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The Measurement of Audio Volume

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A comprehensive discussion of the problems involved and the instruments employed to indicate program level and sine-wave tones in broadcast and recording circuits.

IN ALTERNATING CURRENT THEORY there are three related values of a sine wave by which its magnitude may be expressed. These are the average value, the r.m.s. (or effective) value, and the peak (or crest) value. Certain fundamental electrical measuring devices provide means for determining these values. Complex, non-sinusoidal periodic waves also have the same three readily measured values. As a rule, the problem under consideration determines whether the average, the r.m.s., or the peak value of the wave is of primary importance.

Concept of Audio Volume

In the field of communication engineering, waves which are both very complex and non-periodic are encountered. When an attempt is made to measure such waves in terms of average, r.m.s., or peak values, it is found that the results can no longer be expressed in simple numerical terms since these quantities are not constant but variable with time. Moreover, the values appear to be affected by the charactericties of the measuring instrument and the technique of measurement. The communications engineer, however, is vitally concerned with the magnitude of these non-sinusoidal, non-periodic waves since he must design and operate systems in which they are amplified by vacuum tubes, transmitted over wire circuits, modulated on carriers, and otherwise handled as required by the various communication services. He needs a practical method of measuring and expressing these magnitudes in simple numerical fashion.

This need may be better appreciated by considering a typical example—the communication systems employed for broadcasting. These are often very complicated networks spread over large geographical areas. A typical network may include 20,000 miles of wire line and hundreds of amplifiers situated both along the line and in the 100 to 200 connected broadcasting stations. Every 15 minutes during the day the component parts of such a system may be shifted and connected together in different combinations in order to provide for new points of origin of the programs, for the addition of new broadcasting stations, and for the removal of others from the network. In whatever combination the parts of the system may be assembled, it is necessary that the amplitude of the transmitted program waves —at all times and at all parts of the system—remain within the limits which the system can handle without impairment from overloading or from noise. To accomplish this, some convenient method of measuring the amplitude of program waves is needed.

These and similar considerations led to the conception of a fourth electrical quantity, known as "volume", whereby the magnitude of waves encountered in electrical communications, such as speech or program waves, may be readily expressed. This quantity is a purely empirical value, created to meet a practical need. *It is not definable by means of a precise mathematical formula in terms of any of the familiar electrical units of power, voltages or current.* Volume is simply the indication of an instrument known as a volume indicator, which has specified dynamic and other characteristics and which is calibrated and read in a prescribed manner. Because of the rapidly changing character of the program wave, *the dynamic characteristics* of the instrument are fully as important as the value of sine-wave power used for instrument calibration. The readings of volume have been customarily expressed in terms of decibels with respect to some volume level chosen as the "reference" level.

Volume Indicator Applications

Volume indicators are used extensively to indicate the correct transmission level for speech and program waves in audio systems employing amplifiers, program-actuated automatic devices, program wire circuits, modulators, sound recorders and reproducers, or wherever the transmission of speech and program waves are involved. In this capacity volume indicators serve as a guide to the avoidance of overloading. Equally important, they serve as a means of indicating approximately the comparative loudness with which various elements of a complete program will be heard when finally converted to sound.

Volume indicators are also used for checking transmission gains and losses in program networks and audio systems by simultaneous measurements at a number of points on particular peaks or impulses of the program wave which is being transmitted. They are also used for sine-wave transmission measurements on audio systems and circuits.

In spite of its importance and its extensive and universal use, the volume indicator is probably the least understood of all audio measuring instruments. For this reason the standard volume indicator, its reference level, its method of calibration and the teminology used for volume measurements is covered in detail in the following paragraphs.

Peak vs. r.m.s. Volume Indicators

In the study that led to a standard volume indicator[1] the decision had to be made as to whether the standard volume indicator should be of the r.m.s. or of the peak-reading type. These two types of instrument represent two schools of thought. The peak-reading instrument is favored for general use by many European engineers and is specified by the F.C.C. for use as modulation monitors in this country. The r.m.s. type has however, been employed in this country on broadcast program networks and for general telephone use. In view of the importance of the decision and the difference of opinion that has existed, the basis on which the choice was made is discussed below in some detail.

