This paper gives a summary of the sound tube developed in the investigation for a small and simple sound-absorption measuring device. The principle of operation of the sound tube developed in this investigation for measuring coefficients of sound absorption is as follows. A loudspeaker is located at one end of a wooden tube. At the other end of the tube the material being tested for sound absorption is bolted to a mounting frame. When a sound wave of a given frequency is emitted by the loudspeaker this wave travels down the tube to the test specimen. If the specimen is a good reflector of sound nearly all of the sound will be reflected. If the loudspeaker is properly located this reflected wave will arrive back at the loudspeaker in phase with other waves of the same frequency that are being generated. A microphone is located at the same position as the loudspeaker and it indicates the vector sum of the reflected sound. An amplifier is used to increase its output sufficiently to be read on a copper-oxide rectifier-
type voltmeter.

With this arrangement the voltage readings are an inverse function of the sound-absorbing ability of the material, the higher the voltage reading the lower the coefficient of sound absorption. The apparatus is calibrated with materials having known coefficients. Calibration curves are made at 512, 1024, 2048, and 4096 cycles. It is impossible to calibrate the tube for frequencies much lower than 512 cycles because the natural period of vibration of the tube occurs in this region.

The sound tube is built of $\frac{3}{4}$-inch fir wood and is composed of two tubes. The inner tube is 15$\frac{1}{4}$ inches by 15$\frac{3}{4}$ inches inside diameter. Around this tube is placed a layer of 1-inch hairfelt and around this is the second tube, the outside dimensions of which are 20$\frac{1}{2}$ inches by 20$\frac{3}{4}$ inches. This arrangement keeps extraneous sounds from reaching the microphone and it also keeps the loudspeaker tones from getting out into the room. The loudspeaker is mounted in a box 18 inches long. This box is completely lined with one-inch hairfelt to eliminate standing waves on the back side of the dynamic loudspeaker. A threaded rod and a crank is so arranged that the loudspeaker box can be easily moved in the tube.

The method of backing the materials when mounted on the sound tube has some effect on the results. This
is especially noticeable at 512 cycles. At 4096 cycles different backings have no effect on the results.

The use of high grade electrical equipment makes it possible to build a reliable sound-absorption measuring device that is relatively small and compact, can operate in a noisy location, and sound-absorption measurements can be made rapidly and simply. The equipment is especially useful for routine quantitative measurements such as testing manufactured sound absorbing materials at a factory. General sound absorption tests can be made satisfactorily with this equipment.
SIMPLIFIED ELECTRICAL MEASUREMENTS
OF SOUND ABSORPTION

By

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INTRODUCTION
SIMPLIFIED ELECTRICAL MEASUREMENTS
OF SOUND ABSORPTION

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INTRODUCTION

The use of sound absorbing materials has greatly increased in the last few years. Until recently architectural acoustics has been seriously neglected. However, physicists, engineers, and architects have made rapid strides in the development of architectural acoustics and many of the incorrect concepts have been modified. Builders, and the public alike, once thought that the acoustics of a room were non-predictable; good results were just a matter of luck. Today the acoustics of a room can be engineered and the outcome of the design can be assured to be very close to that predicted.

Radio broadcast stations require sound-absorbing material to reduce the reverberation of sound in the studios. The microphone is less tolerant to reverberation than the human ear. This means that specially designed studios having the proper acoustic treatment are necessary. In the past auditoriums have been built which were a marvel of beauty but which had such a long period
of reverberation and such other serious acoustic faults that they did not serve the purpose for which they were designed. The proper use of sound-absorbing materials in these buildings has greatly improved them. Churches, schools, commercial buildings, theaters, music halls, and sound-recording studios all require acoustic treatment. Noises in offices have been greatly reduced through the proper application of sound-absorbing materials.

By reverberation (5) is meant the successive reflections of sound waves by the boundaries of the enclosing surfaces of the room inside of which the sound is emitted. For example, in a bare room these reflections cause the sound to be prolonged and to remain audible several seconds after the sound source has stopped. The time required for a specified sound to die away to one one-millionth of its initial intensity is known as the reverberation time.

