THESIS

on

AN ELECTRICAL METHOD FOR MEASURING THE SOUND ABSORBING PROPERTIES OF ACOUSTIC MATERIALS

Submitted to the

OREGON STATE AGRICULTURAL COLLEGE

In partial fulfillment of
the requirements for the
Degree of

MASTER OF SCIENCE

by

William Richard Bullis

May 14, 1931

APPROVED:

Redacted for privacy

Assistant Professor of Electrical Engineering

In Charge of Major

Redacted for privacy

Head of Department of Electrical Engineering

Redacted for privacy

Chairman of Committee on Graduate Study

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SYNOPSIS

It has long been known that the electrical impedance as measured between the terminals of a loudspeaker or a telephone receiver is readily changed when outside forces act upon their diaphragms. When sound waves are the disturbing forces the changed impedance is called "acoustical impedance". It was believed that this phenomenon could be used in some way to measure the sound absorbing and reflecting properties of various substances. Therefore the purpose of this investigation was to develop an electrical apparatus, which would be simple and inexpensive, for testing the acoustic properties of materials.

A loudspeaker driven by a vacuum tube oscillator through an impedance bridge was used as a source of sound. The loudspeaker was placed in front of the material with the intervening distance accurately measured. The individual sound reflection and absorption properties of the materials changed the measured impedance of the loudspeaker which was easily detected by balancing the impedance bridge. The problem was attacted from two angles, namely:

Constant frequency of sound with a variable distance between the loudspeaker and material, and

Constant distance with variable frequency.

Three different tests were made: 1. The loudspeaker placed in a bare wooden tube and the material clamped on

one end; 2. with the wooden tube lined with hairfelt; and 3. with both the loudspeaker and the material placed outside the tube in open air. It was found in the constant frequency bare tube tests that resonant peaks of effective resistance and reactance were obtained whose heights were related to the standard sound absorption coefficients of the specimen, but with the tube lined with hairfelt no peaks of resistance were found and the results of the different specimens were inconsistent. In open air resonant peaks were found whose values were somewhat inconsistent with the sound absorbing properties of the materials. In the variable frequency tests the results with the bare wooden tube showed resonant peaks whose heights were related to the acoustic properties of the materials, but with the tube lined with hairfelt no resonant peaks were found and the results obtained were inconsistent with those of the other tests. In open air no peaks of resistance were obtained, but each material gave a curve whose ordinate values with respect to each other were related to their acoustic properties.

The apparatus was calibrated by testing some materials whose absorption coefficients were known and calibration curves were drawn showing the relation between acoustical resistance and standard absorption coefficients. By using this means an unknown material may easily be tested and the acoustical properties found directly as a coefficient.

INTRODUCTION

The acoustic properties of materials have long been difficult to determine to any reasonable degree of accuracy except by expensive and laborious processes. Now since the advent of broadcast radio programs and sound motion pictures it is increasingly being realized that the much sought-after quality-of-reproduction depends a great deal upon the acoustic properties of both the recording and reproducing surroundings. Architects now recognize the importance of acoustics when building auditoriums, churches, halls, and theaters; therefore an apparatus which can test the sound properties of materials quite accurately, yet remains simple and inexpensive, promises to be of value to both architects, sound engineers, and manafacturers of acoustic materials.

Before progressing further it will be well to determine what some of the acoustic properties of materials are.

Sound is a longitudinal wave motion in the surrounding media formed by vibrating particles. In order to conduct sound a material must have volume elasticity. When once generated there are three things which may happen to a sound wave; it may be transmitted, reflected, or absorbed. In usual practice three are present to act upon the wave; however transmission and absorption are always present, and reflection may or may not be present.

Reflection of sound takes place when the wave passes from a medium of one density into that of a greater density. The reflection is small from porous materials but as much as 96% may be reflected from very dense substances.

Absorption is the changing of sound energy into mechanical energy usually in the form of heat. It is caused by the friction of the air particles among themselves when air is the conducting medium, but with greater magnitude by friction in porous materials such as cloth, hair, wool or hairfelt.

Transmission is the conducting of sound waves through some medium such as a wall. In any material there are three ways in which transmission occurs. First, the waves may pass through the holes or pores if any are present; second, transmission through trains of waves set up in the material itself; and third, by the material vibrating as a whole somewhat with diaphragm action. In the latter case the transmitting material becomes a vibrating member and sets up new sound waves on the other side of the wall.

The acoustic properties of materials was first studied from a scientific standpoint by Professor W. C. Sabine of Harvard University. His now classic experiments with organ pipes and theater cushions in various rooms and auditoriums may be found in his "Collected Papers On Acoustics".

Sabine reasoned that with a constant source of energy the intensity of sound increased according to a definite law until the rate at which energy was lost by absorption in the process of reflection, and by transmission through the walls became equal to the rate of generation. When this point of equilibrium was reached the intensity was at a maximum and remained constant. Curve A-B in Figure 1, page 6 shows this condition at point B. Sabine further reasoned that if the constant source of sound energy were suddenly stopped the absorption properties of the walls would govern the rate and therefore the length of time required for the sound energy to completely die out. Curve B-C shows the shape of a typical sound decay curve. It will be noticed that the curves look very much like the growth and decay of current in an inductive circuit. If the length of time required for the sound to die down in a room could be accurately measured a comparative value of the sound absorbing properties of the room would be obtained; this is illustrated in Figure 1. Suppose the time D-C was required for the sound to die down in a certain room, if some sound absorbing material was added and assuming the same intensity of sound, the decay curve would take some position B-C' because the quantity of sound would be absorbed faster and the time would be D-C'. The ratio of the two values of time would be directly proportional

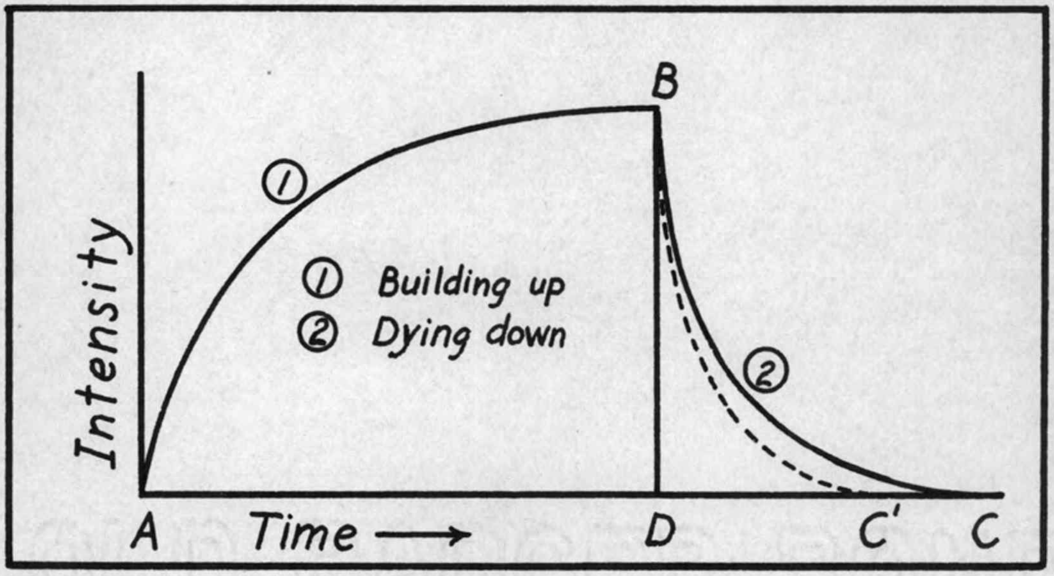


Fig. 1. Growth and decay of sound in a room.

to the sound absorbing property of the material added. This was the method Sabine used in his first acoustic investigations with organ pipes and theater cushions.

A sensitive manometric gas flame measured by a micrometer telescope was first tried then photographing the flame was tried, but as these methods did not measure sound intensity in the same way the ear does both were discarded. A sensitive electrical chronograph to measure time and the ear to measure audibility to the threshold value was found to give very satisfactory results, so this method was used. Tests were made in a lecture-room whose acoustic properties were notably bad. Theater cushions were brought into the room and tests were made; it was found that the duration of reverberation varied inversely, approximately as a straight line function, to the number of cushions. This room whose time of reverberation was 5.6 seconds was now reduced to 2 seconds with all the seats covered with cushions. The lecture room was now very noticeably improved for speech, though the acoustic conditions were yet not ideal.

This first investigation gave a standard for comparison of sound absorption, namely numbers of cushions. Sabine made many experiments measuring the absorption properties of felt, cretonne cloth, canvas, hairfelt, and even of a man and a woman always by determining the number of running meters of cushions that would produce the same effect. Sabine soon realized that his cushion standard was not easily reproduceable, so he started working on a standard that was constant and could easily be reproduced. In an open field there is no reverberation because there is nothing to cause reflection of sound; the waves travel outward and are absorbed and transmitted by the air. Some slight reflection from the ground would only travel upwards never to return if there were no heavy, low hanging clouds. Sabine used this phenomenon in developing his universal standard by using an open window of one square meter in area and specifying that there be no nearby objects which could reflect the sound waves back into the opening. This standard is still used with its absorbing ability expressed as unity so that all other materials can be compared to it as a coefficient of less than one. However, in English speaking countries this unit is defined as one square foot of open window or material, but obviously, this does not change the numerical coefficients.

For accurate results this method of measurement requires a large amount of material to be built into the walls of the measuring room; so is therefore only adapted to laboratory use. It was believed that a loudspeaker and a sensitive impedance measuring apparatus could be used to measure sound reflection and absorption in a much easier way; so this investigation was started with that object in view. Before continuing farther it will be well to discuss the theory of a loudspeaker.

THEORY OF A LOUDSPEAKER

THEORY OF A LOUDSPEAKER

A telephone receiver or a loudspeaker is a particular type of reciprocating electromagnetic motor, coupled to an acoustic radiating system, which is designed to convert alternating current electrical energy into sound energy. It is well known that the impedance of an induction motor changes greatly with load; and two tests, rotor free and rotor blocked, are usually run to determine its characteristics. Similarly the same tests, diaphragm free and diaphragm damped, are applied to the telephone receiver motor to study its characteristics. There are two methods of blocking or damping the diaphragm, namely; mechanically and acoustically. In the tests under consideration in this report the damping was accomplished by an acoustical means; however in no case was the diaphragm entirely blocked, but stages or increments of acoustic blocking were employed in such a way as to study the magnitude of damping which determined the absorbing characteristics of the material rather than the characteristics of the telephone motor itself.

Kennelly[2] made a great many very exhaustive tests of telephone receivers and found that the magnitude of impedance measured between terminals depended upon many factors. Tests with the diaphragm damped and with it free at the

2 Bibliography 2

same frequency showed a considerable difference in both resistance and reactance. At some frequencies the damped or blocked values were greatest while at other frequencies the free values were the largest; this was due to the movement of the diaphragm in the free test. The vector difference between the free and damped values is called the motional impedance or the mechanical impedance of the diaphragm. Part of this impedance is caused by the mechanical flexural motion of the diaphragm which would be evident if the entire receiver (or loudspeaker) were operated in a vacuum; the remaining is caused by the medium in which the diaphragm vibrates, and may be called acoustic impedance. The energy used in overcoming the resistance component of motional impedance is radiated as acoustic energy and was used in the following outlined tests to measure the sound properties of materials.

