HARMONIC ANALYSIS OF A DAMPED
AND UNDAMPED ORGAN PIPE

by

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INTRODUCTION

The investigation of problems in acoustics by the use of such electrical instruments as the cathode-ray oscillograph and the electrical harmonic analyzer is a comparatively new field in physics. The investigation which will be described lies in this field.

The object of the investigation was to determine the effect of lining an open-closed organ pipe with sound-absorptive material. Felt was used for the latter, which had the effect of reducing the frequency of the fundamental and of the partials, of diminishing the intensity of the fundamental, and of disproportionately diminishing the intensities of the partials.

APPARATUS

Some of the instruments employed in the investigation are standard pieces of equipment. Others were constructed here in the physics shop by Professors E. K. Chapin and E. V. Floyd. The photograph, Plate I, shows the arrangement of the apparatus. A cross-sectional diagram, Plate II, is submitted, on which parts referred to will be specified by letters.

The circular tank, "A", is an arrangement for supplying compressed air to blow the pipe. This tank was built in two sections, an upper, smaller section which telescoped into a larger lower section. Weights

Plate I. Photograph showing arrangement of apparatus used in this investigation.

Plate I.

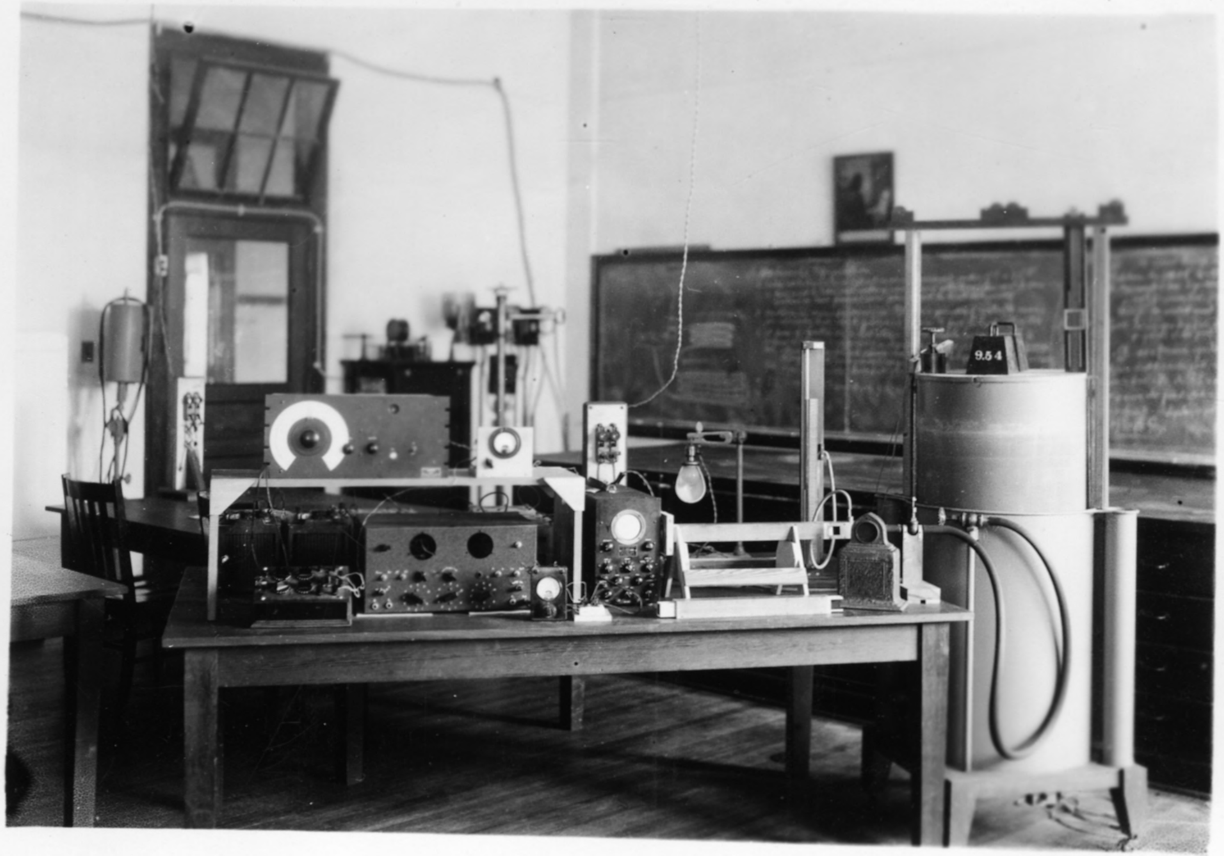


Plate II. Schematic diagram of apparatus.