According to Knudsen in his book (5) on Architectural Acoustics, the absorption of sound by porous materials is the result of viscous forces incident to the flow of air through minute capillary pores of the material. The impingement of sound waves upon the surface of porous materials produces an alternating pressure which forces the air within the pores into a vibratory motion. Friction with the walls of the pores results and all of the sound
waves that are not reflected are dissipated as heat. Although the absorption of sound in most acoustical materials is attributable to the dissipation of sound in the pores and interstices of the material, a considerable amount of sound energy, especially sound at low frequency, is absorbed by the flexural vibration of the material. The addition of holes in sound absorbing material materially increases the sound absorptivity of the material. Not only do the holes increase the area of surface exposed to the sound waves and thus increasing the number of pores and interstices, but it also provides absorbing boundaries at the surface of the material. The edges made by the holes introduce irregularities of density and elasticity which contribute effectively to the loss of reflected sound.

There is a large variety of materials manufactured for the purpose of absorbing sound, some are decorative and others are plain. They are in the form of panels having rough surfaces, curtains, rugs, felts, tiles, and plasters. Thus it is possible to secure materials that can be used for many different types of structures. For a given frequency the sound-absorbing ability of these commercial materials varies from perhaps 10% of the sound that strikes them to nearly 100%. It is customary to speak of the ability of materials to absorb sound in
terms of coefficients of sound absorption. For example, a material that absorbs 50% of the sound that strikes it is said to have a coefficient of sound absorption of 0.50.

The most common method of determining the coefficient of sound absorption is by the reverberation method. Briefly it is as follows: A specially built room or chamber is filled with sound waves at some definite frequency and then the sound is suddenly stopped. With the aid of a microphone, an amplifier, a recorder and a timing device the time required for the sound to die out is determined. This method of determining the reverberation time is a recent development; the old method was to use trained observers and stop watches. The next step is to mount the sound-absorbing material, which must be a rather large sample, in the chamber and then repeat the process as before. From such data as the dimensions of the room, the area of the sample tested and the reverberation time of the two tests, the coefficient of sound absorption can be calculated. It is customary to make these measurements at 128, 256, 512, 1024, and 4096 cycles per second.

This equipment is large and requires considerable floor space and special structures. Large test samples must also be used. It is slow in its use. However, it is perhaps the most reliable method of measuring sound
absorption that is known, for it makes measurements on large samples of material much in the same way as they are used in practice.

Some experimenting has been done with the use of sound tubes of different sizes, with a source of sound at one end and the material to be tested located at the other end. A wide variety of indicators have been used by experimenters to measure the amount of sound absorbed by the samples. Most of this equipment has, however, been crude and unreliable, could make test only over a very limited frequency range, and was rather slow and awkward to manipulate. Most of the experimenters attempted to determine the coefficients of sound absorption by calculations.

In recent years, however, electrical sound equipment has been developed that is reliable and satisfactory for use over a wide range of frequencies. By incorporating high-grade electrical sound equipment with a sound tube it was thought that a suitable sound-absorption measuring device could be engineered. It was desired to make measurements over a wide range of frequencies, to have a simple and rapidly operating device, require very little equipment, operate satisfactorily in a noisy location, and occupy a small floor space.
The principle of operation of the sound tube described in this paper is as follows: A loudspeaker is located at one end of a wooden tube. At the other end of the tube the material being tested for sound absorption is placed. When a sound wave of a given frequency is emitted by the loudspeaker this wave travels down the tube to the test specimen. If the specimen is a good reflector of sound nearly all of the sound will be reflected. If the loudspeaker is properly located this reflected wave will arrive back at the loudspeaker in phase with other waves of the same frequency that are being generated. A microphone is located at the same position as the loudspeaker, and it indicates the vector sum of the reflected sound. An amplifier is used to increase its output sufficiently to be read on a voltmeter.

With this arrangement the voltage readings are an inverse function of the sound-absorbing ability of the material, the higher the voltage reading the lower the coefficient of sound absorption. The apparatus was calibrated with materials having known coefficients.
DESCRIPTION OF APPARATUS
DESCRIPTION OF APPARATUS

MICROPHONE

Over a century ago it was noticed that certain crystalline substances, when subjected to a pressure, gave off an electric charge. Many tests have since been made on a large number of crystalline and non-crystalline substances to determine whether or not they exhibited this property of giving off a charge when compressed, the phenomena being known as the piezo-electric effect. It was found that Rochelle salt crystals exhibited the greatest piezo-electric effect.

