THE EFFECT OF WIND PRESSURE ON THE FREQUENCY OF OPEN AND CLOSED FLUE ORGAN PIPES

by

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TABLE OF CONTENTS

INTRODUCTION

How the wind sets up and maintains the vibrations of air in flue organ pipes is a question that has attracted the attention of many investigators. Many interesting facts pertaining to this phenomenon have been discovered, but scientists are still not entirely agreed upon the primary factors involved. The fact that the frequency of open and closed flue organ pipes is affected by a change in wind pressure has been known for some time. Explanations for this change in frequency, however, have been uncertain. Little information is available regarding the quantitative differences existing between pressure changes and the resulting alterations in frequency. The purpose of this study was to investigate the effect of wind pressure on the frequency of open and closed flue organ pipes.

REVIEW OF LITERATURE

How a jet of air maintains the vibrations in the column of air in a flue pipe was investigated by Weber and Weber as early as 1826, according to Jones (11). Their idea was that the first puff of wind from the windway starts a wave which travels up and down the body of the pipe. Each time that the wave comes back to the mouth it acts on the wind that is coming from the windway, thus setting up compressions and rarefactions in this blowing wind; and these in turn maintain the vibrations in the body of the pipe. In other words, their explanation seemed to be that the column of air in the pipe behaves like a vibrating coiled spring and that sound is maintained by alternating compressions and rarefactions in the wind sheet either before it leaves the windway or immediately after.

In 1873, Smith (18) described an experiment demonstrating that the sheet of air from the windway of an organ pipe vibrates like a reed, bending alternately toward the inner and outer sides of the upper lip. The vibration of this reed seemed to him to be the most important factor in the maintenance of sound in a flue pipe. He showed that the stream of air at the mouth of the pipe constitutes a free reed by inserting pieces of tissue paper on the languid just within the mouth; these pieces are caught by the air and vibrate as a reed. His statement of the law of vibration of the air reed is as follows: "As its arcs of vibration are less, its speed is greater," or "The times of vibration vary with the amplitude." This is different from the usual law of a vibrating reed in which the time is independent of the amplitude of vibration.

The art in voicing a pipe, according to Smith (17), "consists in so directing the stream of air that it shall avoid striking the lip and shall smoothly glide past without shock or noise; you get no tone until it does." He regarded the idea that a sharp edge is essential to the functions of a flue organ pipe as one of the most common errors entertained by physicists. The flue organ pipe is "a free-reed instrument."

The streaming air reed, as he termed it, carries with it a part of the air from each side of the reed and so produces some diminution of pressure creating a vacuum as in the case of a chimney. The decrease of pressure travels up the pipe as a pulse of rarefaction followed by a pulse of condensation. Now that a vibration of the air in the pipe has been set up, the vibration keeps the reed bending back and forth and thus the vibration of the air in the pipe is maintained. He found that with an increase in pressure there is a proportionate rise in frequency except at certain critical pressures where there is a jump in frequency to a harmonic. At these critical pressures the closed pipes jumped to an odd harmonic and the open pipes to an even harmonic. Smith (18) concluded that investigators should look to the disturbance of the equilibrium of air pressure as the chief element in determining the pitch of sounds produced by organ pipes.

About this time, but independently, Schneebeli (15) gave a similar explanation of the maintenance of a flue pipe. Schneebeli demonstrated the existence of the reed by mixing smoke with the air in an experimental flue pipe that had a movable lip and slit and a glass back which enabled him to see the motion of the reed directly. When he placed the lip and slit so that the stream of air passed entirely outside of the pipe, no sound occurred; but if he blew gently upon this sheet of air at right angles, the pipe sounded. Under these circumstances it was very rare to find that any smoke entered the pipe. If the sheet of smoked air passed entirely inside of the pipe, there was also no sound. Smith (18) and Schneebeli (15) agreed that for the formation of the reed it is essential for the exciting air to pass the lip but not to enter the mouth.

Helmholtz (8) explained the functioning of flue pipes by observing that the sheet of air that comes from the windway is unstable and easily deflected. When the wind sheet strikes the upper lip or passes close to it, a slight disturbance of the air in the body of the pipe occurs. This disturbance gives rise to a small vibratory motion of the air up and down in the pipe. Consequently, the air at the mouth swings slightly in and out of the pipe carrying with it the sheet of air from the windway. When the air sheet is deflected inward, it adds to the pressure inside of the mouth; and when it is deflected outward, it decreases the pressure inside the pipe. In this manner the condensations and rarefactions needed to maintain the vibrations in the pipe are formed. This view was also maintained by Capstick (5). Helmholtz (8) explained the motion of the air in both open and closed pipes when vibrations in the pipes are occurring by the theory that the motion of the air taking place in a pipe is much like a system of plane waves reflected back and forth between the ends of the pipe. At the closed end of the pipe the reflection of every wave striking it is perfect, so that the intensity of the wave is the same as it was before. In any train of waves that may be moving in a given direction, the velocity of the oscillating molecules in the condensed part of the wave takes place in the same direction, and in the rarefied part of the wave their velocity is in the opposite direction. At the closed end of the pipe the foreward motion of the molecules is stopped. Therefore, the incident and reflected waves combine so that the molecules of the air will oscillate in the opposite direction and their phases of pressure will agree because the opposite motions of oscillation and propagation will be the same; thus at the stopped end there is no motion but a great alteration of pressure. The reflection of the wave has occurred in such a manner that the phase of condensation is not changed, but the direction of the oscillation of the molecules is reversed. At the open end of the pipe no perceptible condensation can take place. It is usually assumed that both condensation and rarefaction disappear at the open ends of pipes, but Helmholtz (8) stated that this is not exactly correct. He explained the action of the open pipe by stating that a wave of condensation is excited at the mouth of the pipe. It runs foreward to the other end where it is reflected as a rarefaction, runs back again to the mouth end where it is reflected with an alteration of phase as a wave of condensation; it then repeats by travelling the same path to the other end and back again. The repetition of this process occurs twice through the length of the pipe. The time required for this action is equal to twice the length of the pipe divided by the velocity of sound; and the tone emitted is the pipe's fundamental. In the closed pipe a condensation is started at the mouth and then travels to the closed end where it is reflected as a condensation, and on its return to the mouth it will be reflected with an altered phase as a rarefaction. This occurs four different times. At the open end the wave changes phase but not at the closed end. This means that the fundamental tone of a stopped pipe has twice as long a period of vibration as that of an open pipe of the same length.