Kennelly begins his theory with a rigid diaphragm which fits closely inside a frictionless tube; the driving mechanism is fastened securely to the center. If a vibromotive force is applied to the rigid disc the air which surrounds it will also be set in a motion whose magnitude and velocity will have the same amplitude and phase as the disc. As work is required to move the surrounding air a retarding force is exerted upon the two sides of the disc whose phase relation is 180 degrees to that of the vibromotive force. This opposition to the vibrational velocity is called the acoustic impedance of the air which is the vector sum of acoustic resistance and acoustic reactance. These two properties are defined by Kennelly as follows: "In a frictionless fluid, acoustic resistance absorbs and dissipates the energy imparted by the vibromotive force. Acoustic reactance cyclically stores and releases, without dissipation, the energy of acoustic vibration. Acoustic impedance is thus a particular form of mechanical impedance. If a diaphragm is thrown into vibrational velocity by an impressed vibromotive force and is in contact with a fluid on either or both of its surfaces, the impedance of the diaphragm will be partly composed of acoustic impedance."*

Kennelly used an acoustic tube of variable length to show the effect of an air column upon the acoustic impedance of a telephone receiver. He showed that changing the length of the acoustic tube, with frequency and current constant, produced peaks and valleys in both the resistance and reactance curves when plotted against tube length. He further states that it has been found that the resistance and reactance, as measured by a bridge, is changed when a person walks about in a room in which a telephone receiver is eminating a constant frequency of

* Bibliography 2

tone. He predicts that this method might be used to determine the acoustical properties of materials, for example, in determining the sound-reflection coefficient of draperies.

In his investigations Kennelly used telephone receivers, but it was believed that a loudspeaker would be more practical and easier to work with; its larger energy output and better sound characteristics would more nearly duplicate actual working conditions. In addition larger specimens could be tested, and the characteristics of a loudspeaker allow a much wider variation of frequency without distortion of sound.

PRELIMINARY TESTS

PRELIMINARY TESTS

A few introductory tests were first made to determine if such phenomena as Kennelly mentioned could be reproduced. A Magnavox electro-dynamic loudspeaker was used for the tests, and a comparison type of impedance bridge was used to measure its resistance R and reactance X. A variable frequency vacuum tube oscillator was used for the source of alternating current power; tests were made at a frequency of 1000 cycles. The bridge was balanced with the loudspeaker free in a separate room from the bridge; a heavy cloth covering was then thrown over the entire loudspeaker and the bridge again balanced; finally the cloth was removed and a 3/4 inch drawing board substituted while the bridge was again balanced. The tests showed that there was a change of both resistance and reactance, but it was nearly impossible to reproduce even the open test results. It was later found that this was mostly due to the fact that the test materials could not be replaced exactly the same each time, wherefore the wide variation of results.

At this stage of testing another phenomenon was discovered which presented a difficulty at the time being. It was found that a bridge balance did not remain constant for any length of time when apparently nothing was changed. The correct values of R and X as measured with the bridge could be followed up and down the scale by changing the resistance arm and the inductometer, but no apparent reason for such action could be found until it was noticed that turning the lights in the room on or off noticeably effected the bridge readings. A voltmeter on the 110 volt line showed that the line voltage and bridge readings changed simultaneously; so the reason was made quite apparent. The direct current field was supplied from the 110 volt alternating current power line by means of a copper oxide rectifier; so any slight variation of line voltage changed the field strength and therefore the impedance between terminals of the loudspeaker as measured by the bridge. The use of a 24 inch Western Electric cone speaker was considered, but discarded because of the diaphragm or bending action of the cone which was not desired. It was believed that piston action like that of the simple rigid disc as mentioned before, rather than flexural diaphragm action would give the best results; so attention was reverted to the dynamic type of speaker. A Farrand inductor dynamic type of loudspeaker was then tried and found to give excellent results. In this device the magnetic field is obtained by two powerful cobalt steel permanent magnets; otherwise, it operates on the same principle as the electro-dynamic.

Attention was then turned toward the impedance bridge.

Heretofore a comparison type of bridge using a decade resistance box and an inductometer was used to balance out R and X respectively, but difficulty was encountered in obtaining a "sharp" balance--that is, one in which the sound is balanced out completely. Indeed it was difficult to read accurately to a value as large as ten ohms, and the accuracy in reading reactance was no greater. Other types of bridges were tested for accuracy and sharp balance--among them the resonance bridge and the Skew bridge. It was found that the series resonance type gave the best results, for it easily balanced sharply enough to enable values as small as 1 ohm to be read; with a little practice on the part of the operator and with the aid of a calibrated rheostat it was found that readings to 0.2 ohm could be measured quite accurately. With this type of bridge X was balanced by capacitance instead of inductance; so a variable air condenser used in conjunction with a tapped mica standard condenser was used. The variable air condenser could be adjusted by means of slow motion adjustment which gave very accurate balances of X. A Western Electric headset had been used as the sound detecting device and had given good results, but a visual indicator consisting of a multistage vacuum tube voltmeter (designed and built by Mr. R. H. Batchelor, senior in Electrical Engineering) was tried. Tests showed that X could be balanced somewhat more accurately, but R could not be balanced closer than about 5 ohms; as values of resistance were the main interest in this investigation this detecting means was discarded, and the headset was used throughout the remainder of the test.

After these added refinements tests were again made with the heavy cloth and board; the open test results were found to be easily reproduceable, and the other tests remained constant if the materials were not moved. It may be of interest to enumerate an accidental test. During an open test a person opened the door of the loudspeaker room and walked toward the speaker. The operator at the bridge could easily determine when the door was opened by the change of sound in the headset, but when this person approached the loudspeaker the sound in the earphones changed alternately from loud to soft as many as perhaps 6 times. This was puzzling at first, but the first actual test of the complete apparatus showed exactly the same results--resonant peaks of resistance and reactance.

APPARATUS

(Construction)

APPARATUS

(Construction)

It has been previously mentioned that piston action rather than flexing diaphragm action was desired of the loudspeaker. Therefore a dynamic speaker with an inverted cone shaped "diaphragm" was chosen; this cone composed of heavy parchment paper was 10 inches in diameter and 3 inches from base to apex. The conical shape caused it to follow the driving rod rigidly as it moved longitudinally back and forth. It is therefore a misnomer to call it a diaphragm; so hereafter it will be designated as the cone of the loudspeaker.

When the cone of a loudspeaker is set in motion the air on both sides is effected and conversely the air on both the front and back produce an effect upon the cone. It can therefore be understood that the effect of acoustic impedance is approximately equal on both sides of the cone. As it would indeed be difficult to place a specimen of the material both in front and in back with the distances from the effective center of the cone equal, it was thought best to use one specimen in front of the cone and maintain the acoustic properties back of the cone constant for all tests. This was accomplished by mounting the loudspeaker in a box one end of which was cut with a 10 inch hole to fit the cone and therefore form a small baffle board. The box was made of 3/8 inch veneer except the baffle board which was made of 3/4 inch veneer. The inside of the box was lined with 1-1/2 inch hairfelt, and staggered strips of hairfelt were hung from the top of the box. The interior of this loudspeaker box showing the loudspeaker and baffles in place is shown in a photograph in Figure 2, page 20.

With this construction the sound from the back of the loudspeaker was absorbed by the hairfelt maintaining the acoustic impedance constant; this enabled it to be placed in different positions to obtain the desired acoustic effect from the front only.

Before being mounted in the padded box the loudspeaker itself was tested with a phonograph and amplifier. Tests showed that the loudspeaker would stand tremendous volume without blasting, rattling, or distorting in any way, but the quality of reproduction was impaired by the absence of low notes; this was no doubt due to the fact that no baffle board was used. The same tests were performed after the loudspeaker was mounted in the completely closed hairfelt-lined box. It was found that there was still no distortion even at maximum volume, but the volume was noticeably reduced. It is interesting to note that the quality of reproduction was markedly improved, for the low notes were reproduced equally as well as the high ones giving the

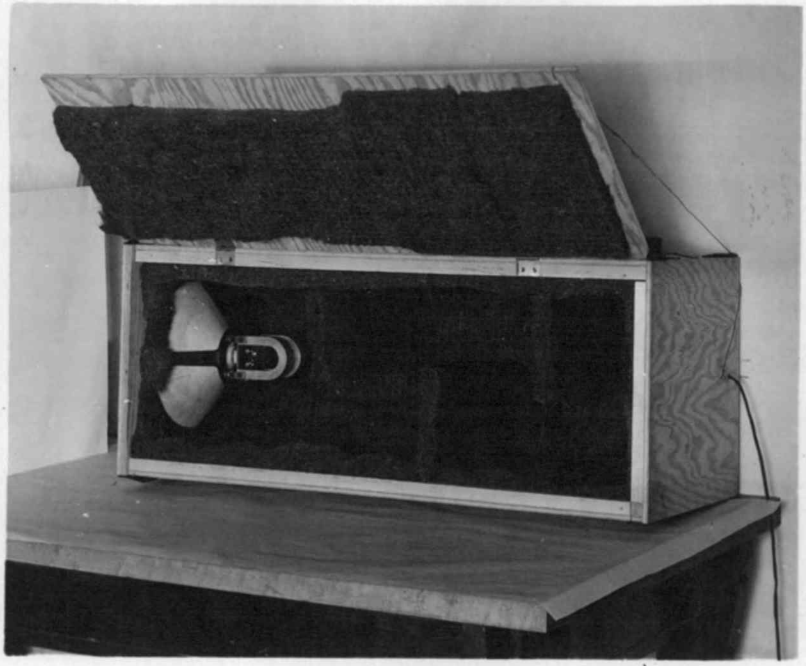


Fig. 2. Interior view of the loudspeaker box showing the back of the loudspeaker, and the hairfelt lining and baffling.

loudspeaker a very pleasing fullness of tone. Evidently the hairfelt-lined box acted much like a large baffle board, for this particular loudspeaker was designed to operate with a three foot baffle. The reduction in volume of sound was due to the large amount absorbed from the back of the cone; this was particularly noticeable at the high frequencies, because they are more easily absorbed than the lower frequencies.

The loudspeaker box was made 3 feet long and 15 inches square (outside dimensions) so it would fit inside of a square wooden tube whose inside dimensions were 15-1/4 inches. This loudspeaker tube which was 8 feet long was made of 3/4 inch fir lumber. A photograph of the open tube with the loudspeaker box just inside is shown in Figure 3, page 22. The long bolts which project out in front were used to hold the specimen of absorbing material to be tested in place. The loudspeaker cone can be seen in the front of the loudspeaker box. Figure 4, page 23 shows a photograph of the loudspeaker tube with a specimen clamped in position for testing. A square wooden frame was placed over the material and washers were used under the wing nuts so the pressure on the specimen would be distributed as evenly as possible.

In order to easily move it to the position desired a small windlass was arranged on the back end, and a meter

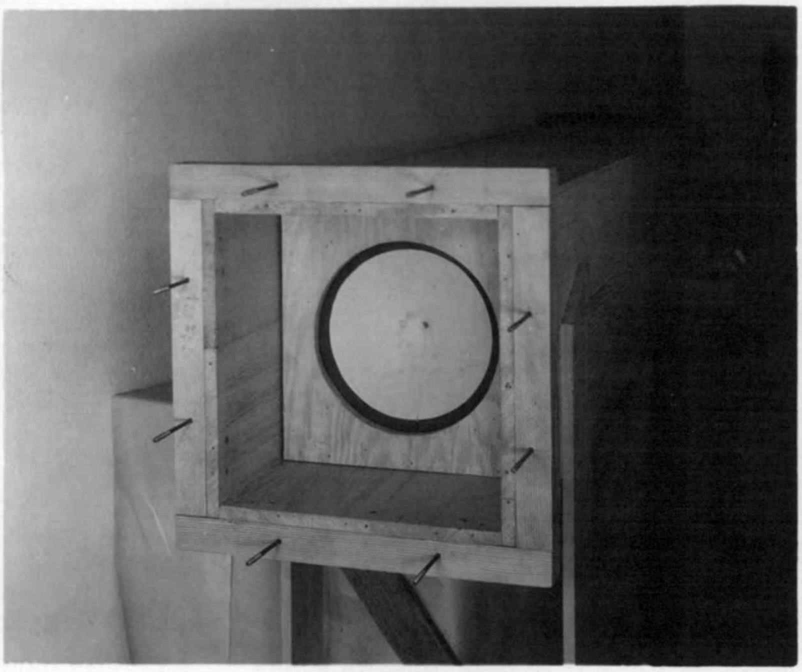


Fig. 3. Unlined wooden tube showing the position of the loudspeaker, and the material clamping bolts.