The Brush Development Company has done considerable research on the use of Rochelle salt crystals for microphones and have developed some very satisfactory crystal microphones. The microphone used in these tests was their type B303 microphone, which is entirely free from any inherent noise and has essentially a flat frequency response from 60 to 6,000 cycles per second. This microphone requires no external field excitation. The output level of this particular microphone is approximately -40 db, the reference level being 6 milliwatts. Its output impedance is composed of ohmic resistance and capacitive reactance. These values are roughly 5 megarons
for the ohmic resistance and the capacity is approximately 0.001 mfd. This makes it possible to operate the microphone directly into the grid of an amplifier tube. Since its output impedance is so high it is necessary to use a shielded lead to connect it to an amplifier.

The case, which is of aluminum, contains the small crystal element which is actuated by the linen-bakelite diaphragm. A heavy screen protects the face of the microphone. The construction is such that it is moisture proof, will stand rough handling and ordinary temperature changes have no effect on its output.

LOUDSPEAKER

As it is desirable to have a source of sound originating from an oscillating piston-type of sound producer, a dynamic or moving-coil type loudspeaker was used. This type of loudspeaker has undergone a marked improvement in design in the last few years, and is a very popular type of loudspeaker in present-day radio receivers.

Essentially it is composed of a specially-designed magnetic circuit, a polepiece, and a field coil. This field coil, when energized by direct current, furnishes a very strong magnetic field. The audio-frequency currents are passed through a few turns of wire wound in a small coil and suspended in air around part of the polepiece.
This coil is connected to a small paper cone which furnishes the coupling to the air. When alternating current flows through the small coil, it moves at right angles to the lines of force across the air-gap. These motions are imparted to the cone and in turn to the air.

The dynamic loudspeaker used in these measurements was a model 152 Magnovox loudspeaker. It is designed for push-pull audio circuits using type 45 or 47 tubes. An impedance matching transformer is used to couple the low resistance voice coil to the audio voltage source. The voice coil has a d-c resistance of 1.28 ohms. The impedance matching transformer is arranged to couple to a push-pull circuit, but in the tests only one half of the primary winding was used. The 1000-cycle ohmic resistance measured on the primary side with the voice coil connected to the secondary side is 1910 ohms for one half of the winding.

The field supply for normal operation is 6.25 watts, but satisfactory operation can be obtained on wattages ranging from 4.5 to 12 watts. This model of speaker has a field coil resistance of 6 ohms.

**SOUND TUBE**

In Fig. 1 a general view of the sound tube is shown. It is composed of two tubes, one inside of the other.
Fig.1—Front view of the sound tube.
The inside dimensions of the inner tube is 15½ inches by 15½ inches. Surrounding this tube is a one-inch layer of hairfelt, and on top of this is a second wooden tube 20½ inches by 20½ inches outside dimensions. The overall length of the tube as a whole is 50 inches. The two tubes are made of ¾-inch fir wood and the pieces in each tube are glued together. Fig. 1 is a front view of the tube. It shows the mounting frame with a felt strip and the mounting bolts. This mounting frame is separated from the outer tube by about ½ inch and is fastened to the inner tube. Fig. 2 shows an end view of the construction of the tube, the picture being taken at the back end. This double tube construction, with the hairfelt separating them, is an aid in keeping extraneous noises away from the microphone and also to keep the tone from the loudspeaker from getting out into the room.

The loudspeaker is mounted in a fir plywood box that can be moved in the inner tube by a threaded rod and a crank. The microphone is located on the front of this box. Fig. 3 shows the inside of the loudspeaker box; the view is looking down into the box from the top. The box is approximately 18 inches long and is completely lined (including the lid) with one-inch hairfelt. Two additional hairfelt baffles were used to help absorb
Fig. 2—End construction of sound tube.

Fig. 3—Inside of loudspeaker box.
any sound radiated from the back of the loudspeaker cone, thereby eliminating any possibility of reflected waves from interfering with its operation on the back side of the cone. The threaded $\frac{3}{8}$-inch rod can be seen at the bottom of the box.

In Fig. 4 the completely assembled back end of the tube is shown. The crank is for the purpose of moving the loudspeaker box in the tube. Above the crank is the scale for indicating the position of the face of the baffle (to which the loudspeaker is fastened) in relation to the surface of the test specimen on the front of the tube. This indicator is composed of a flexible steel tape that has been reversed in its holder and the free end fastened to the back of the loudspeaker box. The tape was cut so that it would give a direct reading in inches of the location of the loudspeaker with respect to the test specimen.

