excited by periodic fluctuations of the orifice area. These would have the same frequency, or a multiple of the frequency of the *Pfeifentöne*, and would be produced by the development and periodic shedding of vortices from the orifice giving rise to the *Reibungstöne*.

During the period in which the vortex is attached to the wall of the orifice, it goes through phases such as the following. Initially the thickness of the boundary layer is zero, and there is no vortex attached to the circumferential surface of the orifice. Gradually, the boundary layer begins to thicken and a nascent vortex, attached circumferentially to the orifice, begins to grow.[18] The growing vortex continues to reduce the effective cross section of the orifice. Eventually, the vortex is suddenly shed, whereupon the effective orifice diameter springs back to its original geometrical value. The shedding is periodic, the frequency being proportional to the discharge velocity or the square root of the discharge pressure.[6] It is this periodic shedding that gives rise to the *Reibungstöne*.

The fluctuation of effective orifice diameter, or area, creates periodic fluctuations in the discharge rate,[19] and therefore, a fluctuation in the pressure inside the pipe in the vicinity of the orifice. These periodic pressure pulses propagate upstream in the pipe. If the frequency of these pulses (*Reibungstöne*) is just equal to one of the natural frequencies of the pipe-orifice combination,

[18] L. Prandtl and O. G. Tietjens, *Applied Hydro and Aeromechanics* (McGraw-Hill Book Company, Inc., New York and London, 1934), photographs on pp. 279–306.

[19] *A. S. M. E., Fluid Meters, Part I—Their Theory and Application* (The American Society of Mechanical Engineers, New York, 1937), fourth edition.

the column of air in the pipe will sing out to give a *primary Pfeifenton.*[6]

If the discharge pressure is now gradually increased, and if the effect of the pipe were removed, the frequency of the *Reibungstöne* would rise along the curved dotted envelope shown in Figs. 2–3. Since the effect of the pipe is not removed, the *Pfeifenton* excited in the pipe reacts on the *Reibungston* at the orifice to give the inclined line segments shown, with a rise of pressure.

When the discharge pressure is increased still further, to a point on the dotted curve near the value where the undisturbed *Reibungston* frequency is equal to the next natural overtone of the pipe-orifice geometry, the frequency in the pipe jumps suddenly to the next *primary Pfeifenton*. In the figures this is indicated by the left-hand end point of the next higher line segment.

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