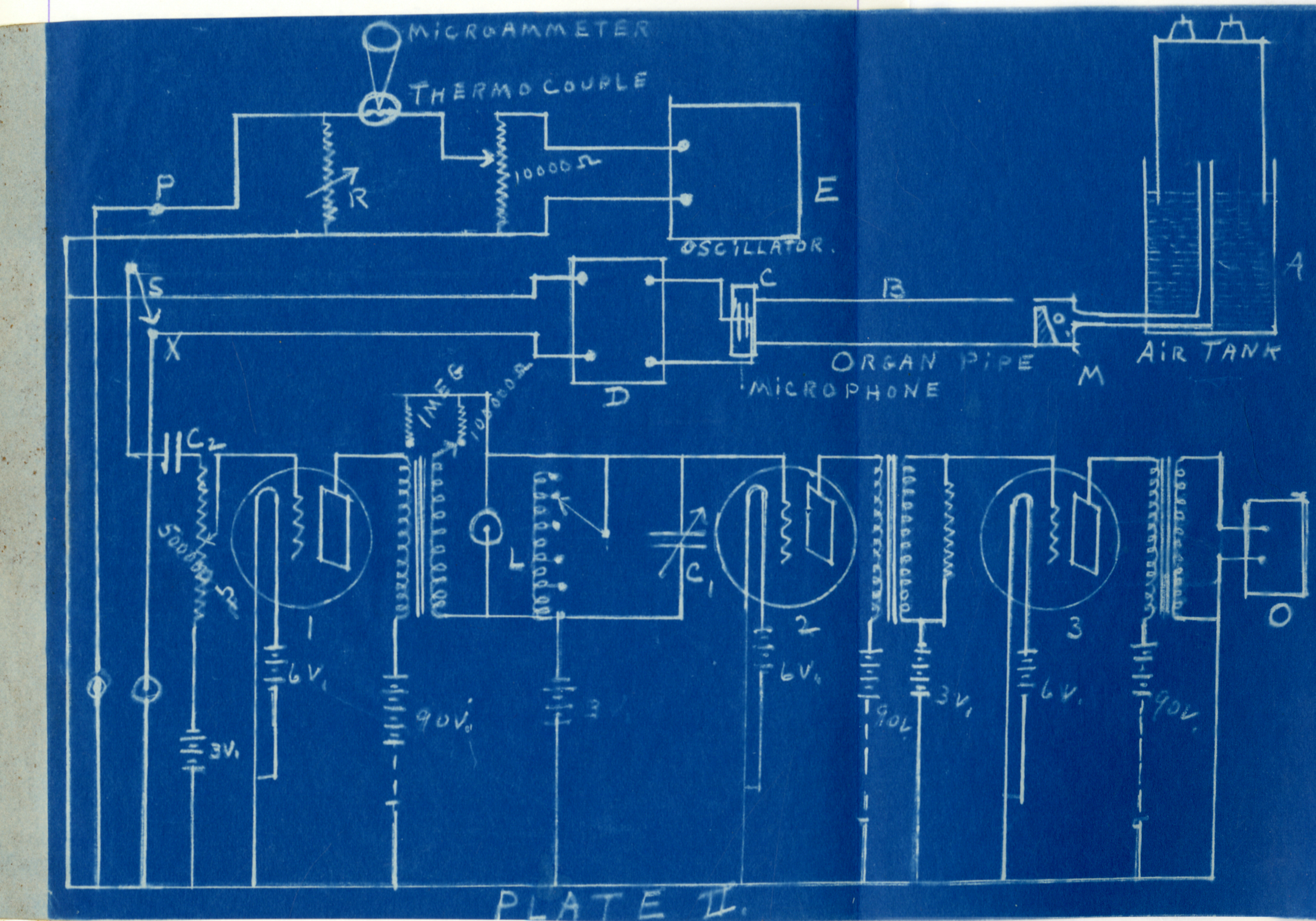

MICROAMMETER
THERMOCOUPLE
R
10000Ω
E
OSCILLATOR.
P
S
X
C
B
A
D
ORGAN PIPE
MICROPHONE
M
AIR TANK
1MEG
C2
L
C1
1
2
3
6V.
90V.
3V.
O
PLATE II.

Plate II.

were placed upon the top of the upper section to secure proper pressure. Two valves were employed to regulate the pressure which was maintained with not more variation than one millimeter of water from that desired for best performance of the pipes. To prevent the upper section of this tank from moving downward with uneven flow, guide irons were attached to the sides of the framework, which are not shown in the diagram. A water manometer was attached to the air chamber of the pipe at the part marked "M" in the diagram, and was used to measure all pressures.

Microphones

A condenser microphone, No. 1007-A, constructed by Western Electric, was used in this investigation. This type of microphone was chosen because the curve showing response frequency characteristics suited the needs of this problem. Figure 1 shows such a chart reproduced from the research of Jones (4). For the frequencies encountered in this problem, 150 - 1500, the line is quite smooth and nearly horizontal, indicating that any partials within this range should be transmitted with little distortion or undue emphasis (5). The natural period of the diaphragm of this particular microphone is about 5,000 cycles per second, which is well above any frequencies encountered in this investigation. The diaphragm is constructed of aluminum alloy which, due to its light weight, increases its sensitivity and is suitable for use in this problem.

