An Indicating Meter for Measuring Intensity Level of Sound

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https://dx.doi.org/doi:10.21220/s2-bk84-4z02

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AN INDICATING METER
FOR MEASURING
INTENSITY LEVEL OF SOUND

by

Walter Sanders Foster
SUBMITTED IN PARTIAL FULFILLMENT

OF THE REQUIREMENTS

OF

COLLEGE OF WILLIAM AND MARY

for the degree

MASTER OF ARTS

1986
OUTLINE

I. INTRODUCTION
   1. Review of literature
      a. Historical
      b. Audiometer
      c. Acoustimeter

II. UNITS OF MEASUREMENT
    1. "Nepers"
    2. "Decibel"

III. STATEMENT OF PROBLEM

IV. DESCRIPTION AND DIAGRAM OF THE INDICATING METER
    1. General
    2. Microphone
    3. Amplifier
    4. Indicator

V. MEASUREMENTS

VI. SUMMARY

VII. BIBLIOGRAPHY

VIII. VITA
INTRODUCTION

With the advent of modern scientific advancement has come a "New World to Conquer." This by-product of the machine age is catalogued under that branch of Physics called sound. To be more exact, it is that disturbing and distracting feature referred to as "noise," sound without definite pitch.

Little or no work had been done in a direct way toward measuring intensity level of noise, as is revealed in the following report of the National Research Council. Indirectly, though, a start had been made back in the nineteenth century toward the measurement of sound intensity of musical quality. Most of the work, however, has been done since the World War.

An instrument capable of measuring intensity level of sound has various applications. It can be used in the study of noise, in determining the intensity level of the different musical instruments in an orchestra, in revealing the characteristics of the ear to various sound frequencies of equal sound level, in training singers to control the intensities of their voices, in the manufacturing of sound-proofing materials, in studying the acoustics of buildings, in psychological and physiological studies, and in many other ways.

The report submitted in 1922 by the Committee of the Division of Physical Sciences of the National Research Council on "The
Measurements of Sound Intensities in Absolute Units" stated that several aspects of the question had not been thoroughly investigated, among which was listed the subject, "Methods of Absolute Measurement."

Up to that time, the methods employed for the comparison of sound intensities were not as a whole capable of giving results in absolute units.

One of the earliest instruments used in making sound intensity measurements was a form of vibration manometer, devised by M. Wien in 1889. A diaphragm similar to that of an aneroid barometer was used to cover one end of a resonator. The pressure from the sound produced motion in the diaphragm. This movement was transmitted to a small mirror, one point of which was in contact with the diaphragm, and which rotated with the motion of the latter. The motion of the diaphragm was measured by the width of the beam of light reflected.

The Rayleigh Disc provided a method of determining the relative values of sound intensities. It consists of a small thin glass disc, suspended so that the plane of the face is vertical. When the modulus of torsion of the fiber suspension is known, the value of the alternating air stream velocity can be calculated from the deflection produced by the sound.

The electrostatic telephone transmitter was used to measure the pressure variation in sound. The diaphragm of the transmitter
serves as one plate of a variable condenser. The fixed plate is close to the diaphragm. The motion of the latter varies the capacitance of the condenser and causes a pulsating current in the circuit. These pulsations are amplified and measured on a microammeter. Calibration in absolute units is carried out by use of the thermophone. The two instruments, the transmitter and thermophone, are placed close together and the pressure changes are computed from the alternating current in the latter which produces the sound.

It is a well-known fact that sound affects the ear in a very complex way, whereas the response of the measuring instrument must be made relatively simple, if it is to operate under ordinary conditions. Consequently, there are differences in opinion as to how sound intensity level should be measured. In general, there are two fundamental methods of measurement, namely, the subjective or audiometric evaluation of the intensity level by the ear, and the objective or acoustiometric measurement of it by a meter. At present the British acoustic engineers prefer the former method, while the American acoustic engineers prefer the latter.

As this paper deals primarily with the acoustiometric sound measuring device, and, since both methods are commonly employed, it is only fitting that a discussion of the more general audiometric methods be made. The discussion follows.