Helmholtz (8) further explained that at the open ends of pipes a fraction of the wave always escapes into the open air so that the intensity of the reflected wave is not as great as that of the incident wave. This means a loss of work which, if not replaced, will cause the sound wave to die. Therefore, if at those times and places where the air is condensed, a small amount of air is regularly forced in, the vibration of the pipe will be maintained.

In 1877, Van Tricht (19) and Lootens both followed up the experiments made by Smith (18). They introduced smoke into the blowing wind, as Schneebeli (15) had done, in order to see where the wind goes. They found that part of the wind goes up past the outer side of the lip and part of it follows a looped path that curves over to the back of the mouth inside the pipe and then comes out through the mouth. Van Tricht (19) concluded that, if the current comes horizontally from the mouth and crosses the principal current from the windway, each of these currents must be periodically interrupted in order to let the other pass. The horizontal current from inside the pipe thus acts like the plate of a siren and the principal current breaks through it periodically and so gives rise to a musical tone.

According to Miller (13), Masson and Sondhaus in 1853 performed an experiment in which they produced tones by directing a stream of air against an isolated sharp edge. This phenomenon has been studied by many investigators since that time and was largely responsible for the experimental and theoretical work of Hensen (9) in 1900 and Wachsmuth (20) in 1904. Their work led to what is known as the edge-tone theory, which offers a somewhat different explanation for the origin of tone in lipped pipes and musical instruments of the flute type.

In 1900, Hensen (9) carried out a number of experiments by moving a lighted taper to various points in several organ pipes. He found a general streaming of the air very similar to that described by Van Tricht (19) and Lootens. His illustration showed an inner primary stream going to the back of the pipe and then, after making a loop, coming out at the mouth. In another of Hensen's (9) experiments a stream of air was blown against the side of a flame coming from a jet, and under proper conditions a musical tone of fair intensity was obtained. He explained the resultant tone as a struggle between the ortho-lamella and the transverse-lamella so that there is a hemming in of the flow, resulting in a compression of the material (gas or air), first in one lamella and then in the other. For the production of tone he found it necessary that the transverse-lamella push against the ortho-lamella; if it cut clear through, he got no sound. Hensen (9) observed also that a tone could be produced when the gas jet was not burning.

In the next year Friedrich (7) conducted experiments in an attempt to find if the vibration of a pipe was maintained in the manner described by Hensen (9). From his work he concluded that the formation of the transverse-lamella was an important factor in the production of sound. He showed that if a small object was placed inside of the mouth preventing the forming of the transverse-lamella, no sound resulted. By using a pipe with glass sides, Friedrich (7) observed the formation of a system of vortices which was shown by blowing smoke into the pipe along with the jet of air. He reasoned that if the vortices were essential for the production of sound in a pipe, anything that would prevent their formation would make sound in the pipe impossible. He did prevent the formation of the vortices by lowering a thin board into the pipe until it was only a few centimeters above the languid. He found that the board made little difference in the speech of the pipe.

About 1903, Weerth (22) used a simple wedge with its sharp edge placed a short distance above a slit corresponding to the windway of a pipe and noted that when the wind strikes such an edge, it often produces a fairly clear musical tone. A gradual increase in blowing pressure was followed by a gradual rise in pitch, but at certain points a small increase in pressure was accompanied by a sudden jump in pitch. Weerth (22) also introduced smoke into the streaming air and, observing it stroboscopically, found that when the wind glided smoothly up the sides of the wedge, no sound was produced. When sound was produced, he could see the air sheet bending back and forth for a short distance below the wedge and the air in the sheet flowing first to one side and then to the other. His explanation for the sound produced was that the air sheet failed to divide itself equally at the edge, causing an increase in pressure on one side of the wedge and forcing the air sheet over to the other. In this manner unequal pressures on each side of the wedge were established and the streaming air reed was forced to swing back and forth. As a result, the column of air in the pipe was set in vibration by the same swinging motion.

In 1903, Wachsmuth (20) found that the transverse-lamella did not function as Friedrich thought it did. He explained that by placing a wooden object in the pipe so as to screen the ortho-lamella from the transverse-lamella, as Friedrich (7) had done, the ortho-lamella is deflected inward and the air sheet no longer passes close enough to the upper lip to give rise to a tone. He noted that if the upper lip was moved inward a short distance, the air sheet again struck the lip and the pipe spoke as well as before the object was inserted. Wachsmuth (20) also obtained photographs showing how the wind sheet moves by adding tobacco smoke to the streaming jet of air. His pictures show that the air stream bends and then breaks into turbulent motion and that as long as the wind sheet broke up into vortices, sound was produced; but when there were no vortices, there was no sound. As a result of this work, Wachsmuth (20) suggested that the frequency of a pipe may be governed by the regular formation of the vortices. He was probably the first to recognize that a flue pipe, along with its slit and edge, comprises a coupled system. If the natural frequency of the resonator does not differ too widely from that of the edge-tone, the edge-tone adjusts itself to that of the resonator.

Skinner (16), in 1917, refuted the Tyndall theory which explained the cause of speech in pipes as depending on the air issuing from the flue and striking the sharp upper lip of the pipe and dividing itself thereon. Skinner (16) maintained that inasmuch as this flame of air, as he called it, technically known as the wind sheet, does not touch the upper lip at all, the contention of the Tyndall theory falls to the ground. Skinner (16) gave the following two proofs for his contention as a result of observations made in one of his experiments:

> First, when a light thin vane was pivoted at its midpoint some distance above the lip of the pipe, the air from the jet forced the portion of the vane outside of the pipe upward. Second, when a wad of cotton was introduced into the top of the pipe, it immediately fell to the bottom and came out at the mouth.

These observations seemed to him to prove that the air jet never strikes the lip of the pipe at all.

Barton's (1) explanation for the maintenance of flue pipes was substantially the same as that of Helmholtz (8). Barton (1) and Helmholtz (8) agreed that for the determination of the frequency of a flue pipe, numerical additions must be made to the lengths of both open and closed pipes. These additions to the length are called end corrections. Open pipes have two corrections, one for the open end and one for the mouth, while the closed pipes have a correction for the mouth only. Barton (1) explained the necessity for this correction by pointing out that because of the inertia of the air the vibrations must extend beyond the actual open end of the pipe so that the acoustical length of the pipe will be the sum of the actual length and an end correction. He further stated that the correction of an open end is a function of the wave length and that for pipes of very short wave lengths the end correction tends to vanish. Barton's (1) value for the open end correction is 0.6 of the radius of the pipe. He gave Cavaille-Coll's whole correction for an open pipe as 3.33 times the radius. This would make an allowance of 2.7 times the radius as the correction for the mouth alone.