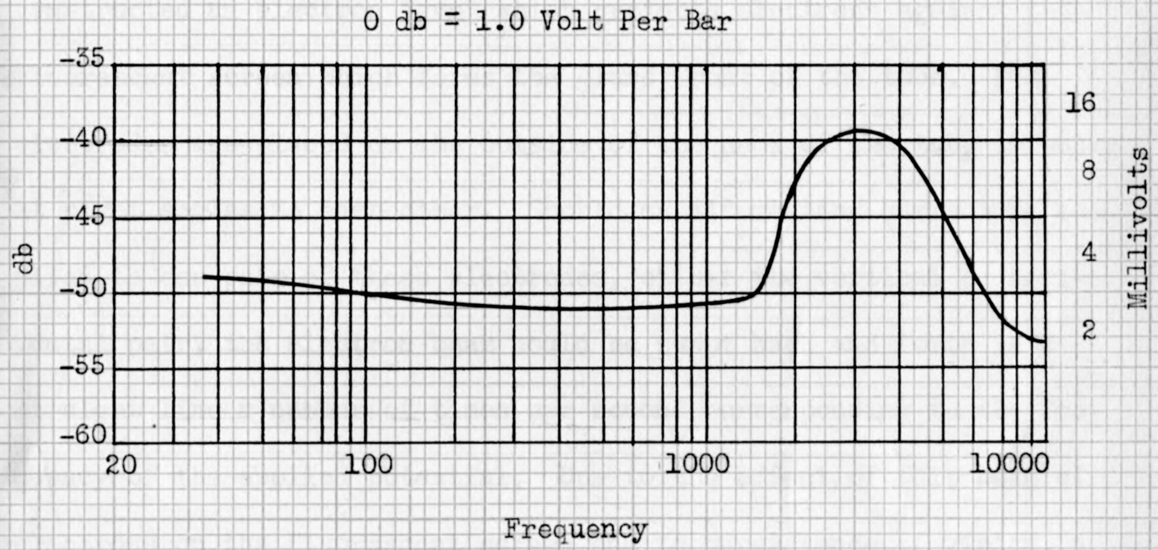


Fig. 1 Field Calibration of 394-type Condenser Microphone

Cathode-ray Oscillograph

The cathode-ray oscillograph is the type TMV-122-B, manufactured by R.C.A. Co., Inc. of Camden, New Jersey. The essential feature of this piece of apparatus is a cathode-ray tube in the base of which is constructed an electron "gun" which projects electrons against the fluorescent screen which forms the glass front of the tube. Four electrodes are placed on the outside of the neck of the tube in pairs at right angles to each other. Should an alternating current be applied to one pair of these electrodes, either the vertical or horizontal pair, the electron beam would be swept back and forth in a straight line a number of times per second corresponding to the frequency of the applied potential. Due to the effect of this beam of electrons on the fluorescent screen and to persistence of vision, a bright green line would appear upon the screen in a vertical or horizontal position, depending upon the pair of electrodes to which the alternating potential was attached. By applying alternating potentials to both of these pairs of electrodes simultaneously, various patterns appear upon the screen, the pattern being determined by the relative frequencies and amplitudes of the A.C. potentials applied at the electrodes (3). The alternating current from the microphone may be applied to one pair of electrodes, and with a field controlled frequency applied at the other pair, the wave form from the microphone appears on the screen (2). A large number of these wave forms were observed and several were traced through translucent paper. Some of these wave forms are reproduced and marked figure 2.

Beat Frequency Oscillator

The beat frequency oscillator is the type TMV-52-E, and is also manufactured by the R.C.A. Co., Inc. of Camden, New Jersey. This instrument employs the beating of two radio frequency oscillators together to obtain a desired audio frequency. It provides a wave form which is nearly sinusoidal and is fitted with a calibrated dial which was used to read the frequency of the organ pipes being tested.

Analyzer

The analyzer was constructed in the physics laboratories especially for harmonic analysis work by Professor E. K. Chapin. The drawing referred to as Plate II shows the construction somewhat in detail. The inductance marked "L" was a torroidal ring made of permalloy metal about 13 cm. in diameter, nominal permeability 75, wound with 6,750 turns of number 22 copper wire. Five taps were allowed, making it possible to use all of the turns or specified fractions of them.

The variable condenser marked "C_1" was an ordinary decade condenser of one microfarad capacity. The three tubes used in the analyzer are