The material to be tested is mounted on the front end of the tube and bolted to the mounting frame with four bolts. An additional frame and a piece of $\frac{3}{4}$-inch fir plywood is used to back the test material. Fig. 1 shows the mounting before a test specimen is in place and Fig. 5 shows the specimen completely mounted. In Fig. 1 a strip of felt can be seen on the surface of the mounting frame. This felt aids in making a seal between
Fig. 4—Electrical equipment arranged for making sound-absorption measurements.
Fig. 5—A test specimen mounted on the tube and some of the standard specimens.
the end of the tube and the test specimen so that the end of the tube is completely closed.

OSCILLATOR

The source of audio frequency voltage was a Western Electric 8-A audio oscillator. As it was not calibrated at 512, 1024, 2048 and 4096 cycles, the frequencies used in standard sound-absorption tests, it was necessary to calibrate the oscillator at these frequencies. This was accomplished by using a Western Electric 1-B impedance bridge. By adding a condenser decade box in series with the inductance arm of the bridge the inductance and capacitance could be adjusted to resonate at the different frequencies required and the oscillator tuning was adjusted until a balance was indicated by a pair of headphones.

AMPLIFIER

The amplifier for increasing the output of the microphone sufficiently to be read by a copper-oxide rectifier type voltmeter was a General Radio type 514-H three-stage resistance-coupled amplifier. Type 30 tubes are used in it and the entire circuit, including the batteries, is shielded. Fig. 6 shows the wiring diagram of the amplifier. This amplifier has a voltage gain of
CIRCUIT DIAGRAM OF THE ELECTRICAL EQUIPMENT FOR SOUND ABSORPTION MEASUREMENTS

FIG. 6
slightly more than 200 with a load impedance of 20,000 ohms, the impedance of the General Radio copper-oxide voltmeter. This amplifier and voltmeter have a flat frequency response over the range of frequencies used in the tests. This voltmeter is well adapted as an indicator of the amplifier output because it is rugged and can withstand overloads. It also has the advantage that it has several voltage scales.
MEASUREMENTS
MEASUREMENTS

After investigating several possible methods of making sound-absorption measurements in a sound tube with the use of a microphone as an indicator, the arrangement shown in Fig. 1 was decided as being the most practical. Instead of attempting to compute the coefficients of sound absorption from pressure readings in the tube, as most experimenters have in the past, it was decided that a comparison method would be more practicable. This comparison method was found to be necessary with the equipment available if measurements were to be made over a wide range of frequencies.

Before discussing the comparison method an investigation of the sound wave resonance peaks in the tube should be made. Let it be assumed that a varnished wood panel was bolted to the test frame at the end of the tube. With a source of audio signal from the oscillator applied to the loudspeaker through the thermocouple, a reading of a-c volts at the output of the amplifier will be had. Fig. 6 shows the circuit diagram of the equipment. The reason for the double potentiometer across the leads from the audio oscillator was to have a rough and a fine adjustment of the a-c voltage applied to the loudspeaker; this is an aid in holding some predetermined a-c current
through the loudspeaker. The d-c field current was held constant at 1.0 amperes for the tests.

Let it further be assumed that a frequency of 512 cycles is being used, that the a-c current flowing through the loudspeaker circuit is 1.42 milliamperes and the loudspeaker baffle is 4 inches from the wood test panel at the end of the tube. Referring to Fig. 7, the curve indicates that 2.7 volts was measured. As the loudspeaker was moved farther away from the end of the tube the voltage output of the amplifier decreased until 10 inches was reached. Beyond 10 inches the voltage is shown by the curve to rise, reaching a peak of 16.9 volts at 13.25 inches. At this point the tube is said to be properly adjusted for resonance at 512 cycles. This voltage peak, which corresponds to pressure, is one-half wavelength from the end of the tube. At 26.5 inches another peak, though smaller in magnitude, is shown. This peak is one wavelength from the end of the tube. Due to the sound waves suffering frictional losses in the air and from the walls the second peak is attenuated more than the one at 13.25 inches. Figs. 8, 9, and 10 show resonance curves for 1024, 2048, and 4096 cycles respectively.