Bate (2) stated that when a pipe of ordinary length is blown and the pressure increased, the note will be sharpened until it jumps to its first overtone. He explained this phenomenon by showing that the jet frequency is restrained by the column of air in the pipe resulting in a change of end correction. The change occurs until the column of air breaks down into two half wave lengths if the pipe is open, and into three quarter wave lengths if the pipe is closed. When a pipe several wave lengths long is used, an increase of air pressure does not cause the note to sharpen to the same extent but to jump to a higher frequency. This was to be expected since an extra node is more easily formed in a pipe containing a number of nodes than in one containing only one node; therefore, the jet determines the frequency when the pipe is long and the pipe determines the frequency when the latter is of normal length. He concluded that the mouth conditions, chiefly the air pressure and the distance from slit to lip, may be varied considerably when the pipe is short, the natural jet frequency being distorted by lengthening or shortening the pipe as required.

In 1925, Carriére (6) obtained results from an experiment that showed the shape of the sheet of air between the slit and edge. When a pipe spoke its fundamental, the wind sheet seemed to vibrate as a whole, much like a metal reed. When the wind sheet had a bend in it between the slit and edge, the pipe spoke its first overtone; and when it had two bends, the pipe spoke its second overtone. He also observed that the sheet broke into a system of vortices and suggested that their formation might have some part in the production of sound in a pipe.

Wood (23) agreed with Wachsmuth (20) in the idea that the column of air in the pipe and the space between the slit and edge form a resonator. Leet (12) suggested that the distance from the slit to edge is equal to, or a multiple of, the wave length between the successive vortices in the same row. He contended that the pitch of a pipe is governed almost entirely by the resonant air column, but the generally accepted theory is that the pitch is obtained by the coupling of the edge-tone with the fundamental frequency of the pipe. However, since the column of air in the pipe is by far the stronger damped component, in the main it governs the system, whereas the edge-tone at the mouth may be pulled out of its natural period of vibration in order to secure equality of period.

According to Watson (21), the greatest motion of the air occurs where it enters the mouth of the pipe. When an open pipe speaks its fundamental, the points of greatest motion of the air are at the open ends. Midway between these two points is a node. Since the distance between two antinodes (or points of greatest air motion in a pipe) in standing waves is one-half the wave length, or $\lambda/2$, it follows that $\lambda = 2L$, where L is the length of the pipe. The frequency of the fundamental tone is V/2L, where V is the velocity of sound. If the wind pressure is increased, a shorter wave may be set in motion, a node being established at one-fourth the whole length of the pipe from the mouth and another at the same distance from the top. The pipe then speaks its first octave or harmonic of the fundamental. If the pressure is further increased, three nodes will form, the first being one-sixth of the length of the pipe from the mouth and the third a similar distance from the top, the second lying halfway between the first and third. In this manner the second harmonic is formed, and with a further increase in pressure other harmonics will occur in like manner. Therefore, an open pipe will speak a full train series of harmonics if the wind pressure is sufficiently increased. In a closed pipe the procedure is different. When such a pipe speaks its fundamental, the point of greatest motion is at its mouth but the column of air is unbroken, the only node being at the stopped end; therefore, the length of the pipe is one-fourth of its wave length and its frequency must be V/4L. If the air pressure is sufficiently increased, another node is set up at one-third of the length of the pipe from its mouth; and with the second harmonic a node forms at one-fifth of the length from its open end. In any case the stopped end is always a node. A stopped pipe thus gives a series of odd harmonics.

Richardson (14) stated that the precise cause for the formation of vortices is obscure but concluded that their formation is evidently connected with the viscous drag of the stationary air upon the rapidly moving air from the jet. According to Richardson (14), about 1912 Karman and Ruback made a mathematical investigation of the system of vortices between the edge and slit of an organ pipe. The theory they offered regarding the double file of vortices formed at the jet is that, for stability, the distance h between the two files must bear a definite ratio to the distance L from one vortex to the next in the same file. They calculated the ratio h/L to be 0.27. Jones (11) did not believe this ratio was constant because photographs show that the files are not parallel but rather spread out in a fan-like manner. Richardson (14) contended that before sound can be elicited in a pipe the edge must bisect the two rows of vortices exactly and his entire explanation for the maintenance of sound in flue pipes was based upon the existence of vortices in the streaming air.

Richardson (14) and Leet (12) agreed that the distance L from slit to edge becomes equal to, or is a multiple of, the wave length of the vortex system. This means that there is a minimum distance f_0 between slit and edge for any given velocity V of any jet of air at which a tone can be produced. If these vortices strike the edge with a velocity U, and L equals the distance between them in the same row, then the frequency n equals U/L; or since L equals f_0 and V is the velocity at the jet, then U = aV, where a is a constant. Therefore, the relation nf_0/V is a constant, assuming that the velocity U of the vortex system is less than but proportional to V. The relation, $n = aV/f_0$, is often called the edge-tone formula. Richardson (14) stated that an organ pipe should be so designed that at normal blowing pressures the edge-tone frequency n is proportional to Vj/f and is equal to the fundamental of the pipe. The distance f_0 to f_1 from jet to edge when the pipe speaks its fundamental is equal to j or 1, f_1 to f_2 is equal to j or 2, etc. Richardson (14) further explained that a certain amount of mutual accommodation always takes place between pipe and edge-tone; but if the values of their natural frequencies are gradually caused to separate from each other, the period of vibration of the pipe is changed to a small extent. However, if the velocity of the jet of air is increased, the frequency of the edge-tone rises beyond the fundamental of the pipe; but the pipe will continue to force its own frequency upon the edge-tone until the frequency of the edge-tone will be nearer to the first harmonic of the pipe than to its fundamental. At this point a jump in frequency occurs in the pipe which both edge-tone and pipe retain until the next jump occurs.

Organ companies determine the distance f from slit to edge from years of experience gained in the building of their instruments. The leading pipe organ companies seem to agree with Boner (3) that the value of f should be approximately one-third of the width of the mouth for a pipe to speak its fundamental tone.

Brown (4) and Jeans (10) agreed regarding the relationship between edge-tones and air vibrations in the pipe. Jeans (10) strongly emphasized the importance of the vortex system for tone production, and Brown (4) believed that the to-and-fro motion of the jet at the edge is not modified appreciably by the superimposed vortex system as long as such motion is not greatly developed. Jones (11) believed that the alternating flow of air is aided and its frequency partly determined by the vortices that usually accompany a jet of air, but that further work is needed before one can be certain as to the importance of the presence of vortices in the determination of the frequency of flue organ pipes.