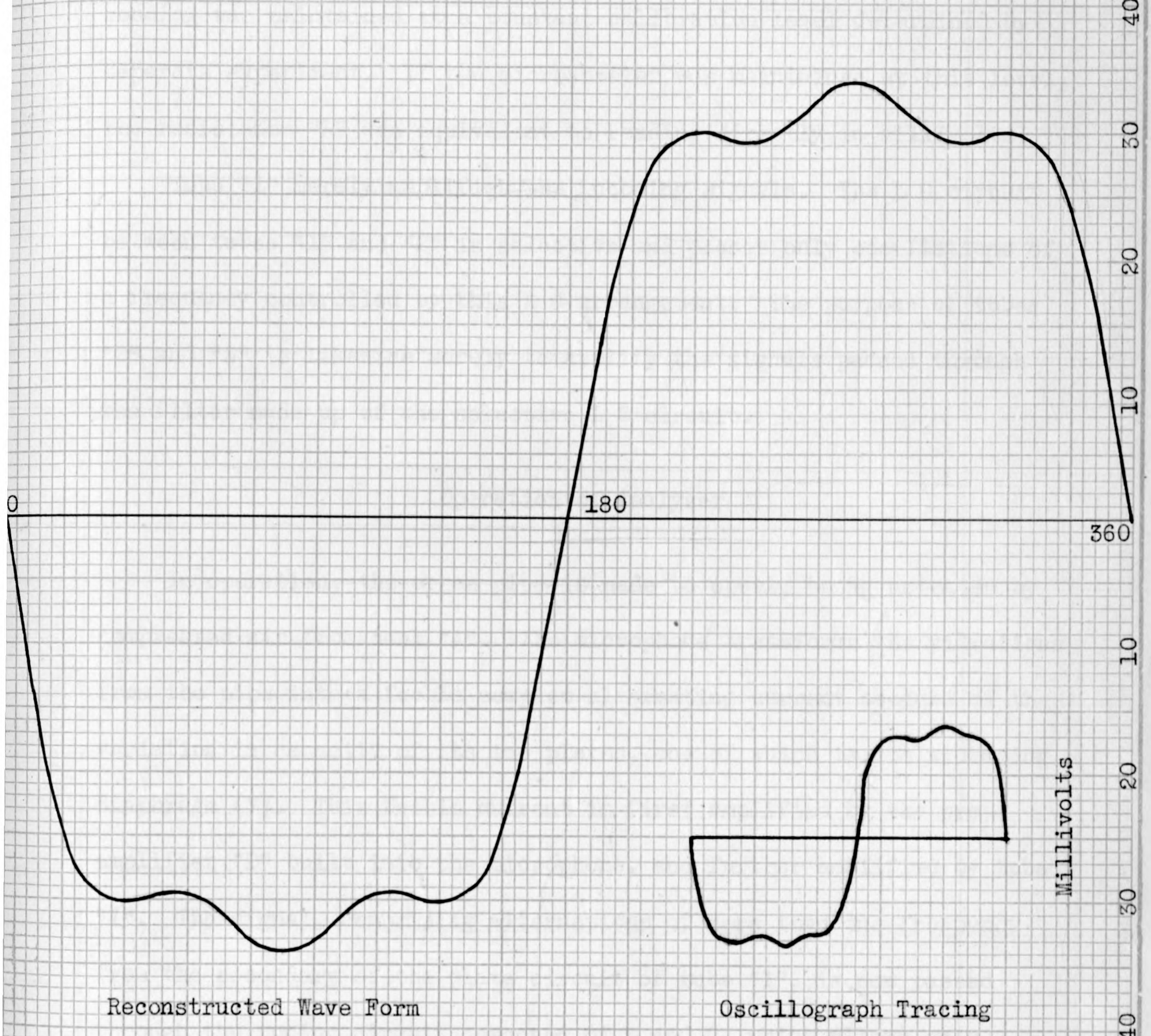


Fig. 2. Graph Comparing Wave Formed Reconstructed From Measured Partials with Oscillograph Tracing.

of the 12A general purpose type. The thermocouple operates from the feeble a.c. current coming from the oscillator. The microammeter reading was maintained at a constant calibration level determined by separate experiment. If the microammeter was maintained at this level, the resistance "R" was equivalent to reading directly in millivolts.

Tube "1" merely amplifies the incoming signals. The L C circuit between tubes "1" and "2" is selective and passes only oscillations of a frequency controlled by this L C arrangement. The purpose of tubes "2" and "3" is likewise merely to amplify the signals passed through the filter made up of the selective L C circuit.

Operation of Analyzer

In operation, the organ pipe is made to speak, being actuated by compressed air from tank "A". The microphone transforms the vibrations from the pipe into a feeble complex alternating current because of the variation in capacity of its two plates, one of which is the vibrating diaphragm (7). This feeble current is first amplified by the pre-amplifier "D" built into the microphone, and further amplified by tube "1". The signal, comprising alternations of more than one frequency from the secondary of the plate circuit of tube "1", is now passed through the tuning circuit composed of L and C, which allows only alternations of a single frequency, determined by the relative values of the inductance L and capacity C, to be passed on to tubes "2" and

"3". Here the alternating current passed by the filter is further amplified and registered on meter "O". The value of "C_1" is regulated until the reading at meter "O" is a maximum. This occurs when the impedance of the L C circuit is a maximum. This allows a maximum of current to pass on to meter "O" and so indicates resonance. The circuit will indicate as many different resonance points as there are different sets of frequencies making up the complex wave form passed on by the microphone.

After a reading has been secured on meter "O", switch "S" is turned from its position "X" to "P", and then "R" is regulated until the reading on meter "O" is duplicated, making sure first that the dial on the oscillator has been adjusted so that it emits oscillations of the same frequency as those to which the L C circuit was resonant. The reading on "R", necessary to bring about this condition, is equivalent to millivolts as previously explained. In this manner the first partial and any others present in a complex wave may be sorted out and their relative amplitudes determined.

Organ Pipe Construction

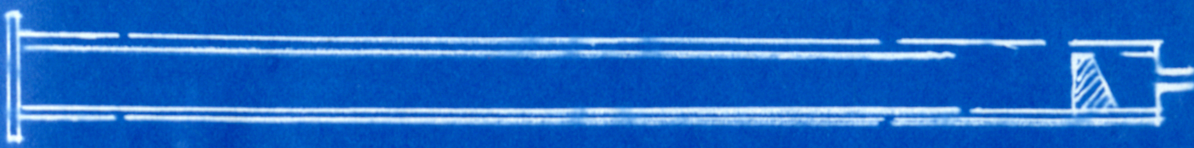
Two organ pipes were constructed by Professor E. V. Floyd. One of them had two central parts which were interchangeable. This was accomplished by making the central section of the pipe with sleeve end fittings so that the voicing element and the closed end element would telescope tightly into place when the pipe was assembled. The way in which these parts fitted together is more clearly shown by referring to the accompanying sketch, figure 3. The two central portions were intended to be exact duplicates of each other as to length and internal diameter. One of these central portions, which may be called a pipe, was varnished within with clear shellac, making a smooth hard surface. The other central pipe was cut down the thickness of the felt and lined with a black felt, about 0.14 cm. thick, weighing about 0.032 gms. per sq. cm. at a relative humidity of 42% and a temperature of 34°C.

Care was taken to make the length, as well as the internal dimensions of the two pipes, as nearly the same as possible, counting the felt as part of the pipe wall. Both pipes were of closed-open construction. The reason for making a telescoping barrel was to avoid attempting to make two voicing elements just alike, which would be very difficult if at all possible. The sliding joints of the telescoping sections were carefully fitted so as to avoid air leaks which would give somewhat the effect of an open-open pipe. The joints were further sealed with surgeon's tape to assure freedom from air leaks. The dimensions of the assembled pipe appear below.