In accord with common practice, the terms "r.m.s." and "peak-reading" are used rather loosely herein. The essential features of an r.m.s. instrument are a rectifier or detector and a d.c. milliammeter. The movement of the latter is not especially fast, generally requiring tenths of a second to reach substantially full-scale deflection. Obviously, if a wave of sufficiently low frequency is applied, say one whose frequency is one or two cps, the instrument can follow it and the true peaks of the wave will be indicated. But when much higher frequency waves are applied, such as the complex speech or program waves, the instrument is too slow to indicate the instantaneous peaks, rather, it averages or integrates whole syllables or words. As shown by tests and practical experience, it is of secondary importance whether the detector actually has an r.m.s. (or square law) characteristic, or has a linear or some intermediate characteristic.

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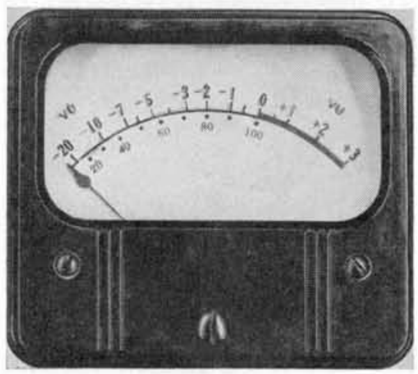
[1] Chinn, Gannett and Morris; *Proc. I.R.E.*, Vol. 28, No. 1, p. 1, Jan. 1940.

Fig. 1. An installation of twelve standard volume indicators, on an equal number of outgoing program circuits in the CBS shortwave master control room.

A peak-reading instrument capable of truly indicating the sharpest peaks which occur in a high-quality program wave would have to respond to impulses lasting only a very small fraction of a millisecond. Cathode-ray oscilloscopes or gas-tube trigger circuits are capable of doing this and consequently, might be used as a peak-reading volume indicator. However, the so-called peak-reading volume indicators used in practice, designed to give a visual indication on an instrument, are far from having the above speed although they are much faster than the r.m.s. instruments. They generally respond to impulses whose duration is measurable in hundredths or thousandths of a second. As a result they truly indicate the peaks of waves whose frequencies do not exceed say, 50 to 100 cps. They are similar to the r.m.s. instruments in that they are not fast enough to indicate the instantaneous peaks of speech or program waves but tend to average or integrate a number of peaks of the wave.

A feature of the usual peak reading instrument which is superficially impressive, but from which the analytical standpoint is of secondary importance, is that it is usually given a dynamic characteristic of rapid response coupled with very slow decay. This is usually acomplished by a circuit wherein a capacitor is charged through a full-wave vacuum-tube rectifier, the rates of charge and discharge being determined by resistances. A d.c. amplifier and instrument indicate the charge on the capacitor. The advantage of making the discharge rate of the capacitor very slow is that the indicating instrument itself need not then be particularly fast and, moreover, the ease of reading it is greatly increased.

From the above analysis it is seen that the r.m.s. and the peak-reading instruments are essentially similar and differ principally in degree. Both indicate peaks whose durations exceed some value peculiar to the instrument and both average or integrate over a number of peaks the shorter, more rapid peaks encountered in speech or program waves. Either may have an r.m.s. or square-law detector, or one of some intermediate characteristic. The important difference between the two types lies in the speed of response as measured by the length of impulses to which they will fully respond, or what is the same thing, in the time over which the complex wave is integrated.



Courtesy General Electric Co.

Fig. 2. The "A" type standard volume indicator scale emphasizes the VU markings and has an inconspicuous voltage scale. This type of scale is commonly used for transmission measuring sets.