APPARATUS

The apparatus (see Plate I) used in this experiment consisted essentially of three parts: a source of controlled air pressure, the pipes upon which the determinations were made, and the mechanism used to determine the frequencies of the pipes.

The air pressure was obtained from a continuous air supply having an average pressure of 85 pounds per square inch, the flow of this air supply being controlled by means of a needle valve. The valve controlled the air supply to an equalizer which consisted of a tank floating on water. The needle valve was used in adjusting the air supply to the tank so that the pressure would be constant throughout any part of the experiment. Variable pressures were obtained by placing various combinations of weights on the top of the floating tank of the equálizer. These pressures were measured by means of an open water manometer connected to the air line close to the pipe upon which determinations were made. A mercury-in-glass thermometer was used to measure the temperature of the air just before it entered the pipe.

The pipes used in this work were 5.22 cm. in diameter, having mouths 4.2 cm. in width. The distance from the languid of the pipe to its lip was adjusted by means of a thumb screw. Proper voicing of the pipe was obtained by the manipulation of this screw. Six pipes were used, three open and three closed. The length of each pipe was indicated by means of a vernier gauge attached to the framework supporting the pipe. The length of the closed pipes, that is, the distance between the languid and closed end, was adjusted by means of a rack and pinion to which a crank was attached. When open pipes were used, the adjustable piston used in the closed pipes was removed. The desired length of the open pipe was obtained by placing additional pieces of pipe, machined to exactly the same inside diameter, on the top of the pipe from which the piston had been removed. Special care was taken in making the joints air tight to prevent the escape of any air from the pipe. A tightly fitting sleeve held the added section of pipe securely in place while the various tests were made.

The determination of the frequency of the pipes was made by the stroboscopic method. The tone emitted by the pipe was picked up by a microphone connected electrically to an amplifier, and the frequency of the tone was thus transformed to corresponding changes in electric current that illuminated a neon lamp connected to the amplifier. All objects that might in any way influence the frequency of the sound as it came from the pipe were kept away from the mouth. A rotating disk having 72 equally spaced holes was used, the speed of the disk being easily adjusted by means of a crank. The number of revolutions per unit of time was accurately indicated by the use of a revolution counter and a reliable stop watch was used in observing the time. The apparatus was so constructed that the instant the revolution counter was engaged or disengaged the stop watch automatically started or stopped.

EXPLANATION OF PLATE I

Photograph of pressure equalizer, pipes, and apparatus used in the determination of frequency.

a. Main air supply line.
b. Needle valve.
c. Equalizer.
d. Floating tank of equalizer.
e. Weights.
f. Additional sections of pipe.
g. Pipe.
h. Open manometer.
i. Mercury-in-glass thermometer.
j. Vernier gauge.
k. Rack and pinion.
l. Microphone.
m. Amplifier.
n. Neon lamp.
o. Rotating disk.
p. Variable speed crank.
q. Stop watch and revolution counter.
r. Stroboscope motor.

Plate I

PROCEDURE

This work on organ pipes was done in a sound-proof room in which the walls and ceiling were highly sound absorbent. The variation in temperature was slight, varying no more than 0.4 of a degree Centigrade for any one set of determinations. Six different pipes, designated as A, B, C, D, E, and F, were used in carrying out this study. Of these, A, C, and E were closed pipes and B, D, and F were open pipes. The lengths varied from 31.26 cm. to 37.56 cm. for the closed pipes, and from 67.2 cm. to 79.8 cm. for the open pipes. The range of air pressure was from 18 mm. to 138 mm., measured by an open water manometer attached directly below the languid of each pipe.

Air pressure of 18 mm. was admitted into closed pipe A while the length and the mouth cut-up were adjusted so that the pipe spoke its fundamental clearly. After the piston which closed the end of pipe A was removed, adjustable sleeves were fitted on the pipe. By moving these sleeves up or down on the pipe, the length of open pipe B was adjusted so that it spoke the same frequency as did closed pipe A. This frequency was determined stroboscopically. A section of pipe of the proper length was cut and accurately machined so that its inside diameter was exactly the same as that of closed pipe A. This additional section was fitted on the top of the pipe so that it was air tight and a tightly fitting sleeve was made to hold it securely in place. After determinations were made on pipes A and B, the piston was replaced and the length of closed pipe C was adjusted so that it spoke with a frequency of about 15 vibrations per second higher than closed pipe A. The same procedure was followed as outlined above in obtaining the proper length for open pipe D so that its frequency was the same as that of closed pipe C. Closed pipe E was lengthened so that it spoke a frequency 15 vibrations higher than did closed pipe C. Open pipe F was also lengthened so that its frequency was approximately the same as that of closed pipe E, following the same procedure as that given for open pipe B. Increases of 15 vibrations per second in frequency were used because of the limitations of the length of the pipe in the apparatus.

Most investigators agree that the tones produced at the lip of the pipe and the body vibrations of the column of air in the pipe constitute a coupled system. Jeans (10) stated that for a pipe to speak a clear full tone it is desirable that there be as good resonance as possible between the edgetone and the vibrating column of air in the pipe. The most important factor in obtaining such resonance is the proper adjustment of the distance between the languid and the lip of the pipe. In order to determine the effect of changing the distance between the lip and the edge at various pressures, the distance from slit to edge was adjusted so that the fundamental of the pipe spoke clearly. For example, at a pressure of 18 mm. the distance from slit to edge of a closed pipe was found to be 1.7 cm. for a clear fundamental tone. The distance was decreased until the frequency jumped to the third harmonic and with a further decrease in distance the fifth and seventh harmonics were obtained. In like manner, twelve pressures above 18 mm. were applied and the same procedure followed.

The readings in Table 1 show that with pressures varying from 18 to 138 mm. a distance between 1.7 and 1.3 cm. is most desirable. The distance was then calculated by the rules set forth by Boner (3) and several leading pipe organ manufacturers. Three of the seven organ manufacturers consulted construct their pipes so that the cut-up, or distance from slit to edge, is about one-third of the width of the mouth. One company constructs its pipes so that the distance is approximately two-ninths the width of the mouth, and two companies use patterns and gauges with no definite ratio for the cut-up. The width of the mouth of each pipe used in this work was 4.2 cm., which is almost four-fifteenths of the circumference of the pipes. This is in very close agreement with the ratio used by Boner (3) and two of the organ companies referred to above. The distance from the slit to the edge in each of the pipes used was 1.4 cm., or one-third of the width of the mouth.