Fig. 4. Closed wooden tube with a veneer specimen clamped in place for testing.

stick with a pointer was used to accurately mark the position of the loudspeaker box. Strips of felt were fastened to the inner box to fill the small cracks between it and the tube, and wire springs were used on one side to hold the box constantly against the other side; so the loudspeaker box could never approach a corsswise position in the wooden tube. These latter two refinements were added later and were found to cause the results to be more easily reproduceable.

EXPERIMENTAL PROCEDURE

EXPERIMENTAL PROCEDURE

A photograph of the set-up of the measuring appartus is shown in Figure 5, page 26 and a diagram of connections of the same apparatus is shown in Figure 6, page 27. The letters on each drawing are placed on corresponding instruments whose names and functions are as follows:

A--Bridge arms of equal resistance giving a 1 to 1 ratio.

R--Decade resistance box for balancing out the resistance.

C--Mica variable stepped condenser for balancing out X.

C'-Air standard variable condenser used to reach values of capacitance between the steps of C.

D--Thermocouple for measuring the loudspeaker current and holding it constant.

E--Microammeter used with the thermocouple.

F--High resistance rheostat for close adjustment of oscillator current.

G--Headphones for detecting the bridge balance.

Another list giving the name and number of each piece of apparatus is shown in the appendix; each instrument is listed with the same corresponding letter as is used on the diagram and picture.

The impedance bridge was operated in the usual way, that is adjusted for minimum sound in the headphones. It was found that the quickest method of balancing the bridge was to first adjust the decade resistance box R to ap-

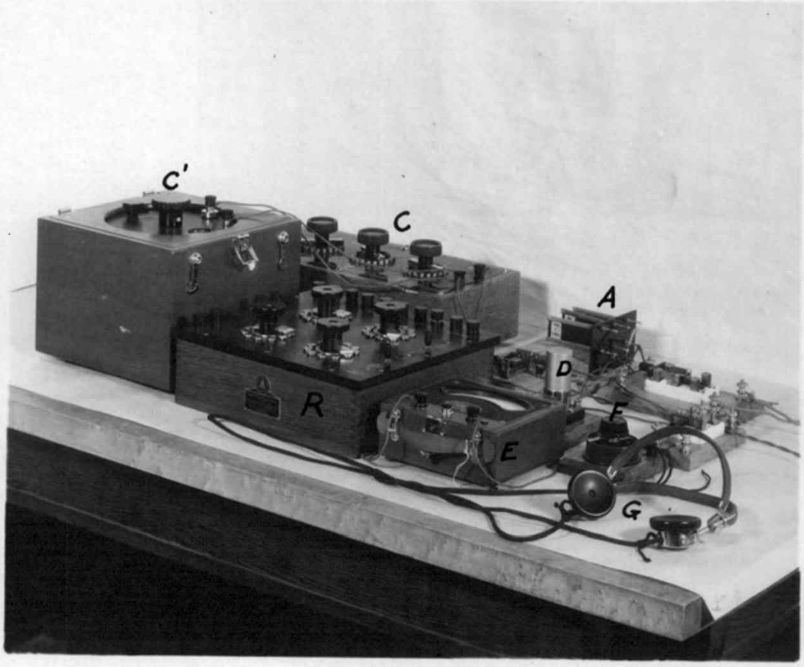


Fig. 5. Set-up of the impedance bridge measuring apparatus. (The small letters correspond to those on the diagram of connections figure 6.)

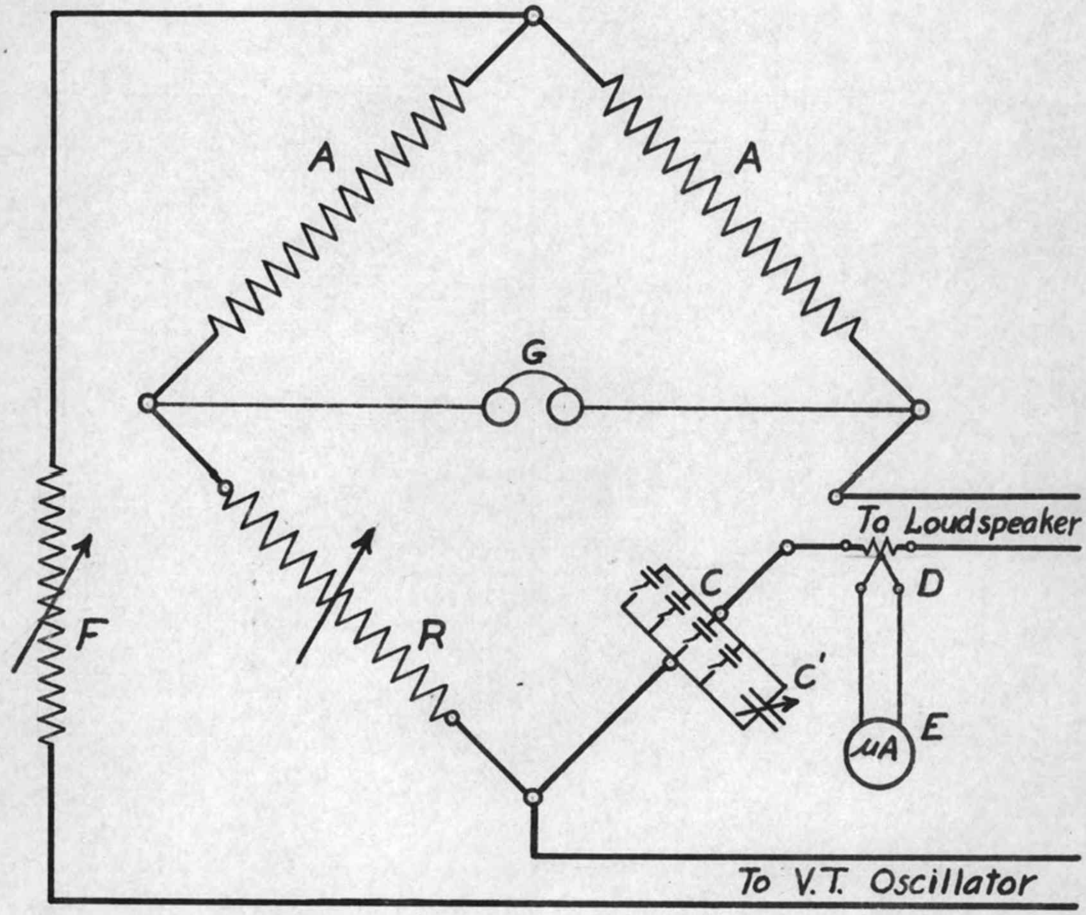


Fig. 6. Diagram of connections. (The letters correspond to those in figure 5.)

proximately the correct value; this could be determined within 100 ohms with X quite far out of balance. Next the Mica condenser C was adjusted to its best value and C' was adjusted to obtain values of capacitance between the steps of C. The resistance box R was then adjusted to the nearest ohm, and the slow motion knob S on C' was used to balance X more accurately. The variable air condenser C' was ungrounded, so body capacitance effected its setting; therefore a long wooden handle was used for its final adjustment. Body capacitance effected the decade resistance box only slightly so its knobs were turned with the hand. The final adjustment was made by setting R at some value of resistance and changing C' slowly with the long wooden handle on the vernier knob; R was then changed slightly and C' again moved slowly through its point which gave minimum sound. This was done until the value of R was found which allowed the sound to be balanced out most completely by adjusting C'. During all these operations the current input to the loudspeaker was closely observed and maintained to its normal value of 1.5 milliamperes by adjusting the attenuating rheostat F. It was observed that changing R produced little effect upon the current, but a small adjustment of C changed the current considerably. A little study of the diagram of connections will show that when in balance C is in resonance with the inductive reactance of the loudspeaker; so a little change from the point of resonance either way would reduce the current.

Tests were first attempted with the loudspeaker and measuring apparatus in the same room, but difficulty was encountered in balancing the bridge. When listening closely with the ear covered with the headphones actual nodes and anti-nodes of sound were detected as the head was moved slightly back and forth or even turned. It was found that if the bridge were accurately balanced with the head held in one position the balance was changed if the head was moved slightly. No data were taken on this phenomenon, but it was discovered that these nodes or periods of large and small amplitude could be readily traced in all parts of the room even with only the ear as a detecting device; their shape conformed approximately to that of the room with the loudspeaker as the center of the disturbance. It is suggested that it would be interesting to make a scientific and thorough study of this phenomenon with a sensitive pick-up and measuring device, for the results would doubtlessly show something of the shape of sound waves in a room. These nodes were approximately only a few inches apart and may be due to interference with the original sound waves and the reflected waves from the walls. Obviously this phenomenon reduced the accuracy of the bridge materially; so the loudspeaker and the wooden tube were moved into an adjoining room. This reduced the sound in the measuring room so much that no difficulty was experienced in balancing the bridge very accurately; however it slowed up the progress of the constant frequency tests when the loudspeaker position was changed before each bridge reading.

The different materials were clamped on the front of the wooden tube by means of the long bolts and wing nuts as has been previously explained. All materials were of approximately the same area which was large enough to receive the long bolts in properly drilled holes; thus the materials were held in exactly the same position for each test. Changes were easily made by unscrewing the wing nuts, and placing a different material in position.

Before the testing had proceeded very far another phenomenon was found which previous to its discovery threatened to make the results nearly worthless. The curves showed some very erratic readings--which could not be reproduced by running another curve. It was finally noticed during the operation of the bridge that these erratic readings were more difficult to balance than the others. The sound could not be as well balanced out and the position of least sound was broader in scale divisions. An investigation was made which disclosed the fact that there were two possible bridge readings when these erratic results occurred; one reading was sharp and easy to balance, but the other was "fuzzy" and very difficult to balance. The sharp readings were found to be the ones desired for they gave results which made a smooth curve. These double readings were not thoroughly investigated, but with a little practice on the part of the operator it became comparatively easy to determine when the bridge was being balanced at the wrong reading. They were not noticed particularly except near peaks of resistance in the variable distance tests. Sometimes the wrong reading was above and sometimes it was below the true reading, depending upon which side of the resistance peak observations were being made. The difference between the two readings was also a variable factor. Here again is a field for further investigation.