Suppose the loudspeaker is brought to the peak at 13.25 inches and the voltage is recorded. The wood test specimen is then removed and a material that is a good
CURVE SHOWING RESONANCE PEAKS IN THE SOUND TUBE

Frequency - 512 Cycles  Input - 1.42 Ma.
Field Current 1.0 Amp.  Wood End

DISTANCE IN INCHES FROM END OF TUBE

FIG. 7
CURVE SHOWING RESONANCE PEAKS IN THE SOUND TUBE
Frequency-1024 Cycles  Input-1.42 Ma.
Field Current 1.0 Amp.  Wood End

Fig. 8
CURVE SHOWING RESONANCE PEAKS IN THE SOUND TUBE
Frequency-2048 Cycles  Input- 3 Ma.
Field Current 1.0 Amp.  Wood End

FIG. 9
CURVE SHOWING RESONANCE PEAKS IN THE SOUND TUBE

Frequency - 4096 Cycles  Input - 1.42 Ma.
Field Current - 1.0 Amp.  Wood End

FIG. 10
sound absorber is clamped to the test frame. With the same power delivered to the speaker the output from the amplifier will be materially reduced, indicating that less sound is reflected back to the microphone. A slight readjustment of the loudspeaker position may be necessary to compensate for any change in the effective length of the tube due to the construction of the test material. The peaks at resonance will be materially broadened as well as lessened in magnitude with a good sound absorber on the end of the tube.

By taking data in a similar manner for different sound-absorbing materials having known coefficients of sound absorption, a calibration curve can be made with volts output from the amplifier as one axis and coefficients of sound absorption as the other axis. Fig. 11 shows a curve made in this manner. Figs. 12, 13, and 14 are similar calibration curves for different frequencies. For known values of sound absorption the following materials were used: Acousti-Celotex types B, BB, BBB, and old type B; Fir-tex wall board \( \frac{1}{2} \) and 1 inch thick; standard Celotex; varnished wood; three thicknesses of felt (\( \frac{1}{8} \), \( \frac{3}{8} \), and 1 inch). The coefficients for these materials will be found in the appendix.

The mounting of the various specimens on the end of the tube was not all quite the same. The Acousti-Celotex
CALIBRATION CURVE FOR COEFFICIENTS OF SOUND ABSORPTION FOR THE SOUND TUBE

Frequency-512 Cycles  Input-1.42 Ma.  Field Current-1.0 Amp.
Distance Between Loudspeaker And Test Material 13 Inches

SOUND ABSORPTION COEFFICIENTS %

100  80  60  40  20  0

VOLTS OUTPUT OF AMPLIFIER

0  2  4  6  8  10  12  14  16  18

FIG. II
CALIBRATION CURVE FOR COEFFICIENTS OF SOUND ABSORPTION
FOR THE SOUND TUBE
Frequency-1024 Cycles Input-1.42 Ma. Field Current-1.0 Amp.
Distance Between Loudspeaker And Test Material 6 inches

Fig. 12
CALIBRATION CURVE FOR COEFFICIENTS OF SOUND ABSORPTION FOR THE SOUND TUBE

Frequency-2048 Cycles Input-3.0 Ma. Field Current-1.0 Amp.
Distance Between Loudspeaker And Test Material 13 Inches

FIG. 13
CALIBRATION CURVE FOR COEFFICIENTS OF SOUND ABSORPTION FOR THE SOUND TUBE

Frequency - 4096 Cycles  Input - 1.42 Ma.  Field Current - 1.0 Amp
Distance Between Loudspeaker and Test Material  9 Inches

SOUND ABSORPTION COEFFICIENTS

VOLTS OUTPUT OF AMPLIFIER

FIG. 14
types B, BB, BBB, and old B were nailed to a piece of $\frac{3}{8}$-inch fir plywood. The other materials were not nailed to a panel. In making the tests all of the materials were backed by a $\frac{5}{8}$-inch wood panel which was bolted at four points to the back of the material. Fig. 5 shows this method of mounting. In this photograph type B Acousti-Celotex is mounted on the end of the tube and on the floor directly under the tube is type BBB Celotex. To the right of this material is a sample of standard Celotex. Leaning against the wall above this sample is a test sample of $\frac{1}{2}$-inch Fir-Tex wall board and to the left of it is type BB Celotex. The large holes in the samples are for the mounting bolts on the end of the tube. The area subjected to the sound waves does not include these holes.

However, before the calibration curves were made, a test was performed to determine the most satisfactory values of input to the loudspeaker at the different frequencies used. These current values were found by plotting a series of curves for the various frequencies, using current input to the loudspeaker as abscissa and the difference in voltage readings from the output of the amplifier between varnished wood and type BBB Acousti-Celotex as ordinates. This curve is shown in Fig. 15. For a given frequency, the same location of the loudspeaker
VOLTAGE DIFFERENCES
FOR VARNISHED WOOD AND
BBB CELOTEX FOR
VARIATIONS IN A.C.
CURRENT TO LOUDSPEAKER

VOLTS DIFFERENCE

A.C. CURRENT INPUT TO LOUDSPEAKER - MA.