Table 1. The effect of changing the distance between the slit and lip upon the frequency of a closed pipe.

Pressure (mm.)	Distance from languid to lip (cm.)	Occurrence of partials	Pressure (mm.)	Distance from languid to lip (cm.)	Occurrence of partials
18	1.70	Fundamental	78	2.70	Fundamental
	.60	3d partial		1.15	3d partial
	.50	5th partial		.50	5th partial
	.35	7th partial			
			88	2.75	Fundamental
28	1.90	Fundamental		1.20	3d partial
	.70	3d partial		.50	5th partial
	.50	5th partial			
	.40	7th partial	98	2.75	Fundamental
				1.30	3d partial
38	2.10	Fundamental		.55	5th partial
	.80	3d partial			
	.45	5th partial	108	2.75	Fundamental
				1.30	3d partial
48	2.20	Fundamental		.60	5th partial
	.90	3d partial			
	.45	5th partial	118	2.75	Fundamental
				1.30	3d partial
				.60	5th partial
58	2.40	Fundamental			
	1.00	3d partial	128	2.80	Fundamental
	.50	5th partial		1.30	3d partial
				.60	5th partial
68	2.60	Fundamental	138	2.80	Fundamental
	1.10	3d partial		1.30	3d partial
	.50	5th partial		.60	5th partial

This value lies well within the limits of 1.7 and 1.3 cm. mentioned above.

Particular care was taken in inspecting the apparatus for leaks in the air line and in obtaining proper adjustment of the needle valve, and the floating tank of the equalizer was checked for its proper level before each reading. This precautionary procedure was necessary because the least fluctuation in air pressure affected the frequency of the pipes, and any irregularity in frequency resulted in errors in the readings. Beginning with a pressure of 18 mm., the pressure was increased in steps of 10 mm. until a pressure of 138 mm. was reached. This variation in pressure was obtained by increasing the number of weights placed on the top of the equalizer.

At each change in pressure the pipe frequencies indicated by the neon lamp and the holes in the rotating disk were synchronized stroboscopically. The stop watch and revolution counter were started, and the time for 500 revolutions of the disk was observed and recorded. Three trials were taken for each frequency and the average time for 500 revolutions computed and recorded. The temperature of the air entering the pipe was also read and recorded for each trial. The frequency was computed by dividing the product of the number of revolutions (500) and the number of holes in the disk (72) by the average time required for 500 revolutions.

From Tables 2 to 7 it will be noted that a jump in frequency occurred in each pipe. Observing the two readings immediately before and after the jump in frequency was difficult because of the presence of a harmonic frequency, and many of the readings at these points were taken as many as six or seven times.

RESULTS

The results from these experiments conducted on six organ flue pipes, three open and three closed, show that an increase in wind pressure is always accompanied by an increase in frequency. Tables 2 to 7 show that some variations occur between the frequencies of open and closed pipes when equal changes in pressure are applied. Figures 1, 2, and 3 are graphs plotted from the data in Tables 2 to 7, the pressure being plotted as the abscissa and the frequency as the ordinate. These graphs show that the greatest change in frequency occurred between pressures of 18 and 38 mm., the changes in the closed pipes A, C, and E being much greater than the changes in the open pipes B, D, and F. Also the increase in frequencies of the closed pipes was much greater than the frequencies of the open pipes for changes in pressure above 38 mm.

The average change in frequency resulting from changes in pressure ranging from 38 mm. to the point where the frequency jumped to its harmonic in closed pipe A was 1.2 vibrations per second per centimeter change of pressure. In closed pipes C and E, the average change in frequency resulting from the same increase in pressure was 1.3 vibrations per second per centimeter of pressure. Since the temperature change occurring during any one set of determinations was never greater than 0.4 degree Centigrade, corrections for temperature were not made. The data taken on the three closed pipes used in this experiment indicate that increases of pressure from 38 mm. to the pressure causing a jump to the first harmonic effected a change in frequency of very nearly 1.3 vibrations for each centimeter change in wind pressure. In the three open pipes the corresponding changes in pressure did not cause so great a variation in frequency, as is shown by the graphs. For the same range of pressures used in the three closed pipes, the average change for pipe B was 0.3, and for pipes D and F, 0.4 vibration per second for each centimeter change in pressure. For the open pipes the average change in frequency was slightly less than 0.4 vibration per centimeter change in pressure.

In each of the six pipes, a critical point in pressure was reached where the frequency jumped to another harmonic. The data show that in the closed pipes the frequency of the harmonics was approximately three times that of the fundamental, but for the open pipes the frequency of the harmonics was two times that of the fundamental. In all cases the jump to a harmonic occurred at lower pressures in the open than in the closed pipes. The results further show that when the length of either an open or closed pipe was increased, the jump to a harmonic occurred at lower pressures. The graphs in Figures, 1, 2, and 3 for all six pipes show that at pressures ranging from 38 mm. to the pressure at which the jump to a harmonic occurred, the frequency change was very nearly proportional to the change in pressure.

Below is a copy of data from Carriére (6), showing the effect on the frequency of an edge-tone when the pressure is increased.

Pressure (mm.)	Frequency of edge-tone
30	23
40	25
50	28
60	30
80	33
100	35
120	40
140	42
158	44
182	46
200	48

Figures 1, 2, and 3 also show Carriére's (6) edge-tone curve with the frequency plotted against the pressure. This curve resembles very closely the curves for frequency changes of the closed pipes used in this study. The slopes of the curves for the change in frequencies of the open pipes were not as steep as those of the closed pipes.

Obtaining accurate observations for the determination of the change in frequencies in the harmonic series was

Table 2. Variation in frequency of the fundamental and harmonic of closed pipe A (length, 37.56 cm.).

Temperature (degrees C.)	Pressure (mm.)	Time for 500 revolutions (seconds) Trial 1	Trial 2	Trial 3	Average time for 500 revolutions (seconds)	Frequency
		Fundamental				
33.8	18	180.1	179.9	180.0	180.0	200.0
33.9	28	177.4	177.8	177.5	177.5	202.8
33.9	38	176.0	175.9	176.1	176.0	204.5
34.0	48	175.0	175.1	174.9	175.0	205.7
34.0	58	173.7	173.7	173.7	173.7	207.2
34.0	68	172.6	172.3	172.7	172.7	208.4
34.0	78	171.7	171.7	171.7	171.7	209.6
34.0	88	170.6	170.3	170.9	170.8	210.7
		Harmonic				
34.0	98	59.0	59.3	59.3	59.3	607.0
34.0	108	59.4	59.0	59.3	59.2	608.1
33.9	118	59.3	59.2	59.0	59.1	609.1
33.9	128	59.2	59.2	59.0	59.1	609.1
33.9	138	59.2	59.0	59.0	59.0	610.0

Table 3. Variation in frequency of the fundamental and harmonic of open pipe B (length, 79.8 cm.).