Peak Checking

An important use of volume indicators is that of checking the transmission losses or gains along an audio system or a program network by measurements made on the program material being transmitted. The circuits which make up broadcasting networks, for instance, are in continuous use for many hours each day and during that period are switched together in as many combinations as called for by the operating schedules. It is seldom possible to free a circuit for sine-wave transmission measurements. Therefore to check the transmission conditions during service hours, it is the custom to take simultaneous readings at two or more points in the program networks on particular impulses of whatever program wave is being transmitted and to coordinate these readings by means of telephone communication. On such readings, the r.m.s. type of instrument is far superior to the peak-reading type. This is because phase distortion and slight nonlinearity in the program circuits (the results of which are too small to be detectable by ear) change the wave shape of the program peaks sufficiently to cause serious errors in the indications of the peak-reading instrument but have no noticeable effect on the r.m.s. instruments.

The effect of a long program circuit on the indication of the peak instrument is partly due to the cumulative effects of the slight nonlinearity in the many vacuum-tube amplifiers and loading coils in the circuit, and partly to phase changes which alter the wave front and amplitude of the peaks. It might be thought that phase changes which destroy some peaks would tend to create others. However, a Fourier analysis of a sharp peak will show that an exact phase relationship must exist between all of the frequency components. The probability that phase shift in a line will chance to cause all of the many frequency components of a complex wave to align themselves in the relationship necessary to create a peak where none existed before, is very slight, indeed infinitesimal compared to the probability of the occurrence of a peak in the original wave.

Data on peak checking showed such a marked advantage for the r.m.s. type as compared with the peak instrument, that it was decided to employ the r.m.s. type of instrument. Other considerations included the possibility of employing copper-oxide rectifiers and thereby eliminating vacuum tubes with their attendant need of power supply; an advantage not shared by peak-reading instruments. Thus, the r.m.s. instrument has advantages of comparative low cost, ruggedness, and freedom from the need of power supply, and can, moreover, be readily made in portable forms when desired.

Dynamic and Electrical Characteristics

It will be appreciated from the above discussion that for a volume indicator to be truly standard, both its dynamic and electrical characteristics must be controlled and specified so that different instruments will indicate alike on the
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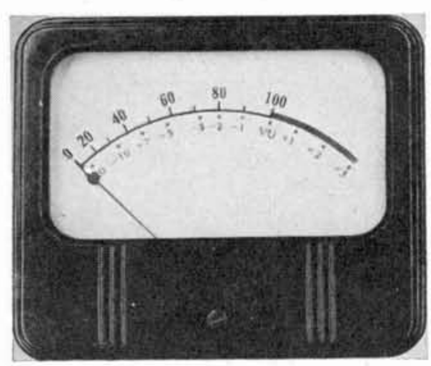

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Fig. 3. The "B" type standard volume indicator scale emphasizes the percentage scale. This scale is used extensively for program transmission applications.

AUDIO VOLUME MEASUREMENT

[*from page 28*]

rapidly varying speech and program waves. In deciding upon the dynamic characteristics, an important factor included in the consideration was the ease of reading the instrument and the lack of eye strain in observing it for long periods.

For ease of reading and minimum of eye fatigue, the movement should not be too fast. As a result of observations under service conditions, and other tests, the requirement was adopted that the sudden application of a 1000-cps sine wave of such amplitude as to give a steady deflection at the scale point where the instrument is to be read, shall cause the pointer to read 99 per cent of the final deflection in 0.3 second.

It was also noted that on speech and program waves, instruments which were critically damped or slightly overdamped had a more "jittery" action than instruments slightly underdamped. Consequently the strain of reading the former type is greater than for the latter. A theoretical study of the problem verified the validity of this subjective observation. The requirement was therefore adopted that the standard volume indicator movement shall be slightly less than critically damped, so that the pointer will overswing not less than 1 per cent nor more than 1.5 per cent when the sine wave mentioned in the preceding paragraph is applied.

The question of whether the rectifier, which is a part of the standard volume indicator, should be half-wave or full-wave needs little discussion. As is well known, many program waves (particularly speech) show a marked lack of symmetry. Obviously, if an instrument is to give the same indication, no matter which way it is poled, a balanced full-wave rectifier is required.

Throughout this discussion, the term "r.m.s." has been used loosely to describe the general type of instrument under consideration. The equation that relates the instrument coil current to the potential applied to the volume indicator is:

$$i = ke^p$$

where i = instantaneous coil current.
e = instantaneous potential.
k = a constant.