The audiometric methods make use of a direct comparison
between a standard source of sound, i.e., one of a known intensity, and the source to be measured. This comparison is made with the ear. The standard is energized and held at a fixed distance from the ear. The time required for the standard to become inaudible is an inverse measure of the unknown sound intensity in the proximity of the observer.

A brief description of some of the audiometric instruments is given in the paragraphs immediately following.

One form of audiometer consists of an ordinary phonograph on which are "played" records, each of which gives a "warble-tone," i.e., a tone in which the frequency goes up and down, covering a particular band of frequencies in which it is presupposed that the sound in question resides. The output of the phonograph is passed through a suitable amplifier and to an earphone. When a sound of unknown intensity has been made, the observer hurriedly adjusts the attenuator of the amplifier until the warble-tone just makes the sound. The reading of the calibrated attenuator is then the value of the intensity level of the unknown sound. A schematic diagram of this type of instrument is shown in Fig. 1.

![Schematic diagram of the phonographic type of audiometer.](image)

**Fig. 1:**

Schematic diagram of the phonographic type of audiometer.

A = Phonograph
B = Attenuator
C = Amplifier
D = Receiver
Another form of audiometer is that which was devised by Berkhausen. This is shown in schematic arrangement in Fig. 2. It consists of an electric buzzer, an attenuator and an earphone. The buzzer generates an alternating e.m.f. of frequencies covering a very broad range within the audible spectrum. The attenuator is calibrated to read directly in some specific unit. The earphone has an offset attachment to it. In order to make a measurement of a particular sound, the attenuator is set at a value such that the note issuing from the audiometer is barely masked by the unknown sound. As before, the relative intensity of the unknown source is indicated by the reading of the attenuator, which has previously been calibrated by comparison with a standard.

![Fig. 2.](image)

**Schematic diagram of the buzzer type audiometer.**

A = Buzzer  
B = Attenuator  
C = Earphone

Of the various subjective methods for evaluating the intensity level of sound, perhaps the tuning fork method is by far the simplest. The fork is struck and then held at a given distance from the ear of the observer. The time required for its sound to become masked by that of the disturbance in question is a factor.
depending on the intensity of the latter. A mathematical interpretation\(^1\) of the tuning fork audiometer is as follows:

\[
\text{If,} \quad I_0 = \text{Initial intensity of the sound from the tuning fork.} \\
I_t = \text{Intensity of the tuning fork after an interval } t. \\
a = \text{A constant of the fork.} \\
t = \text{Time of audiable duration, i.e., before masking.}
\]

Then \(I_t = I_0e^{-at}\) \(\text{(1)}\)

Thus, the decay characteristic of a tuning fork is exponential.

The subjective method is not satisfactory as a whole because the results are based upon the ear. The ear is as variable as the weather in its response, from hour to hour, for either constant or changing frequency, in the same individual as well as among different individuals. All sound measurements must be made in terms of the effect of sound on the average normal ear. So the objective method of measuring intensity levels is resorted to because of the fact that the ear plays no direct part therein.

The several classes of acoustiometric instruments for measuring the intensity level of sound are fundamentally alike, but differ somewhat in details. Essentially they are composed of the following parts:

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\(^1\)Olson and Massa, \textit{Applied Acoustics}, p. 377.
1. A pickup (Microphone)
2. An attenuator
3. An amplifier
4. An indicator

One class of meters measures the total sound energy regardless of the frequencies used. The other class is capable of measuring the sound energy of a particular frequency, or a combination of frequencies, by suitable filtering.

Schematic diagrams of the two classes of instruments are shown in Fig. 4 and Fig. 5.

![Schematic diagram](image)

**Fig. 4.**

Schematic diagram of a simplified acoustimeter

A = Microphone  
B = Amplifier  
C = Indicator
With the change-over switch in position 1, the sound can be analyzed. In position 2, the total sound can be measured.

A - Microphone  
B - Attenuator  
C - Weighting network  
D - Amplifier  
E - Output meter  
F - Oscillator  
G - Detector  
H - Mechanical filter  
I - Amplifier  
S1 - Switch  
S2 - Change-over switch

A modification of the class of meters mentioned first is shown in Fig. 6. This particular apparatus integrates the sound energy. The reading of the meter W, divided by the duration of time of a particular observation, will give the average sound level for that period of time. This instrument is also suitable

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See Electronics, April, 1935, Vol. 8, No. 4, p. 111.
for measuring fluctuating sound energies.