Temperature (degrees C.)	Pressure (mm.)	Time for 500 revolutions (seconds)			Average time for 500 revolutions (seconds)	Frequency
		Trial 1	Trial 2	Trial 3		
			Fundamental			
33.3	18	179.8	180.0	180.2	180.0	200.0
33.5	28	179.3	179.3	179.4	179.3	200.7
33.5	38	178.8	178.8	178.8	178.8	201.3
33.5	48	178.4	178.3	178.4	178.4	201.7
33.5	58	178.2	178.2	178.1	178.2	202.0
			Harmonic			
33.5	68	89.9	89.9	89.9	89.9	400.4
33.5	78	89.7	89.7	89.7	89.7	401.3
33.4	88	89.5	89.4	89.5	89.5	402.2
33.4	98	89.5	89.3	89.3	89.3	403.1
33.4	108	89.3	89.2	89.2	89.2	403.5
33.3	118	89.1	89.2	89.1	89.1	404.0
33.3	128	89.0	89.0	89.0	89.0	404.5
33.2	138	88.9	88.9	88.9	88.9	404.9

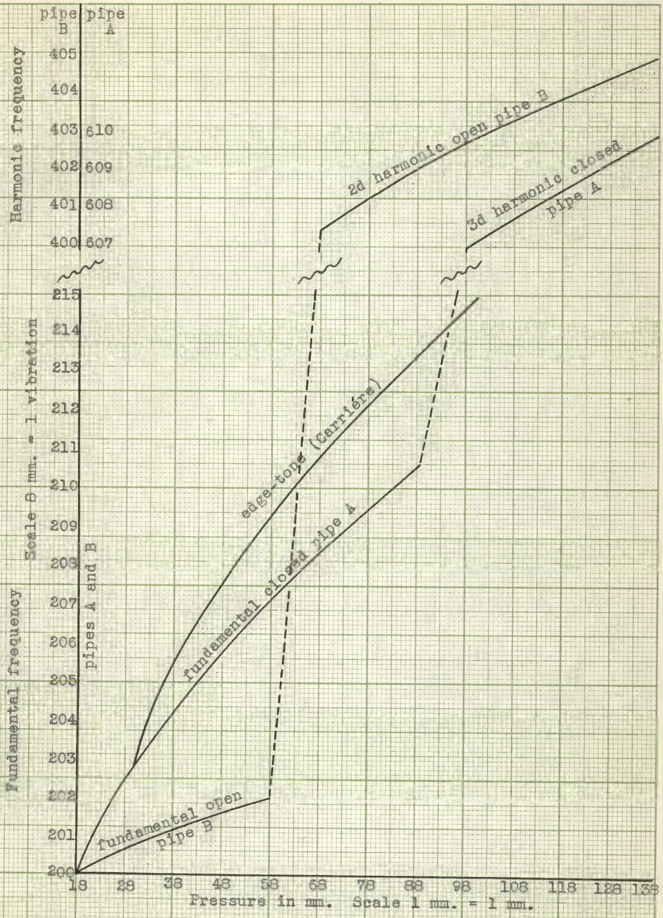

Fig. 1. Graphs showing the frequency changes in the fundamentals and harmonics of closed pipe A, length 37.56 cm., and open pipe B, length 79.80 cm.

Table 4. Variation in frequency of the fundamental and harmonic of closed pipe C, (length, 34.39 cm.).

Temperature (degrees C.)	Pressure (mm.)	Time for 500 revolutions (seconds) Trial 1	Trial 2	Trial 3	Average time for 500 revolutions (seconds)	Frequency
			Fundamental			
34.1	18	167.5	167.4	167.4	167.4	215.0
34.2	28	164.8	164.7	164.7	164.7	218.5
34.2	38	163.1	163.0	165.0	163.0	220.8
34.2	48	161.7	161.8	161.9	161.8	222.5
34.2	58	160.9	160.7	160.8	160.7	223.9
34.2	68	159.9	159.9	159.7	159.9	225.1
34.2	78	158.8	158.8	158.9	158.8	226.7
34.2	88	158.2	158.2	158.1	158.2	227.5
34.2	98	157.2	157.2	157.1	157.2	229.0
			Harmonic			
34.2	108	54.6	54.7	54.7	54.7	658.1
34.2	118	54.5	54.6	54.5	54.53	660.1
34.1	128	54.4	54.5	54.5	54.46	661.0
34.1	138	54.4	54.5	54.3	54.4	661.7

Table 5. Variation in frequency of the fundamental and harmonic of open pipe D (length, 73.2 cm.).

Temperature (degrees C.)	Pressure (mm.)	Time for 500 revolutions (seconds)			Average time for 500 revolutions (seconds)	Frequency
		Trial 1	Trial 2	Trial 3		
			Fundamental			
33.4	18	167.7	167.8	167.7	167.7	214.7
33.5	28	166.6	166.7	166.7	166.7	215.9
33.6	38	166.1	166.0	166.1	166.1	216.7
33.6	48	165.9	165.9	166.0	165.9	217.0
33.6	58	165.5	165.5	165.5	165.5	217.5
33.7	68	165.1	165.2	165.1	165.1	218.0
			Harmonic			
33.8	78	82.7	82.9	82.8	82.8	434.8
33.7	88	82.4	82.7	82.6	82.6	435.8
33.7	98	82.5	82.6	82.4	82.5	436.3
33.7	108	82.5	82.3	82.6	82.4	436.8
33.6	118	82.3	82.3	82.6	82.3	437.4
33.6	128	82.0	82.4	82.0	82.2	437.9
33.6	138	82.2	82.2	82.2	82.2	437.9