The exponent p in the above equation is 1.2 for the standard volume indicator. Therefore its characteristics are intermediate between a linear ($p=1$) and a square-law or "root-mean-square" ($p=2$) characteristic.

In many applications *the rectifier law is just as important as the other electrical and dynamic characteristics* of the standard volume indicator. Unfortunately, there is a tendency to overlook this fact in many instances and to simply specify that the indicating instrument of some particular piece of measuring equipment "shall have dynamic characteristics identical to that of the standard volume indicator."

Instrument Scale

Among the more important features to be considered in the development of a volume indicator is the design of its scale. In broadcasting studios, volume indicators are under observation almost continuously by the control operators. Consequently, the ease and accuracy of reading, and the degree of eye strain are of major importance.

It is evident that the instrument scale should be easy to read in order that the peak reached by the needle under the impetus of a given impulse may be accurately determined. The instrument scale, therefore, should be as large as practical since, in the case of the broadcast and recording applications, attention is often divided between the action in the studio and the volume indicator.

Volume level indicators are used (a) as an aid to tailoring the wide dynamic range of an original performance to that of the associated transmission medium and (b) for locating the upper part of the dynamic range just within the overload point of an equipment during its normal operation. For the first of these uses, a scale having a wide decibel range is preferable. For the latter purpose, a scale length of 10 db is usually adequate. Since a given instrument may be used for both applications neither too large nor too small a range is desirable in volume level indicators for the above purposes. A usable scale length covering 20 db appears to be a satisfactory compromise.

Both VU markings[2] and markings proportional to voltage are incorporated in the new instrument scale. The need for the former is obvious, but the philosophy which lead to the inclusion of the latter may require some explanation.

It is evident, assuming a linear system, that the voltage scale is directly proportional to percentage modulation of radio transmitter or recording system upon which the program is finally impressed. If the system is adjusted for complete modulation for a deflection to the 100-per cent mark, then subsequent indications show the degree of modulation under actual operating conditions. In the interests of best operation, it may be desirable, of course, to adjust the system for somewhat less than complete modulaton when the 100 per cent indication is reached.

In any event, the indications on the voltage scale always show the *percentage utilization of the channel.* This is a decided advantage because everyone concerned (both technical and non-technical personnel) has a clear conception of a percentage indication. Furthermore, since the scale does not extend beyond the 100 per cent mark (except in the form of a red warning band) and since it is impossible to obtain more than 100 per cent utilization of the facilities, there is less incentive on the part of non-technical people connected with program origination, to request "an extra-loud effect" on special occasions.

Actually, two scales, each containing both VU and voltage markings, have been standardized. One of these known as the type A scale, *Fig. 2*, emphasizes the VU markings and has an inconspicuous voltage scale. The second, known as the type B, *Fig. 3*, reverses the emphasis on the two scales. This arrangement permits the installation of the instrument which emphasizes the scale that is most important to the user, while retaining the alternate scale for correlation purposes.

Ever mindful of the possibility of eye fatigue even the color of the scale card has been standardized. It is a light orange-yellow, which seems to be a satisfactory compromise between high contrast and reduced eye-strain. This choice was based upon the preference of a large group of skilled observers and upon the reports of certain societies for the improvement of vision. The use of matte-finished instrument cases having fairly high reflection coefficients, such as light gray, is also desirable for ease of vision.

Finally in studio applications the scale must be properly illuminated so that the relative light intensity on the face of the instrument is comparable to that on the sound stage. Unless this condition prevails, the eye may have difficulty in accommodating itself with sufficient rapidity to the changes in illumination as the operator glances back and forth from the studio to the volume-indicator instrument.

(To be concluded)

[2] Terminology is explained in a following section.

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The Measurement of Audio Volume

H. A. CHINN*

Part II—A comprehensive discussion of the problems involved and the instruments employed to indicate program level and sine-wave tones in broadcast and recording circuits.

A THOROUGH COMPREHENSION of the connotations of the term "reference volume" is fundamental to any studio engineering endeavor. Unfortunately, experience has shown that this subject is often completely misunderstood. It is hoped that the following will dispel the vague understanding that sometimes surrounds this simple subject.