Schematic diagram of an integrating sound meter

A = Microphone
B = Amplifier
W = Watt-hour meter

There are on the market a number of acoustiometric meters which are patented under various trade names. Among the leading manufacturers of such instruments are:

The Electric Research Products, Inc.
E. E. Free Laboratories
General Electric Co.
General Radio Co.
Western Electric Co.
Westinghouse Electric and Mfg. Co.

The foregoing gives a brief review of what has been done in the measurement of sound intensity, and a statement of the present status of the problem.

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Before going into the discussion of the main problem, the units for expressing the intensity level of sound pressure will be reviewed.

**UNITS OF MEASUREMENT**

For a long time there was no unit which was universally used in this country, or abroad, for measuring sound level, neither was there a convenient way of converting one system into another.

The Weber-Fechner law, a well-known law in psychology, which represents empirically the response of the nervous system to a stimulus, suggests a logarithmic scale for measuring relative sound intensities. This law states that the magnitude of the sensation (of hearing) produced is proportional to the logarithm of the stimulus (sound pressure). Applying this law to hearing, the fractional change in intensity is, in the opinion of Fletcher, a constant independent of the frequency or intensity involved.

Basing their conclusions on the foregoing, the International Advisory Committee on Long Distance Telephony unanimously recommended the adoption of units representing the logarithm of the ratio of two powers as standards for comparing sound levels. These units were named the "neper" and the "bel" respectively, in honor of two distinguished men of Science, John Neper (Napier), who conceived the idea of logarithms, and Alexander Graham Bell, the

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4Knudsen, _Architectural Acoustics_, 1933, pp. 79 - 80.
5Fletcher, H., _Speech and Hearing_, 1929, p. 145.
pioneer in telephony.

As a result of the above recommendations there have come into use two general systems of units which differ in logarithmic bases, and hence in magnitude. The neper has been adopted in Europe as the standard unit, whereas the bel has been adopted by these United States.

By expressing algebraically the intensity level of two sound powers, \( P \) and \( P_0 \), in the Naperian and Briggs systems of logarithms respectively, the following equations are obtained:

\[
\text{neper} = \frac{1}{2} \log_e \left( \frac{P}{P_0} \right), \\
\text{bel} = \log_{10} \left( \frac{P}{P_0} \right).
\]

Waves of a given frequency in a medium (where the velocity is constant) have constant wave lengths, but the amplitude, power, or intensity may vary. For an increase in amplitude, the particle under consideration must move with increased velocity, and since the kinetic energy of the particle is proportional to the square of the velocity, it follows that the intensity, or power, or energy, is proportional to the square of the amplitude, or the square of the voltage, or the square of the current. Thus, equations (2) and (3) may be re-written as follows, where \( E, I, \) and \( A \), represent voltage, current and amplitude, respectively:

\[
\text{neper} = \log_e \left( \frac{V}{V_0} \right), \\
\quad = \log_e \left( \frac{I}{I_0} \right),
\]

As a result of the above recommendations there have come into use two general systems of units which differ in logarithmic bases, and hence in magnitude. The neper has been adopted in Europe as the standard unit, whereas the bel has been adopted by these United States.

Waves of a given frequency in a medium (where the velocity is constant) have constant wave lengths, but the amplitude, power, or intensity may vary. For an increase in amplitude, the particle under consideration must move with increased velocity, and since the kinetic energy of the particle is proportional to the square of the velocity, it follows that the intensity, or power, or energy, is proportional to the square of the amplitude, or the square of the voltage, or the square of the current. Thus, equations (2) and (3) may be re-written as follows, where \( E, I, \) and \( A \), represent voltage, current and amplitude, respectively:

\[
\text{neper} = \log_e \left( \frac{V}{V_0} \right), \\
\text{bel} = \log_{10} \left( \frac{P}{P_0} \right).
\]
\[ z = \log_e \left( \frac{A}{A_0} \right). \]  
(6)

\[ \text{bel} = 2 \log_{10} \left( \frac{V}{V_0} \right). \]  
(7)

\[ = 2 \log_{10} \left( \frac{I}{I_0} \right). \]  
(8)

\[ = 2 \log_{10} \left( \frac{A}{A_0} \right). \]  
(9)