Unlined pipe, length 50.80 cm., width 2.50 cm.

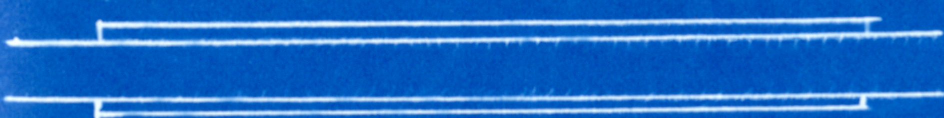
Lined pipe, length 50.78 cm., width 2.50 cm.

Fig. 3. Showing sectional organ pipe assembled and separate sections.



ASSEMBLED PIPE.

UNLINED SECTION.



LINED SECTION.

FIG. 3.

ORGAN PIPE THEORY

There are two main classes of organ pipes, closed-open pipes and open-open organ pipes. Sketches are shown of both types, figures 4 and 5.

Closed-open Pipes

In the closed-open pipe, one end is closed and a voicing element makes up the open end, which is a device for setting the air in vibration. A compression thus set up travels the length of the pipe and strikes the closed end, where it is reflected without change of phase, since the closed end is of greater density than the contained air. The closed end becomes, therefore, the node of a standing wave, and there the motion of the air is zero. In the other end of the pipe a reverse situation exists since, here we have maximum disturbance and the antinode of the standing wave. This is indicated in figure 4a, and the length of the closed pipe is roughly 1/4 of the wave length. There are other possible modes of vibration in which the closed end is a node and the open end an antinode (8). Some of these are indicated in figure 4b, c. See Smith (6).

The length of the open-closed resonator is any odd number of quarters of the resonant wave-length. Hence the open-closed pipe yields odd partials only. A common formula for the closed pipe is

Fig. 4 and 5. Showing how standing wave may be formed in open-closed and open-open organ pipes.

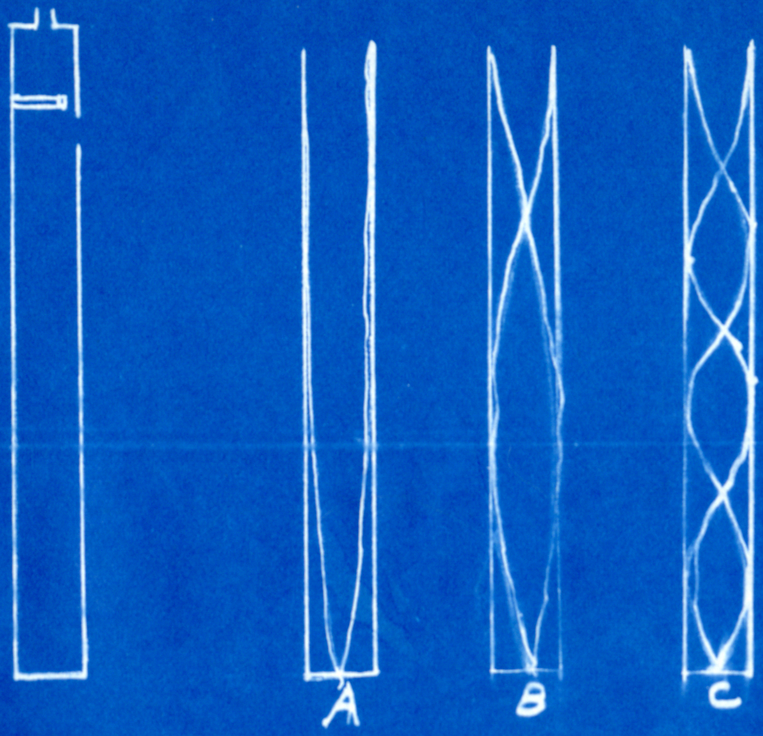


Fig. 4

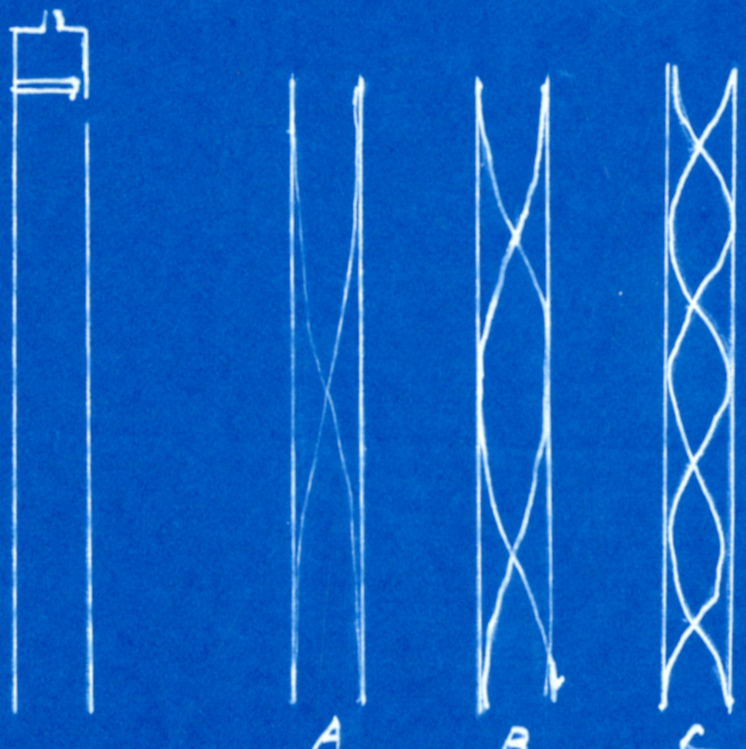


Fig. 5

$N = \frac{V}{4l}$, where N = frequency, V = velocity of sound, and l = length of closed pipe. Barton (1) gives this formula corrected for mouth opening and diameter, $N = \frac{V_o \sqrt{1+AT}}{4(L+C)}$, where N = frequency, Vo = velocity of sound at 0^oC, L = length of pipe, C = 2.7 R, where R = radius of pipe, A = coefficient of expansion of air, T = temperature Centigrade. The frequency of the pipe, whose dimensions were given above and which was used in all tests quoted excepting the first as calculated by this formula, was 162, when $T = 36^oC$.