It is important to appreciate that reference volume is a practical and useful concept, but one which is quite arbitrary and not definable in fundamental terms. As already mentioned, it cannot be expressed in any single way in terms of the ordinary electrical units of power, potential, or current. Reference volume is describable only in terms of the electrical and dynamic characteristics of an instrument, its sensitivity as measured by its single-frequency calibration, and the technique of reading it. In other words, reference volume may be defined as that level of program which causes a standard volume indicator, when calibrated and used in the accepted way, to read zero VU.

The sensitivity of the standard volume indicator is such that reference volume corresponds to the indication of the instrument when it is bridged across a 600-ohm resistor[3] in which is flowing one milliwatt of sine-wave power.

It is especially cautioned that *reference volume should not be confused with the single-frequency power* used to calibrate the zero volume setting of the volume indicator. If a volume indicator is calibrated so as to read zero VU on a sine wave power of, say, one milliwatt in a stated impedance, a speech or program wave in the same impedance whose intensity is such as to give also a reading of zero VU will have instantaneous peaks of power which are several times one milliwatt and an average power which is only a small fraction of a milliwatt. It is therefore erroneous to say that reference volume is one milliwatt.

Moreover, it should be emphasized that although it is convenient to measure the performance of amplifiers and systems by means of single frequencies there is no *exact* universal relationship between the single-frequency load-carrying capacity indicated by such measurements, and the load-carrying capacity for speech and program waves expressed in terms of volume level. This relationship depends upon a number of factors such as the rapidity of cutoff at the overload point, the frequency bandwidth being transmitted, the quality of service to be rendered, and similar factors.

The question may well be raised why reference volume has been related to a calibrating *power* rather than to a calibrating *voltage,* inasmuch as a volume indicator is generally a high-impedance, voltage-responsive device. A reference level could conceivably be established based on voltage and the unit of measurement might be termed "volume-volts." However, volume measurements are a part of the general field of transmission measurements, and the same reasons apply here for basing them on power considerations as in the case of ordinary transmission measurements using sine waves. If the fundamental concept were voltage, apparent gains or losses would appear wherever impedance transforming devices (such as transformers) occur in a circuit. This difficulty is avoided by adopting the power concept, making suitable corrections in the readings when the impedance is other than 600 ohms.

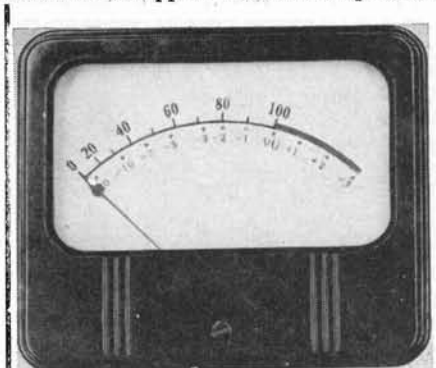

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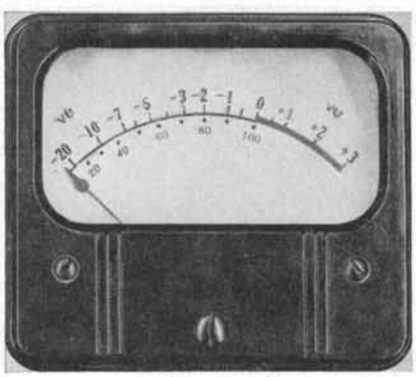
Fig. 3. The "B" type standard volume indicator scale emphasizes the percentage scale. This scale is used extensively for program transmission applications.



Courtesy General Electric Co.

Fig. 2. The "A" type standard volume indicator scale emphasizes the VU markings and has an inconspicuous voltage scale. This type of scale is commonly used for transmission measuring sets.

Volume Measurement Terminology

(a) VU. The terminology that is used to express volume measurements was created to avoid confusion as to the type of volume indicator used and the reference level. The term "VU" (pronounced "vee-you") is used; the number of VU

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[3] A standard impedance of 600 ohms was chosen originally since, keeping in mind the telephone plant, there was more audio equipment designed to this impedance than to any other.