CONSTANT FREQUENCY TESTS

VARIABLE DISTANCE

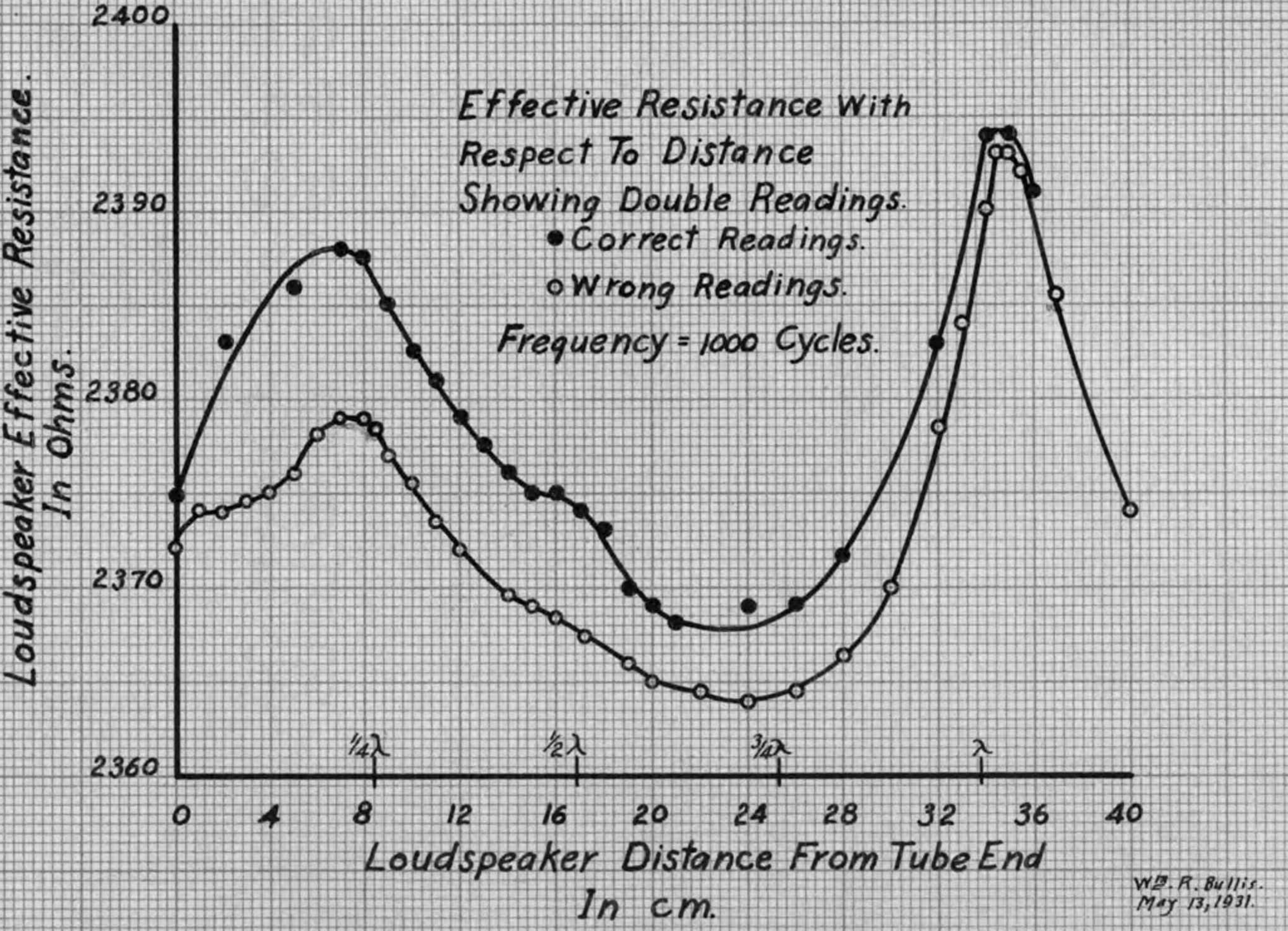
CONSTANT FREQUENCY TESTS

VARIABLE DISTANCE

Bare Wooden Tube:

Tests were first made with the wooden tube open to determine the effect of tube length upon the effective resistance of the loudspeaker. The wooden tube was placed in a large open room adjoining the oscillator and impedance bridge measuring apparatus, with the connecting wire run through a hole in the partition. Tests were started with the loudspeaker box baffle board flush with the end of the wooden tube; this was called the zero position. Impedance bridge readings were made as the loudspeaker box was moved back from the end of the tube in centimeter increments. The curve of loudspeaker effective resistance plotted against open tube length is shown on page 33. The abscissa scale is also calibrated in wave length as well as in centimeters. It will be noticed that a peak of resistance occurs at approximately one wave length and another lesser one at one quarter wave length. The reason the peaks do not occur at exactly one quarter and at one wave length is because actual measurements were made from the baffle board of the loudspeaker box instead of the effective center of the cone which should be somewhere near the base of the baffle board. A few simple calculations of wave length will show where this effective center

CONSTANT FREQUENCY
VARIABLE DISTANCE OPEN TEST
IN THE BARE TUBE.



occurs. The velocity of sound is:

$$V = f \lambda$$

Where V is velocity in cm. per sec.

f is frequency in cycles per sec.

and is wave length in cm.

The frequency f is 1000 cycles per second, and V can be calculated--

$$V_t = V_o\sqrt{1 + 0.00367\ t}$$

Where Vo is the velocity of sound at $0^oC.$ = 33, 170 cm. per sec.

and t is the room temperature which was $23^oC.$

Therefore:

$$V_t = 33170\sqrt{(1 + 0.00367)(23)}$$

$$V_t = 34{,}150 \text{ cm. per second}$$

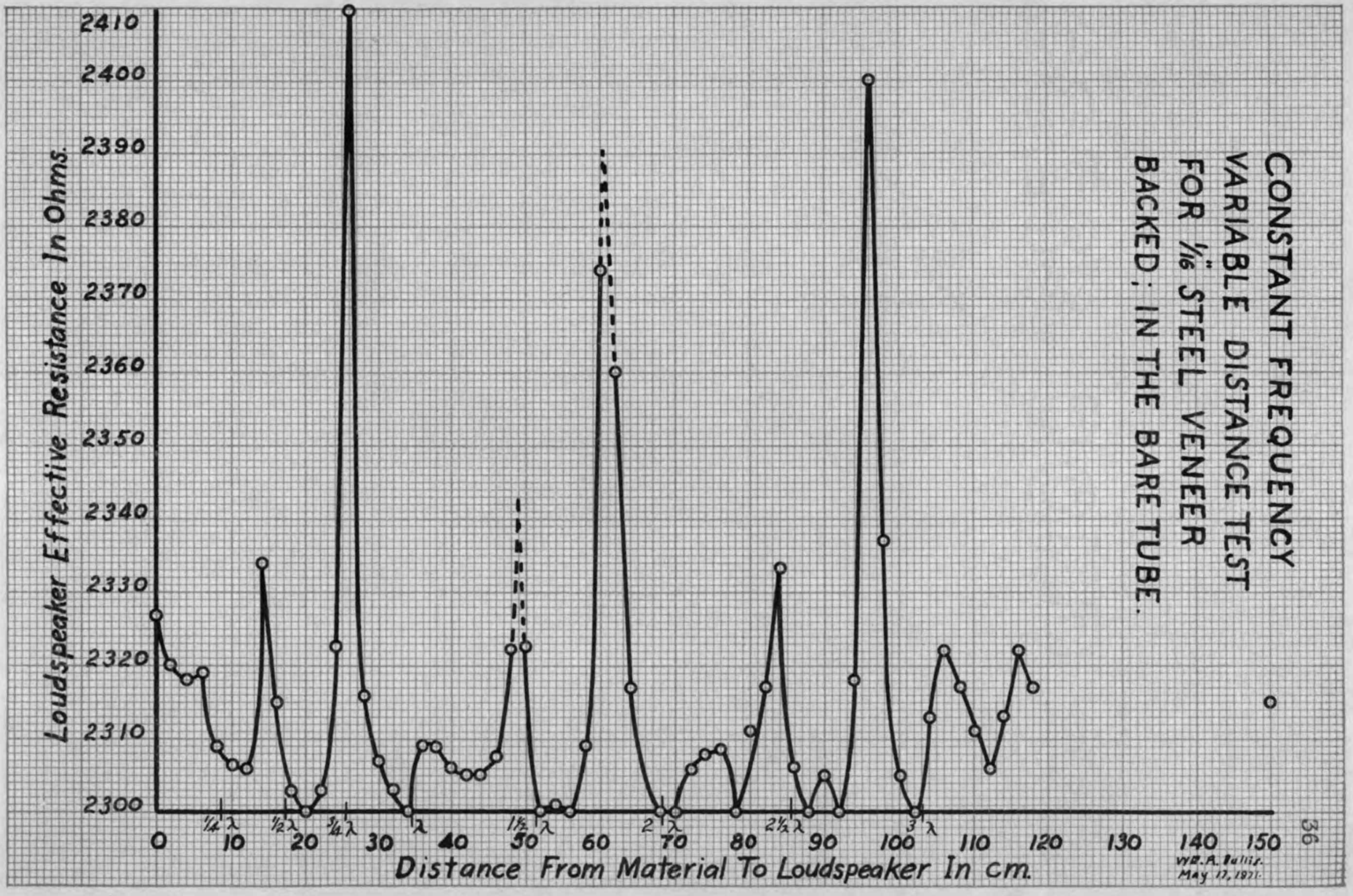
Solving the original equation:

$$\lambda = \frac{V}{f} = \frac{34{,}150}{1{,}000} = 34.15 \text{ cm.}$$

The one wave length peak of resistance occurs at 34.75 cm. which is (34.75-34.15)= 0.50 cm. <u>outside</u> of the loudspeaker box and baffle board entirely. Evidently the sound acts as if it were caused by a vibromotive force being applied to a rigid frictionless disc 0.5 cm. out from the loudspeaker box baffle board.

In this open test both the "right" and the "wrong" points are plotted showing that there is approximately a constant difference between them. The curve which has the greatest ordinate values is the correct one; the lower curve being plotted from the incorrect points of the double readings which were explained on page 31. This open test will be used later to obtain a reference point of resistance with which to compare the values obtained from the tests of the various materials.

The wooden tube was then closed by clamping a piece of 3/8 inch veneer on the front and a similar test was run. The resulting curve of loudspeaker effective resistance plotted against tube length is shown on page 36. This was the first closed test made, so it was not known where the peaks should occur; therefore smaller increments of distance were not taken as the peaks were approached. Because of this the heights of the resistance peaks were not accurately determined, but their locations are clearly marked. The abscissa scale is also calibrated in wave length to show at what fraction of a wave length the peaks were found. It will be noticed that R reaches its greatest depression at one wave length just after a peak. Apparently the greatest peaks occur at approximately 3/4 of a wave length and a lesser one at about 1/2 of a wave length. This was found to be the case throughout all tests, but later and more careful tests showed that the greatest and sharpest peak occurred at about 1/2 of a wave length. This