Open-open Pipes

In the case of an open-open pipe, a condensation may be forced down the pipe precisely as in the case of the closed pipe, but upon striking the end of the pipe, which is now a less dense medium, the condensation will be reflected with a reversal of phase. This will be true at both ends, and consequently, an antinode of a standing wave will form at each of the two ends of the pipe, and a node in the center of the pipe. As may be seen from figure 5a, the pipe length will be 1/2 of the wave length of the resonating column. There are other possible modes of vibration that would make the two open ends antinodes. Again referring to figure 5b and c, it is clear that the length of the open-open-resonator may be any number of half-waves. There should be a full train of partials, even as well as odd. Only open-closed pipes were used in this investigation.

TESTS WITH FIRST PIPE

The first pipe was a square wooden one 5.1 cm. on a side and 49.5 cm. long, yielding a fundamental tone of 146.6. The microphone was attached to the closed end of the pipe, being screwed to the detachable end plate, the whole of which formed the closed end of the pipe. The wooden block, forming the end of the pipe, was pierced by a small hole to allow the pressure to be transmitted to the microphone, and thus to be analyzed. With a hole 0.04 in. in diameter, the output in millivolts, with the relative amplitudes of the various partials, is shown in table 1.

Table 1.

Microphone at end of pipe.

Partial	Frequency	Amplitude	Pressure
1st	N = 146.6	2189 mv.	8.8 cm.
2nd	2N	305 mv.	8.8 cm.
3rd	3N	186 mv.	8.8 cm.
4th	4N	16 mv.	8.8 cm.
5th	5N	16 mv.	8.8 cm.
6th	6N	9 mv.	8.8 cm.
7th	7N	7 mv.	8.8 cm.

Further readings were taken, making the hole 0.07 in., 0.120 in., 0.23 in., 0.50 in., and finally 1 in. in diameter. The output was not materially changed, either in the number of partials, or in their relative intensities, nor in the intensity of the fundamental.

The results are doubtful because of the presence of even partials. It was first planned to take this pipe apart, and after lining it, to reassemble the pipe, and thus to learn the effect of damping with felt. It was later thought better to construct a pipe with two central portions, one lined and the other unlined. All further work on the first pipe was abandoned and attention was directed toward learning the reason for the apparent presence of the even partials.

EXPERIMENTS WITH SECOND PIPE

When using the second pipe, with two interchangeable central sections, the microphone was again placed at the end of the pipe, in fact the microphone formed the end of the pipe. After being rigidly fastened on with screws to the end section, it was further protected against air leaks by covering the seam with Hall's elastic cement. Many readings were taken over a range of air pressures but the set of readings in table 2 is typical.

Table 2

Microphone at end.

Partials	Frequency	Amplitude	Pressure
1st	N	1270 mv.	8.8 cm.
2nd	2N	880 mv.	8.8 cm.
3rd	3N	300 mv.	8.8 cm.
4th	4N	125 mv.	8.8 cm.
5th	5N	160 mv.	8.8 cm.
6th	6N	50 mv.	8.8 cm.
7th	7N	60 mv.	8.8 cm.
8th	8N	0 mv.	8.8 cm.
9th	9N	60 mv.	8.8 cm.

The disturbing even partials still persisted. There seemed to be two possible explanations. First, even partials might be present in spite of theory. Second, the equipment might be overloaded and thus yield an incorrect analysis because of distortion somewhere in the system. The second idea admitted of two possible explanations. The amplifiers might be overloaded. The diaphragm of the microphone itself might be overloaded. Tests showed that the amplifier could stand well over 2,000 millivolts output without distortion.

To learn whether or not the microphone was overloaded, a solid base block of hard maple, 1.25 cm. in thickness, was screwed to the microphone, and this combination was made the end of the closed pipe. Precautions against air leaks were again taken by sealing all seams with Hall's elastic cement. This differs from previous arrangements in that the base block had no hole in it and formed the end of the pipe rather than the microphone. Table 3 shows the data secured in this manner.

Table 3

Microphone at end.

Partials	Frequency	Amplitude	Pressure
1st	N	260 mv.	8.8 cm.
2nd	2N	0 mv.	8.8 cm.
3rd	3N	17 mv.	8.8 cm.
4th	4N	0 mv.	8.8 cm.
5th	5N	4 mv.	8.8 cm.

Several interesting conclusions may be drawn from the above data. First in importance, is the fact that no even partials occur, and this in spite of the fact that the odd partials are fairly prominent. Had the even partials been generated in the pipe, it is logical to suppose that the base block would have transmitted them with the same ease as the odd partials. Another item to be taken into account is the lower output. In previous readings, where the even partials were present, the output was well over 1,200 millivolts for the first partial, whereas here the output is 260 millivolts. Evidently, in the case of the larger output the diaphragm was overloaded, and the distortion introduced the even harmonics.