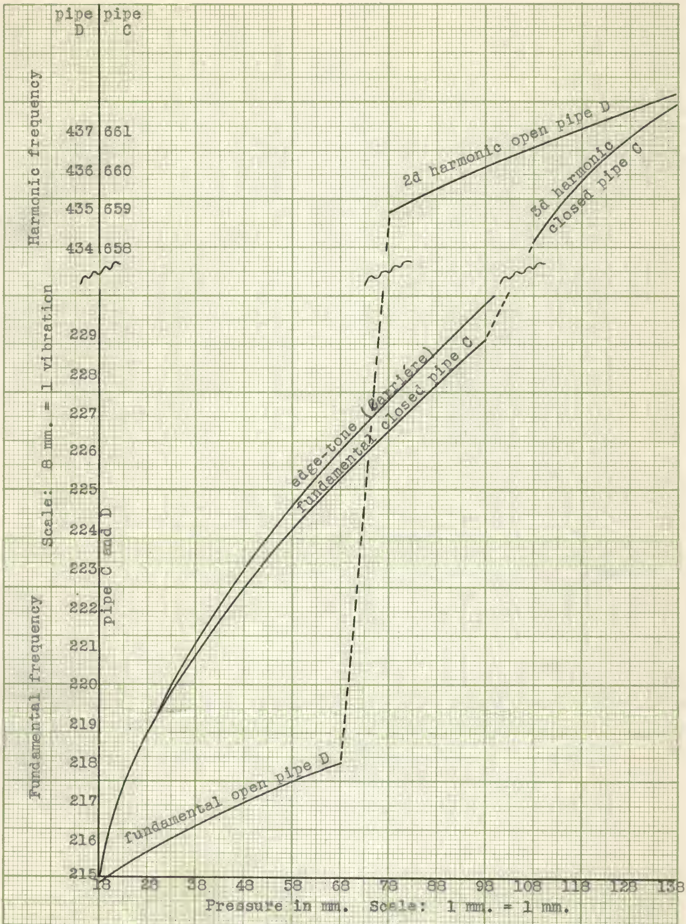

Fig. 2. Graphs showing the frequency changes in the fundamentals and harmonics of closed pipe C, length 34.39 cm., and open pipe D, length 73.20 cm.

Table 6. Variation in frequency of the fundamental and harmonic of closed pipe E (length, 31.26 cm.).

Temperature (degrees C.)	Pressure (mm.)	Time for 500 revolutions (seconds) Trial 1	Trial 2	Trial 3	Average time for 500 revolutions (seconds)	Frequency
		Fundamental				
35.3	18	155.3	155.6	155.1	155.3	231.8
35.2	28	152.6	152.0	151.9	152.0	236.8
35.2	38	150.9	150.8	150.7	150.8	238.7
35.2	48	149.9	149.9	149.9	149.9	240.1
35.2	58	148.9	148.9	148.8	148.9	241.7
35.1	68	148.1	148.0	148.0	148.0	243.2
35.1	78	147.3	147.2	147.2	147.2	244.5
35.0	88	146.6	146.6	146.6	146.6	245.5
35.0	98	145.7	145.7	145.8	145.7	247.0
34.9	108	145.1	145.2	145.2	145.2	247.9
		Harmonic				
34.9	118	51.6	51.9	51.7	51.7	696.3
34.9	128	51.5	51.6	51.6	51.6	697.6
34.9	138	51.5	51.8	51.6	51.5	699.0

Table 7. Variation in frequency of the fundamental and harmonic of open pipe F (length, 67.2 cm.).

Temperature (degrees C.)	Pressure (mm.)	Time for 500 revolutions (seconds)			Average time for 500 revolutions (seconds)	Frequency
		Trial 1	Trial 2	Trial 3		
			Fundamental			
34.8	18	155.0	155.0	155.1	155.0	232.2
34.8	28	154.0	153.8	153.6	153.8	234.0
34.7	38	153.4	153.4	155.5	153.4	234.6
34.7	48	153.2	153.0	153.0	153.1	235.1
34.7	58	152.9	152.7	152.8	152.8	235.6
34.7	68	152.6	152.5	152.5	152.5	236.0
34.6	78	152.3	152.4	152.3	152.3	236.3
			Harmonic			
34.6	88	76.4	76.4	76.5	76.4	471.2
34.6	98	76.3	76.4	76.3	76.3	471.8
34.6	108	76.4	76.0	76.2	76.2	472.4
34.5	118	76.2	76.3	75.8	76.1	473.0
34.5	128	76.2	76.1	75.8	76.0	473.6
34.5	138	75.8	76.1	75.9	75.9	474.3

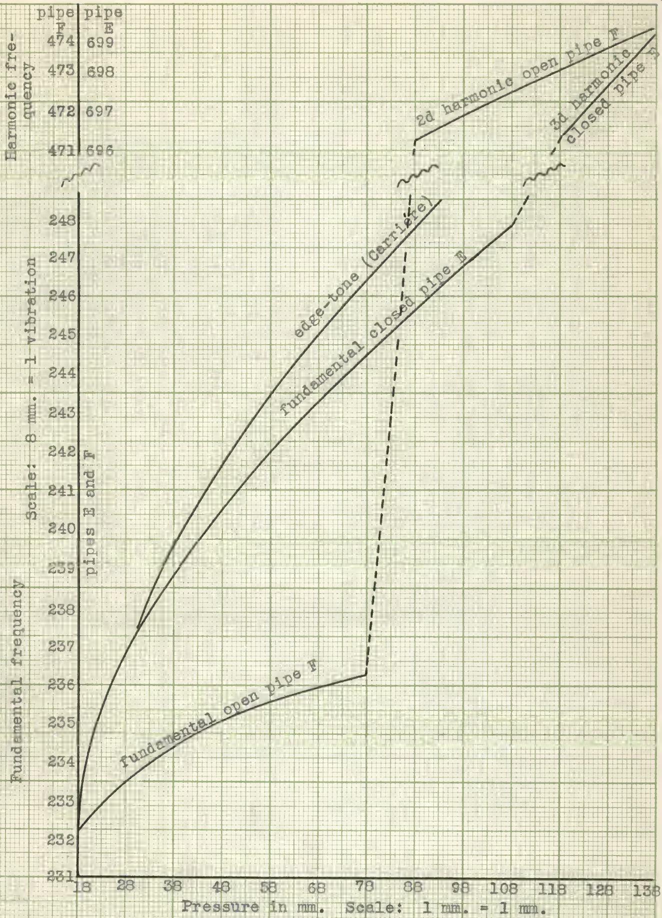

Fig. 3. Graphs showing the frequency changes in the fundamentals and harmonics of closed pipe E, length 31.26 cm., and open pipe F, length 67.20 cm.

difficult because of the presence of other frequencies appearing in the stroboscope. However, readings were taken on the harmonics appearing in all six pipes. The average rise in frequency for open pipes B, D, and F was 0.6 vibrations per centimeter change of pressure. Because of the limitations of the pressure equalizer, a sufficient number of readings on the closed pipes could not be obtained for the calculation of a reliable average, the closed pipes being much slower in jumping to their respective harmonics than the open pipes. However, the graphs indicate that the frequency changes per centimeter change in pressure of the harmonic series do not differ greatly from those of the fundamental series.