FIG. 15
was used. The approximate positions were as follows: for 512 cycles it was 13 inches; for 1024 cycles it was 6 inches; for 2048 cycles it was 13 inches; for 4096 cycles it was 9 inches. The reason for selecting these particular points was two-fold. The voltage peaks at these points are high, and the positions are relatively close together, aiding in rapid measurements. Figs. 7, 8, 9, and 10 show these conditions.

Referring to Fig. 15 again, the curves show that for 512 cycles the curve peaks at 1.5 ma. input; for 1024 cycles the peak is 1.8 ma. input; for 2048 cycles the peak is 3.0 ma. input; for 4096 cycles the peak is 1.5 ma. There are two reasons why these curves do not have the same magnitudes. One reason is that the sound-absorption coefficients for the type BBB Acousti-Celotex is different for different frequencies, and the other reason is that the frequency response of the loudspeaker is not constant.

As it is desirable to have the largest voltage difference possible between these two materials without overloading the amplifier when varnished wood (having a very low coefficient of sound absorption) is used as a test specimen, currents as close as practical to these values indicated by the curves were used. The range of the thermocouples was the limiting factor. For 512,
1024, and 4096 cycles a value of 1.42 ma. was used because of the convenience in reading it on the microammeter and because it gave almost full scale deflection. For 2048 cycles another thermocouple was used. It was possible to get a satisfactory reading at 3 ma. with this thermocouple.

It might be thought that the proper positions of the loudspeaker could not be selected for making the current test shown in Fig. 15 without the resonance curves in Fig. 7, 8, 9, and 10 and vice versa, but this is not the case. With any practical current value input to the loudspeaker a preliminary test can be made that will indicate the location of the most satisfactory resonance peaks for different frequencies.
DISCUSSION
DISCUSSION

GENERAL

The objective in the building of this sound-absorption measuring device was to make a piece of equipment that was simple, small, and compact and that would give satisfactory measurements over a wide range of frequencies. In the investigation many different pieces of equipment were experimented with and many different arrangements were used.

Several locations of the microphone in the tube were tried and it was finally decided that by mounting it on one corner of the loudspeaker baffle, as shown in Fig. 1, was the most practical place consistent with satisfactory results. The amount of direct pick-up through the mounting of the microphone to the baffle was found to be small. After trying three different loudspeakers of the moving-coil type one was found to give good results.

A great deal of difficulty was experienced in securing calibration curves for all of the frequencies. In some of the first test large differences in voltage output from the amplifier, when comparing a material having a very low coefficient of sound absorption with one that had a high coefficient of sound absorption, were possible only at one or two frequencies. This difficulty was
overcome in the final equipment only after the curves in Fig. 15 were used. In Fig. 15 any value of current to the left of the peaks on the curves was found to be satisfactory until the values became very low. On the right-hand side of the peaks the values were found to be unsatisfactory. The amplifier was not only overloaded but apparently the sound-absorbing material could not absorb the same percentage of sound at these higher sound levels as at the lower levels.

RESONANCE CURVES

The resonance curves in Figs. 7, 8, 9, and 10 show some interesting facts. In Fig. 7 the 512-cycle curve is smooth. Since the wavelength of the 512-cycle signal is relatively large there are practically no reflections from any objects within the tube except the end of the tube, where the test material is located, and the loudspeaker end. At this frequency the loudspeaker is operating solely as a piston. Fig. 8 shows the resonance curve for 1024 cycles. This curve indicates that some reflections are taking place from other objects in the tube. This is shown by the unsymmetrical peaks in the curve. The wavelength has become half that at 512 cycles, and some of the objects are so located that minor resonance conditions are set up with them and the loudspeaker.
This becomes more noticeable as the frequency is increased. In the region between 1024 cycles and 2048 cycles the paper cone of the loudspeaker begins to depart materially from a rigid plunger action into a wave action or progressive deflection (4). This may have some effect on the resonance curves.

When one of these resonance peaks is approached it was found that the current input to the loudspeaker will vary slightly; this is especially noticeable at the lower frequencies. This change indicates that the impedance of the loudspeaker is changing. The cause for this change is due to the change in acoustic load on the loudspeaker. After passing through a resonance peak the impedance will return to its normal value. While this impedance change is not large it is sufficient at the peaks to cause a slight change in current flow. In the tests the applied voltage was readjusted at the peaks so that the current remained constant. It was found that the difference in voltage readings at the output of the amplifier were not changed materially if this correction was not made.