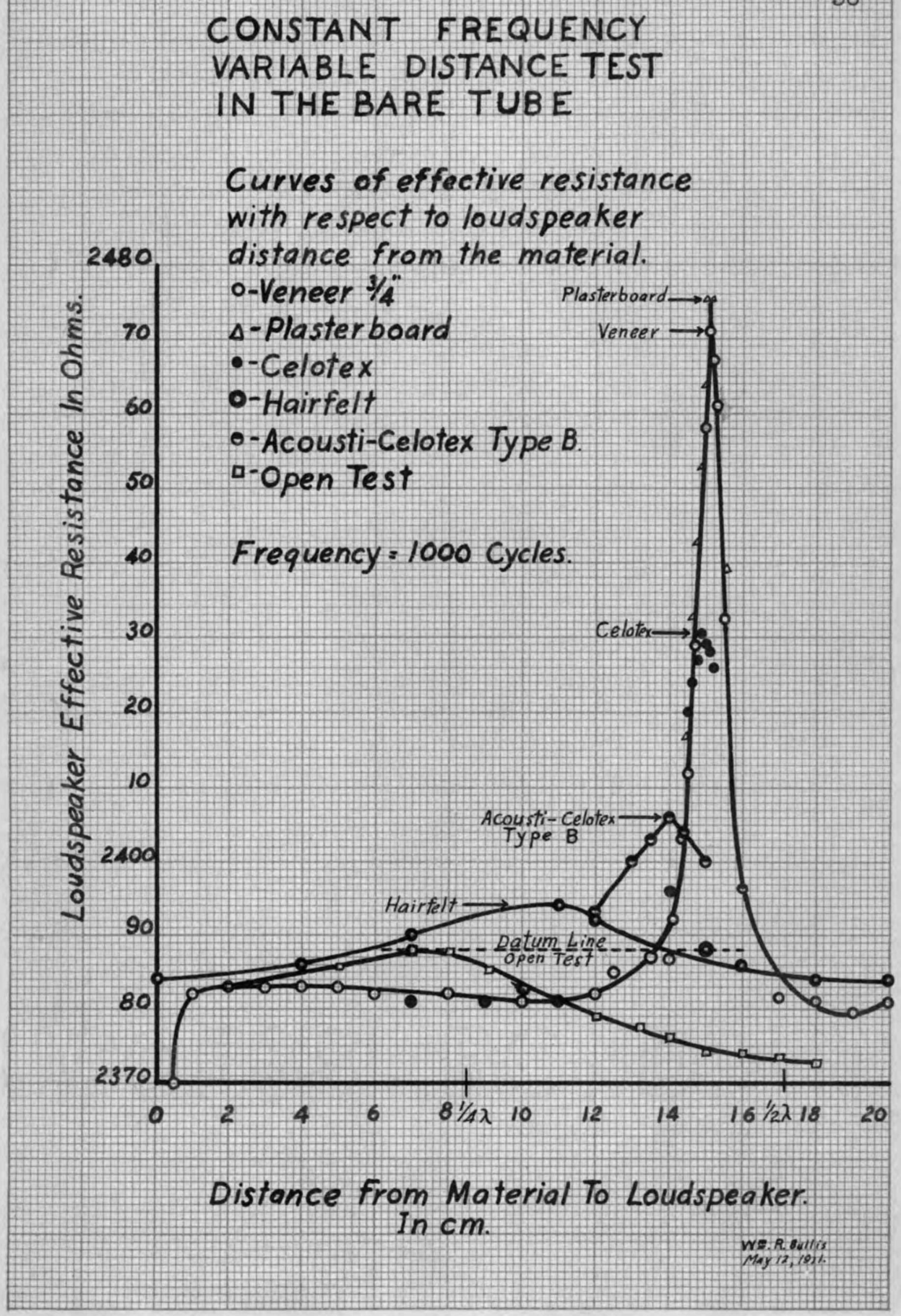

CONSTANT FREQUENCY
VARIABLE DISTANCE TEST
FOR 1/16" STEEL VENEER
BACKED; IN THE BARE TUBE.
Loudspeaker Effective Resistance In Ohms.
2410
2400
2390
2380
2370
2360
2350
2340
2330
2320
2310
2300
1/4 λ
1/2 λ
3/4 λ
λ
1 1/2 λ
2 λ
2 1/2 λ
3 λ
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
Distance From Material To Loudspeaker In cm.
May 17, 1971.

peak was found to be so sharply defined that it was necessary to use distance increments of one mm. to accurately determine the height.

Tests were made on both the 1/2 and the 3/4 wave length peaks using various materials. The 1/2 wave length peak was the most difficult to work with because of its sharpness, but the results of the tests were much more consistent. Curves of different materials are shown on page 38. The curves of 3/4 inch veneer and one inch hairfelt are shown drawn, but the points only of the other materials are shown plotted. The heights of the peaks are shown accurately marked. It will be observed that plaster board has the highest peak and hairfelt the lowest with the other materials distributed between in the order of their sound absorbing coefficients. It is by the comparative heights of these peaks that the sound absorbing coefficients of the materials are measured. This will be referred to later.

Hairfelt Lined Tube:

The wooden tube was then lined with hairfelt and the same tests were again made. A photograph of the hairfelt lined tube is shown in Figure 7, page 39. It was believed that the absorbing material would eliminate standing waves and therefore give better results, although the peaks were not expected to be as great as with the open tube. It was


CONSTANT FREQUENCY
VARIABLE DISTANCE TEST
IN THE BARE TUBE
Curves of effective resistance
with respect to loudspeaker
distance from the material.
○-Veneer 3/4"
△-Plasterboard
•-Celotex
⊙-Hairfelt
⊙-Acousti-Celotex Type B.
□-Open Test
Frequency = 1000 Cycles.
Plasterboard
Veneer
Celotex
Acousti-Celotex Type B
Hairfelt
Datum Line Open Test
Loudspeaker Effective Resistance In Ohms.
2480
70
60
50
40
30
20
10
2400
90
80
2370
0
2
4
6
8 1/4λ
10
12
14
16 1/2λ
18
20
Distance From Material To Loudspeaker. In cm.
Wm. R. Bullis
May 12, 1931.

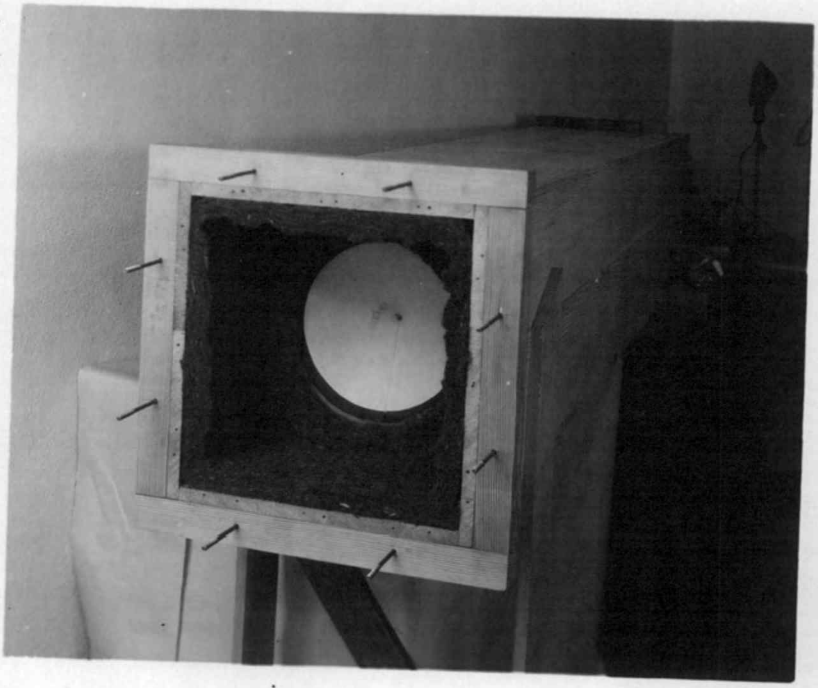


Fig. 7. Lined wooden tube showing the hairfelt lining and the loudspeaker in position.

found that changing the loudspeaker distance produced no peaks of resistance as did the former test. The loudspeaker was then placed in the position where the peak of resistance previously occurred and all materials were successively tested by clamping them on the tube and reading the bridge. The results were disappointing because of their inconsistancy; plaster board showing only a little poorer absorbing qualities than hairfelt, and celotex testing a much better absorber than hairfelt. Tests also showed that steel was a better absorber than hairfelt. These results are obviously contrary to good judgment; so this method of testing was discarded, and the results were considered as not worth recording in this report. The hairfelt lining seemed to absorb most of the emitted sound and the reflected sound also, resulting in the absence of the resistance peaks.

Open Air Tests:

The loudspeaker box was then entirely removed from the tube and placed on the edge of a table in open air. The materials were mounted on a light wooden frame in front of the loudspeaker. A photograph of the set-up of the apparatus is shown in Figure 8, page 41. Tests were made in the same way with the different materials. Great care was taken in setting up the frame and placing the materials in position to get them parallel to the front of

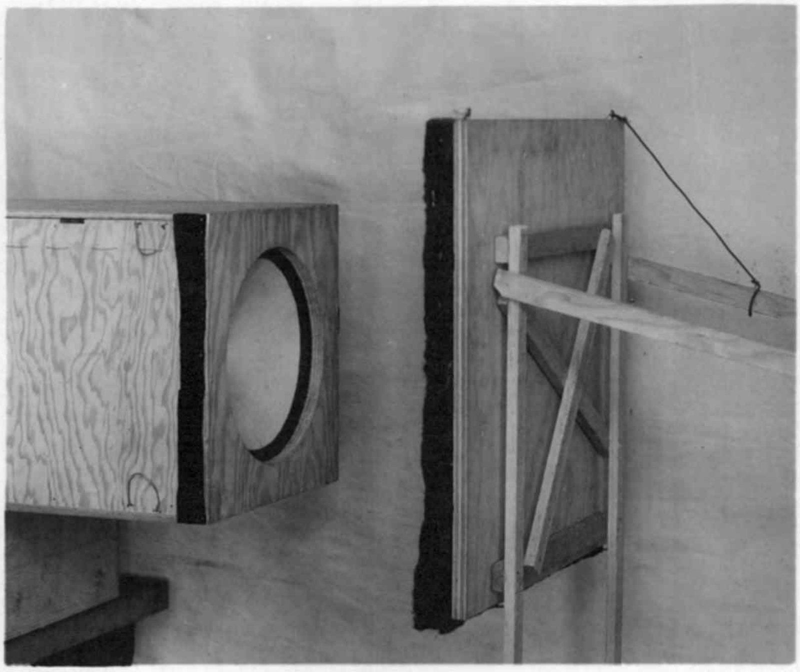
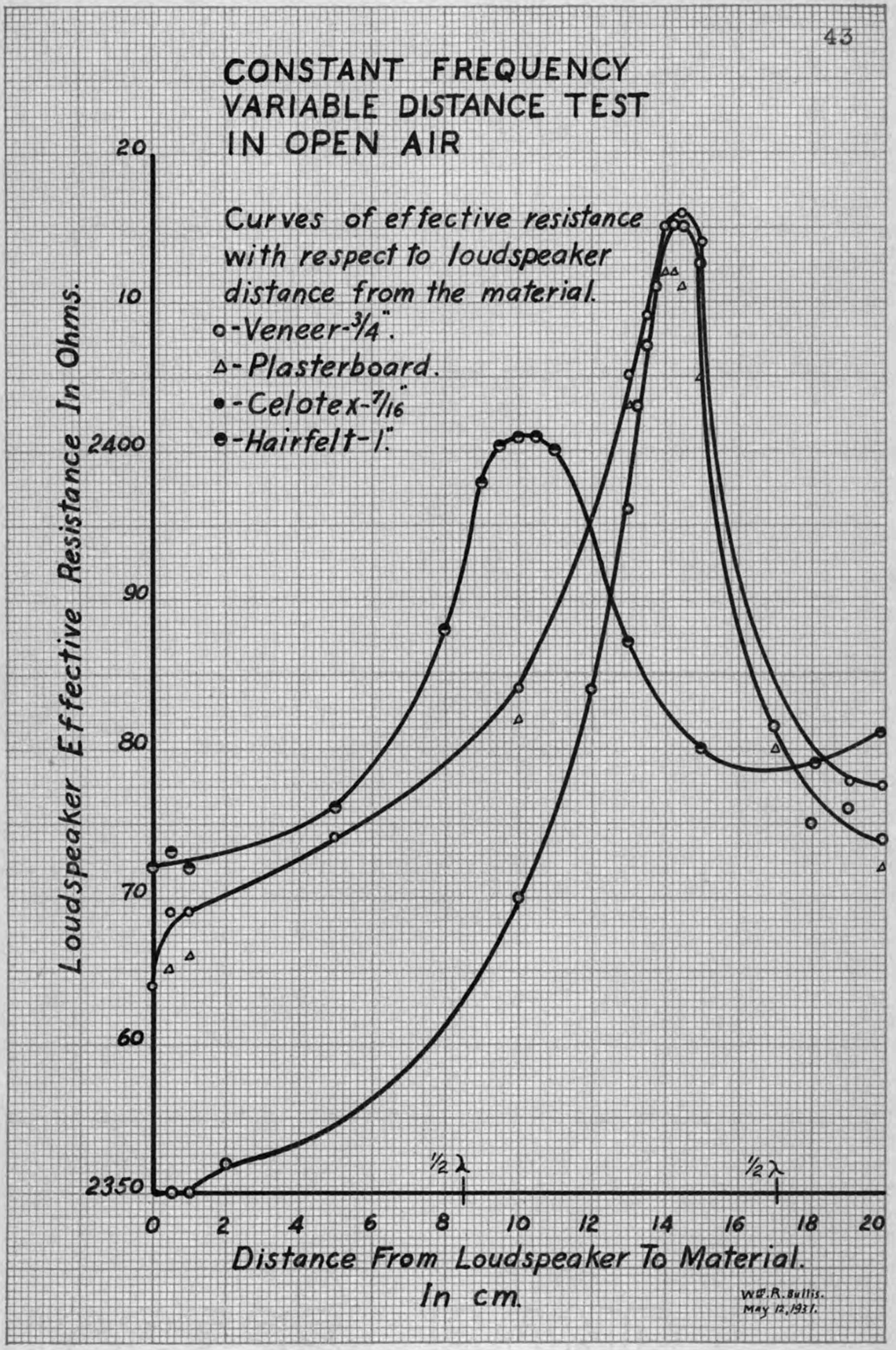


Fig. 8. View of the loudspeaker set-up for making the open air tests. The wooden frame on which the materials were mounted is also shown.

the loudspeaker box or baffle board. The results of this test are shown on page 43, where loudspeaker effective resistance curves are plotted against distance between the material and the loudspeaker. These results although better than the hairfelt lined tube are not as consistent as those of the bare wooden tube, for celotex is shown as the poorest absorber with both veneer and plaster board as better absorbers--a condition which is obviously incorrect. However, the hairfelt curve is at approximately the correct height. In all probability the reflection from the walls, floor and ceiling in the room effected the loudspeaker impedance causing errors in the results. However, if the apparatus were placed in an open field with no nearby objects to cause sound reflection this test might possibly give excellent consistent results. This condition would be difficult to obtain practically and gusts of wind would effect the loudspeaker diaphragm making a bridge balance difficult to obtain.