DISCUSSION

Some of the results of this work are what would be expected under the given conditions. Others may not be so readily explained since there is still some disagreement among investigators in accounting for some phases of the behavior of organ pipes.

The fact that the pitch increases with an increase of wind pressure is well demonstrated in this study. This rise in pitch may be explained on the basis of several of the theories offered for the origin of tone in a pipe. Smith (18) suggested that when the stream of air passes the edge, a part of the air in the pipe is carried along with the stream, thus forming a rarefaction within the pipe. When the inertia of the outward moving air particles is overcome by the streaming air and atmospheric pressure on the outside, the air stream is forced back into the pipe by the pressure of the outside air, forming a condensation within the pipe. In this manner the air stream is kept vibrating and the sound of the pipe is maintained. On this theory, an increase in pressure results in an increase in the amplitude of the vibrations of the air reed and also in an increase in frequency.

From the edge-tone formula given by Bate (2), $V/nh = k$, where V = the velocity of the air jet, h = the height of the mouth, n = the frequency of the edge-tone, and k = a constant (value 2.0), one obtains $n = V/hk$. Throughout this experiment the value of h was kept constant so that the only variables in the formula were n and V. As the velocity of the blowing wind increases with an increase in pressure, the frequency of the edge-tone must also rise. Most writers agree that the distance from slit to edge, along with the column of air in the pipe, forms a coupled system. If this is true, the conclusion must be that at perfect resonance the pipe will speak a tone of the same frequency as that of the edge-tone.

The rise in pitch at low pressures in both open and closed pipes was probably due to the fact that the frequency of the edge-tones and the natural frequency of the pipe had not reached the point of full resonance. It is probable that the frequency of the edge-tone at a pressure of 18 mm. was far below the natural frequency of the column of air in the pipe. Because of the pulling effect of the column of air in the pipe on the frequency of the edge-tone, the data obtained show only the resultant frequencies at pressures ranging from 18 to 28 mm. which were the pressures at which the greatest change in frequencies occurred.

The curves in Figures 1, 2, and 3 indicate that for equal changes in pressure, the frequency change was greater in the closed than in the open pipes. Since the closed pipe has but one open end, the loss of energy of the molecules of air in motion is less than in the case of a pipe having two open ends. This explanation is in accordance with the theory presented by Helmholtz (8) that at the closed end of a pipe the reflection of a wave is practically complete, that is, there is no perceptible loss in molecular motion but merely a change in phase. At the open end, however, a fraction of the wave always passes into the open air so that the intensity of the reflected wave is always less than that of the incident wave. Helmholtz (8) suggested that in order for a pipe to continue its vibrations, the work lost at the open ends must be replaced at every backward and forward reflection by some other kind of action. If at those times and places where the air is condensed, a small amount of air is forced into the pipe, then the loss of molecular motion will be compensated and the pipe will continue to speak. If Helmholtz' (8) explanation is correct, more wind is required to maintain a given frequency in an open pipe than in a closed pipe. His theory substantiates the results obtained in this experiment which show a greater variation in frequency resulting from equal changes in pressure for the closed than for the open pipes.

The average change of 1.3 vibrations per second for each centimeter change in wind pressure for closed pipes and of 0.4 vibration for the open pipes merely indicates the variation in frequency per centimeter change in pressure for pipes of the same diameter as those used in this work.

The jump in frequency to a harmonic, as seen in Tables 2 to 7, occurred more quickly under lower pressure changes in the open than in the closed pipes. This is contrary to what might at first be expected; however, on further analysis it may be readily explained. As has been shown, a closed pipe speaks an odd train of harmonics and the open pipe speaks a full train. This means that the frequency of the first harmonic spoken by a closed pipe is three times the frequency of its fundamental, but in an open pipe the first harmonic spoken has a frequency two times that of its fundamental. Therefore, more energy would be required to force a pipe to jump to a frequency that is three times its fundamental than to jump to one only two times its fundamental. Because of the wide difference between their fundamental and natural harmonic frequencies and because of the fact that open pipes exhibit a smaller frequency change than closed pipes for corresponding changes in pressure, an open pipe should be expected to jump to its harmonic quicker than a closed pipe. This conclusion is in agreement with Bate (2), who stated that the jet decides the frequency when the pipe is long and the pipe decides the frequency when the latter is of normal length.

The edge-tone formula, n = V/hk, shows that the frequency is proportional to the velocity of the air. The curves show the frequency range as being approximately proportional to the pressure. It should not be expected, however, that the graphs be straight lines since theoretically, according to Bate (2), the velocity is proportional to the square root of the pressure. If velocities were plotted against the pressures, the resulting curve would have characteristics much like the pressure-frequency curves illustrated.

The average pressure used by Carriére (6) was 60 mm., and the average on the three pipes used in this work was 58 mm. This average represents the one used for a similar range of frequency changes. However, the comparison of Carriére's (6) edge-tone curve with the curves of the closed pipes used in this experiment must be taken as being approximate because of the difference in the distance between the slit and lip used in his experiment and that of 1.4 cm. used in this work. The characteristics of his curve are those that one might expect upon the application of the edge-tone formula, remembering that the theoretical velocity of the wind is proportional to the square root of the pressure.

The frequency changes in the harmonics of the closed and open pipes correspond closely to those of the fundamental. However, because of difficulties encountered in obtaining data, the curves for the harmonics must be regarded as being approximate.

CONCLUSIONS

1. As the wind pressure is increased, the pitch of both open and closed organ flue pipes rises.

2. The rise in pitch is greater in both closed and open organ pipes as the wind pressure is increased at low pressures than when similar increases are made at higher pressures.

3. The frequency change is greater in closed pipes than in open pipes for corresponding changes in wind pressure.

4. The average change in frequency for the closed pipes used in this study was 1.3 vibrations per second per centimeter change in wind pressure while in the open pipes it was 0.4 vibration per second per centimeter change in pressure.

5. A jump in frequency to a harmonic occurred at lower pressures in the open pipes than in the closed pipes.

6. At pressures ranging from 38 mm. to the pressure at which the frequency jumped to a harmonic, the frequency change

was very nearly proportional to the change in wind pressure.

7. Frequency changes resulting from an increase in pressure in closed pipes correspond more nearly with the frequency changes of edge-tones than do those in open pipes.

8. The frequency changes caused by an increase in pressure correspond closely in both the fundamental and harmonic series.

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