Again referring to equation (2), it is evident that when the difference in the intensity level is one neper, the value of \( P \) is 7.39 times greater than \( P_0 \). This is determined as follows:

\[ 1 \approx \frac{1}{2} \log_e \left( \frac{P}{P_0} \right). \]  
(10)

\[ \left( \frac{P}{P_0} \right) = e^2. \]  
(11)

\[ P = e^2 P_0. \]  
(12)

\[ P \approx 7.39 P_0. \]  
(13)

Likewise, it can be shown from equation (3) that for a difference in sound level of one bel, it requires a change in value of \( P \) which equals ten times the value of \( P_0 \).

Since both the neper and the bel are too large for most practical purposes, decimal sub-multiples have been adopted, namely, the "decineper" and the "decibel."

It so happens that the decibel (db) is approximately the minimum change in power level that can be distinguished by the average normal human ear. Thus, the ratio of intensities of two sounds which differ by 1 db is obtained from the relation:

\[ \log_{10} \left( \frac{P}{P_0} \right) \approx 0.1. \]  
(14)

Therefore \( \frac{P}{P_0} \approx 1.259. \)  
(15)
Similarly, a sound which is 5 db. above another of $P_0$ will have an intensity of $3.162P_0$.

Since the decibel is a logarithm of a power ratio, it has zero dimension. It has been found experimentally that a change in power level of one decibel is approximately $10^{-16}$ watt per sq. cm. (at a frequency of about 1000, which is the region of maximum sensitivity of the normal ear), and is equivalent to sound pressure of 0.207 millibar. It has been suggested that $10^{-16}$ watt per sq. cm. be taken as the standard for the threshold intensity of sound.

STATEMENT OF PROBLEM

The purpose of this paper is to describe a semi-portable acoustiometer for measuring intensity level of sound, which can be constructed in any modern or well-equipped laboratory at a nominal cost. Most of the parts are standard laboratory equipment. A schematic diagram of this meter is shown in Fig. 4, while Fig. 7 shows a circuit diagram of it.

DESCRIPTION AND DIAGRAM OF INDICATING METER

The sound is picked up by the microphone, $P$. From there it passes through the pre-amplifier, where the voltage is amplified. Then it enters the main amplifier, where it receives further intensification. The amplifier is coupled by means of a transformer, $T_3$, to the grid of a '01A thermionic tube. There is
Diagram of
Indicating Sound Meter

Fig. 7.
DESCRIPTION OF PARTS SHOWN IN FIG. 7.

$C_1 = 0.1 \text{ mfd. Condenser, 400 volts.}$

$C_2 = 1.0 \text{ mfd. } 500 \text{ volts.}$

$C_3 = 8.0 \text{ mfd. } 400 \text{ volts.}$

$C_4 = 10.0 \text{ mfd. } 25 \text{ volts.}$

$C_5 = 0.5 \text{ mfd. } 400 \text{ volts.}$

$M = \text{ Microammeter.}$

$P = \text{ Velocity Microphone, 2000 Ohms impedance.}$

$R_1 = 2000 \text{ ohms, 1 watt.}$

$R_2 = 1 \text{ megohm, 1 watt.}$

$R_3 = 250,000 \text{ ohms, 2 watt.}$

$R_4 = 50,000 \text{ ohms, 1 watt.}$

$R_5 = 500,000 \text{ ohms, potentialometer.}$

$R_6 = 1000 \text{ ohms, 2 watt.}$

$R_7 = 1850 \text{ ohms, 1 watt.}$

$R_8 = 10,000 \text{ ohms, 1 watt.}$

$R_9 = 700 \text{ ohms, 20 watt.}$

$R_{10} = 400 \text{ ohms, potentialometer.}$

$R_{11} = 15,000 \text{ ohms, 58 m.a., voltage divider, tapped at 2500 ohms,}$

$R_{12} = 25,000 \text{ ohms, 10 watt.}$

$T_1$ and $T_2 = \text{ Matched push-pull transformers (541-J General Radio).}$

$T_3 = \text{ Output transformer (541-D General Radio).}$

$T_4 = \text{ Power transformer. Primary for use on 110-120 volts a.c.}$
Primary windings are as follows:

1 = 3, center-tapped at 2; 2.5 volts = 3.50 amp.
4 = 6; " " 5; 2.5 " = 7.0 ".
7 = 9; " " 8; 5.0 " = 3.0 ".
10 -12, " " 11, 750.0 " = 250.0 ".

impressed across the grid a negative voltage which is just sufficient to prevent a flow of electrons when there is no sound impinging upon the microphone. The plate is connected in series with a sensitive microammeter and to the positive terminal of a 90 Volt d.c. supply.