It will be noticed that the peaks of resistance occur in approximately the same place, about 1/2 wave length, for both the bare tube and the open air tests; however the peak of the hairfelt curves consistently occur at a position somewhat shorter than the other materials. This is due to the porous structure of the substance which makes the effective reflecting surface somewhere in the material


CONSTANT FREQUENCY
VARIABLE DISTANCE TEST
IN OPEN AIR
Curves of effective resistance with respect to loudspeaker distance from the material.
○-Veneer-3/4".
△-Plasterboard.
●-Celotex-7/16"
◐-Hairfelt-1".
Loudspeaker Effective Resistance In Ohms.
20
10
2400
90
80
70
60
2350
0
2
4
6
8
10
12
14
16
18
20
1/2 λ
1/2 λ
Distance From Loudspeaker To Material.
In cm.
Wm. R. Bullis.
May 12, 1931.

rather than at the physical surface which is exposed to the loudspeaker.

CONSTANT DISTANCE TESTS

VARIABLE FREQUENCY

CONSTANT DISTANCE TESTS

VARIABLE FREQUENCY

Bare Wooden Tube:

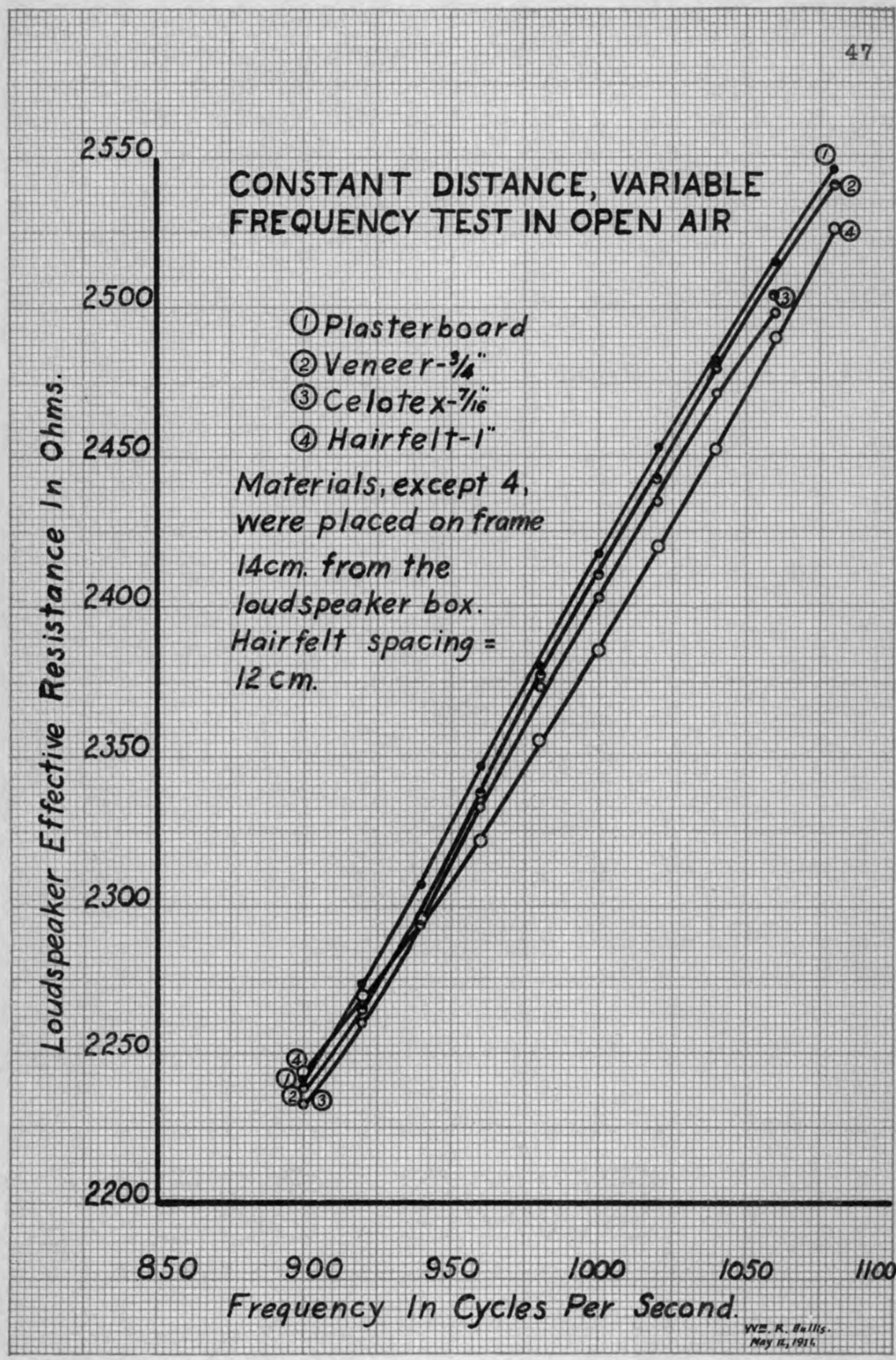
The loudspeaker box was placed in the bare wooden tube at the position where the resonant peaks of resistance were previously obtained (15 cm.). A material was clamped in position on the front of the tube and tests were made by varying the frequency of the oscillator from 900 to 1100 cycles in 20 cycle steps. Since wave length depends upon the frequency this had the same effect as changing the distance. Resonant peaks of resistance were obtained, but they were not sharply defined as in the constant frequency bare tube tests; however there was a fairly consistent relation between their height and the sound absorbing coefficients of the various materials which were tested. This method presents a possibility of determining the acoustic properties of materials if the frequency of the sound source is variable in small increments. However, it does not produce as great a difference of acoustical resistance as the constant frequency, variable distance, bare tube method; therefore the accuracy would in all probability be less.

Hairfelt Lined Tube:

The inside of the wooden tube was lined with hairfelt and with the loudspeaker set at 15 cm. the same tests were again performed. The resonant peaks of resistance were not found, but comparatively smooth curves were obtained whose ordinate values were different for the various materials but were not consistently proportional to the sound absorbing coefficients. Therefore this test was considered of no value so no data are included.

Open Air Test:

Variable frequency constant distance tests in open air were made on some of the materials. The loudspeaker was set at the position where the resonant resistance peak occurred in open air, while the frequency was changed in steps from 900 to 100 cycles. No resistance peaks were found, but smooth curves were obtained whose ordinate values showed a consistent relation to the sound absorption coefficients of the materials. These curves are shown on page 47. It will be noticed that they are separated and are approximately in proportion to the acoustic properties of the specimens. Because of the comparatively small resistance change between materials no attempt was made to obtain a relation to the standard sound absorption coefficients for the accuracy would be rather poor. However this test proves that there is a relation between the impedance of a loudspeaker and the sound absorbing characteristics of the surrounding media.


CONSTANT DISTANCE, VARIABLE FREQUENCY TEST IN OPEN AIR
① Plasterboard
② Veneer-3/4"
③ Celotex-7/16"
④ Hairfelt-1"
Materials, except 4, were placed on frame 14cm. from the loudspeaker box. Hairfelt spacing = 12 cm.
Loudspeaker Effective Resistance In Ohms.
2550
2500
2450
2400
2350
2300
2250
2200
850
900
950
1000
1050
1100
Frequency In Cycles Per Second.

DISCUSSION OF RESULTS

DISCUSSION OF RESULTS

Altogether six distinct tests were made which may be divided into two general groups; constant frequency and variable frequency. Of each group three separate tests were made: 1. with the bare tube, 2. the hairfelt lined tube, and 3. with both the loudspeaker and specimens in open air.

Of the variable frequency tests, those with the bare wooden tube were fairly consistent, but those with the hairfelt lined tube were too erratic to be of any value. The open air test showed very consistent results and was by far the best of the variable frequency tests. All of the variable frequency tests had the disadvantage of only a small resistance change between materials of different absorption coefficients; this reduced the accuracy of the results. Small resonant resistance peaks were found in the bare tube tests, but not in the other two tests.

Of the constant frequency tests the hairfelt lined tube gave no results which might be used to determine the acoustic properties of the materials. No resonant resistance peaks could be found. The open air tests gave resistance peaks which were somewhat erratic, but nevertheless this test could be improved to obtain accurate and consistent results if the tests could be made in an open field or in a room which was well deadened acoustically.

The tests with the unlined wooden tube showed the most consistent results, and the values of resistance between the various materials were separated far enough to obtain an accurate indication of their acoustic properties.