In view of the above results, it became necessary to change the method of taking readings. The end block of hard maple was left intact and the pipe was then assembled. The microphone was placed6.1 cm. to one side of the voicing element, which arrangement was not changed in any of the subsequent investigation. It will be observed that the diaphragm and amplifying system were far from overloaded, since the maximum output, 38 millivolts, was much below the previously tested safe output of 260 millivolts.

Two groups of readings will be presented in tables 4 and 5. Many other groups of readings were taken under slightly varying conditions, such as varying the position of the microphone, varying pressure of air, etc., but these results will not be tabulated. Both sets of readings tabulated below were taken within a blanketed booth to exclude extraneous noises. To further facilitate the taking of reliable readings, the work was done in the evening when the building was quiet.

An oscillograph record was also traced to serve as a rough check on the reliability of the analysis. More will be said about this later.

Table 4

Microphone 6.1 cm. to side. Unlined pipe. Pressure 8.8 cm.

Partials	Frequency	Trial 1	Trial 2	Trial 3	Trial 4	Average
1st	N = 162	37.0 mv.	38.0 mv.	38.0 mv.	38.0 mv.	37.75 mv.
2nd	2N	0	0	0	0	0
3rd	3N	8.0 mv.	8.0 mv.	8.0 mv.	8.0 mv.	8.0 mv.
4th	4N	0	0	0	0	0
5th	5N	4.0 mv.	3.8 mv.	3.8 mv.	3.7 mv.	3.8 mv.
6th	6N	0	0	0	0	0
7th	7N	1.6 mv.	1.5 mv.	1.6 mv.	1.5 mv.	1.55 mv.
8th	8N	0	0	0	0	0
9th	9N	0.6 mv.	0.6 mv.	0.6 mv.	0.7 mv.	0.6 mv.

Table 5

Microphone 6.1 cm. to side. Lined pipe. Pressure 8.8 cm.

Partials	Frequency	Trial 1	Trial 2	Trial 3	Trial 4	Average
1st	N = 150	5.8 mv.	6.0 mv.	6.0 mv.	5.8 mv.	5.9 mv.
2nd	2N	0	0	0	0	0
3rd	3N	0.6 mv.	0.5 mv.	0.6 mv.	0.6 mv.	0.6 mv.
4th	4N	0	0	0	0	0
5th	5N	3.0 mv.	3.1 mv.	3.1 mv.	3.0 mv.	3.05 mv.
6th	6N	0	0	0	0	0
7th	7N	0.5 mv.	0.5 mv.	0.5 mv.	0.5 mv.	0.5 mv.
8th	8N	0	0	0	0	0
9th	9N	0.5 mv.	0.5 mv.	0.5 mv.	0.5 mv.	0.5 mv.

TESTS OF ANALYZER

An oscillograph record was secured of the wave form by placing tracing paper over the fluorescent screen. These tracings appear as figure 2. The wave formed by plotting the various partials with their measured amplitudes, assuming zero epoch angle, appears beside them. While the agreement is not complete, the record of the oscillograph serves as an excellent check upon the accuracy and reliability of results. The graph appearing as figure 6 shows how the output of the analyzer varies with the frequency. Resonance is fairly sharp. The frequency range covered is only one-half of that actually met with in this investigation.

Another interesting test of the analyzer was tuning it to resonance with the third partial of the pipe being investigated. An input of 10 mv. gave a certain reading on the meter marked "O" on Plate II. Oscillations corresponding in frequency to the third partial of the pipe were being generated by the beat frequency oscillator. The oscillator was then made to generate oscillations of double the original frequency, leaving all other parts unchanged. The value of "R" was now altered to bring the reading of meter "O" back to its original. It was found that 345 millivolts were necessary to restore the original reading. The influence of one partial, the first perhaps, upon any other is, therefore, very small. Inasmuch as only odd partials were present in this investigation, the influence is less than that indicated above.