When sound strikes the ribbon of the microphone it causes a pulsating e. m. f. to be impressed upon the grid of the 'OIA tube. This causes the grid potential to become more negative during half of a cycle and less negative during the remaining half. The grid bias, being adjusted to such a value as to prevent current in the plate circuit when there is no sound, will permit the flow of current during that part of the cycle when the voltages are in opposite direction with respect to each other. The greater the intensity of sound being measured, the less negative the effective grid voltage will become, and, as a consequence, the greater will be the current through the indicating meter.

In order to duplicate results in measurements it is necessary that certain fixed conditions be established. The magnitude of the primary voltage of the power transformer, $T_4$, should be taken
at a value which is accessible under most ordinary conditions. For instance, in Williamsburg the average line voltage is around 120 volts, and varies no great amount from this value. Under this and similar conditions 115 volts is a satisfactory value to select for the primary.

The attenuator, $R_5$, should be regulated so as to prevent oscillation in the amplifier. This adjustment should be critical, for in a high gain amplifier it greatly affects the power out-put. A desirable setting for the attenuator is at a point just below that which causes oscillation. This critical point may be located by adjusting $R_5$ with a vernier and observing a milliammeter placed in the plate circuit of the '58 amplifier tube. When the sound is nil, the pointer rests at some fixed value, say 3.6 m. a. If a loud sound in the neighborhood of the microphone causes oscillations in the amplifier, the reading of the milliammeter will fall to, say 2.4 m. a., and the pointer will vibrate. Under normal operating conditions, the milliammeter will register a slight increase as the result of sound.

In designing the acoustiometer, a velocity microphone of high impedance was selected for the pick-up in preference to the condenser type or magnetic type. The velocity microphone has a linear response over a wide frequency range within the audible band. That is, for equal sound intensities but of unlike frequencies, equal e. m. f's. will be generated in the microphone. This is not true
of the magnetic type. Also, the velocity microphone is free from frequency distortions; whereas, the condenser type is not. The condenser microphone is very fragile and subject to calibration changes. These features are not present in the velocity microphone.

The amplifier is composed of a pre-amplifier, which intensifies the microphone e. m. f., and the 2A3 push-pull power amplifier. The latter includes transformers which have linear response characteristics.

In building the amplifier great care was exercised in laying out the various parts. As far as it was practicable, the connecting wires were not crossed. The leads in the grid circuit of the pre-amplifier were made of shielded cable. The '56 and '57 tubes were shielded; also, a metallic housing was placed around the power transformer. The above exercised precautions were effective in reducing the 60-cycle hum, which was very distracting at first.

The facts previously mentioned concerning the indicator, along with the circuit diagram (Fig. 7.), should suffice in describing it. It should be added, however, that the 90 volts d.c., plate e. m. f. may be supplied by a set of B-batteries, or, it may be taken from a suitable tap on the voltage divider. Either the "C" bias was supplied from an external source -- a 45 volt B-battery.

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If it is desired, the microammeter may be calibrated with a standard so as to read directly in decibels, microwatts per sq. cm., millibars, or nepers.

MEASUREMENTS

The constancy of the instrument was checked by three different methods, the first two of which were not entirely satisfactory for reason that the personal equation entered into them. The latter method, however, proved to be very convincing. For the sake of clarity, a few comments should be made at this point. On account of the acoustical properties of the rooms in which the following readings were taken, the inverse square law does not conform. In fact, certain places in the rooms more remote than others gave resulting sound levels higher than those closer to the microphone.