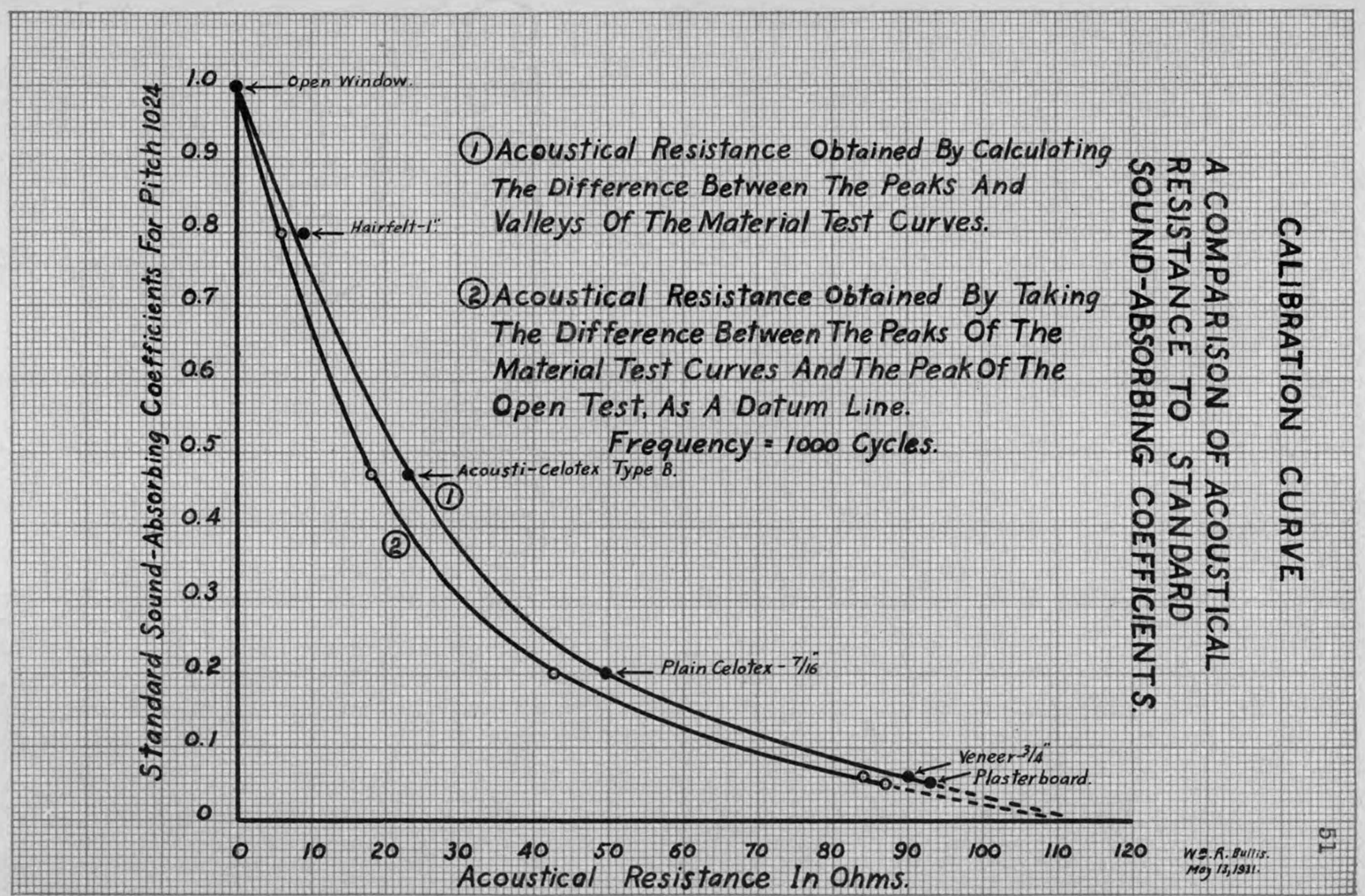
Motional impedance was discussed in "Theory Of A Loudspeaker". It was found to be "that part of the total apparent impedance which is due to the counter electromotive force generated in the windings by the motion of the diaphragm---------------------The motional impedance of a telephone receiver (or loudspeaker) at any given frequency of vibration may also be defined as the difference between its impedance with the diaphragm free to vibrate and its impedance when such vibration is prevented."* This impedance may be divided into parts, one of which is acoustical resistance; this is the vector component of motional impedance, which is due to the acoustic properties of the surrounding media. As the loudspeaker was damped acoustically, which has been explained before, the difference between the damped and undamped condition is known as "acoustical resistance". The theory of operation depends upon various stages of acoustical damping which is caused by the sound absorbing properties of the materials; therefore this acoustical resistance can be

* Bibliography No. 4.

used to measure the sound absorbing properties of the materials.

It was desired to obtain a relation between the measured values of acoustical resistance and the standard sound absorbing coefficients; so calibration curves of which each material contributed a point were plotted. These curves are shown on page 51. Each material was plotted as a point with acoustical resistance as abscissa and standard sound absorption coefficients as ordinates. A smooth line was drawn through the points which gave the calibration curve, and shows a definite relation between acoustical resistance and sound coefficients. The values of absorbing coefficients were obtained from tables in Watson's "Acoustics Of Buildings", and "Acoustics" by Stewart and Lindsay. Values at "pitch 1024" were used, because this corresponds very closely to a frequency of 1000 cycles which was used in the tests.

The abscissa or acoustical resistance values of the materials were obtained by two methods hence the two similar curves. Number one was obtained by taking the difference of resistance between the peak and minimum constant value as shown on the curve of page 38. This minimum constant value is not the lowest possible reading but is the average low part of the valley just preceding the peak. An example of plain celotex will be given:


CALIBRATION CURVE
A COMPARISON OF ACOUSTICAL RESISTANCE TO STANDARD SOUND-ABSORBING COEFFICIENTS.
① Acoustical Resistance Obtained By Calculating The Difference Between The Peaks And Valleys Of The Material Test Curves.
② Acoustical Resistance Obtained By Taking The Difference Between The Peaks Of The Material Test Curves And The Peak Of The Open Test, As A Datum Line.
Frequency = 1000 Cycles.
Standard Sound-Absorbing Coefficients For Pitch 1024
Acoustical Resistance In Ohms.
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
10
20
30
40
50
60
70
80
90
100
110
120
Open Window.
Hairfelt-1"
Acousti-Celotex Type B.
Plain Celotex - 7/16"
Veneer-3/4"
Plasterboard.
①
②
W. R. Bullis.
May 13, 1931.

Peak value = 2430.5 ohms

Min. constant value = 2381.0 ohms

Difference 49.5 ohms

this gives the abscissa value for plain 7/16 inch celotex on curve number 1.

The abscissa values for curve number 2 were obtained by taking the difference between the peak value of the materials and the peak value of the open test which is shown plotted on page 33 ; it is also plotted as a datum line with the curves of the materials on page 38 . An example of celotex is as follows:

Peak value = 2430.5 ohms

Open test peak value = 2388.0 ohms

Difference 42.5 ohms

which gives the abscissa value for 7/16 inch celotex on curve number 2.

Both curves fall smoothly on the points excepting the hairfelt point of curve number 1. This point was hard to determine because of the difficulty in finding the minimum constant value of hairfelt. Its curve shows why this is true. Although both curves appear to be quite accurate calibration curves of the apparatus, number two is somewhat the smoother and all the points fall on the curve. In addition, the method by which the abscissa values of number two were obtained is the most logical and consistent with the tests and the theory of acoustical resistance. For the peak values of acoustical resistance were used to determine the properties of the materials; so it seems reasonable to believe that the peak value of the open test should be used as the datum point on which to base calculations. This may be thought of in terms of Sabine's open window standard for comparison. The peak of acoustical resistance from the open test corresponds to the open window; other materials are simply placed in this "open window" and their acoustical properties compared to it. Since the areas are the same all materials are directly comparable as a function of their acoustical resistance, and by using the calibration curve the acoustical properties may be found directly in absorption coefficients.

CONCLUSIONS

Advantages and limitations

CONCLUSIONS

Advantages and Limitations:

The apparatus described in this paper presents a simple and quite accurate means of measuring the acoustical properties of materials. The apparatus itself is quite simple and inexpensive and requires but little floor space. The vacuum tube oscillator is probably the most complicated and expensive part of the measuring apparatus. Even this could be made simple and inexpensive for this particular use. The method of testing is quite simple and easily accomplished and requires no particular skill on the part of the operator except to balance the impedance bridge; however a little practice is necessary to be able to distinguish between the correct and incorrect impedance bridge readings. With this method no special room or surrounding conditions need be provided for except to maintain the temperature nearly constant. Even normal sounds do not effect the readings except if the sounds are near enough or loud enough to prevent an accurate balancing of the impedance bridge. The loudspeaker and wooden tube with materials cannot be too close together else the bridge will be difficult to balance. It was found that best results were obtained when the loudspeaker and materials were in another room from the impedance bridge.

Materials may be easily clamped on the wooden tube and measurements accomplished in a few minutes; this is much simpler and easier than building a material into the wall of an especially constructed acoustic room. Another advantage is that only a small sample of material is needed. In this case a piece only 18 inches square was used. Another great advantage is that tests may be easily made at different frequencies; so the coefficient at various pitches of sound may be easily measured. This variation of frequency is limited only by the frequency range of the vacuum tube oscillator. In this paper all constant frequency tests were run at a frequency of 1000 cycles per second; therefore in the calibration curve all ordinate or coefficient values of absorption were taken from the tables which were calibrated at a pitch of 1024 cycles per second. If other frequencies were used for tests a calibration curve for each pitch would have to be plotted. Due to limitations of time extensive tests were not made at anything but 1000 cycles, but enough tests were performed to prove that this apparatus would also give equally consistent results at various other frequencies.

This apparatus does not measure true sound reflection as the term was defined in the introduction, for its operation depends upon the reflected sound which in turn depends upon the magnitude of absorbed and transmitted sound. This can be expressed as follows: reflected component = total volume of sound produced - absorbed component - transmitted component. Thus the sound absorption measured, includes that actually absorbed plus that transmitted by the material. This broader definition of absorption is in reality more frequent in actual practice where acoustic materials are used to absorb sound. The materials were each backed with 3/4 inch veneer to make the results as comparable as possible, for this condition occurs most frequently in actual practice. That the transmission component is quite small, thereby causing only a small error, is proven by the fact that the results of acoustical resistance are very comparable to the sound-absorbing coefficients; this is shown by the calibration curves.

APPENDIX

Test data and apparatus data

CONSTANT FREQUENCY, VARIABLE DISTANCE

TEST WITH THE UNLINED TUBE

Frequency = 1000 cycles. Temp. = 24.0° C.

C = 0.017 microfarads. Current = 1.5 ma.

LEGEND

D = distance between the loudspeaker and material.

R = loudspeaker effective resistance in ohms.

C = mica condenser capacitance.

C'= variable air condenser scale divisions.

VENEER $\frac{3}{4}$"			VENEER $\frac{3}{4}$"			VENEER $\frac{3}{4}$"		
D	R	C'	D	R	C'	D	R	C'
0.0	2377	68.9	12.0	2382	67.5	17.0	2382	74.0
0.5	2370	73.1	12.5	2385	65.9	18.0	2381	72.0
1.0	2382	69.6	13.5	2387	64.0	19.0	2380	71.8
2.0	2383	70.4	14.1	2392	64.5	20.0	2381	69.6
3.0	2383	69.8	14.3	2403	62.6	22.0	2387	66.5
4.0	2383	69.8	14.5	2412	62.3	24.0	2405	66.7
5.0	2383	69.7	14.7	2429	60.9	25.0	2429	67.7
6.0	2382	70.0	15.0	2458	64.2	25.5	2452	67.2
7.0	2381	70.2	15.1	2472	65.8	26.0	2464	71.3
8.0	2382	69.6	15.2	2467	71.0	26.5	2455	75.5
9.0	2381	69.0	15.3	2461	75.3			
10.0	2381	69.1	15.5	2433	79.2	OPEN	TEST	
11.0	2381	68.7	16.0	2397	77.2	15.12	2391	72.1

CONSTANT FREQUENCY, VARIABLE DISTANCE

TEST WITH THE UNLINED TUBE

(Continued)

7/16" PLAIN CELOTEX			PLASTERBOARD			TYPE B ACOUSTI-CELOTEX		
D	R	C'	D	R	C'	D	R	C'
9.0	2381	71.9	0.0	2388	67.4	0.0	2376	67.6
10.0	2378	73.4	9.0	2369	74.4	0.5	2380	68.0
14.0	2396	70.4	10.0	2385	68.0	1.0	2383	67.0
14.5	2420	67.7	11.0	2378	71.7	2.0	2383	67.7
14.6	2424	68.8	14.0	2396	61.8	3.0	2383	67.7
14.7	2425	69.0	14.5	2417	60.6	4.0	2383	67.4
14.8	2427	70.2	14.6	2420	60.3	5.0	2382	66.9
14.9	2431	71.4	14.7	2432	60.0	7.0	2383	66.9
15.0	2429	73.0	14.8	2443	59.7	9.0	2386	65.7
15.2	2426	75.0	14.9	2453	61.2	10.0	2388	65.5
18.0	2376	75.2	15.0	2464	63,5	11.0	2389	66.4
22.0	2379	71.7	15.1	2475	66.9	12.0	2393	65.7
24.0	2400	67.3	15.2	2475	70.5	13.0	2400	66.5
25.0	2424	66.3	15.5	2439	78.5	14.0	2406	67.0
25.5	2441	67.0	18.0	2378	74.3	14.5	2404	68.6
26.0	2455	70.2	22.0	2373	73.6	15.0	2400	69.6
26.5	2454	76.0	25.0	2438	63.4	16.0	2380	72.3
27.0	2444	79.6	25.5	2460	64.1			
26.3	2455	74.1	26.0	2486	71.1	OPEN TEST		
0.0	2390	57.8	26.5	2481	78.0	0.0	2404	66.0