The general method used by most experimenters in making sound-absorption measurements in a sound tube was to adjust the length of the sound tube so that standing waves existed between the sound source and the test specimen. The standing waves were then explored with a
sound intensity measuring device such as a microphone.

It was found to be more simple and practical in the investigation to mount the sound intensity measuring device (the piezo-electric microphone) on the front of the loudspeaker box. This arrangement does not make it possible to explore the standing waves in the tube. It is only possible to measure the sound intensity at the same location as the loudspeaker.

The shape of the resonance curves shown in Fig. 7, 8, 9, and 10 can best be explained by referring to Fig. 7, the 512-cycle curve. If the loudspeaker was located at 13.25 inches from the end of the tube the output of the amplifier would indicate a peak of 16.9 volts. This distance from the end of the tube to the loudspeaker would be one-half wavelength.

Starting with the cone of the loudspeaker at rest, suppose that it was pushed in a direction toward the end of the tube by the 512-cycle alternating current. A sound wave would be generated. This sound wave would travel down the tube and would be reflected by the wood panel at the end of the tube. During the interval the cone of the loudspeaker would have reached the end of its stroke in the forward direction and would have reversed and gone in the opposite direction. The time required for the reflected wave to arrive back at the
loudspeaker box would be the same as the time required for the cone to go from its normal position to the end of its backward stroke and back to the normal position again. In this manner the sound waves at the loudspeaker would be reenforced at definite intervals. The microphone located at this position would be subjected to an oscillating pressure corresponding to these reenforcements and rarefactions.

At 26.5 inches the curve shows another peak, though of lesser magnitude. At this position a sound wave reflected back to the loudspeaker arrives after the loudspeaker cone has made two complete cycles from the time the initial sound wave was generated. If the loudspeaker was located at some position other than multiples of one-half wavelengths the reflected sound waves would be out of phase with the movement of the cone of the loudspeaker. The magnitude of the resulting pressure oscillations would be greatly lessened.

CALIBRATION CURVES

The calibration curves, at a first glance, appear to be very poor, especially those for the lower frequencies. Many ordinary electrical measurements can be made with an accuracy of better than one percent. However, in acoustical measurements this is not the case.
According to an article in "Less Noise--Better Hearing" (1) the following statement is made regarding sound-absorption coefficients. "In order not to emphasize unduly the precise value of the absorption coefficients of a material, it should be borne in mind that experiments show that the results of a single measurement of coefficient depart from the mean of a large number of measurements as much as 7% of the mean value".

There are several other reasons why the points for the calibration curves do not fall in a smooth curve. One reason is that the standards available for calibrating the tube were not the best. Only the three samples of felt were actually measured directly in a sound chamber by the reverberation method. These samples were measured at the Bureau of Standards and the values of sound-absorption coefficients apply only to a large surface of the material and does not necessarily hold for the somewhat smaller area tested. Then to, it was not mounted in the same way as it was at the Bureau of Standards. At the Bureau of Standards it apparently had been glued to a wall. In the tests made with the sound tube it was bolted to a plywood panel at the outer edges and was compressed some. The other materials used as standards for the tests were taken from the stocks of the manufacturers. The values of coefficients used for them were
for samples similar to types in stock that had been tested by the reverberation method. The method of mounting used in securing the coefficients of sound absorption was not known for some of the materials and this would have some effect on the results.

A test was made to see what effect the backing of the material had on the voltage output of the amplifier, and it was found that by taking off the $\frac{3}{4}$-inch wood panel used as a backing in all the tests that it had no effect at 4096 cycles. At 2048 cycles the effect was just noticeable, becoming increasingly greater as the frequency was lowered. At 512 cycles this change amounted to a reduction in voltage reading of almost one volt for type B Acousti-Celotex.

MAKING SOUND-ABSORPTION MEASUREMENTS

This sound tube is very simple to use to measure unknown sound-absorbing materials. This can be accomplished by bolting the specimen to the mounting frame and with a field current of 1.0 amperes applied to the loudspeaker the voltage output of the amplifier is recorded. The alternating current input to the loudspeaker is maintained at the value specified by the calibration curve and the correct position of the loudspeaker is used. From the voltage reading the
coefficient of sound absorption can be read directly from the calibration curve for that particular frequency.