Each of the tests was made with settings as shown below:

- primary voltage, 115 volts a.c.;
- grid bias across the '01A, 12 volts;
- filament current of the '01A, 0.25 amperes;

Test 1. A cast iron sphere was dropped repeatedly from a height of 100 cms., striking a piece of hard wood, which was mounted on a metal plate. A series of readings was taken and then the improvised gauge was moved to other points in the room.
Scale reading 0 - 2000 microamperes

Distance in cms.

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Test 2. A circular piece of sheet iron, about 75 cms. in diameter was suspended so that its faces were parallel to the face of the microphone. This plate was struck by a pendulum bob which swung through a predetermined arc. This sound-making apparatus was set up at different locations from the microphone. Sets of readings were made which are given in the following table:

Scale reading 0 - 2000 microamperes.

Distance in cms.

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<td>350</td>
<td>570</td>
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<td></td>
</tr>
</tbody>
</table>
The data obtained in this test shows conclusively that the sound level at a particular point is a function of the acoustical properties of its surroundings.

Test 3. The loud speaker of an oscillator of variable frequency was placed 100 cms. in front of the sound meter pick-up. Three sets of readings were taken, each set for a different frequency note. A single-throw, double-pole, switch in the filament circuit of the 'OLA tube was opened and then closed, thus causing the pointer to rise to the level of sound and then fall back to its zero position. The values of the readings observed are shown in the first three columns of figures which follow. The second set of three columns of figures indicates the results from a similar set of observations which were taken several days later.
Scale reading 0 - 200 microamperes.

\( L_o = 8.57 \) henrys (Oscillator).

Plate voltage, 145 volts (Oscillator).

<table>
<thead>
<tr>
<th>( C_o = 1 \text{ mf} )</th>
<th>( C_o = 0.2 \text{ mf} )</th>
<th>( C_o = 0.3 \text{ mf} )</th>
<th>( C_o = 0.1 \text{ mf} )</th>
<th>( C_o = 0.2 \text{ mf} )</th>
<th>( C_o = 0.3 \text{ mf} )</th>
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<tbody>
<tr>
<td>169</td>
<td>9.5</td>
<td>25</td>
<td>168</td>
<td>8</td>
<td>26</td>
</tr>
<tr>
<td>167</td>
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<td>168</td>
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<td>9</td>
<td>26</td>
<td>170</td>
<td>9.5</td>
<td>26</td>
</tr>
</tbody>
</table>

At a distance of approximately 10 ft. the following measurements were made:

<table>
<thead>
<tr>
<th>Reading of Microammeter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wooden legged stool slid over a concrete floor</td>
</tr>
<tr>
<td>Steel &quot; &quot; &quot; &quot; &quot; &quot; &quot; &quot; &quot; &quot;</td>
</tr>
<tr>
<td>Table pushed over a concrete floor</td>
</tr>
<tr>
<td>&quot; pulled &quot; &quot; &quot; &quot; &quot; &quot; &quot; &quot; &quot; &quot;</td>
</tr>
<tr>
<td>Loud whistle (human)</td>
</tr>
<tr>
<td>Brick upset</td>
</tr>
<tr>
<td>Quiet conversation</td>
</tr>
<tr>
<td>Average radio program</td>
</tr>
<tr>
<td>Alarm Clock</td>
</tr>
</tbody>
</table>
SUMMARY

This paper has briefly reviewed the general stages of development in the field of measurements in the intensity level of sound. It has outlined the requirements for a meter which will measure sound level, and has described an indicating meter which has been developed meeting these requirements.

It is believed that this instrument will prove a valuable tool in the laboratory, not only as a sound level indicator, but also as a high fidelity amplifier.

The investigation reported herein was undertaken at the suggestion of Dr. W. W. Merrymon, Associate Professor of Physics, College of William and Mary, and conducted under the direction of Dr. R. C. Young, Professor of Physics, College of William and Mary. The author wishes to express his sincere thanks and appreciation to both Professors Young and Merrymon for their many valuable suggestions and efforts. He also wishes to acknowledge with thanks the assistance rendered by Professor F. B. Haynes, Physics Department, Virginia Polytechnic Institute, Blacksburg, Virginia, and Messrs. Gilman Bailey, Lewis Kissenger and Galen Ewing, students at the College of William and Mary.
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