CONSTANT FREQUENCY, VARIABLE DISTANCE

TEST WITH THE UNLINED TUBE

(Continued)

1/16" STEEL BACKED WITH 3/8" VENEER			BISON BOARD VENEER BACKED			1" HAIRFELT VENEER BACKED		
D	R	C'	D	R	C'	D	R	C'
0.0	2376	70.0	0.0	2373	62.6	0.0	2384	64.1
1.0	2376	71.1	1.0	2375	71.8	4.0	2386	70.2
2.0	2375	71.7	3.0	2374	72.1	7.0	2390	73.4
6.0	2370	72.9	5.0	2372	72.5	11.0	2394	73.2
10.0	2369	72.5	7.0	2371	72.0	12.0	2392	75.1
12.0	2372	70.1	10.0	2366	73.0	14.0	2390	75.0
13.0	2374	68.2	12.0	2372	70.8	15.0	2388	74.0
13.5	2377	67.4	13.0	2379	67.2	16.0	2386	73.8
14.0	2380	67.2	13.5	2384	67.3	18.0	2384	73.7
14.5	2390	64.7	14.0	2384	66.0	20.0	2384	75.3
14.7	2403	64.8	14.2	2397	63.1			
14.9	2418	63.8	14.6	2414	62.0			
15.1	2433	65.3	14.8	2430	62.4			
15.2	2442	67.0	14.9	2441	63.0			
15.3	2449	69.2	15.0	2454	67.2			
15.4	2449	72.6	15.1	2459	69.8			
15.5	2441	76.3	15.2	2457	72.4			
16.0	2389	80.1	15.5	2426	79.0			
17.0	2371	76.3						

CONSTANT FREQUENCY, VARIABLE DISTANCE

TEST WITH THE UNLINED TUBE

(Continued)

Open tube test showing double bridge readings.

	CORRECT		WRONG			CORRECT		WRONG	
D	R	C'	R	C'	D	R	C'	R	C'
0.0	2374	75.4	2375	75.6	17	2368	76.2	2374	75.0
0.5	2374	75.3			18	2366	76.2	2373	74.9
1.0	2374	75.7			19	2366	76.0	2370	76.6
2.0	2374	75.6	2383	73.5	20	2365	76.0	2369	76.4
3.0	2375	75.4			22	2364.5	75.5	2368	76.1
4.0	2375	75.4			24	2364	75.0	2369	75.7
5.0	2376	75.5	2386	73.7	26	2365	74.5	2369	75.0
6.0	2378	75.4			28	2367	73.8	2372	74.4
7.0	2379	75.7	2388	74.5	30	2370	73.2		
7.5	2379	76.0			32	2379	72.7	2383	73.7
8.0	2379	76.2	2388	75.0	33	2384	72.7		
8.5	2379	76.4			34	2390	73.6	2394	75.3
9.0	2377	76.8	2385	75.4	35	2393	75.3	2394	75.5
10.0	2376	76.8	2383	75.5	36	2391	77.0	2391	78.0
11.0	2374	76.7	2381	75.6	37	2386	77.8		
12.0	2372	76.3	2379	75.5	40	2374	78.0		
13.0	2370	76.2	2378	75.6	42	2371	78.5		
14.0	2370	76.5	2376	75.3	45	2369	78.0		
15.0	2369	76.3	2375	75.3	48	2368	77.7		
16.0	2369	76.5	2375	75.1	50	2368	76.8		

CONSTANT FREQUENCY, VARIABLE DISTANCE

TEST WITH THE UNLINED TUBE

(Continued)

Complete test on 1/16" steel, backed with 3/8" veneer.

Showing the location of peaks and valleys of resistance.

D	R	C'	D	R	C'	D	R	C'
0.0	2327	14.3	40.0	2306	23.3	80	2311	21.3
2.0	2320	19.5	42.0	2305	23.4	82	2317	29.2
4.0	2318	19.4	44.0	2305	23.0	84	2333	22.0
6.0	2319	18.4	46.0	2308	21.3	86	2306	23.0
8.0	2309	22.5	48.0	2322	16.5	88	2300	25.0
10.0	2307	23.0	50.0	2323	29.5	90	2305	21.0
12.0	2306	18.5	52.0	2300	25.5	92	2300	21.7
14.0	2334	17.0	54.0	2301	23.2	94	2318	18.5
16.0	2315	28.5	56.0	2300	20.0	96	2400	18.0
18.0	2303	22.7	58.0	2309	17.0	98	2337	37.0
20.0	2306	23.0	60;0	2374	22.4	100	2305	33.0
22.0	2303	18.8	62.0	2360	34.0	102	2290	30.0
24.0	2323	13.0	64.0	2317	32.6	104	2313	24.5
26.0	2416	30.6	66.0	2313	27.0	106	2322	28.4
28.0	2316	33.3	69.0	2300	27.9	108	2317	25.6
30.0	2307	30.3	70.0	2300	29.3	110	2311	26.5
32.0	2303	28.3	72.0	2306	27.5	112	2305	27.2
34.0	2300	26.7	74.0	2308	24.8	150	2315	23.0
36.0	2309	23.8	76.0	2309	24.5			
38.0	2309	22.8	78.0	2300	27.0			

CONSTANT DISTANCE, VARIABLE FREQUENCY

TEST IN OPEN AIR

Temp. = 23.5 ° C. Loudspeaker current = 1.5 ma.

LEGEND

D = distance between the loudspeaker and material.

R = loudspeaker effective resistance in ohms.

C = Mica balancing condenser capacitance.

C'= Variable air condenser scale divisions.

F = frequency in cycles per second.

VENEER ¾"

D = 14 cm.

F	R	C	C'
900	2238	0.0023	25.7
920	2265	0.0022	26.3
940	2293	0.0021	27.5
960	2337	0.0020	33.0
980	2377	0.0019	51.2
1000	2411	0.0018	71.3
1020	2442	0.0017	88.9
1040	2480	0.0017	30.1
1060	2506	0.0016	58.8
1080	2540	0.0015	89.7

PLAIN CELOTEX 7/16"

D = 14 cm.

F	R	C	C'
860	2158	0.0025	48.3
880	2198	0.0024	27.8
900	2232	0.0023	25.7
920	2260	0.0022	24.7
940	2293	0.0021	25.5
960	2333	0.0020	30.7
980	2373	0.0019	49.8
1000	2404	0.0018	70.2
1020	2438	0.0017	87.6
1040	2471	0.0017	30.0
1060	2497	0.0016	59.0

CONSTANT DISTANCE, VARIABLE FREQUENCY

TEST IN OPEN AIR

(Continued)

PLASTERBOARD				HAIRFELT 1"			
D = 14.0 cm.				D = 12.0 cm.			
F	R	C	C'	F	R	C	C'
900	2241	0.0023	20.4	900	2243	0.0023	31.0
920	2273	0.0022	25.0	920	2269	0.0022	30.8
940	2307	0.0021	27.7	940	2294	0.0021	34.2
960	2347	0.0020	30.6	960	2322	0.0020	38.7
980	2380	0.0019	51.6	980	2355	0.0019	55.9
1000	2408	0.0018	70.6	1000	2385	0.0018	73.6
1020	2453	0.0018	8.2	1020	2419	0.0017	89.7
1040	2482	0.0017	29.3	1040	2452	0.0017	29.8
1060	2614	0.0016	57.9	1060	2489	0.0016	57.9
1080	2545	0.0015	88.4	1080	2526	0.0015	88.8
1100	2578	0.0015	39.0	1100	2561	0.0015	38.6

CALIBRATION DATA

A COMPARISON OF ACOUSTICAL RESISTANCE WITH STANDARD SOUND-ABSORBING COEFFICIENTS

Table 1. Acoustical resistance obtained by calculating the difference between the peaks and valleys of the material test curves.

MATERIAL	MIN. VALUE	PEAK VALUE	DIFF.	SOUND COEFF.
PLASTERBOARD	2382	2475	93	0.05
VENEER $\frac{3}{4}$"	2382	2472	90	0.06
PLAIN CELOTEX	2381	2431	50	0.20
ACOUSTI-CELOTEX (Type B)	2383	2406	23	0.47
HAIRFELT 1"	2385	2394	9	0.80

Table 2. Acoustical resistance obtained by taking the difference between the peaks of the material test curves and the peak of the open test.

MATERIAL	OPEN TEST	PEAK VALUE	DIFF.	SOUND COEFF.
PLASTERBOARD	2388	2475	87	0.05
VENEER $\frac{3}{4}$"	2388	2472	84	0.06
PLAIN CELOTEX	2388	2431	43	0.20
ACOUSTI-CELOTEX (Type B)	2388	2406	18	0.47
HAIRFELT 1"	2388	2394	6	0.80

APPARATUS

Instrument data and serial numbers

A - Impedance bridge arms (designed and constructed by Mr. R. H. Batcheller senior in E.E. at OSAC).

R - Decade resistance box. Western Electric type 14-B No. 10,606.

C - Leads & Northrup mica variable condenser, cap.= 1 mf. type 1070 No. 140,518.

C'- Leads & Northrup variable air condenser No. 142,746.

D - Western Electric thermocouple type 22L, No. 33,404.

E - Weston microammeter model 322, No. 2,751.

F - General Radio rheostat, 2,500 ohms.

G - Western Electric headphones type 509 W.

Western Electric 8 - A Oscillator, 100 - 50000 cycles. No. 11,450.

Farrand Inductor Dynamic loudspeaker, 10" cone. No. 100,320.

MATERIALS

VENEER - made of pine and built up to a thickness of $\frac{3}{4}$".

PLAIN CELOTEX - made by the Celotex Co. 7/16" thick.

ACOUSTI-COLOTEX - type B, made by the Celotex Co.

HAIRFELT - approximately one inch thick.

PLASTERBOARD - 3/16" thick.

ACKNOWLEDGMENT

The author is deeply indebted to, and wishes to express his sincere appreciation to Assistant Professor Arthur L. Albert for suggesting this investigation, and for helpful suggestions and encouraging guidance in carrying out the tests. Thanks are also due Dr. W. Weniger and Assistant Professor Fred B. Morgan of the Physics Department for suggestions and help in formulating the theory of acoustics as applied to a loudspeaker. The cooperation given by Professor R. H. Dearborn, under whose department the tests were conducted, is greatly appreciated.

The author also wishes to express his thanks to Dalton Foster for making the photographs of the apparatus in this report, and the assistance given by Norval G., Reetz in running some of the tests is greatly appreciated. Both of the latter two are 1931 seniors in electrical engineering.

BIBLIOGRAPHY

1 - COLLECTED PAPERS ON ACOUSTICS by- W. C. Sabine.

2 - ELECTRICAL VIBRATION INSTRUMENTS by- A. E. Kennelly.

3 - ACOUSTICS by- Stewart and R. B. Lindsay.

4 - TELEPHONE COMMUNICATION by- Wright and Puchstein.

5 - ACOUSTICS OF BUILDINGS by- F. R. Watson.

6 - THEORY OF VIBRATING SOUNDS by- I. B. Crandall.

7 - DICTIONARY OF PHYSICS by- Glazebrook.

8 - THE SOUNDS OF SPEECH by- I. B. Crandall.
Bell Telephone Laboratories Reprint B - 162- 1.