The calibration curves have been checked over a period of more than a week and they do not vary more than 2% of the mean values. In making the calibration curves every effort was made to have the apparatus warmed up so that it was stable. The oscillator plate and filament voltages were held constant at their specified values to insure good wave form.

LOW FREQUENCY MEASUREMENTS

Measurements were attempted at 256 cycles, but due to the natural period of vibration of the sound tube these measurements proved to be unsatisfactory. It is recommended that if such a tube is to be used at frequencies below 512 cycles that thicker boards be used for its construction, increasing the mass of the tube materially.

COMMERCIAL APPLICATION

While the results from the apparatus described in this paper are not as satisfactory as those of the reverberation chamber method they are reasonably good and would be satisfactory for less accurate needs. This equipment would be very useful and entirely satisfactory for quantitative testing. Such a use would be the checking
checking of a manufacture's sound-absorbing product periodically, perhaps many times a day, to see if it was being made properly.
CONCLUSIONS
CONCLUSIONS

1. The accuracy of the sound-absorption measurements made with the sound tube depends upon the standards used to calibrate it.

2. The effect of different methods of mounting the materials is more pronounced at the lower frequencies.

3. By using good quality commercial apparatus a sound-absorption measuring device can be made that will prove satisfactory for general sound-absorption measurements.

4. This apparatus is especially useful for routine quantitative measurements.

5. To make measurements at low frequencies the natural period of vibration of the tube must be low.
APPENDIX
### TABLE OF COEFFICIENTS OF SOUND ABSORPTION

Values Used For Calibration Curves

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness Inches</th>
<th>512 Frequency-Cycles</th>
<th>1024 Frequency-Cycles</th>
<th>2048 Frequency-Cycles</th>
<th>4096 Frequency-Cycles</th>
<th>Authority</th>
</tr>
</thead>
<tbody>
<tr>
<td>Varnished Wood</td>
<td>3/4</td>
<td>0.03</td>
<td>0.03'</td>
<td>0.03'</td>
<td>0.03'</td>
<td>F. R. Watson</td>
</tr>
<tr>
<td>Fir-Tex</td>
<td>1/2</td>
<td>0.28</td>
<td>0.31</td>
<td>0.44</td>
<td>0.55</td>
<td>V.O. Knudsen</td>
</tr>
<tr>
<td>Plain</td>
<td>1</td>
<td>0.39</td>
<td>0.43</td>
<td>0.41</td>
<td>0.50</td>
<td>II</td>
</tr>
<tr>
<td>Acousti-Celotex  B</td>
<td>5/8</td>
<td>0.48</td>
<td>0.63</td>
<td>0.75</td>
<td>0.81</td>
<td>Bureau Of Standards</td>
</tr>
<tr>
<td>BB</td>
<td>13/16</td>
<td>0.62</td>
<td>0.76</td>
<td>0.73</td>
<td>0.74</td>
<td>II</td>
</tr>
<tr>
<td>BBB</td>
<td>1 1/4</td>
<td>0.84</td>
<td>0.97</td>
<td>0.76</td>
<td>0.57</td>
<td>II</td>
</tr>
<tr>
<td>Old B</td>
<td>3/4</td>
<td>0.40</td>
<td>0.62</td>
<td>0.64</td>
<td></td>
<td>II</td>
</tr>
<tr>
<td>Celotex Standard</td>
<td>7/16</td>
<td>0.20</td>
<td>0.24</td>
<td>0.20</td>
<td>0.22</td>
<td>Average</td>
</tr>
<tr>
<td>Felt From Bureau Of Standards</td>
<td>1/2</td>
<td>0.27</td>
<td>0.48</td>
<td>0.74</td>
<td>0.62</td>
<td>Bureau Of Standards</td>
</tr>
<tr>
<td></td>
<td>3/4</td>
<td>0.36</td>
<td>0.63</td>
<td>0.80</td>
<td>0.71</td>
<td>II</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>0.48</td>
<td>0.73</td>
<td>0.88</td>
<td>0.76</td>
<td>II</td>
</tr>
</tbody>
</table>

'Note: Assumed by author
ACKNOWLEDGEMENT

The author wishes to take this opportunity to thank Mr. A. L. Albert, Associate Professor of Communication Engineering at Oregon State College, for suggesting this subject on sound-absorption measurements and also for the helpful suggestions during its development.
BIBLIOGRAPHIES

1. Acousti-Celotex Co. Less noise—better hearing. Celotex Acoustical Department, vol. 6, no. 1, 1934