SUMMARY OF EFFECT OF DAMPING

The first effect was the change in frequency. The frequency of

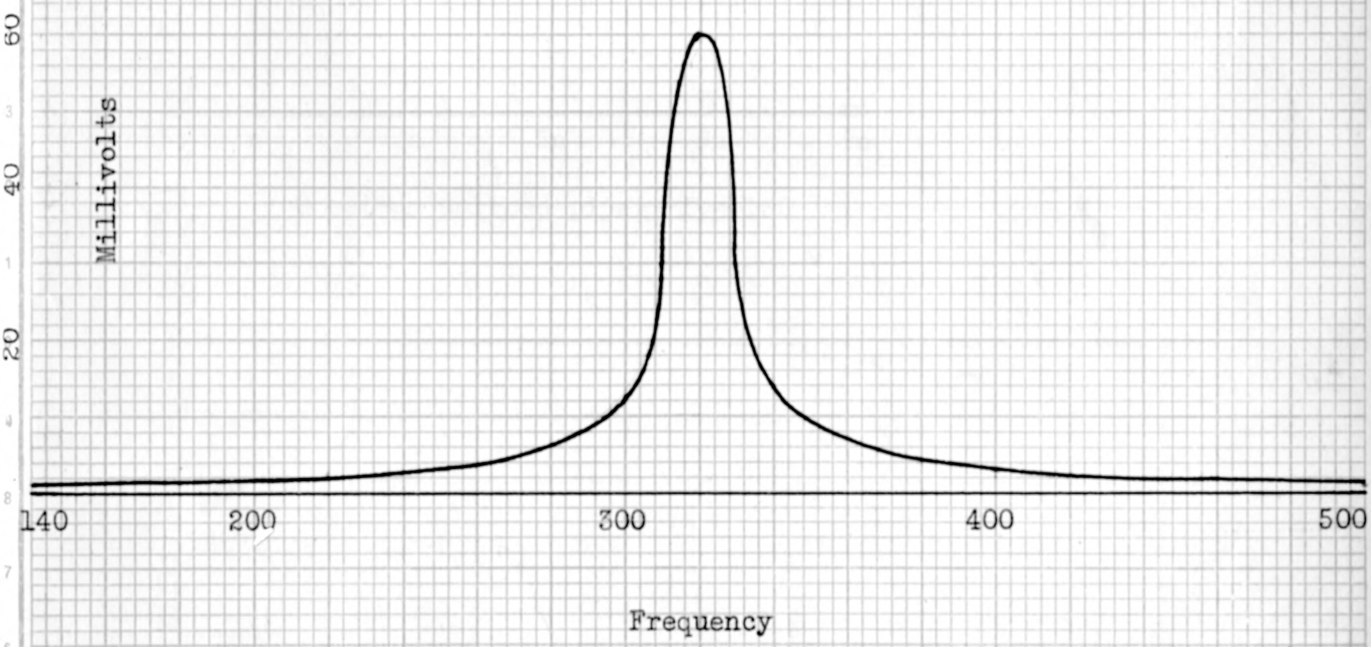
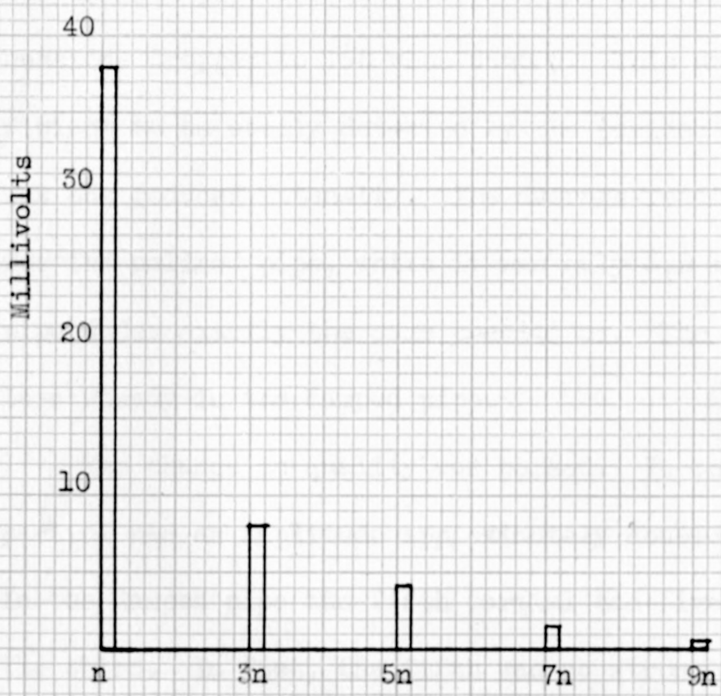
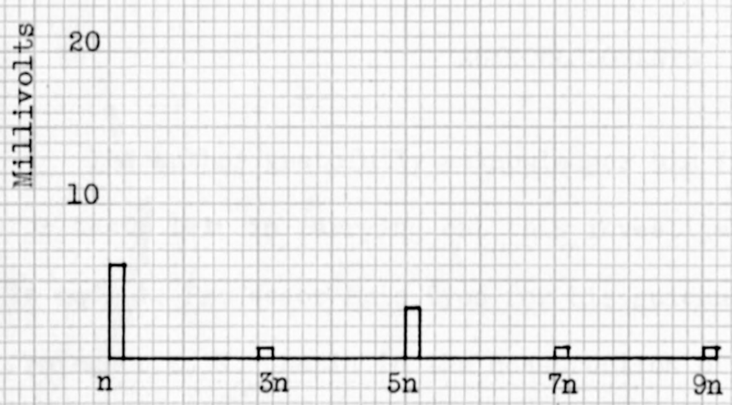


Fig. 6. Resonance Graph of Analyzer



Spectrum unlined pipe. f = 162



Spectrum lined pipe. f = 150

Fig. 7. Graph Showing Comparative Values of Partials in Lined and Unlined Pipes.

the unlined pipe was 162, whereas the frequency of a pipe of like dimensions dropped to 150 when damped. This drop in frequency was sufficient to be easily detected by the unaided ear. The second effect was the reduced intensity. The average reading was 37.75 millivolts for the unlined pipe, while it was only 5.9 millivolts for the damped pipe under exactly the same conditions. The tone was also somewhat less steady in the damped pipe.

The change in quality was marked. In the undamped pipe the third partial had an amplitude approximately double that of the fifth partial. In the damped pipe the fifth partial had five times the amplitude of the third. In fact, the fifth was so strong in the damped pipe that its amplitude approximated one-half that of the fundamental tone. In the undamped pipe this same fifth partial had a value of only about a tenth of the fundamental. Figure 7 shows the comparative strengths of the partials in the two cases.

ACKNOWLEDGMENTS

The author gratefully acknowledges his indebtedness to his teachers for their help in carrying out this investigation. Especial reference is made to Professor Eric Lyon for his guidance as major instructor, to Professor E. K. Chapin in the construction of the harmonic analyzer, to Professor E. V. Floyd for the construction of the organ pipes, and to Professor J. O. Hamilton for his courtesy in photographing the equipment.

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